

Experimental Study of Liquid Film Flow in Simulated Nuclear Fuel Rod Assembly

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Contents

1 General Introduction

References

2 Development of Non-intrusive Measuring Techniques of Dynamic Behavior of a Liquid Film Flow

2.1 Introduction

2.2 Fluorescence Dye Method

2.2.1 Principle of Measurement

2.2.2 Optical System

2.2.3 Image Processing and Measurement Procedures

2.2.4 Discussion of Measuring Accuracy

2.3 Ultrasonic Echo Method

2.3.1 Principle of Measurement

2.3.2 Data Processing

2.3.2.1 Raw Data from Ultrasonic Flaw Detector

2.3.2.2 Interpolation to Reconstruct Two-Dimensional Data

2.3.3 Discussion of Measuring Accuracy

2.3.4 Preliminary Test

2.4 Summary

References

3 Characteristics of Liquid Film Flow in a Horizontal Rectangular Channel

3.1 Introduction

3.2 Experimental Apparatus and Conditions

3.3 Liquid Film Flow Pattern Observation

3.3.1 Lateral Film Thickness Distribution across Channel Cross-Section

3.3.2 Longitudinal Film Thickness Distribution at Centerline of Channel

3.4 Results and Discussion

3.4.1 Classification of Waves

3.4.2 Power Spectral Density Distribution of the Film Thickness Fluctuation

3.4.3 Number of Passing Waves

3.4.4 Mean Wave Height

3.4.5 Mean Wave Velocity

3.4.6 Mean Axial Width and Cross-Sectional Area

3.4.7 Wave Steepness

3.5 Summary

References

4 Characteristics of Liquid Film Flow affected by Obstacle

4.1 Introduction

4.2 Experimental Apparatus and Conditions

4.3 Results and Discussions

4.3.1 Overview of the Liquid Film Flow in Obstacle Region

4.3.2 Overview of the Liquid Film Flow in Up- and Downstream Region of Obstacle

4.3.3 Time-Averaged Liquid Film Thickness around Front Edge

4.3.4 Time-Averaged Liquid Film Thickness around Rear Edge

4.4 Summary

References

5 Characteristics of Vertically Upward External Flow in an Annulus

5.1 Introduction

5.2 Experimental Apparatus and Conditions

5.3 Liquid Film Flow Pattern Observation

5.4 Results and Discussions

5.4.1 Time-Averaged Liquid Film Thickness

5.4.2 Power Spectral Density Distribution of the Film Thickness Fluctuation

5.4.4 Characteristics of Disturbance Wave and Ripple

5.5 Summary

References

6 Characteristics of Liquid Film Flow in a 3×3 Rod Bundle with Spacers

6.1 Introduction

6.2 Experimental Apparatus and Conditions

6.3 Overview of Dynamic Behavior of Liquid Film Flow

6.4 Results and Discussions

6.4.1 Cross-Sectional Averaged Liquid Film Thickness

6.4.2 Longitudinal Evolution of Time-Averaged Liquid Film Thickness

6.4.3 Circumferential Distribution of Time-Averaged Liquid Film Thickness

6.4.4 Ununiformity of Liquid Film Thickness Distribution Around Rod

6.4.5 Time-Averaged Liquid Film Thickness in Upstream Region of Spacer

- 6.4.6 Time-Averaged Liquid Film Thickness in Downstream Region of Spacer
- 6.4.7 Effects of Projections in Downstream Region of Spacer
- 6.4.8 Effect of Dimples in Farther Downstream Region of Spacer
- 6.4.9 Dependency of Liquid Flow Rate on Liquid Film Thickness
- 6.4.10 Power Spectral Density Distribution of the Film Thickness Fluctuation
- 6.4.11 Characteristics of Interfacial Waves

6.5 Summary

References

7 Conclusion

- 7.1 Development of Non-Intrusive and Multi-Dimensional Measuring Techniques
- 7.2 Effects of Obstacle on Liquid Film Flow
- 7.3 Recommendations for Future Work

Acknowledgement

1. General Introduction

Annular dispersed flow is an important flow pattern, which appears in various industrial instruments such as boiler and nuclear reactor. As a prime factor to determine thermal limitation of these instruments, liquid film dryout phenomenon plays a vital role in annular dispersed flow. Especially, nuclear fuel assembly in reactor core has a large thermal power and is operated under high heat flux condition; thus, to ensure its cooling characteristics is crucial for nuclear reactor safety. Therefore, great amounts of experimental works have been done about liquid film dryout phenomenon in past few decades and numerical simulations also carried out recently.

For thermal-hydraulic analysis in nuclear fuel assembly, subchannel analysis is used considering small channel (subchannel) surrounded with fuel rods and channel wall as control volume in which coolant flows as illustrated in figure 1.1(a). In one of the earliest subchannel code called COBRA by Rowe [1-3], two-phase flow in subchannel was treated by two-fluid model. However, in annular dispersed flow regime occurring in fuel rod assembly, parts of liquid phase (most parts in dryout region) flow as liquid droplets in gas phase. Thus recent analysis codes, for example as FIDAS [4-8], solve conservation equations for mass, momentum and energy in each subchannel with three fluid model taking into account of liquid droplets and liquid film formed on fuel rod surface and vapor flow at where a balance between entrainment, droplets deposition and evaporation governs liquid film on fuel rod. Therefore, critical heat flux is characterized by liquid film dryout.

On the other hand, nuclear fuel rod bundle is a complicated geometry consisted of many fuel rods and clearance between each fuel rod is narrow from restriction to reactor core physics. Mechanical spacers are equipped to keep this clearance adequately; these spacers obstruct two-phase flow in turn. Thus time-dependent film flow structure is changes before and after these spacers as shown in figure 1.1(b).

Therefore, accurate prediction of time-dependent spatial distribution of liquid film thickness is indispensable for an evaluation of critical heat flux of fuel rod assembly. However, we do not have reliable database for non-homogeneous liquid film flow on the fuel rods mainly because of a lack in accurate non-intrusive measuring techniques.

From these points of view, we developed new non-intrusive liquid film measuring techniques giving no additional upset to two-phase flow in the beginning. We studied spacer effects on liquid film flow both in a horizontal channel and in a 3×3 simulating nuclear fuel rod bundle experimentally in this research.

This thesis is consisting of 7 chapters. Outline of each chapter is summarized as follows.

Chapter 1 General Introduction

Background of this thesis is explained.

Chapter 2 Development of Non-intrusive Measuring Techniques of Dynamic Behavior of a Liquid Film Flow

Since liquid film flow that occurs in dryout region is sensitive to external agitation, optical technique and ultrasonic echo technique were applied to measure instantaneous multi-dimensional film thickness distribution for internal and external liquid film flows. Details of the Fluorescence Dye Method (FDM) using a sheet wise laser light and small amount of fluorescence dye contained in liquid phase and the Ultrasonic Echo Method (USEM) adopting a highly rotating reflector, discussions about measuring accuracy and typical results are described.

Chapter 3 Characteristics of Liquid Film Flow in a Horizontal Rectangular Channel

The FDM was applied to clarify macroscopic characteristics of the liquid film flow. Several flow patterns were visualized in a horizontal rectangular channel as a case of the maximum curvature of circular tube. Reconstructed multi-dimensional images as bird's eye view graphics and contour plots gave excellent understandings of liquid film behavior. Characteristics of surface waves, such as wave velocity, width and wave steepness, were obtained. Types of interfacial waves on liquid film are also discussed in this chapter.

Chapter 4 Characteristics of Liquid Film Flow affected by Obstacle

Liquid film flow is often affected by flow obstacle such as spacers in nuclear reactor fuel rod assembly since film thickness becomes thin at flow conditions of high gas velocity and low liquid flow rate enough to be agitated by external obstructions. To clarify the fundamental characteristics of obstacle effect on liquid film flow, time-dependent liquid film thickness distribution was measured by the FDM under the affection of obstacle having cross-sectional shapes of rectangle, trapezoid and inverted

trapezoid in a horizontal rectangular channel. Influence of placement height of obstacle and effect of obstacle shape will be discussed in this chapter.

Chapter 5 Characteristics of External Flow in a Vertical Upward Annulus Tube

Characteristics of a vertically upward external liquid film flow will be discussed in this chapter. Annulus tube was used as a simplified case of complex subchannel geometry in nuclear fuel rod assembly. Time-dependent liquid film thickness around tube was measured by the USEM. Reconstructed multi-dimensional images are displayed in bird's eye view, contour plots and consecutive plots. Characteristics of surface waves such as wave width, wave height, number of wave and power spectral density are discussed.

Chapter 6 Characteristics of Liquid Film Flow in a 3×3 Rod Bundle with Spacers

Nuclear fuel rod bundle is a complex geometry consisted of many fuel rods and clearance between each fuel rod is narrow by restriction of reactor core physics. Mechanical spacers are equipped to keep this clearance adequately; these spacers obstruct two-phase flow in turn. Thus time-dependent liquid film flow structure is changed before and after these spacers. Concerning with this, time-dependent spatial distributions of liquid film thickness in a simulating 3×3 rod bundle supported by circular cell type spacer was measured by the USEM, and the results about the liquid film behavior around spacer will be discussed in this chapter.

Chapter 7 Conclusion

Results obtained in each chapter are summarized and future views are mentioned.

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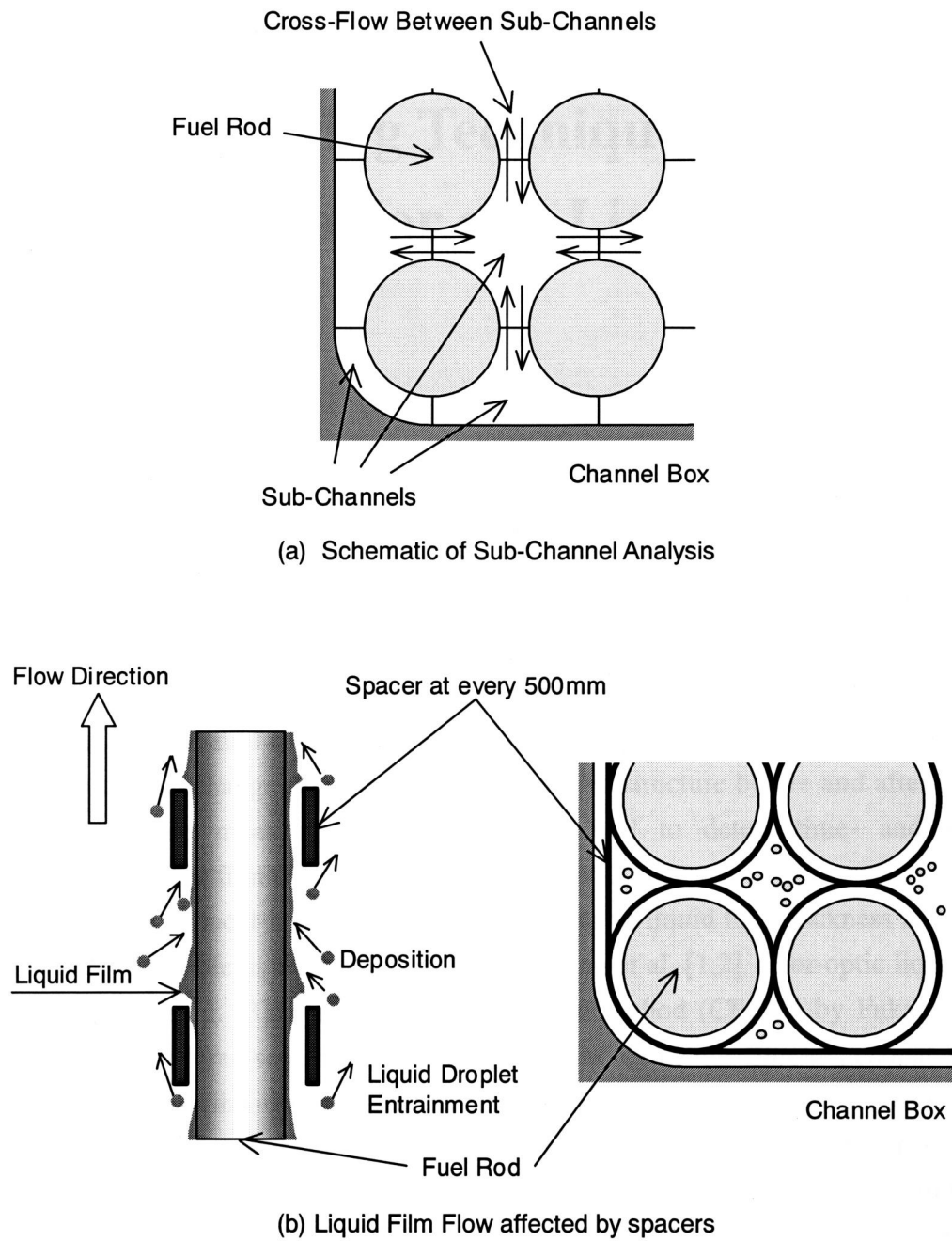


Figure 1.1 Schematic of Liquid Film Flow in a BWR Channel Box

2. Development of Non-intrusive Measuring Techniques of Dynamic Behavior of a Liquid Film Flow

2.1. Introduction

In annular dispersed flow occurring in fuel rod assembly near dryout region, balance between entrainment, droplets deposition and evaporation governs liquid film behavior flowing on fuel rod. Since fuel rod assembly is a complicated geometry consisted of a lot of fuel rods, mechanical spacers are used to keep clearance between each rod in turn to change time-dependent liquid film structure before and after spacer. Therefore accurate measuring technique is required to detect time- and spatial dependence of liquid film thickness.

Many kinds of local-instant measuring technique of liquid film thickness have been developed for example as flush wire method by Kang et al. [1,2], fiber-optic liquid film sensor by Ohba et al. [3], constant electric current method (CECM) by Fukano [4,5]. Combination of plural sensors is often applied for detecting time-dependent multi-dimensional liquid film distribution. Kang et al. [6] used 10 flush-wire probes with 4mm intervals in span wise direction and another probe placed downstream of these probe array to measure two-dimensional distribution of instantaneous liquid film thickness and wave velocity simultaneously. Strand et al. [7] used 4 resistance probes with 13.3mm interval and measured time traces of two-dimensional liquid film thickness. They also used LDA equipment for measurement of both gas and liquid phase velocity.

Among several techniques to measure the time- and spatial sequences of two-phase film flow, the most interesting one is the super multiple point-electrode probes method proposed by Sekoguchi et al. [8,9]. This method used 409 contact needle probes for detecting the instantaneous phase distributions in a cross-sectional area of the flow and

then reconstructed the time-sequential images of the liquid films. However, so many probes placed in the flow will certainly generate additional disturbance to the flow, and hence, the images might have been skewed.

Non-intrusive techniques are therefore desired not to disturb the flow. Several optical methods satisfying this demand have been previously proposed, for example, the axial view technique by Hewitt et al. [10,11] and parallel light technique by Hewitt and Whalley [12]. Although the former method can visualize the liquid droplets motions in the radial direction of flow channel, it is difficult to measure the dynamic behavior of liquid film flow at a certain cross-sectional area. The parallel light technique enables us to obtain the cross-sectional images of a liquid film flow. However, it has also a limit in its application to measure film flow in a long channel, since this technique requires a short flow channel in order for the laser light to reach the area of interest.

On the other hand side, X-ray tomography, neutron radiography and ultrasonic technique are considered as other non-intrusive measuring techniques without using a visible ray. Ikeda et al. [13,14] measured void fraction of two-phase flow in horizontal U-tube channel by X-ray CT Scanner and confirmed its propriety of application from comparison with other results obtained by hot-film velocimetry. Morooka et al. [15] discussed about an extension of medical X-ray CT Scanner to void fraction measurement in a simulated BWR fuel assembly for evaluation of cross-sectional averaged void fraction. Akiyama et al. [16] measured void fraction both under stable and unstable condition of simulated 5×5 fuel rod bundle of PWR subchannel by γ -ray CT Scanner. Inoue et al. [17] applied X-ray CT Scanner for void fraction measurement in a simulated BWR fuel rod bundle and they compared its results with numerical simulation obtained by COBRA/BWR and THERMIT-2.

Harris et al. [18] demonstrated several applications of real time neutron radiography studied at Harwell. They discussed about flow patterns appeared in heated stainless steel tube during cooling by water and improved thin layer boiling theory for nuclear safety analysis code. Mishima et al. [19-21] visualized air-water two-phase flow in narrow rectangular metal duct by neutron radiography and applied image processing technique to determine void fraction. Carlisle et al. [22] also obtained void fraction distribution by image processing technique with neutron radiography in two-phase flow. Their results agreed well with calculation and direct observation. They clarified that vortex occurred after passage of slug in slug flow [23]. Glickstein et al. [24] measured both void fraction and bubble velocity by image processing technique with neutron radiography. Takenaka et al. [25-28] showed various works on two-phase flow in rod bundle.

Above two techniques (X-ray tomography, neutron radiography) were available for non-intrusive measurement of void fraction in opaque channel such as metal tube, however, they had difficulty to measure thin liquid film thickness because of their spatial resolution. On the other hand, ultrasonic technique is possible to be used for liquid film measurement.

Starkovich et al. [29] measured liquid film thickness by pulse echo method previously used for non-destructive detection of crack in material. Namely, they used flaw-detector and ultrasonic transducer to measure liquid film thickness on static water and falling down liquid film. Practicability of ultrasonic technique was shown that the technique had fast response time, direct calibration, high durability and small dependency of temperature. Dallman [30] mentioned that ultrasonic technique was available to apply for film thickness measurement of smooth film and highly distorted film by cylindrical obstacle. Park et al. [31] applied ultrasonic pulse echo method to measure liquid film thickness with comparison of theoretical results and analyzed effects of tube wall thickness, emission frequency of ultrasound, tube material on the measured value. Moreover, they measured liquid film thickness of air-water stratified flow both in horizontal rectangular and circular test channel with different frequency of ultrasonic pulse echo. Shekariz and Brenden [32] developed a unique technique adopting ultrasound to reconstruct two-dimensional distribution of particle in solid-water two-phase flow. Chang et al. [33-35] also contributed for applications of ultrasonic technique to two-phase flow.

Concerning above mentioned, optical technique and ultrasonic echo technique were applied to measure time-dependent multi-dimensional film thickness distribution for internal and external liquid film flows. In this chapter, details of the Fluorescence Dye Method (FDM) [36,37] based on LIF (Laser Induced Fluorescence Method) and the Ultrasonic Echo Method (USEM) [38-40], discussions about measuring accuracy and typical results are described.

2.2. Fluorescence Dye Method

2.2.1. Principle of Measurement

LIF is a technique to obtain several information of flow field by luminescence from a specified component accompanied in fluid with laser light [41]. LIF is widely applied for measurement of gas density, temperature and velocity distribution in combustion field. Lorencez et al. [42,43] applied a photo chromic dye activation method to stratified flows with smooth and wavy gas-liquid interface and measured liquid film velocity distribution. Though there are many kinds of luminous mechanism, suitable luminous material and laser optical system have to be chosen not to additionally disturb flow field. Luminescence is classified into two types: fluorescence having shorter lifetime than about 10nsec and phosphorescence having a long lifetime. In each case, luminous material has strong emission characteristics with rather narrow absorption wavelength, emission light from the excited molecular or ion has lower energy than that of incident laser and has longer wavelength.

Rhodamine B was adopted as luminous material for the FDM. Molecules of Rhodamine B contained in liquid phase are excited with absorption of incident laser light. Molecules of Rhodamine B raised to excited singlet state emit excess energy as vibrational energy and shift from high vibrational level to the minimum vibrational level. It takes about 10^{-12} ~ 10^{-9} sec for this energy deactivation process. Then molecules shift to singlet ground state from the excited singlet state with radiating excited energy as fluorescence. This process requires about 10^{-9} ~ 10^{-6} sec, thus, lifetime of fluorescence from Rhodamine B can be regarded as about 10^{-9} ~ 10^{-6} sec because nonradiation transition process takes negligible short time against fluorescence radiation.

Rhodamine B emits fluorescence by absorbing a light with wavelength ranging from 200nm to 600nm. The wavelength at the maximum absorption is 517nm and the dye emits a light having 590nm in wavelength. Therefore we used argon-gas laser (SPECTRA PHYSICS LASERS Inc. Model 2016-04S) as a light source to excite the fluorescence dye.

Serizawa et al. [36] proposed an axial view method based on a fluorescence technique using a sheet wise laser light. This method was applied to observe disturbance waves in a horizontal rectangular channel. However, it had still several points to be improved for practical uses to detect interfacial wave structures. Firstly, the rear part of a wave may be occasionally hidden by the front part of the wave as illustrated in figure 2.1(a). Here, the rear part means the upstream side of a wave, and the front part means the downstream side. The second problem, as shown in figure 2.1(b), was that the

observed disturbance wave is hidden by successive wave that locates between the laser incident area and detection video camera in a short period. In this case, the image of objective disturbance wave cannot reach the video camera, because the emitted light is scattered and is also absorbed by the downstream wave.

In order to overcome the above-mentioned shortcomings and to visualize the whole part of a liquid film, the viewing direction was set from the bottom through the channel wall as illustrated in figure 2.2. Fluorescence light refracts at the boundary between the channel wall made of acrylic resin and the liquid phase (water) and that between the gas phase (air) and the wall. The refractive index of acrylic resin is 1.49 and that of water is 1.33.

The FDM was applied with two different ways of observation of the film flow behavior. One of them is a perpendicular incidence type that enables us to visualize cross-sectional view of liquid film against flow direction as illustrated in figure 2.3(a). The laser sheet excites fluorescence dye contained in the liquid phase perpendicular to the flow direction. The other is a parallel incidence type as shown in figure 2.3(b). This type can measure both wave shape in the flow direction and the wave traveling velocity simultaneously.

2.2.2. Optical System

The laser light is adequately processed by an optical system before it excites the liquid phase. The optical system applied in this work is shown in figure 2.4. A cylindrical lens is used to convert a laser light from a beam to a sheet. To let this laser sheet become thin enough for high spatial resolution, two convex lenses are used. The laser sheet thickness in 0.1mm was realized at measuring planes. This sheet size was about 100mm long and about 80mm wide around the focal plane.

Fluorescence having 590nm wavelength is used for visualization, thus scattered laser light from channel wall in test section was eliminated by an optical filter equipped with video camera in order to be distinct the recorded images.

Image intensifier and image booster were also applied to enhance intensity of fluorescence. Function generator was used to control the image intensifier for providing exposure time being 10^{-4} sec. Digital shutter of video camera was thus set at bulb. The fluorescence light originating from the measuring liquid plane was recorded by the high-speed video camera (Nac Inc. MEMRECAM Ci, Photoron Inc. FASTCAM-Rabbit-2) at a speed of 1,000 frames per second (400 frames per second by the latter video camera). Arrangement of visualization system is shown in figure 2.5.

2.2.3. Image Processing and Measurement Procedures

Luminosity of fluorescence (F) recorded on video memory is expressed as below,

$$F = K \cdot I_0 \cdot C \cdot \varepsilon \cdot \varphi \cdot l \quad (2.1)$$

where K is device coefficient, I_0 is intensity of incident laser, C is concentration of luminous material, ε is absorption coefficient of luminous material, φ is quantum yield of luminous material and l is optical path length in test channel, respectively. Intensity of incident laser light was considered to be constant value in this research considering attenuation of laser light during propagation in thin liquid film being small. K , C , ε and φ are treated as constant values, too.

Optical path length l is acquired as demonstrated in figure 2.6. Viewing area on video memory is divided into three regions, (i): near channel bottom, (ii): center of liquid film and (iii): near gas-liquid interface. In the region (i), luminosity rises up from bottom of the video memory (point A) and becomes the maximum value at the interface between (i) and (ii) (point B). Luminosity has nearly constant value in the region (ii) since optical path length l in this region is constant. In the region (iii), luminosity decreases straightly from point C to point D corresponding to the gas-liquid interface. That is to say, luminosity on video memory distributes like in a trapezoid shape. Attenuation of fluorescence in liquid phase is neglected to calculate optical path length in each viewing region.

Typical example of luminosity distribution on the video memory (8bit) is demonstrated in figure 2.7(a). Liquid film corresponds to high luminosity part and the other part is gas phase. It is clearly recognized here that the luminosity increases from 0mm and then becomes a nearly constant value being about 250. The luminosity gradually decreases from about 8mm corresponding to the gas-liquid interface.

Binarization of luminosity on the video memory is often used in image processing technique to clearly identify objectives, however this technique is not appropriate for the FDM. Because both ends of the video frame is too dark to be distinguished as liquid phase in binarization due to the Gaussian intensity distribution of incident laser sheet. On the other hand, difference of luminosity between neighboring two positions in height is more clearly detected compare to the luminosity as shown in figure 2.7(b). Therefore, line-tracing method was applied to determine local liquid film thickness at a specified horizontal location as follows.

Video frame memory is separated into many pixels as illustrated in figure 2.8(a). Liquid film thickness at a specified horizontal location in i -axis is calculated by tracing the difference of luminosity in j -axis. When the luminosity at the position (i, j) exceeds a slice level corresponding to the liquid phase, this j is regarded as the point "A" that

corresponds to the point “A” denoted in figure 2.6. The point “C” is determined as a position of which luminosity firstly becomes 20% of the minimum difference of luminosity as indicated in figure 2.7(b). This point appears in the near side of the range between the points “C” and “D”. Then, distance between the points “A” and “C” provides liquid film thickness. Spatial resolution for thickness measurement in this processing is about 80 μ m since 15mm of test channel height is divided into 188 pixels.

Each video frame was fed to an A/D converter board equipped on a personal computer and then was processed using the line-tracing method with usual image pre-processing; interlace field interpolation, dynamic range expansion, logarithms filtering and smoothing operation. An example of original video image of liquid film cross-section, the processed image and the result of film thickness distribution are shown in figures 2.8(b), (c) and (d), respectively.

2.2.4. Discussion of Measuring Accuracy

It should be noted that the FDM gives the maximum film thickness of liquid film that passes through the visualization area during the exposure time of video camera. The visualization area of liquid film in flow direction depending on the fluorescence lifetime is expressed as follows,

$$(t + \tau) \times v + d \quad (2.2)$$

where t is the lifetime of fluorescence of the order 10^{-6} sec, τ is shutter speed of the video camera controlled by the function generator, v is liquid film traveling velocity and d is thickness of the laser sheet as illustrated in figure 2.9. τ chosen at 10^{-4} sec being much longer than t , therefore Eq. (2.2) is simplified as below,

$$\tau \times v + d \quad (2.3)$$

It can be said that the visualization area with this method thus mainly depends on τ and d for constant liquid film velocity. Equation (2.3) calculates visualization area being about 0.11mm long for liquid film velocity $v=1$ m/s, $\tau=10^{-4}$ sec and $d=0.1$ mm. Though the largest liquid film thickness detected during this process is identified as the instant liquid film thickness on this video frame, tolerance is considered to be enough small.

As it is known, the gas-liquid interface is a complex structure having over hangs of liquid film like a prominence as illustrated in figure 2.10(a). Though several positions of gas-liquid interface in the incident plane of the laser sheet will be candidates for detection in such cases, the nearest position to the channel bottom was selected to determine the local liquid film thickness in this method. Liquid film formed on the top of test channel in annular dispersed flow also emits fluorescence as illustrated in figure

2.10(b), however, this information was not considered to obtain liquid film thickness for the upward liquid film because the fluorescence light coming through the rough surface of the lower liquid film is considered to be skewed.

We compared this measuring method with contact needle probe method to confirm adoptability of the new method to a static water surface. Contact needle was inserted into the test area from above not to disturb liquid film as similar as presented in figure 2.17(a). The result is shown in figure 2.11. Both results agree well with each other.

2.3. Ultrasonic Echo Method

2.3.1. Principle of Measurement

Serizawa et al. [36,38] successfully applied an ultrasonic transmission technique based on a time of flight to the measurement of local time-dependent liquid film thickness in a horizontal rectangular channel. The present method is an extension of this earlier technique to measure circumferential distribution of time-dependent liquid film thickness formed on a vertical tube simulating nuclear fuel rod.

Figure 2.12 shows a schematic of the ultrasonic transmission technique applied to the liquid film thickness measurement in a horizontal rectangular channel. The pulse-like ultrasonic wave reflects at boundaries between two different materials, that is, transducer-channel wall boundary, wall-liquid and gas-liquid interfaces.

Based on the time-of-flight principle, the liquid film thickness is calculated by Eq. (2.4).

$$l = \frac{\Delta t \times v}{2} \quad (2.4)$$

where l , Δt and v are liquid film thickness, flight time and propagation velocity of the ultrasonic waves in the liquid phase, respectively.

Generally, the ultrasonic transmission technique is applied to a point measurement for internal flow because of the difficulty in high speed scanning. We have overcome this difficulty by adopting a rotating reflector.

Figure 2.13 shows the measuring device used in the USEM. The device consists of a transducer emitting and receiving the ultrasonic waves, an aluminum rotating reflector and a micro-motor. The transducer and the reflector unit are contained in two separate small brass tubes. A supporting pole having 2mm width in order to keep the distance between them constant connects these two units. The assembly of the device is then mounted inside of a tube (simulated nuclear fuel rod) filled with water to assure the ultrasound propagation.

Ultrasonic waves reflected at the supporting pole were used as a reference signals to determine the relative location of each measurement point in circumferential direction. The reflector has a flat surface inclining 45 degrees with respect to the transducer axis. The reflector is rotated by the micro-motor at a speed of 20,000 rpm (the scanning time is therefore 3msec per round). The frequency of the ultrasonic wave is 10 MHz with emission frequency being 10 kHz. The transducer diameter was chosen to be 6.4mm for the moment that should be desirably reduced for further accurate measurement (we used a commercially sold probe).

The ultrasonic wave beam expands from the center of the transducer with an angle φ_0 given by Eq. (2.5).

$$\varphi_0 \approx 70 \frac{C}{D_E f} \quad (2.5)$$

where φ_0 , D_E , f and C are the expansion angle, transducer diameter, frequency of ultrasonic wave and the sound propagation velocity in the liquid phase, respectively. In the present work, the expansion angle φ_0 is about 1.6 degrees. A distance between the transducer and the reflector is 8mm, and that between the reflector and the wall inner surface is 5.5mm with 2mm tube wall thickness. The diameter of the ultrasonic wave beam thus becomes about 0.9mm at gas-liquid interface to be measured.

The echo signals are fed to an AD converter board of a personal computer. The maximum sampling rate is 10 MSps (MSps: mega-samples per second) and gives time resolution being 75 μ m assuming the sound velocity in water being 1,500m/s. Simple wave theory calculates also a same accuracy of the film thickness measurement from a half wavelength of the ultrasonic wave. The minimum detective film thickness is 150 μ m since two time series data are required to determine the peak of reflected wave.

The maximum sampling time is 1.6 seconds at moment due to a memory capacity of data acquisition system (16 MW). A low pass filter was also used to eliminate the noise components with frequencies higher than 1 MHz.

2.3.2. Data Processing

2.3.2.1. Raw Data from Ultrasonic Flaw Detector

Figure 2.14(a) shows a typical raw signal of the ultrasonic waves reflected at materials boundaries in the case of a liquid film existing on the outer surface of the tube. The first peak marked "A" in figure 2.14(a) corresponds to the reflection at the transducer surface. The second peak marked "B" is a reflection at the inner surface of the tube. The third peak "C" corresponds to the reflection at tube outer surface. The forth peak "D" is a reflection at the gas-liquid interface. The time lag between the peak "C" and "D" is used as Δt in Eq. (2.4).

Figure 2.14(b) is a case of no liquid film on the tube outer surface showing a similar trend to that observed in figure 2.14(a). However the forth peak "E" in figure 2.14(b) does not originate from the gas-liquid interface. It indicates the multiple echoes at the tube wall. The tube wall thickness and the wave velocity in acrylic resin determine the position where the multiple echoes appear. Since the amplitude of multiple echoes is smaller than that at the gas-liquid interface, the multiple echoes can be easily distinguished from the signal originating at the gas-liquid interface.

Figure 2.14(c) shows a typical example of the signal indicating the reflection at the supporting pole (peak “F”). Because the supporting pole is located nearer to the reflector than the inner wall of the tube, the reflection peak “F” is followed by the peak corresponding to the reflection at the inner wall of the tube denoted by “B” in figures 2.14(b) and 2.14(c).

2.3.2.2. Interpolation to Reconstruct Two-Dimensional Data

In the USEM using a single transducer, the local liquid film thickness at any circumferential position around tube surface is detected at every scanning time in a form of the time series of signals (in a spiral way) as shown in figure 2.15. Therefore, interpolation of liquid film thickness data is required to reconstruct two-dimensional images of the liquid film thickness distribution. Interpolating operation was processed as follows.

At first, the original time series of film thickness distribution around tube was stored in one-dimensional data array. Then, two-dimensional data array was constructed using this one-dimensional data array by detecting the pole data, to say with every scanning cycle. Here, the number of measuring data in one scanning is slightly different since the rotation speed is not necessarily constant (as illustrated in figure 2.15(1)). Therefore it is crucial to adjust the circumferential locations adequately between each scanning cycle when the two-dimensional data array is stored. In addition, in order to evaluate liquid film thickness at certain locations around tube, the number of elements in every row of two-dimensional data array should be same. Hoshide et al. [44] reported that time-averaged liquid film thickness had different value around nuclear fuel rod before spacer to be the minimum at where fuel rod surface was exposed to fast gas flow. Taking this result into account, the two-dimensional data array was reconstructed so as to separate one scanning into 24 locations with every 15 degrees around tube. Data set in every row was obtained by linear interpolation.

It should be noted here that the most important matter in the construction of two-dimensional data array is determination of the standard location in circumferential direction corresponding to the supporting pole. Width of the supporting pole being 2mm becomes about 24 degrees in view of angle, since the inner surface of the supporting pole is located at about 1mm inside of the test tube having 6mm inner radius. Thus, two or three measurement points give the pole data continuously for the scanning time (3msec) that calculates 12 degrees of angle between consecutive two measurement points. Concerning this, the standard location, to say 0 degree in circumferential direction, was determined as below.

- 1) Only the first data is pole data: This is 0 degree.
- 2) The first and the second data are pole data: Center of these location is 0 degree.
- 3) Between the first and the third data are pole data: The second is 0 degree.

At last, two-dimensional data array (dimensions: circumferential location and time lapse) is constructed using above data array by linear interpolation as illustrated in figure 2.15(2) and below,

$$f(i_c, t) = \frac{f(i_c, t_2) - f(i_c, t_1)}{24} \times i + f(i_c, t_1) \quad * \text{interpolated data at } i_c \text{ and } t$$

$$t_1 = 24 \times g_1 + i_c$$

$$t_2 = 24 \times g_2 + i_c = 24 \times (g_1 + 1) + i_c$$

$$t = (24 \times g_1 + i_c + i) \times \frac{N_d}{24} \times 0.1$$

$$f(i_c, t_1), f(i_c, t_2) : \text{measured data} \tag{2.6}$$

$$i : \text{time lapse at } i_c \ (i = 0 \sim 23)$$

$$i_c : \text{circumferential location} \ (i_c = 0 \sim 23)$$

$$g_1, g_2 : \text{number of scanning cycle (group of measured data)}$$

$$N_d : \text{number of data in every scanning cycle} \sim 30$$

where $f(i_c, t)$ is an interpolated value at certain circumferential location (i_c) and at time t . $f(i_c, t_2)$ and $f(i_c, t_1)$ are measured liquid film thickness. The number 24 drawn in Eq. (2.6) is the number of circumferential positions.

This operation is done for each location of measurement around the tube. It should be noted that the time resolution of measurement at the each position depends on the scanning time. Therefore the surface waves on the liquid film of which traveling time to pass the measurement location is shorter than the scanning time will be distorted by this linear interpolation. The time resolution of the method conjugated with the interpolating operation can be improved by increasing the rotation speed. However, there is a limitation in the rotation speed of the reflector.

2.3.3. Discussion of Measuring Accuracy

The number of measurement points is reduced by increasing the rotation speed of the reflector under the same transmitting rate of ultrasonic pulse waves. Thus the spatial resolution in the circumferential direction becomes poorer. The upper limit of transmitting rate of the ultrasonic pulses is determined by time of flight of ultrasonic waves in the materials. The total time of flight is about 25msec under the present

experimental setting. Therefore the upper limit will be about 20 kHz. Neighboring ultrasonic pulses will be superposed in the higher transmitting rate. On the other hand, transmitted ultrasonic pulses can not be detected by increasing of rotating speed because the surface of reflector goes away during ultrasonic pulse wave is traveling between reflector and gas-liquid interface. We evaluated the upper limit of rotation speed of reflector as following.

Flight path of the ultrasonic waves reflected by the reflector can be given depending on the rotation angle of the reflector. Axes are considered as illustrated in figure 2.16.

Each ultrasonic wave reflected at gas-liquid interface and at reflector surface are determined as incident vector and reflection vector, respectively. Normal vector at the reflector surface is also considered as indicated in figure 2.16. The coordinates x and z are taken to be the same as the incident vector and the perpendicular line from reflector to ultrasonic transducer, respectively. These three vectors have the following relation to each other.

- 1) Incident angle between reflection vector and normal vector is same to that of between incident vector and normal vector.
- 2) Length of reflection vector is same to that of incident vector.
- 3) These three vectors exist on the same plane.

Here, the gas-liquid interface is treated to be parallel to the channel wall surface.

Components of each vector are given as following.

- 1) Incident vector: (1, 0, 0)
- 2) Normal vector: (s, t, u)
- 3) Reflection vector: (x, y, z)

Here, for easiness of calculation, length of normal vector is set to 1 at any time. Therefore, following relation can be determined.

$$u^2 = \frac{1}{2}; s^2 + t^2 = \frac{1}{2} \quad (2.7)$$

From the relations between each vector, next equations are induced,

$$\overrightarrow{out} \cdot \vec{n} = - \frac{|\overrightarrow{out}|}{|\overrightarrow{in}|} \overrightarrow{in} \cdot \vec{n} \quad (2.8)$$

where $\overrightarrow{out}$ and $\overrightarrow{in}$ are reflection vector and incident vector, respectively.

Because $|\overrightarrow{out}|$ is equal to $|\overrightarrow{in}|$, Eq. (2.8) is refined to simple as Eq. (2.9).

$$\overrightarrow{out} \cdot \vec{n} = -\overrightarrow{in} \cdot \vec{n} \quad (2.9)$$

From the third relation mentioned before, reflection vector is expressed by incident vector and normal vector as Eq. (2.10),

$$\overrightarrow{out} = a\overrightarrow{in} + b\overrightarrow{n} \quad (2.10)$$

where a and b are parameter for calculation and have next relation which is conducted from Eq.(2.7), Eq.(2.9).

$$b = -s(1+a) \quad (2.11)$$

Moreover, Eq. (2.10) can be simplified from the relation that $|\overrightarrow{out}|=1$ and Eq. (2.11) as Eq. (2.12).

$$\overrightarrow{out} = \overrightarrow{in} - 2s\overrightarrow{n} \quad (2.12)$$

Thus, each-components of reflection vector can be expressed as following.

$$(x, y, z) = (1 - 2s^2, -2st, -2su) \quad (2.13)$$

It is necessary that the reflection vector directs to the transducer for reflected ultrasonic wave is detected. The transducer has a diameter of 6.4mm, however, we treat that ultrasonic wave should come into a circle which has 3.2mm diameter concerning beam expansion and roughness of gas-liquid interface. Clearance between the reflector and the transducer is 8mm.

Assuming that the reflector rotates θ degree while the ultrasonic wave goes and comes back between the reflector and gas-liquid interface, then normal vector becomes as Eq. (2.14).

$$\vec{n} = (s, t, u) = \left(-\frac{1}{\sqrt{2}} \cos \theta, \frac{1}{\sqrt{2}} \sin \theta, \frac{1}{\sqrt{2}} \right) \quad (2.14)$$

Therefore, reflection vector is expressed as below.

$$\overrightarrow{out} = (\sin^2 \theta, \sin \theta \cos \theta, \cos \theta) \quad (2.15)$$

Consequently, the angle between the reflection vector and z-axis has to be smaller than the angle α , which corresponds to the sensitive circle, and thus the reflection vector must satisfy the next relation.

$$\cos \theta > \cos \alpha = \frac{8}{\sqrt{8^2 + 1.6^2}} \quad (2.16)$$

Rotation angle is roughly about 10 degrees when Eq. (2.14) is satisfied. Time of flight of ultrasonic wave while it goes and comes between reflector and gas-liquid interface is about 12μsec, thus rotation speed will be order of about 100,000 rpm. In actual experiments, limit of rotation angle will be somewhat smaller because gas-liquid

interface is not always parallel to channel wall, therefore reflected ultrasonic waves cannot be detected if rotation speed is high.

In order to assess the measurement accuracy, comparisons were made between the USEM and contact needle probe method using the experimental apparatus shown in figure 2.17(a) where a static liquid film having a constant thickness is formed on the tube. Figure 2.17(b) is a comparison of the average film thickness. Results obtained with the USEM and contact needle method agree well with each other.

2.3.4. Preliminary Test

The preliminary experiment was carried out for a water film flow falling down freely on an acrylic tube (15mm O.D.) which contains in its inside the assembly of the newly developed measuring device as shown in figure 2.18. The liquid phase emerges from an injection slit having 1mm gap located at the top of the tube. The liquid flow rate was set constant at 3.5 l/min. The ultrasonic transducer was located at 20mm downstream from the injection slit of water.

Figure 2.19(a) shows a typical time sequence of liquid film thickness distribution around tube periphery. The liquid film thickness has circumferentially non-uniform distribution due to non-uniform liquid supply at the injection slit. The liquid film thickness varies little with time in the case of low liquid flow rate and thus the local liquid film thickness at any position around the tube tends to be nearly constant. The periodic trend of the liquid film thickness trace presented in figure 2.19(a) corresponds to the non-uniform liquid film thickness distribution around the tube.

Figure 2.19(b) shows a spiral plot of the original reconstructed image of the film thickness distribution without interpolating operation. It is not easy to see how liquid film surface distributed around tube periphery. Figure 2.19(c) shows the interpolated film thickness obtained at the same experimental condition. We can see the behavior of liquid film flow easier than the result of without interpolating operation. The front area of tube tends to have thicker film thickness than other area.

This trend is also confirmed from figure 2.20(a) showing cross-sectional plots of the same data set (top view). Figure 2.20(b) shows a bird's eye view to be able to see the whole part of liquid film surface at the same time. Both front part of tube and behind of tube are visualized by this plotting. Figure 2.20(c) shows a contour plot of the liquid film thickness. Time-dependent two-dimensional characteristics of the liquid film thickness around the tube can be seen very well.

2.4. Summary

Principle of the non-intrusive and multi-dimensional measuring methods of time dependent film thickness distribution, to say the Fluorescence Dye Method (FDM) based on LIF and the Ultrasonic Echo Method (USEM) were described in this chapter.

The FDM visualizes instantaneous liquid film cross-sectional shapes by detecting fluorescence coming from the luminous material accompanied in liquid phase excited by a sheet wise laser light. Rhodamine B and an argon gas laser were applied for the purpose. It was confirmed that the technique was enable to measure two-dimensional film thickness distribution in a relatively small error compare to the results of contact needle probe method in static water.

Spatial resolution of the FDM is about 80 μ m due to the size of the viewing area and digitization. The time resolution to detect time sequence of liquid film behavior is 1msec depending on the high-speed video camera at moment. These values are expected to be precise with improvement of applied systems.

Ultrasonic transmission technique that has been used for local measurement of instantaneous liquid film thickness formed on internal surface of channel was improved to measure multi-dimensional distribution of film thickness formed on external surface of tube adopting high-speed rotating reflector and interpolation processing.

The accuracy of the film thickness measurement is 75 μ m assuming the sound velocity in water being 1,500m/s. Since the USEM employs couple of one transducer and reflector, scanning time of reflector becomes major factor to reconstruct multi-dimensional image of liquid film flow precisely. The scanning time is about 3msec at moment. This value can be increased to 2msec by using higher rotation micro motor.

Liquid film thickness obtained by the USEM was compared with results by contact needle probe method in still water. Both results agreed well with each other. Reconstructed images of falling liquid film displayed both in bird's eye view and contour plot give excellent understanding of its behavior.

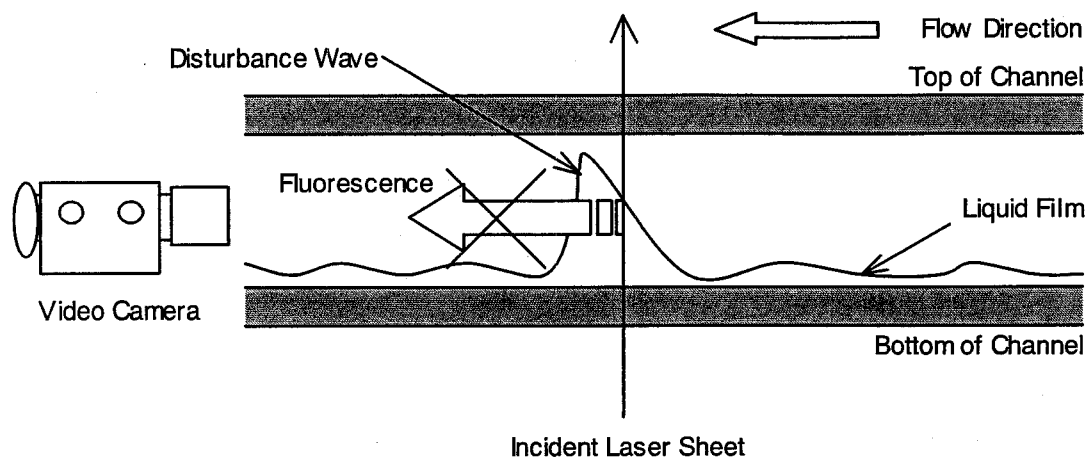
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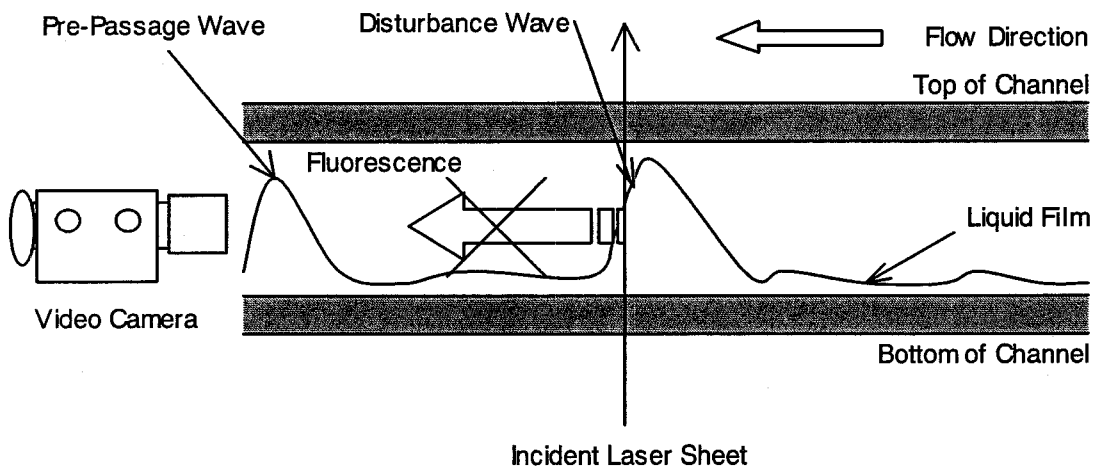
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(a) Hidden by the front part of the wave



(b) Hidden by successive wave

Figure 2.1 Obstruction of the Observation by Liquid Film

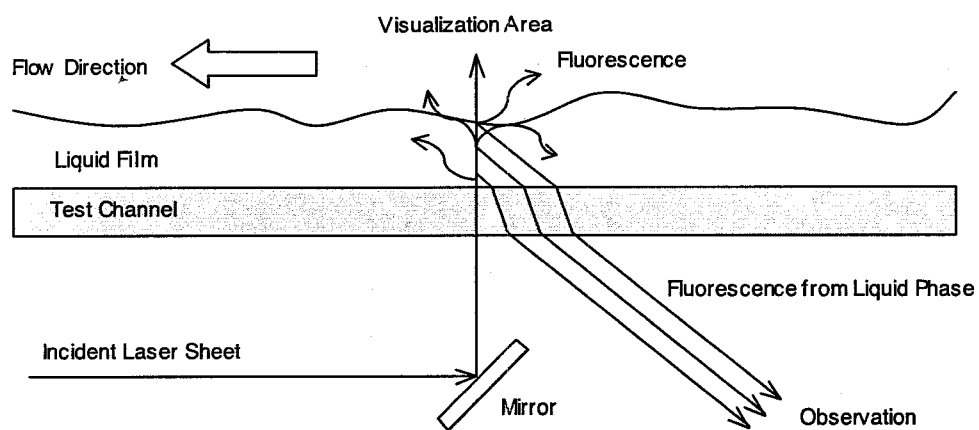
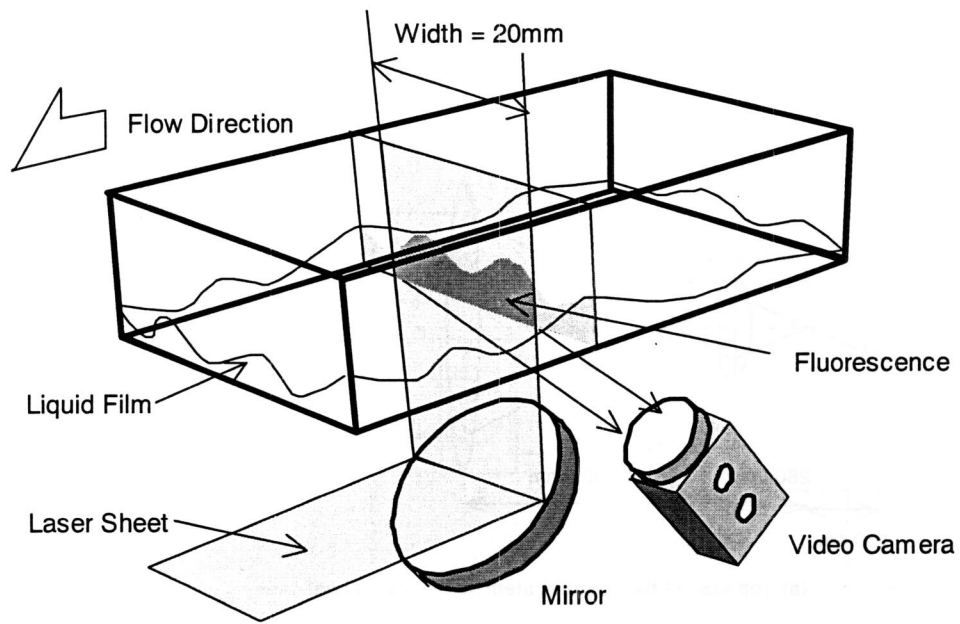
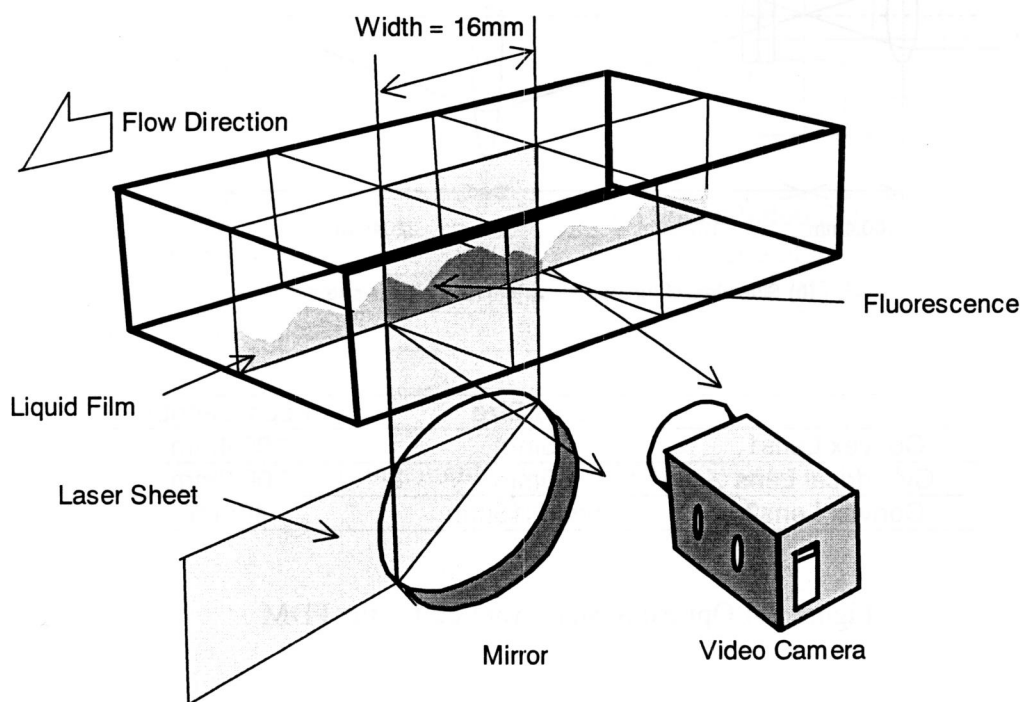


Figure 2.2 Incidence of Laser Sheet and Observation of Fluorescence

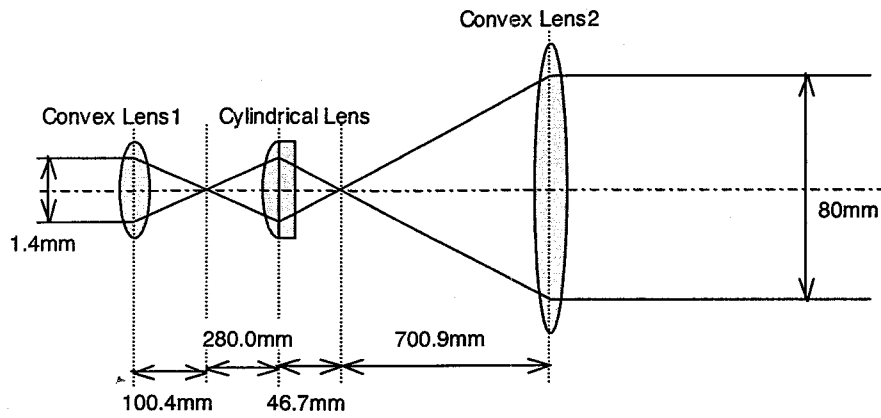


(a) Perpendicular incidence type of the FDM

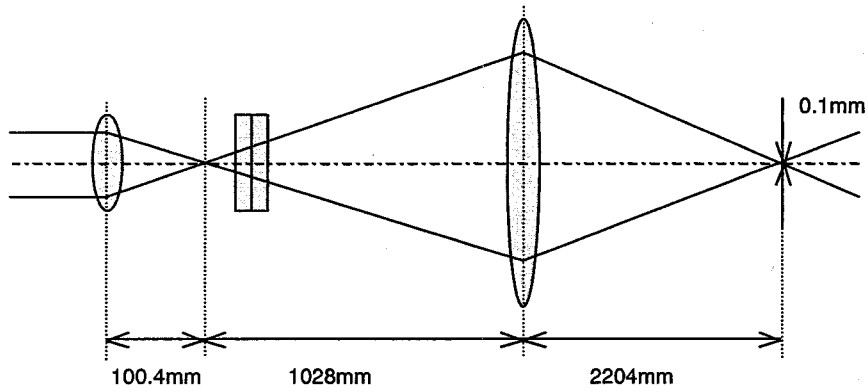


(b) Parallel incidence type of the FDM

Figure 2.3 Types of the Fluorescence Dye Method



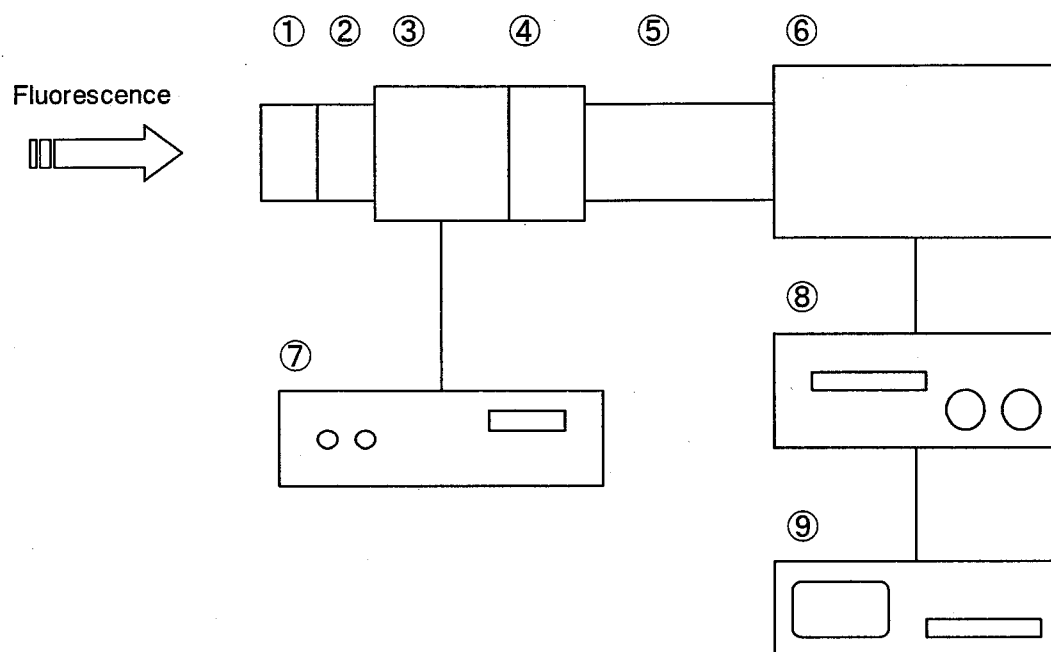
(a) Top view of the optical system for the laser sheet



(b) Side view of the optical system for the laser sheet

	Lens Size	Focal Length
Convex Lens1	15mm	100.4mm
Cylindrical Lens	80mm	700.9mm
Convex Lens2	15mm×15mm	40mm

Figure 2.4 Optical System Applied for the FDM



①	Optical Filter	⑥	High Speed Video Camera
②	Close-up Lens	⑦	Function Generator
③	Image Intensifier	⑧	Video Recorder (NTSC)
④	Image Booster	⑨	Personal Computer
⑤	Relay Lens		

Figure 2.5 Arrangement of Visualization System

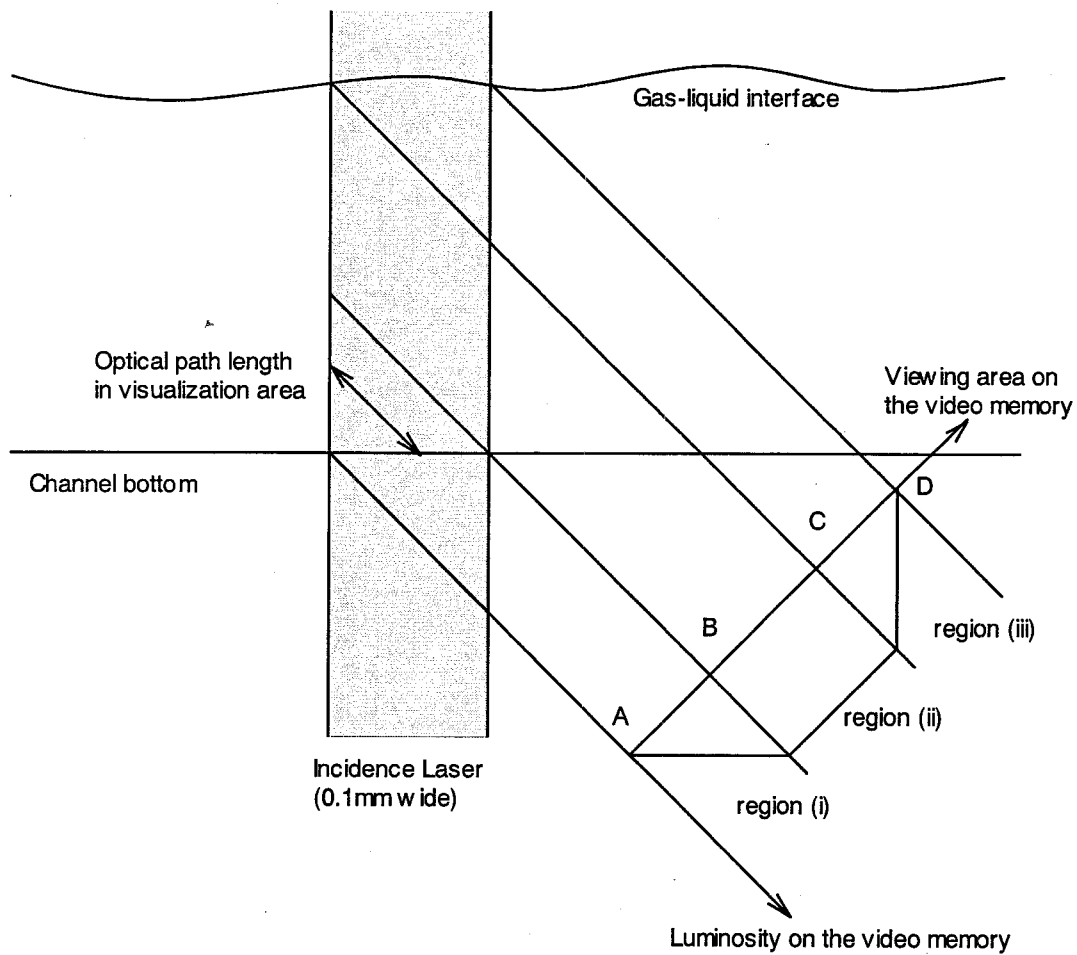
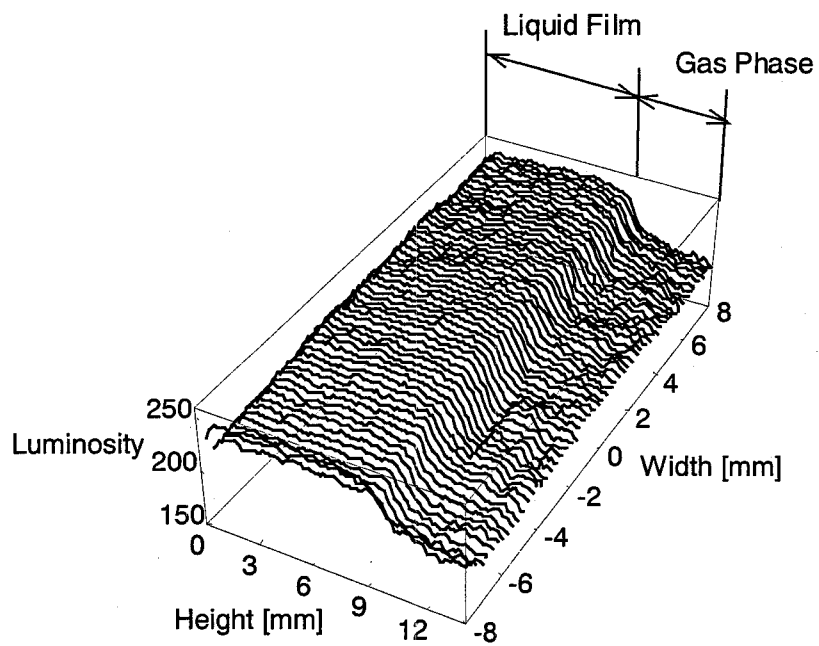
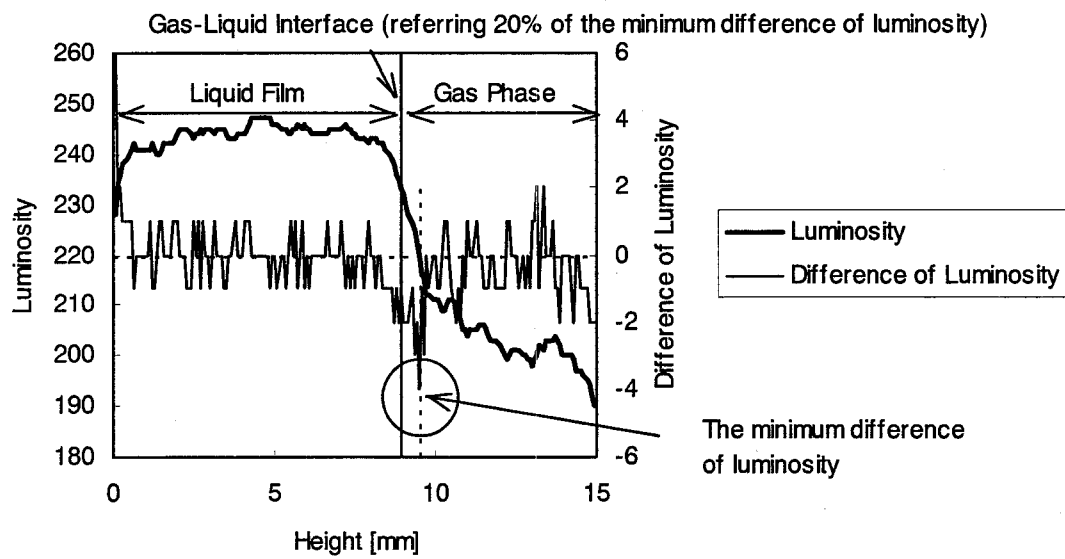


Figure 2.6 Luminosity Distribution in Viewing Area

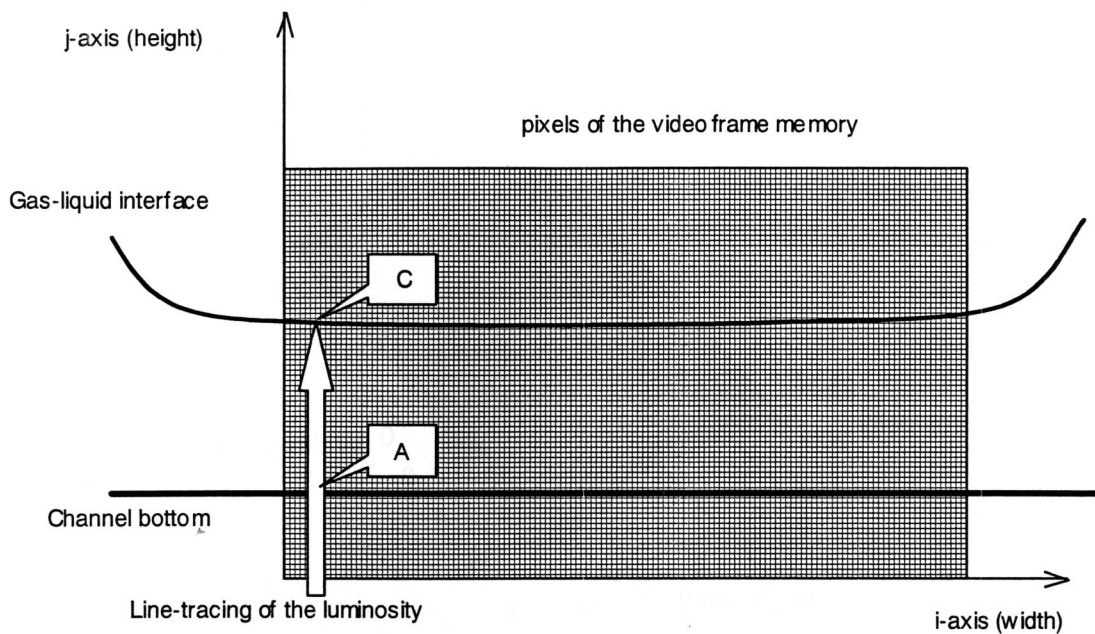


(a) Luminosity distribution in a video frame

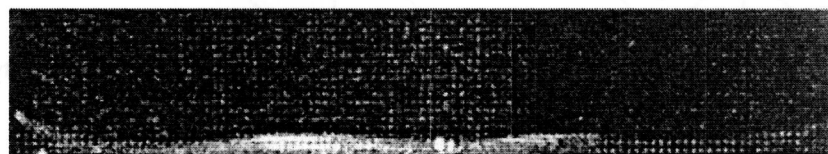


(b) Distributions of luminosity and its difference

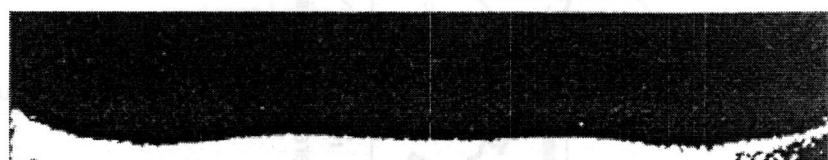
Figure 2.7 Examples of Luminosity Distribution on the Video Memory



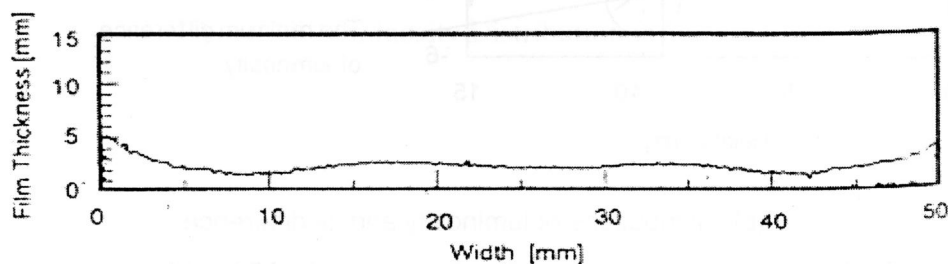
(a) Line-tracing method to calculate liquid film thickness



(b) Original cross-sectional image of liquid film



(c) Processed image for clarifying luminosity



(d) Liquid film thickness distribution in the channel width direction

Figure 2.8 Procedure of the Data Processing and the Typical Result

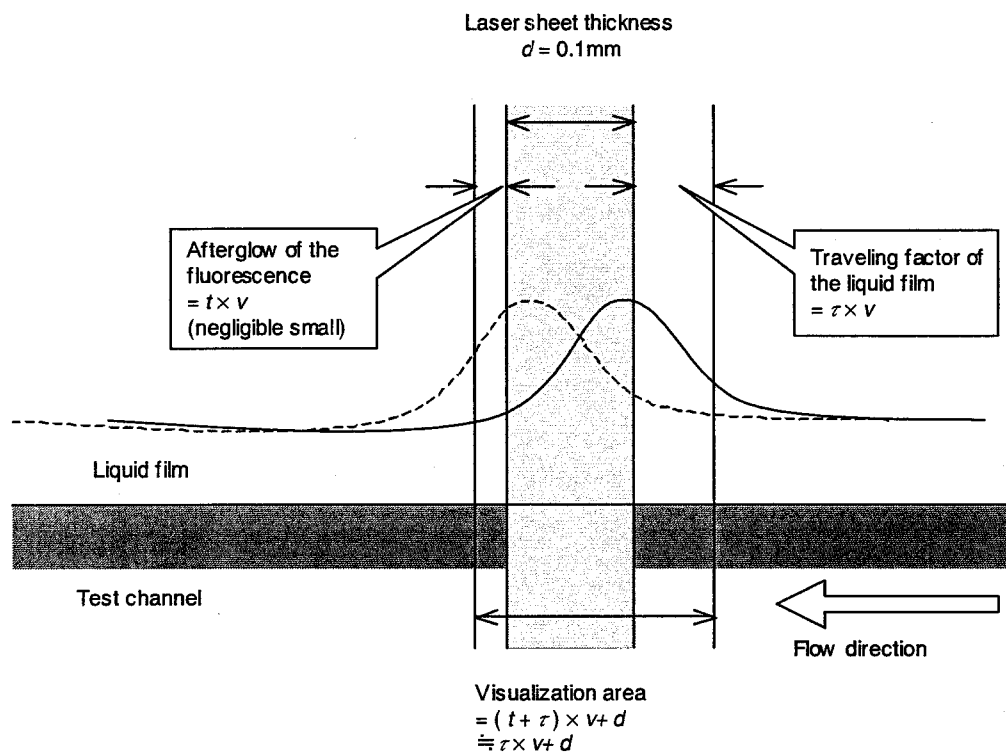
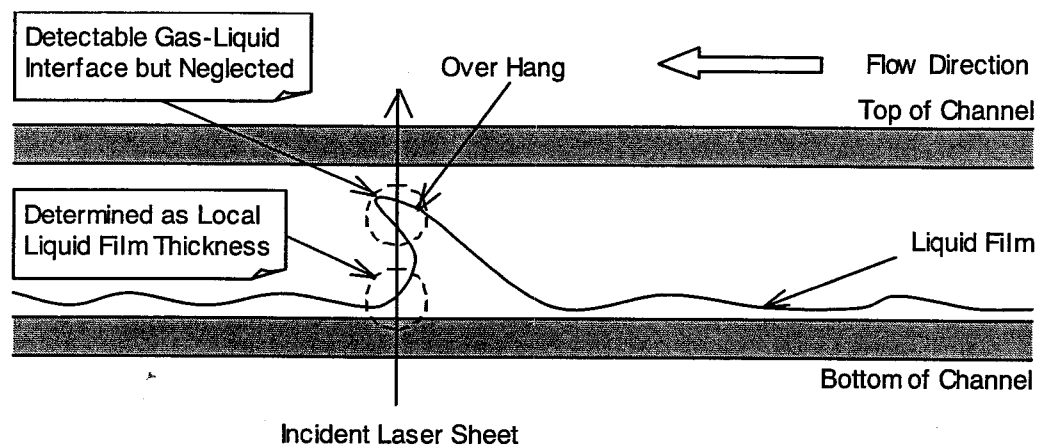
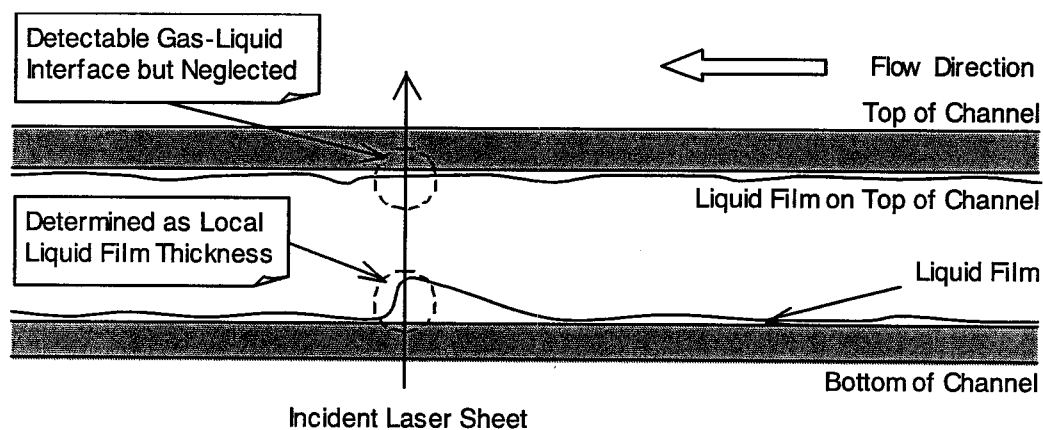


Figure 2.9 Schematic of the Visualization Area



(a) Over Hang of Disturbance Wave



(b) Liquid Film on Top of Channel in Annular Dispersed Flow

Figure 2.10 Determination of Liquid Film Thickness in a Complicated Film Structure

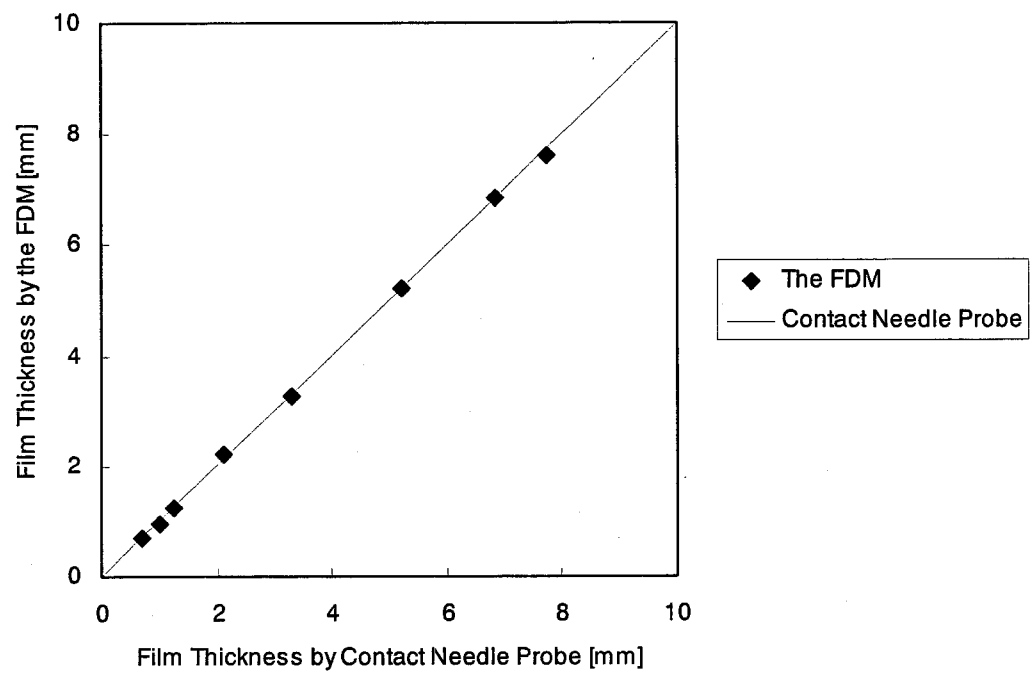


Figure 2.11 Comparison between the FDM and Contact Needle Probe Method

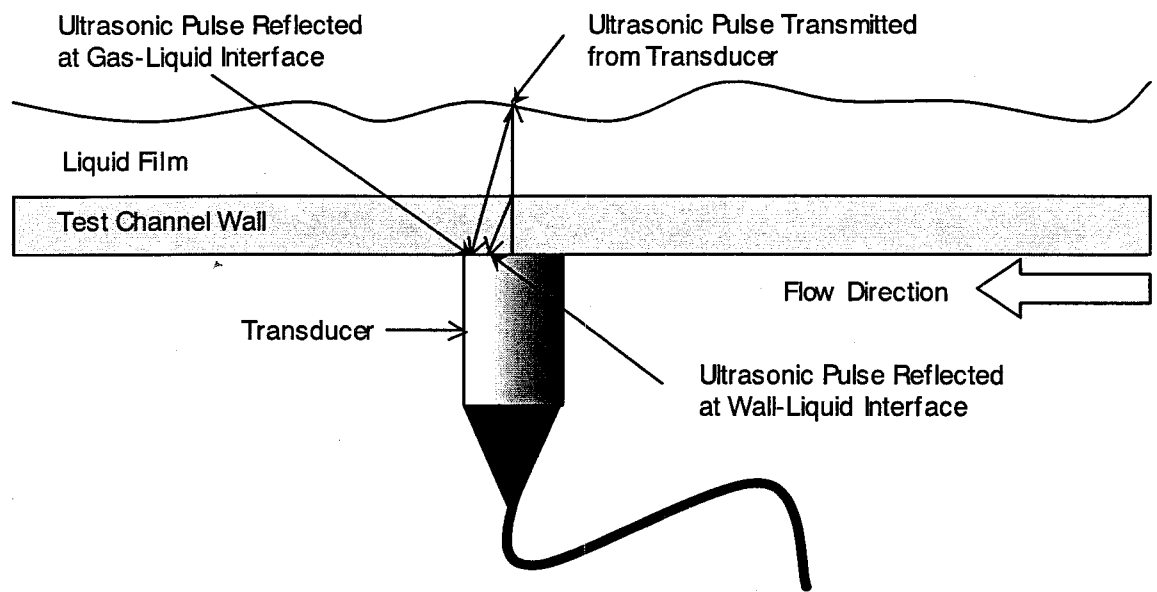


Figure 2.12 Schematic of Ultrasonic Echo Technique

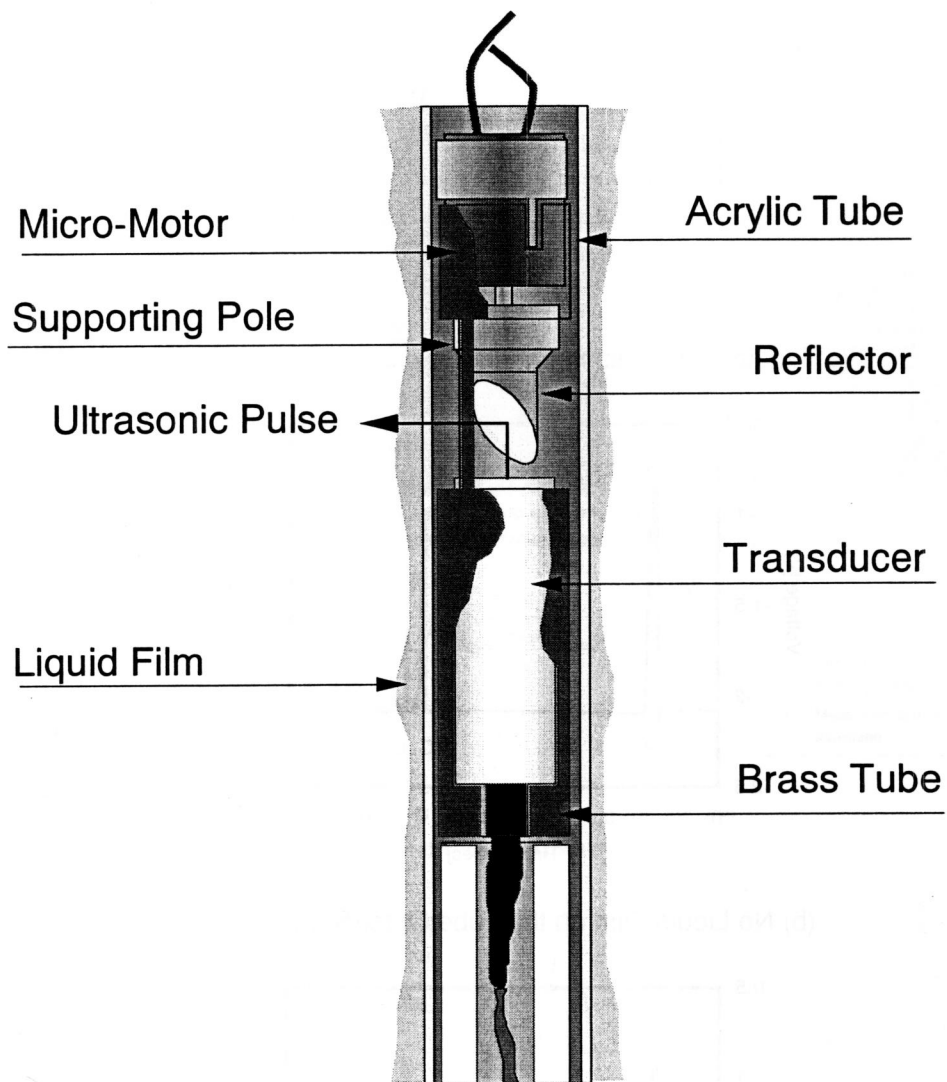
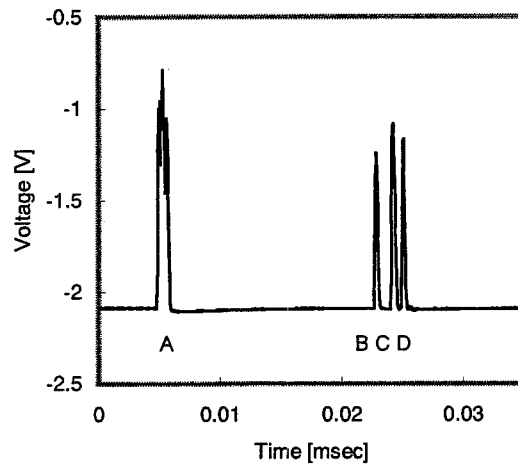
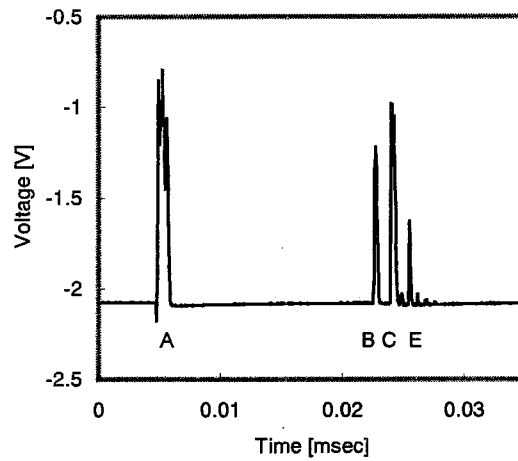


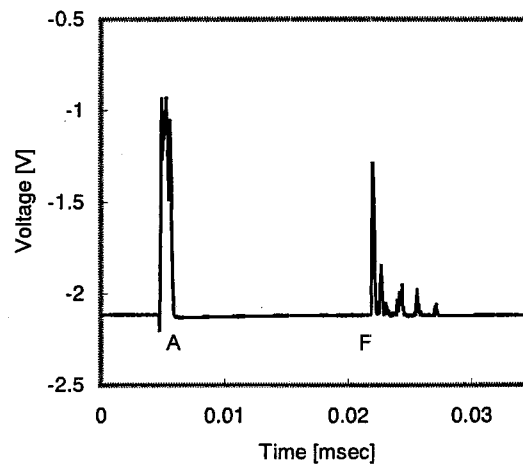
Figure 2.13 Newly Developed Ultrasonic Device with a Rotating Reflector



(a) Liquid Film Existing on the Tube Outer Surface



(b) No Liquid Film on the Tube Outer Surface



(c) Reflector Faces to the Supporting Pole

Figure 2.14 Typical Raw Signal from the Flaw Detector of the USEM

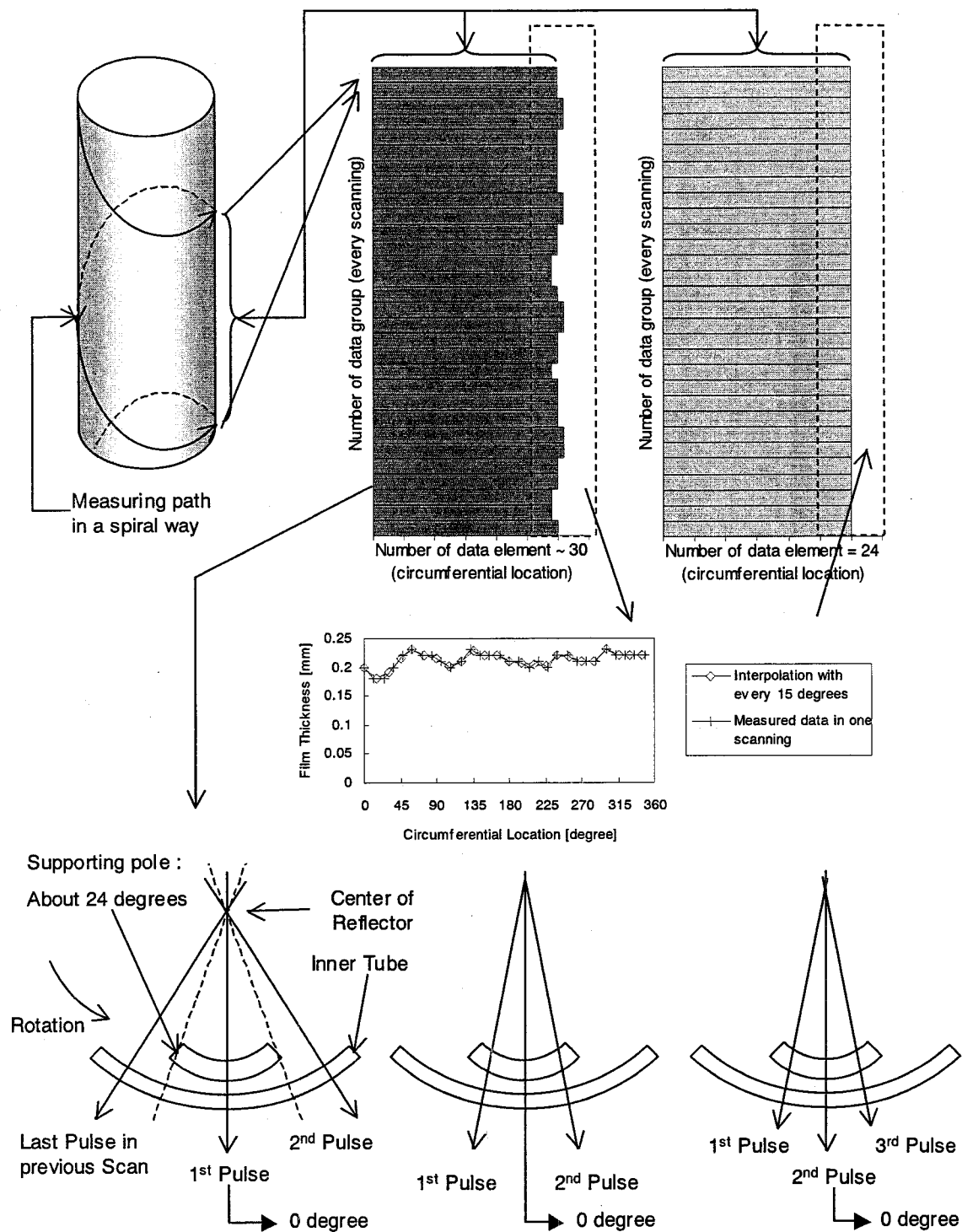


Figure 2.15 (1) Outline of Interpolation Procedure to Obtain Two-dimensional Image

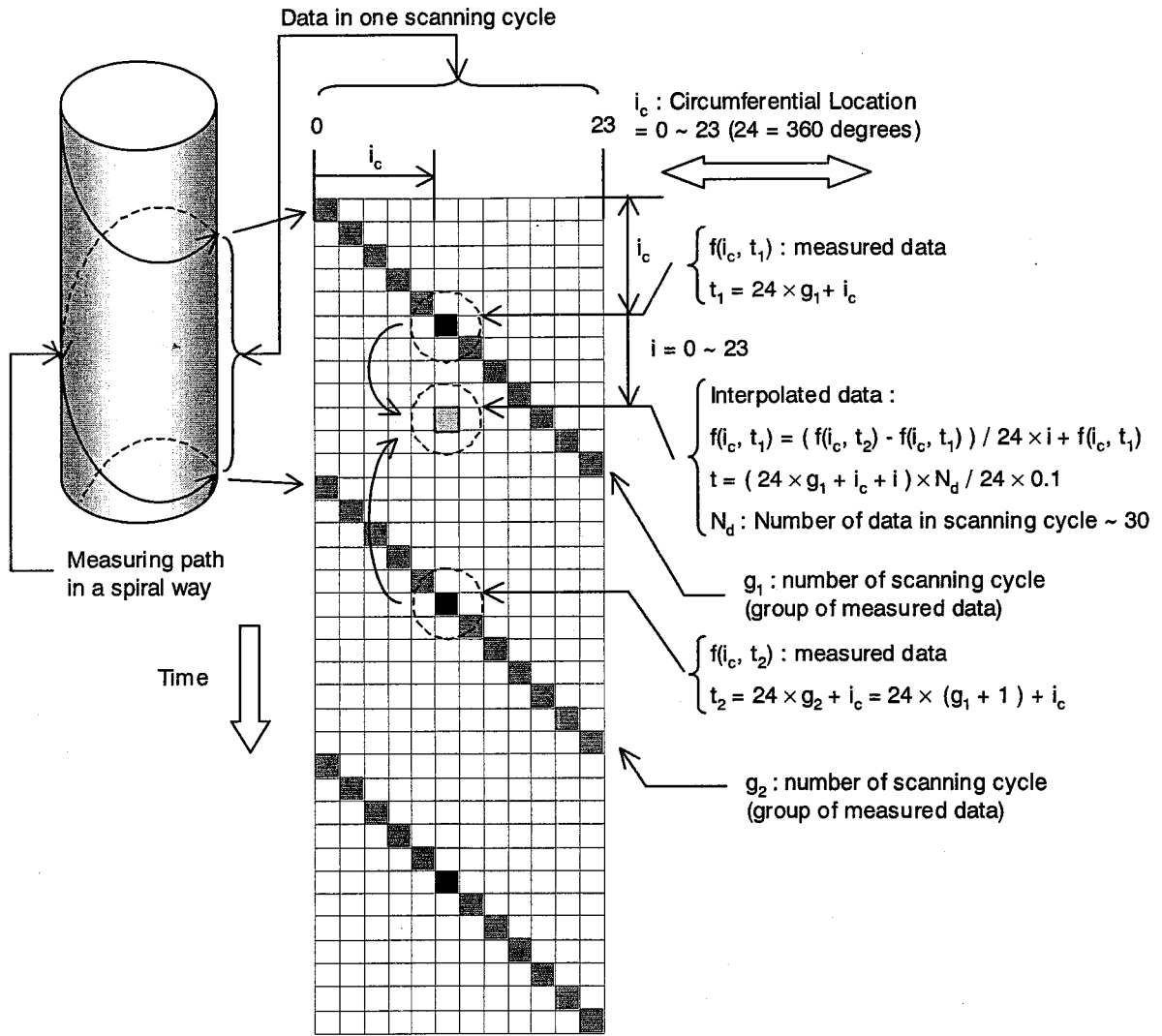


Figure 2.15 (2) Outline of Interpolation Procedure to Obtain Two-dimensional Image

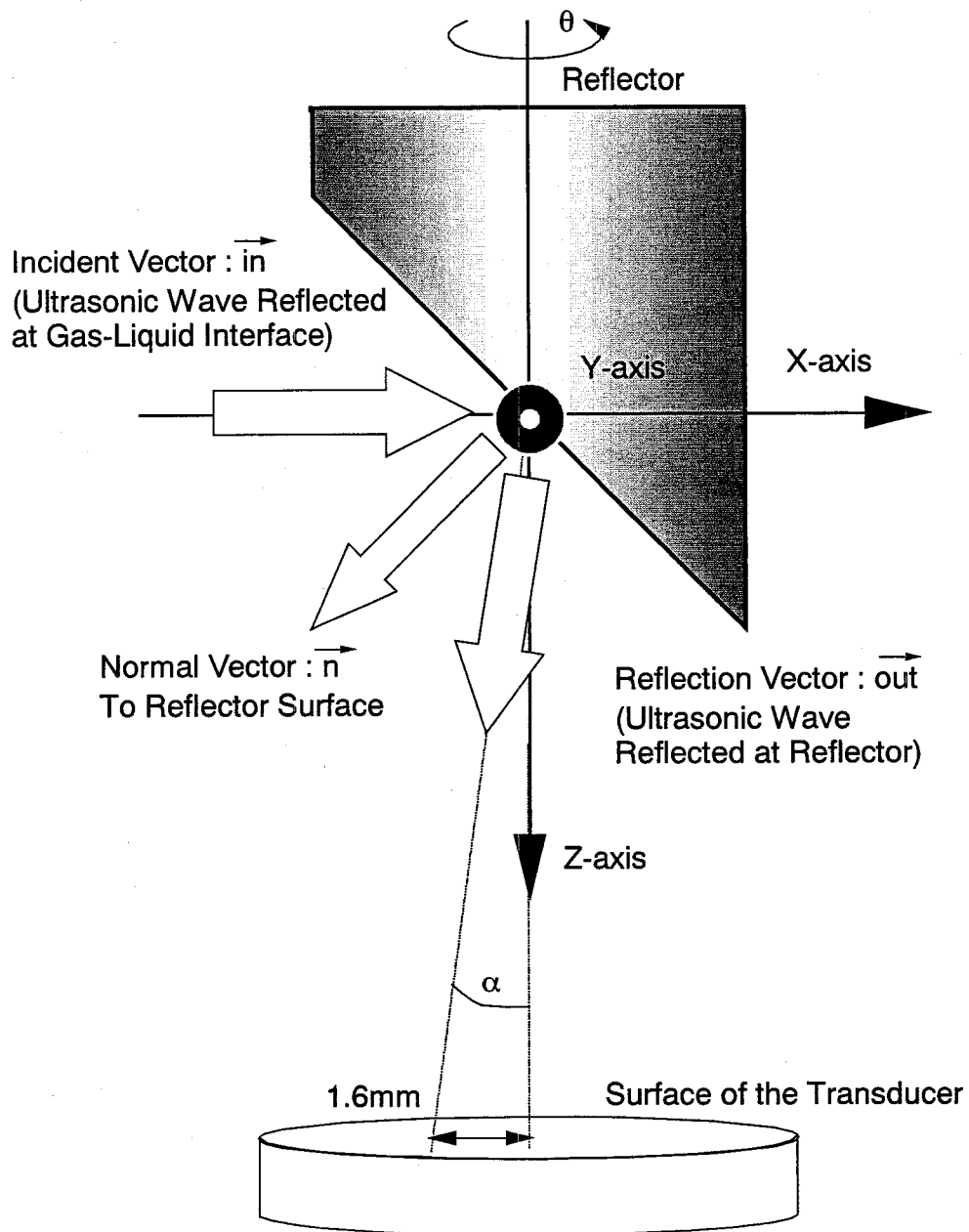


Figure 2.16 Axes Used To Calculate Flight Path of Ultrasonic Wave Before and After Reflected at Reflector

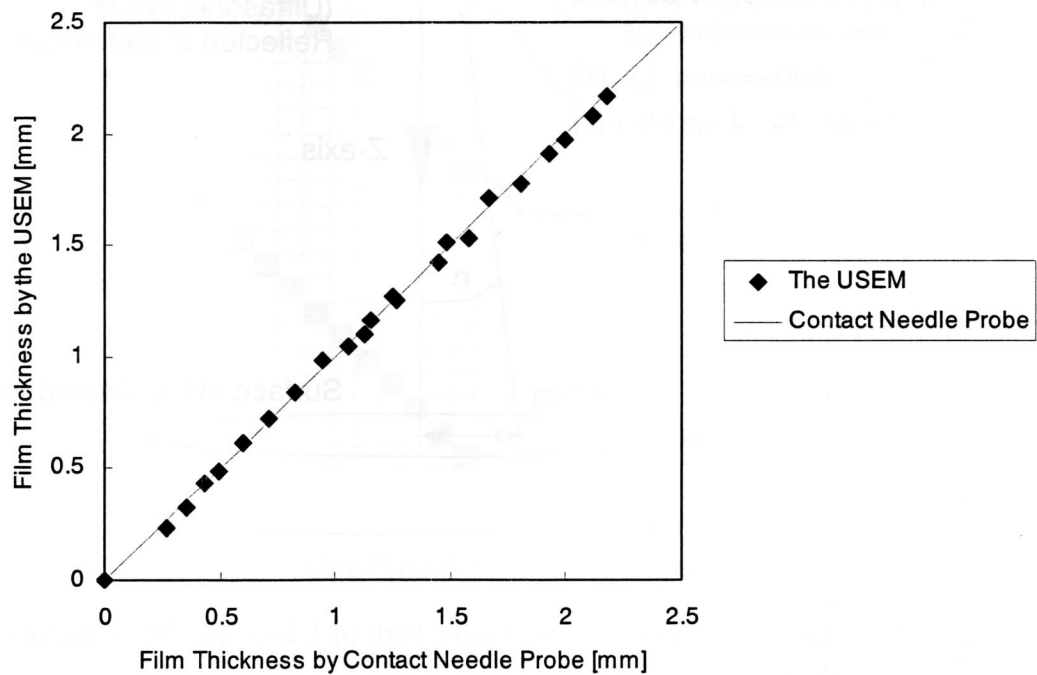
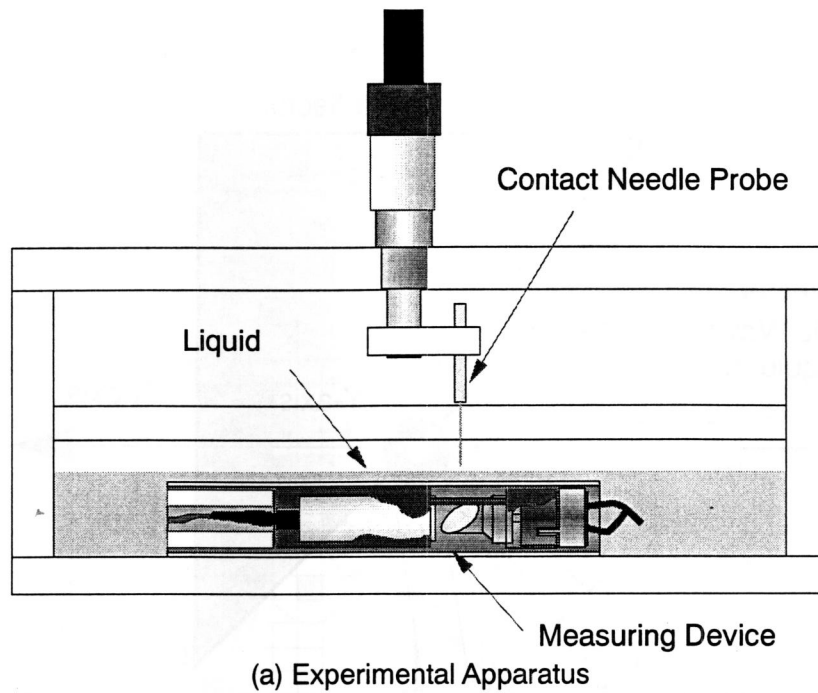


Figure 2.17 Comparison between the USEM and Contact Needle Probe Method

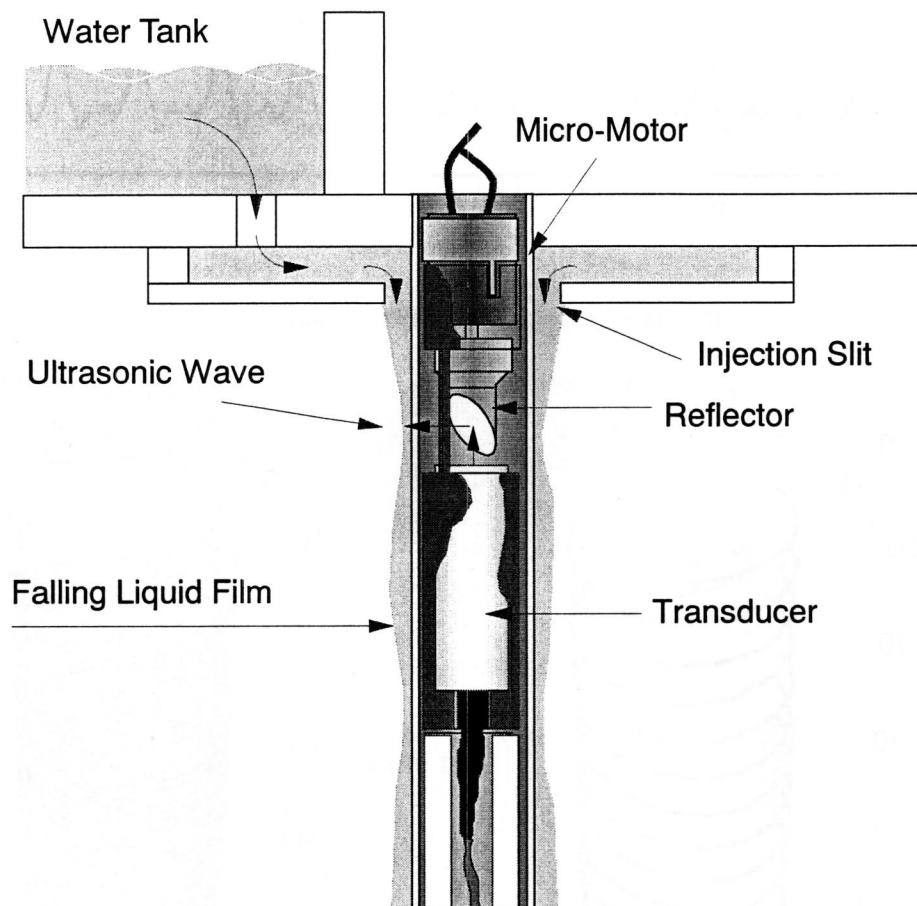
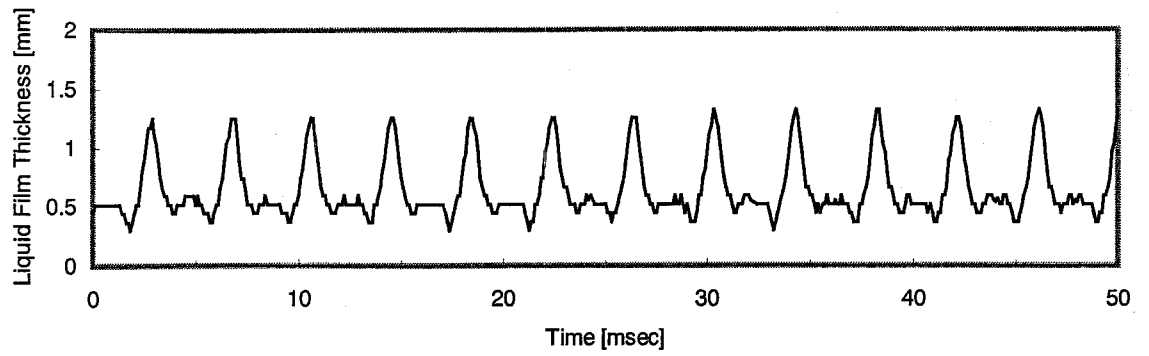
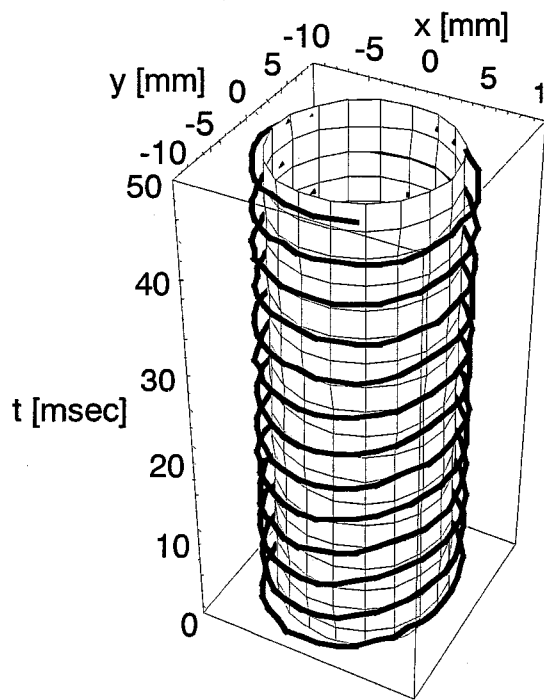


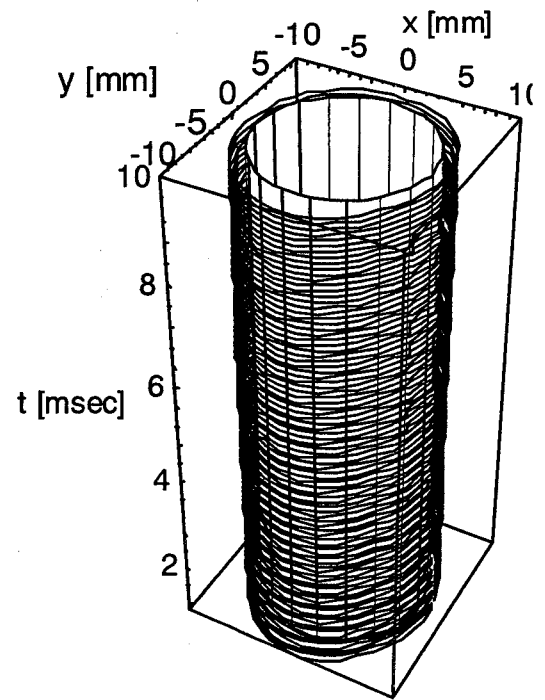
Figure 2.18 Schematic of the Experimental Apparatus for Preliminary Test



(a) Time Trace of Liquid Film Thickness

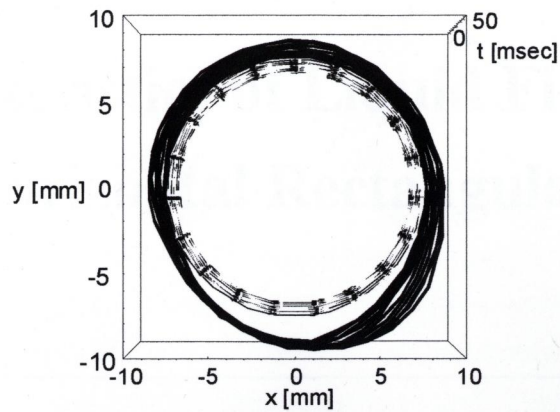


(b) Without Interpolating Operation

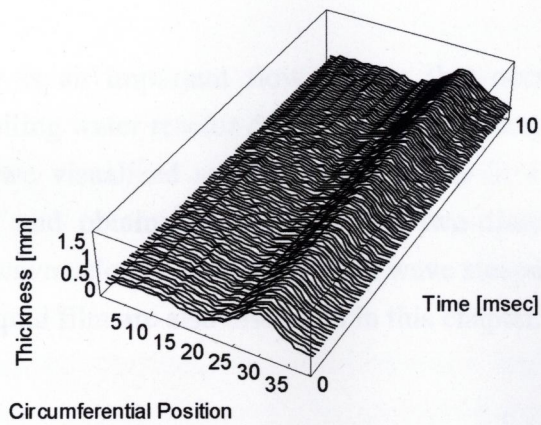


(c) Interpolating Operation

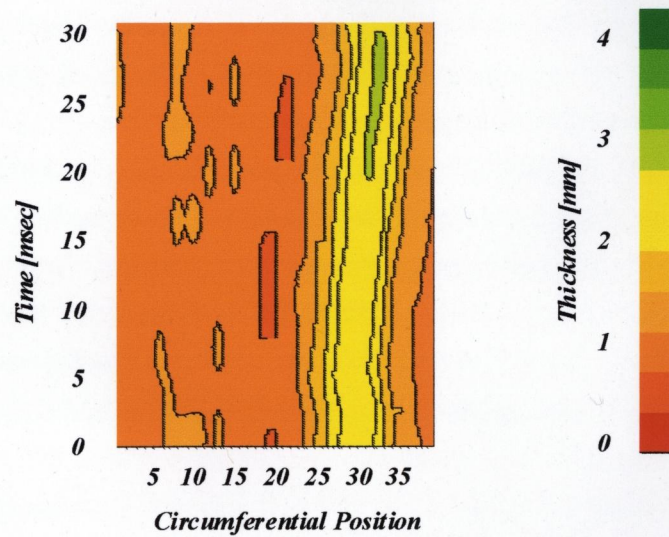
Figure 2.19 Reconstructed Image of Liquid Film Formed Around Tube



(a) Cross-Sectional Plot (Top View)



(b) Bird's Eye View Graphic



(c) Contour Plot

Figure 2.20 Three-Dimensional Plots of Reconstructed Film Thickness Distribution

3. Characteristics of Liquid Film Flow in a Horizontal Rectangular Channel

3.1. Introduction

Liquid film flow is an important flow pattern that occurs in many industrial instruments such as boiling water reactor core. To clarify macroscopic characteristics of the liquid film flow, we visualized several flow patterns in a horizontal rectangular channel by the FDM and obtained time-dependent two-dimensional distribution of liquid film thickness, wave velocity, axial width and wave steepness and so on. Types of interfacial waves on liquid film are also discussed in this chapter.

3.2. Experimental Apparatus and Conditions

A schematic of the experimental apparatus is shown in figure 3.1. The test section is a 50mm wide, 15mm high and 2,000mm long horizontal rectangular channel made of acrylic resin. The flow is in a developing region since $L/D=87$ (D : equivalent diameter). The working fluid was an air-water two-phase flow containing a small amount of fluorescence dye (Rhodamine B) in the liquid-phase. The water flows into the test section from the lower part of the inlet section and air flows from the upper part of inlet section to form a liquid film flow. In order to minimize the flow perturbation caused by a pump, an over-flow tank was used. All experiments were carried out at atmospheric pressure and ambient temperature.

Experimental conditions are shown in figure 3.2. The range of superficial gas velocity was 8.0~20.0m/s, and superficial liquid velocity was 0.007~0.069m/s. The flow patterns observed in this flow condition were disturbance wave flow; ripple wave flow and annular dispersed flow. Each flow pattern was defined by visual observation and classified as illustrated in figure 3.2. Flow patterns defined by Fukano et al. [1] also indicated in figure 3.2.

Disturbance wave flow was observed with relatively low gas velocity and large liquid flow rate. Liquid film is consisted of a base film having several three-dimensional small waves and intermittently appearing large two-dimensional disturbance waves. The disturbance wave is characterized with its large traveling velocity. Most parts of liquid phase flows on the bottom of a channel except small rivulets on other surfaces. Annular dispersed flow was realized with large gas and liquid flow rate. In a microscopic view, the basic structure of the liquid film in this flow pattern is same to the disturbance wave flow. However, whole inner surface of the channel is covered with liquid film by deposition of liquid droplets entrained from waves due to the large interfacial shear stress of high gas velocity. Ripple wave flow was seen with small liquid flow rate and high superficial gas velocity. Liquid film structure is also similar to the disturbance wave flow but height of large waves is slightly reduced and liquid film occupies only the bottom of the channel.

3.3. Liquid Film Flow Pattern Observation

3.3.1. Lateral Film Thickness Distribution across Channel Cross-Section

Perpendicular incidence type of the FDM was applied to measure lateral film thickness distribution across channel cross-section. The laser sheet was incident at 1,700mm downstream from the inlet section. The results are demonstrated as bird's eye

view graphics in figures 3.3-3.5. Horizontal axis is the lateral direction and depth axis is the time lapse during 240msec with 1msec interval.

Figure 3.3 shows results of constant liquid velocity at $j_l=0.04\text{m/s}$. The flow pattern was disturbance wave flow for the case of $j_g=10.2\text{m/s}$ shown in figure 3.3(a). A large disturbance wave reconstructed at 10msec indicates that its front surface is steeply inclined and has several peaks in the lateral direction. On the other hand, its backside moderately inclines. In addition, the rear surface is much rougher than its front surface. Small waves are also seen on the base film. It is also remarkable that the gas-liquid interface following the large disturbance wave tends to undulate in the lateral direction. Sekoguchi et al. [2] reported similar behavior in a vertical upward liquid film flow.

Figure 3.3(b) shows a result of $j_g=14.8\text{m/s}$. The flow pattern is disturbance wave flow, too. Gas-liquid interface is nearly smooth from 0msec to 60msec, and then large disturbance wave is glowing up. Liquid film thickness seems somewhat small than the case of $j_g=10.2\text{m/s}$. An example of $j_g=20.2\text{m/s}$ is shown in figure 3.3(c). Flow pattern changes to annular dispersed flow. Relatively large two-dimensional waves are seen at 30msec and at 130msec, however their height becomes smaller than other results obtained at smaller gas velocities.

Results of $j_l=0.069\text{m/s}$ are demonstrated in figure 3.4. Figure 3.4(a) is a result of $j_g=9.7\text{m/s}$ and its flow pattern is disturbance wave flow. Sekoguchi and Takeishi [3] noted that the disturbance waves appear more frequently with an increase of liquid flow rate for the constant gas velocity. The result displayed in figure 3.4(a) shows this trend with a comparison of figure 3.3(a) measured under the similar j_g and lower j_l . Undulation of the gas-liquid interface is also recognized, for example, around 30msec. Figure 3.4(b) is a result of $j_g=12.4\text{m/s}$. Flow pattern is annular dispersed flow. A large disturbance wave is seen at 150msec. Figure 3.4(c) is a result of $j_g=19.1\text{m/s}$. Flow pattern is also annular dispersed flow. It is seen that the height of disturbance waves becomes smaller than those results of smaller gas velocities.

Figure 3.5 shows results of large j_g and j_l . Every flow pattern is ripple wave flow. Figure 3.5(a) is a result of $j_l=0.007\text{m/s}$ and $j_g=17.8\text{m/s}$. Relative large wave is observed at 30msec, however its height is smaller than the result of similar gas velocity and larger liquid flow rate as seen in figure 3.4(c). Figure 3.5(b) is a result of $j_l=0.011\text{m/s}$ and $j_g=18.0\text{m/s}$. No remarkable disturbance wave is seen here. Figure 3.5(c) shows a result of $j_l=0.027\text{m/s}$ and $j_g=18.4\text{m/s}$. More disturbance waves are recognized against the figures 3.5(a) and 3.5(b) associated with large j_l .

Figure 3.6 shows contour plots of the same results demonstrated in figures 3.3-3.5. Here, figures are classified with flow patterns, to say, figures of disturbance wave flow

are plotted in the first row and then annular dispersed flow, and ripple wave flow. Liquid film thickness was divided into 17 elevations with 0.1mm interval. Warm color indicates small liquid film thickness and cold color corresponds to large liquid film thickness. Right hand side of each figure tends to be small liquid film thickness due to an inclination of test channel.

It is clearly seen that large two-dimensional disturbance waves are appearing in disturbance flow regime. It should be noticed that the duration time of large waves is different for the case of relatively small gas velocity as shown in figure 3.6(a-1). For example, the wave appearing at 10msec has long duration time being about 30msec while other waves have shorter duration time than 10msec. Assuming that the traveling velocity of these waves is constant, volume of the former wave will be much greater than the latter waves. Such a difference is not obviously recognized in other figures obtained with larger gas velocities and lower liquid flow rates. This type of large wave seems to be the "Huge Wave" that was discovered by Sekoguchi et al. [3,4] in a vertical upward liquid film flow. Huge wave is characterized with its great size and fast transit velocity, and is observed at relatively large liquid flow rate and small gas velocity. Classification of waves will be discussed later again, since traveling velocity of waves was not measured with perpendicular incidence type of the FDM.

Several large two-dimensional disturbance waves are reconstructed in annular dispersed flow regime, too. Duration time of disturbance waves becomes longer with increase of liquid flow rate, however no large wave treated as huge wave is observed in this flow regime. It seems that two-dimensional disturbance waves exist in ripple wave flow from the distribution of green contour lines as seen in figure 3.6(c-1), but their height is much smaller than that of disturbance wave flow.

3.3.2. Longitudinal Film Thickness Distribution at Centerline of Channel

Parallel incidence type of the FDM was applied to measure both longitudinal film thickness distribution and wave velocity at the centerline of the channel lateral cross-section simultaneously. The laser sheet was incident to be its center of viewing area located at 1,700mm downstream from the inlet section. Experimental results are demonstrated as bird's eye view graphics in figures 3.7-3.19. Horizontal axis is the longitudinal direction among 16mm of viewing area and depth axis is the time lapse during 1,000msec with 1msec interval. It is apparently seen that wave cross-sectional shape is excellently visualized. Outline of the liquid film behavior will be described in this section.

Figures 3.7-3.11 show results of disturbance wave flow. Several large waves are

well reconstructed. It is seen that some of large waves drastically change their cross-sectional shape during their passage in the viewing area (for example at 600msec in figure 3.7) while other waves, for example appearing at 180msec in figure 3.7 and so on, keep their shape. Wave velocity also can be estimated from the time required for the wave to pass through the viewing area being 16mm long. For example, the large wave observed at 600msec in figure 3.7 takes about 13msec, thus its traveling velocity is about 1.2m/s. However, traveling velocity of large waves seems to be different each other. A lot of small waves are also observed on the base film. These small waves keep their cross-sectional shape during their passage, and the traveling velocity estimated being about 0.6m/s is somewhat smaller than that of large wave.

As mentioned before, the large waves can be classified into two types, that is to say disturbance wave and huge wave. Sekoguchi et al. [2,3] suggested another type of large wave having smaller traveling velocity than disturbance wave called "Ephemeral wave". However, the ephemeral wave was not considered in this work since they often reduce their traveling velocity while their passage in a long distance within about a few meters. "D" and "H" denote disturbance wave and huge wave in figures 3.7-3.11, respectively. Classification of these two types of large waves will be discussed in the next section.

Figures 3.12-3.15 are results of annular dispersed flow. Relatively large waves, recognized here as disturbance waves, appear more frequently than the cases of disturbance wave flow, however, their wave height becomes much smaller. It should be noticed that no huge wave was observed in this flow regime and more frequent small waves occur than in disturbance wave flow. Annular dispersed flow is realized at large superficial gas velocity, thus waves can not have large wave height due to the interfacial shear stress that is high enough to entrain liquid droplets from the wave crest.

Figures 3.16-3.19 show results of ripple wave flow. There is no remarkable large wave in these flow conditions. Ripple wave flow occurs at low liquid flow rate, therefore, large wave is not constructed. On the other hand, small waves called ripples appear much more frequently.

Contour plots of the same results are displayed in figures 3.20-3.32. In these plots, wave velocity is easily identified, to say, wave velocity corresponds to an inclination of same contour lines from top to left as illustrated in figure 3.20. Large inclination angle of a wave indicates fast wave velocity. It can be seen from the cases of disturbance wave flow in figures 3.20-3.24 that disturbance waves have larger wave velocity than small waves. Wave velocity of huge wave seems to be a little bit larger than that of disturbance waves. In annular dispersed flow regime (figures 3.25-3.28), both small waves and large waves tend to have similar large velocities. Results of ripple wave flow

are shown in figures 3.29-3.32. Most part of gas-liquid interface is covered with thin base film and small waves having large traveling velocity are frequently observed.

3.4. Results and Discussions

3.4.1. Classification of Waves

The large waves introduced in the previous sections were classified by taking account of their axial width (duration time), height and velocity as illustrated in figure 3.33(a). At first, time-averaged liquid film thickness was obtained from the time series of liquid film thickness at 0mm in the viewing area. Time-averaged film thickness is shown in figure 3.33(c). The film thickness shows a general trend that it decreases with an increase of superficial gas velocity for constant liquid flow rate. This is because the liquid film is accelerated by interfacial shear stress in high gas velocity region, and then, liquid film thickness is decreased to keep the mass conservation law. In annular dispersed flow regime, liquid droplets entrained from liquid film deposit on whole surface, thus, liquid film thickness at bottom of a channel naturally becomes small. These trends agree well with the experimental results by Fukano et al. [5]. The minimum film thickness refers to 95 % probability of liquid phase existence in terms of the cumulative curve as usually defined. Wave was distinguished at where time trace of liquid film thickness exceeds the time-averaged liquid film thickness. Axial width was determined as a duration time of wave. Wave height was given by a difference between the maximum film thickness detected in the wave duration time and the minimum film thickness. Wave velocity was determined from a slope of linear regression line of wave front in several consecutive cross-sectional distribution of liquid film thickness as shown in figure 3.33(b). Then, wave cross-sectional area was calculated as a product of axial width, wave height and wave velocity to distinct the wave types.

Figure 3.34 shows distribution of wave properties (axial width, height and velocity) vs. wave cross-sectional area for every wave detected by the present method. Figure 3.34(a) shows a typical example of disturbance wave flow without huge wave. It is interesting that wave cross-sectional area seems to be divided into two ranges larger and smaller than 10mm^2 regarding to disturbance wave and ripple, respectively. On the other hand, other properties seem not to drastically change between disturbance wave and ripple. Figure 3.34(b) shows a result of typical ripple wave flow. It should be said that the definition mentioned above is reasonable since most waves have smaller cross-sectional area than 10mm^2 . Concerning with this, small waves appearing in disturbance wave flow and annular dispersed flow are also called as ripple in following sections. Figure 3.34(c) shows a result of disturbance wave flow including several huge

waves having very large cross-sectional area exceeding 100mm^2 . Thus, large waves were identified as huge waves with their cross-sectional area larger than 100mm^2 . On the other hand, Sekoguchi et al. [3] determined following criteria regarding wave velocity from their results of wave behavior maps and visual examination:

$$u_h > 1.2 \times u_d$$

where u_h and u_d are the velocity of huge and disturbance wave, respectively.

Close-up views of disturbance wave and huge waves determined by the above criteria are demonstrated in figure 3.35. It seems that the disturbance wave keeps its longitudinal cross-sectional shape nearly in constant as seen in figure 3.35(a) while crest of huge waves, in figures 3.35(b) and 3.35(c), is strongly distorted. Longitudinal cross-sectional film thickness distribution of the disturbance wave and the huge wave are plotted again as consecutive graphics in figure 3.36. It can be seen that the disturbance wave has almost symmetric geometry around the maximum film thickness and the surface is fairly smooth. On the other hand, the huge wave obviously leans toward flow direction and its crest is roughly agitated. In view of the clearance between the crest of the huge wave and channel top being about 5mm, the interfacial shear stress increases due to accelerated gas flow in this small clearance and the crest of the huge wave will be highly distorted.

3.4.2. Power Spectral Density Distribution of the Film Thickness Fluctuation

Figure 3.37 shows results of power spectral density distribution of film thickness fluctuation (PSD) obtained at 0mm of the viewing area by Fast Fourier Transform. Figure 3.37(a) shows a typical example of disturbance wave flow, $j_l=0.069\text{m/s}$ and $j_g=8.0\text{m/s}$. A remarkable strong peak is observed in lower frequency region less than about 10Hz. Concerning with the film flow behavior presented in figure 3.10, the largest peak is considered to be formed by huge waves. The peak appearing at about 20Hz seems to be frequency of disturbance waves since the power associated with the wave amplitude is relatively large. Other peaks having higher frequencies than 30Hz, thus, correspond to ripples.

Figure 3.37(b) shows a case of annular dispersed flow, $j_l=0.04\text{m/s}$ and $j_g=19.9\text{m/s}$. It is clearly seen that peaks in low frequency region disappear and two large peaks are formed between 10Hz and 50Hz. The former peak seems to be the frequency of disturbance wave and the latter is ripples since more waves become to occur in this flow regime due to the accelerated wave propagation velocity enlarged by high gas flow.

Figure 3.37(c) shows a result of ripple wave flow, $j_l=0.007\text{m/s}$ and $j_g=19.5\text{m/s}$. A solitary peak is seen in low frequency region considered to be disturbance waves but the

power is fairly small in comparison with the case of disturbance wave flow, this is because that disturbance waves cannot grow up to have a large amplitude in ripple wave flow regime that is realized with small liquid flow rate. It also seems that higher frequency region tends to distribute almost continuously up to a few hundred Hz. In ripple wave flow, many ripples having small height and short length cover most part of the base film, therefore they appear much frequently and then power of high frequency waves is enhanced to be a similar value of lower frequency. Paras and Karabelas [6,7] also reported a similar spectra shift to be a broad distribution of PSD for liquid film flow in a horizontal channel.

3.4.3. Number of Passing Waves

Number of waves was determined by counts of consecutive liquid film thickness series exceeding mean film thickness at 0mm of the viewing area. The type of detected waves was defined by the method mentioned before.

Figure 3.38(a) shows a result of ripples. Number of ripples increases with an increase of gas velocity due to enlarged Kelvin-Helmholtz instability. This trend agrees with the result of Fukano et al. [8]. It is seen that number of ripples has large value for small liquid flow rate in higher gas velocity region and becomes smaller value for small liquid flow rate in lower gas velocity region. This reversal seems to be caused by a balance between wall friction effect and interfacial shear stress on gas-liquid interface since the wall friction effect is negligible small in high gas velocity, on the other hand, wall friction effect becomes somewhat large compare to the interfacial shear stress in lower gas velocity especially for small liquid flow rate.

It can be seen from figure 3.38(b) that number of disturbance wave increases both with gas velocity and liquid flow rate. It is considered that disturbance wave has large wave height enough to neglect wall friction effect. A few number of disturbance wave are also detected in ripple wave flow regime. Results of Sekoguchi and Takeishi [3] carried in vertically upward channel indicate a similar trend to the present work.

Number of huge wave is also displayed in figure 3.38(c) with the results of Sekoguchi and Takeishi [3]. It is seen that huge wave appears in limited flow conditions and the number of huge wave has a peak around at about 12m/s of gas velocity. It seems that huge wave is separated into several disturbance wave due to fast gas flow.

3.4.4. Mean Wave Height

Mean wave height was obtained as arithmetic mean averaged value of every wave detected by the method previously mentioned. Mean wave height of ripples is shown in

figure 3.39(a). It indicates a similar trend to time-averaged liquid film thickness that ripple height decreases with an increase of gas velocity. Wave height determined as the difference between 99 % and 1 % probability of liquid phase existence in terms of the cumulative curve obtained by Fukano et al. [8] agrees well with the present work.

Comparisons of the wave height among ripple, disturbance wave and huge wave are demonstrated in figure 3.39(b). It can be seen that the huge wave has the largest value in every wave type being about twice of disturbance wave height and about four times of ripple height.

3.4.5. Mean Wave Velocity

Figure 3.40(a) shows mean wave velocity of ripple. The wave velocity increases monotonically with gas velocity for a certain liquid flow rate and tends to have large value for large liquid flow rate. Mean wave velocity of disturbance wave is shown in figure 3.40(b) indicating a similar trend to ripple, however, the wave velocity of disturbance wave is higher than ripple. Results of wave velocities (Fukano et al. [5] and Andritsos [9]) obtained from the peak in normalized cross-correlation function of two film thickness signals providing the averaged time needed for a wave to travel from one probe to the other are plotted in figures 3.40(a) and 3.40(b). It seems that the results from cross-correlation function show well correspondence to ripple wave velocity than that of disturbance wave for the present work.

Figure 3.40(c) shows comparisons of mean wave velocity of disturbance wave and huge wave. The results of Mori et al. [4] shown in figure 3.40(c) were determined as a slope of linear regression line of main wave vein of waves, to say disturbance wave and huge wave, expressed in a wave behavior map that was similar to the bird's eye view graphics such as shown in figure 3.7. It seems that huge wave has larger wave velocity than disturbance wave as denoted by Sekoguchi and Takeishi [3] and Mori et al. [4]. This is because huge wave has large wave height being about twice of disturbance wave height, thus drag force will be large for huge wave to increase its traveling velocity.

3.4.6. Mean Axial Width and Cross-Sectional Area

Figure 3.41(a) shows comparisons of mean axial width among ripple, disturbance wave and huge wave. It is interesting that axial width of ripple and disturbance wave is not affected much by gas velocity. Thus, wave dimension, to say wave actual width, in longitudinal direction will increase monotonically with gas velocity for a certain liquid flow rate concerning the wave velocity. On the other hand, axial width of huge wave rapidly decreases for large gas velocity. This reveals that properties of huge wave get

close to those of disturbance wave and then, huge waves are not generated in high gas velocity region.

Mean wave cross-sectional area is shown in figure 3.41(b). As discussed in the previous section, huge wave has larger value of cross-sectional area than 100mm^2 and that of ripple is smaller than 10mm^2 . It can be seen that the cross-sectional area of disturbance wave for large gas velocity has similar value to the border of disturbance wave and ripple.

3.4.7. Wave Steepness

A useful geometric parameter describing the shape of waves is the wave steepness as noted by Paras and Karabelas [6]. As known well, wave shape is like a triangle and somewhat leans toward flow direction, thus, steepness at front side and at rear side of wave will be different. Therefore, steepness at front side was defined between the location at where film thickness exceeding the mean film thickness and the maximum, and steepness at rear side was defined between the maximum thickness and the location at where film thickness falling the mean film thickness in the viewing area as shown in figure 3.42(a).

Wave averaged mean steepness at front side of waves detected at 0mm in viewing area including ripple, disturbance wave and huge wave was determined is presented in figure 3.42(b). The wave steepness, S , in the results of Paras and Karabelas [6] was determined as

$$S = \arctan(0.5\Delta h / \Delta L)$$

where ΔL and Δh were substituted by the mean axial width and twice the mean wave amplitude, respectively. Thus, it assumed an isosceles triangle on wave shape.

It is seen that the steepness at front side tends to decrease with increasing gas velocity. It is remarkable that the present data is superior to the extrapolation line based on an exponential approximation of the data obtained by Paras and Karabelas [6]. On the other hand, the steepness at rear side agrees well with the results by Paras and Karabelas [6] as shown in figure 3.42(c). Therefore, it should be noted that wave leans toward flow direction. Paras et al. [6] denoted that steepness decreases with increasing liquid flow rate, however, an opposite tendency is clearly observed both for front and rear side of wave in the present work.

3.5. Summary

Liquid film flow in a horizontal rectangular channel was visualized by the FDM and characteristics of liquid film flow were clarified. Time-dependent two-dimensional film thickness distribution was reconstructed in bird's eye view graphics and contour plots providing excellent understandings of liquid film behavior.

It was observed by perpendicular incidence type of the FDM that large disturbance waves had several peaks on their crest in the span wise direction. A lot of interesting features of waves, i.e., number of waves, wave height, wave velocity, axial width and wave steepness, were obtained by parallel incidence type of the FDM.

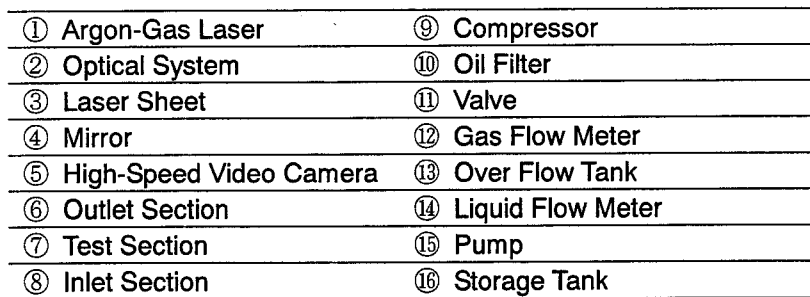
Waves were also classified into three types by using the above features, to say, conducted value of wave longitudinal cross-sectional area as a product of wave height, width and velocity. "Huge wave" was determined having larger value of wave cross-sectional area than 100mm^2 , "ripple" having smaller than 10mm^2 and the rest for "disturbance wave".

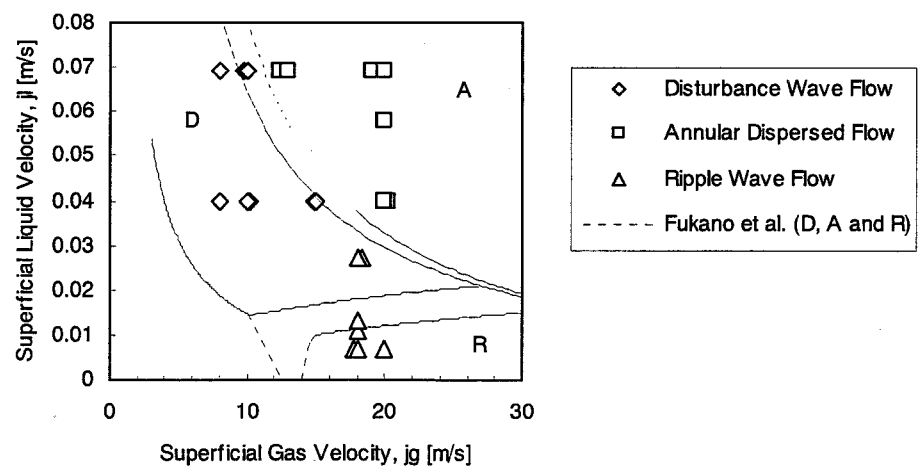
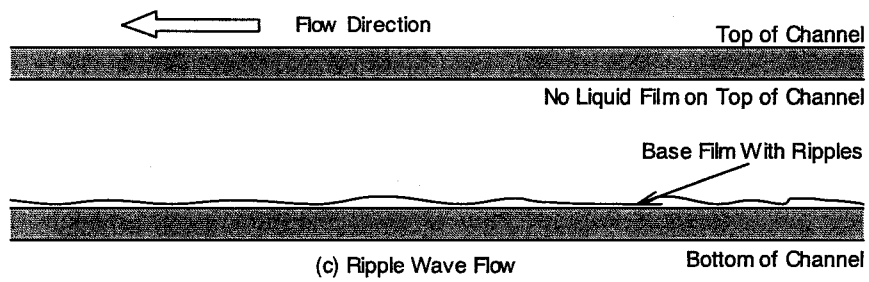
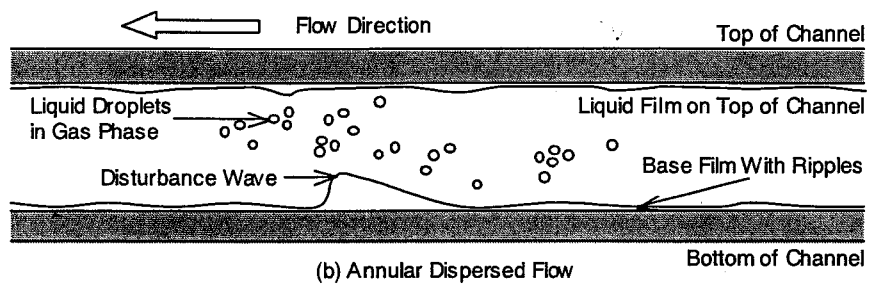
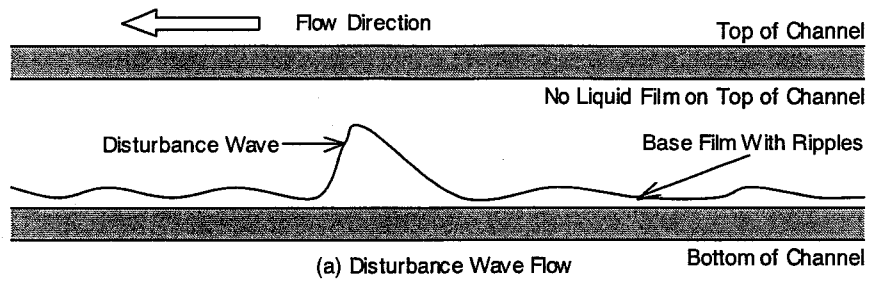
Huge wave was observed in relatively low gas velocity and relatively large liquid flow rate. Huge wave had a severely rough surface compare to disturbance wave. Their appearing frequency was less than about 2Hz. The traveling velocity was somewhat larger than that of disturbance wave. The wave height was about twice of disturbance wave height and four times of ripple.

From the results of averaged wave steepness, it was found that waves lean toward flow direction and the steepness decreases with increasing gas velocity. It was also seen that wave steepness increases with increasing liquid flow rate.

References

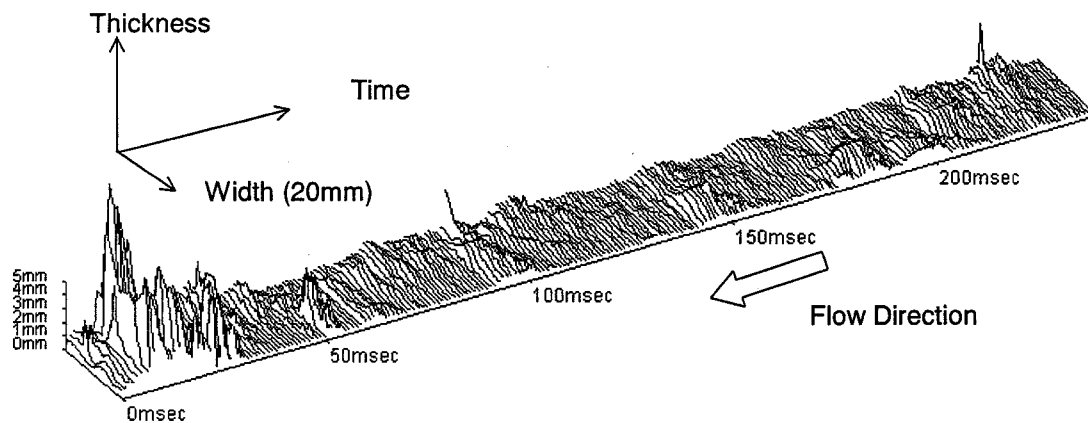
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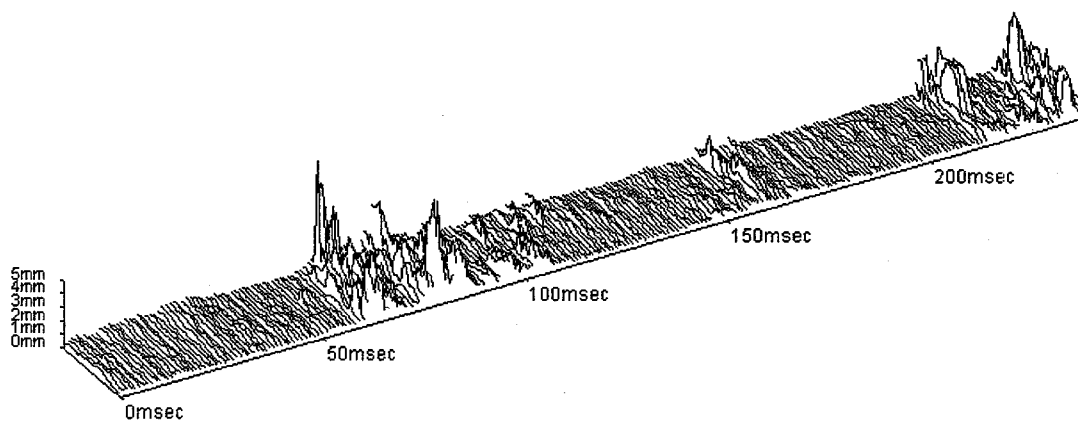


(d) Flow Pattern Map

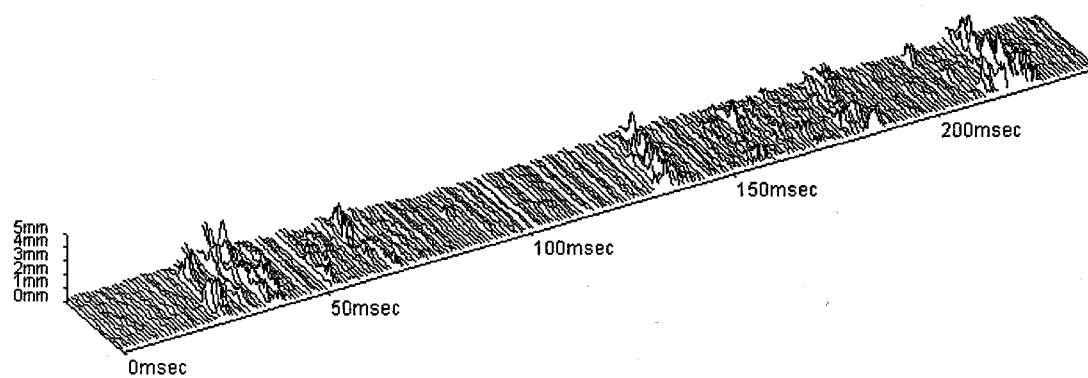
Figure 3.2 Flow Pattern Defined in the Present Work and Flow Pattern Map



(a) $j_l=0.04\text{m/s}$, $j_g=10.2\text{m/s}$ (Disturbance Wave Flow)

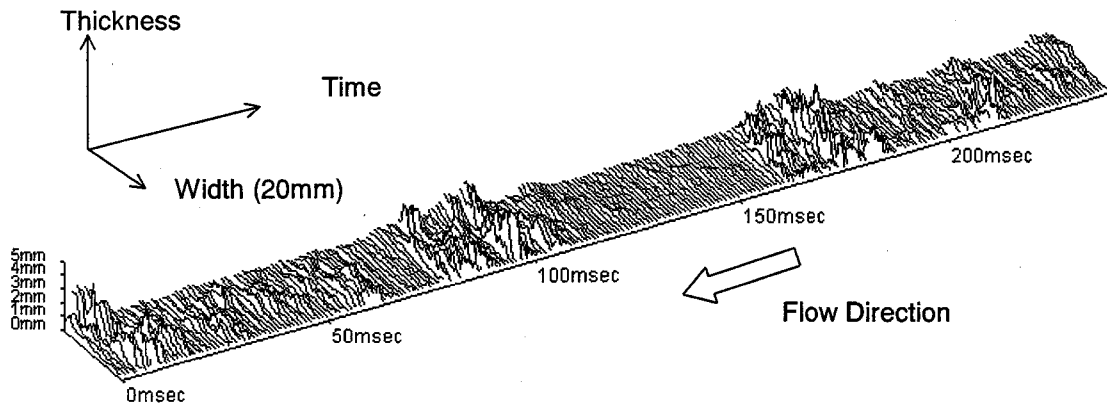


(b) $j_l=0.04\text{m/s}$, $j_g=14.8\text{m/s}$ (Disturbance Wave Flow)

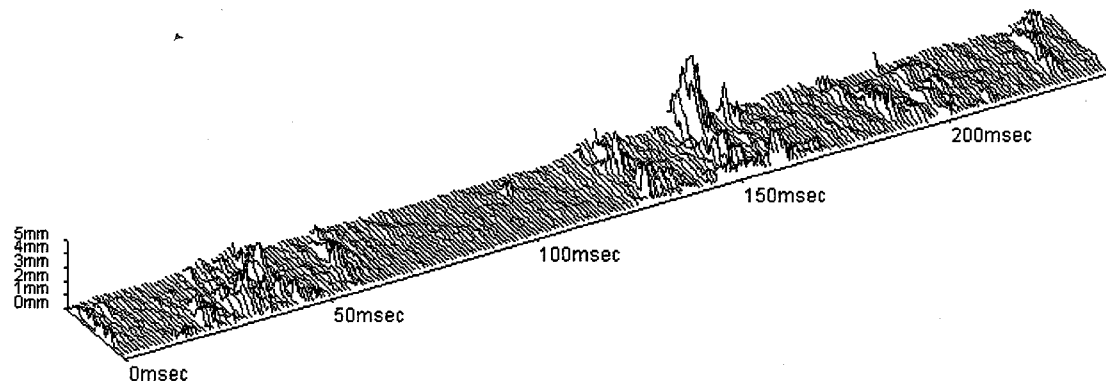


(c) $j_l=0.04\text{m/s}$, $j_g=20.2\text{m/s}$ (Annular Dispersed Flow)

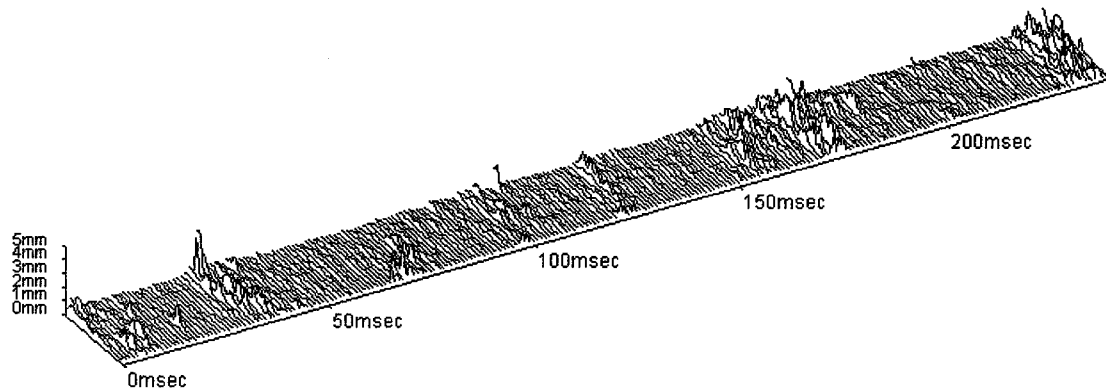
Figure 3.3 Bird's Eye View of Time-Dependent Lateral Distribution of Liquid Film Thickness



(a) $j_l=0.069\text{m/s}$, $j_g=9.7\text{m/s}$ (Disturbance Wave Flow)

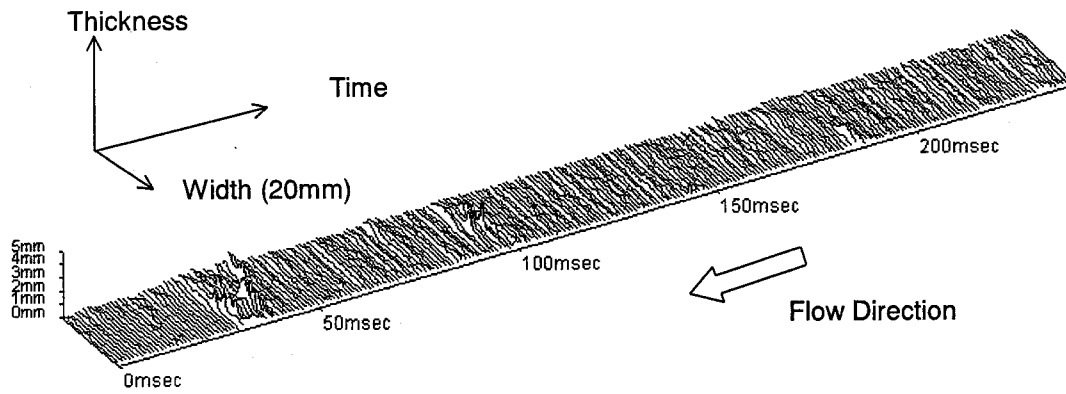


(b) $j_l=0.069\text{m/s}$, $j_g=12.4\text{m/s}$ (Annular Dispersed Flow)

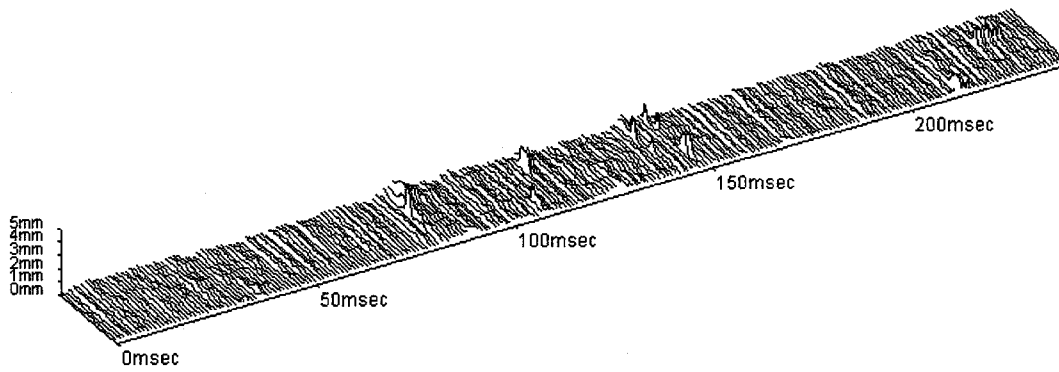


(c) $j_l=0.069\text{m/s}$, $j_g=19.1\text{m/s}$ (Annular Dispersed Flow)

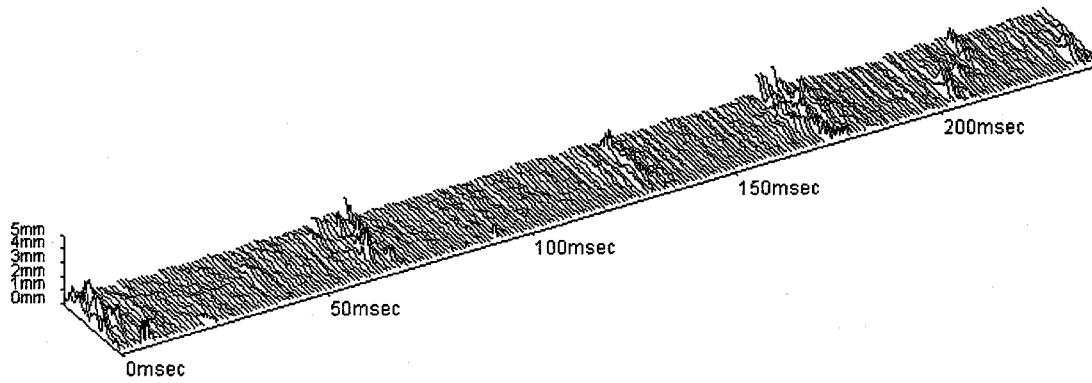
Figure 3.4 Bird's Eye View of Time-Dependent Lateral Distribution of Liquid Film Thickness



(a) $j_l=0.007\text{m/s}$, $j_g=17.8\text{m/s}$ (Ripple Wave Flow)



(b) $j_l=0.011\text{m/s}$, $j_g=18.0\text{m/s}$ (Ripple Wave Flow)



(c) $j_l=0.027\text{m/s}$, $j_g=18.4\text{m/s}$ (Ripple Wave Flow)

Figure 3.5 Bird's Eye View of Time-Dependent Lateral Distribution of Liquid Film Thickness

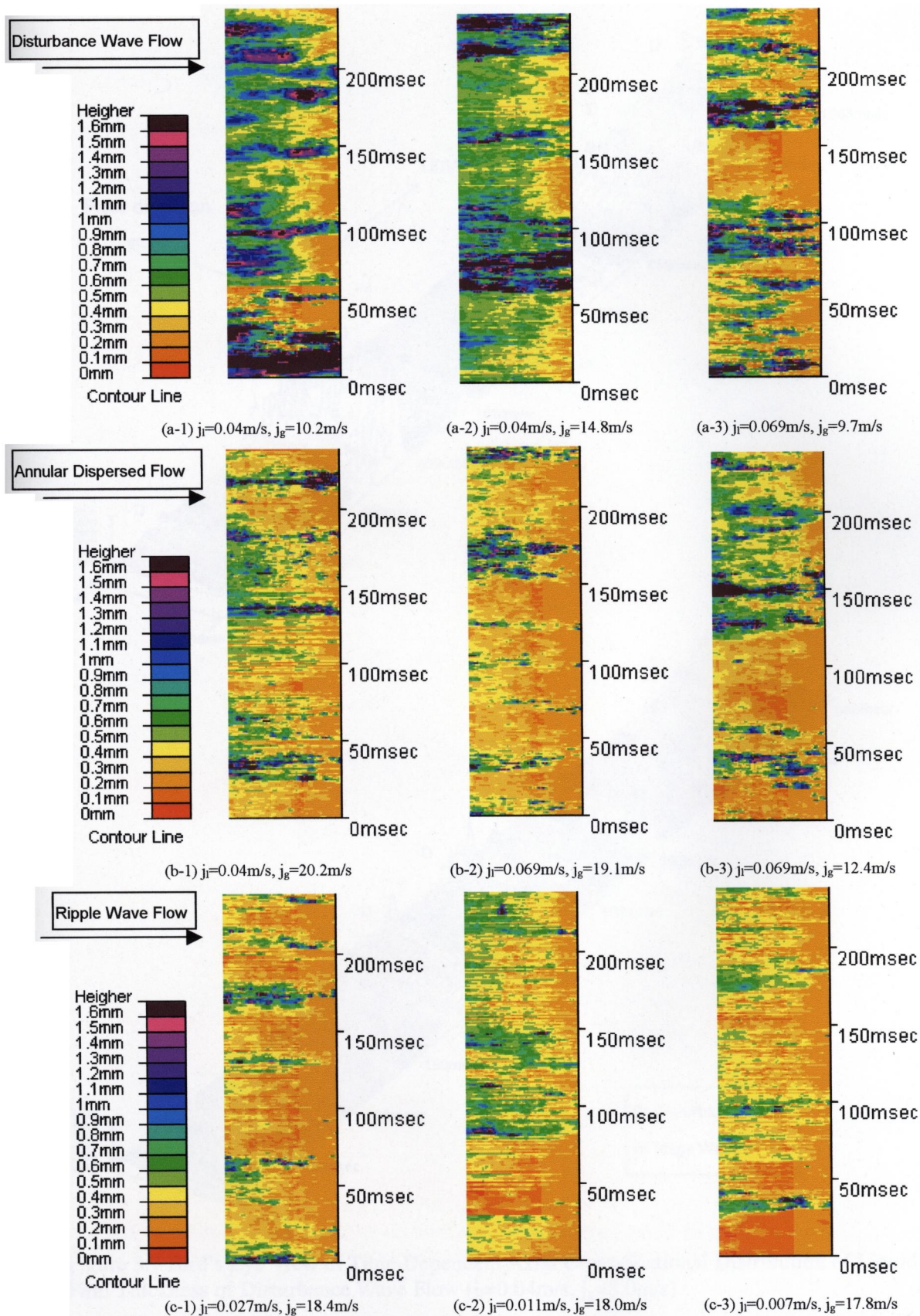


Figure 3.6 Contour Plot of Time-Dependent Lateral Distribution of Liquid Film Thickness

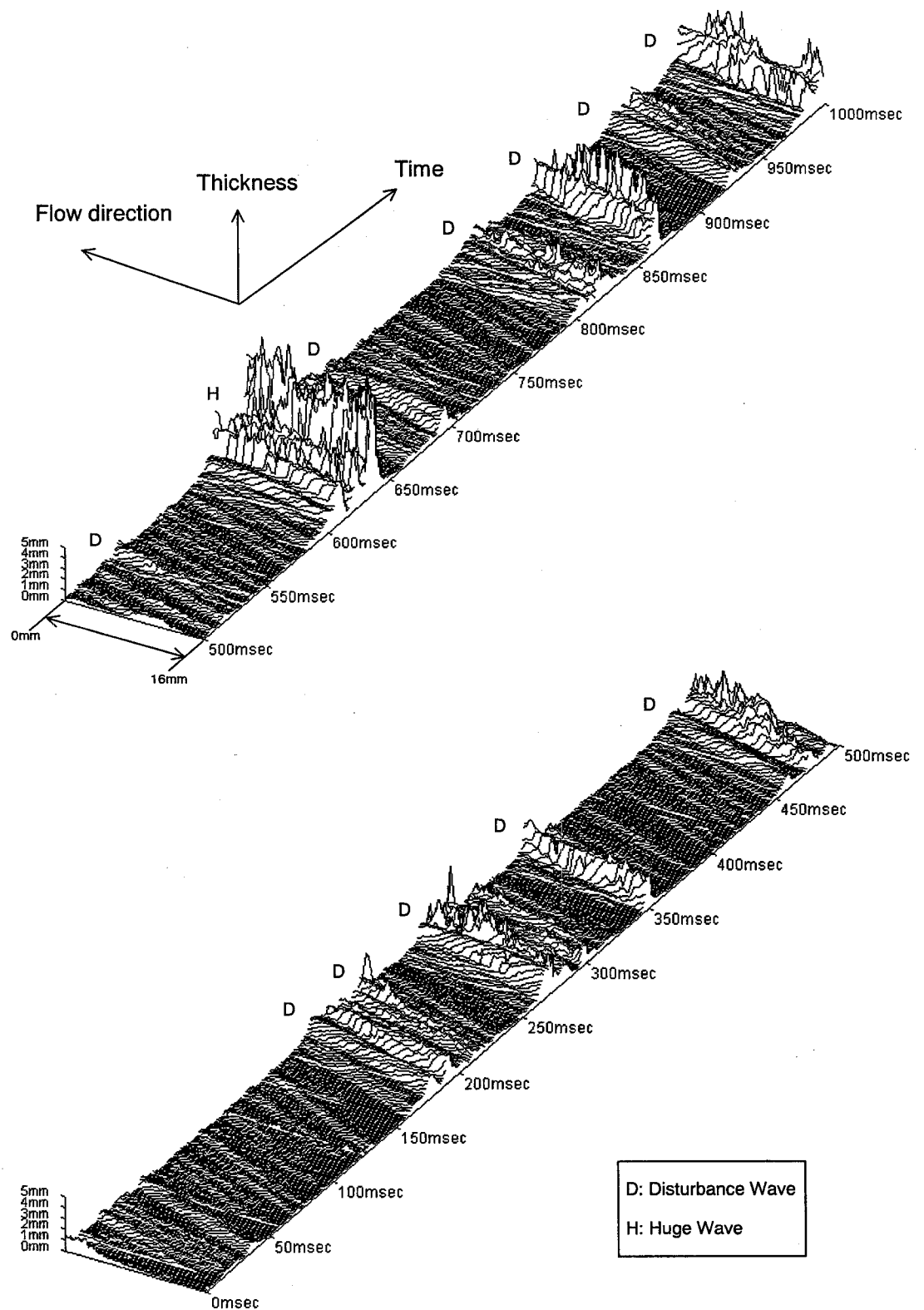


Figure 3.7 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=8.0\text{m/s}$)

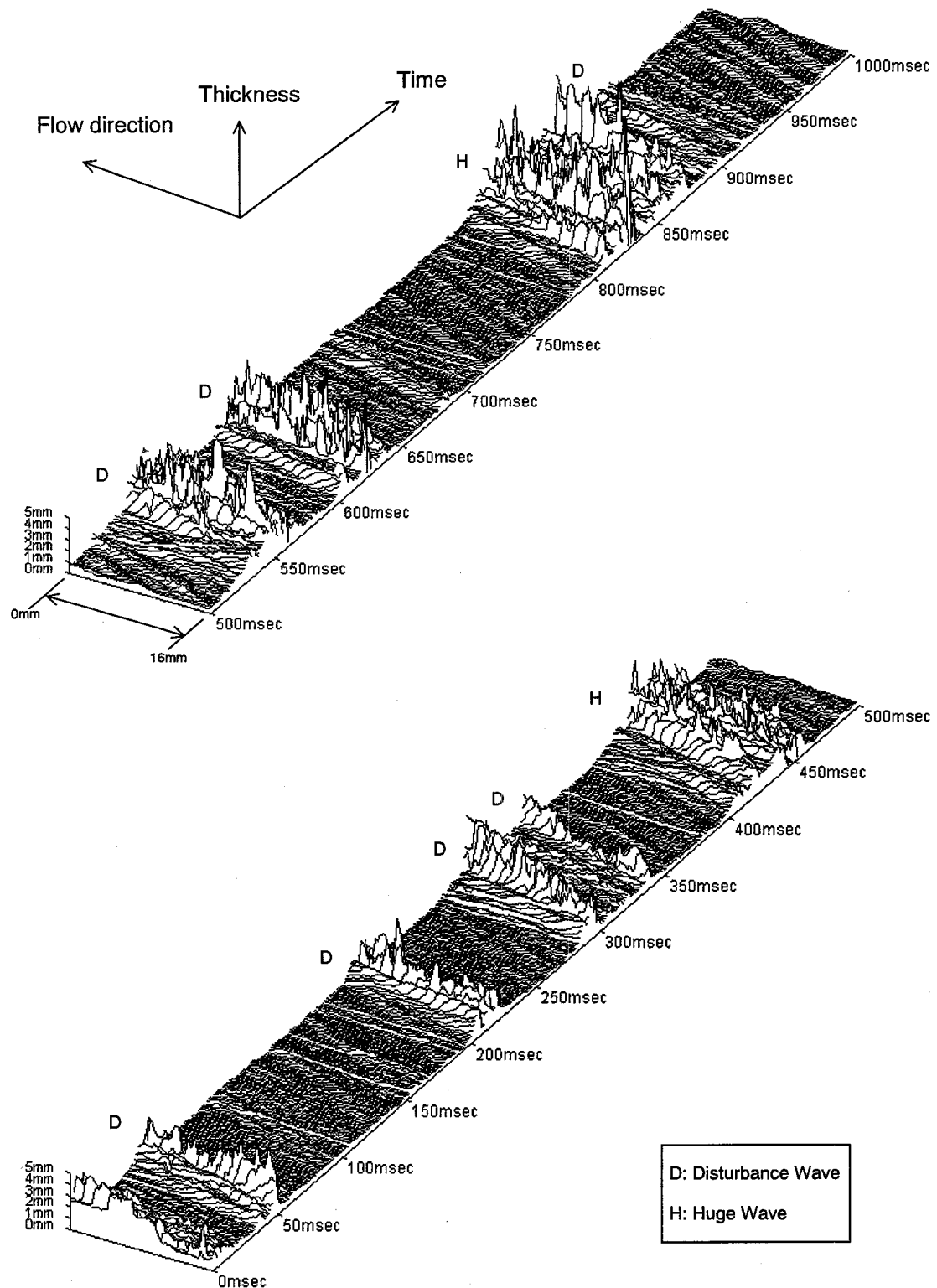


Figure 3.8 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=10.3\text{m/s}$)

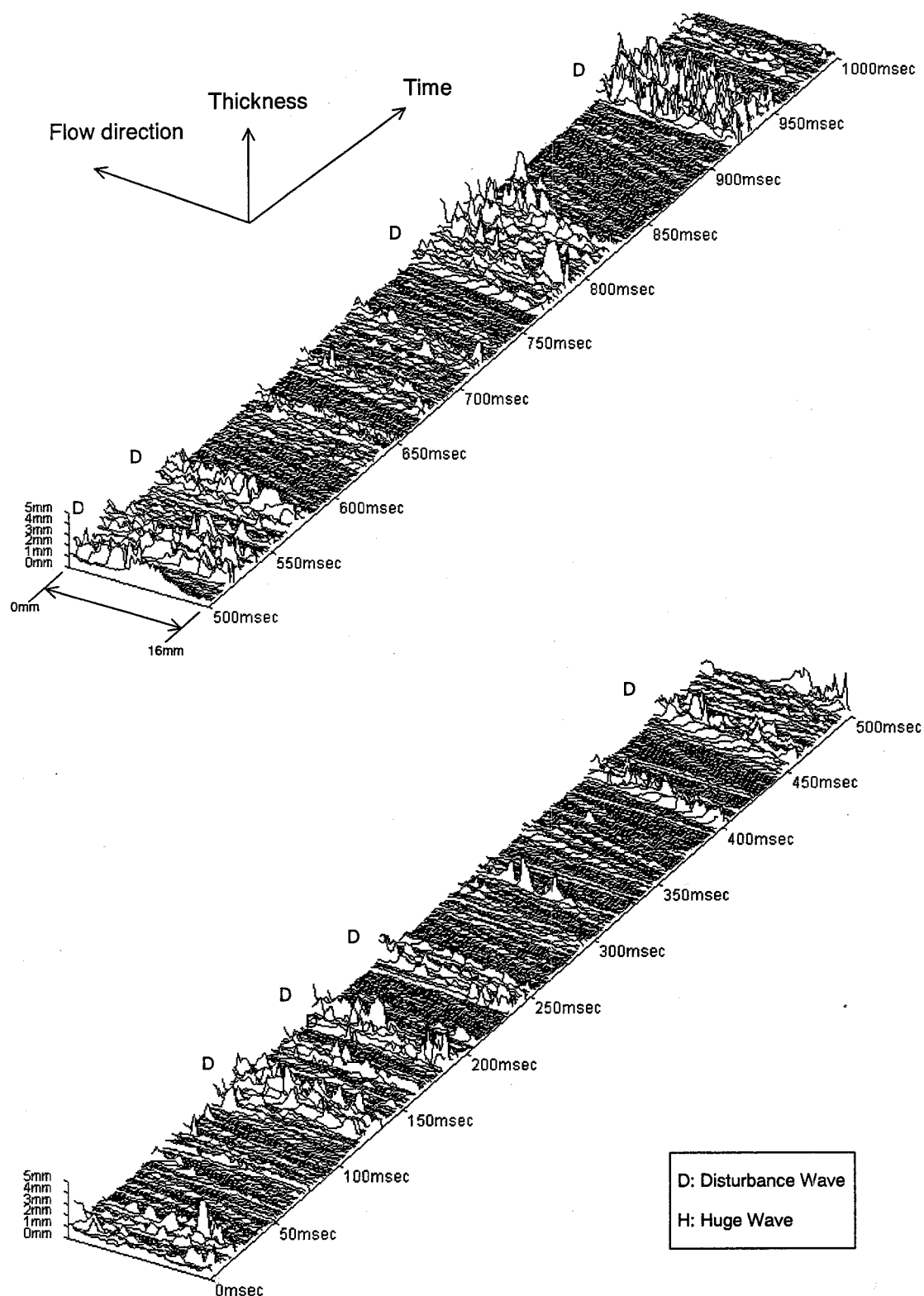


Figure 3.9 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=14.9\text{m/s}$)

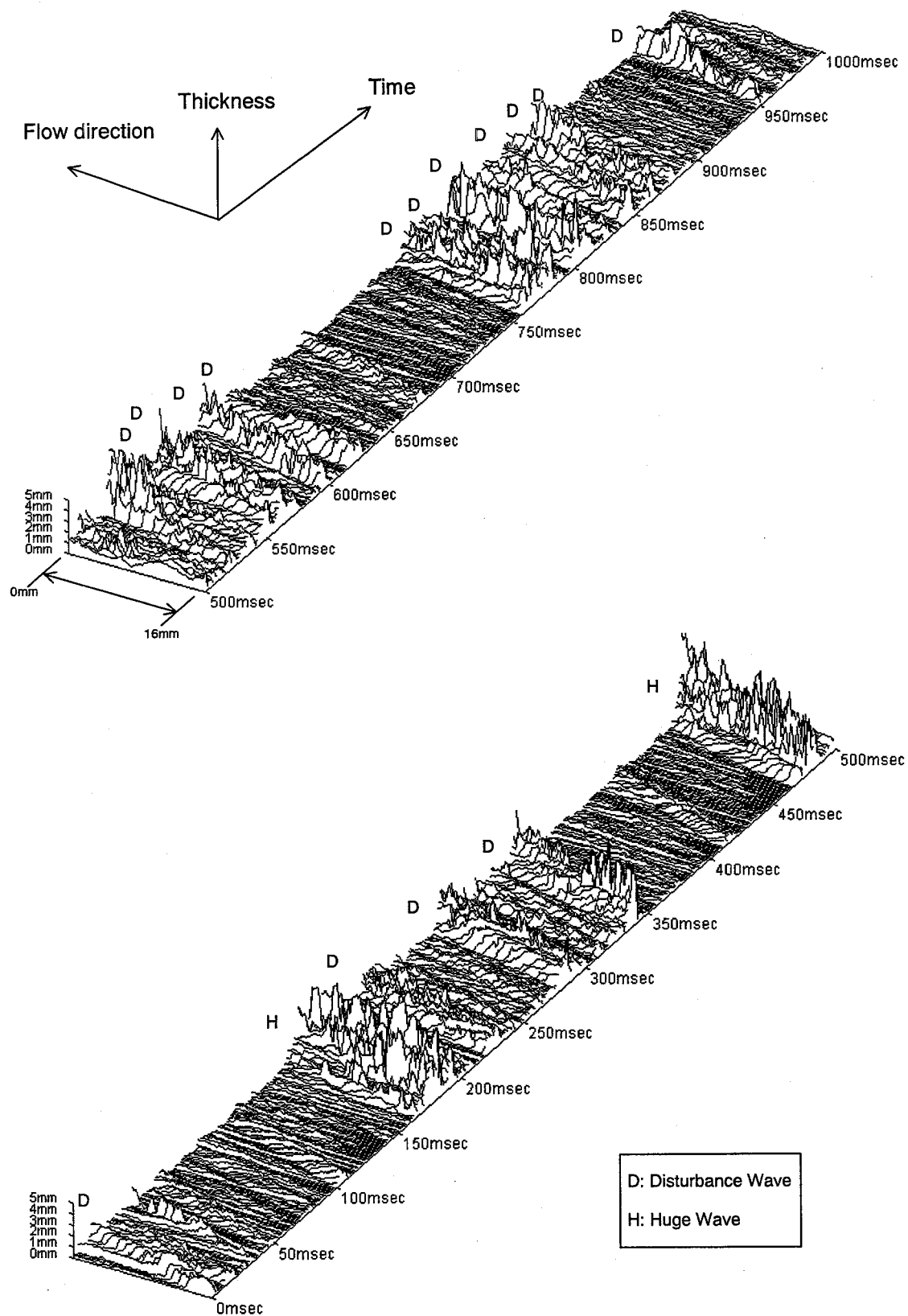


Figure 3.10 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.069\text{m/s}$, $j_g=8.0\text{m/s}$)

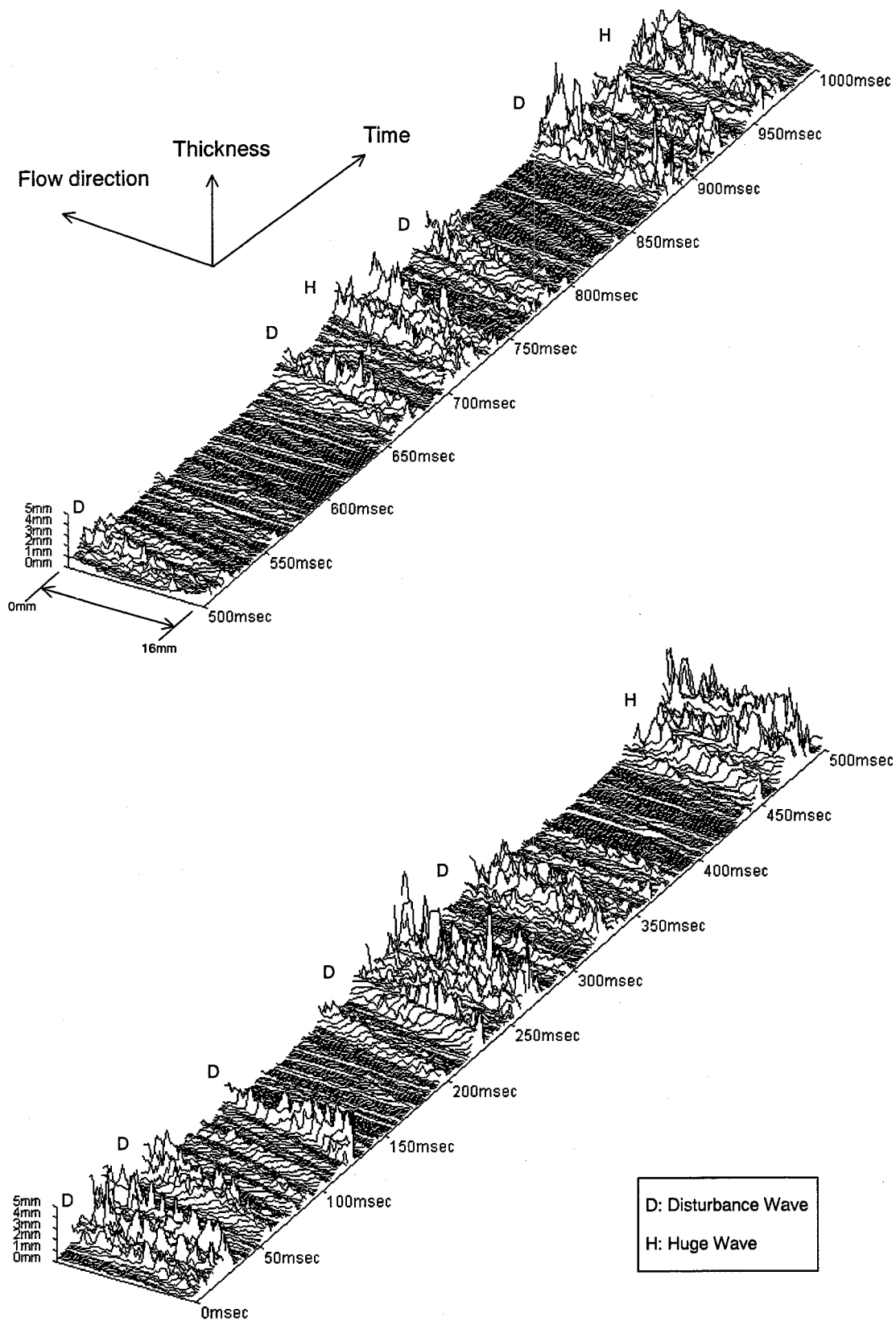


Figure 3.11 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_i=0.069\text{m/s}$, $j_g=10.0\text{m/s}$)

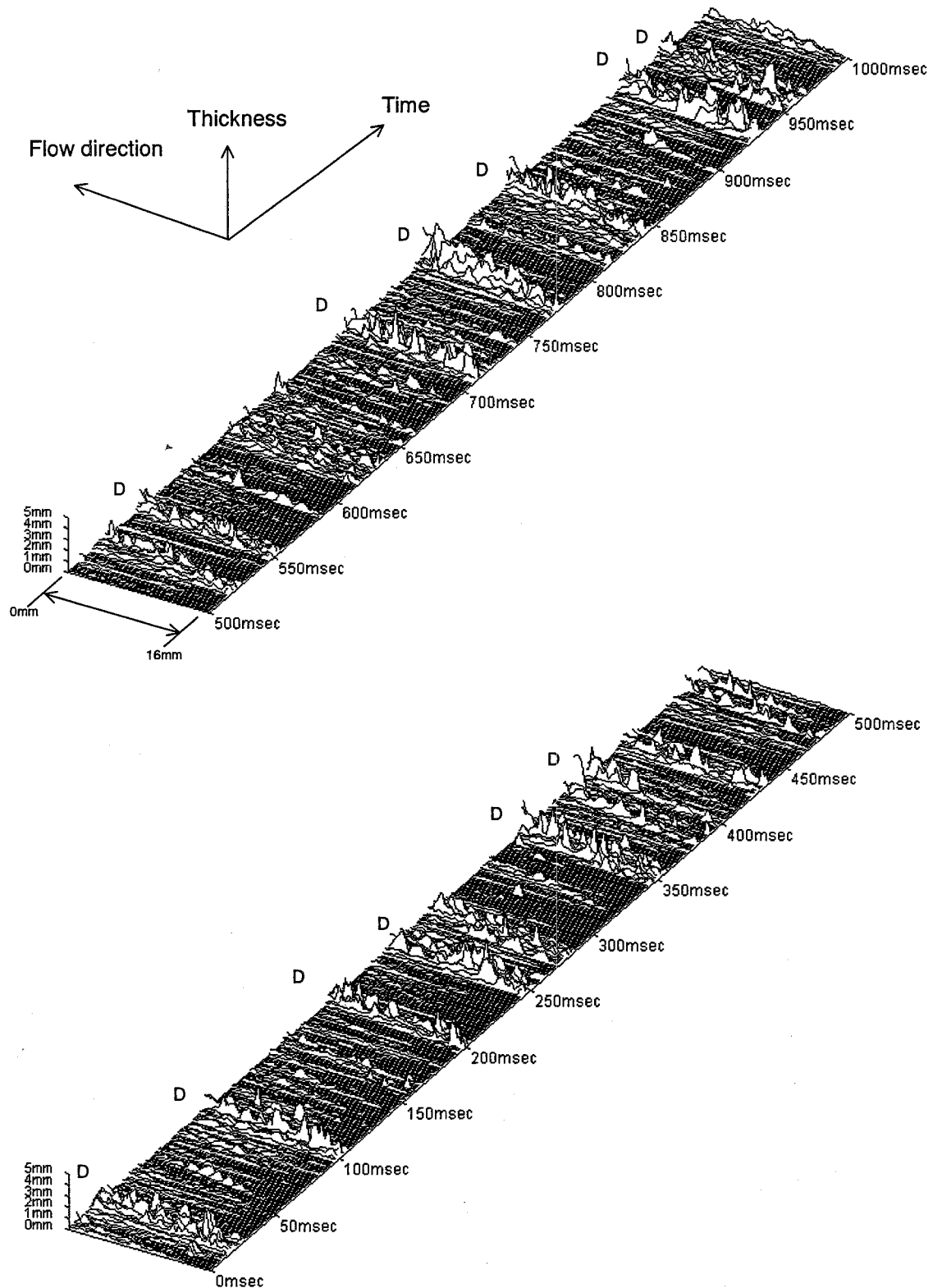


Figure 3.12 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.04\text{m/s}$, $j_g=19.9\text{m/s}$)

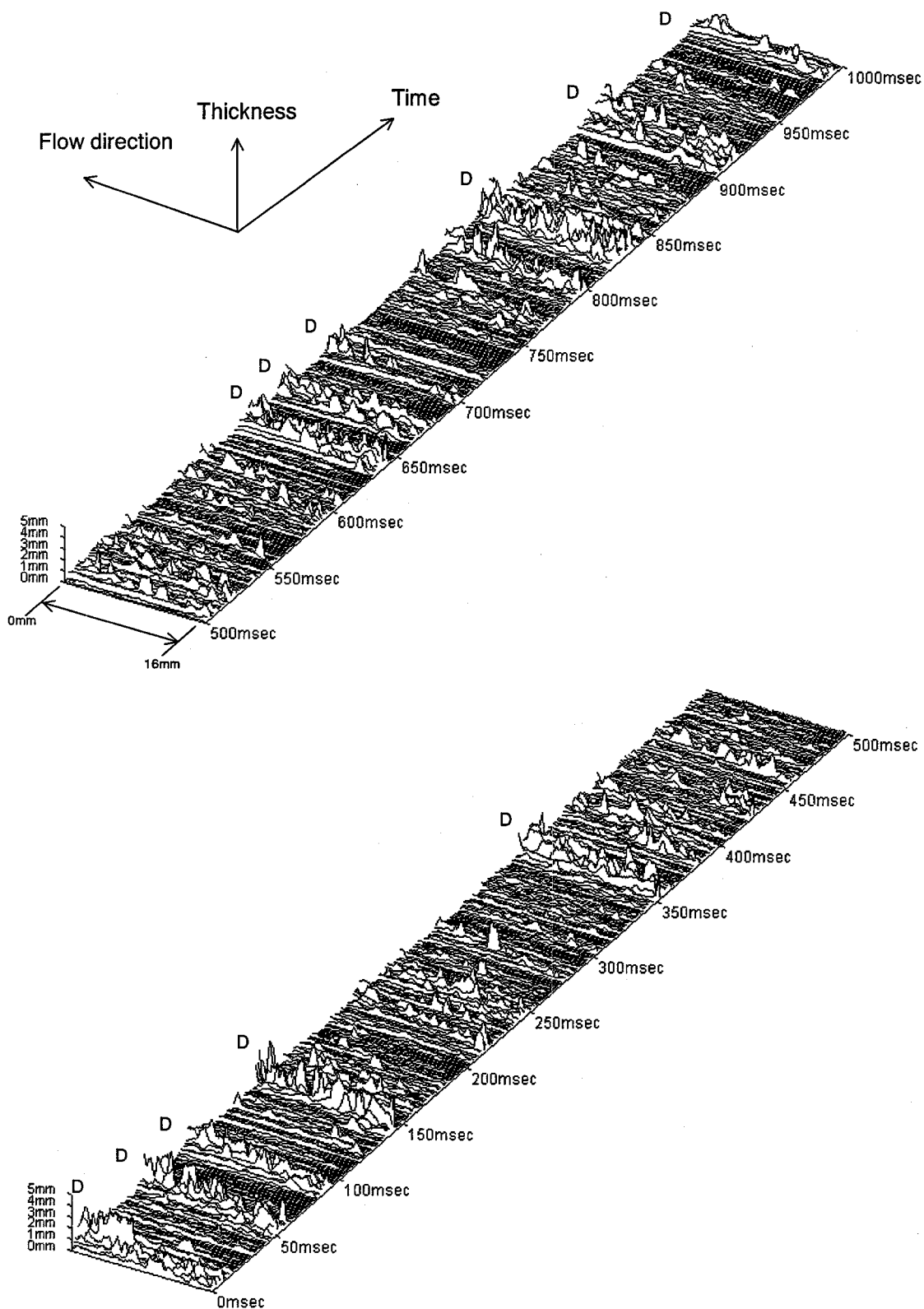


Figure 3.13 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.058\text{m/s}$, $j_g=19.9\text{m/s}$)

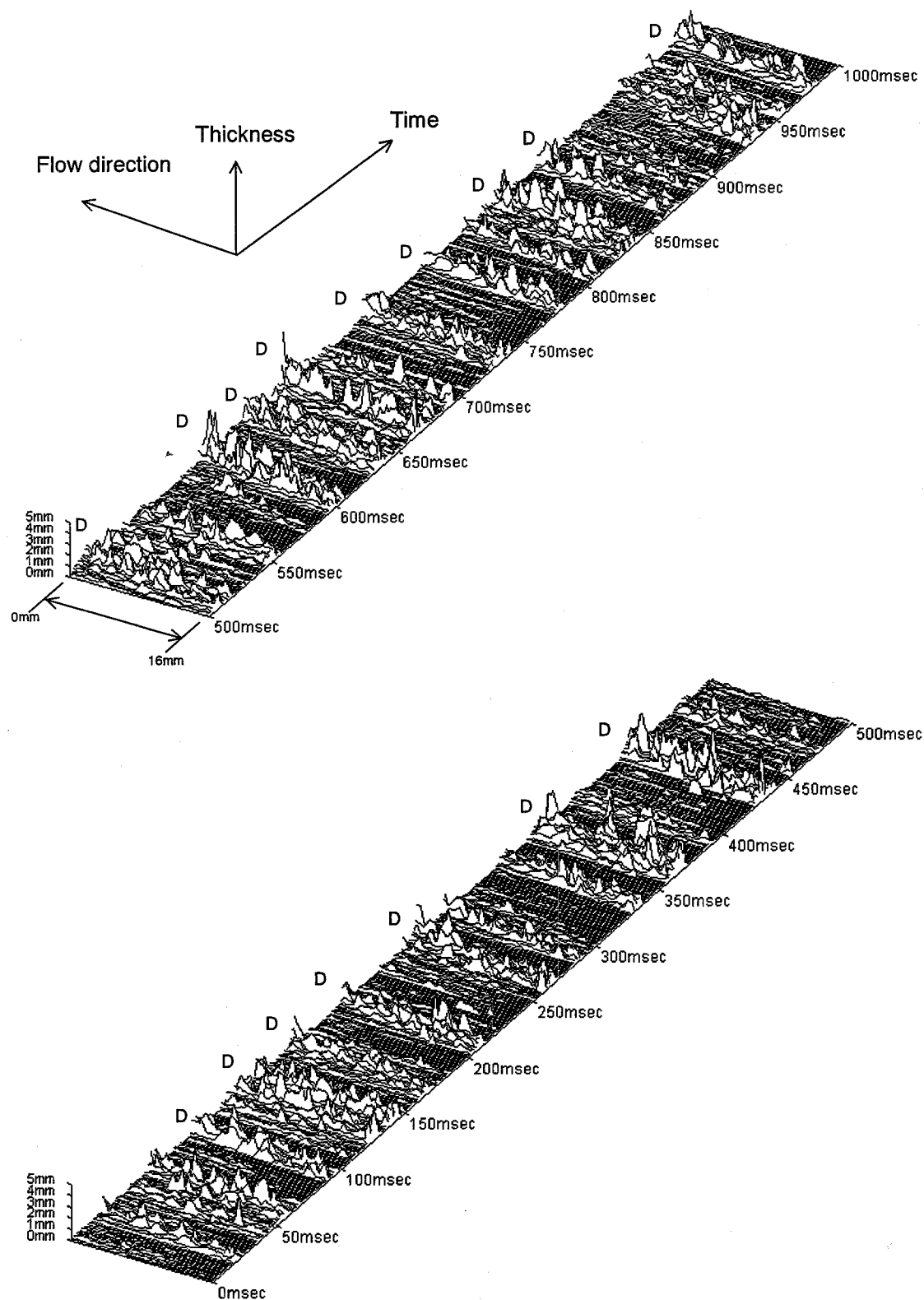


Figure 3.14 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=19.9\text{m/s}$)

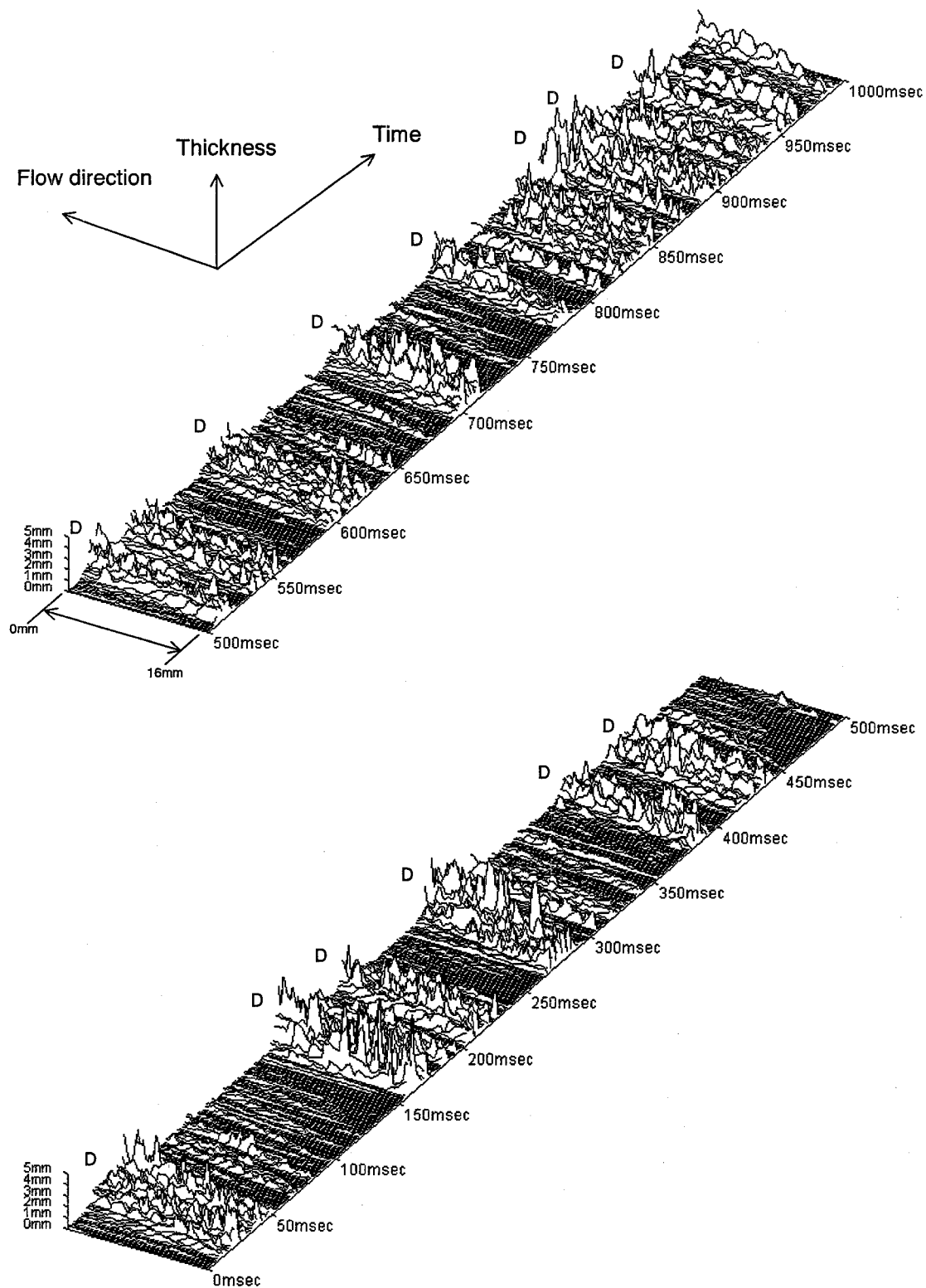


Figure 3.15 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=13.0\text{m/s}$)

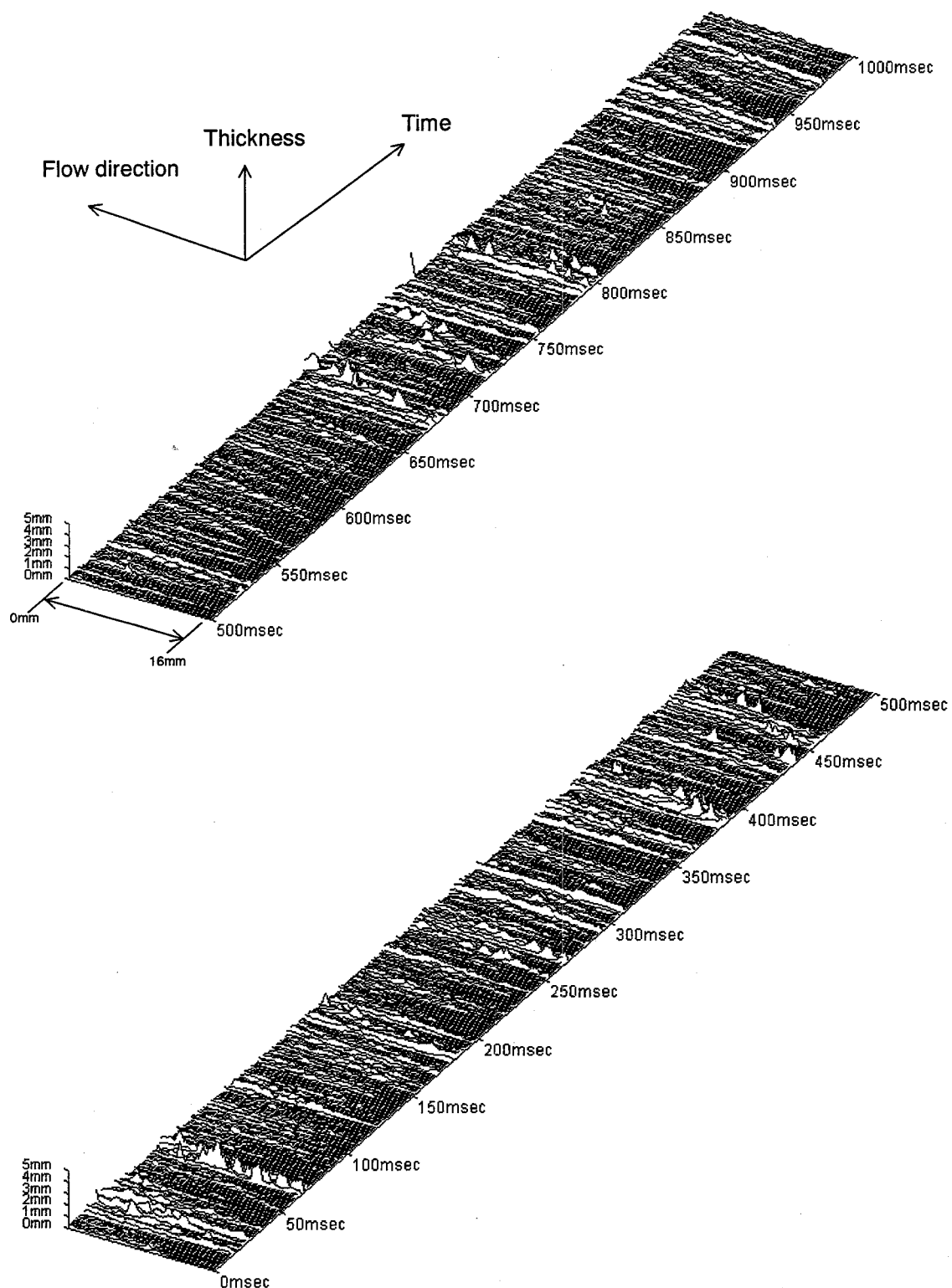


Figure 3.16 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=19.5\text{m/s}$)

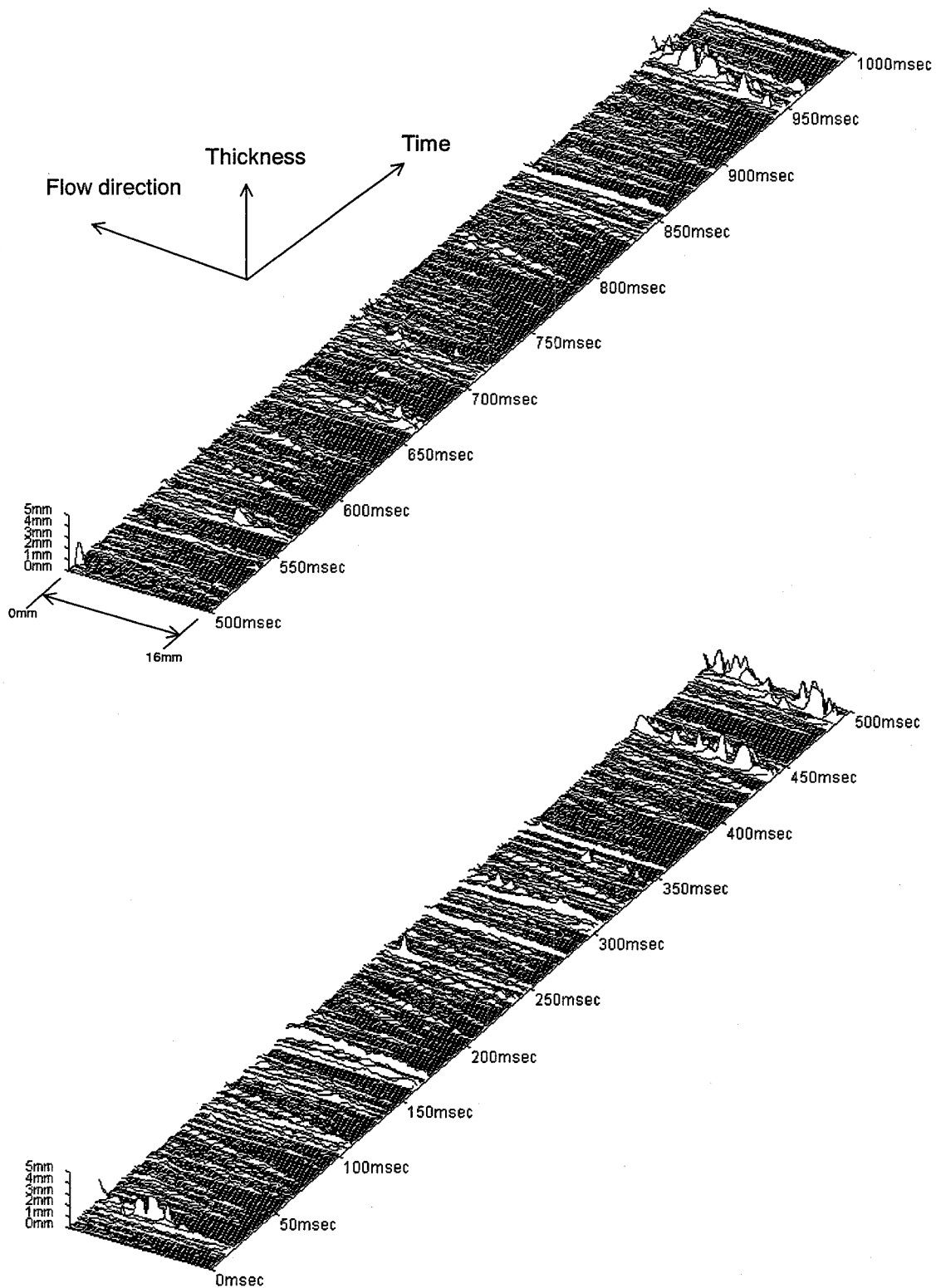


Figure 3.17 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=18.1\text{m/s}$)

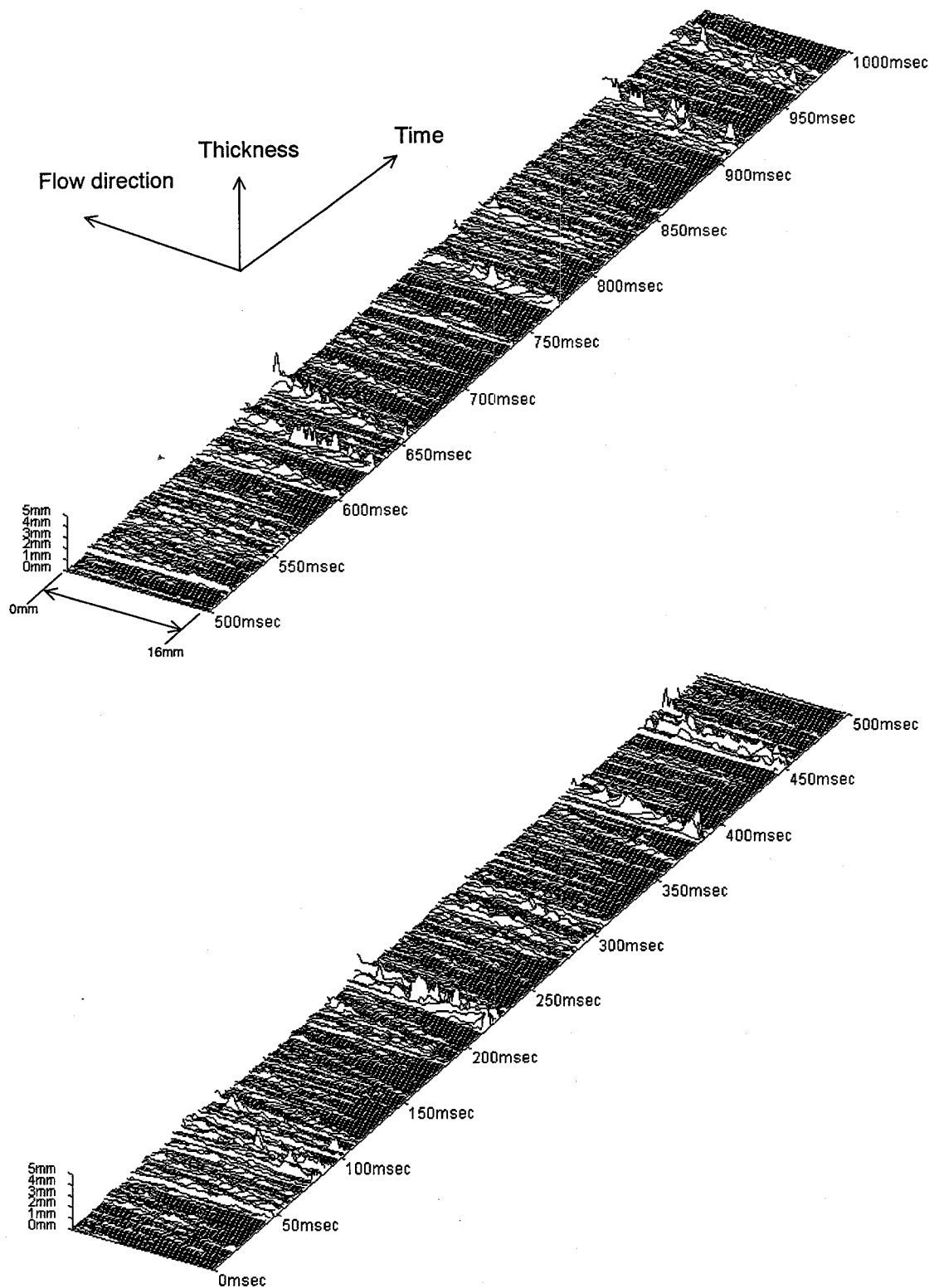


Figure 3.18 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_i=0.013\text{m/s}$, $j_e=18.1\text{m/s}$)

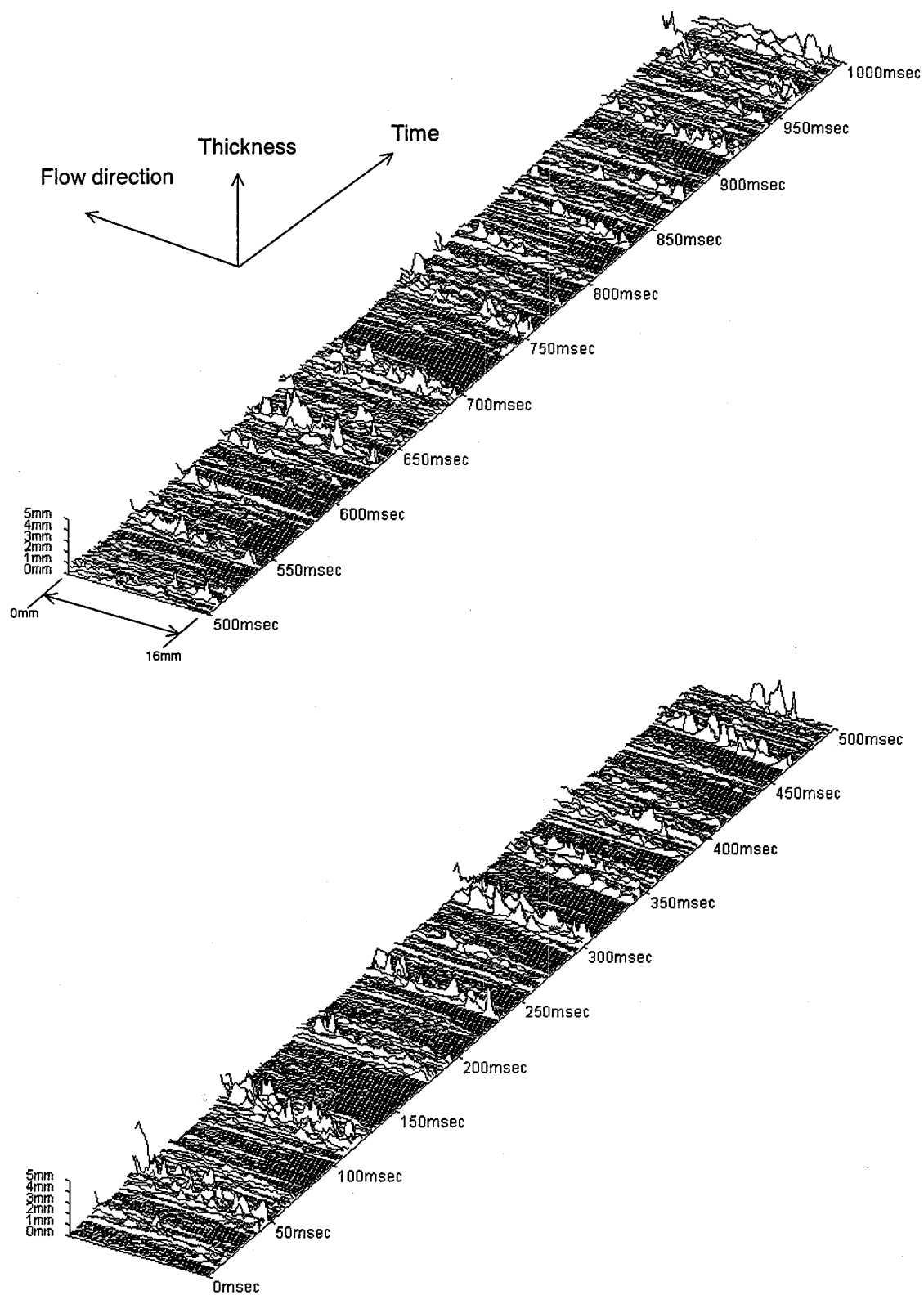


Figure 3.19 Bird's Eye View of Time-Dependent Axial Cross-Sectional Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.027\text{m/s}$, $j_g=18.1\text{m/s}$)

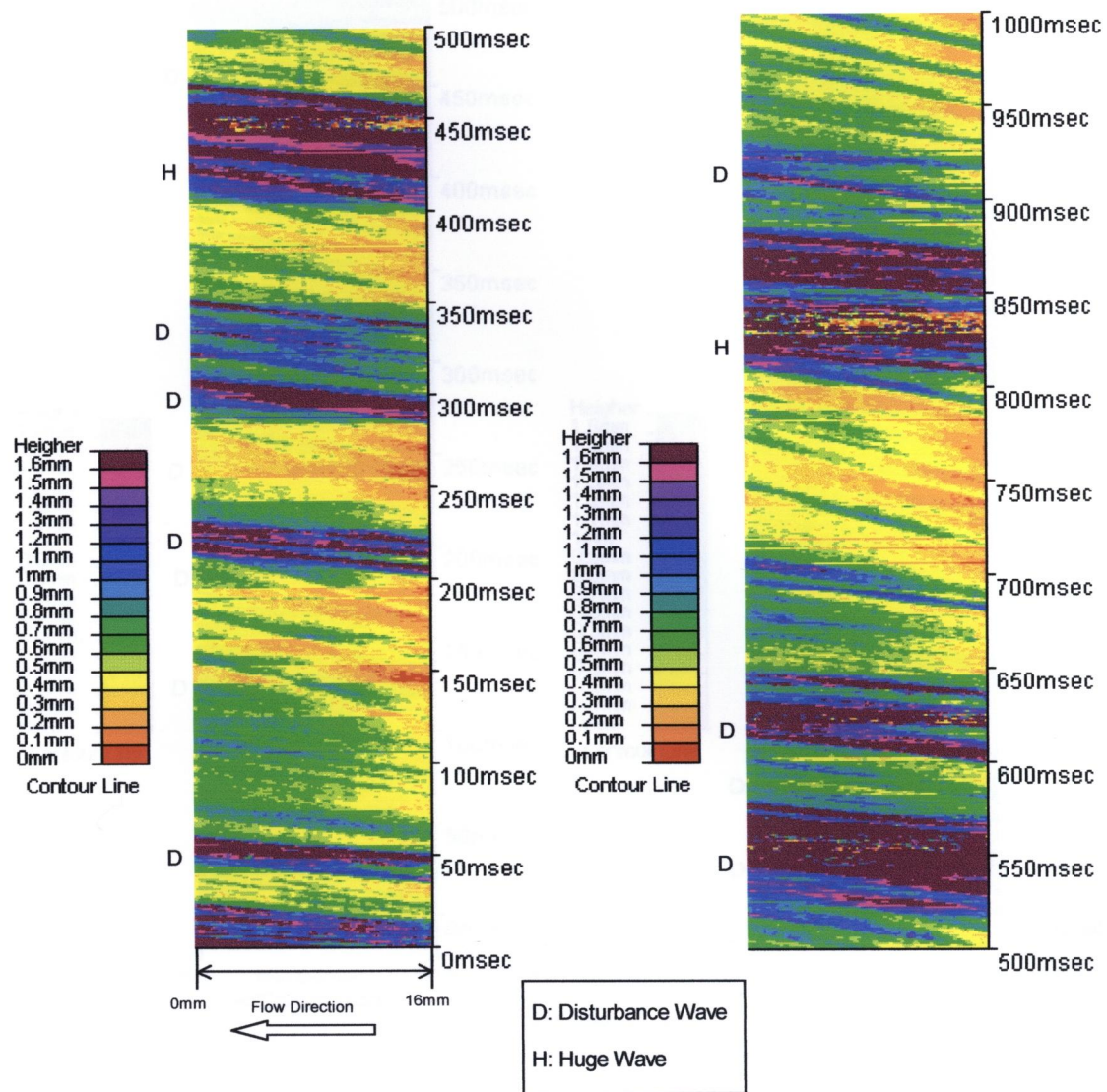


Figure 3.21 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=10.3\text{m/s}$)

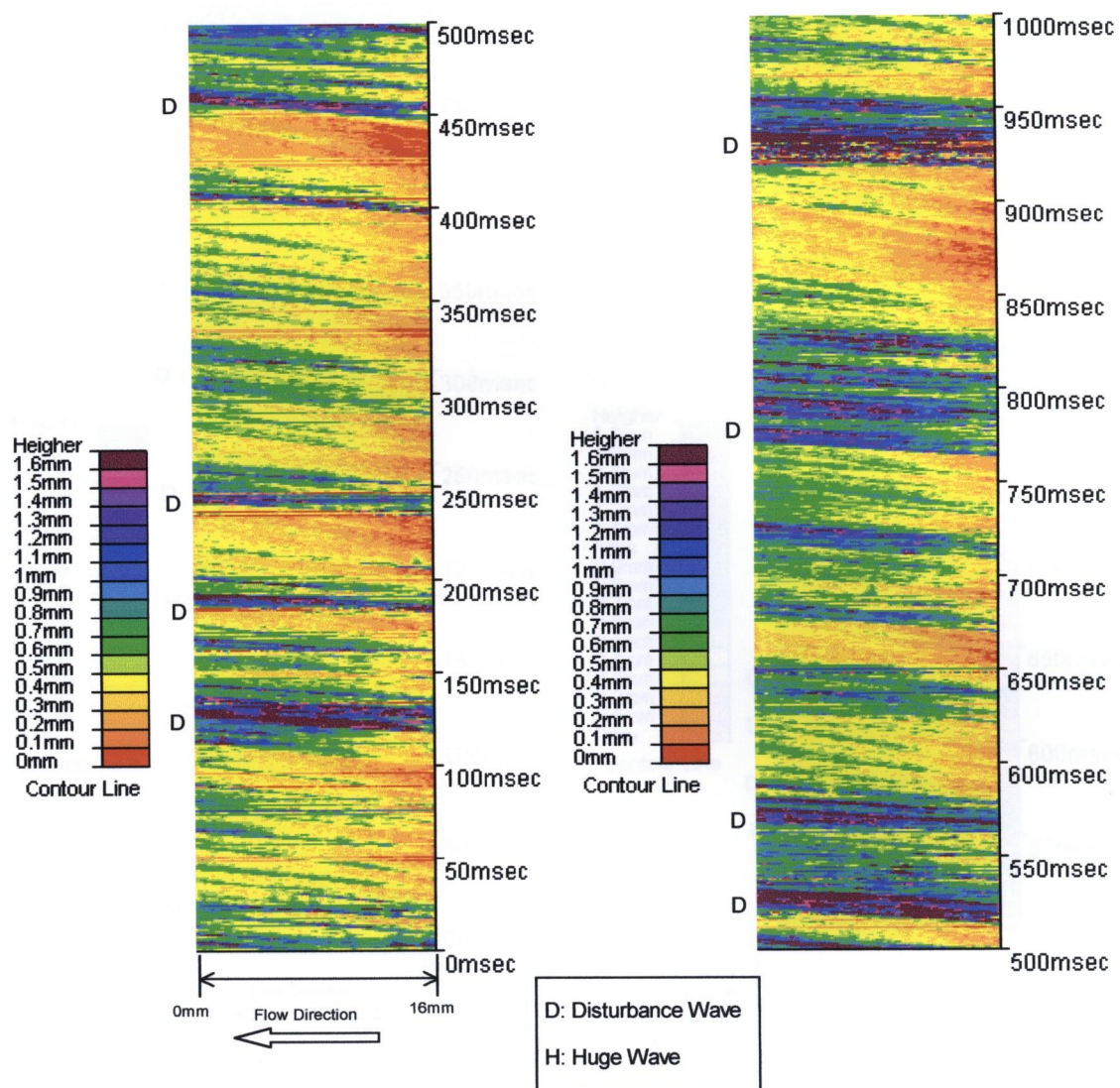


Figure 3.22 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=14.9\text{m/s}$)

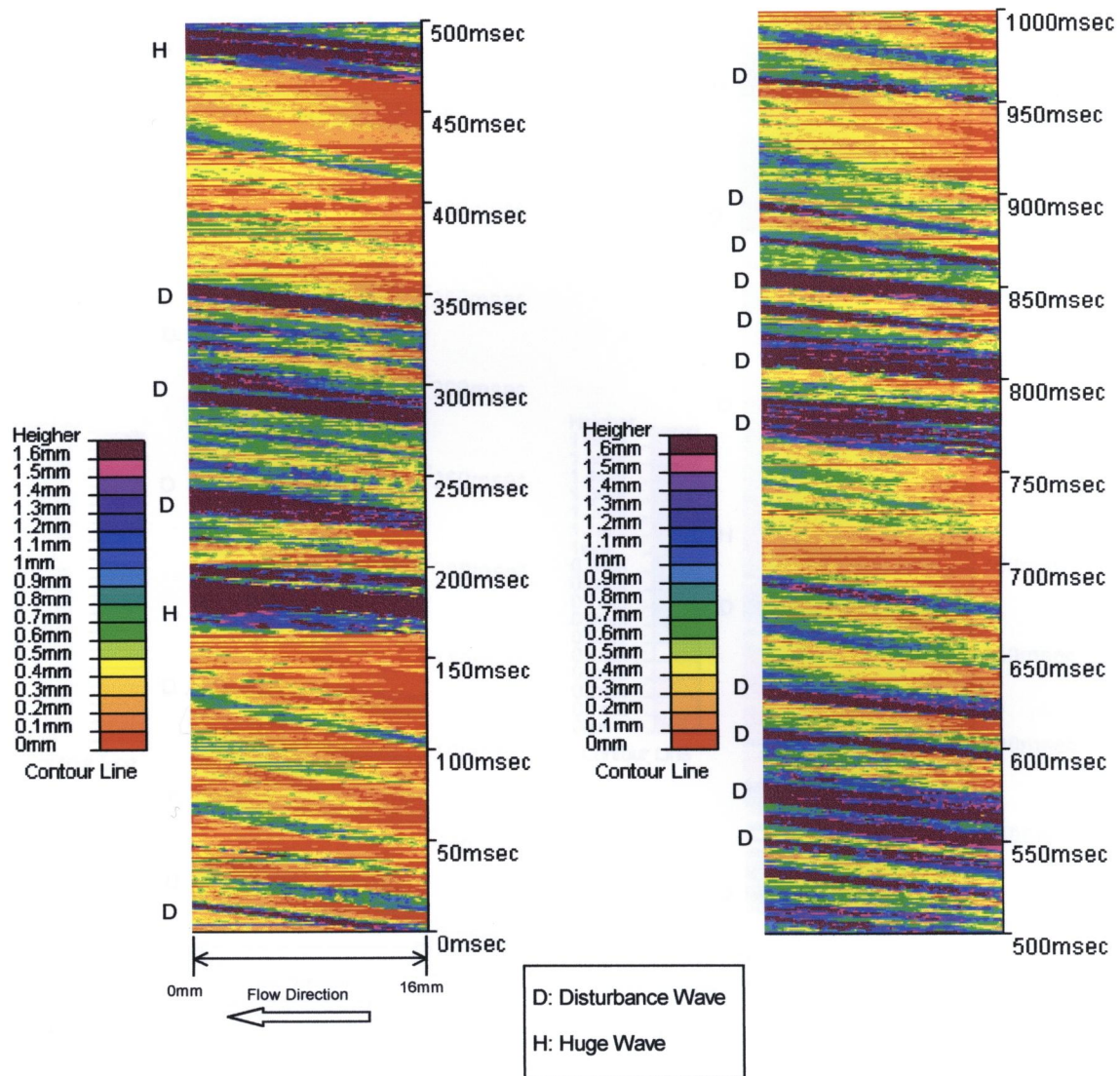


Figure 3.23 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.069\text{m/s}$, $j_g=8.0\text{m/s}$)

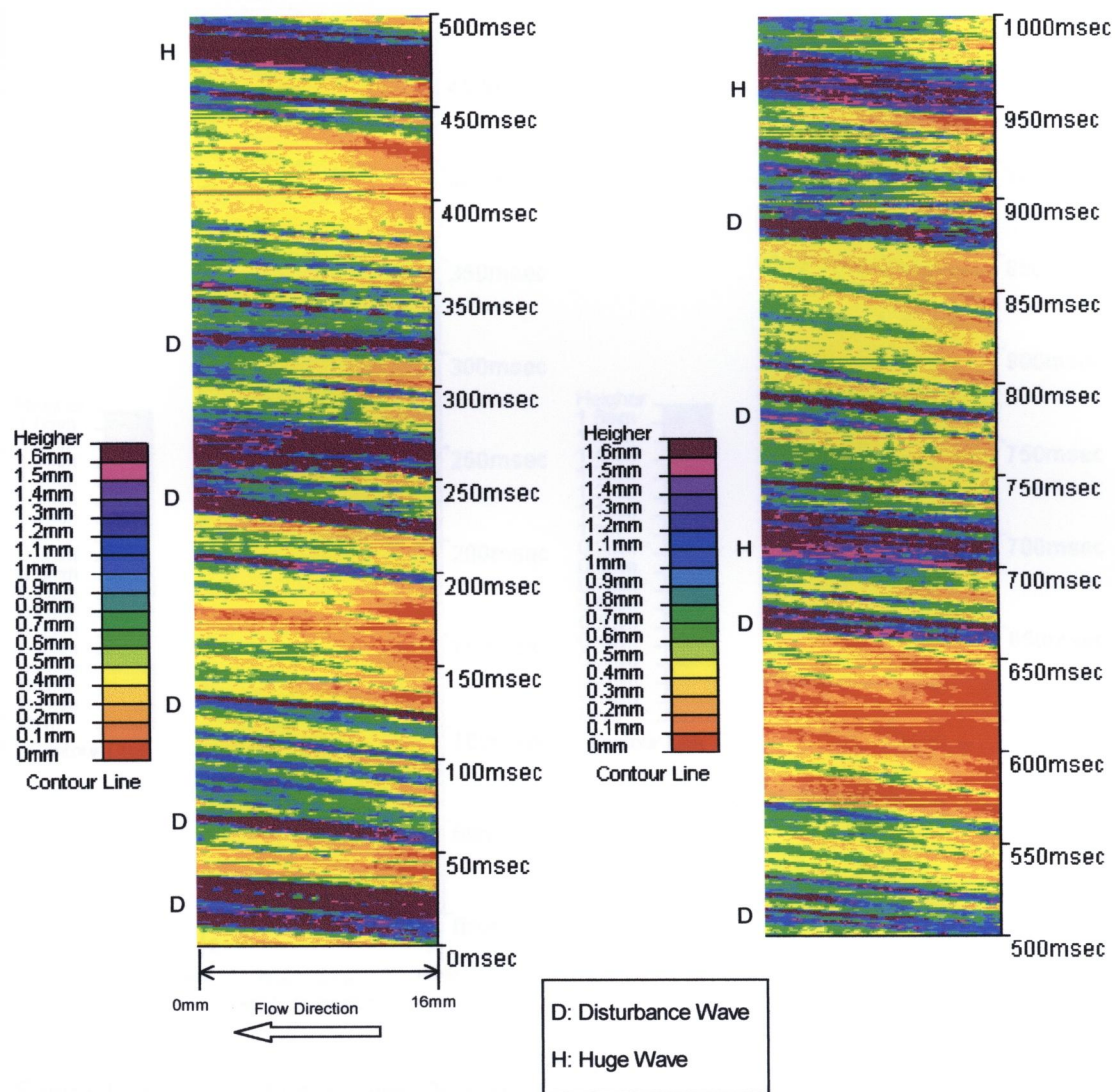


Figure 3.24 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.069\text{m/s}$, $j_g=10.0\text{m/s}$)

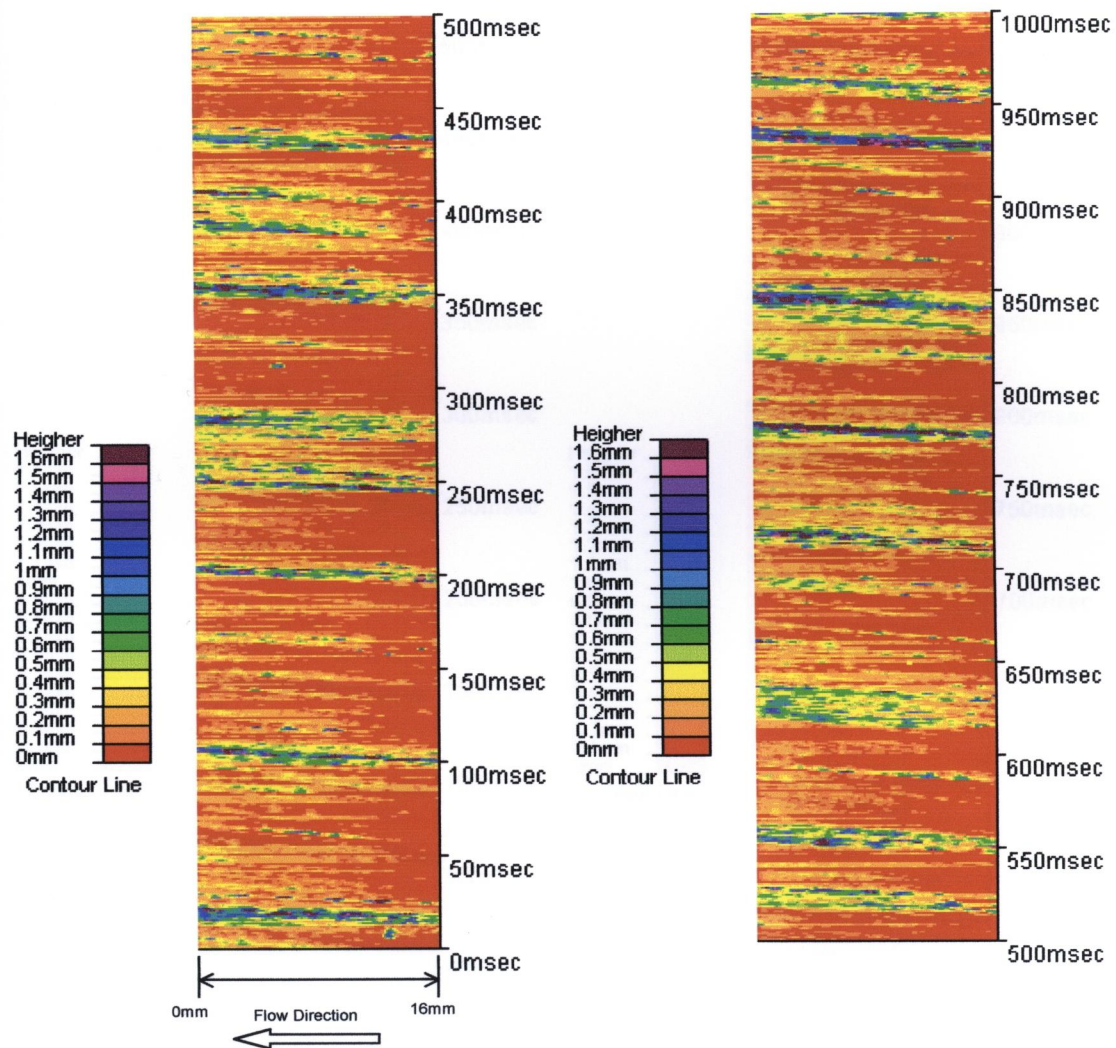


Figure 3.25 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.04\text{m/s}$, $j_g=19.9\text{m/s}$)

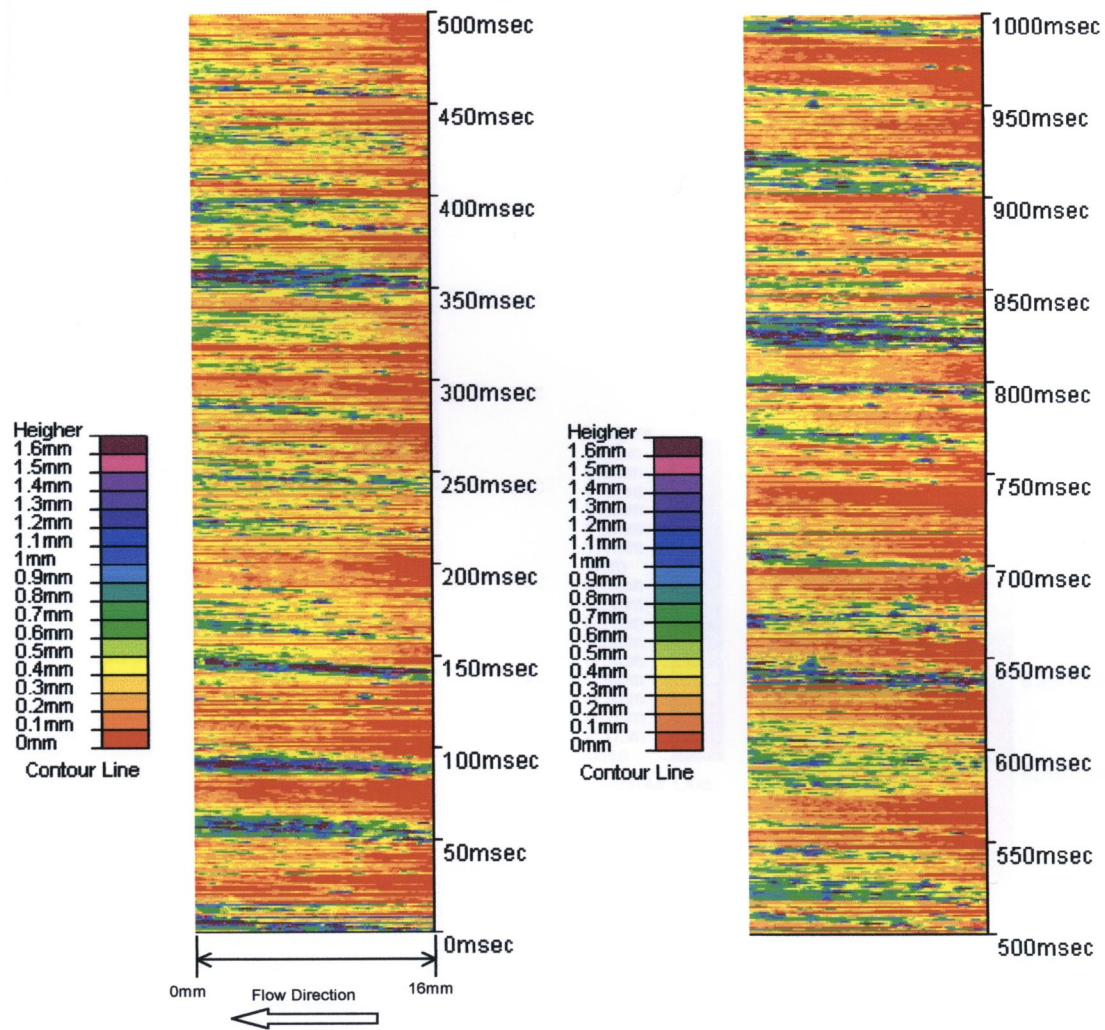


Figure 3.26 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.058\text{m/s}$, $j_g=19.9\text{m/s}$)

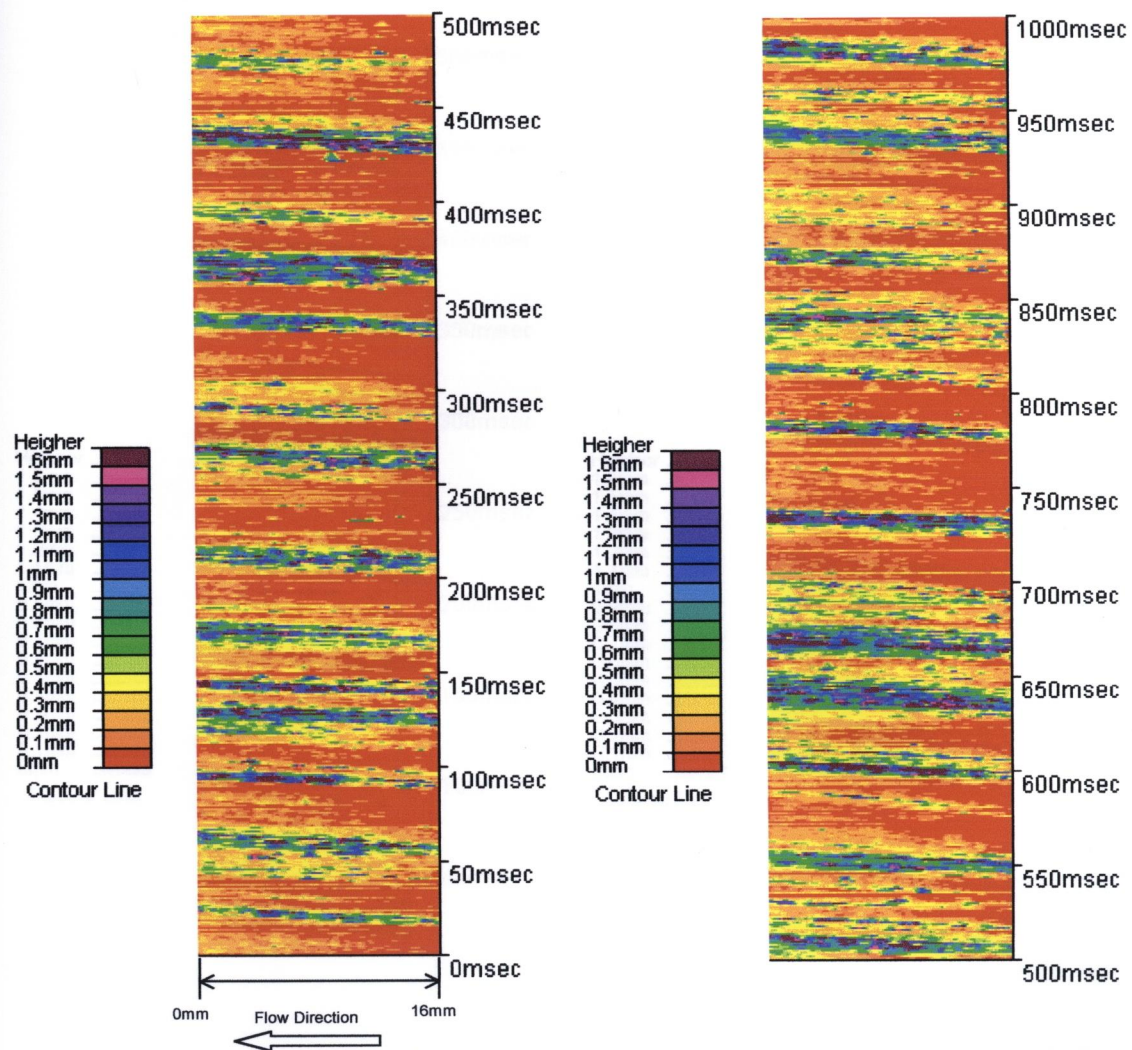


Figure 3.27 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=19.9\text{m/s}$)

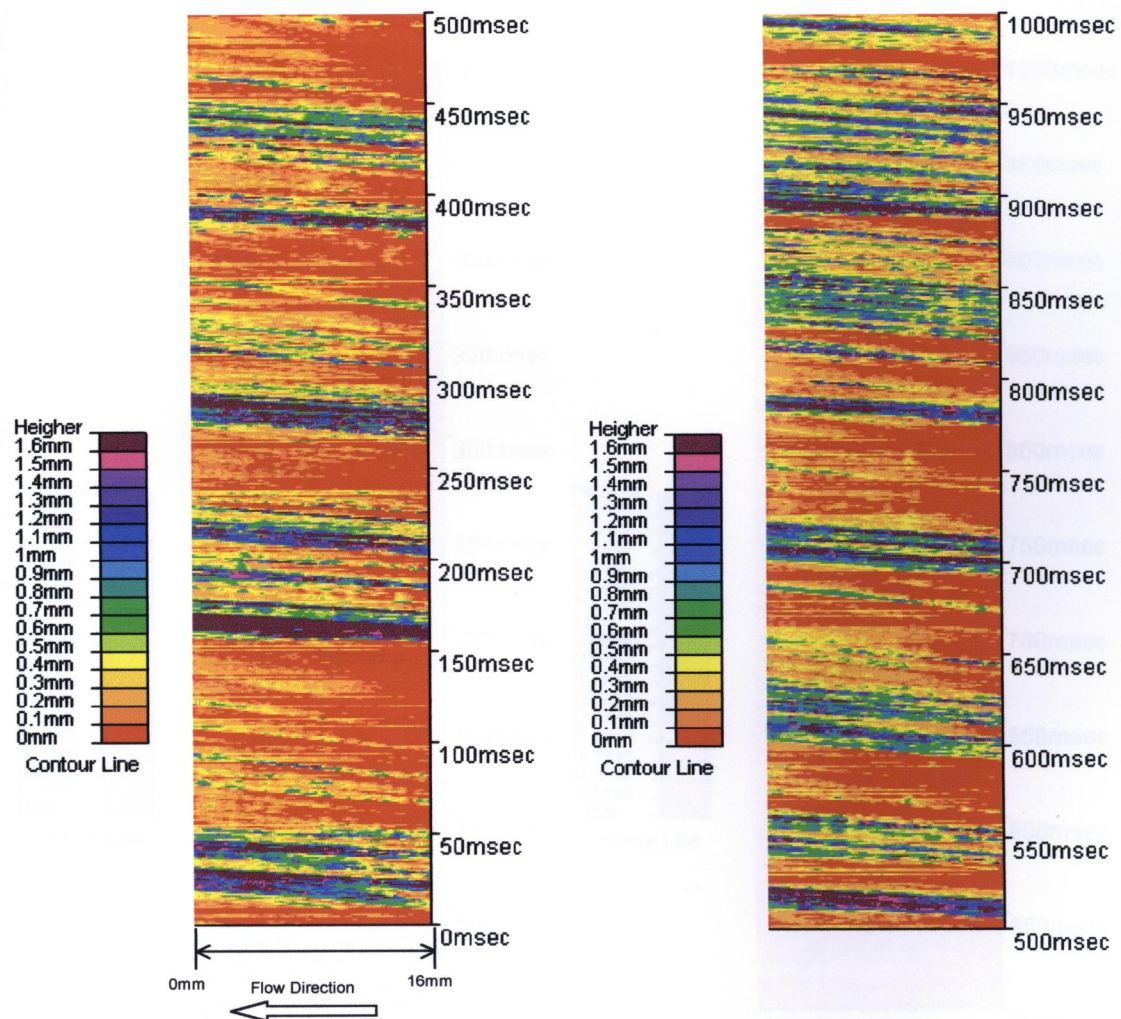


Figure 3.28 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=13.0\text{m/s}$)

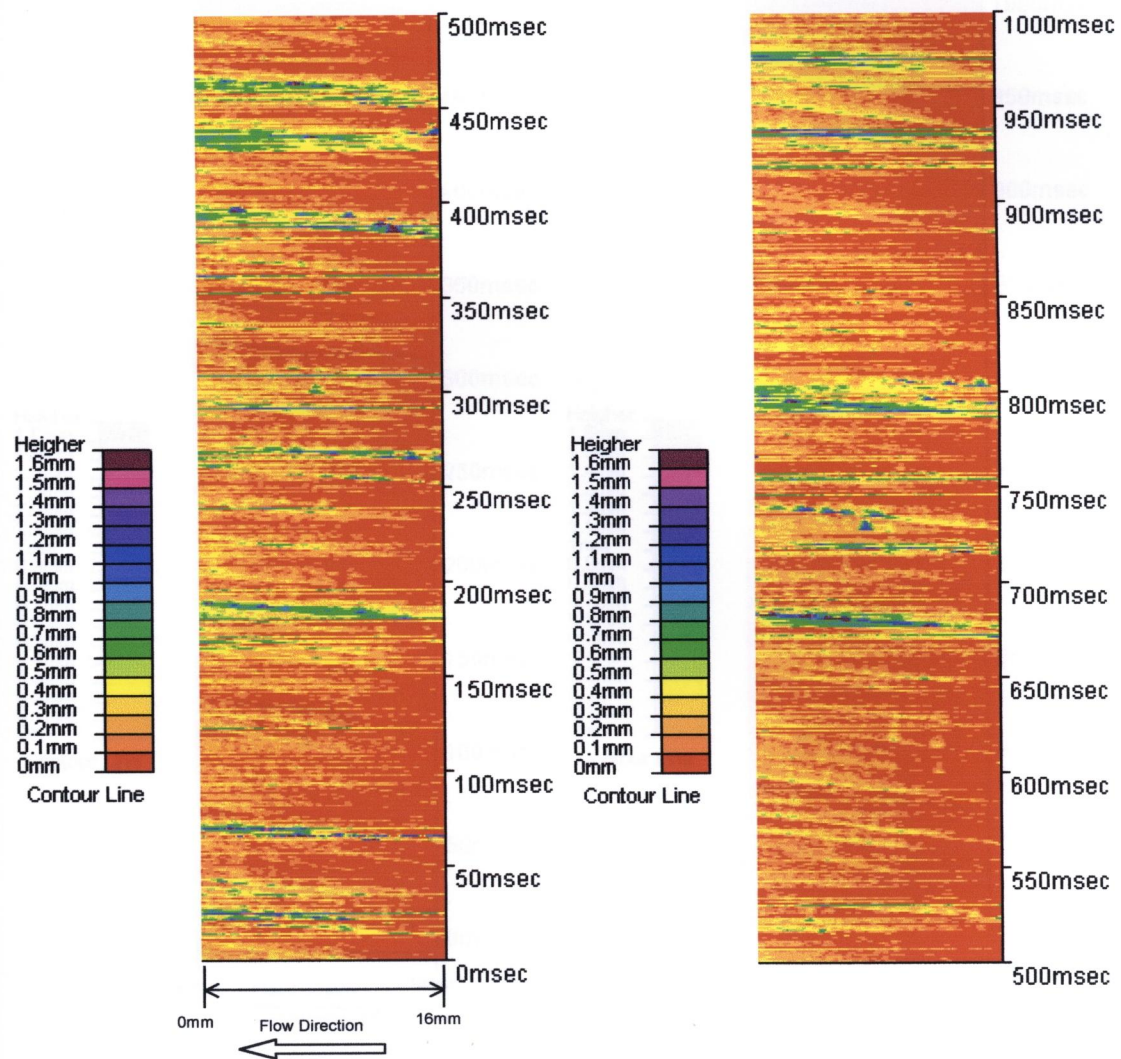


Figure 3.29 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=19.5\text{m/s}$)

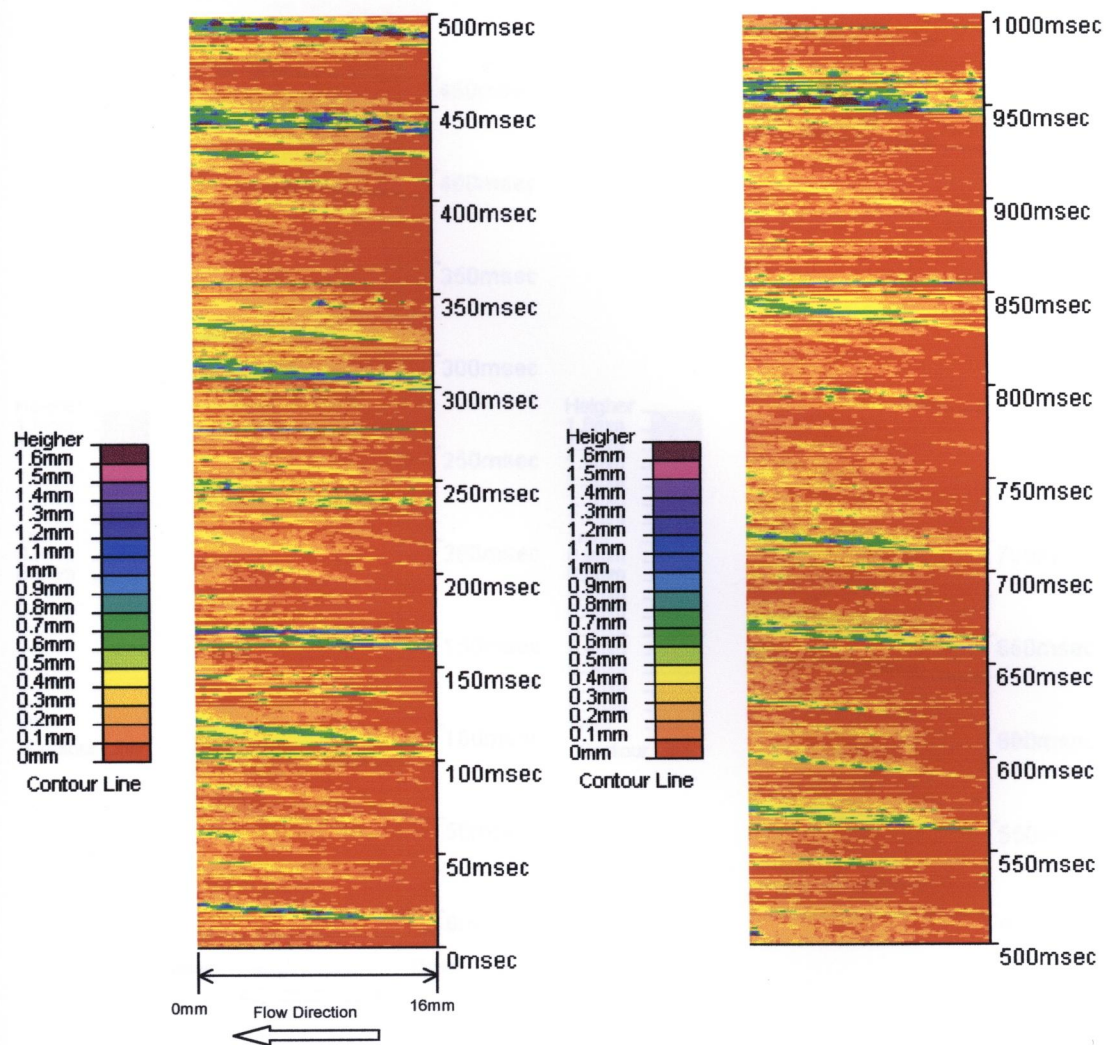


Figure 3.30 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=18.1\text{m/s}$)

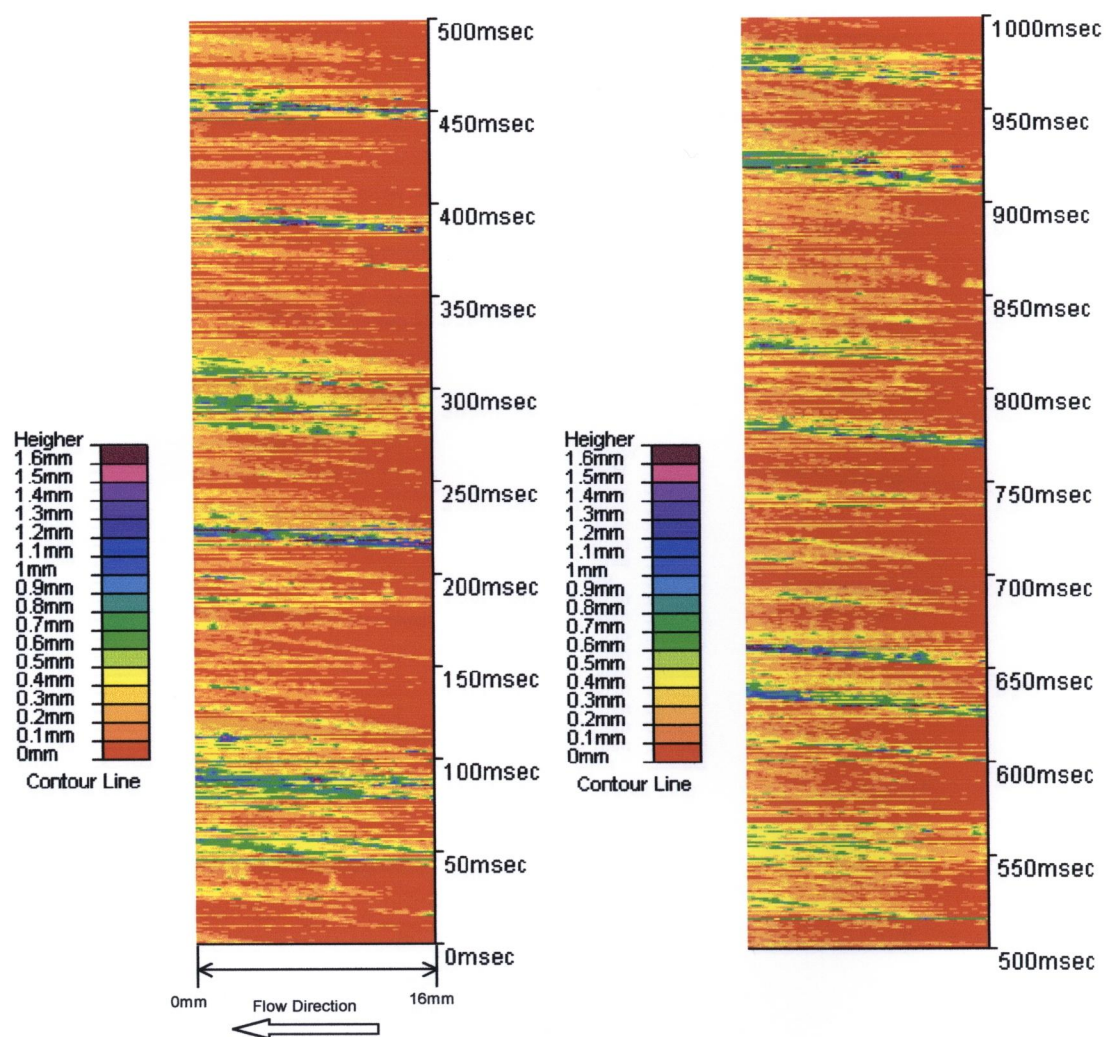


Figure 3.31 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.013\text{m/s}$, $j_g=18.1\text{m/s}$)

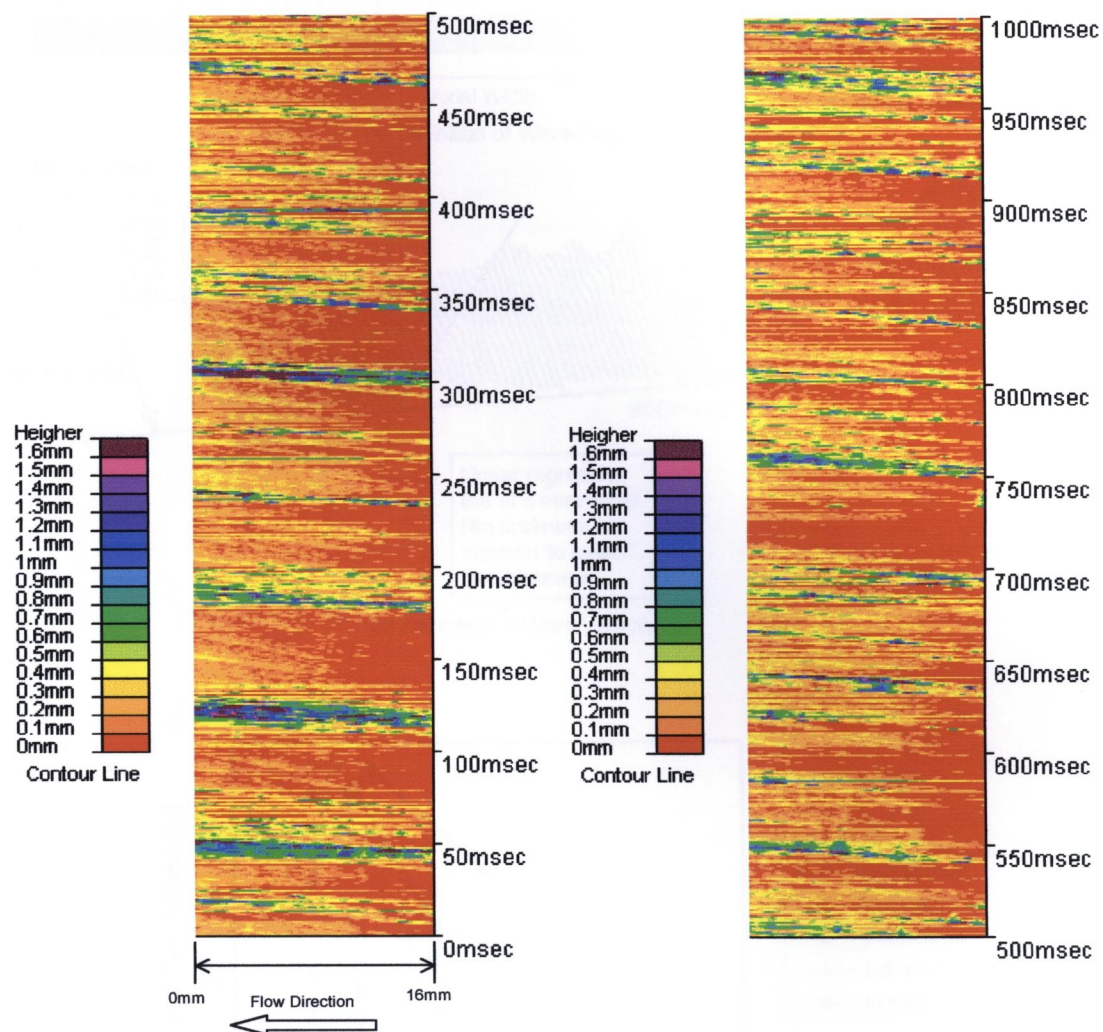
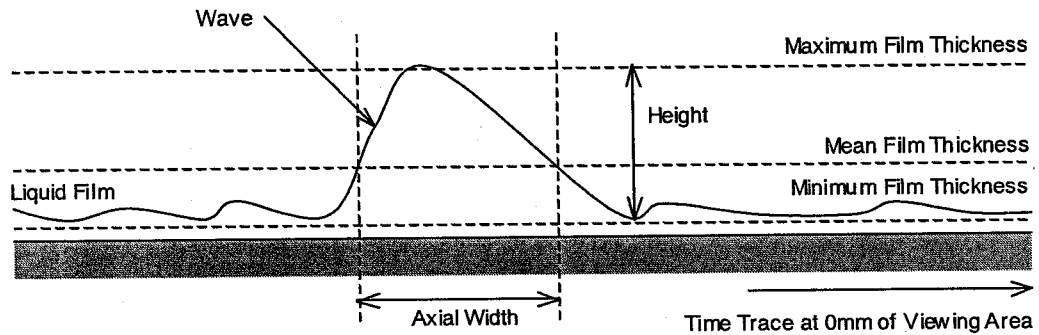
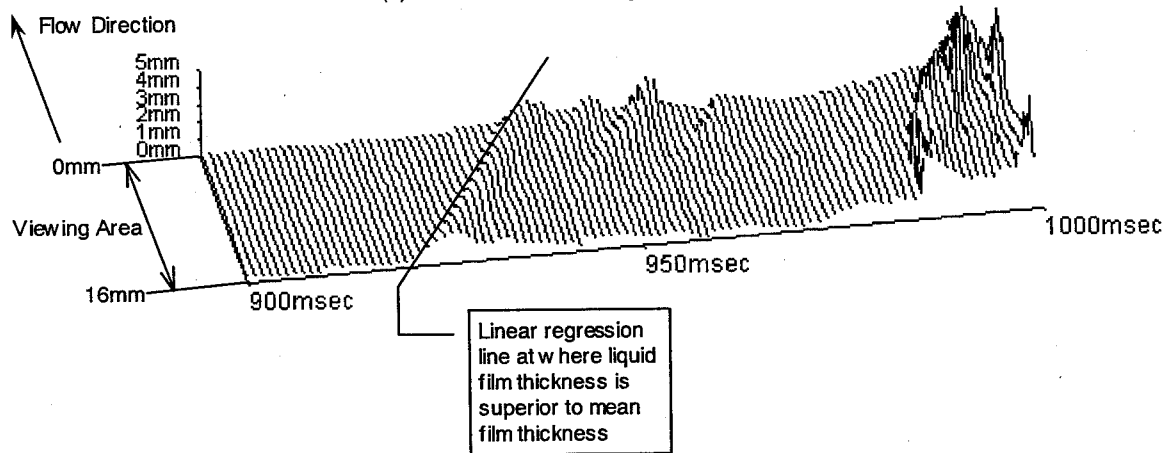


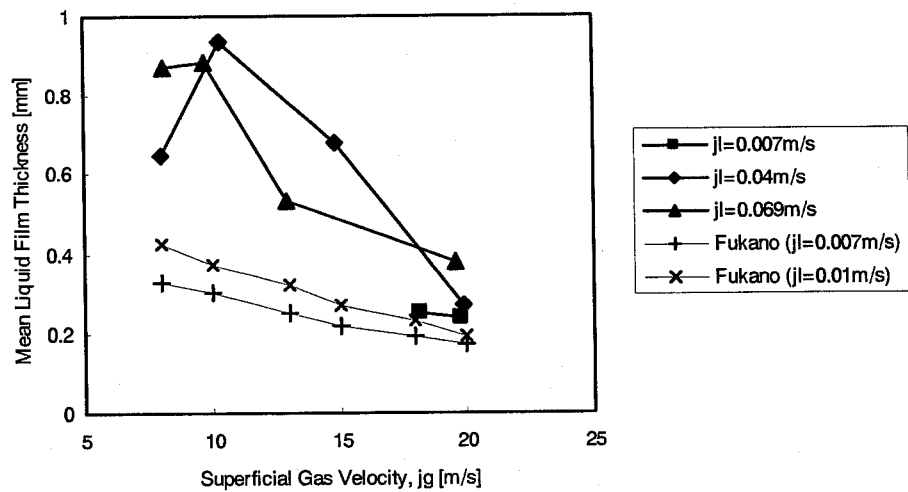
Figure 3.32 Contour Plot of Time-Dependent Distribution of Liquid Film Thickness of Ripple Wave Flow ($j_l=0.027\text{m/s}$, $j_g=18.1\text{m/s}$)



(a) Definition of Wave Height and Axial Width

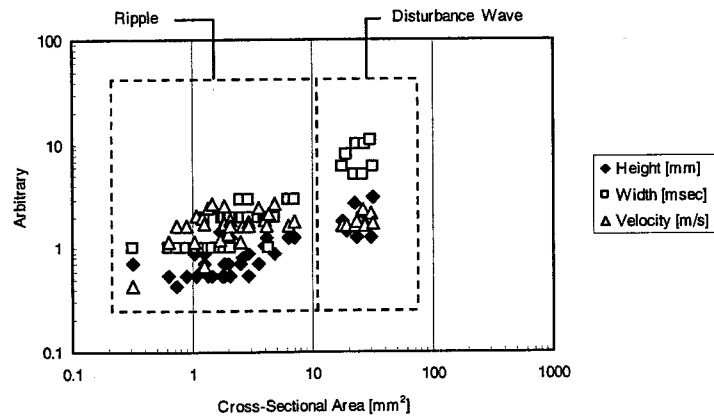


(b) Definition of Wave Velocity

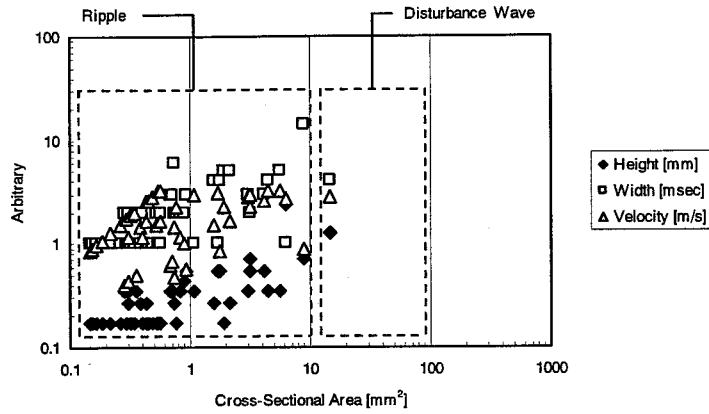


(c) Time-Averaged Mean Liquid Film Thickness

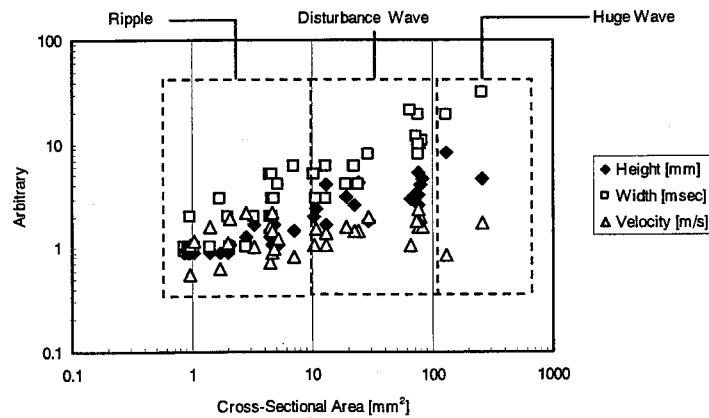
Figure 3.33 Definition of Characteristics of Wave and Time-averaged Liquid Film Thickness



(a) Typical Example of Disturbance Wave Flow without Huge Wave ($j_i=0.04\text{m/s}$ and $j_g=14.9\text{m/s}$)

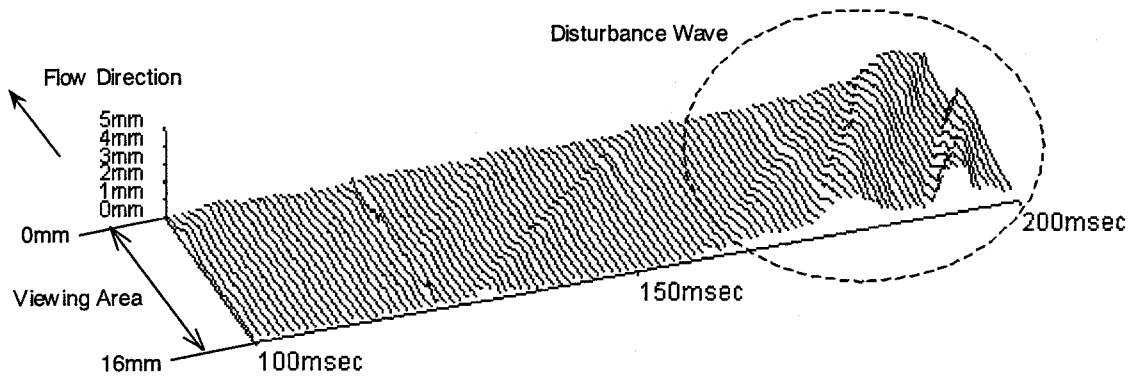


(b) Typical Example of Ripple Wave Flow ($j_i=0.007\text{m/s}$ and $j_g=19.5\text{m/s}$)

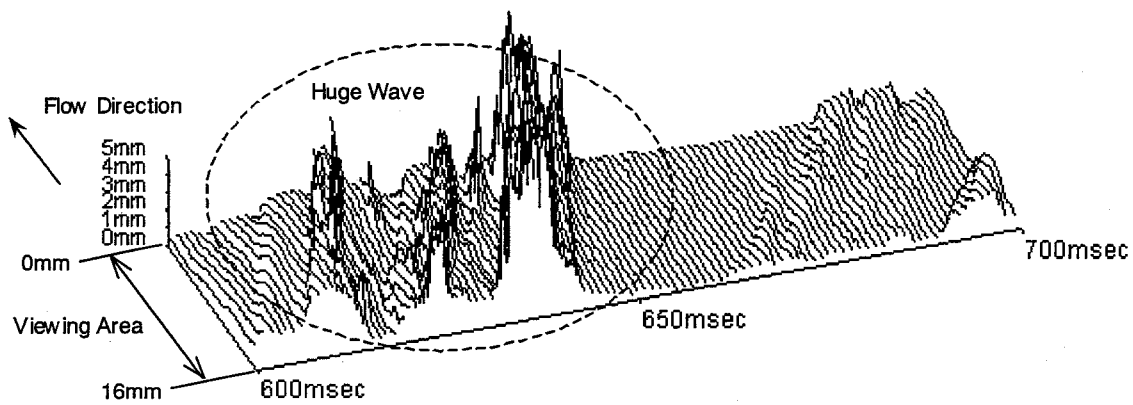


(c) Typical Example of Disturbance Wave Flow with Huge Wave ($j_i=0.069\text{m/s}$ and $j_g=8.0\text{m/s}$)

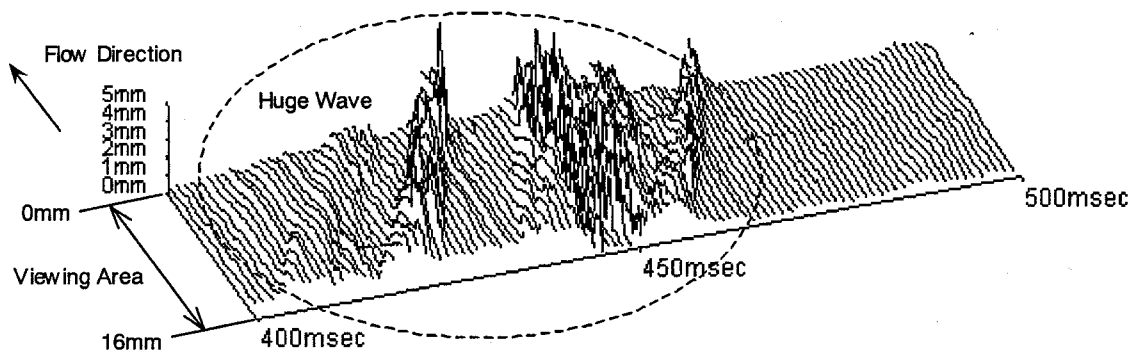
Figure 3.34 Cross-Sectional Area vs. Height, Width and Velocity of Waves



(a) Typical Example of Disturbance Wave ($j_i=0.04\text{m/s}$, $j_g=8.0\text{m/s}$)

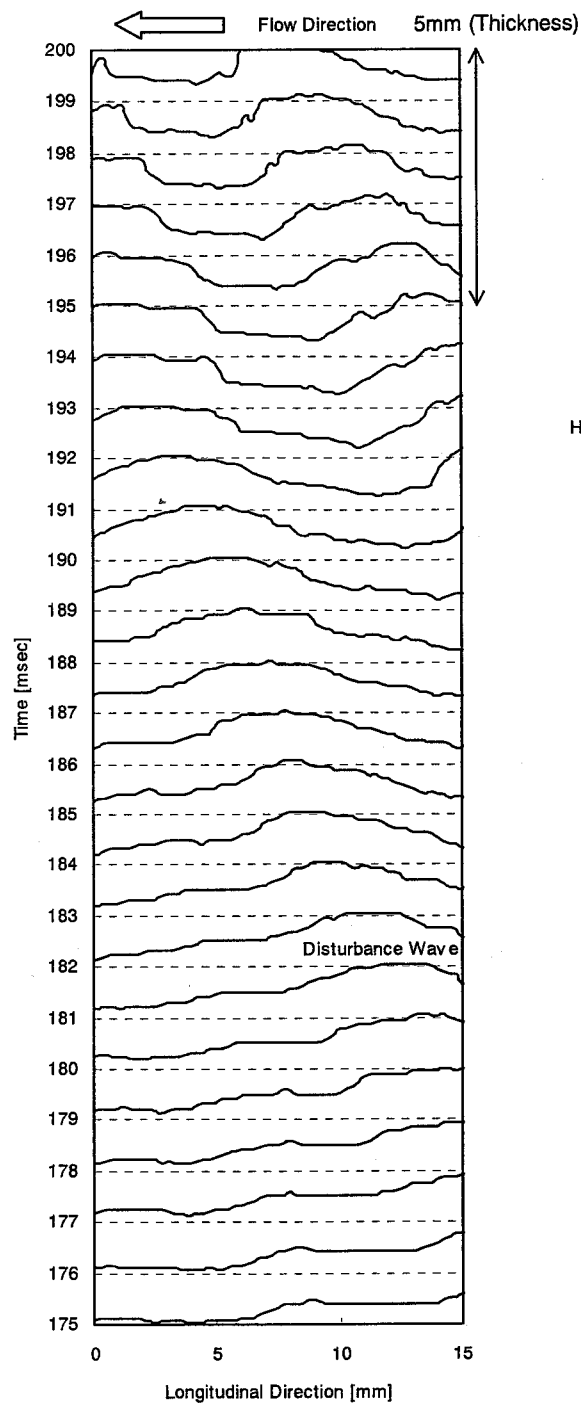


(b) Typical Example of Huge Wave ($j_i=0.04\text{m/s}$, $j_g=8.0\text{m/s}$)

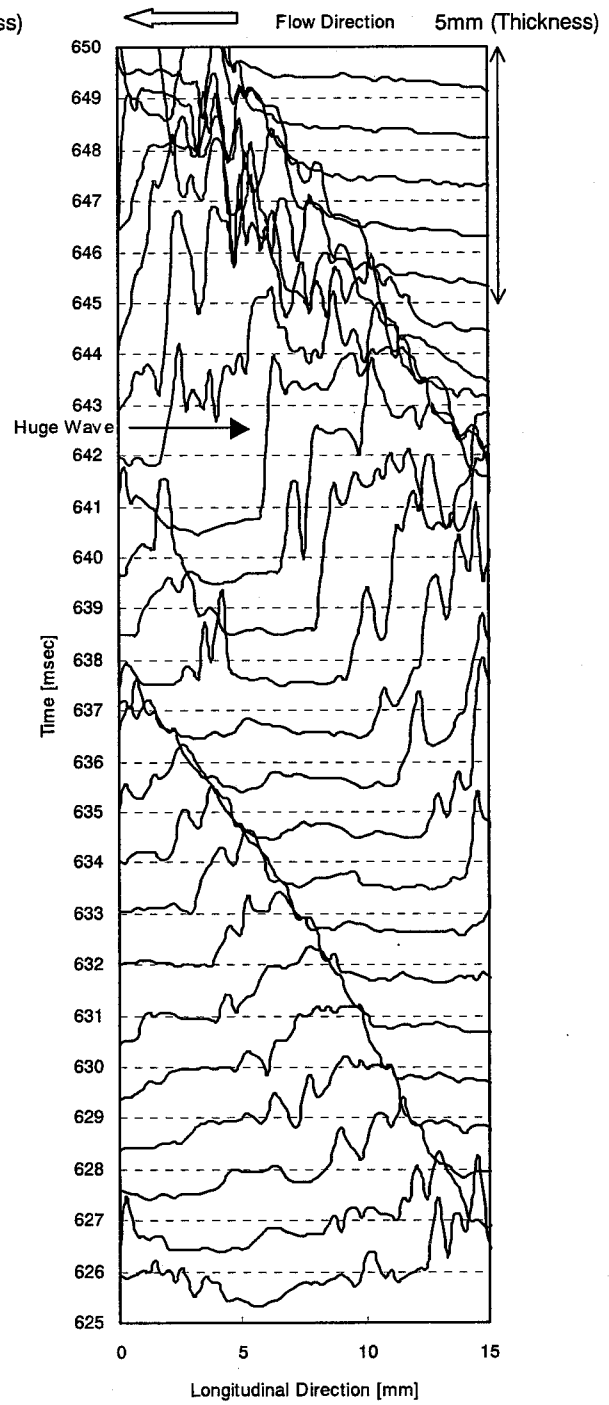


(c) Typical Example of Huge Wave ($j_i=0.04\text{m/s}$, $j_g=10.3\text{m/s}$)

Figure 3.35 Close-up View of Disturbance Wave and Huge Wave

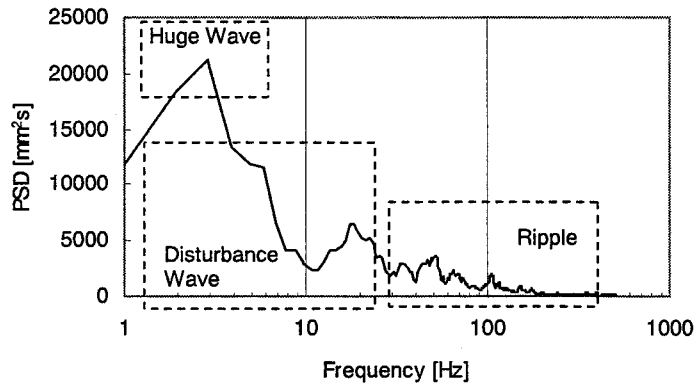


(a) Disturbance Wave

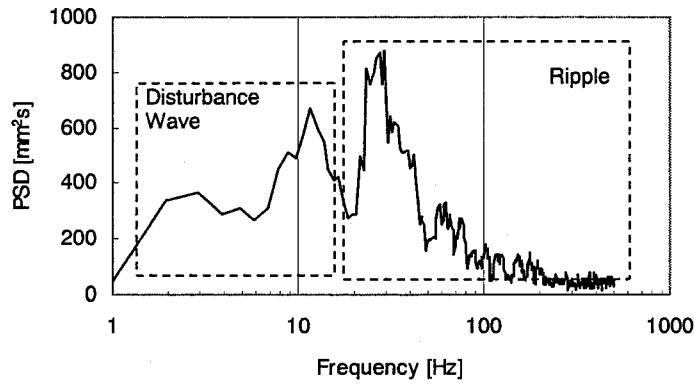


(b) Huge Wave

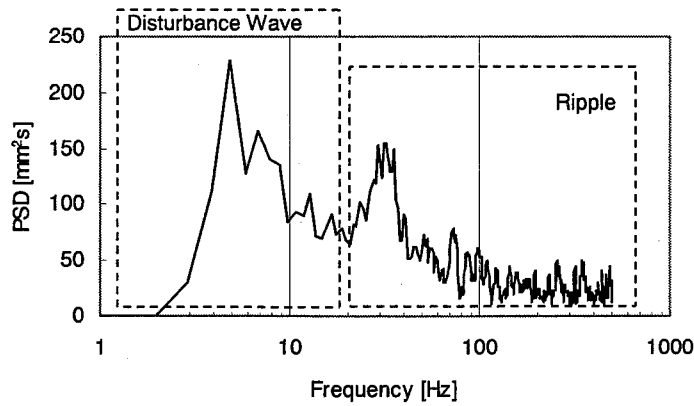
Figure 3.36 Consecutive Cross-Sectional Graphics for the Disturbance Wave and Huge Wave ($j_l=0.04\text{m/s}$ and $j_g=8.0\text{m/s}$)



(a) Disturbance Wave Flow ($j_i=0.069$ s and $j_g=8.0$ m/s)

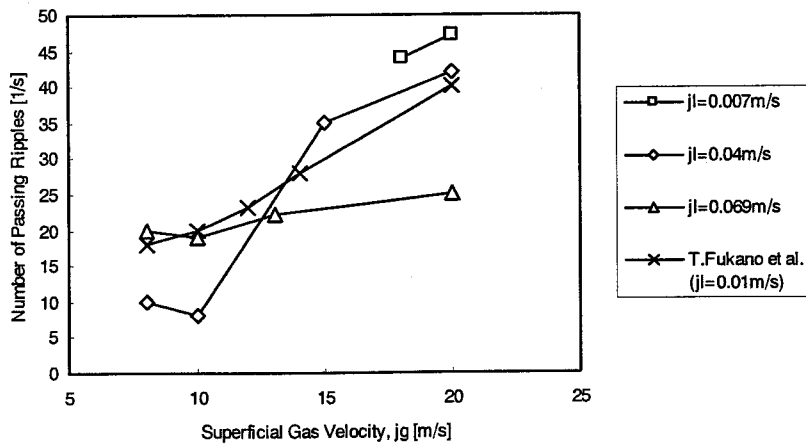


(b) Annular Dispersed Flow ($j_i=0.04$ m/s and $j_g=19.9$ m/s)

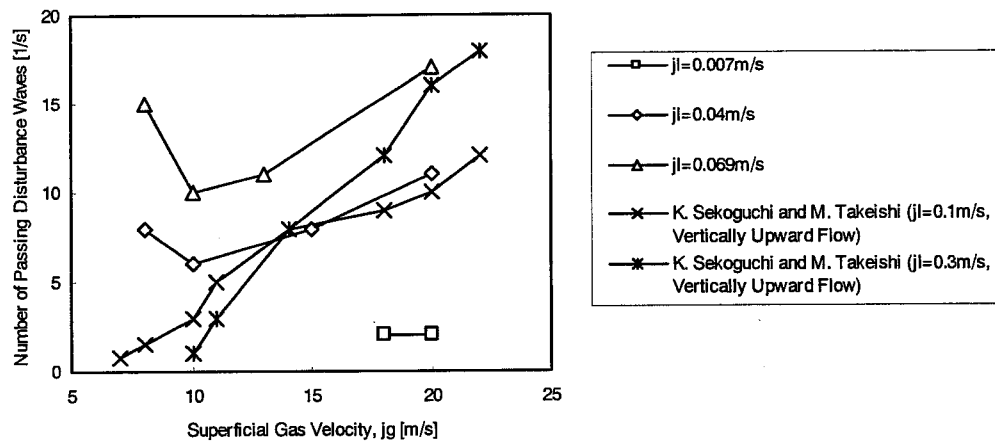


(c) Ripple Wave Flow ($j_i=0.007$ m/s and $j_g=19.5$ m/s)

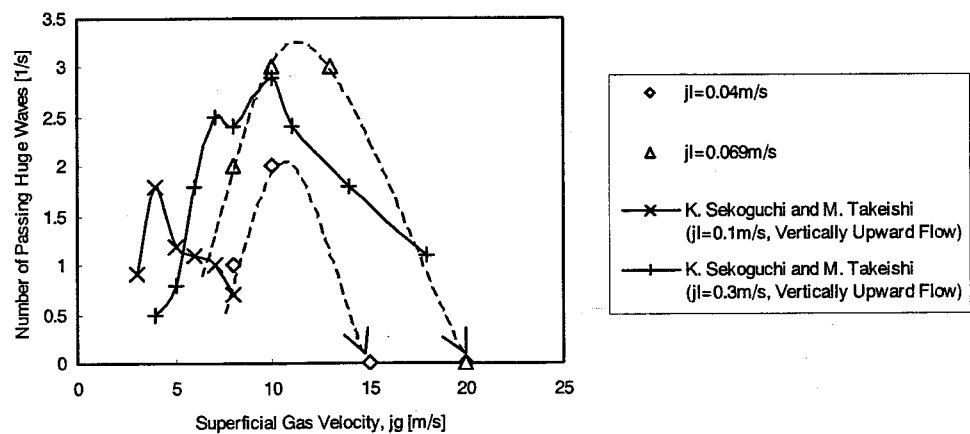
Figure 3.37 Power Spectral Density Distribution of Film Thickness Fluctuation



(a) Ripples

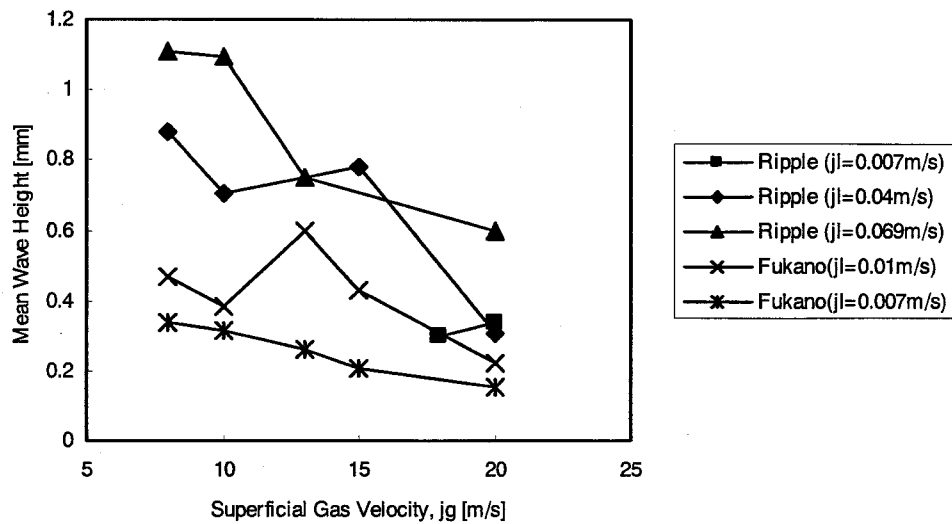


(b) Disturbance Waves

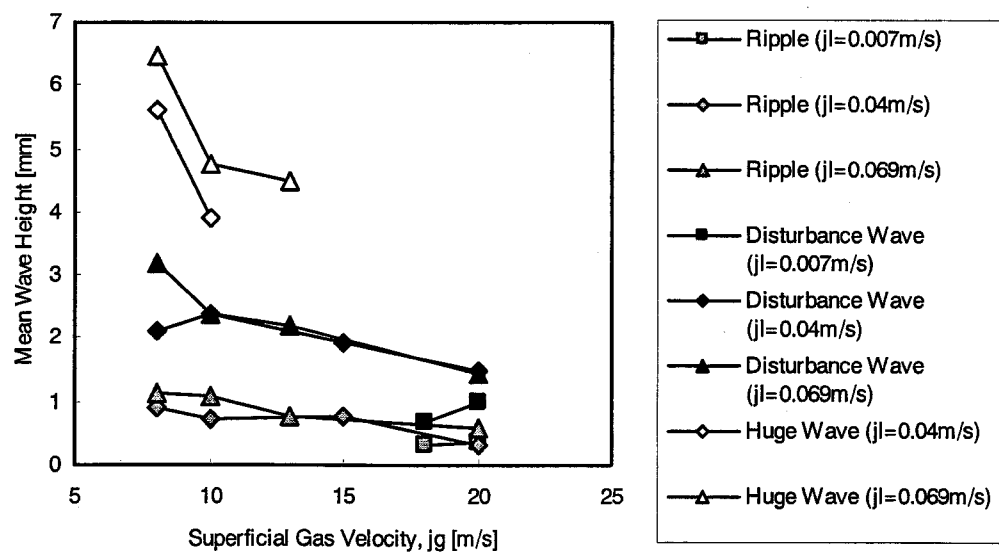


(c) Huge Waves

Figure 3.38 Number of Passing Waves

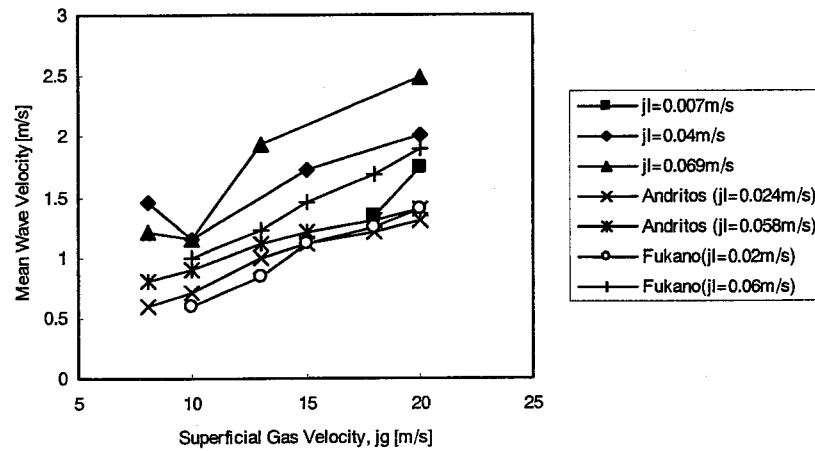


(a) Ripples

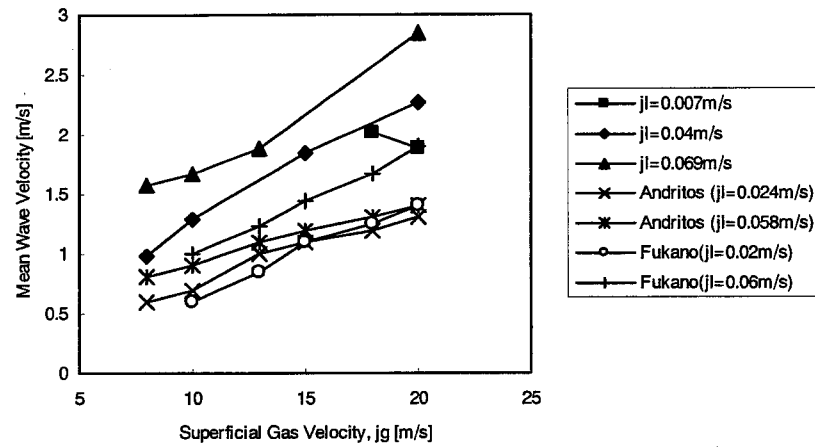


(b) Ripples, Disturbance Waves and Huge Waves

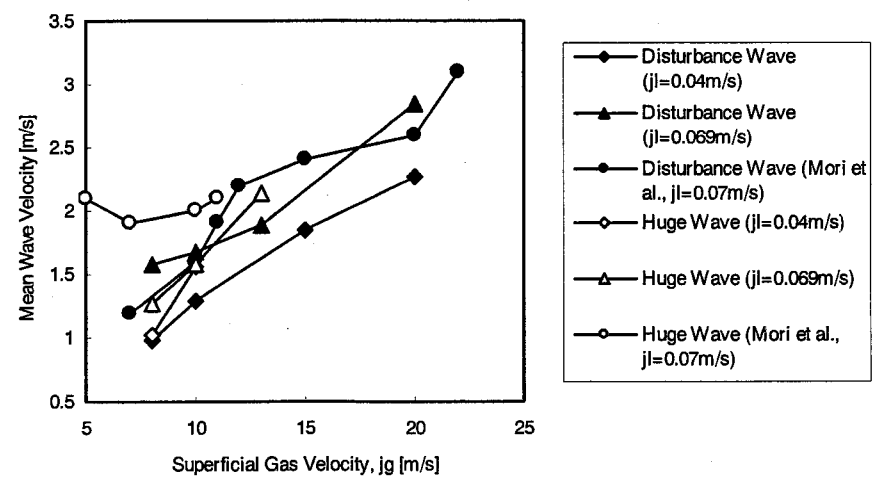
Figure 3.39 Mean Wave Height



(a) Ripples

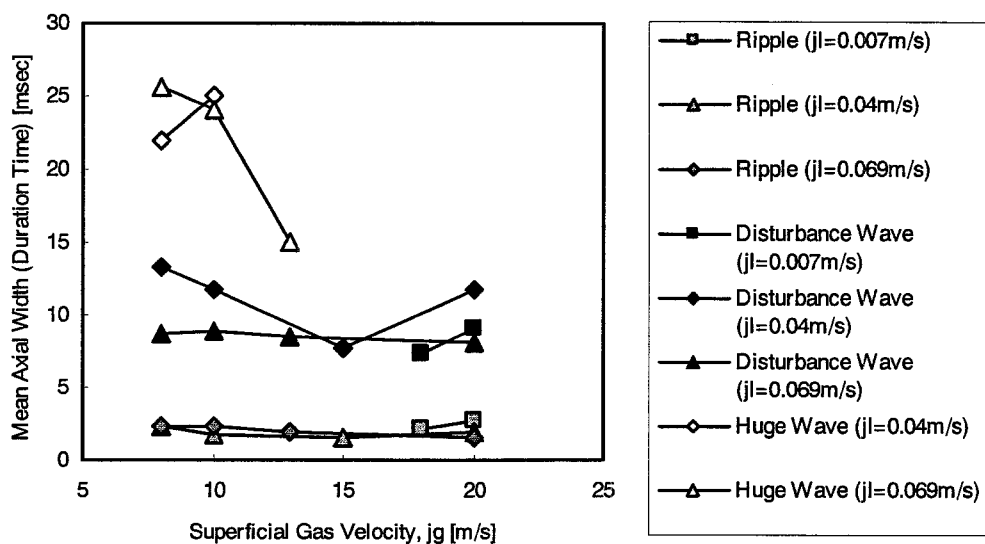


(b) Disturbance Waves

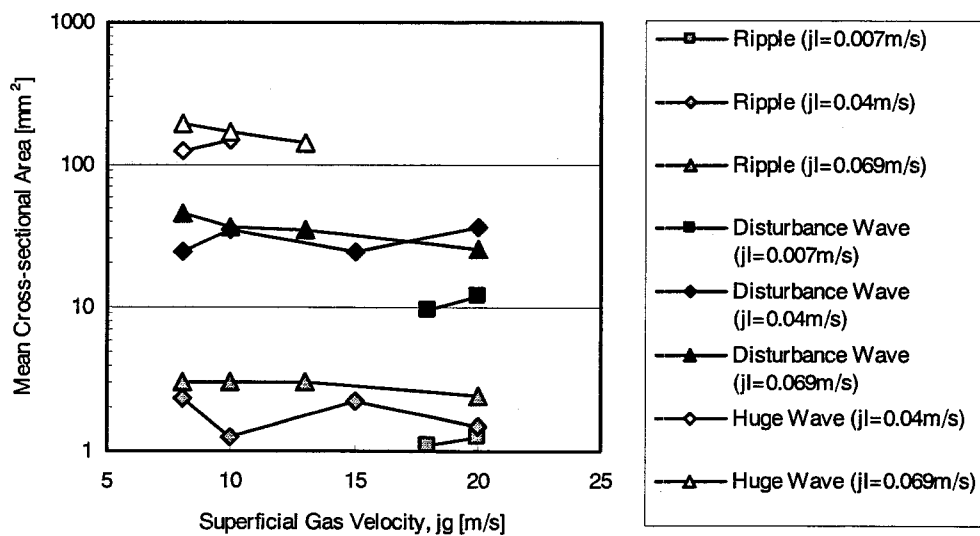


(c) Disturbance Waves and Huge Waves

Figure 3.40 Mean Wave Velocity

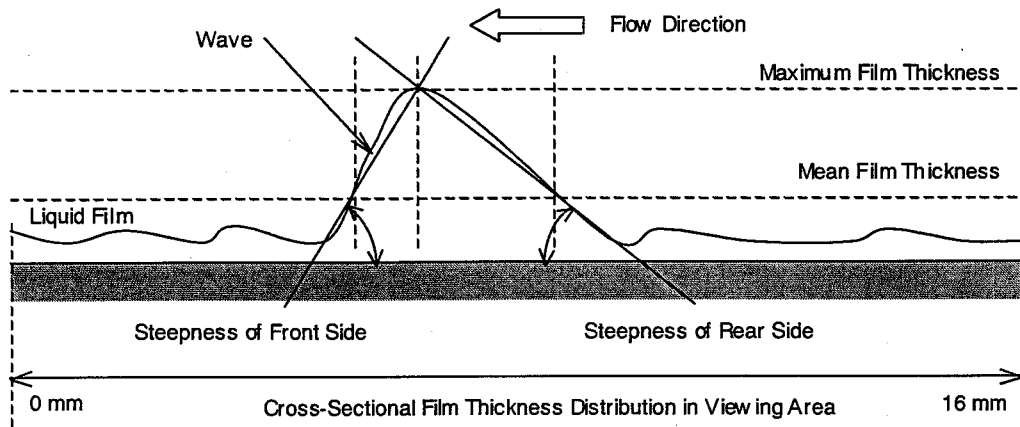


(a) Axial Width

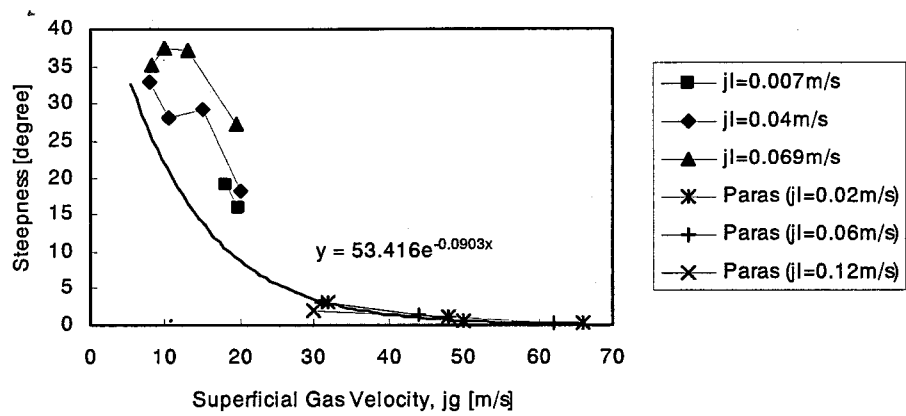


(b) Wave Cross-Sectional Area

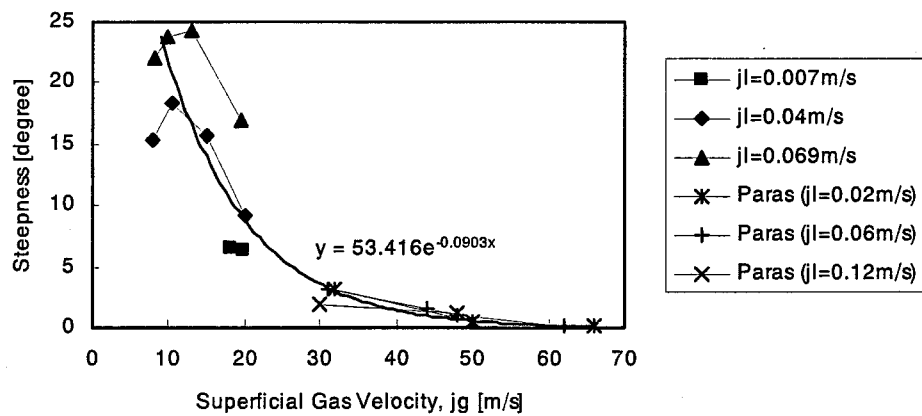
Figure 3.41 Axial Width and Cross-Sectional Area



(a) Definition of Wave Steepness



(b) Wave Steepness at Front Side



(c) Wave Steepness at Rear Side

Figure 3.42 Wave Averaged Mean Steepness at Front Side and Rear Side of Waves

4. Characteristics of Liquid Film Flow affected by Obstacle

4.1. Introduction

Liquid film flow is often affected by flow obstacle such as spacers in nuclear reactor fuel rod assembly since film thickness becomes thin at flow conditions of high gas velocity and low liquid flow rate enough to be agitated by external obstructions.

To clarify the fundamental characteristics of obstacle effect on liquid film flow, time-dependent liquid film thickness distribution was measured under the affection of obstacle having cross-sectional shapes of rectangle, trapezoid and inverted trapezoid. Influence of placement height of obstacle and effect of obstacle shape will be discussed in this chapter.

4.2. Experimental Apparatus and Conditions

Flow channel used here is the same one explained in chapter 3. Flow obstacle was placed at 1,700mm downstream from the inlet section. Experimental conditions and the flow pattern map are shown in figure 4.1. The range of superficial liquid velocity and superficial gas velocity were between $j_l=0.012\text{m/s}$ and $j_l=0.069\text{m/s}$, between $j_g=8.0\text{m/s}$ and $j_g=33\text{m/s}$, respectively. Droplet entrainment rate is estimated being about 2% by Wallis's equation [1] under present flow condition, thus it is smaller than that of the normal BWR operating conditions (about 50%). All experiments were carried out at atmospheric pressure and ambient temperature.

Flow obstacle was manufactured as shown in figure 4.2. The obstacle was a flat plate made of aluminum having a supporting pole of 3mm diameter at the center of plate for movement by a micrometer. Three types of obstacle were applied for the experiment. Their cross-sectional shapes were rectangle, trapezoid and inverted trapezoid as illustrated in figure 4.2. The rectangle type is called "Type A" in the following sections. Type A obstacle has different dimensions, to say, 1.4mm thick, 46mm wide, 20mm long and 1.6mm thick, 46mm wide, 30mm long. The trapezoid type has two different chamfers being 45 degree at their front and rear edge. One of them having upward chamfer is called "Type B" and the other having downward chamfer is called "Type C". Both Type B and Type C are 1.6mm thick, 46mm wide and 30mm long.

Obstacle was placed at between 0.5mm and 3mm from bottom of the channel. Film thickness measurements were done by parallel incidence type of the FDM at the centerline of channel lateral cross-section. Viewing area of the liquid film behavior inside of obstacle and around obstacle edge are indicated in figures 4.3(a) and 4.3(b), respectively. Among 16mm long area in longitudinal direction for inside of the obstacle was observed, and 20mm long area including 5mm in obstacle region around obstacle edge was visualized.

4.3. Results and Discussions

4.3.1. Overview of the Liquid Film Flow in Obstacle Region

Figures 4.4-4.6 show bird's eye view graphics of longitudinal distribution of liquid film thickness at centerline of channel cross-section in obstacle region. Flow direction is from right to left in these figures. Placement of obstacle is also illustrated in each figure.

Figure 4.4 shows results of different placements of obstacle obtained at $j_l=0.04\text{m/s}$

and $j_g=8.0\text{m/s}$ corresponding to the disturbance wave flow regime without obstacle. It is seen that some of large waves touch the obstacle placed at 3mm from channel bottom and small waves are not affected much by the existence of obstacle in figure 4.4(a). It is interesting that the wave appearing at 400msec does not change its cross-sectional shape in spite of the contact to obstacle causing frictional drag on wave.

Result of obstacle placed at 2mm in figure 4.4(b) shows similar trend as the case of 3mm placement. However, more waves contact to obstacle.

Figure 4.4(c), the case of 1.5mm placement of obstacle, shows interesting features such as flow reversal at 150msec and bubble containing in a large wave or liquid film stagnation at 230msec. The former feature indicates that liquid film flows backward from the downstream edge of obstacle as to occupy the channel-obstacle clearance. Velocity of this motion is about 0.1m/s toward upstream direction being much smaller than the wave traveling velocity toward downstream. This flow reversal is rapidly broken by a passage of large liquid lump occurring at 200msec and then, thin liquid film is recovered. Such a flow reversal is also seen around 450msec in the same figure.

Figure 4.4(d) is a result of 1mm placement of obstacle. It is clearly seen that clearance between obstacle and channel is mostly occupied with liquid phase both in time and dimension, only a few bubbles contained in the liquid phase are observed. It should be noted that these bubbles do not necessarily move to downstream direction and their motion is very slow. This indicates that liquid film flows at very small velocity or do not move in the clearance. Large waves frequently occurring in this flow regime seem to move over the obstacle top.

Figure 4.5 shows results of different placements of obstacle obtained at $j_l=0.04\text{m/s}$ and $j_g=19.9\text{m/s}$ corresponding to the annular dispersed flow regime without obstacle. Time-averaged liquid film thickness is small, thus liquid film flow is not affected much in the case of obstacle placement at 3mm as shown in figure 4.5(a). However, it is seen that some waves contact the obstacle in figures 4.5(b) and 4.5(c) for the obstacle placement at 2mm and 1.5mm, respectively. Though a lot of waves contact the obstacle in the case of 1mm obstacle placement, these waves seem to keep their traveling velocity and shape.

Figure 4.6 shows results of several flow conditions at the same placement of obstacle at 1mm. The flow reversal and the bubble in liquid occupation are seen in the results of disturbance wave flow as shown in figures 4.6(a)-4.6(d). A lot of waves contact obstacle in annular dispersed flow as indicated in figures 4.6(e)-4.6(h), these waves are seen to pass through the obstacle-channel clearance with keeping their traveling velocity since gas velocity remains at large. Even though the flow pattern is

annular dispersed flow, liquid film seems to occupy the clearance more frequently at small gas velocity and large liquid flow rate since time-averaged liquid film thickness increases enough to obstruct the gas flow inside obstacle.

Results of ripple wave flow shown in figures 4.6(i)-(l) indicate that liquid film flow is not significantly affected so as to form frequent contacts of liquid film to obstacle. The liquid film presented in figure 4.6(l), at large liquid flow rate, shows a similar trend to the annular dispersed flow since liquid flow rate is relatively large and time-averaged liquid film thickness is enlarged.

4.3.2. Overview of the Liquid Film Flow in Up- and Downstream Region of Obstacle

Figures 4.7-4.12 show bird's eye view graphics of longitudinal liquid film thickness distribution at centerline of channel cross-section both around the front and the rear edge of obstacle being 5mm internal region of obstacle and 15mm external region of obstacle. Flow direction is from left to right in these figures. Every thickness distribution in time lapse was measured with 2.5msec interval here. Flow conditions were set at constant gas velocity, 33m/s, and two of small liquid flow rates at 0.012m/s and 0.023m/s, thus flow patterns were ripple wave flow. Therefore, the results of obstacle placement at 0.5mm are demonstrated here since ripple wave flow is not significantly affected by obstacle placed at high from channel bottom as seen in the previous section.

Figure 4.7 shows results of Type A obstacle obtained at $j_l=0.012\text{m/s}$. It is obviously seen in figure 4.7(a) that the gas-liquid interface is fairly smooth before the obstacle without showing remarkable large waves. Some waves are only seen before the obstacle in a limited range being about 5mm, however these waves do not remain in long time since these waves are sheared by fast gas flow. It is also seen that liquid film thickness in obstacle region becomes 0.5mm indicating contacts of liquid film to obstacle. Liquid film also occupies the clearance between the obstacle and channel bottom in obstacle region around the rear edge.

The most interesting feature extracted from figure 4.7(b) is the rapid increase of film thickness just behind the obstacle within about 5mm. In view of the obstacle thickness being 1.6mm, the quick increased film thickness apparently exceeds obstacle top. It seems that the quick increase of film thickness becomes a large wave after the obstacle, and then it rapidly disappears within about 10mm in longitudinal direction.

Figure 4.8 shows results of Type B obstacle obtained at $j_l=0.012\text{m/s}$. It is also seen in figure 4.8(a) that the gas-liquid interface is smooth before the obstacle and no remarkable wave is seen before the obstacle. Liquid film occupation in the obstacle

clearance is not often seen both around the front edge and rear edge. Increase of film thickness behind the obstacle is also seen in figure 4.8(b), but it is not frequent and its height is smaller than the case of Type A obstacle. Thus, it seems that liquid film flows smoothly from upstream region of obstacle to downstream region of obstacle.

Figure 4.9 shows results of Type C obstacle obtained at $j_l=0.012\text{m/s}$. Liquid film surface before the obstacle is smooth. Several large waves are seen more before the obstacle than the case of Type A obstacle, however, no contact of liquid film is observed in obstacle region as indicated in figure 4.9(a). Liquid film occupation in the obstacle clearance is not significantly seen around the rear edge of obstacle as shown in figure 4.9(b), too. Increase of film thickness behind the obstacle is not so remarkable compare to the results of Type A and Type B.

Figure 4.10 shows results of Type A obstacle obtained at $j_l=0.023\text{m/s}$. Figure 4.10(a) reveals a completely different behavior of gas-liquid interface before the obstacle in comparison with the result of smaller liquid flow rate, $j_l=0.012\text{m/s}$, in spite of the flow pattern considered to be ripple wave flow for every flow condition. It is seen that liquid film thickness increases before the obstacle within about 5mm, and inside region of obstacle is almost constantly occupied with the liquid phase both around the front edge and rear edge as shown in figures 4.10(a) and 4.10(b). The rapid increase of film thickness just behind the obstacle is also seen with this flow condition. This increase of film thickness remains in a somewhat farther distance from obstacle edge reaching about 20mm in flow direction.

Figure 4.11 shows results of Type B obstacle obtained at $j_l=0.023\text{m/s}$. Figure 4.11(a) indicates that the flow pattern with this flow condition is ripple wave flow, thus the previous results of Type A seems to strongly depend on the obstacle shape. This will be discussed in the next section. No remarkable wave is seen before the obstacle. Liquid film occupation in the obstacle clearance is not often seen both around the front edge and rear edge as same as the results of smaller liquid flow rate with same obstacle shape. Increase of film thickness behind the obstacle is seen a little bit more than the results of smaller liquid flow rate, but it is not frequent and its height is smaller than the case of Type A obstacle (in figure 4.11(b)).

Figure 4.12 shows results of Type C obstacle obtained at $j_l=0.023\text{m/s}$. Liquid film surface before the obstacle is very smooth compare to the results of Type A. Several waves are seen more before the obstacle than the case of Type B obstacle. Contact of liquid film in obstacle region is not observed as indicated in figures 4.12(a) and 4.12(b). Increase of film thickness behind the obstacle is seen more frequently than the result of smaller j_l .

4.3.3. Time-Averaged Liquid Film Thickness around Front Edge

Time-averaged liquid film thickness in upstream region of obstacle at $j_1=0.012\text{m/s}$ is shown in figure 4.13. The range between 15mm and 20mm is inside of the obstacle.

It is seen that liquid film thickness increases locally before the obstacle within about 5mm for every type of obstacle. The largest and the smallest increase of film thickness are observed with Type C obstacle and Type B obstacle, respectively. The above trends are explained as follows.

Liquid film flow is obstructed to flow into the obstacle region by an increase of gas pressure before the spacer cell. As illustrated in figure 4.17, gas flow near the liquid film decelerates by the obstacle to reduce interfacial shear stress, and then liquid film thickness increases before the obstacle. This effect seems to be significant for Type A obstacle since this type has no chamfer for the gas flow to smoothly move toward downstream direction.

In addition, the gas flow is divided into two flows both toward narrow clearance and wide clearance by the obstacle, and liquid droplets existing near the liquid film are transported to the liquid film during this procedure. Taking into account of obstacle shape, the amount of liquid droplets will be the greatest with Type C obstacle since this type has downward chamfer to capture most of the droplets in obstacle height, and the smallest with Type B having upward chamfer, most droplets are transported to wide clearance, and moreover, secondary gas flow perpendicular toward liquid film is not generated. Therefore, the largest increase of film thickness is realized with Type C obstacle. Morooka and Kimura [2,3] also indicated that Type C spacer that is treated as obstacle in this work has the larger critical power than Type A and Type B.

Liquid film thickness decreases toward obstacle region because of acceleration of liquid film velocity due to decrease of cross-sectional area in narrow clearance.

It is also clearly seen that the magnitude of the increase of liquid film thickness before obstacle becomes small with obstacle placement. The increase is negligible small at 2.0mm of obstacle placement from channel bottom. Morooka and Kimura [2] reported that critical power of BWR increases when spacer cell is placed near to fuel rod from empirical facts. Numerical simulations carried out by Yamamoto et al. [4] using flat plate spacer, to say Type A in this work, in a horizontal channel showed that most droplets were deposited with a clearance of 0.5 mm, followed by a clearance of 0.75 mm and a clearance of 1.0 mm. Near the upstream end of spacer, there were peaks in droplet number density deposited on the channel for the clearances 0.5mm, 0.75mm, and 1.0 mm, and the peak height was smaller as the clearance increases. With a clearance of 1.25 mm, there was no remarkable peak at this position.

Time-averaged liquid film thickness in upstream region of obstacle at $j_1=0.023\text{m/s}$ is shown in figure 4.14. A general trend is also observed here that liquid film thickness has a peak before the obstacle within about 5mm as discussed in the results of smaller liquid flow rate. However, the result of Type A obstacle placed at 0.5mm shows a different magnitude of the trend compare to the results of other types (figure 4.14(a)).

The result of Type B shown in figure 4.14(b) indicates a quite similar tendency of film thickness distribution to the result of smaller liquid flow rate, to say, liquid film thickness before the obstacle increases slightly as same magnitude as the case shown in figure 4.13(b). This reveals that most of liquid droplets are transported to the wide clearance due to the upward chamfer in spite of the larger liquid flow rate.

The result of Type C shown in figure 4.14(c) also indicates a similar trend of film thickness distribution to the result of smaller liquid flow rate, however, the increase of liquid film thickness before the obstacle is larger than the case of smaller liquid flow rate, since amount of liquid droplets depositing on liquid film by the downward chamfer is enhanced simply depending on the increase of liquid flow rate.

Considering the results of Type B and Type C, it seems that the liquid film structure is changed in the case of Type A with large liquid flow rate as illustrated in figure 4.19.

It was discussed in the previous sections that liquid film becomes to occupy the narrow clearance in cases of large liquid flow rate even though the gas velocity is large. When most part of the clearance is filled with liquid phase, then, liquid film coming from upstream region of obstacle cannot flow into the narrow clearance and liquid film accumulates at obstacle front edge so as to form a strong peak of film thickness before the obstacle. Then, liquid film stagnates at this accumulation and liquid droplets are entrained from the crest of liquid accumulation sheared by fast gas flow.

However, such occupation of liquid film in narrow clearance seems to occur only with Type A obstacle at this flow rate since the gas flow before obstacle flows smoothly into the narrow clearance with other types of obstacle because of their chamfers. It is confirmed in figure 4.14 that time-averaged liquid film thickness in narrow clearance is smaller than the obstacle placement for Type B and Type C, while the narrow clearance is completely occupied with liquid film when obstacle is set at 0.5mm from channel bottom with Type A obstacle.

It is also clearly seen that the magnitude of the increase of liquid film thickness before obstacle becomes small with obstacle placement, however, it seems that liquid film thickness remains at a little bit larger value compare to the results of smaller liquid flow rate.

4.3.4. Time-Averaged Liquid Film Thickness around Rear Edge

Time-averaged liquid film thickness in downstream of obstacle at $j_1=0.012\text{m/s}$ is shown in figure 4.15. The range between 0mm and 5mm is inside of the obstacle.

It is seen that liquid film thickness increases locally after the obstacle within about 5mm for every type of obstacle. The largest and the smallest increase of film thickness are observed with Type A obstacle and Type B obstacle, respectively. The increasing of film thickness after the obstacle and the trend depending on the obstacle shape are explained as follows.

As illustrated in figure 4.18, gas flow from the narrow clearance is decelerated after the obstacle due to expansion of cross-sectional area, then, the interfacial shear stress is reduced to increase liquid film thickness. In addition, turbulence generated after the obstacle enhances droplets deposition and reduces gas pressure, in turn, liquid film thickness is increased. Yamamoto et al. [4] noted that in the downstream region of the spacer, more droplet deposition occurs than in the spacer region since the turbulence energy near the channel bottom is larger than that in wide clearance. This effect seems to be significantly strong for Type A obstacle since other types of obstacle have chamfers for the gas flow to smoothly move toward downstream direction.

Liquid film thickness gradually decreases after the obstacle because of large interfacial shear stress recovered by fast gas flow coming from the wide clearance. It takes about 10mm for this decreasing because the gas flow from wide clearance takes somewhat long distance to arrive the liquid film.

It should be noted that the maximum liquid film thickness after the obstacle appears at near region of the obstacle with Type B as shown in figure 4.15(b), since gas flow from wide clearance is conducted smoothly by the chamfer to the liquid film as illustrated in figure 4.18(b). It is also interesting that the increase of liquid film thickness after the Type C obstacle has a relative broad distribution as shown in figure 4.15(c). This is because the gas flow from wide clearance requires long distance to reach the liquid film as indicated in figure 4.18(c).

It is also clearly seen that the magnitude of increased liquid film thickness after the obstacle becomes small with obstacle placement. The increase is negligible small at 2.0mm of obstacle placement from channel bottom.

Time-averaged liquid film thickness in downstream of obstacle at $j_1=0.023\text{m/s}$ is shown in figure 4.16. A general trend is also observed here that liquid film thickness has a peak after the obstacle within about 10mm as we saw in the results of smaller liquid flow rate. However, the result of Type A obstacle at 0.5mm from channel bottom indicates a great large magnitude of the trend compare to the results of other types as

shown in figure 4.16(a).

The result of Type B shown in figure 4.16(b) indicates a similar tendency of film thickness distribution to the result of smaller liquid flow rate, to say, liquid film thickness after the obstacle increases a little in magnitude as same as the case shown in figure 4.15(b). However, it is seen that liquid film thickness in obstacle region is larger than the case of smaller liquid flow rate. As we discussed in the previous section, most droplets are transported to the wide clearance before the obstacle due to the upward chamfer, thus the increase of thickness in obstacle region seems to depend on simply the increase of base film thickness. The gas flow from wide clearance conducted by the upward chamfer strongly shears the liquid film after the obstacle. Therefore, liquid film thickness is limited in small value after the obstacle. It should be noticed that the peak of film thickness locates much nearer to the obstacle than the case of smaller liquid flow rate.

The result of Type C shown in figure 4.16(c) also indicates a similar trend of film thickness distribution to the result of smaller liquid flow rate, however, the increase of liquid film thickness after the obstacle is larger than the case of smaller liquid flow rate. This seems to be caused by a lot of amounts of liquid droplets transported by downward chamfer before the obstacle. It is interesting that the peak of film thickness shifts to right hand side, to say downstream direction, compare to the result of smaller liquid flow rate.

It seems that liquid film structure after the obstacle is same between lower and higher liquid flow rate for Type B and Type C obstacle except Type A, since the narrow clearance is filled with liquid film for large liquid flow rate for Type A obstacle as we discussed. It is clearly seen that liquid film thickness in obstacle region of Type A is 0.5mm being same to the narrow clearance. Therefore, liquid film will stagnates just behind the obstacle so as to increase liquid film thickness greatly.

It is natural that the magnitude of the increase of liquid film thickness after obstacle becomes small with high obstacle placement. The effect is not clearly seen with 2.0mm of obstacle placement.

4.4. Summary

Effects of obstacle having three different cross-sectional shapes, to say rectangle, trapezoid and inverted trapezoid, on liquid film flow were clarified by using parallel incidence type of the FDM. Reconstructed images showed that the clearance between obstacle and channel bottom becomes to be occupied by the liquid film with decrease of clearance. Flow reversal and bubbles contained in the liquid film were observed.

In upstream region of obstacle, liquid film thickness was locally, within about 5mm, increased with decrease of clearance. This trend was caused due to deceleration of gas flow in turn to reduce interfacial shear stress, and droplets deposition.

Increase of liquid film thickness before the obstacle had the largest value with Type C obstacle since lots of droplets were transported to liquid film by its downward chamfer, and had the smallest for Type B obstacle having upward chamfer enabling to transport liquid droplets to main gas flow.

Liquid film structure was changed when liquid flow rate was enlarged enough for the liquid film to occupy the clearance between the obstacle and channel bottom, and then liquid film stagnates before the obstacle. This was observed only with Type A obstacle under the present experimental conditions.

In downstream region of obstacle, liquid film thickness also increased with decrease of clearance due to deceleration of gas flow coming through the narrow clearance between obstacle and bottom of channel. This tendency was remarkably seen with Type A obstacle showing no dependency on liquid flow rate since turbulence was generated after the obstacle. Namely, gas velocity is strongly reduced by the turbulence and the turbulence also transports a lot of droplets to the liquid film.

It was seen that the peak after the obstacle was located near to it for Type B obstacle because high-speed gas flow was conducted to the liquid film in a short distance. In contrast with this, the peak after the obstacle was located relatively far from the obstacle for Type C because high-speed gas takes long distance to reach the liquid film, and also because gas flow coming through the narrow clearance drag the liquid film.

The trend of increasing liquid film thickness before and after the obstacle depending on different shape and flow conditions will be summarized as follows.

	$j_l=0.012\text{m/s}$	$j_l=0.023\text{m/s}$
Upstream	$C>A>B$	$A>C>B$
Downstream	$A>C\sim B$	$A>C>B$

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1. G.B. Wallis, The Onset of Droplet Entrainment in Annular Gas-Liquid Flow, GE Rep. No.62, GL 127, 1962
2. S. Morooka and J. Kimura, Effect of Spacer Shape on Critical Power, Proceedings of 32nd National Heat Transfer Symposium in Japan, pp.205-206, 1995
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4. Y. Yamamoto, A. Hoshide, T. Mitsutake and S. Morooka, Analytical Study on Effects of BWR Fuel Spacer on Droplet Deposition, Nuclear Engineering and Design, Vol.175, pp.119–129, 1997

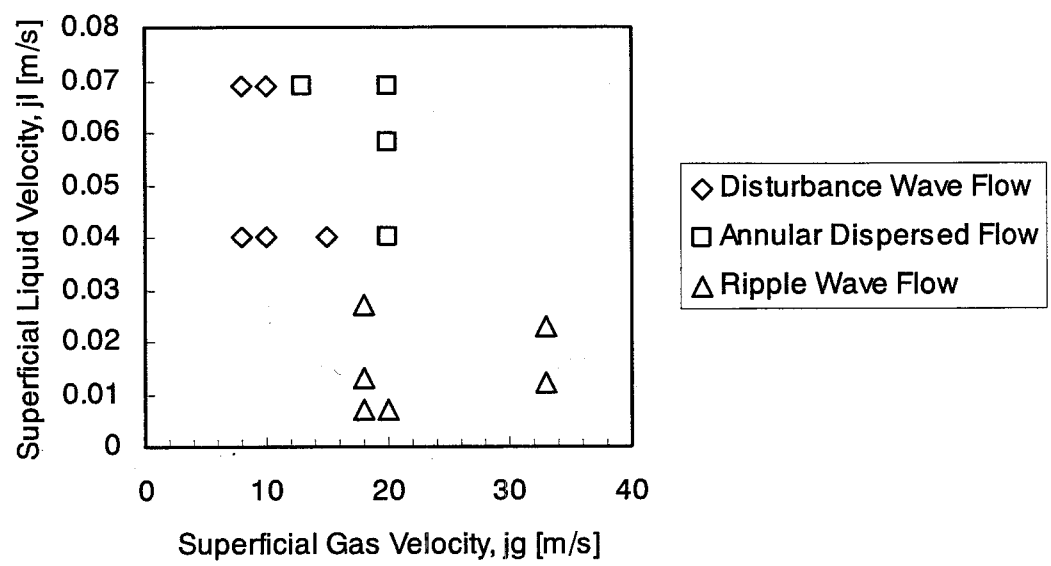
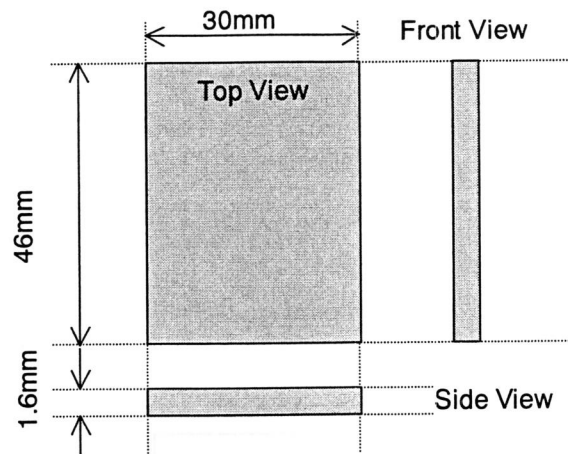
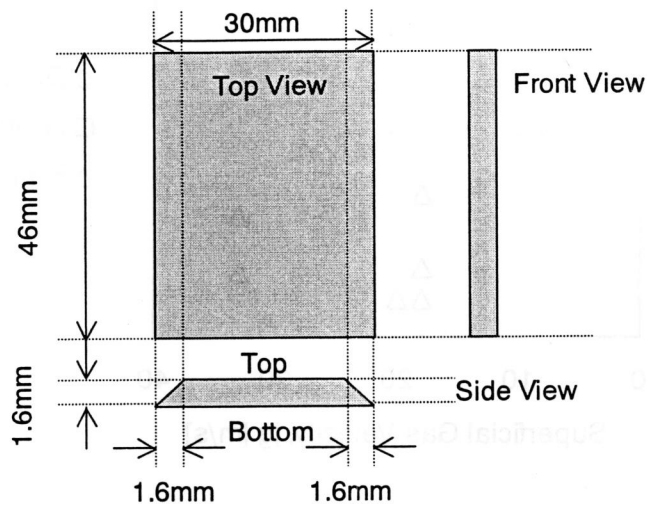


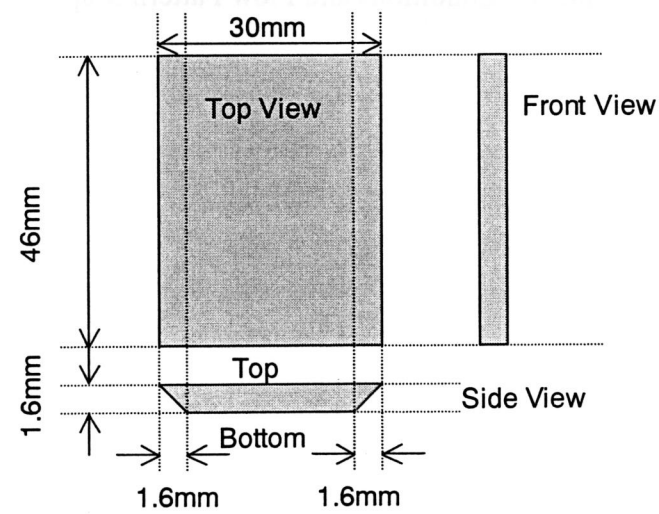
Figure 4.1 Experimental Conditions and Flow Pattern Map



(a) Rectangle Type Obstacle (Type A)

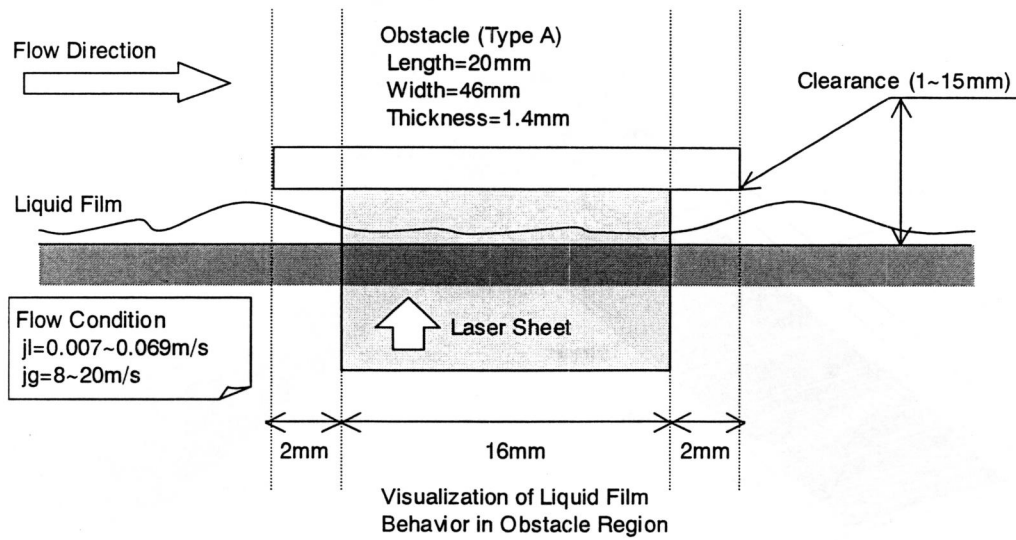


(b) Trapezoid Type Obstacle (Type B)

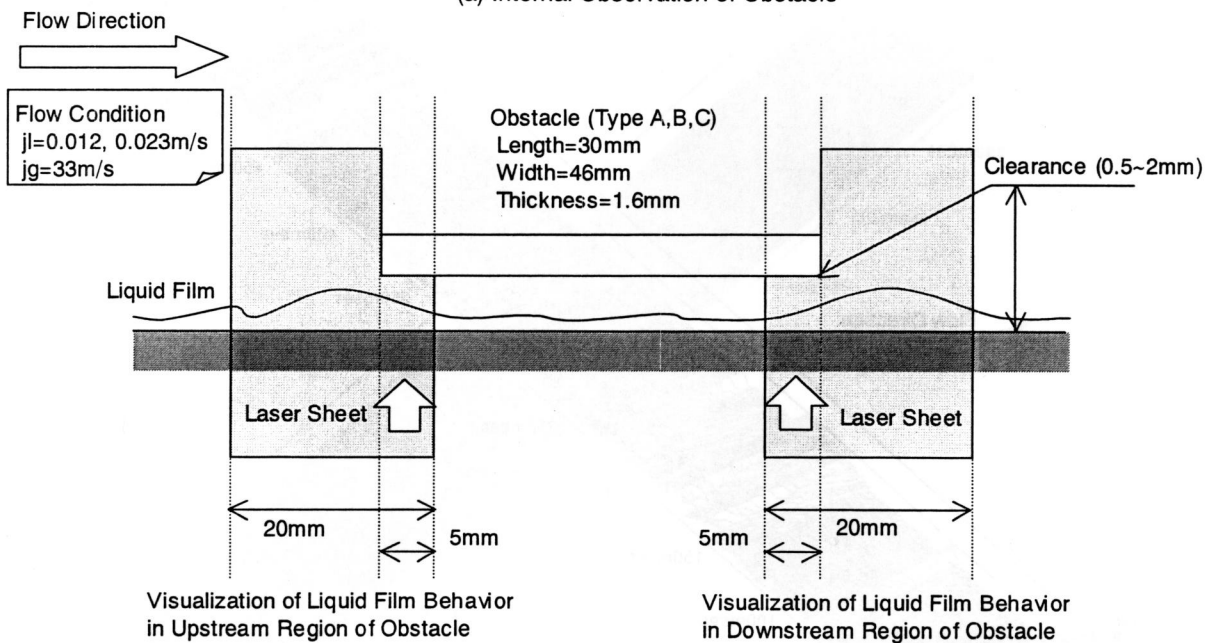


(c) Trapezoid Type Obstacle (Type C)

Figure 4.2 Schematic of Obstacle Shape

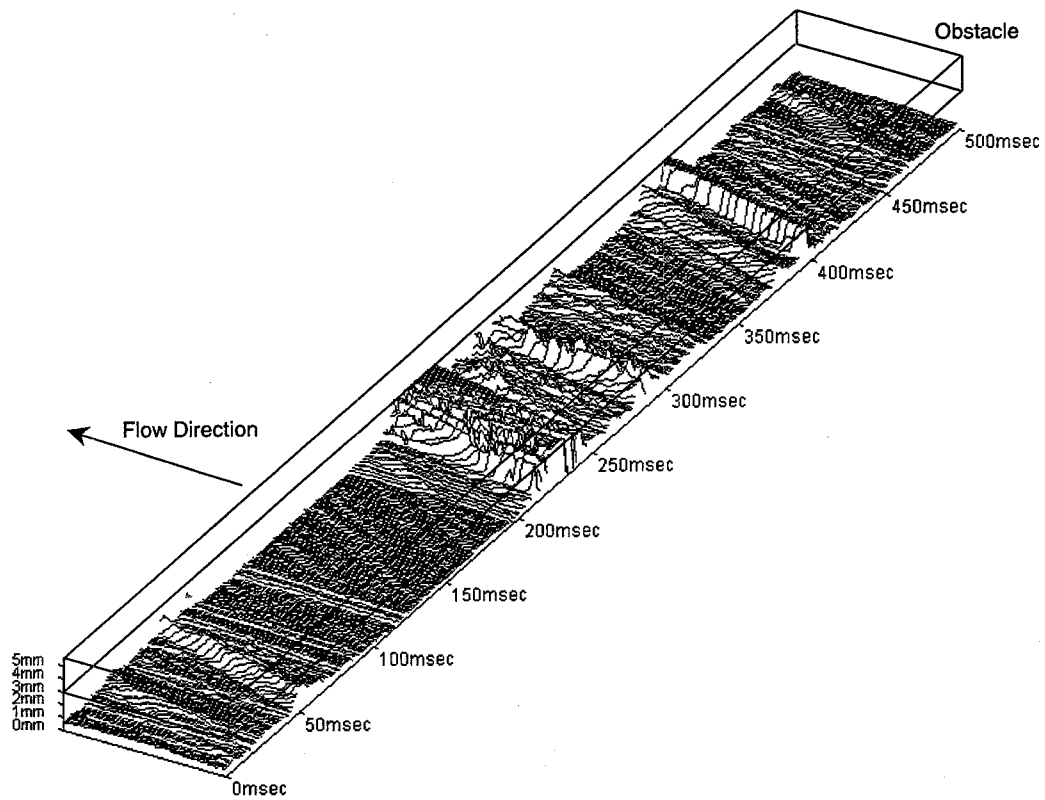


(a) Internal Observation of Obstacle

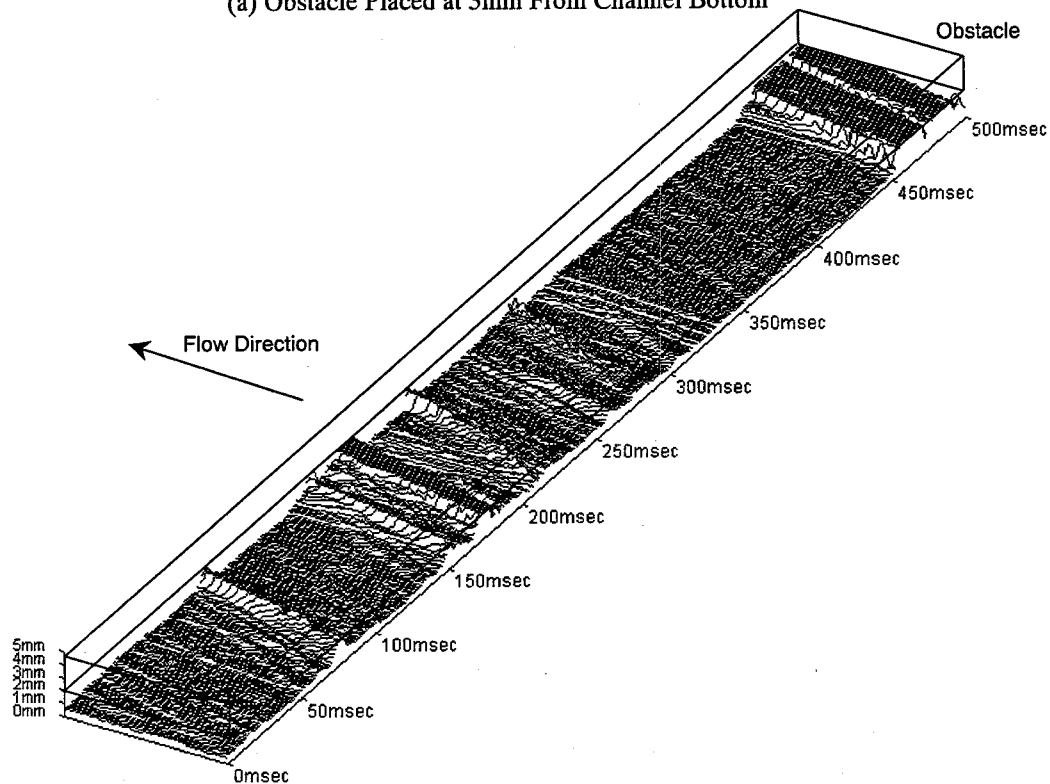


(b) External Observation of Obstacle (around Obstacle Edge)

Figure 4.3 Observation of Liquid Film Behavior by Parallel Incidence Type of FDM at Center Line of Test Channel

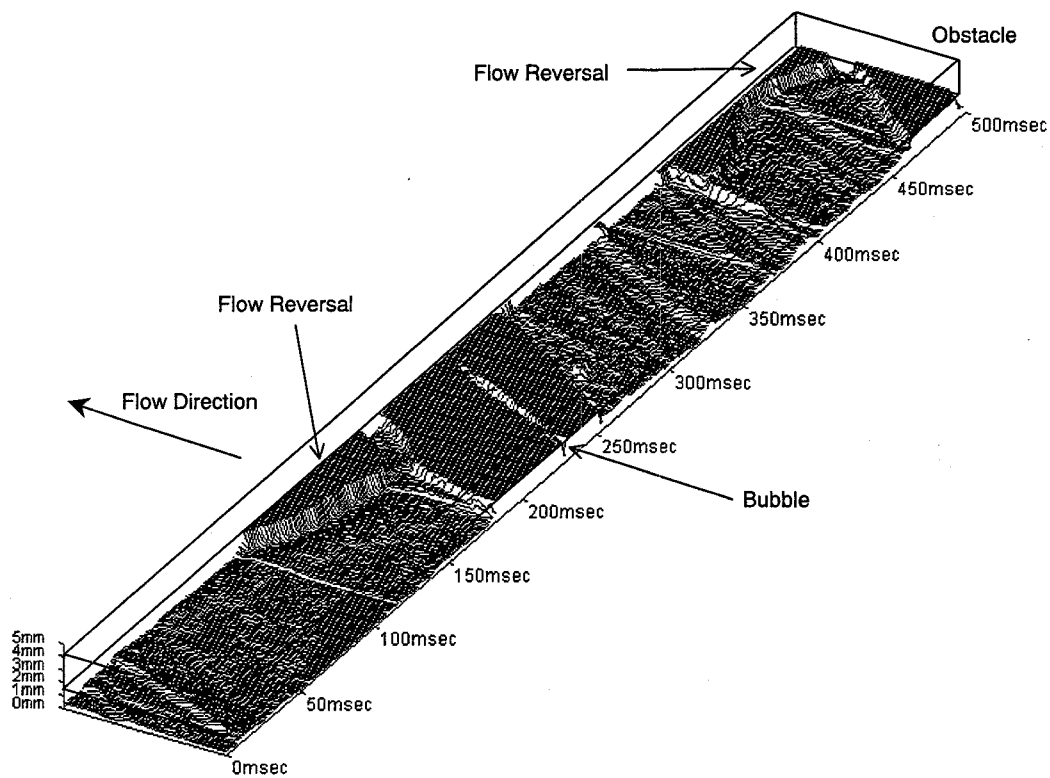


(a) Obstacle Placed at 3mm From Channel Bottom

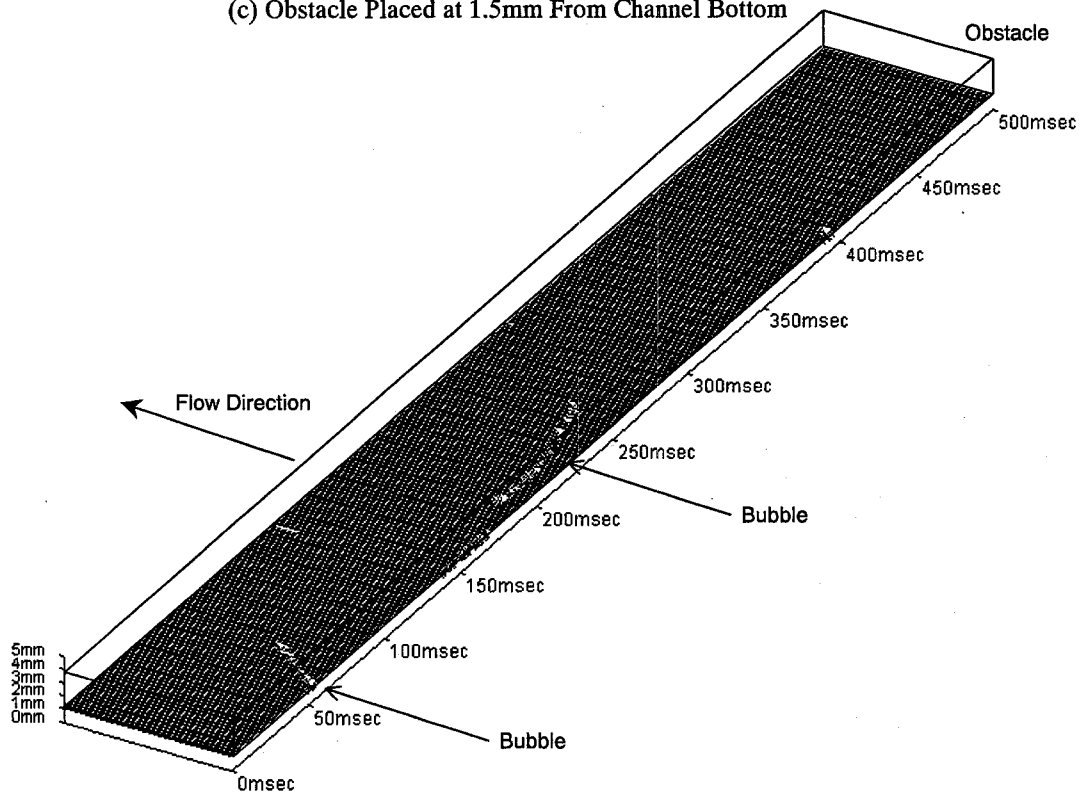


(b) Obstacle Placed at 2mm From Channel Bottom

Figure 4.4 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=8.0\text{m/s}$) Continued

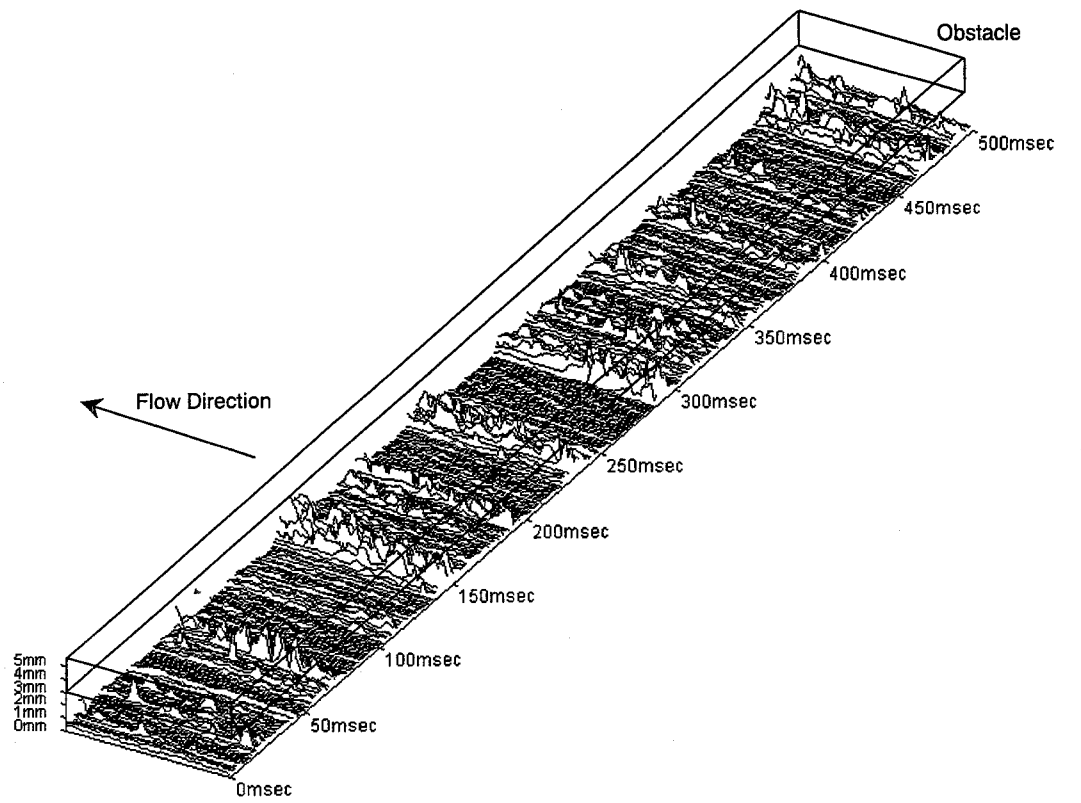


(c) Obstacle Placed at 1.5mm From Channel Bottom

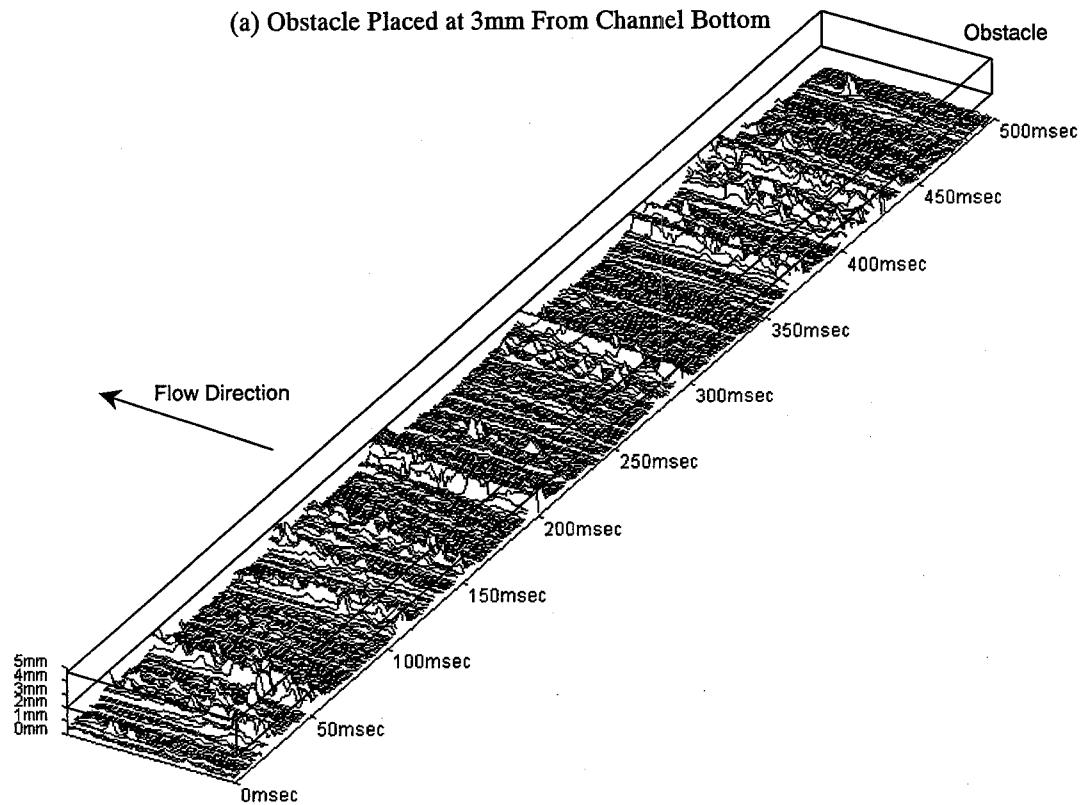


(d) Obstacle Placed at 1mm From Channel Bottom

Figure 4.4 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness of Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=8.0\text{m/s}$)

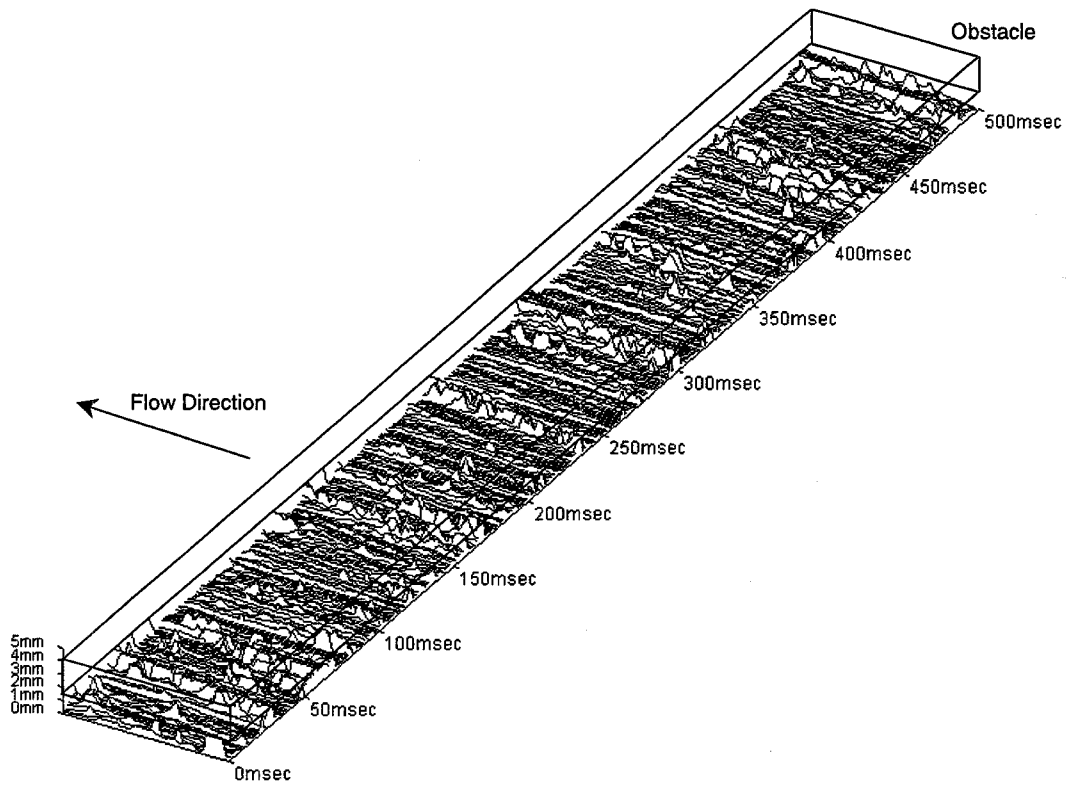


(a) Obstacle Placed at 3mm From Channel Bottom

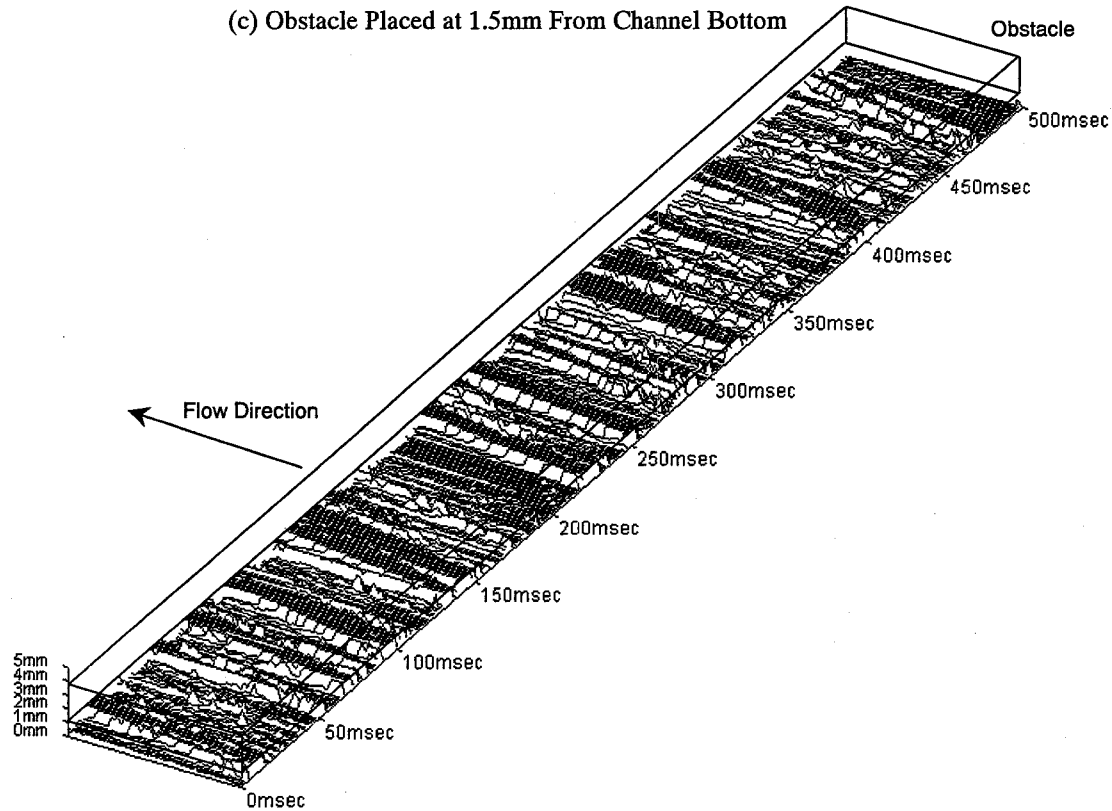


(b) Obstacle Placed at 2mm From Channel Bottom

Figure 4.5 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.04\text{m/s}$, $j_g=19.9\text{m/s}$) Continued

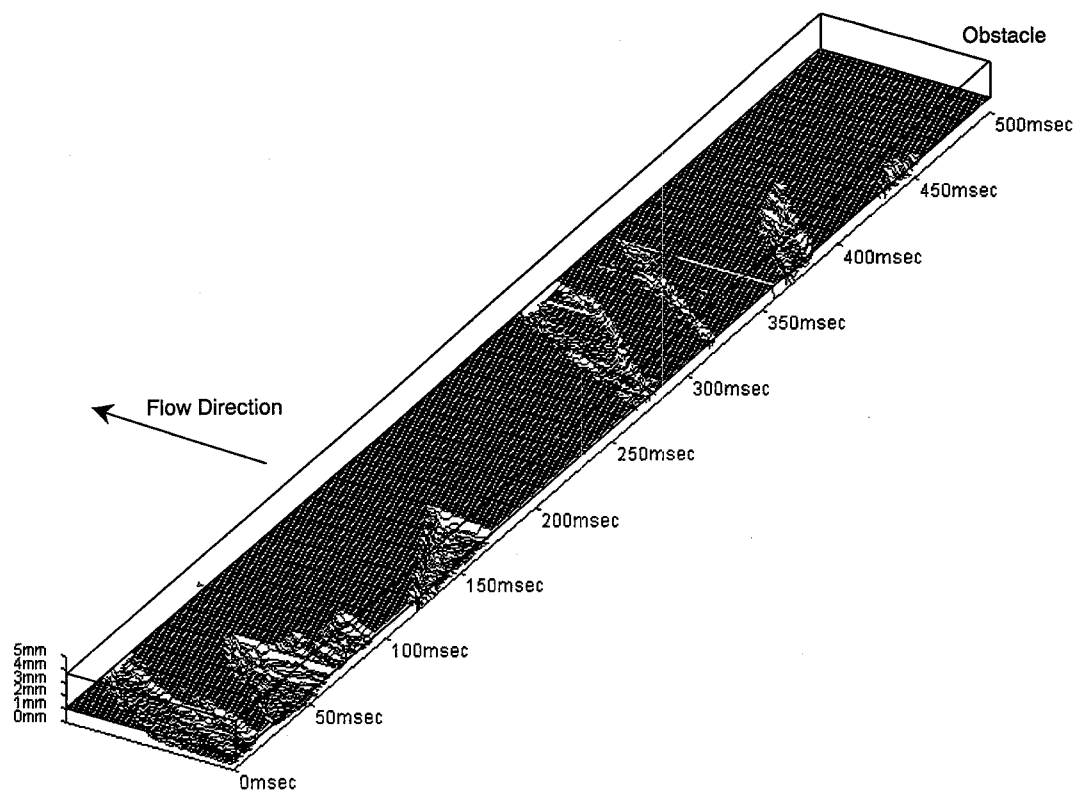


(c) Obstacle Placed at 1.5mm From Channel Bottom

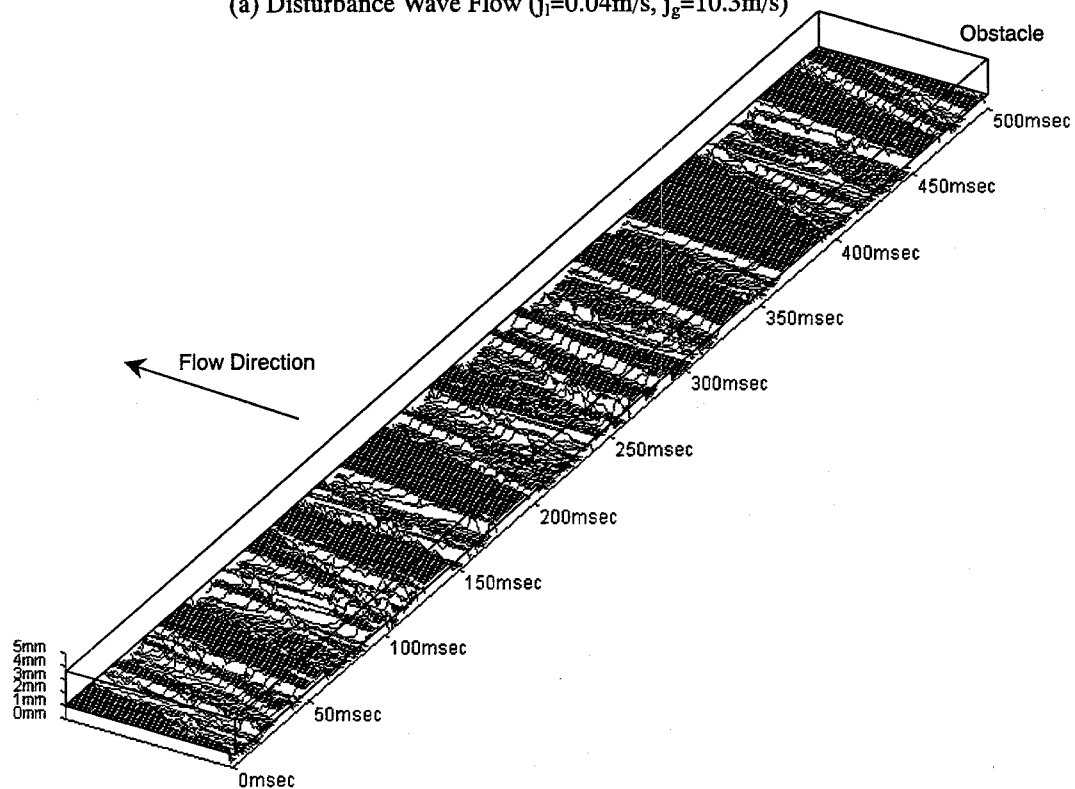


(d) Obstacle Placed at 1mm From Channel Bottom

Figure 4.5 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness of Annular Dispersed Flow ($j_l=0.04\text{m/s}$, $j_g=19.9\text{m/s}$)

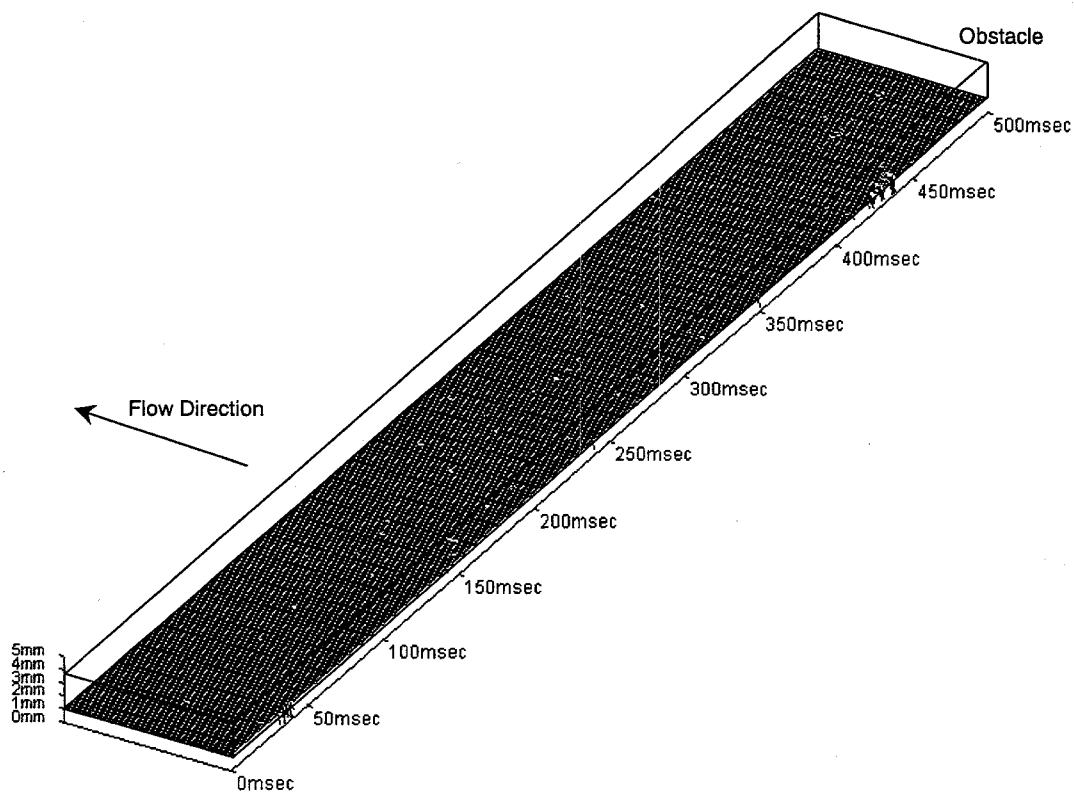


(a) Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=10.3\text{m/s}$)

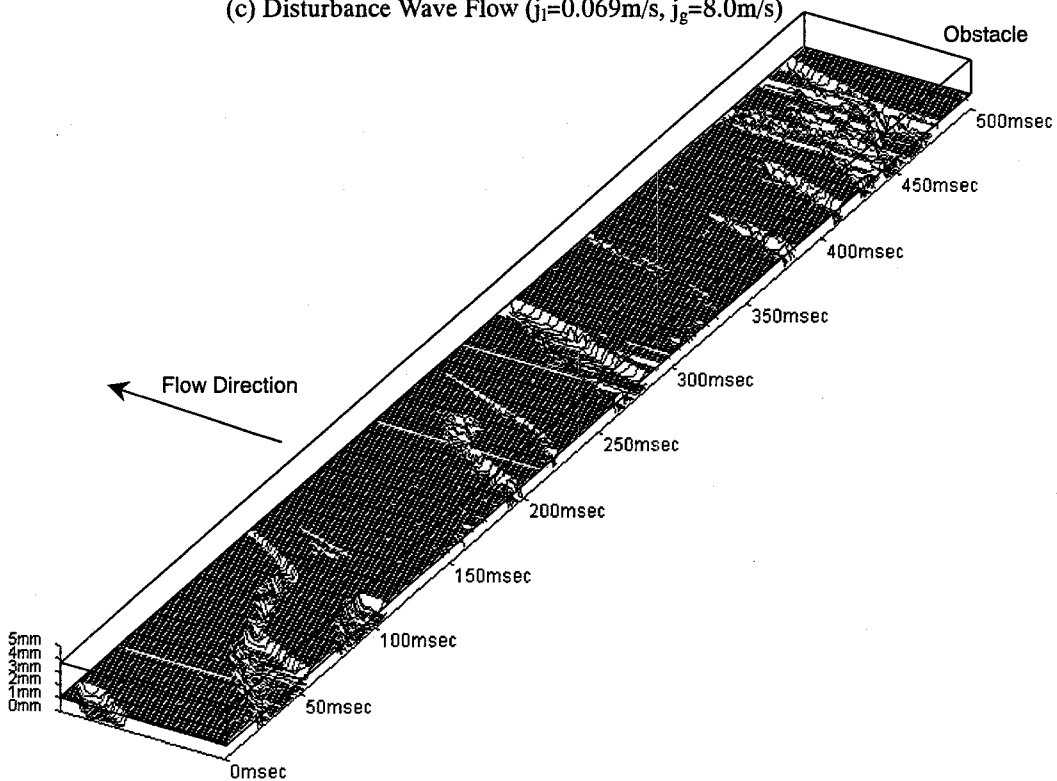


(b) Disturbance Wave Flow ($j_l=0.04\text{m/s}$, $j_g=14.9\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom (Continued)

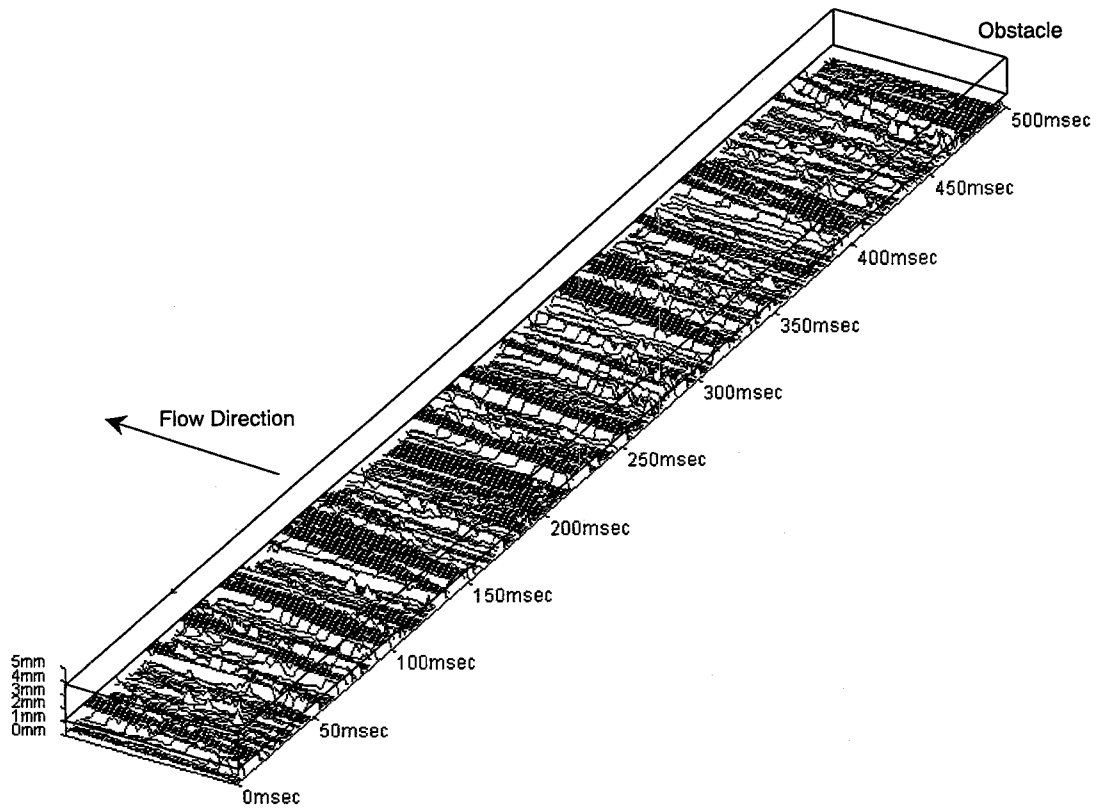


(c) Disturbance Wave Flow ($j_l=0.069\text{m/s}$, $j_g=8.0\text{m/s}$)

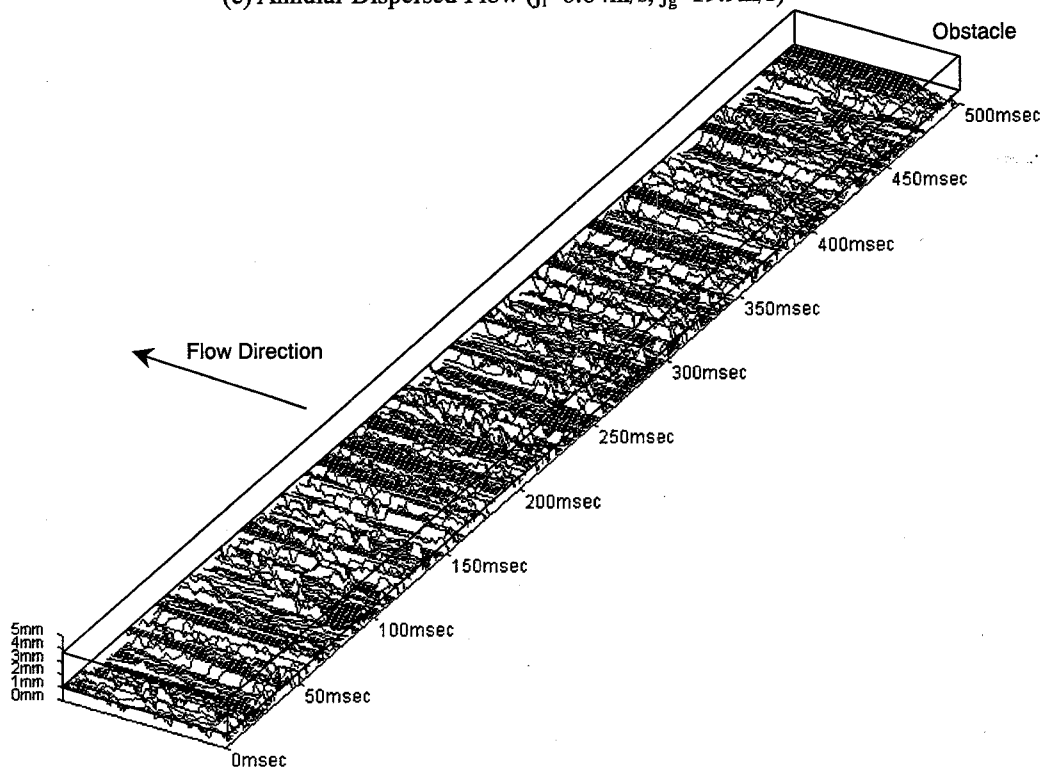


(d) Disturbance Wave Flow ($j_l=0.069\text{m/s}$, $j_g=10.0\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom (Continued)

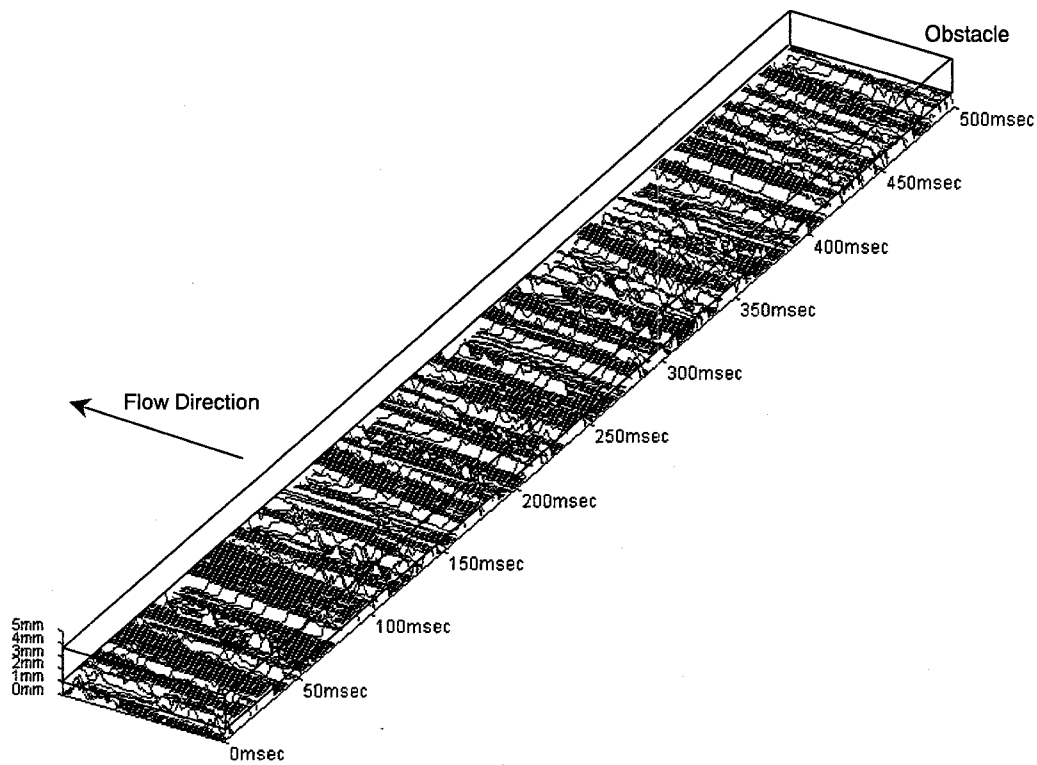


(e) Annular Dispersed Flow ($j_l=0.04\text{m/s}$, $j_g=19.9\text{m/s}$)

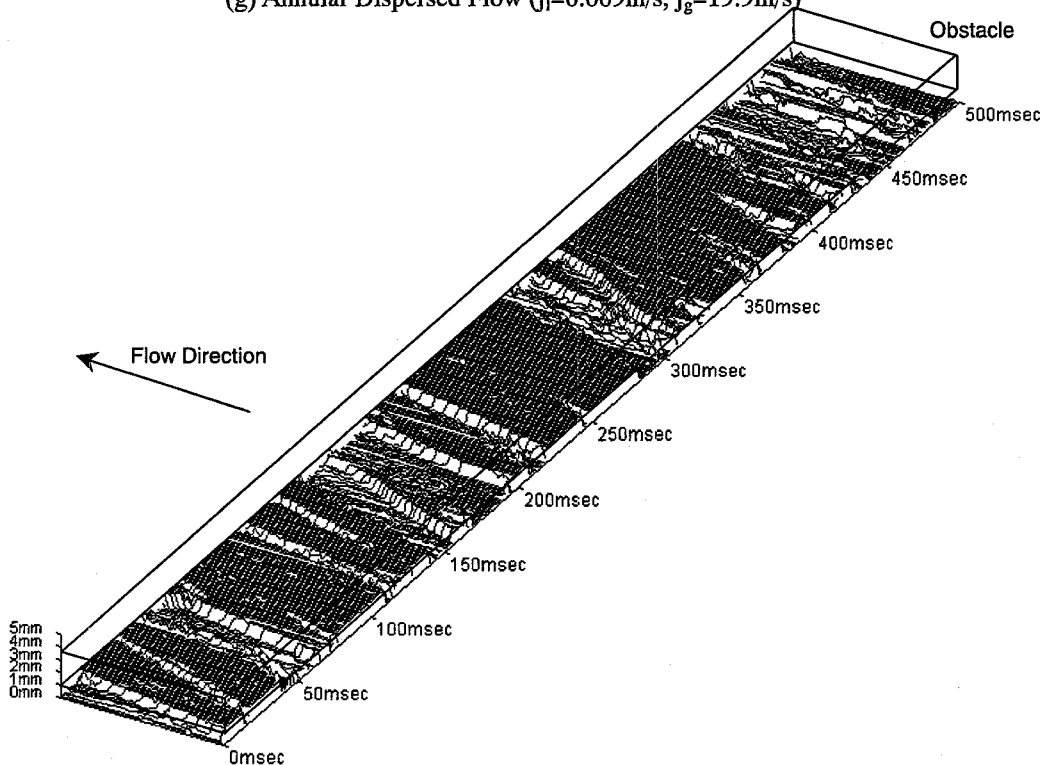


(f) Annular Dispersed Flow ($j_l=0.058\text{m/s}$, $j_g=19.9\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom (Continued)

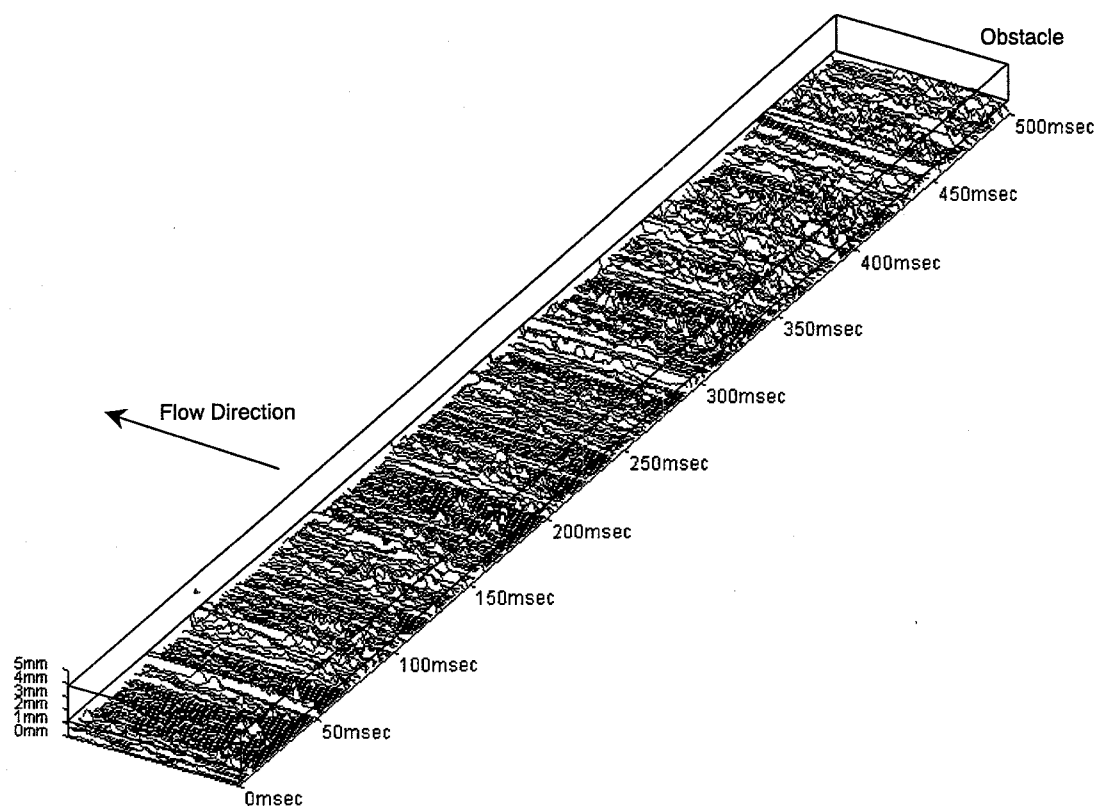


(g) Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=19.9\text{m/s}$)

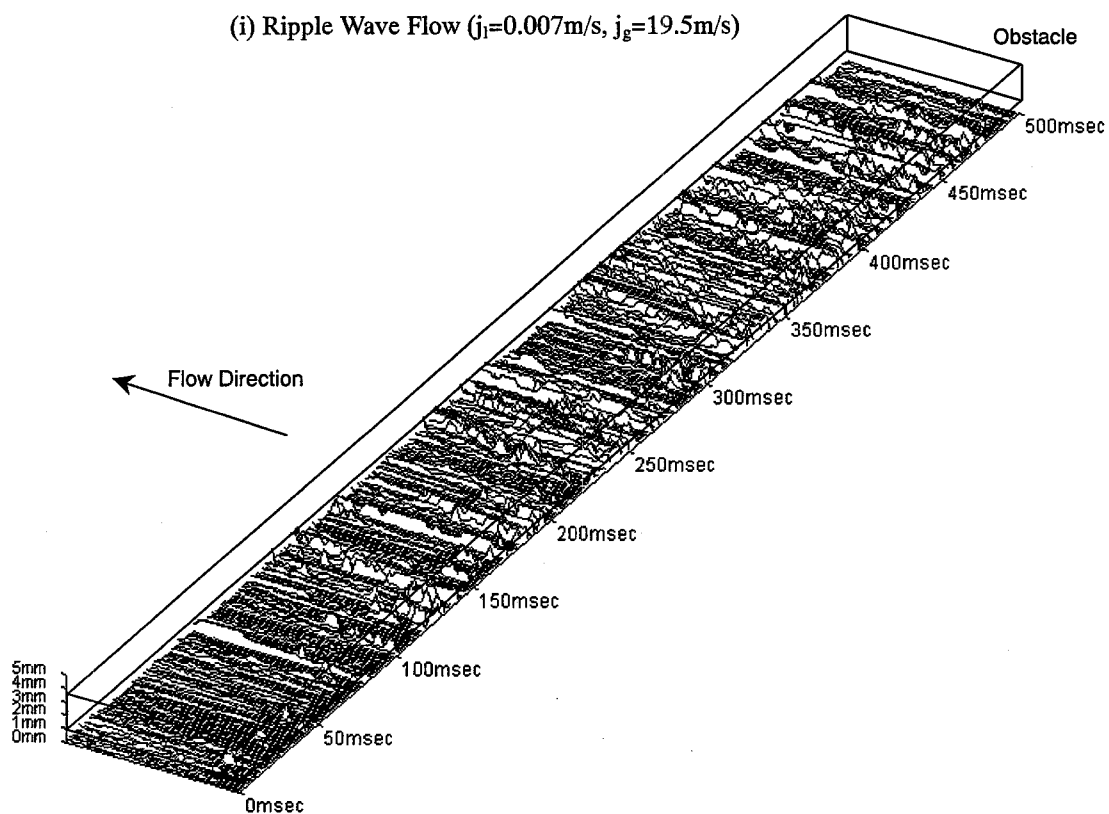


(h) Annular Dispersed Flow ($j_l=0.069\text{m/s}$, $j_g=13.0\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom (Continued)

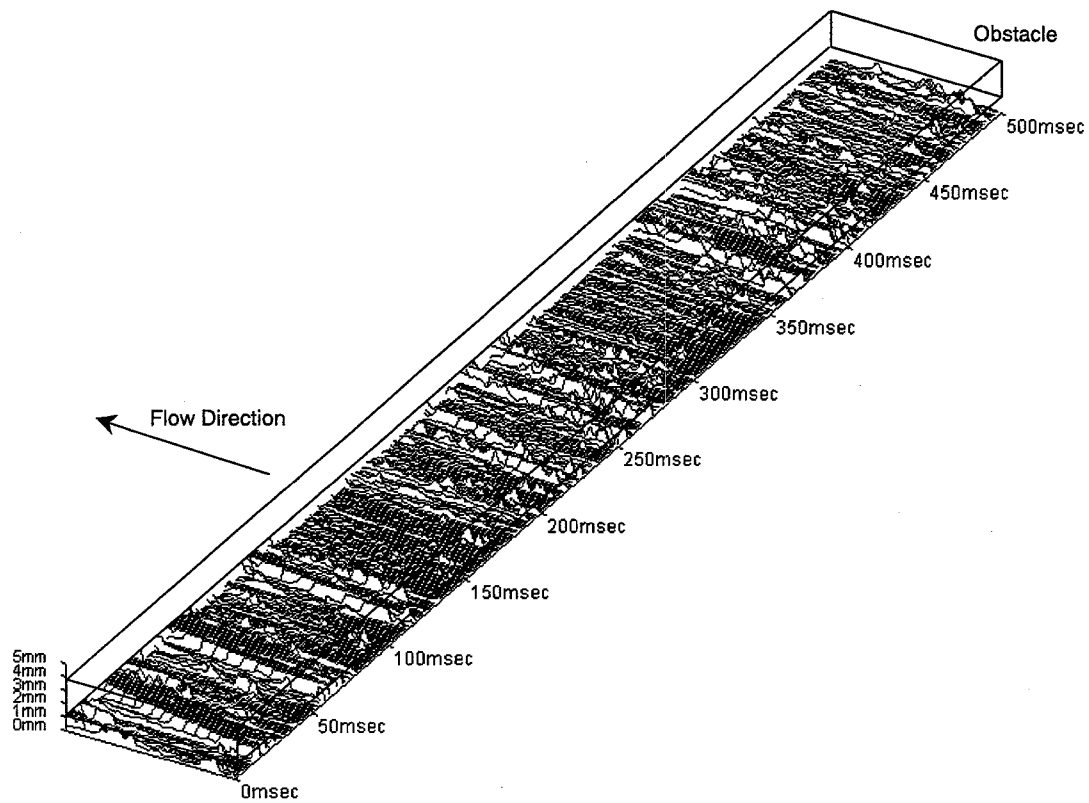


(i) Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=19.5\text{m/s}$)

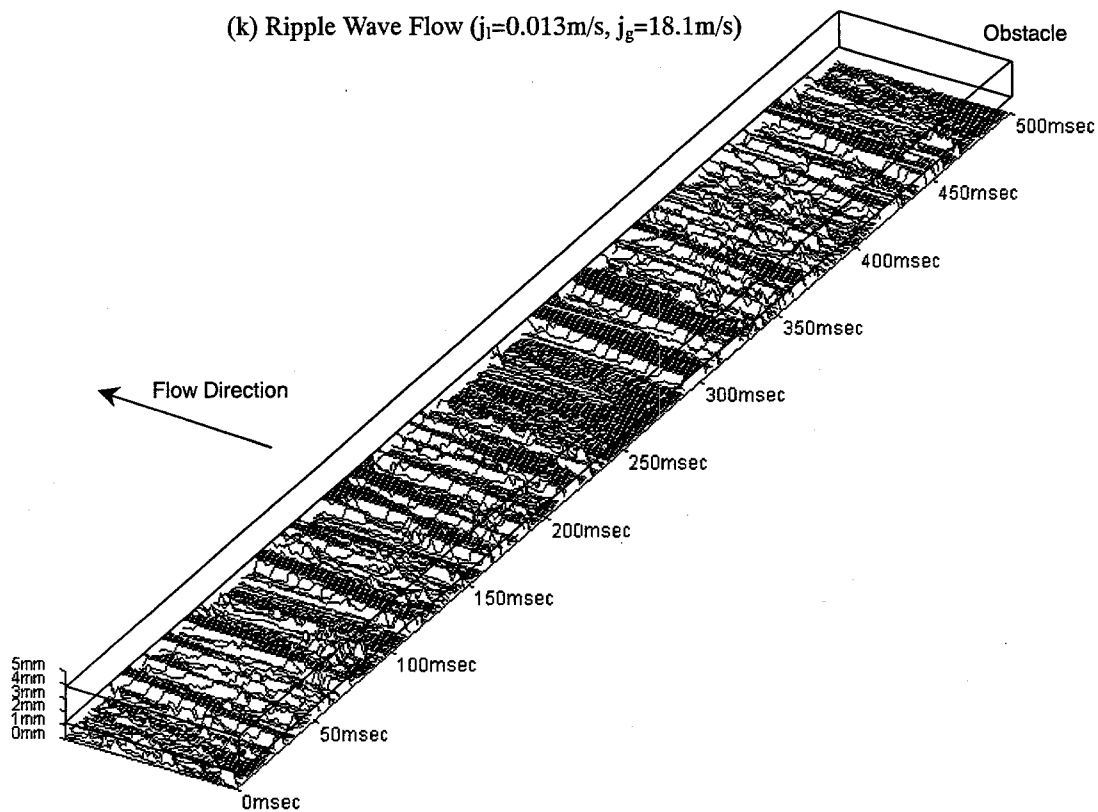


(j) Ripple Wave Flow ($j_l=0.007\text{m/s}$, $j_g=18.1\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom (Continued)

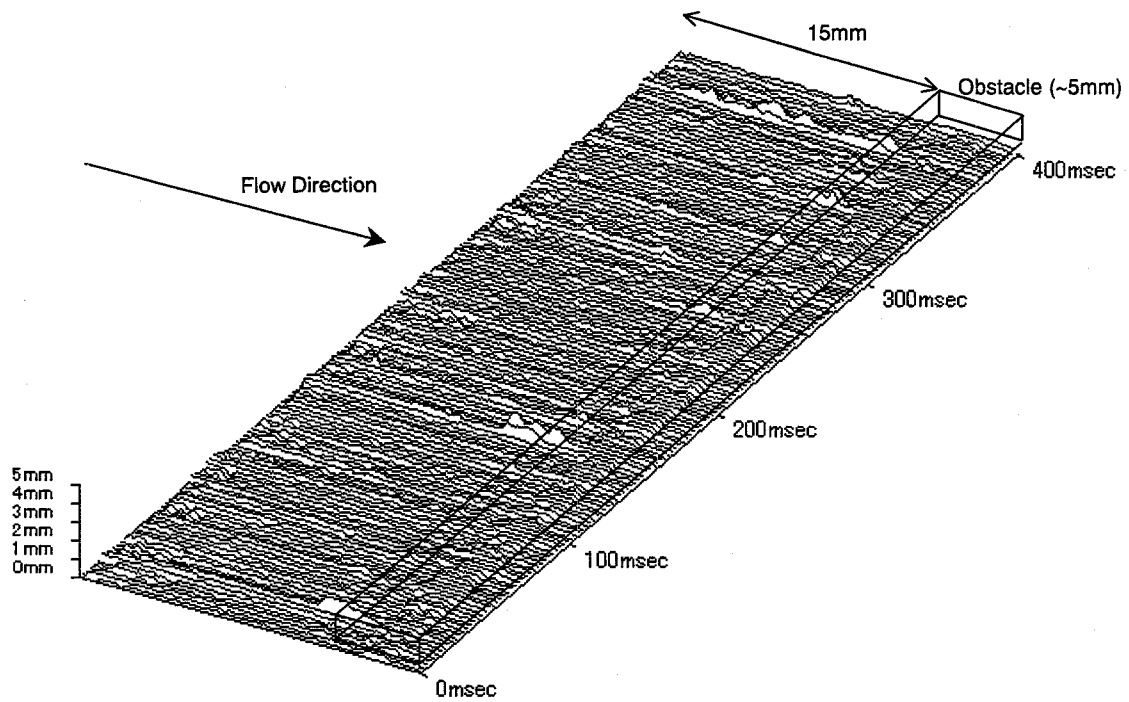


(k) Ripple Wave Flow ($j_l=0.013\text{m/s}$, $j_g=18.1\text{m/s}$)

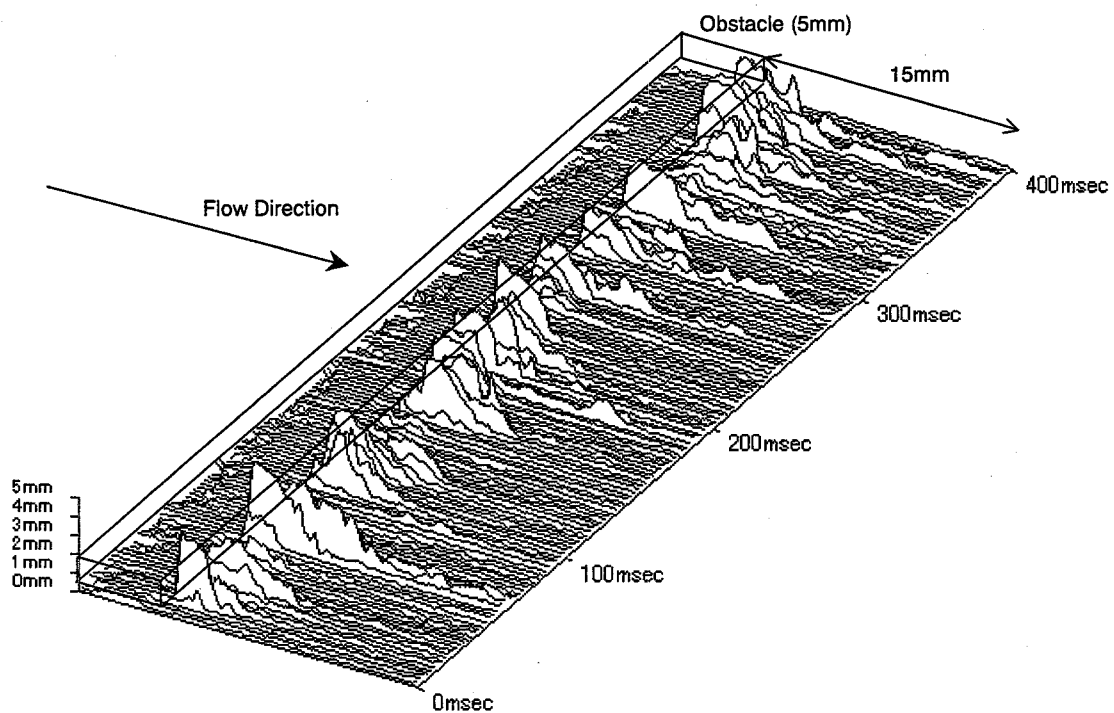


(l) Ripple Wave Flow ($j_l=0.027\text{m/s}$, $j_g=18.1\text{m/s}$)

Figure 4.6 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Obstacle Placed at 1mm From Channel Bottom

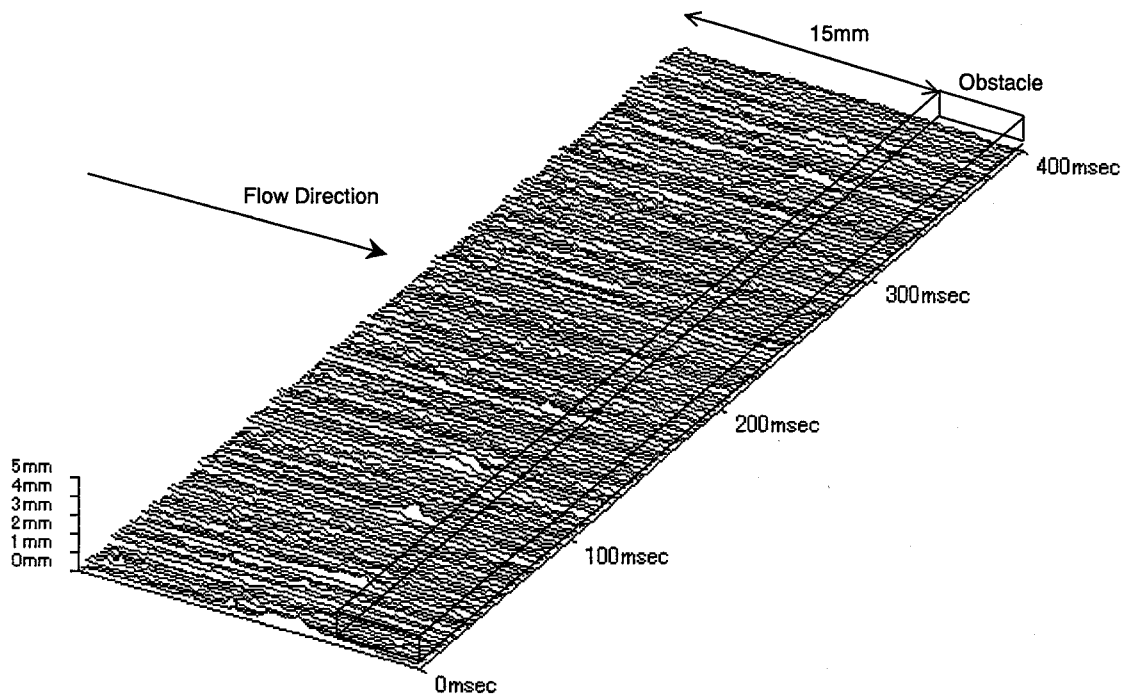


(a) Upstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

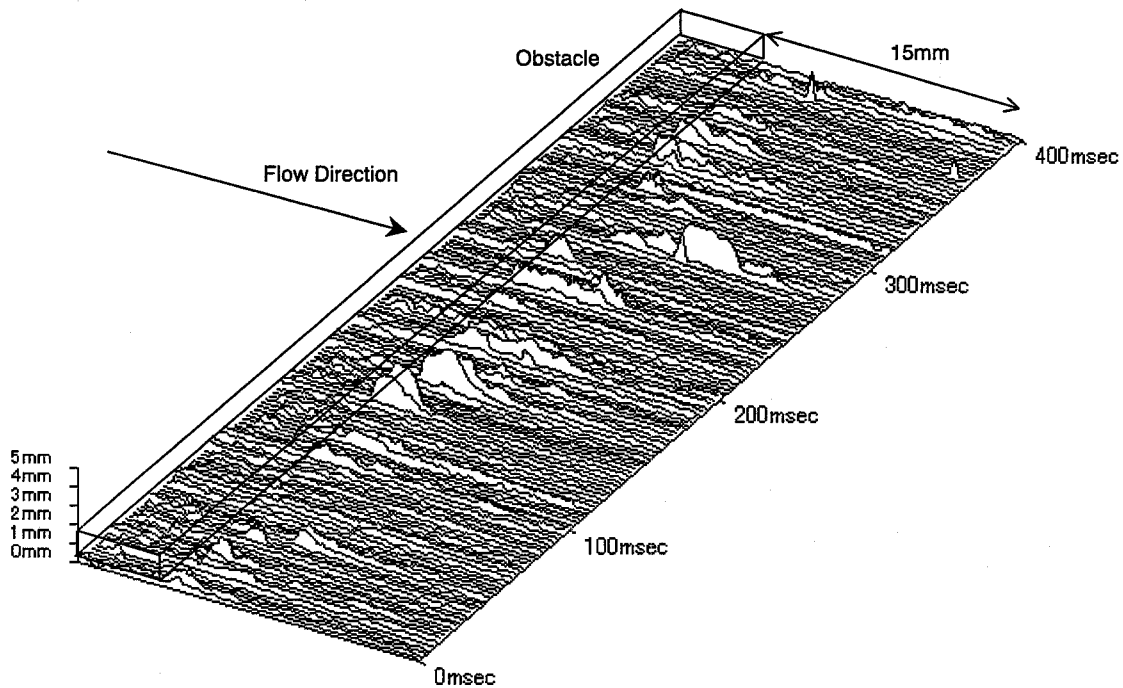


(b) Downstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

Figure 4.7 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type A Obstacle Placed at 0.5mm From Channel Bottom

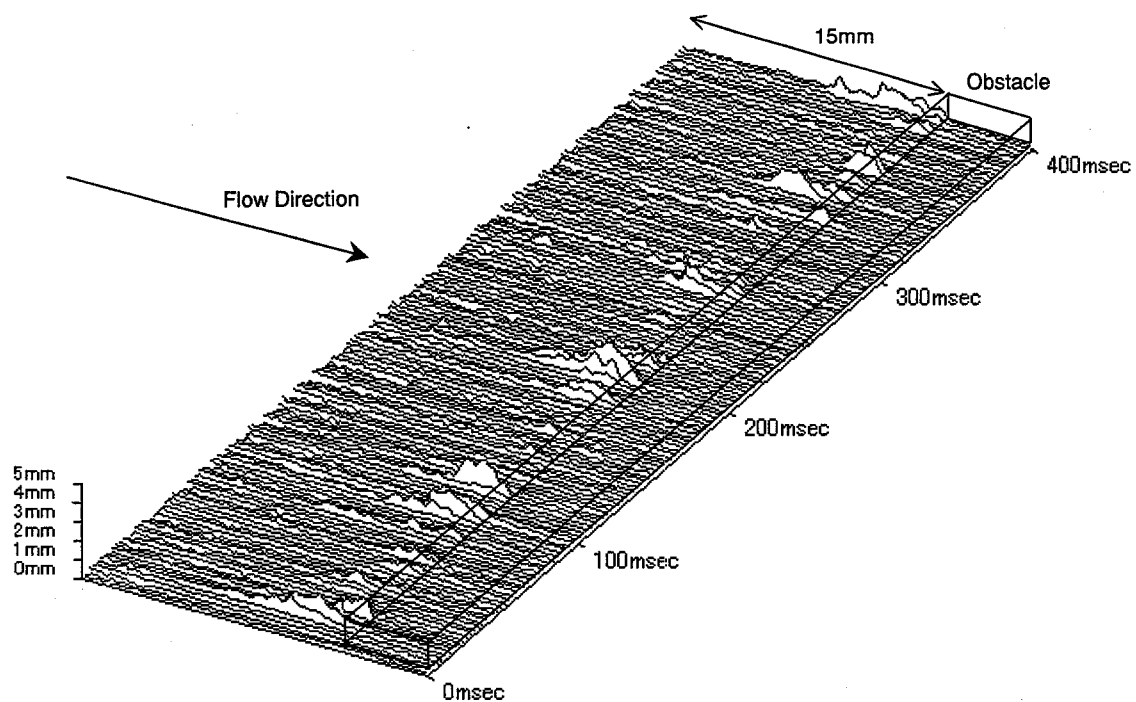


(a) Upstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

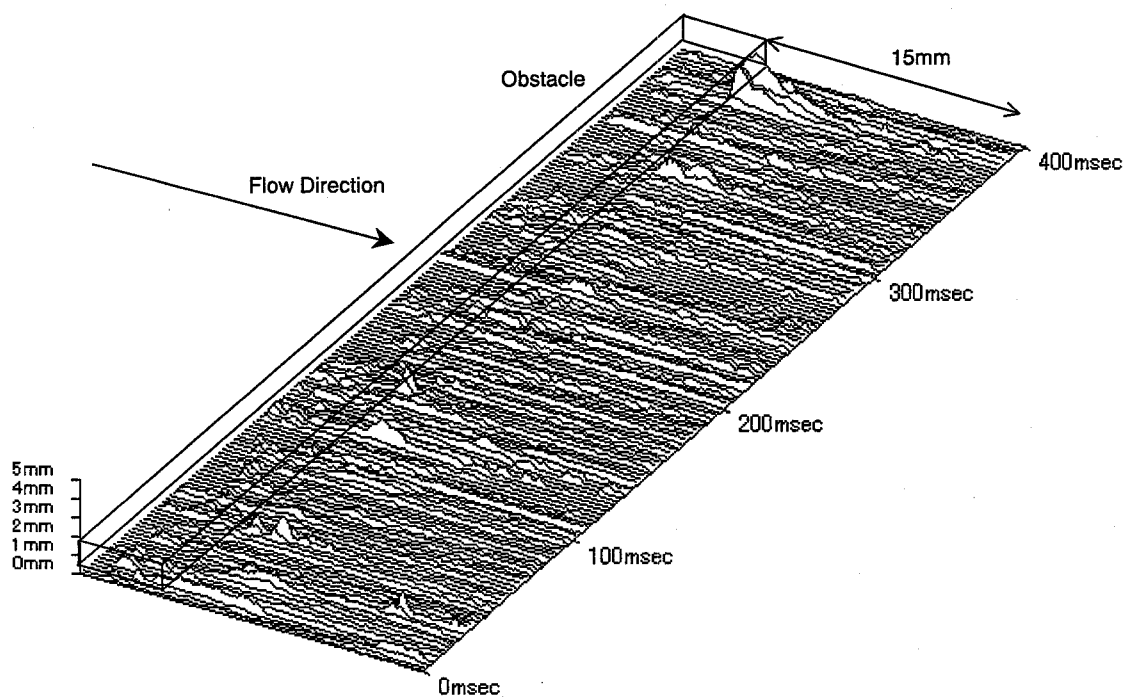


(b) Downstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

Figure 4.8 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type B Obstacle Placed at 0.5mm From Channel Bottom

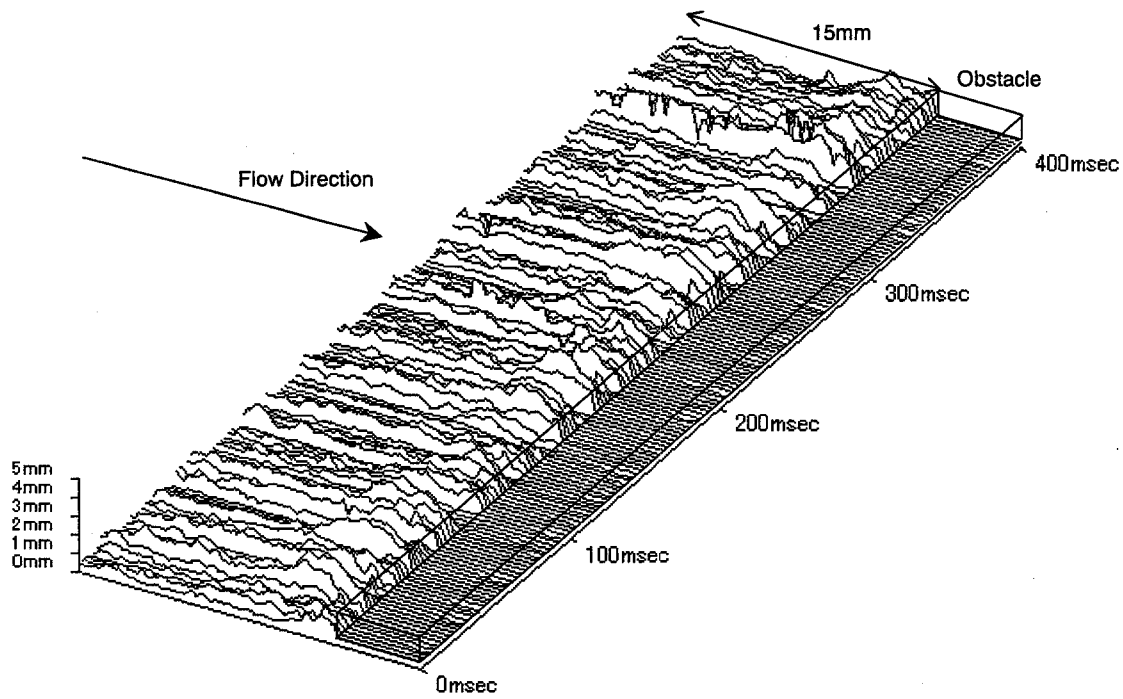


(a) Upstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

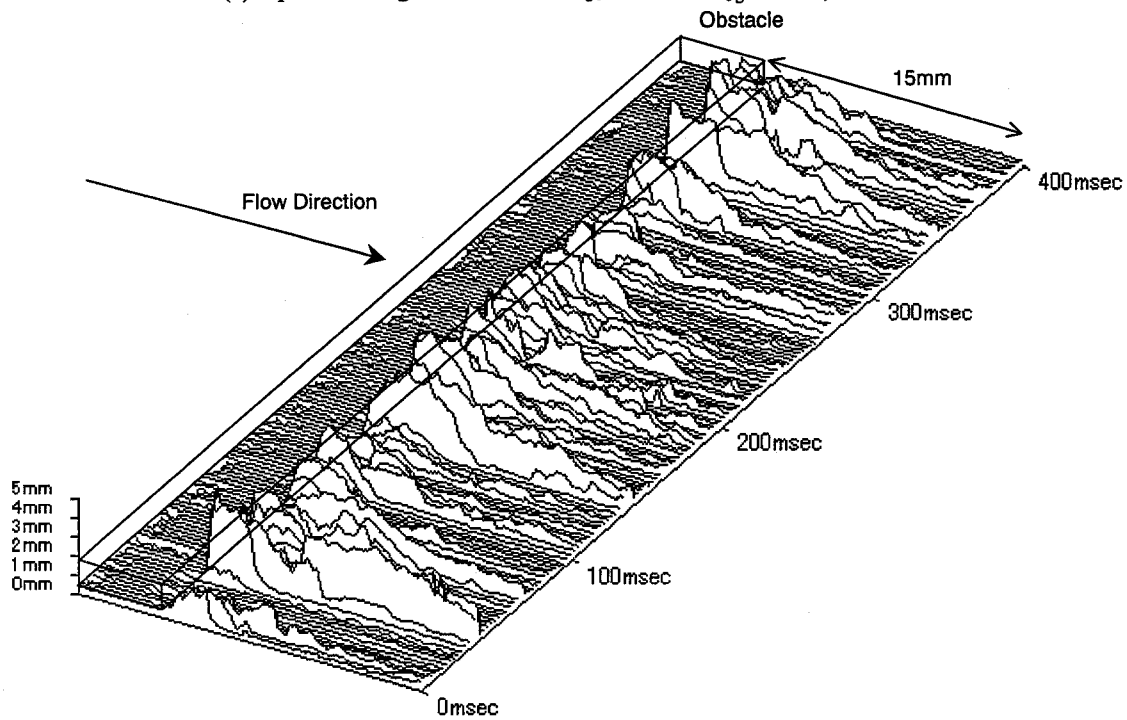


(b) Downstream Region of Obstacle ($j_l=0.012\text{m/s}$, $j_g=33\text{m/s}$)

Figure 4.9 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type C Obstacle Placed at 0.5mm From Channel Bottom

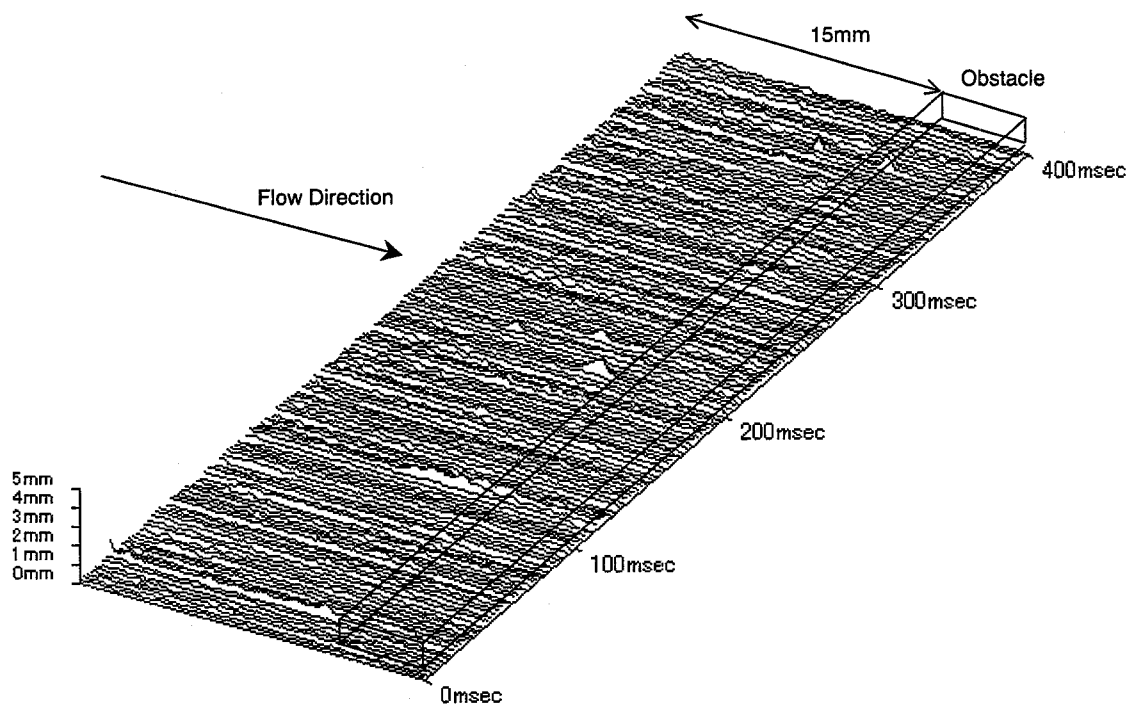


(a) Upstream Region of Obstacle ($j_l=0.023\text{m/s}$, $j_g=33\text{m/s}$)

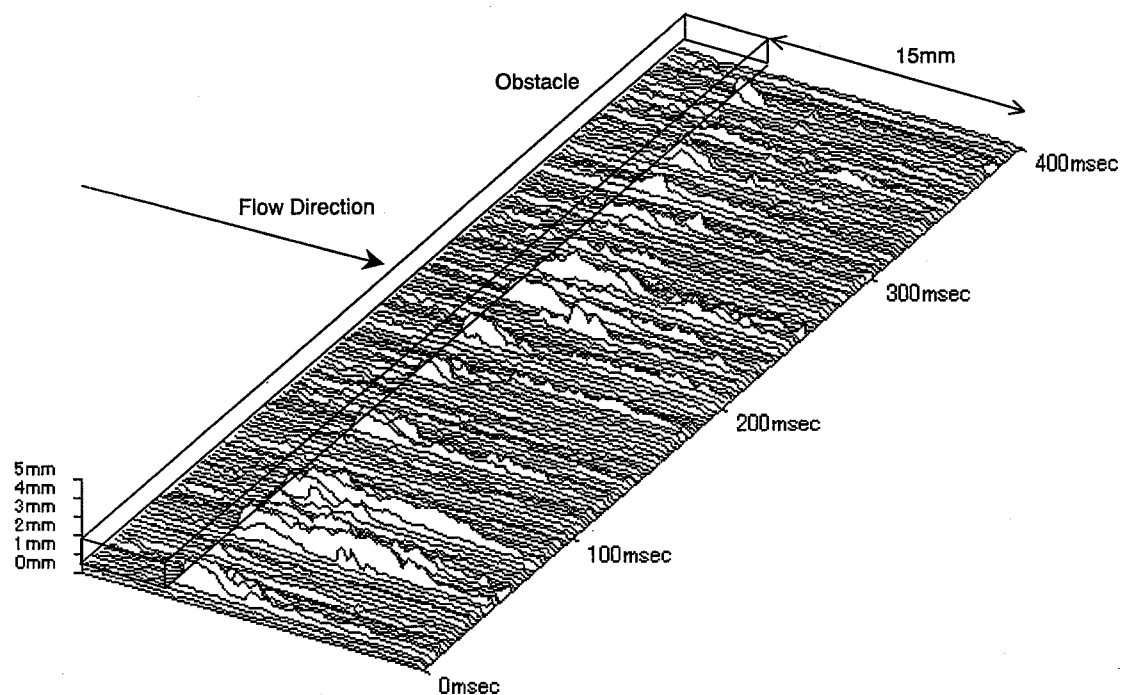


(b) Downstream Region of Obstacle ($j_l=0.023\text{m/s}$, $j_g=33\text{m/s}$)

Figure 4.10 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type A Obstacle Placed at 0.5mm From Channel Bottom

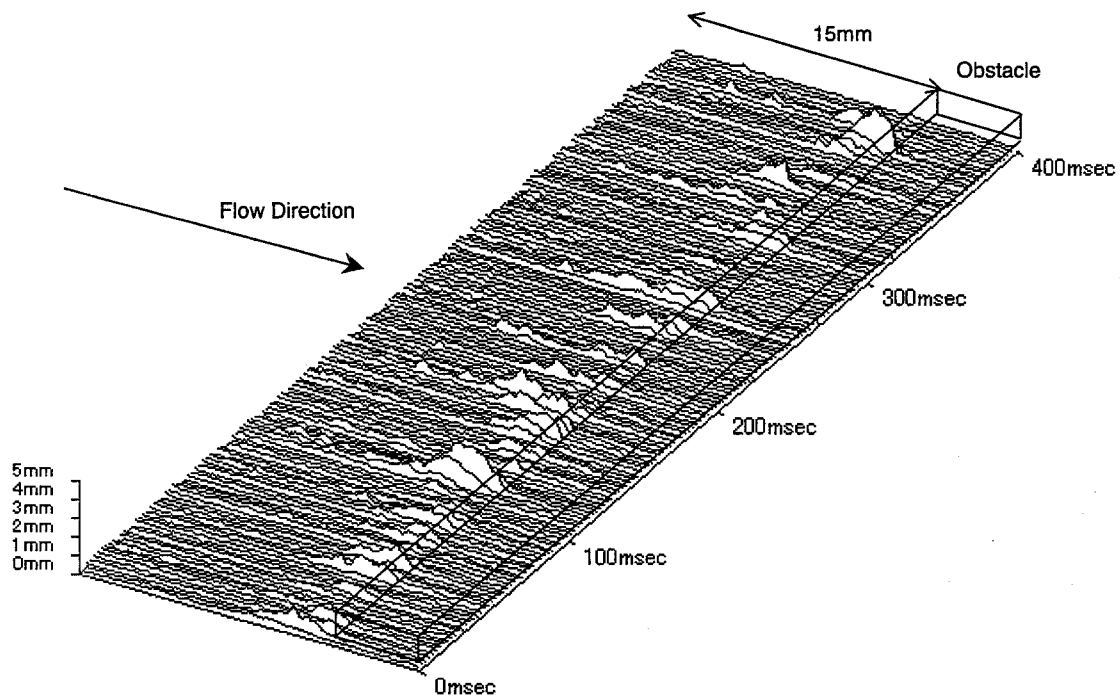


(a) Upstream Region of Obstacle ($j_l=0.023\text{m/s}$, $j_g=33\text{m/s}$)

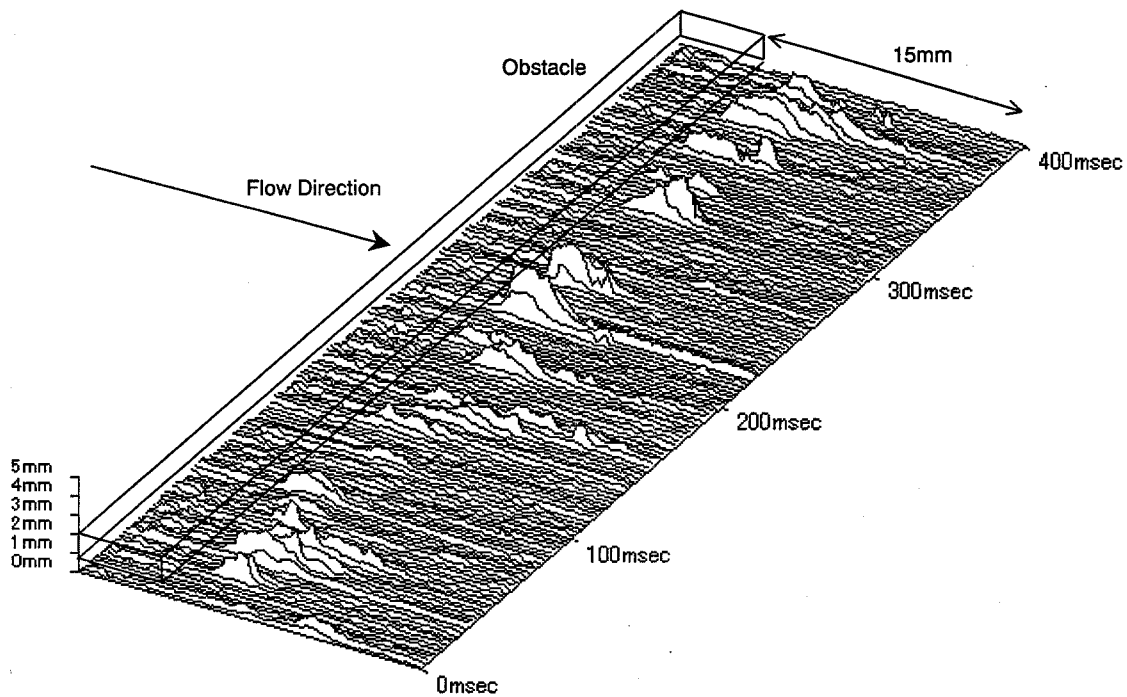


(b) Downstream Region of Obstacle ($j_l=0.023\text{m/s}$, $j_g=33\text{m/s}$)

Figure 4.11 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type B Obstacle Placed at 0.5mm From Channel Bottom

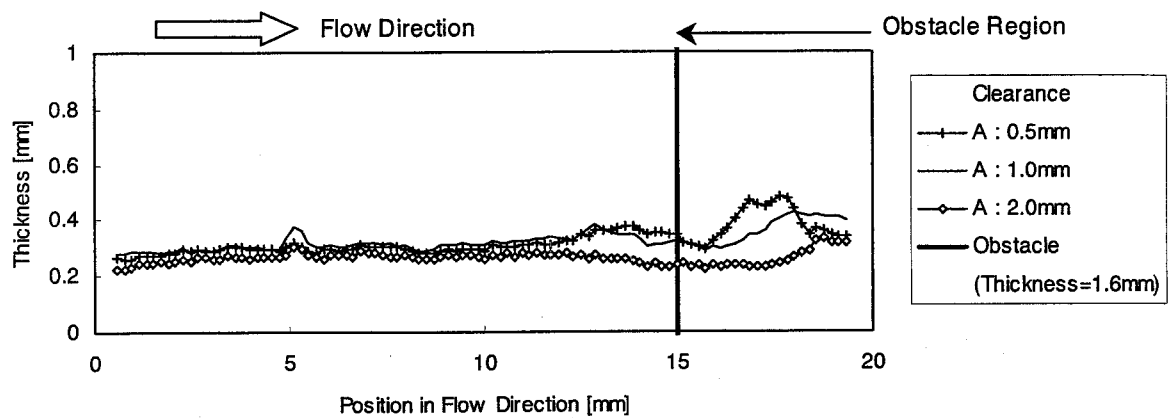


(a) Upstream Region of Obstacle ($j_i=0.023\text{m/s}$, $j_e=33\text{m/s}$)

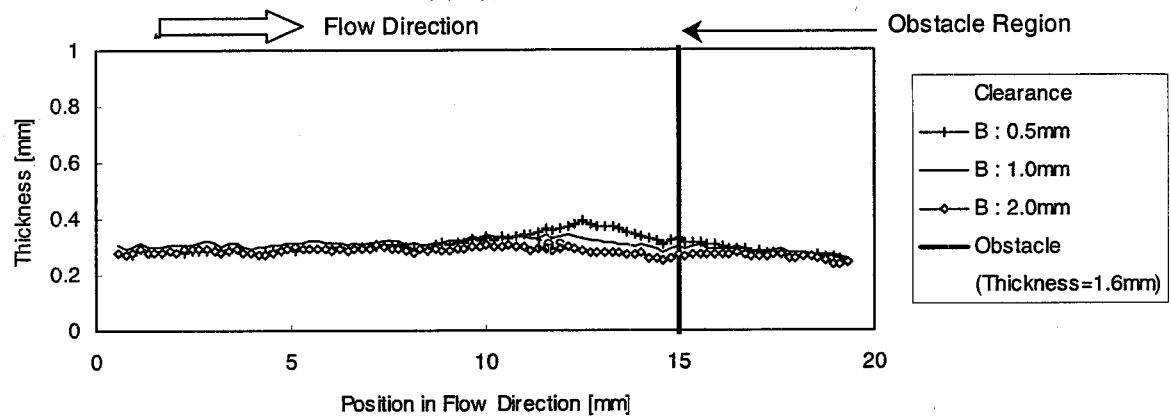


(b) Downstream Region of Obstacle ($j_i=0.023\text{m/s}$, $j_e=33\text{m/s}$)

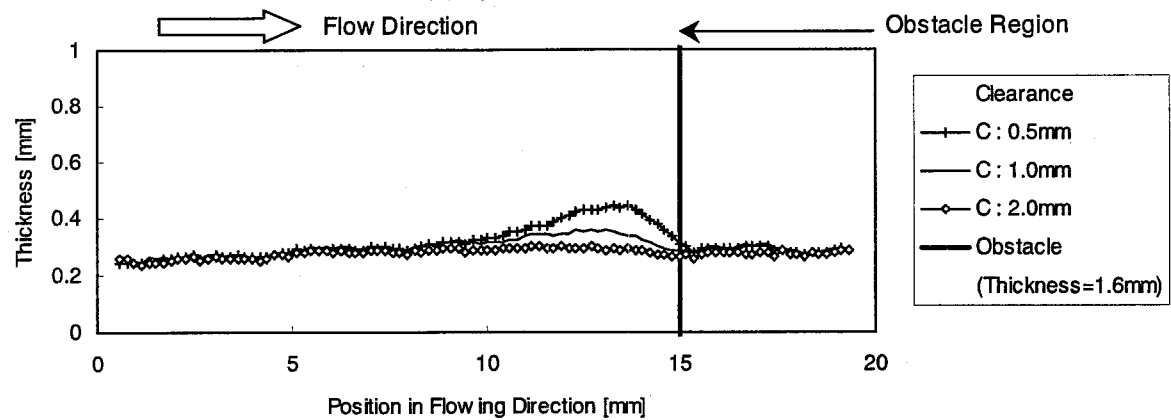
Figure 4.12 Bird's Eye View of Time-Dependent Axial Distribution of Liquid Film Thickness with Type C Obstacle Placed at 0.5mm From Channel Bottom



(a) Type A Obstacle

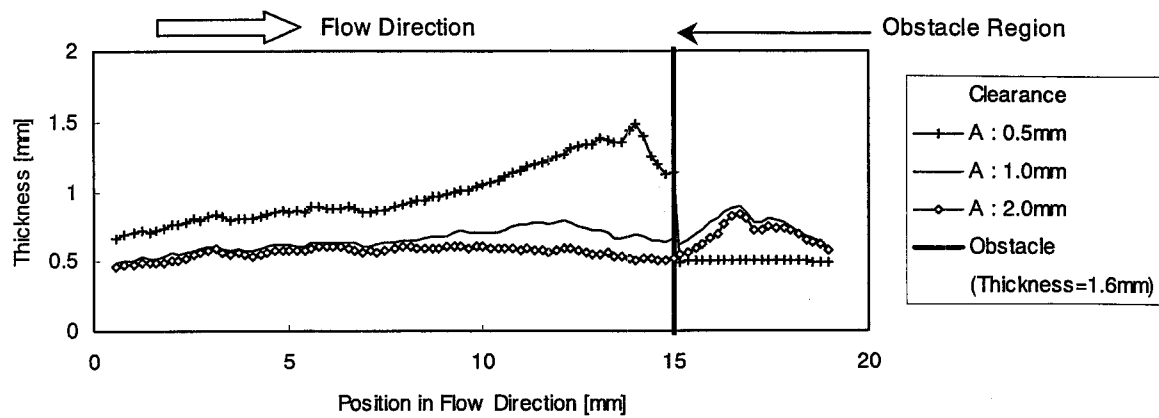


(b) Type B Obstacle

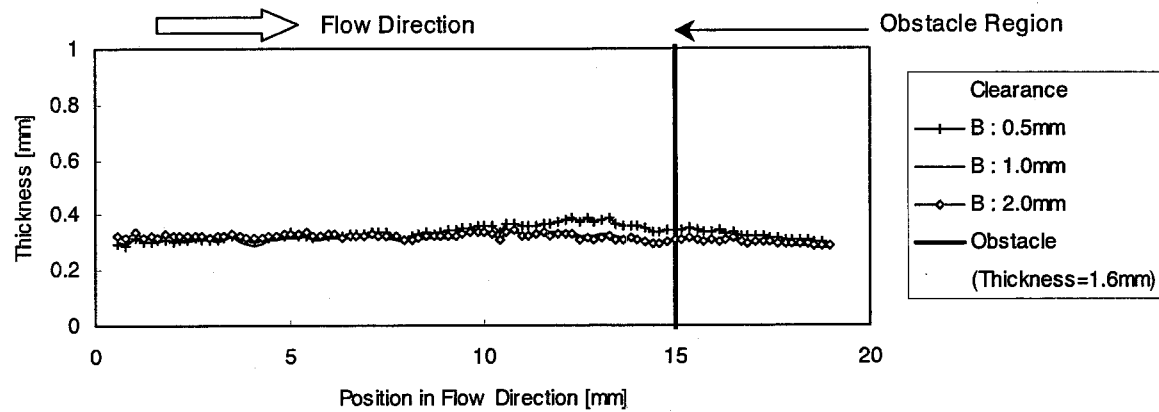


(c) Type C Obstacle

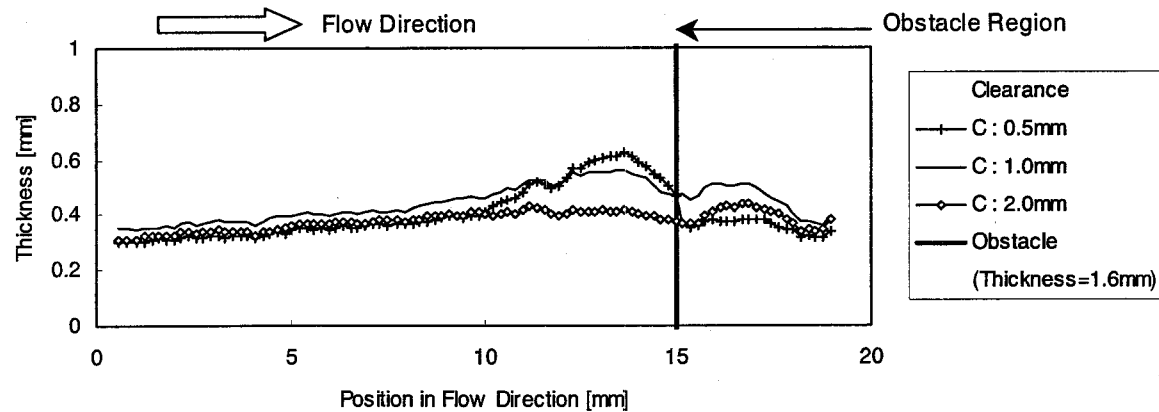
Figure 4.13 Effect of Obstacle Height on Time-Averaged Liquid Film Thickness in Upstream Region ($j_l=0.012\text{m/s}$ and $j_g=33\text{m/s}$)



(a) Type A Obstacle

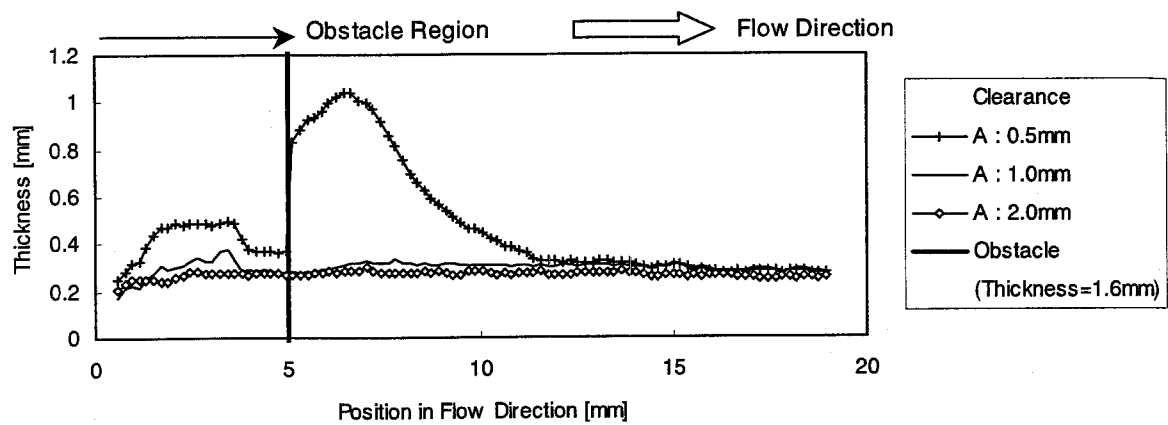


(b) Type B Obstacle

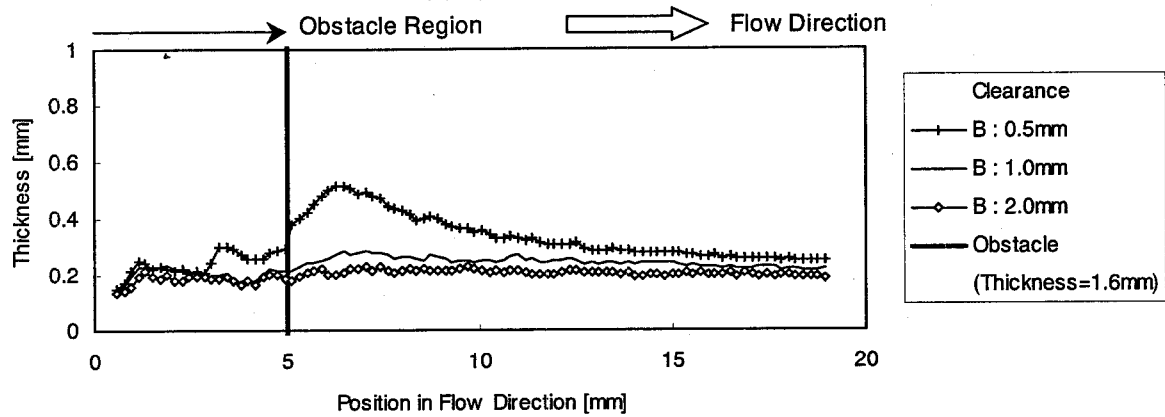


(c) Type C Obstacle

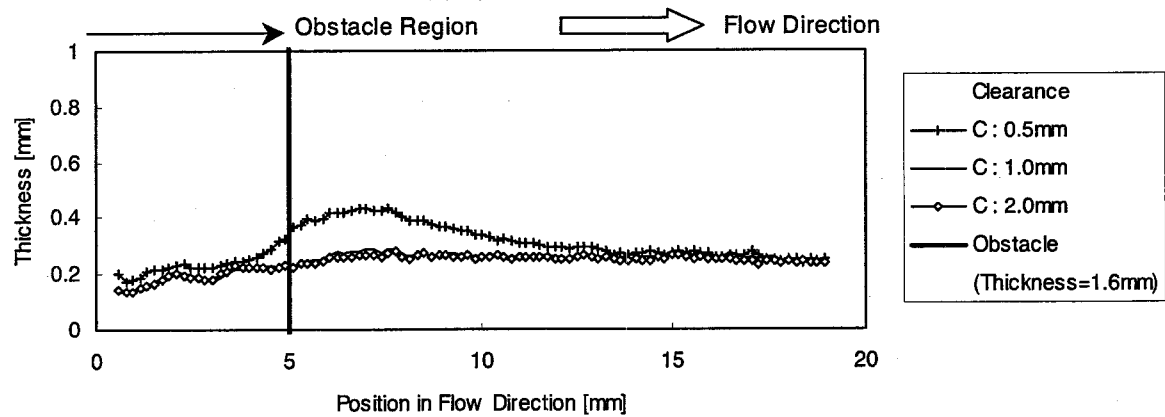
Figure 4.14 Effect of Obstacle Height on Time-Averaged Liquid Film Thickness in Upstream Region ($j_l=0.023\text{m/s}$ and $j_g=33\text{m/s}$)



(a) Type A Obstacle

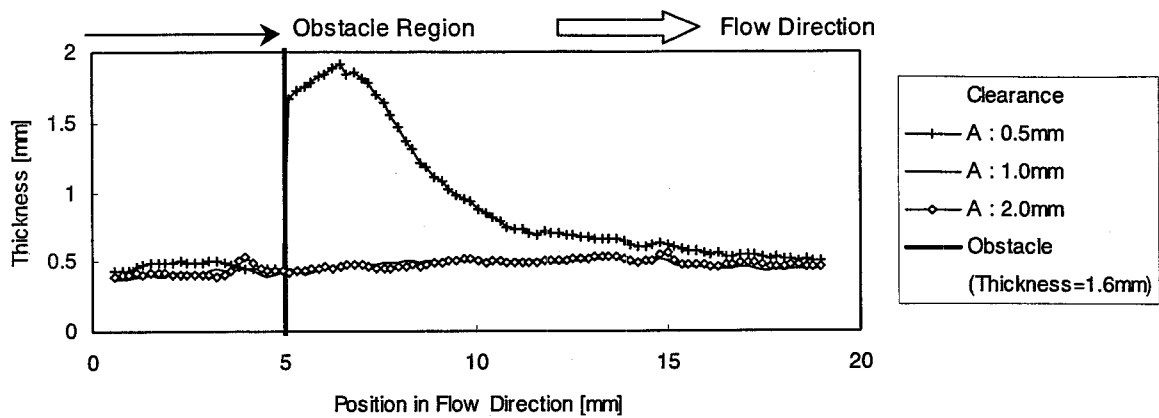


(b) Type B Obstacle

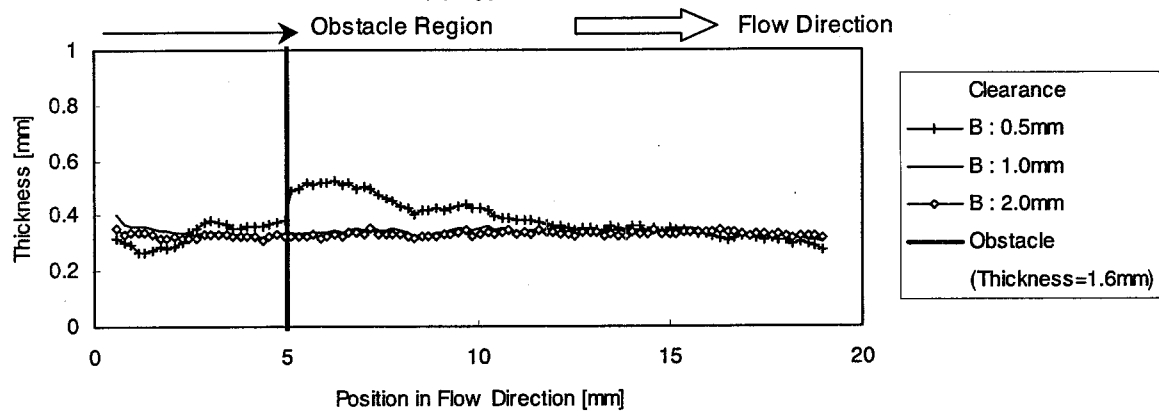


(c) Type C Obstacle

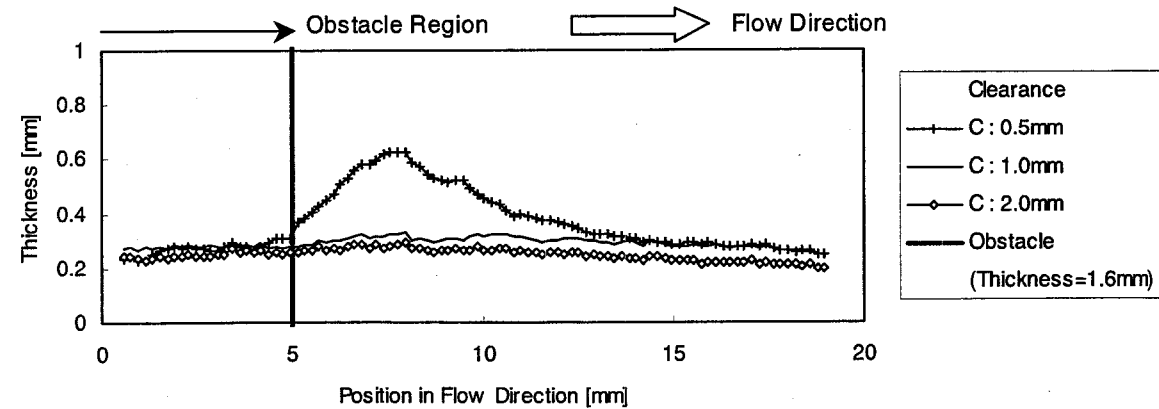
Figure 4.15 Effect of Obstacle Height on Time-Averaged Liquid Film Thickness in Downstream Region ($j_l=0.012\text{m/s}$ and $j_g=33\text{m/s}$)



(a) Type A Obstacle



(b) Type B Obstacle



(c) Type C Obstacle

Figure 4.16 Effect of Obstacle Height on Time-Averaged Liquid Film Thickness in Downstream Region ($j_l=0.023\text{m/s}$ and $j_g=33\text{m/s}$)

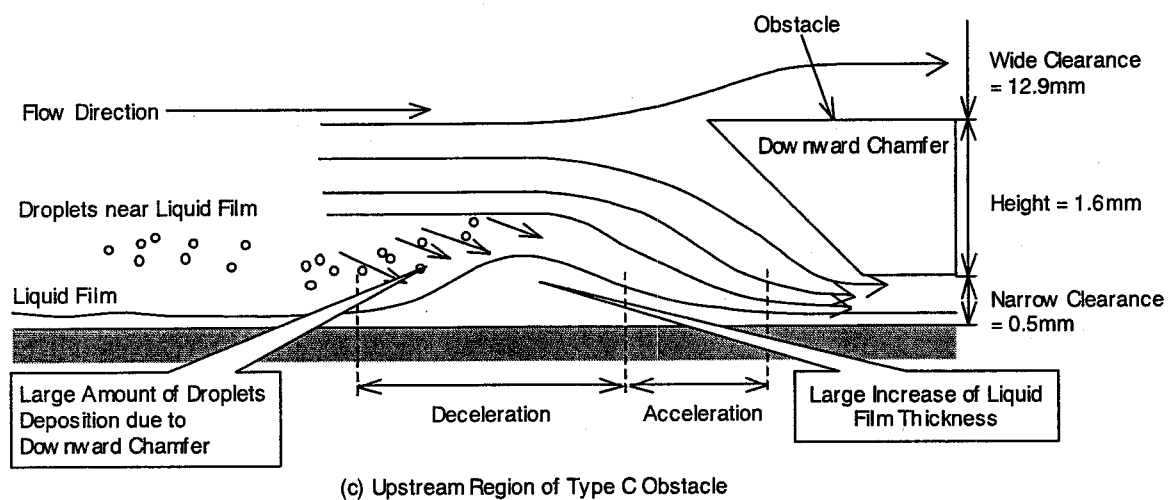
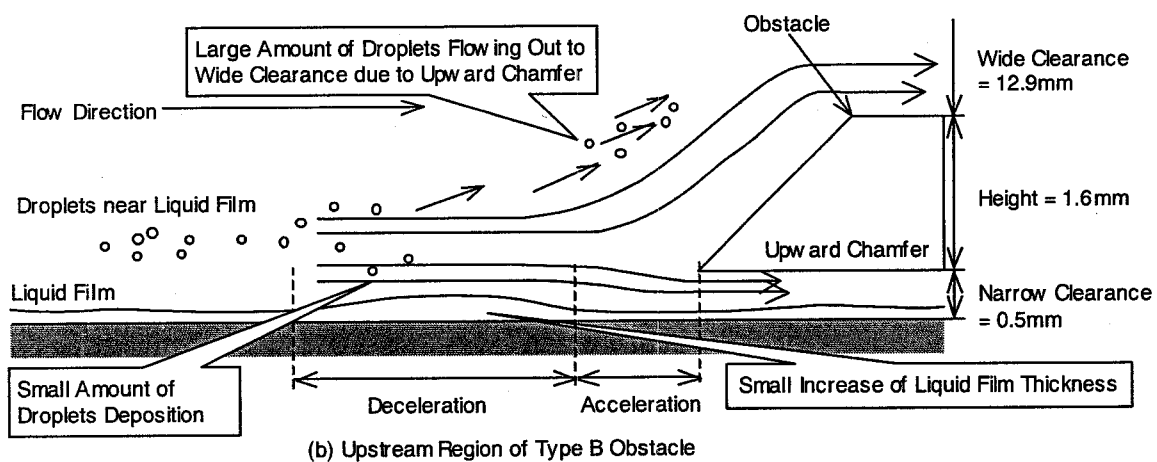
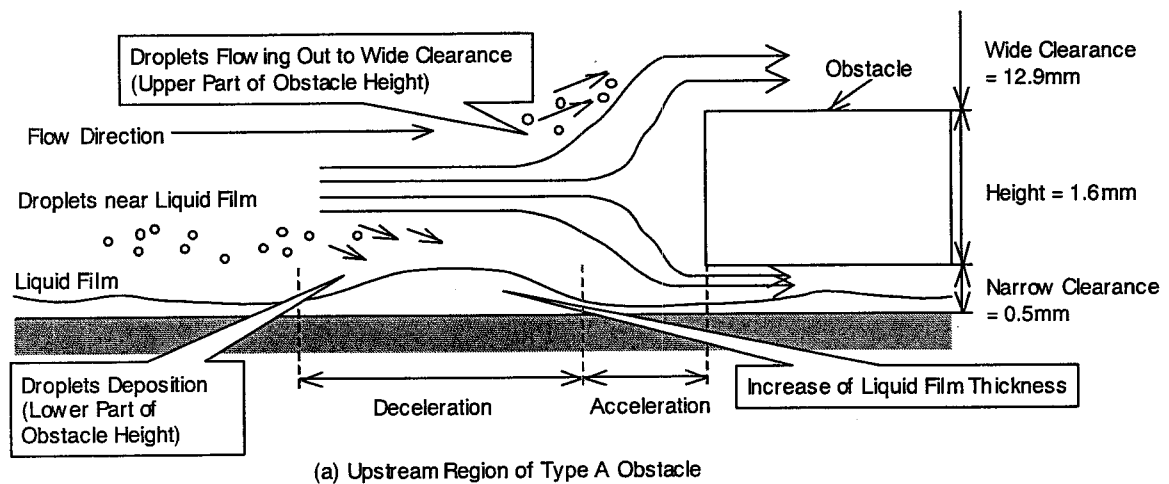
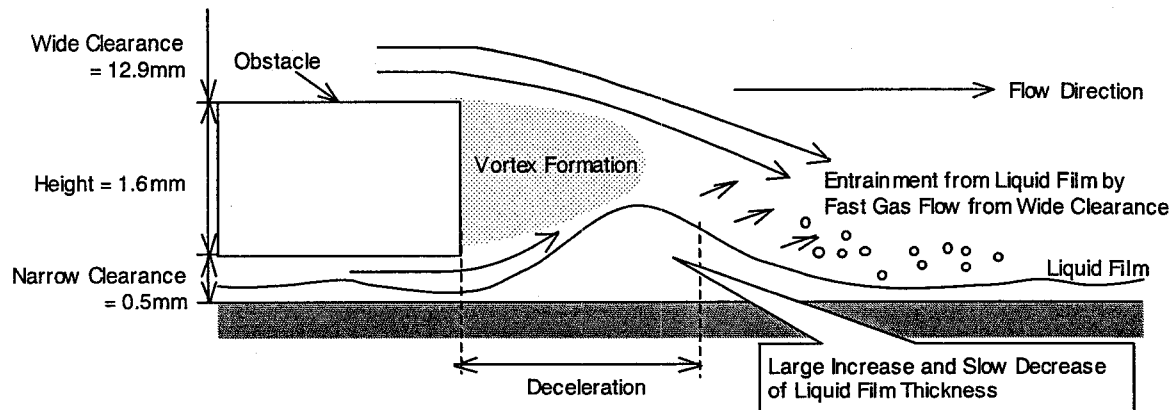
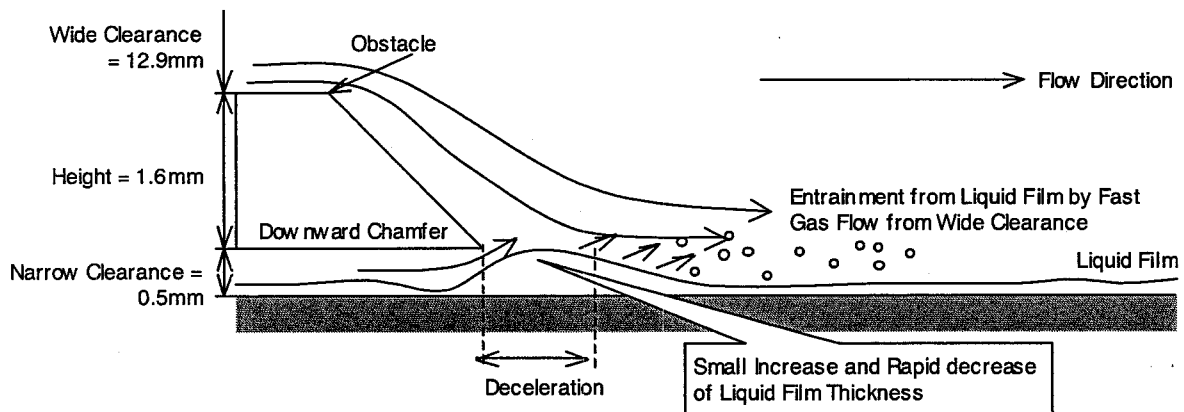


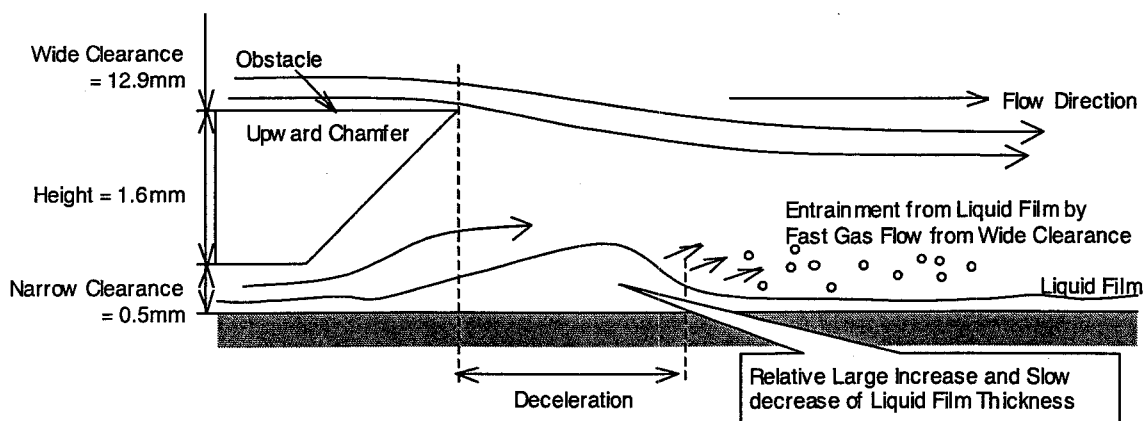
Figure 4.17 Effect of Obstacle Edge on Liquid Film Thickness in Upstream Region



(a) Downstream Region of Type A Obstacle



(b) Downstream Region of Type B Obstacle



(c) Downstream Region of Type C Obstacle

Figure 4.18 Effect of Obstacle Edge on Liquid Film Thickness in Downstream Region

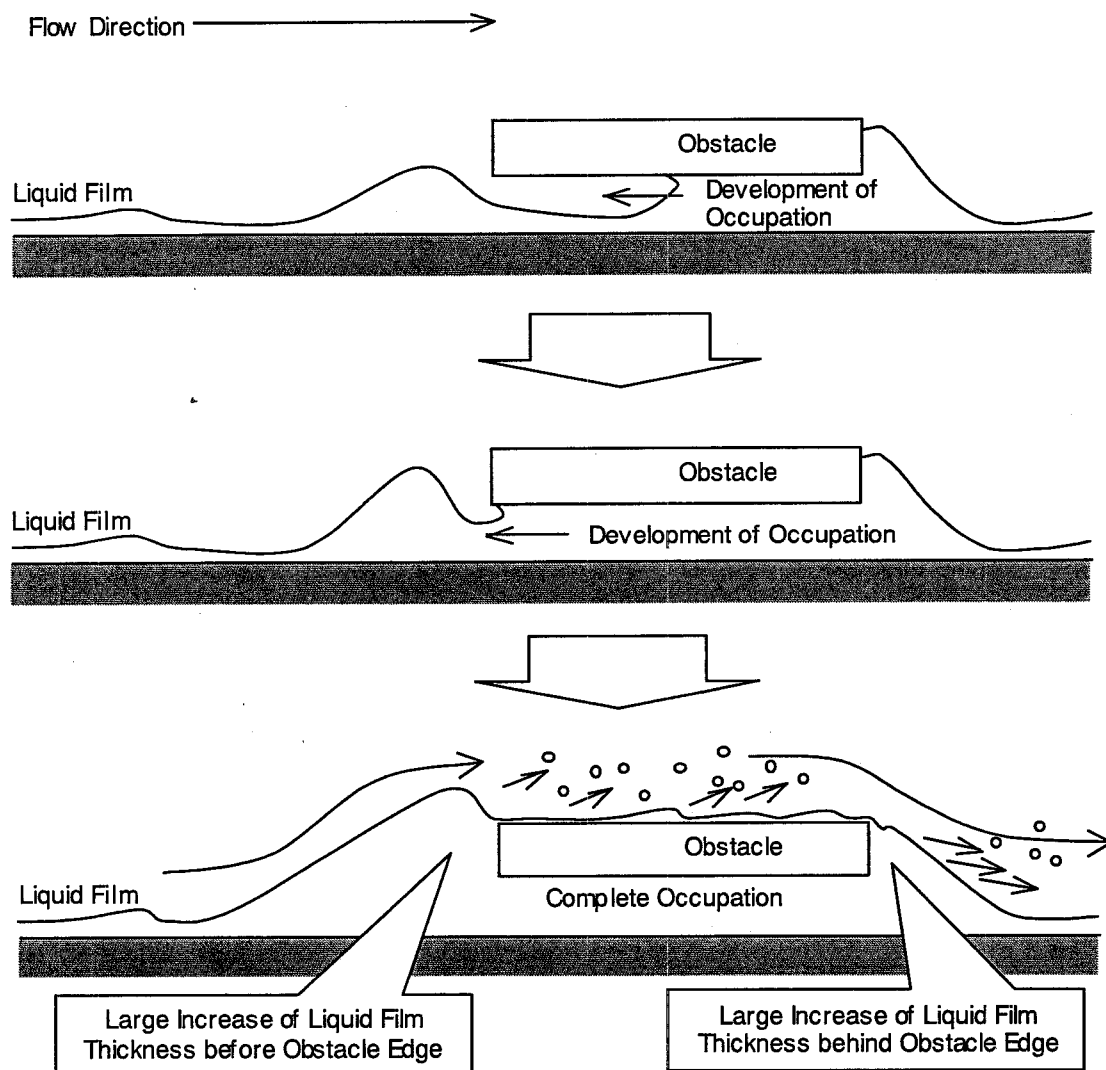


Figure 4.19 Effect of Occupation in Obstacle Clearance

5. Characteristics of Vertically Upward External Flow in an Annulus

5.1. Introduction

Characteristics of a vertically upward external liquid film flow will be discussed in this chapter. Annulus tube was used as a simplified case of complex subchannel geometry in nuclear fuel rod assembly. Time-dependent liquid film thickness around tube was measured by the USEM. Reconstructed images of liquid film flow were excellently obtained.

5.2. Experimental Apparatus and Conditions

The experimental facility used in this work is shown in figure 5.1. The test section is a 1,000mm long annulus, consisting of a 30mm I.D. outer tube and a 15mm O.D. inner tube that simulates nuclear fuel rod. The flow is in a developing region since $L/D=67$ (D : equivalent diameter). Both tubes are made of transparent acrylic resin to allow visual observations. Air and water were metered and fed to a gas-liquid mixing section where the water was injected into the air flowing outside of inner tube through a narrow slit formed around the tube periphery. The measuring device of the USEM was set inside of the inner tube and was located at 950mm downstream of the inlet section to measure liquid film thickness distributions around the tube. Experimental conditions cover $10.7\sim30\text{m/s}$ for the superficial gas velocity and $0.013\sim0.063\text{m/s}$ for the superficial liquid velocity. All experiments were carried out at atmospheric pressure and at ambient temperature.

Figure 5.2 shows a schematic of liquid film structure and a flow pattern map covered in the present experiments. Most of the flow pattern identified in this experiments was disturbance wave flow in which surface of the inner tube was covered with liquid film as illustrated in figure 5.2(a). The liquid film on the inner tube is consisted of a thin base film having lots of ripples and intermittently appearing large two-dimensional disturbance waves. Liquid film was not remarkably observed on the outer tube except rivulets. Concerning the flow pattern defined by Hewitt and Roberts [1] also indicated in figure 5.2(b), it should be said that most of the present tests are corresponding to annular dispersed flow, thus, the rivulets on outer tube will be developed to liquid film covering whole surface of the outer tube in farther downstream region. Some flow conditions were determined as ripple wave flow in which no significant large wave was observed. Transition flow from churn flow to disturbance wave flow was also observed only at $j_l=0.013\text{m/s}$ and $j_g=10.7\text{m/s}$.

5.3. Liquid Film Flow Pattern Observation

Typical examples of time-dependent liquid film distribution around the tube periphery are demonstrated as contour plots in figures 5.3 and 5.4. The thick parts are indicated with bright color and thin parts are colored with dark color. The elevation of various waves was divided into 10 intervals. These images contain results during 1,400msec measurements. Outline of the liquid film behavior will be described here.

Two-dimensional large waves considered being the disturbance wave are observed from these plots. Sekoguchi et al. [2] suggested the existence of "ephemeral large wave"

having the amplitude as large as the disturbance wave but shorter lifetime. They also introduced another type of waves as "huge wave" having higher traveling velocity than the disturbance wave [3]. These waves appear in the region of relatively large superficial liquid velocity (more than 0.1m/s in vertically upward flow) and small superficial gas velocity (less than 10m/s in vertically upward flow), therefore these waves were not considered in the present experiment. It seems that large disturbance waves appear more frequently with an increase of the superficial liquid velocity for constant gas velocity as shown in figures 5.3 and 5.4.

Figures 5.3(a)-(e) show cases of $j_l=0.013\text{m/s}$. Several waves covering almost around the tube periphery, to say two-dimensional disturbance waves, are observed. However, the frequency of disturbance wave is small and most part of the gas-liquid interface is covered with thin base film because of small liquid flow rate. Those waves appearing at 200msec and 700msec having long duration time about 50msec in figure 5.3(a) indicate that the liquid film tends to be like a churn flow.

Figures 5.3(f)-(i) show the results obtained at $j_l=0.025\text{m/s}$. It can be seen that the gas-liquid interface is wavier than those shown in figures 5.3(a)-(e). It is also noted that the disturbance waves are detected clearly which cover around tube periphery.

Figures 5.4(a)-(d) show the cases of $j_l=0.038\text{m/s}$. The gas-liquid interface becomes rough and many waves occur on it. It seems that the frequency of disturbance wave becomes small with increase of gas velocity. A similar trend is also seen in figures 5.4(e)-(h) and figures 5.4(i)-(k) showing the results of $j_l=0.05\text{m/s}$ and $j_l=0.063\text{m/s}$, respectively.

Some of the results discussed above are displayed as bird's eye view graphics in figures 5.5-5.7. Liquid film behavior between 180 and 360 degrees in circumferential direction during 250msec of the corresponding results are presented.

It is seen that the disturbance waves have several peaks in peripheral direction as reported by Sekoguchi et al. [2]. Figure 5.5(d) shows that the gas-liquid interface becomes slightly smooth with small amplitude because of large gas velocity compared to the results shown in figures 5.5(a)-(c). The amplitude of the disturbance waves seems to be enlarged with increase of liquid flow rate from comparisons between figures 5.5(a), 5.6(a) and 5.7(a).

The circumferential profiles of some disturbance waves identified in figure 5.7 are plotted in figure 5.8. Each figure contains 20 images reconstructed with 1 msec time interval. Right hand side of every image corresponds to 0 degree around rod determined by the location of the supporting pole.

It is clearly seen that the waves D1 and D2 illustrated in figures 5.8(a) and 5.8(b)

have several peaks on its crest. The wave D3 in figures 5.8(c) also has the same tendency but the surface seems to be relatively smooth around tube periphery.

Thick parts of these waves seem to move toward the circumferential direction. In other word, these thick parts have horizontal velocity component across the flow direction. Sekoguchi et al. [2] also reported a similar liquid film behavior. However, this trend should be confirmed in more detail by adopting much higher rotating reflector in the near future.

5.4. Results and Discussions

5.4.1. Time-Averaged Liquid Film Thickness

Figures 5.9(a) and 5.9(b) show the results of time-averaged liquid film thickness by the USEM with a stationary reflector and that with a rotating reflector, respectively. These indicate a reasonable general trend that the liquid film thickness decreases with increase of gas velocity because interfacial shear stress is enlarged. Liquid film thickness naturally becomes large for large liquid flow rate. It seems that the results of rotating reflector is a little bit smaller than the results of stationary reflector since largely inclined liquid film surface tends to be lost in measurements of the USEM with a rotating reflector as reported by Serizawa et al. [4,5].

5.4.2. Power Spectral Density Distribution of the Film Thickness Fluctuation

Power spectral density distribution of the film thickness fluctuations (PSD) was obtained by using Fast Fourier Transform and the results are shown in figures 5.10-5.11.

Figure 5.10 shows PSD corresponding to relatively low liquid flow rate. It is observed that increasing gas velocity tends to distribute the energy to waves of higher frequency. The flow pattern occurring in the cases is disturbance wave flow recognized with visual observation except figure 5.10 (d) being ripple wave flow.

In disturbance wave flow, large disturbance waves appear intermittently among ripples. Disturbance waves contribute to arise power spectra as narrow strong peaks in lower frequency region than about 20Hz as indicated in figure 5.10 (a). Other peaks forming a broad distribution in the region higher than about 20Hz are also seen caused by ripples. This can be treated as a typical PSD distribution of disturbance wave flow. Similar trend is also seen in figures 5.11(a) and 5.11(b) obtained at larger liquid flow rate.

PSD shown in figures 5.10(b) and 5.10(c) is somewhat like the disturbance wave flow type, but no remarkable isolated peak in low frequency region is recognized here, because large waves are accelerated by fast gas flow to occur more frequently to shift

the peak to higher frequency region. This can be treated as a typical PSD distribution of annular dispersed flow, though the flow patterns determined by observation are disturbance wave flows. Similar trend is also seen in figures 5.11(c) and 5.11(d) obtained at larger liquid flow rate.

The flow pattern changes to ripple wave flow in the case of small liquid flow rate and large gas velocity, and lots of ripple becomes dominant waves covering whole part of liquid film instead of large disturbance wave. These ripples having small wave height and short wave length appear more frequently to maintain liquid film flow rate, therefore, power spectra of higher frequency waves becomes similar value to the lower frequency waves. Paras et al. [6,7] noted a similar spectra shift for liquid film in horizontal channel. The uniform or broad distribution of PSD seen in figure 5.10(d) will be called “ripple wave flow type” here.

5.4.3. Characteristics of Disturbance Wave and Ripple

Characteristics of waves on liquid film were obtained from the results of stationary reflector measured at a certain circumferential location. Disturbance waves were identified when the liquid film thickness is larger than three times of the mean film thickness and smaller than twice of the minimum liquid film thickness as illustrated in figure 5.12(a).

The width (duration time) of each disturbance wave was given by the time delay between these two edges. Wave height, Δh , was calculated as $\Delta h = f_{\max} - f_{\min}$. Here $f_{\max}$ is the maximum film thickness between front and rear edge of disturbance wave, and $f_{\min}$ is the minimum film thickness referring to 95% probability of liquid-phase existence in terms of the cumulative curve. Wave period was defined as the time duration between successive disturbance waves.

Ripples were identified with similar process described above, however, front edge of ripple was determined when the liquid film thickness is larger than mean film thickness and smaller than three times of mean film thickness. Rear end of ripple was determined by the same criterion of disturbance wave as illustrated in figure 5.12(b).

Characteristics of waves such as “height”, “width”, “passing number” and “period” obtained by wave averaging are plotted in left column of figure 5.13 for disturbance wave and right column for ripple. It is seen that mean wave height and mean wave width decrease with increasing gas velocity both for disturbance wave and ripple. Dependency of liquid flow rate is not obvious, but the characteristics seem to increase a little with increase of liquid flow rate.

The number of passing disturbance waves, to say passage frequency, seems to

decrease with increase of gas velocity as indicated in figure 5.13(c). The passage frequency of disturbance waves distributes at around 10Hz for higher gas velocity showing quantitative agreement with the work by Ohba et al. [8] and by Hagiwara [9], however its dependency on gas velocity does not necessarily show good agreement since the present work were carried in developing region.

It is clearly seen that number of passing ripple increases with increase of gas velocity as indicated in figure 5.13(g). Corresponding to this trend, mean wave period of ripple is shortened with j_g as shown in 5.13 (h).

It is also noted that there are waves having a time scale shorter than the scanning time of rotating reflector adopting in the USEM (The scanning time is 4msec for the experiments discussed in this chapter). The ratio of these waves is plotted in figure 5.14 against the total sample, indicating that about 20% of the disturbance waves for each experimental condition have time scales shorter than the scanning time. The ratio of the waves having shorter wave width than scanning time slightly becomes large with increasing gas velocity. This is because that the traveling velocity of disturbance wave becomes high and the wave width becomes small in this region. However, this result should not be a serious technical problem associated with the method proposed, since this particular issue will be much improved by adopting a higher rotation of the reflector and 20kHz emissions of the ultrasonic waves.

5.5. Summary

Liquid film thickness formed on outer surface of a vertically upward annulus tube simulating a nuclear fuel rod was measured by the USEM. The reconstructed three-dimensional images such as contour plots and bird's eye view graphics showed better understandings of liquid film behavior around tube. The results obtained by a rotating reflector agreed well with the results of a stationary reflector calibrated finely with electrical probe method.

The images clearly revealed that large disturbance wave keep stretch around tube periphery while it passes measuring position. More over, film thickness of disturbance wave is not necessarily constant in the span wise direction so as to have several crests.

Characteristics of waves, such as power spectral density distribution of the liquid film thickness fluctuations, wave height, wave width (duration time), wave period and number of passing waves, were obtained from time-trace of film thickness both for disturbance wave and ripple. Reasonable properties were indicated for wave height and wave width, however, number of passing disturbance wave showed somewhat different dependency of gas velocity due to the experimental setup, i.e., in the developing region of liquid film flow.

The USEM will be improved in the scanning time to more precisely detect disturbance wave that sometimes passes in short time less than scanning time.

References

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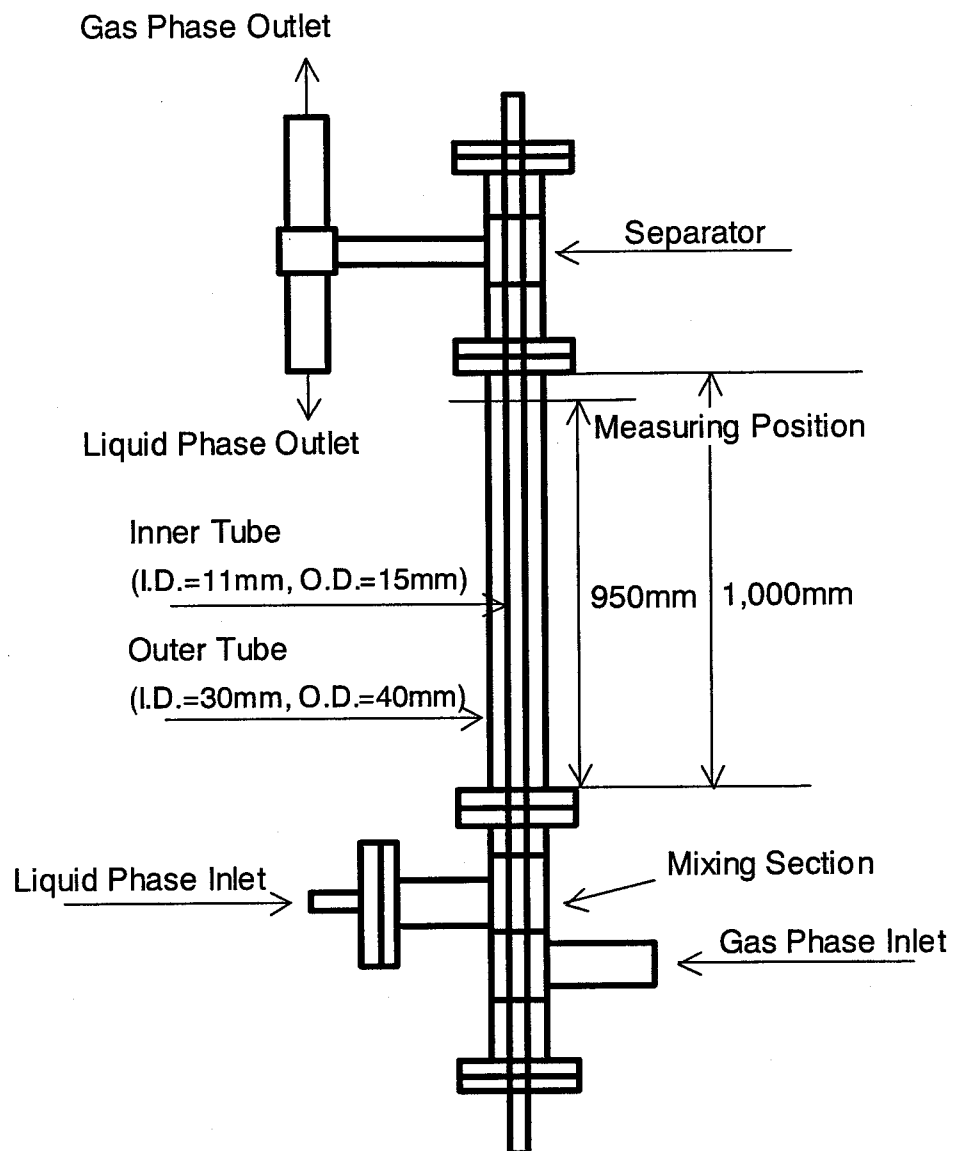
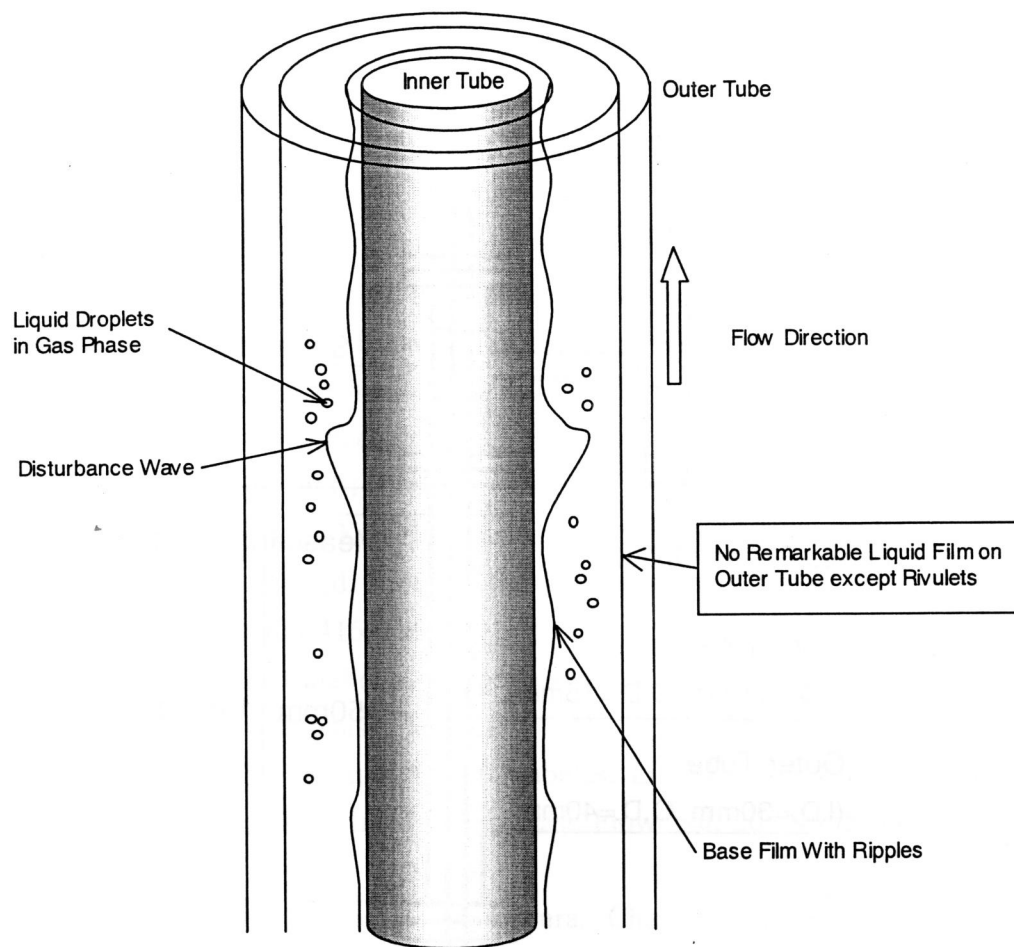
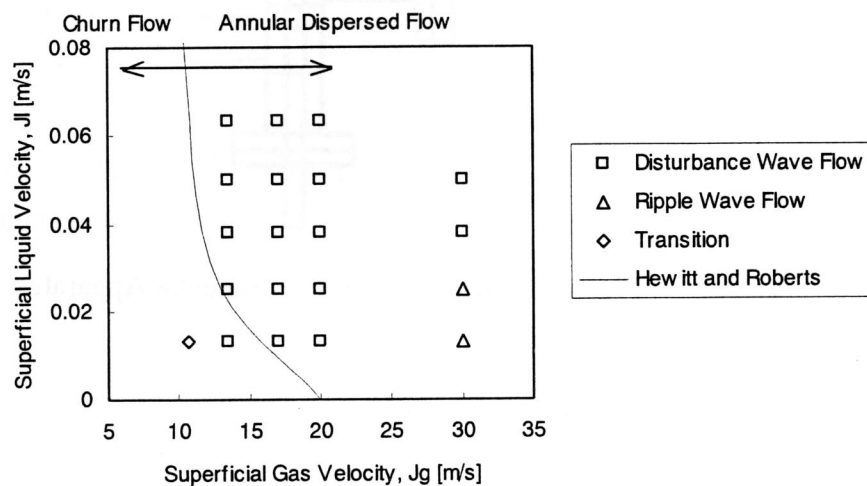


Figure 5.1 Schematic of Experimental Apparatus



(a) Liquid Film Structure



(b) Flow Pattern Map

Figure 5.2 Flow Pattern Defined in the Present Work

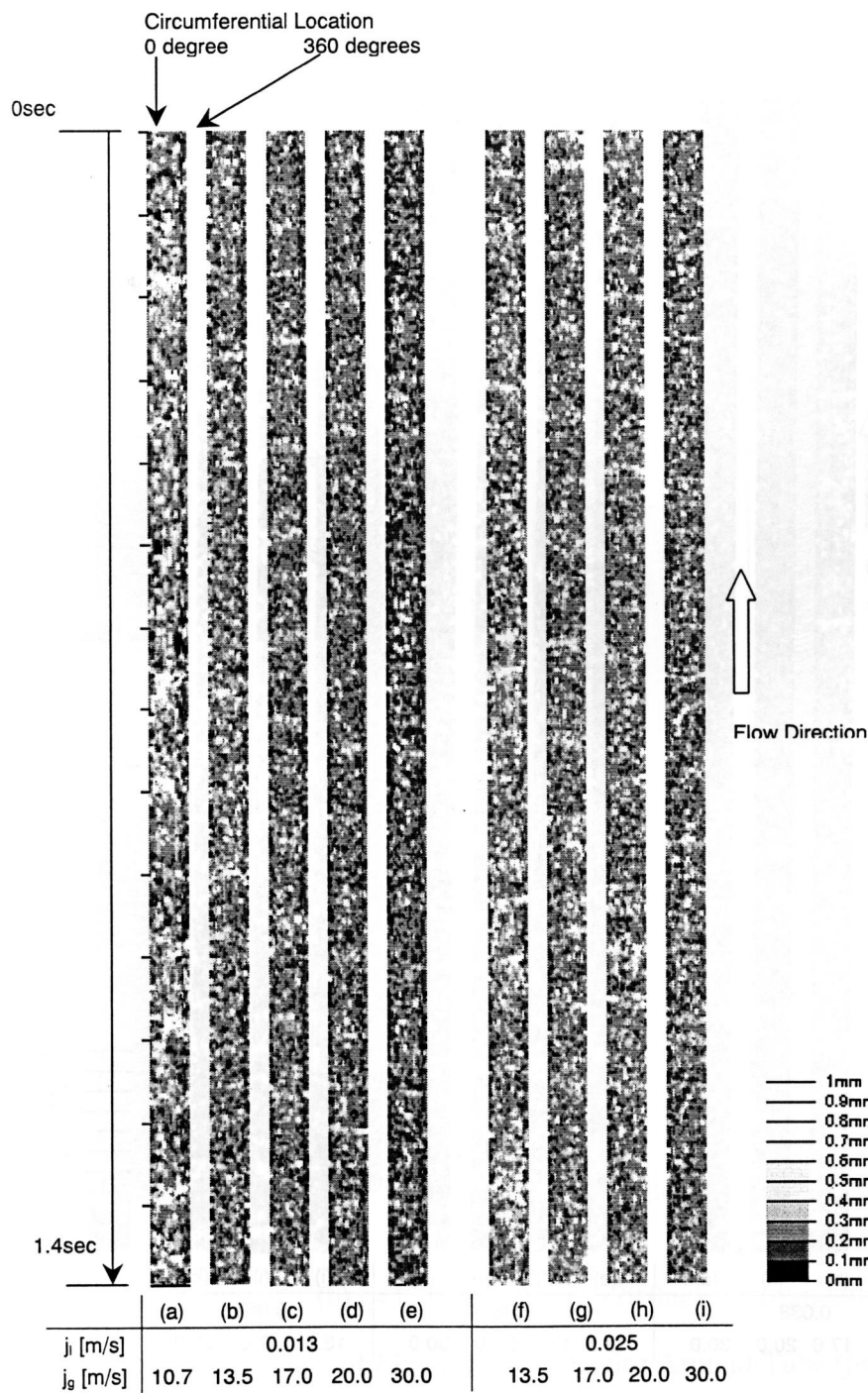


Figure 5.3 Contour Plot of Liquid Film Behavior Around Tube (1)

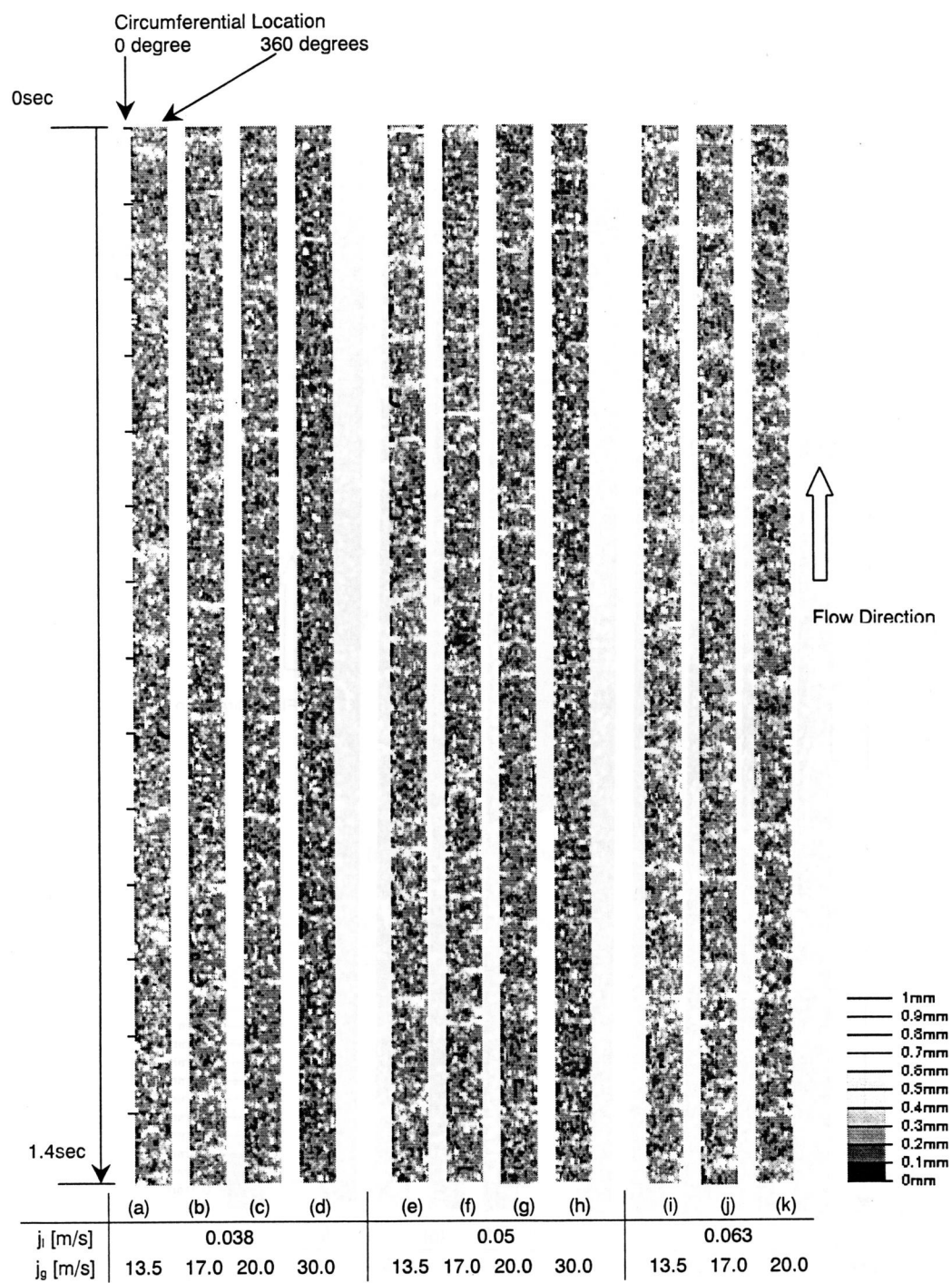


Figure 5.4 Contour Plot of Liquid Film Behavior Around Tube (2)

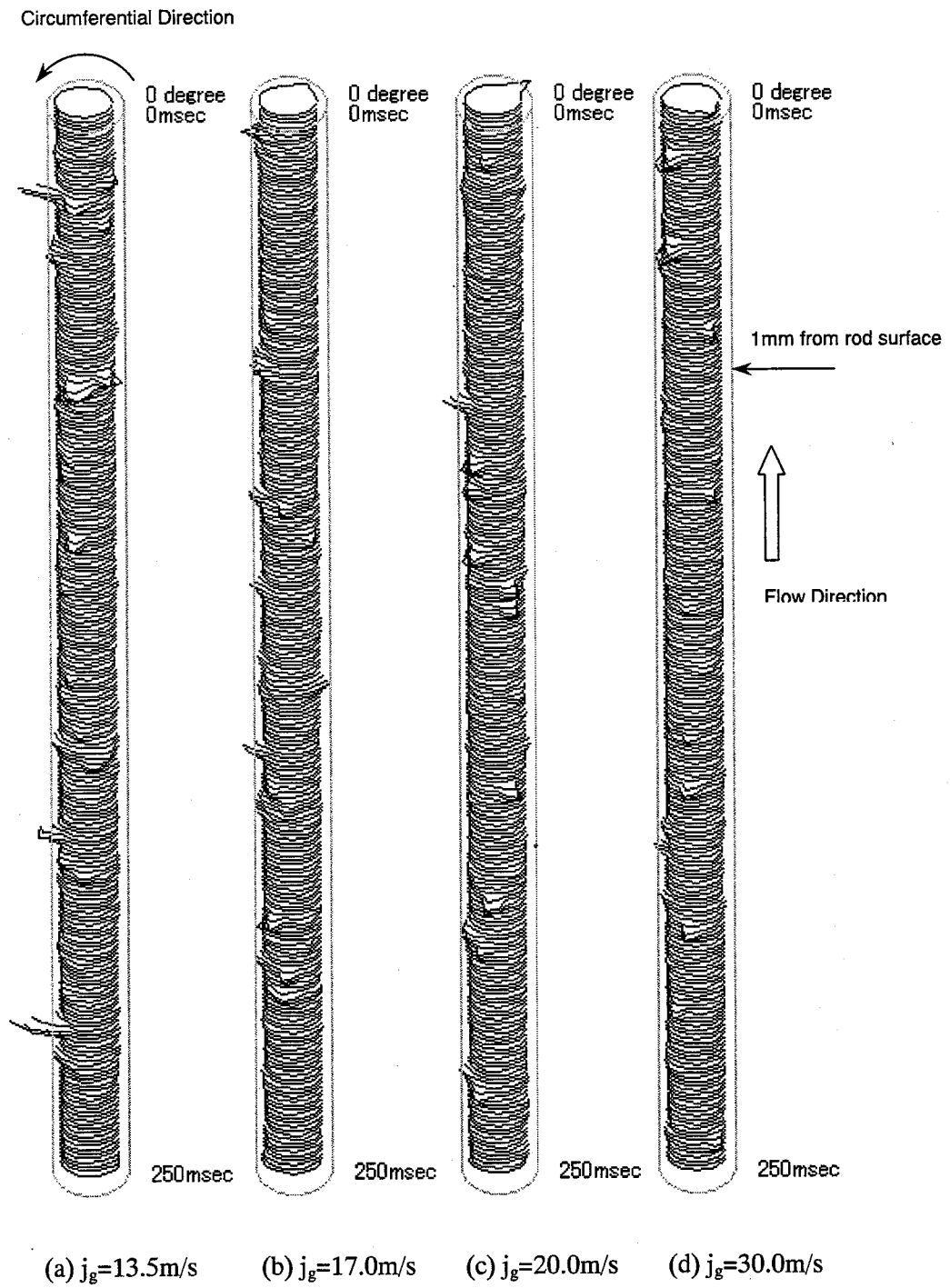


Figure 5.5 Bird's Eye View of Liquid Film Behavior Around Tube ($j_l=0.013\text{m/s}$)

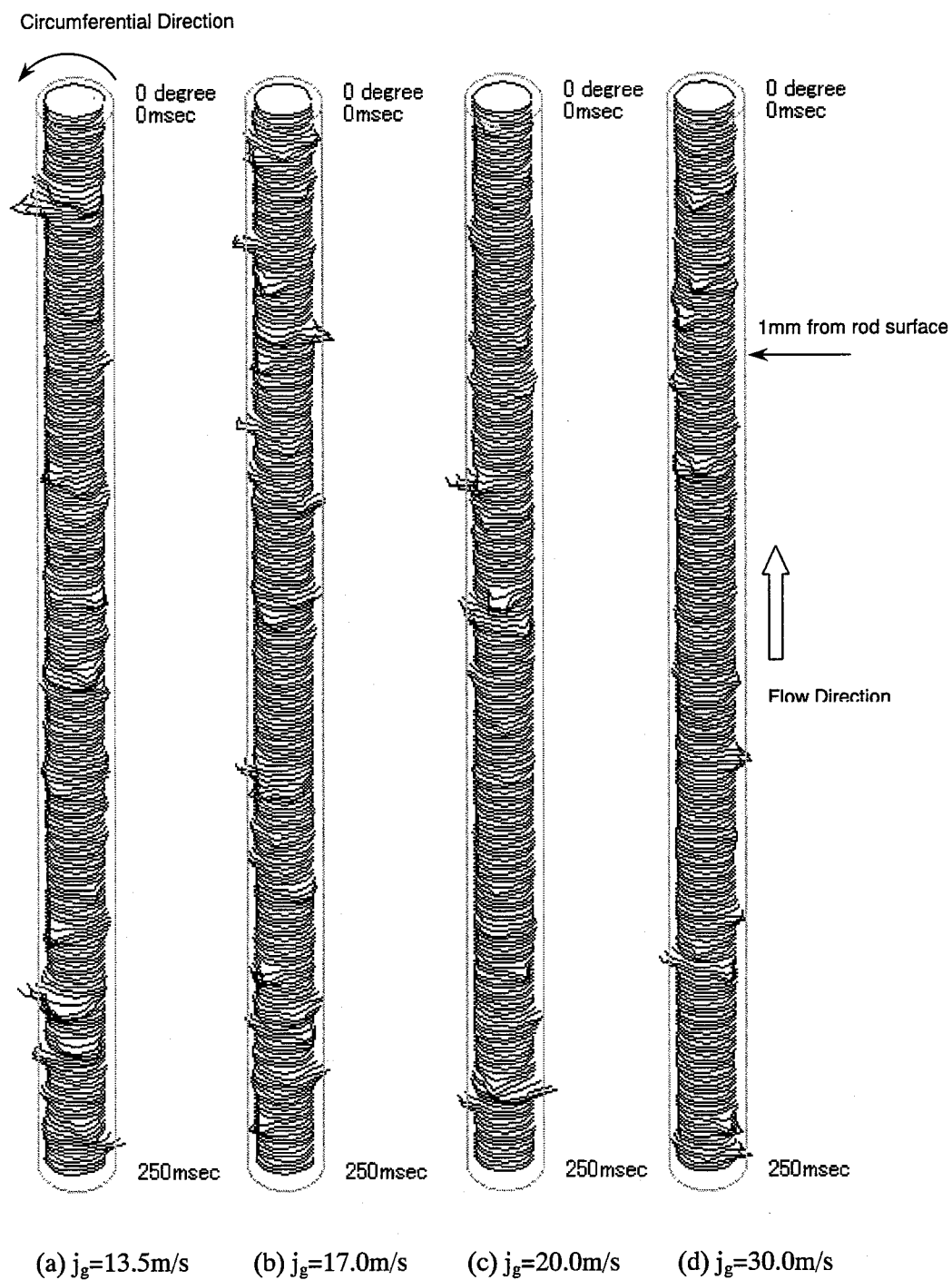


Figure 5.6 Bird's Eye View of Liquid Film Behavior Around Tube ($j_l=0.038\text{m/s}$)

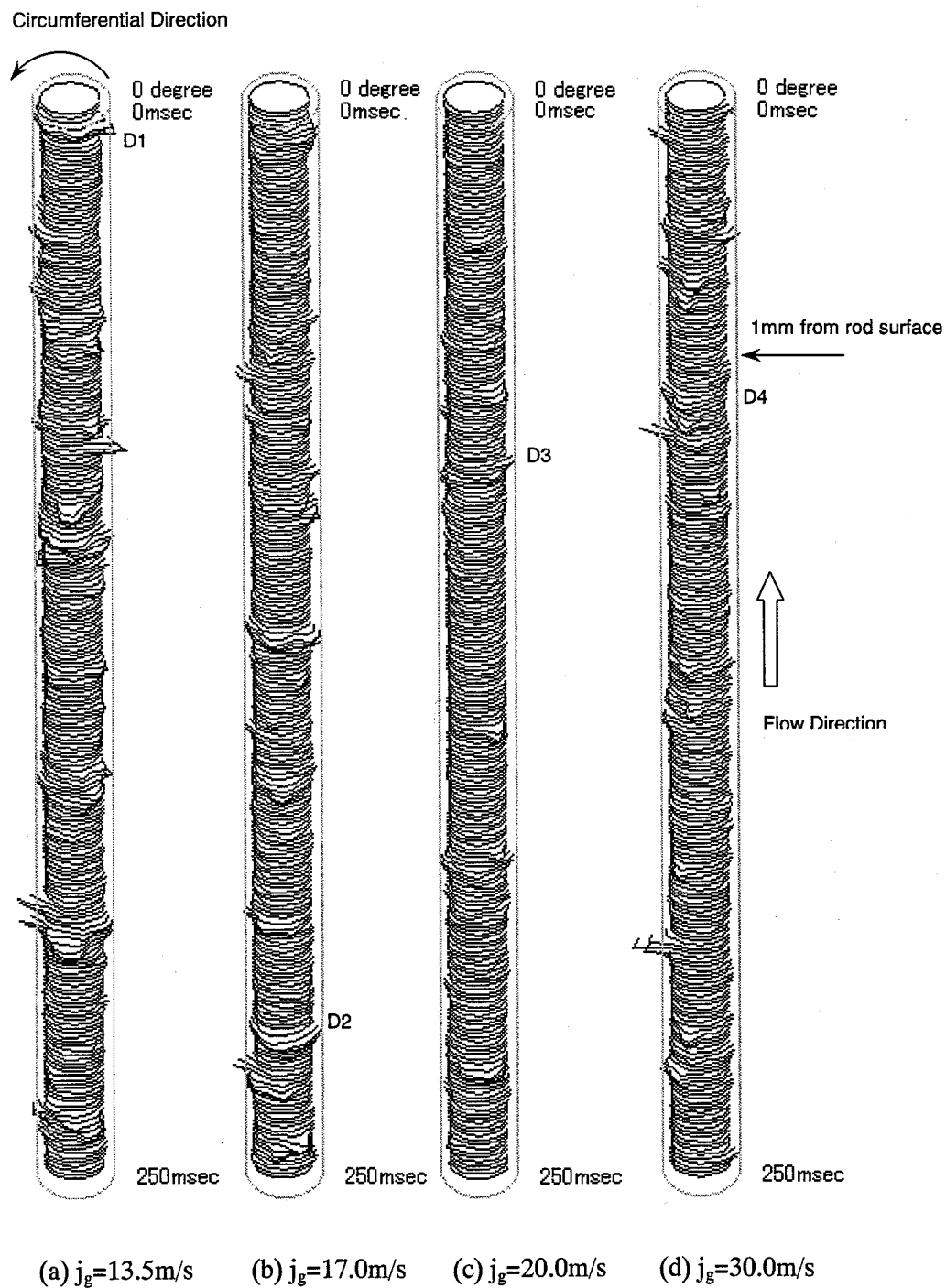


Figure 5.7 Bird's Eye View of Liquid Film Behavior Around Tube ($j_l=0.05\text{m/s}$)

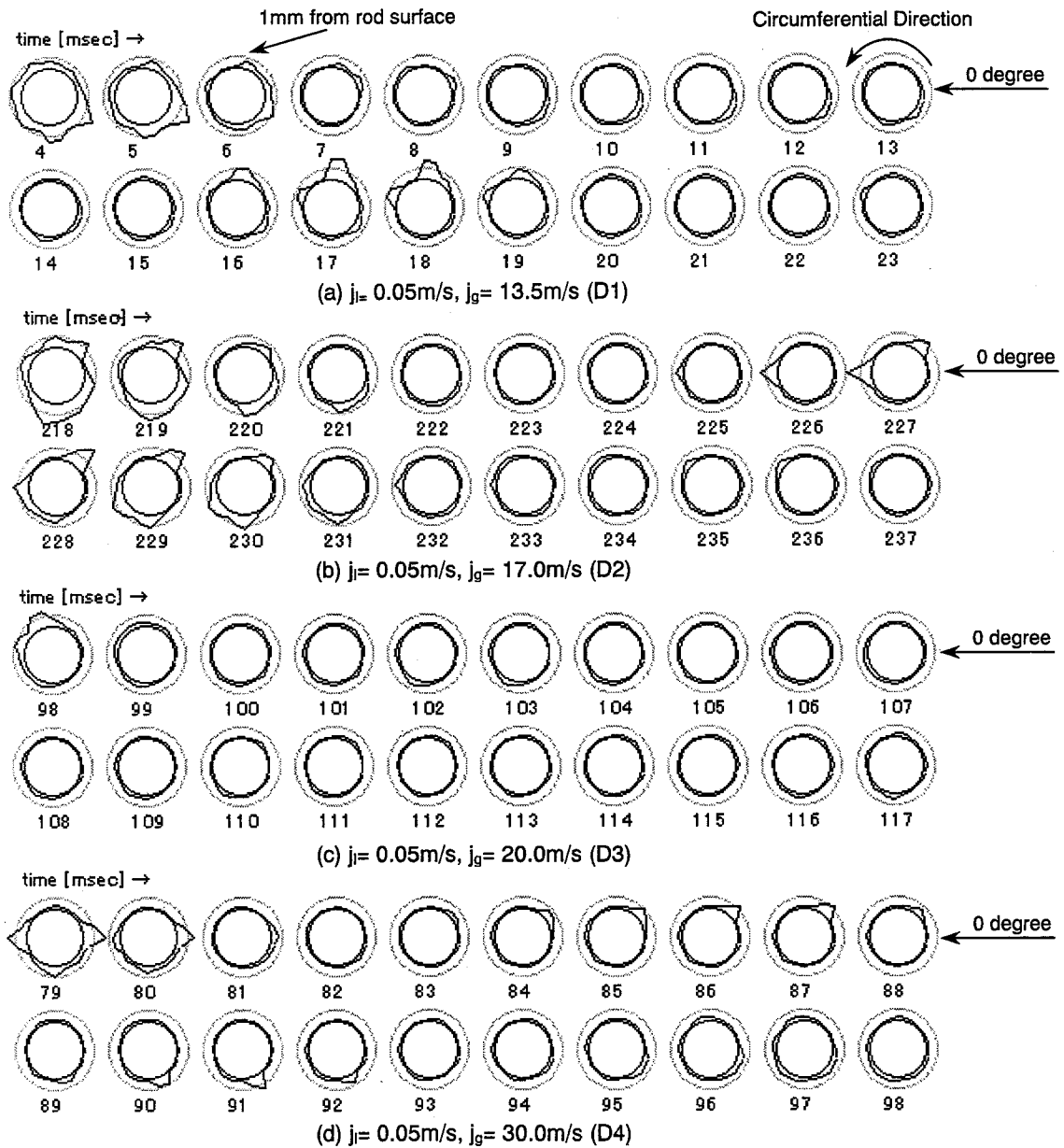
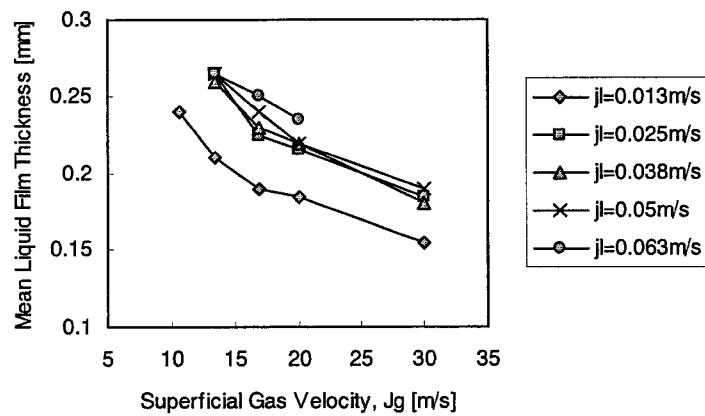
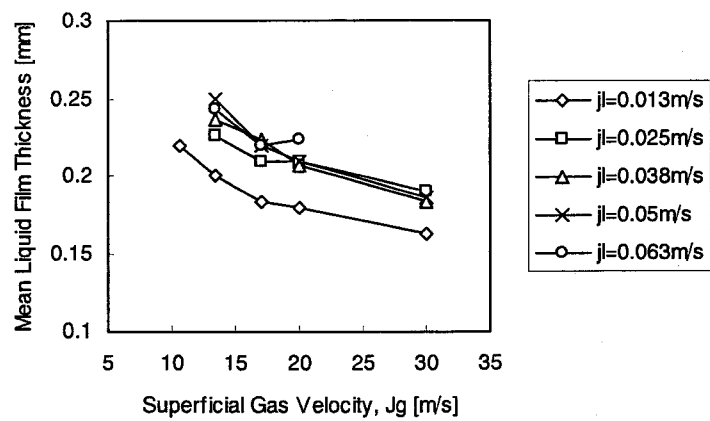


Figure 5.8 Cross-Sectional View of Large Disturbance Waves

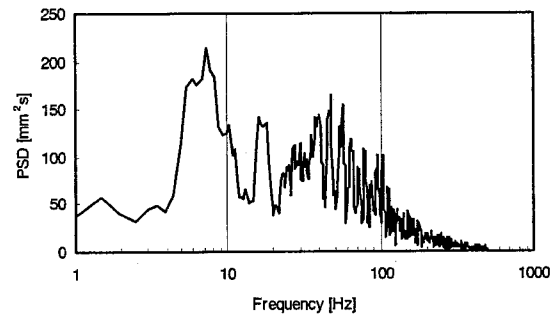


(a) Result of Stationary Reflector

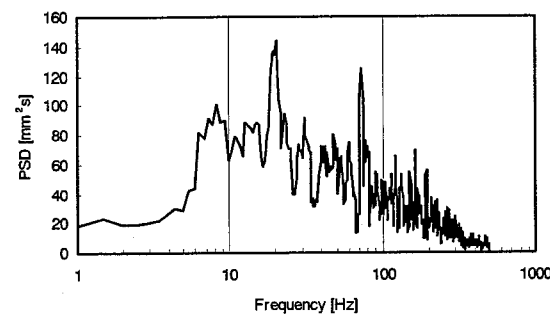


(b) Result of Rotating Reflector

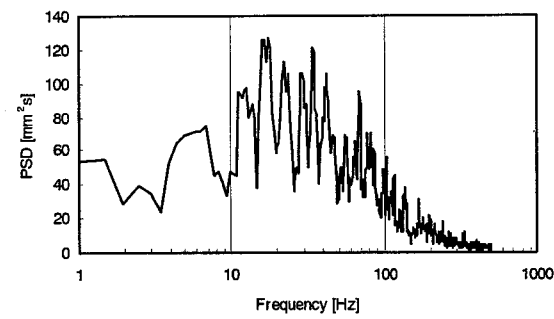
Figure 5.9 Time-Averaged Liquid Film Thickness



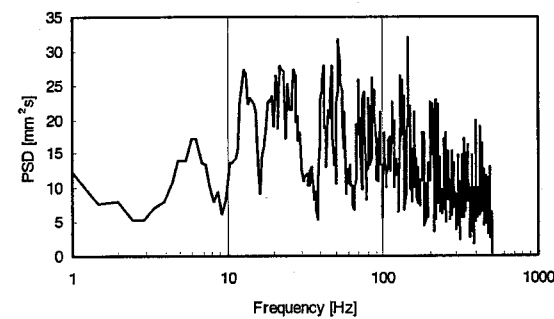
(a) $j_l = 0.013 \text{ m/s}$, $j_g = 13.5 \text{ m/s}$



(b) $j_l = 0.013 \text{ m/s}$, $j_g = 17.0 \text{ m/s}$

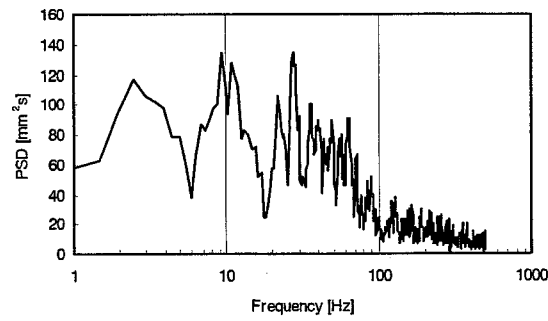


(c) $j_l = 0.013 \text{ m/s}$, $j_g = 20.0 \text{ m/s}$

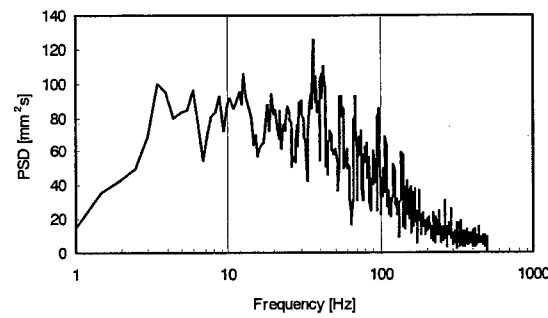


(d) $j_l = 0.013 \text{ m/s}$, $j_g = 30.0 \text{ m/s}$

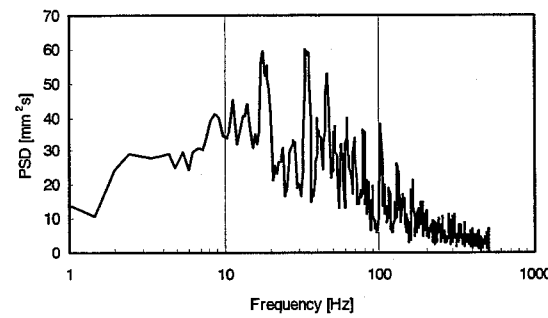
Figure 5.10 Power Spectral Density of Liquid Film Thickness Fluctuation



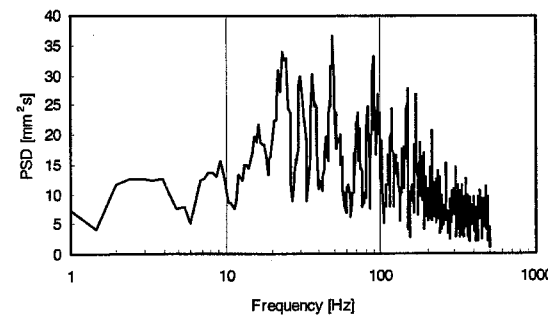
(a) $j_l = 0.05 \text{ m/s}$, $j_g = 13.5 \text{ m/s}$



(b) $j_l = 0.05 \text{ m/s}$, $j_g = 17.0 \text{ m/s}$

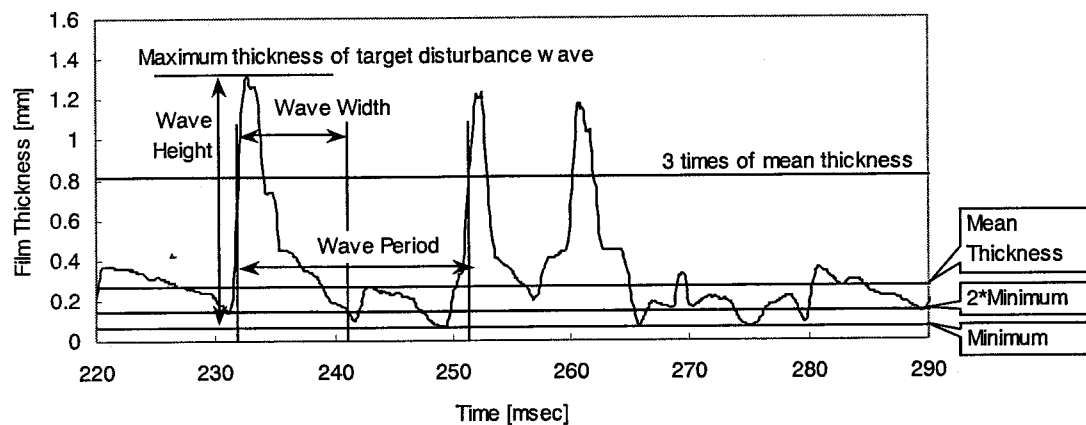


(c) $j_l = 0.05 \text{ m/s}$, $j_g = 20.0 \text{ m/s}$

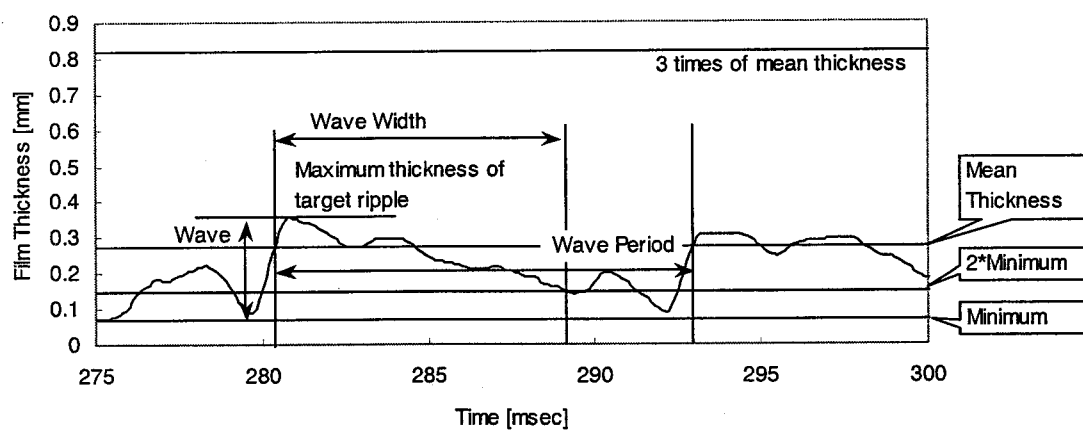


(d) $j_l = 0.05 \text{ m/s}$, $j_g = 30.0 \text{ m/s}$

Figure 5.11 Power Spectral Density of Liquid Film Thickness Fluctuation

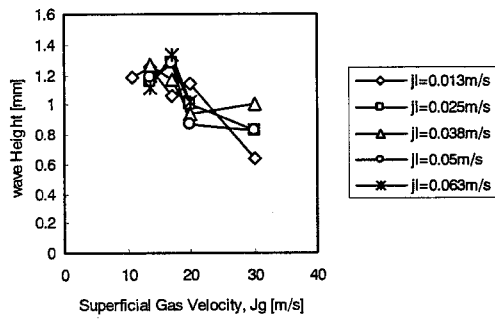


(a) Disturbance Wave

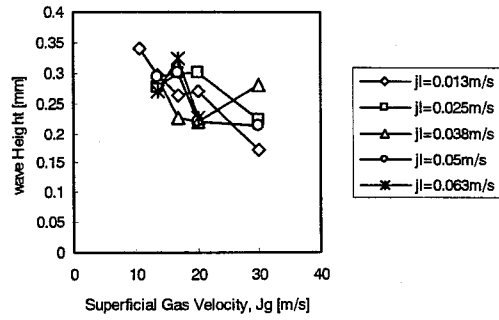


(b) Ripple

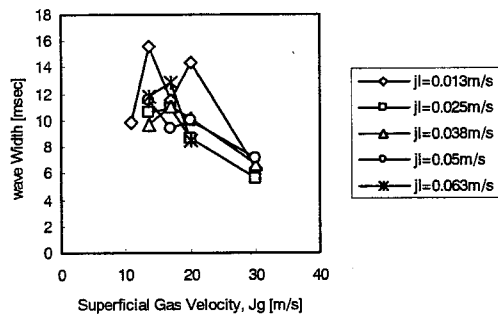
Figure 5.12 Determination of Wave Height, Width (duration time) and Period



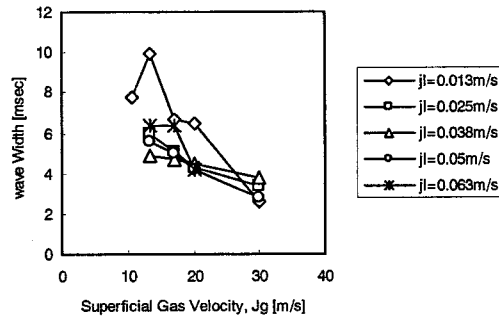
(a) Mean Wave Height of Disturbance Wave



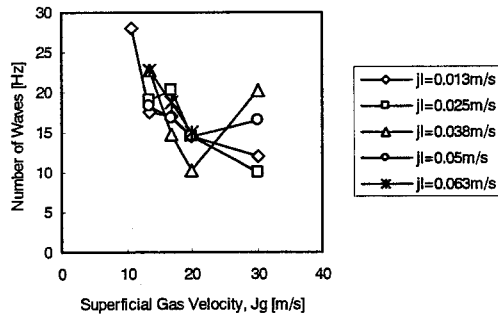
(e) Mean Wave Height of Ripple



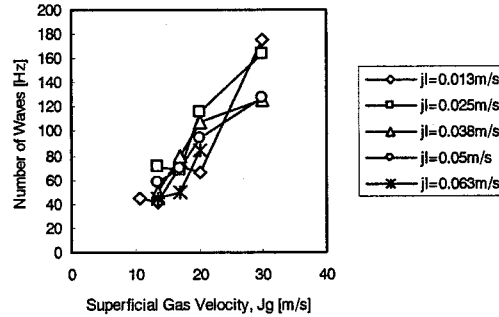
(b) Mean Wave Width of Disturbance Wave



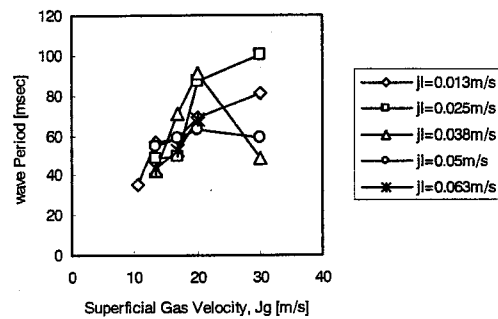
(f) Mean Wave Width of Ripple



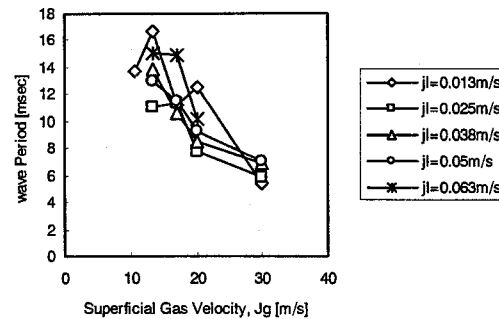
(c) Number of Passing Disturbance Wave



(g) Number of Passing Ripple



(d) Mean Wave Period of Disturbance Wave



(h) Mean Wave Period of Ripple

Figure 5.13 Characteristics of Waves

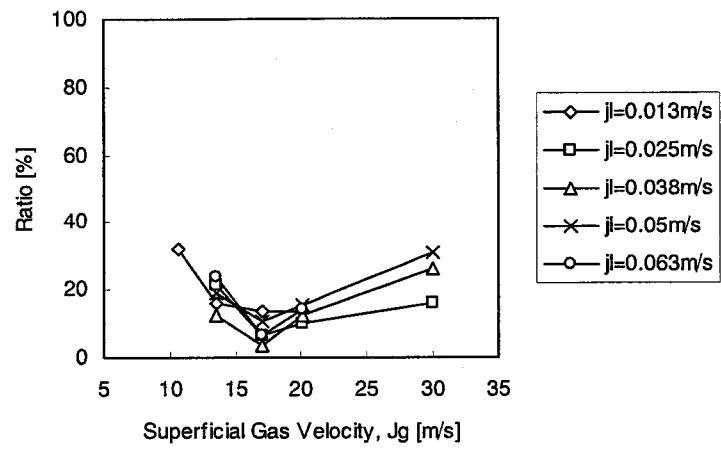


Figure 5.14 Ratio of the Disturbance Wave Shorter than the Scanning Time (4msec)

6. Characteristics of Liquid Film Flow in a 3×3 Rod Bundle with Spacers

6.1. Introduction

Nuclear fuel rod bundle is a complex geometry consisted of many fuel rods and clearance between each fuel rod is narrow by restriction of reactor core physics. Mechanical spacers are equipped to keep this clearance adequately; these spacers obstruct two-phase flow in turn. Thus time-dependent film flow structure is changes before and after these spacers.

Grid-Type spacer equipped in nuclear fuel rod assembly is expected to increase heat flux by several effects such as enhancement of coolant flux near the spacer, turbulence or mixing by turning vane. Yao et al. [1,2] clarified heat transfer mechanism governing liquid droplet flow after CHF theoretically and conducted heat transfer estimating equation. They considered spacer effects to increase phase velocity near spacer and local characteristics of heat transfer at upstream and downstream of spacer. Choi et al. [3] revealed with experimental results that spacer grid was effective on heat removal from nuclear fuel rod in case of LOCA. Liquid droplets collide against non-heated spacer grid and then turbulence is increased by their evaporation. Nishida et al. [4] studied experimentally about spacer effects giving to liquid film flow using full-size mock-up of BWR fuel rod assembly. Characteristics of liquid film flow before and after spacer was measured at corner rod, outside rod and inside rod. They confirmed that liquid film thickness decreased after spacer because of narrow flow channel, and liquid film thickness became thicker at corner rod than other locations. Kanazawa et al. [5] developed a numerical simulation code taking consideration in droplet deposition after spacer to calculate liquid film dryout phenomenon in annular dispersed flow in fuel rod assembly. In this model, liquid film gradually becomes thin to be dryout while it flows downstream.

Fukano et al. [6] observed two-phase flow in a circular tube to experimentally clarify effect of spacer on CHF in BWR fuel rod assembly. Dry-patch occurred in

limited area upstream of spacer gap and this dry-patch was immediately disappeared by passage of large wave. Nishida et al. [7] classified spacer effects on downstream liquid film flow into two types from results of liquid film thickness measurement near spacer in 4×4 and 9×9 simulated fuel rod bundle. The first one was droplets deposition / entrainment enhancement effect due to increasing of gas turbulence. The second one was droplets deposition / entrainment enhancement effect generated by direct contact of liquid film to spacer board. They discussed about spacer-pitch dependence to critical power with the first spacer effect model.

Kanazawa et al. [8] studied about droplet behavior and turbulence intensity around spacer of BWR fuel rod assembly using film flow model for subchannel analysis. Liquid droplets tend to deposit further location with increase of droplet diameter, for example, deposition coefficient for 10μm droplet is half of 50-100μm droplets. Droplet deposition coefficient had maximum value just behind spacer downstream edge.

Kanazawa et al. [9] developed a critical power estimation method adopting three-dimensional analysis of jet flow on droplet behavior to obtain droplet deposition coefficient originated by spacer. Their results showed that droplet deposition characteristics to fuel rod of circular cell type spacer was different from that of grid type spacer and that droplet deposition characteristics was changed between fuel rods in the same subchannel because of flow tab effect. They analyzed critical power both in BWR 8×8 simulating fuel rod bundle and in ATR 36 cluster simulating fuel rod bundle using obtained droplet transfer coefficient, estimation accuracy of critical power was improved.

Concerning heat transfer depletion in BWR, Yano et al. [10] measured entrainment and deposition rate in downstream region of fuel spacer for low-pressure air-water two-phase flow. There were two different types of droplet deposition in response to gas phase velocity, i.e., liquid droplet entrained near spacer deposited far downstream of the spacer for small gas velocity, on the other hand, entrained droplet deposited rapidly to very near area of the spacer for large gas velocity. Yamamoto et al. [11] analytically estimated fuel rod spacer effect to BWR critical power with different spacer geometries.

Specifications of BWR fuel rod spacer strongly affects on critical power and core thermal hydraulics. Spacer had been developed based on experiences thus a lot of experimental data was required. Yano et al. [12] investigated spacer shape effects on droplet deposition rate toward downstream of liquid film flow in open rectangular channel for air-water two-phase flow, and proposed a physical model to explain deposition rate shift toward downstream of flow. Nishida et al. [13] reported experimental and analytical results of annular dispersed flow in BWR. They developed

a spacer model for subchannel analysis based on experiments and discussed about droplet diameter and spatial distribution.

Concerning with these works, time-dependent spatial distributions of liquid film thickness in a simulating 3×3 rod bundle was measured by the USEM, and the results about the liquid film behavior around spacer will be discussed in this chapter.

6.2. Experimental Apparatus and Conditions

Experimental facility used in this work is shown in figure 6.1. The test section is a 1,300mm long, 57mm wide rectangular duct having 4 corners of 10mm radius. 9 tubes of 15mm diameter are equipped inside the main channel that simulates nuclear fuel rods. Both parts are made of acrylic resin to allow visual observation. 3 circular ferrule type spacers locating at 500mm intervals from the inlet section support these tubes. The lower end of the tube is connected to a porous metal tube in order for the liquid phase (water) to flow into the test section. The air was fed into the test channel from each side of the wall to form liquid film flow on the inner tubes. Air and water were used as working fluids. Gas-liquid mixing section was constructed as shown in figure 6.2.

Detail of the spacer shape is illustrated in figure 6.3. The spacer consists of 30mm long 9 cells and a same length bounding board. Each cell has 18mm outer diameter. Both cells and bounding board have 0.5mm thickness, thus the clearance between tube surface and spacer surface is 1mm. They have 4 dimples and 1 spring inside for keeping clearance between rod and spacer tube. The bounding board has 2 guide boards on its all sides to keep the clearance between the spacer and the main channel constant.

Measurements were carried out for center, side-center and corner rods around the third spacer ranging between 30mm upstream and 80mm downstream from the spacer center. Two-phase flow can be considered being free from effects of the mixing section. Minimum interval in axial direction was 1mm. Measuring locations in the upstream region is represented as minus value so to be 0mm at center of the spacer. Thus front edge of the spacer is -15mm and rear edge is +15mm. Supporting pole of measuring device was set as shown in figure 6.4 to determine 0 degree in circumferential direction. Rotating direction of the reflector is counter-clockwise from top view of flow channel. Flow conditions were set as shown in table 6.1. Superficial gas velocity was constant at 16m/s, and superficial liquid velocity was changed from 0.02m/s to 0.04m/s. Droplet entrainment rate is estimated being about 6% by Wallis's equation [14] under present flow condition, thus it is smaller than that of the normal BWR operating condition (about 50%). Flow pattern of every flow conditions was annular dispersed flow. All experiments were carried out under ambient temperature and atmospheric pressure.

Data Name	j_g	j_l
Set 1	16 m/s	0.04 m/s
Set 2	16 m/s	0.03 m/s
Set 3	16 m/s	0.02 m/s

Table 6.1 Flow Condition

6.3. Overview of Dynamic Behavior of Liquid Film Flow

Figures 6.5-6.10 show time-dependent dynamic behavior of liquid film flow around rod as contour plots. The thick parts are indicated with bright color and thin parts are colored with dark color. The elevation of various waves was divided into 10 intervals. Each contour image displays time sequence between 0 sec and 1.4 sec from top to bottom, circumferential distribution from 0 degree to 360 degrees from left to right. Images from left to right hand side in each page present evolution of liquid film flow in axial direction. Outline of the liquid film behavior will be described here.

Figure 6.5 shows results of center rod of set1. Liquid film thickness tends to be relatively large and fluctuate moderately in upstream region of spacer. Circumferential difference of liquid film thickness seems to be small in this region. Two-dimensional large waves are also observed, but their appearing frequency is less than that of annulus channel experiments of similar flow condition shown in chapter 5, i.e., liquid film surface is much smoother. Several contour plots, for example at -20mm , have streaks at where similar liquid film thickness appears continuously in time sequence at the same circumferential location. Such a streak was not observed at all in the annulus channel experiments.

In spacer region between -15mm and $+15\text{mm}$, liquid film thickness apparently becomes thinner than that of in upstream region. Two-dimensional large waves appear distinctly and more frequently. Some large waves have 1mm thickness being same to rod-spacer clearance indicating formation of liquid bridge between rod surface and spacer. Streaks of liquid film are also seen in spacer region for example at -8mm and so on. However, their appearing positions in circumferential direction are different from the cases in upstream region.

Liquid film thickness recovers in downstream region of the spacer at $+19\text{mm}$. Frequency of two-dimensional large waves seems to decrease. Streaks are also observed in this region but span and duration time of these streaks are different from those of in upstream region and spacer region. Liquid film behavior becomes nearly same behavior to that in upstream region of the spacer at $+80\text{mm}$.

Figure 6.6 shows results of center rod of set3. Surface of liquid film seems to be covered with more and smaller waves than the case of set1. Streaks are seen before the spacer at -16mm . Liquid film thickness becomes thin in spacer region as same as the result of set1, however, two-dimensional large waves are not remarkably observed with this flow condition. Streaks also appear in spacer region at the same circumferential locations of set1. Liquid film thickness recovers at $+16\text{mm}$ that is nearer to the spacer

than the recovering position of set1 being at +19mm. Liquid film thickness tends to be large between +20mm and +60mm. Streaks appear in downstream region of the spacer at almost the same locations in circumferential direction and axial direction of set1.

Results of side-center rod are shown in figures 6.7 and 6.8 of set1 and set3, respectively. Though outline of liquid film behavior is similar to the case of center rod, they indicate that some of circumferential locations of streaks to appear are different from the results of center rod at the same axial locations.

Figures 6.9 and 6.10 show results of corner rod of set1 and set3, respectively. Liquid film thickness also has a similar trend to the results of center rod and side-center rod in axial direction, i.e., liquid film thickness decreases in spacer region and recovers after the spacer.

Figure 6.13(a) is a photographic image of liquid film flow in upstream region of the spacer obtained under $j_g=10\text{m/s}$ and $j_l=0.017\text{m/s}$. It can be seen that liquid film surface is relatively smooth in this region. Figure 6.13(b) shows liquid film behavior in downstream region of spacer indicating that liquid film surface becomes much rougher than that in upstream region of spacer and has a liquid accumulation at very limited area after the spacer.

Liquid film thickness distribution around center rod of set1 was represented as bird's eye view graphics in figure 6.11. It is apparently seen that the liquid film surface is much smoother than the results of annulus channel experiments as mentioned before. Peripheral profiles of liquid film thickness are demonstrated in figure 6.12 for center rod of set1. 20 profiles are reconstructed with 1msec interval. Right hand side of each profile is the location of supporting pole of measuring device. It is recognized here that some profiles show contact of liquid film to the spacer cell.

6.4. Results and Discussions

6.4.1. Cross-Sectional Averaged Liquid Film Thickness

In order to understand the liquid film behavior in axial direction, cross-sectional averaged liquid film thickness is plotted in figure 6.14. It reveals a general trend of liquid film thickness evolution as described in the previous section, to say, appearance of film thickness peak just before and after the spacer, decreasing of thickness in spacer region and recovery of film thickness in downstream region of spacer. Nakao et al. [15] and Hoshide et al. [16] also reported a similar trend of liquid film thickness distribution before and after a lattice type spacer in a 3×3 rod bundle using a circular electrode around rod. Decreasing of liquid film thickness in spacer region is caused by acceleration of liquid film velocity since interfacial shear stress is increased by acceleration of gas velocity due to reduction of channel cross-sectional area. Assuming constant liquid flow rate, liquid film is thinning with higher film velocity. Liquid film thickness of center rod seems to be smaller than the cases of other rods since gas velocity around center rod is higher than other rods. Nakao et al. [15] demonstrated vivid difference of film thickness among rods in 9×9 rod bundle measured under relatively large liquid flow rate $j_l=0.09\text{m/s}$ and small gas velocity $j_g=13\text{m/s}$. Liquid accumulation demonstrated in figure 6.13(b) is clearly shown in figure 6.14, too. Details of formation of peaks and recovery of liquid film thickness in downstream region of spacer will be discussed later.

6.4.2. Longitudinal Evolution of Time-Averaged Liquid Film Thickness

Appearance of liquid streaks observed in contour plots at several axial and circumferential locations indicates that time-averaged liquid film thickness changes around rod periphery. Concerning with this, longitudinal evolution of time-averaged film thickness at every 15 degrees is plotted in figures 6.15-17 for every rod. Measuring locations in axial direction are expressed with dots at 0 degree.

Figure 6.15 shows results of center rod. This figure distinctly shows that liquid film thickness distributes inhomogeneous way in circumferential direction at several axial locations. This tendency seems to be caused by geometrical structures such as spacer cell and rod arrangement, since this trend does not mostly depend on flow condition. Pay attention to inside of spacer, there are peaks at 90 degrees of 0mm, at 225 degrees of -10mm and +12mm, at 315 degrees of -10mm and +12mm.

Relation of projections, to say dimples and spring, and time-averaged film thickness is shown in figure 6.18(a). It is clearly seen that peaks of liquid film thickness

in spacer region are corresponding to these projections. Figure 6.18(b) shows effects of projections on liquid film. Dimple is a hemispheric shape having about 1.5mm radius around contact point, thus liquid film stagnates around dimple by surface tension and increases its thickness so as to form liquid streaks in spacer region. Since radius of curvature of dimple is small, liquid film quickly leaves dimple and forms waves or droplets behind dimples. Spring also plays a similar role on liquid film. Spring has 10mm length and 3mm width therefore liquid film stays in a much longer distance around spring than around dimples. If dimples and spring do not tightly contact rod surface or if spring made of a thin metal is distorted to have small gap between them and rod, liquid film can intrude into the gap as illustrated in figure 6.18(b) and liquid film thickness will be given at these contact points.

Figure 6.16 shows results of side-center rod. It is clear that liquid film thickness has peaks at dimples in spacer region. The effect of spring is not apparently seen from this figure because liquid film thickness could not be measured around 0 degree due to existence of supporting pole. Results of corner rod shown in figure 6.17 also reveal the effects of projections in spacer region.

6.4.3. Circumferential Distribution of Time-Averaged Liquid Film Thickness

In order to detect the positions of peaks around rod, circumferential distribution of time-averaged liquid film thickness at every axial location is represented in figures 6.19-6.21.

Figure 6.19 shows results of center rod. It can be seen that liquid film thickness almost uniformly distributes in upstream region of spacer, however, ununiformity of liquid film thickness strongly appears just before the spacer for example at -20mm. Liquid film thickness seems to be large at $90 \times i + 45$ degrees ($i=0-3$) in a systematic way. This ununiformity remains in spacer region until about -13mm and then disappears except effects of projections.

Ununiformity of liquid film thickness appears again in downstream region of spacer, however, it is not so systematic as seen in upstream region of spacer, and appearing peripheral location and height of peaks changes in axial direction. Roughly speaking, liquid film thickness seems to be large at $90 \times i$ degrees ($i=0-3$) between +20mm and +60mm. This ununiformity weakens at +80mm.

Results obtained by stationary reflector at 0 degree and 315 degrees are also plotted by assuming symmetrical distribution in every 45 degrees in figure 6.15(b). These results correspond well to the results of rotating reflector in upstream region of spacer indicating a symmetrical distribution of liquid thickness around center rod. On

the other hand, some of assumed plots of stationary reflector are different from the results of rotating reflector in spacer region, for example at 90 degrees, and in downstream region of spacer. This disagreement seems to be caused by geometrical structures, since the difference in spacer region is clearly occurring at the spring.

Figure 6.20 shows results of side-center rod. Liquid film thickness has fairly flat distribution in upstream region of spacer. Ununiformity also appears just before the spacer as we saw in the results of center rod but only two peaks are apparently seen here at 45 degrees and 135 degrees.

In spacer region, liquid film thickness distributes very uniformly except around projections. Ununiformity of liquid film thickness appears again in downstream region of spacer but positions of peaks near spacer edge are different from the case of center rod though similar trend is seen in farther downstream region of spacer between +40mm and +80mm. Results of stationary reflector obtained at five different circumferential locations mostly agree with the results of rotating reflector.

Figure 6.21 shows results of corner rod. Circumferential distribution in upstream region of spacer is relatively flat though it somewhat undulates. Ununiformity strongly appears just in front of the spacer but the positions of peaks appearing at 135 degrees and 315 degrees are different from the results of center rod and side-center rod. The peak at 135 degrees continues into spacer region, on the other hand, the peak at 315 degrees immediately disappears at spacer edge.

Liquid film thickness distributes almost uniformly in spacer region except dimples and spring showing a same trend of center rod and side-center rod. Ununiformity of liquid film thickness distribution appears in downstream region of spacer again but positions of peaks near spacer edge are different from those of center rod and side-center rod. Results of stationary reflector obtained at five different circumferential locations agree very well with the results of rotating reflector.

6.4.4. Ununiformity of Liquid Film Thickness Distribution Around Rod

Ununiformity of liquid film thickness around rod shown in figure 6.22 was given as follows,

$$(\text{Ununiformity of Film Thickness}) = \frac{\sum_{i=0}^{23} |f_{mean}(i) - f_{mean}|}{f_{mean}} \times 100 \quad (6.1)$$

where f_{mean} is cross-sectional averaged film thickness, $f_{mean}(i)$ is time-averaged film thickness at every circumferential location, i is number of circumferential location so

as to divide the rod periphery, 360 degrees, into 24 locations with 15 degrees.

Ununiformity of liquid film thickness is about 5~10% in upstream region of spacer and has a peak of about 17% around front edge of spacer. It decreases to be about 5~10% in spacer region except projections area. It has a large peak again around rear edge of spacer and then it has the minimum at very limited area of +19mm or +20mm. After this minimum location, ununiformity of liquid film thickness becomes large again and then gradually decreases. From these points of view, it can be said that liquid film thickness does not necessarily distribute uniformly in circumferential direction and the ununiformity changes in axial direction.

6.4.5. Time-Averaged Liquid Film Thickness in Upstream Region of Spacer

As we discussed up to here, it is seen that geometrical structures such as spacer cell and rod arrangement affect liquid film behavior both in axial and circumferential direction. To study more in detail, longitudinal evolution of film thickness at every 45 degrees in upstream region of spacer is plotted in figure 6.23.

Figure 6.23(a) shows results of center rod. No significant trend of liquid film thickness evolution is observed between -30mm and -20mm, but remarkable tendency is seen between -20mm and -16mm, to say, liquid film thickness largely increases at $90^\circ + 45^\circ$ (i=0-3) while increasing of liquid film thickness at 90° (i=0-3) is kept in small. Mechanism to realize this difference can be considered as follows. Figure 6.24 shows this consideration.

Gas velocity profile around rod in a 3×3 rod bundle will be inhomogeneous since cross-sectional area changes in circumferential direction. As shown in figure 6.24, A-A cross-section at where two rods facing each other has narrow clearance to be 3mm, and B-B cross-section at where rod surface is facing to gas main flow has wide clearance to be about 10mm. Therefore, gas velocity in wide clearance will be larger than that in narrow clearance. This causes difference of interfacial shear stress to generate liquid droplets from liquid film, in turn, amounts of liquid droplets transported to rod surface before the spacer will be more at the wide clearance, to say B-B cross-section, and then liquid film thickness will be largely increased.

In addition, gas velocity is reduced in front of the spacer since spacer cell obstructs gas flow, in turn, driving force of liquid film weakens and then liquid film thickness increases both at A-A and B-B cross-sections. However, this contribution for increasing liquid film thickness seems not so great compare to the effect of droplets deposition as long as shown in figure 6.24.

Liquid film thickness gradually decreases from -16mm to inside spacer at every

circumferential location due to acceleration of gas flow by reduction of flow area. Liquid film thickness is somewhat large inside of spacer at A-A cross-section, for example at 225 degrees, because large amounts of droplets flow into spacer region and deposit on liquid film.

Figure 6.23(b) shows results of side-center rod. Difference of liquid film thickness around rod is small between -30mm and -20mm . Large increasing of liquid film thickness before the spacer seems to happen only at 45 degrees and 135 degrees, while liquid film thickness is enlarged a little at 225 degrees and 315 degrees though these locations have analogical geometry around rod. As illustrated in figure 6.4, the angles of 45 degrees and 135 degrees face to the main flow where gas velocity is high, on the other hand, the angles of 225 degrees and 315 degrees face to the near wall sub-channel, thus liquid droplets concentration will be larger for the former locations than the latter cases. Concerning with the discussion of center rod, large amounts of droplets will increase liquid film thickness greatly just before the spacer at 45 degrees and 135 degrees for side-center rod.

Figure 6.23(c) shows results of corner rod. Locations in circumferential direction at where liquid film thickness largely increases are 135 degrees and 315 degrees. The angle of 135 degrees faces to the wide clearance where gas velocity is high enough to entrain a lot of droplets to form a peak of film thickness at the spacer edge. Liquid film thickness inside of spacer is also kept large due to continuous deposition of droplets. In contrast with this, the angle of 315 degrees faces to the corner sub-channel at where gas velocity is considered to have the smallest value in whole cross-section of channel, thus, droplets concentration seems to be small. Other difference seen between 135 degrees and 315 degrees is decrease of liquid film thickness inside of spacer.

It rapidly decreases at 315 degrees indicating that liquid droplets accompanied in gas flow at this angle are little. Thus, it can be considered that liquid film thickness is locally increased in front of spacer edge mainly because of the highly decelerated gas velocity due to the large thickness of spacer at this angle being 1.0mm as a summation of spacer cell and bounding board. This thickness is larger than other analogical locations around rod. In turn, liquid film is not driven enough toward downstream and tends to be thick in spite of small amounts of liquid droplets.

It is interesting that streak does not appear at 315 degrees in contour plots, for example in figure 6.9(1), only intermittent points of large film thickness are recognized while other peaks discussed in this section have their own streaks in contour plots.

Hoshide et al. [16] reported that liquid film thickness had the minimum film thickness at where liquid film faces to fast gas velocity in upstream region of spacer.

However, the present work shows an opposite trend to the results of Hoshide et al., since their measurement was done in 4×4 rod bundle and under different flow condition, to say smaller $j_g=10\text{m/s}$ and large $j_l=0.2\text{m/s}$ than the present work. Taking into account the discussion in chapter 4, flow condition is considered to affect significantly the liquid film structure so as to change film thickness distribution. Moreover, Hoshide et al. measured liquid film thickness with 15mm interval around spacer, thus it seems difficult to detect slight changes of film thickness just before the spacer such as described here.

6.4.6. Time-Averaged Liquid Film Thickness in Downstream Region of Spacer

To interrupt in detail about the inhomogeneous distribution of liquid film thickness around rod in downstream region of spacer, longitudinal evolution of film thickness at every 45 degrees is plotted in figure 6.25.

Figure 6.25(a) shows results of center rod. Liquid accumulation is observed behind the spacer within about +20mm. In this region, axial component of gas velocity coming through the rod-spacer clearance is decreased due to rapid expansion of flow area. In addition, its radial component directing toward gas main flow is also induced (Noriyasu et al. [17], Kodama et al. [18]), then driving force of liquid film is quickly reduced. Moreover, liquid film formed on spacer cell by deposition of liquid droplets leaves at the rear edge of spacer. This phenomenon is called “Run off effect” by Yano et al. [10,12,19,20] and Kodama et al. [18]. Parts of run off liquid film are considered to deposit on liquid film in a short distance from spacer to form the liquid accumulation just behind the spacer.

Such a liquid accumulation seems to exist almost constantly from the contour plots, for example in figure 6.6(2), consequently, it is considered that the gas velocity weakens and droplets are not supplied much to the area behind this accumulation. Then, liquid film thickness becomes small with fairly homogeneous distribution at +19mm and +20mm as seen in figures 6.14 and 6.22.

Liquid film thickness seems to be thick at $90 \times i$ degrees ($i=0-3$) and to be thin at $90 \times i+45$ degrees ($i=0-3$) in downstream of the liquid accumulation. Mechanism of this difference can be considered as demonstrated in figure 6.26.

Since A-A cross-section has small clearance being 3mm and both surfaces of spacer cell face to rod, decelerated gas flow after the spacer requires a long distance to recover and interfacial shear stress is kept in small. Therefore, liquid film is not driven intensely toward downstream. It is assumed here that a secondary gas flow directing to A-A cross-section from gas main flow by the gas velocity difference between main flow in wide clearance and gas flow in narrow clearance based on the similar mechanism of

“drift effect” suggested by Yano et al. [10,12,19,20] and Kodama et al. [18]. Then, parts of liquid droplets accompanied in main flow are transported to the A-A cross-section by this secondary flow and deposit on liquid film by vortexes formed after the spacer. This secondary flow is called here as “W-N (Wide to Narrow) drift flow”. As a result, liquid film thickness will be enlarged at 90° by these effects.

On the other hand, B-B cross-section has large clearance to be about 10mm and only one side of spacer cell faces to gas main flow, thus decelerated gas flow after the spacer recovers more quickly than in A-A cross-section. Another secondary flow, which is same to the “drift flow” by Yano et al., is induced by difference of velocity between gas main flow and gas flow near rod surface. This secondary flow is called here as “radial drift flow”. The effect of radial drift flow at B-B cross-section is relatively small because gas velocity near rod surface is large, in turn, droplets transported from gas main flow will deposit on rod surface at far region from spacer and thus liquid film thickness gradually recovers.

Ununiformity of liquid film thickness around rod becomes small after +60mm. Because liquid film thickness decreases in A-A cross-section by large shear stress due to recovery of gas velocity, and liquid film thickness increases in B-B cross-section by droplets deposition.

Figures 6.25(b) and 6.25(c) show results of side-center rod and corner rod, respectively. Though tendency of liquid film thickness evolution is not so systematic as center rod due to asymmetrical gas velocity distribution around rod, it can be noted here that liquid film thickness is large at 90° ($i=0-3$) and small at $90^\circ + 45^\circ$ ($i=0-3$).

6.4.7. Effects of Projections in Downstream Region of Spacer

From above discussion, it can be said that liquid film thickness has inhomogeneous but nearly systematic distribution around rod in downstream region of spacer, to say, liquid film thickness becomes large at rod-rod clearance and then this ununiformity disappears in farther downstream region of spacer. However, figure 6.19 shows that liquid film thickness does not necessarily have a symmetric trend around center rod even though this rod can be considered to have symmetrical gas velocity distribution around it. As a reason of such complexity, dimples and spring seem to play a role as shown in figure 6.27.

Liquid film thickness is expected to be thin at 225 degrees and 315 degrees in downstream region of spacer based on the previous discussion, but the results show an opposite trend for example at +15mm and +16mm. These locations correspond to the

downstream area of dimples therefore liquid film thickness will be locally enlarged by droplets deposition entrained from highly agitated waves after these dimples.

Effect of spring also occurs apparently between +20mm and +40mm. As we mentioned before, liquid film thickness has large value at 90° in this region, but this trend is especially strong at about 90° where is after the spring. It can be said here also that liquid film thickness is enhanced by droplets deposition entrained from highly agitated waves after the spring. This effect is easily observed for corner rod within about +40mm as shown in figures 6.17 and 6.21.

Due to the enhancement of liquid film thickness, liquid bridge is sometimes formed in downstream region of spacer at rod-rod clearance where gas velocity is relatively slow. When gas velocity is small, gravity becomes superior to lift force and then liquid phase cannot flow toward downstream, as a result, forms a liquid bridge. Photographic image of liquid bridge is shown in figure 6.28(a) obtained with $j_g=10\text{m/s}$ and $j_l=0.017\text{m/s}$. This bridge was not observed in upstream region of spacer and at where rod surface faces toward gas main flow in spite of downstream region of spacer. Figure 6.28(b) shows behavior of liquid bridge in axial direction. Traveling velocity of liquid bridge is small and also flows backward. It survives within about +50mm. Liquid bridge was frequently observed at 180° , i.e., after the spring, of corner rod.

Effect of dimples increases again after +50mm. Parts of liquid droplets generated after dimples are captured by the liquid accumulation behind the spacer, but the rest flows into gas main flow. These droplets accompanied in gas main flow are transported to rod surface by radial drift flow and deposit on it, in turn liquid film thickness at 225° and 315° seems to be increased after +50mm.

6.4.8. Effect of Dimples in Farther Downstream Region of Spacer

Above result suggests that dimples affect on liquid film thickness distribution in farther downstream region of spacer at +80mm, to say, they enlarge liquid film thickness at 90° at where liquid film thickness is normally expected to be small without dimples by high interfacial shear stress. Circumferential distribution of liquid film thickness at 80mm is shown in figure 6.29. Sub-channels in rod bundle assembly and number of dimples in upstream region of each sub-channel are also illustrated in this figure.

Assuming that dimples behave as sources of liquid droplets, droplets concentration will vary depending on the number of dimples in sub-channels as expressed by different hatch in figure 6.29. Liquid film thickness of center rod becomes larger at 225° and 315° where dimples exist in their upstream region than at other symmetrical

angles, to say at 45 degrees and 135 degrees. Though this trend is not so obviously seen for side-center rod, but is clear seen for corner rod. The reason why liquid film thickness is large at 135 degrees of corner rod in spite of no dimple in its upstream region can be considered that dimples of neighboring two rods enlarge liquid droplets concentration in this sub-channel.

Thus, ununiformity of circumferential distribution of liquid film thickness slightly remaining at +80mm indicated in figure 6.22 seems to be caused by the inhomogeneous droplets concentration in sub-channels due to different number of dimples.

6.4.9. Dependency of Liquid Flow Rate on Liquid Film Thickness

Figure 6.30 shows dependency of liquid flow rate on longitudinal evolution of liquid film thickness in downstream region of spacer. It reveals that liquid film thickness rapidly increases within relatively in a short distance and has large peak for small liquid flow rate. On the other hand, liquid accumulation appearing behind the spacer is small and liquid film thickness gradually recovers in a long distance for large liquid flow rate. Nakao et al. [15] also reported that film thickness behind a spacer did not recover to its upstream level with increase of liquid flow rate. These trends can be explained as below.

Figure 6.31(a) shows a case of large liquid flow rate. Because of large liquid film thickness in spacer region, cross-sectional area for gas flow is reduced to accelerate gas velocity near spacer edge. Therefore, liquid film departing from spacer edge by run-off effect is broken up to relatively large liquid droplets by fast gas flow. These droplets reach to farther downstream region of spacer because of large inertia and small drift effect determined by a difference between main gas flow and near rod.

For small liquid flow rate as shown in figure 6.31(b), liquid film leaving from spacer cell will be a liquid lump since gas velocity from spacer region is too small to break up the liquid film into droplets. In addition, since drift effect is large for this case, the liquid lump deposits on rod surface in a short distance.

It should be also noted that liquid accumulation starts from a little bit far for center rod in comparison with other rods due to higher gas velocity around rear edge of spacer for center rod. Moreover, starting point of liquid accumulation is far for the case of large liquid flow rate because gas velocity around rear edge is also high.

In downstream region of liquid accumulation, between +20mm and +50mm, liquid film thickness becomes large since interfacial shear stress is small due to small gas velocity for small liquid flow rate.

6.4.10. Power Spectral Density Distribution of the Film Thickness Fluctuation

Figure 6.32 shows power spectral density distribution of liquid film thickness fluctuation around side-center rod at 135 degrees and corner rod at 270 degrees under condition of set3 by stationary reflector. Large peak is observed at about 2Hz and other peaks are also seen between 10Hz and 100Hz in upstream region of spacer as shown in figure 6.32(a). In spacer region shown in figure 6.32(b), no obvious peak is recognized in low frequency range less than 10Hz indicating that large waves do not appear frequently. General trend of power spectral density distribution in spacer region is similar to a case of high gas velocity discussed in chapter 5. It can be seen that power spectral density distribution in downstream region of spacer recovers to the results of upstream region of spacer as seen in figure 6.32(c). Results of corner rod shows almost same tendency of power spectral density distribution to those of side-center rod.

6.4.11. Characteristics of Interfacial Waves

Concerning with previous discussions, characteristics of interfacial waves on liquid film are expected to change both in axial direction and in circumferential direction by the inhomogeneous gas velocity distribution around rods. Characteristics of surface waves obtained by the same criterion described in chapter 5, however using the data of rotating reflector here, will be discussed in this section.

Axial evolution of minimum liquid film thickness is shown in figure 6.33. The minimum film thickness refers to 95% probability of liquid-phase existence in terms of the cumulative curve as usually defined. Physically the minimum film thickness averaged over a long measurement time represents the base film thickness. Similar trend is seen as mean film thickness though peak at rear edge of spacer is not clear.

Cross-sectional averaged number of passing large waves is shown in figure 6.34. Number of passing large waves is about 2Hz in upstream region of spacer and dependency of liquid flow rate seems little. Thus, it can be said that the peak appeared in low frequency region of power spectral density distribution in figures 6.32(a) and 6.32(e) were caused by large waves. Number of passing large waves distinctly increases in whole length of spacer region for set1 but is limited to have several peaks for set3. This trend is confirmed in contour plots, too. It is interesting that number of passing waves in upstream region is less than the results of annulus channel experiment in spite the influence of spacer is negligible small, and number of passing waves increases in spacer region. Mechanism causing these trends will be considered as follows.

As shown in figure 6.42, gas velocity around rod does not distribute uniformly in external region of spacer because of inhomogeneous cross-sectional area. Therefore,

liquid film is not dragged homogeneously enough to form two-dimensional large waves. In contrast with this, liquid film is dragged by almost homogeneous gas flow in spacer region since rod-spacer clearance is constant except projections such as dimples and spring. Therefore two-dimensional large waves are easily generated and liquid film thickness also flatly distributes around rod in spacer region as seen in figures 6.19 or 6.21. Some of large waves contact with spacer cell as to form liquid bridges under large liquid flow rate.

Figure 6.35 shows cross-sectional averaged wave height of large waves. It is seen that wave height decreases in spacer region. Compare to mean film thickness, dependency of liquid flow rate is clearly occurred, that is to say, wave height becomes large in spacer region for large j_1 . It seems that large waves being about 1mm height in upstream region of spacer will collide with spacer cell.

Figure 6.36 shows cross-sectional averaged wave width (duration time) of large waves. Wave width is narrow in spacer region and gradually decreases toward spacer rear edge indicating that gas flow is accelerated in this region. This trend is clearly seen for set1 and also recognized in contour plots, figures 6.5(2) and 6.5(3).

Cross-sectional averaged wave period of large waves shown in figure 6.37 has short value in spacer region and has long value in downstream region of spacer.

Cross-sectional averaged number of passing small waves, i.e., ripples, is shown in figure 6.38. It seems that number of passing ripples a little bit increases in spacer region of side-center rod and corner rod for set3 due to acceleration of gas flow. It is also seen that number of passing ripples decreases in downstream region of spacer because of deceleration of gas flow. Number of passing ripples does not remarkably change in downstream region of spacer for set1 since gas velocity is relatively high enough to agitate roughly liquid film surface.

Cross-sectional averaged wave height and wave width of ripples are shown in figure 6.39 and figure 6.40, respectively. These characteristics tend to distribute quite similar to the evolution of cross-sectional averaged liquid film thickness in axial direction. Cross-sectional averaged wave period of ripples is shown in figure 6.41. It is seen that the wave period changes little from upstream region to inside region of spacer and slightly increases in downstream region of spacer.

From above discussions, characteristics of ripple seem to be useful to understand liquid film behavior. Longitudinal evolution of ripple characteristics around rod is plotted in figures 6.43, 6.44 and 6.45. Figure 6.43 shows results of center rod. Wave height, width and period increase at where liquid film thickness increases due to low gas velocity. Number of passing ripples decreases at the same locations. Results of

side-center rod in figure 6.44 and results of corner rod in figure 6.45 also indicate a same trend.

Figure 6.46 shows binary plots of time-dependent liquid film thickness distribution in order to estimate lateral dimension of waves. Liquid film thickness being larger than twice of the minimum film thickness was determined as wave and expressed with white dot in this plots. Black dot indicates the base film part. It is seen that liquid film is covered with widely spreading waves and lots of small waves. It seems that ratio of small waves is superior to wide waves in spacer region and small waves occur more for small liquid flow rate. It was difficult to distinguish disturbance waves from ripples in lateral direction, thus both waves were treated same in the following discussions.

Figure 6.47 shows number histogram of waves having different span, to say lateral dimension. Span was calculated between two angles exceeding twice of the minimum film thickness in circumferential direction. Rod periphery was used to convert this angle to actual length. Thus, 360 degrees corresponds to about 47mm of span. It can be seen from this figure that number of passing small waves increases in spacer region. Peak appearing at about 47mm is wide waves that spreads whole around rod. It also should be noted that number of passing wide waves is small in spacer region.

Figure 6.48 shows longitudinal evolution of mean wave span. It is clearly seen that mean wave span decreases in spacer region due to highly agitated liquid film surface by accelerated gas flow. Wave span has a peak just behind the spacer because of widely expanding liquid accumulation. It seems that wave span of accumulation is large for small liquid flow rate.

6.5. Summary

Liquid film thickness on simulated fuel rods in a 3×3 rod bundle was measured by the USEM. Effects of geometrical structures such as spacer and rod bundle on liquid film flow were clarified as below.

Time-dependent liquid film thickness distribution around rod was reconstructed as contour plots, bird's eye view graphics and peripheral plots. Excellent understandings of the liquid film behavior affected by spacer were obtained. Cross-sectional averaged liquid film thickness indicated a general trend, that is to say, liquid film thickness has a small peak in front of spacer, decreases in spacer region, has another peak just behind the spacer and recovers in downstream region of spacer. Film thickness is slightly small at center rod since its surrounding gas velocity is relatively high.

Decreasing of cross-sectional averaged liquid film thickness in spacer region is due to acceleration of gas velocity caused by reduction of flow area. In spacer region, liquid film thickness distributes almost uniformly around rod since constant rod-spacer clearance forms homogeneous gas velocity distribution, however, locally increases at dimples and spring.

Peak of liquid film thickness before the spacer seems to occur by obstruction of liquid film flow due to an increase of gas pressure before the spacer cell and also by liquid droplet deposition. Droplet entrainment is large at where rod surface faces to fast gas flow, thus the peak is enlarged at this direction and also film thickness in spacer region is thickened due to remaining droplets. Liquid film thickness also becomes large at channel corner because of large spacer thickness and low gas velocity. Therefore, ununiformity of liquid film thickness around rod strongly appears in a limited area within about 5mm from spacer front edge.

Liquid accumulation behind the spacer seems to be created by decelerated gas velocity and deposition of liquid droplets or liquid lumps departing from spacer cell by run off effect. Liquid film leaving from spacer cell easily becomes liquid lump and deposit near of spacer for small liquid flow rate, however liquid accumulation is small for large liquid flow rate since liquid film from spacer cell is destroyed into droplets which are transported toward downstream.

In downstream region of spacer, inhomogeneous liquid film thickness distribution is formed by several factors, such as different gas velocity profile, droplet entrainment after the dimples and spring, different droplet concentration in sub-channels due to number of dimples in upstream region. Excluding effects of projections, liquid film thickness seems to be thick at rod-rod clearance where gas velocity is small and be thin

at where rod surface faces to gas main flow since interfacial shear stress is increased and drift effect is small.

Liquid film thickness rapidly recovers and has large peak after the spacer with low liquid flow rate. This is because gas velocity from rod-spacer clearance is small enough to form liquid accumulation and also to enhance drift effect. Liquid bridge is sometimes formed in downstream region of spacer at corner rod because of large liquid film thickness due to reduced gas velocity.

Power spectral density distribution of liquid film thickness fluctuation in external region of spacer has a large peak in low frequency region and has several peaks between 10Hz and 100Hz. On the other hand, in spacer region, the power spectral density distribution do not have significant peak in lower frequency and frequencies distribute continuously to higher region being about 200Hz.

Though two-dimensional large waves do not often appear in external region of spacer compare to the experiments in annulus channel but frequently occur in spacer region with relatively large liquid flow rate. This is because that gas velocity profile in external region of spacer is inhomogeneous around rod so as to disable to create two-dimensional large wave, but becomes uniform in spacer region due to constant clearance between rod and spacer cell and then liquid film is uniformly dragged to develop large waves. Such large waves often contact spacer cell forming liquid bridge.

Characteristics of ripples such as number of passing waves, wave height, wave width (duration time) and wave period changes with gas velocity profiles around rod as expected from time-averaged liquid film thickness distribution. To say, number of passing waves decreases and the rests increase at where liquid film thickness is large due to small gas velocity.

Span of interfacial waves decreases in spacer region and has a peak behind spacer at where liquid accumulation occurs. It is seen that ratio of waves having small span slightly increases to occupy liquid film surface for small liquid flow rate.

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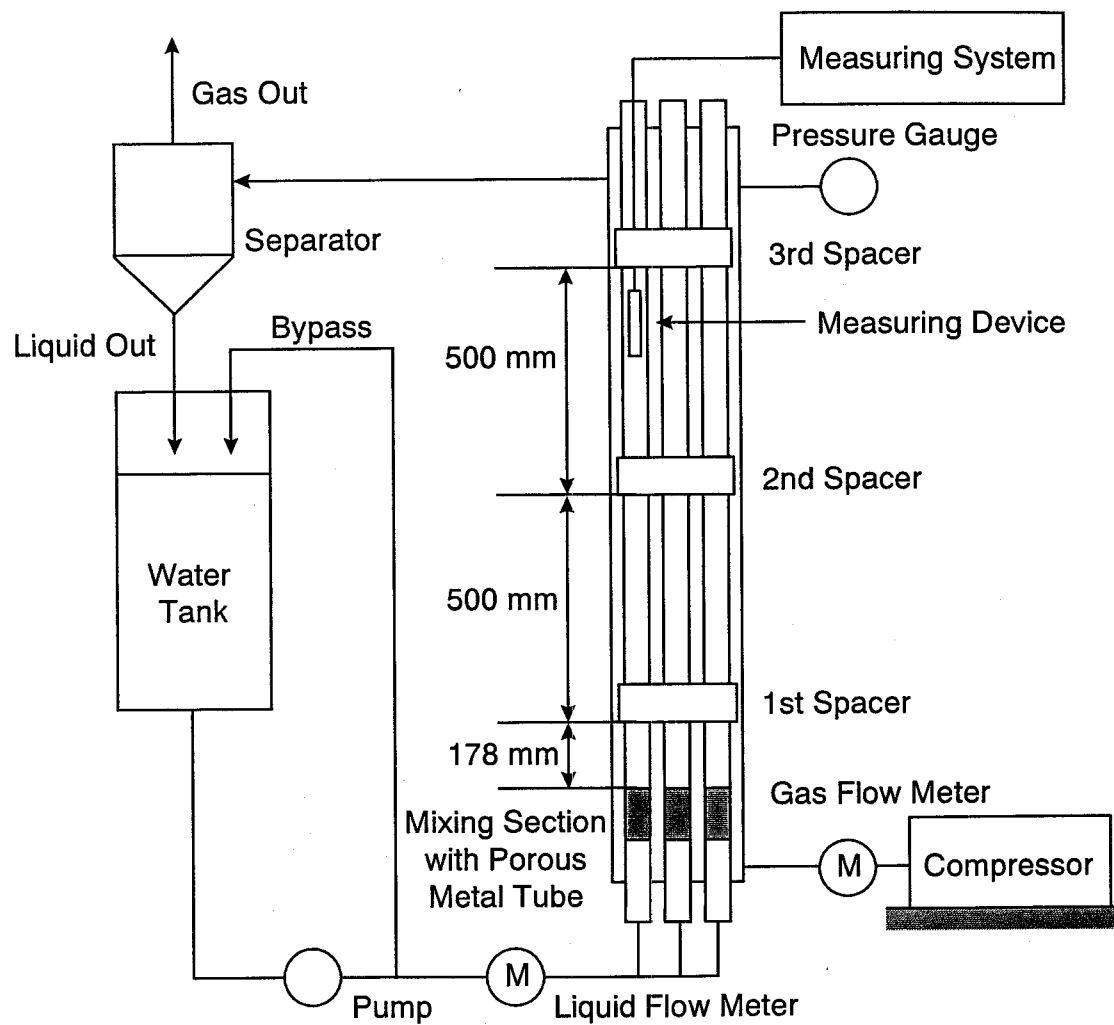


Figure 6.1 Schematic of the Experimental Apparatus

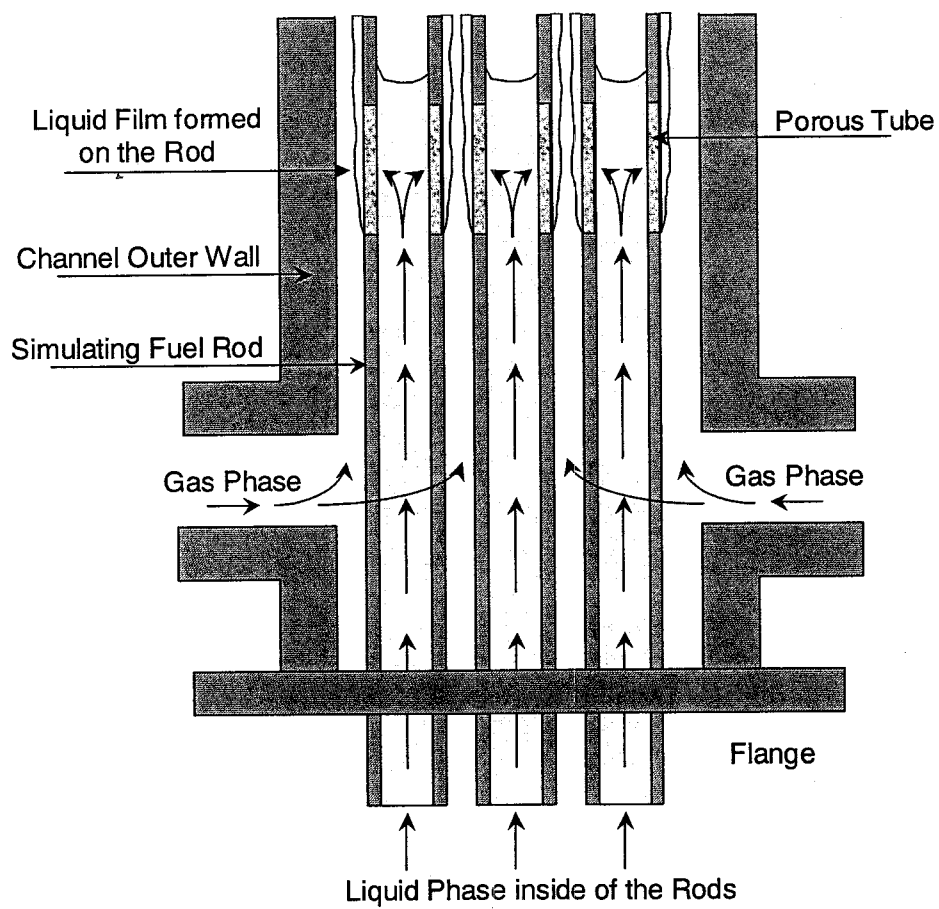


Figure 6.2 Schematic of Gas-Liquid Mixing Section

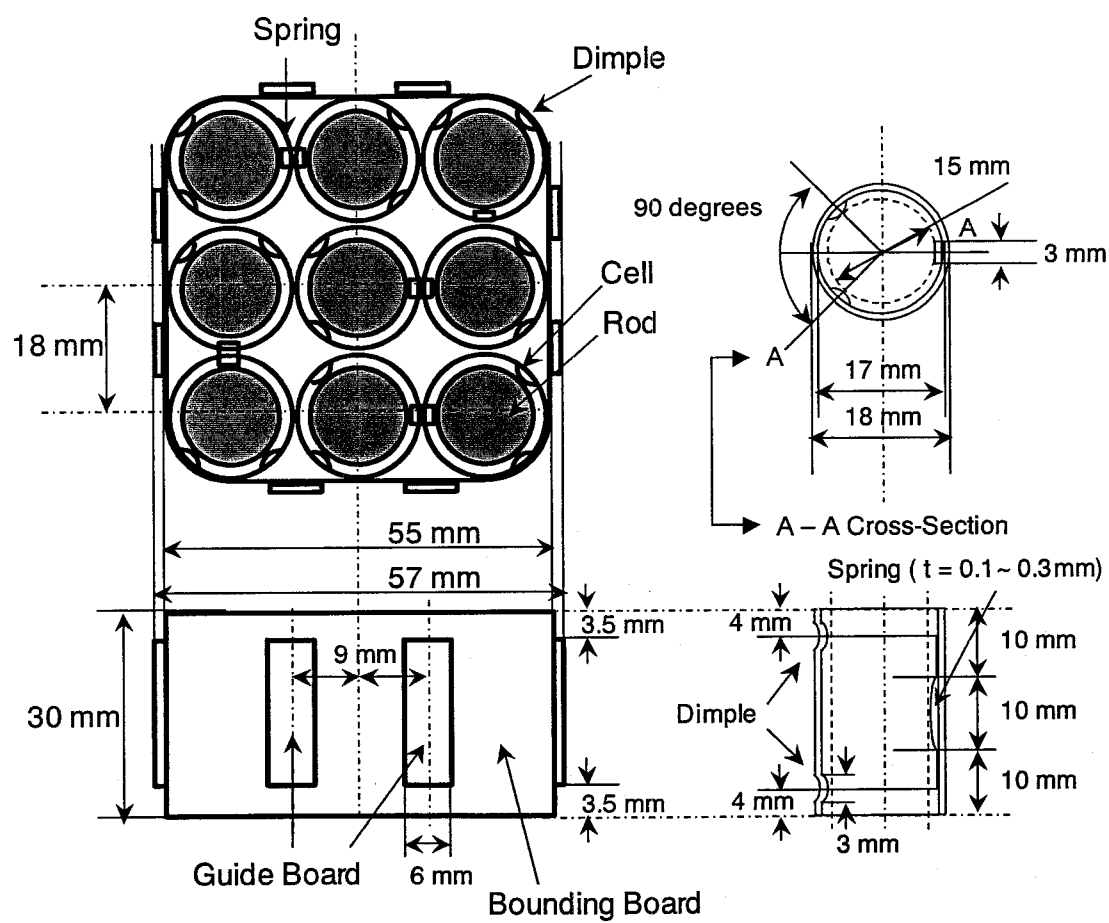


Figure 6.3 Detail of Circular Spacer Shape

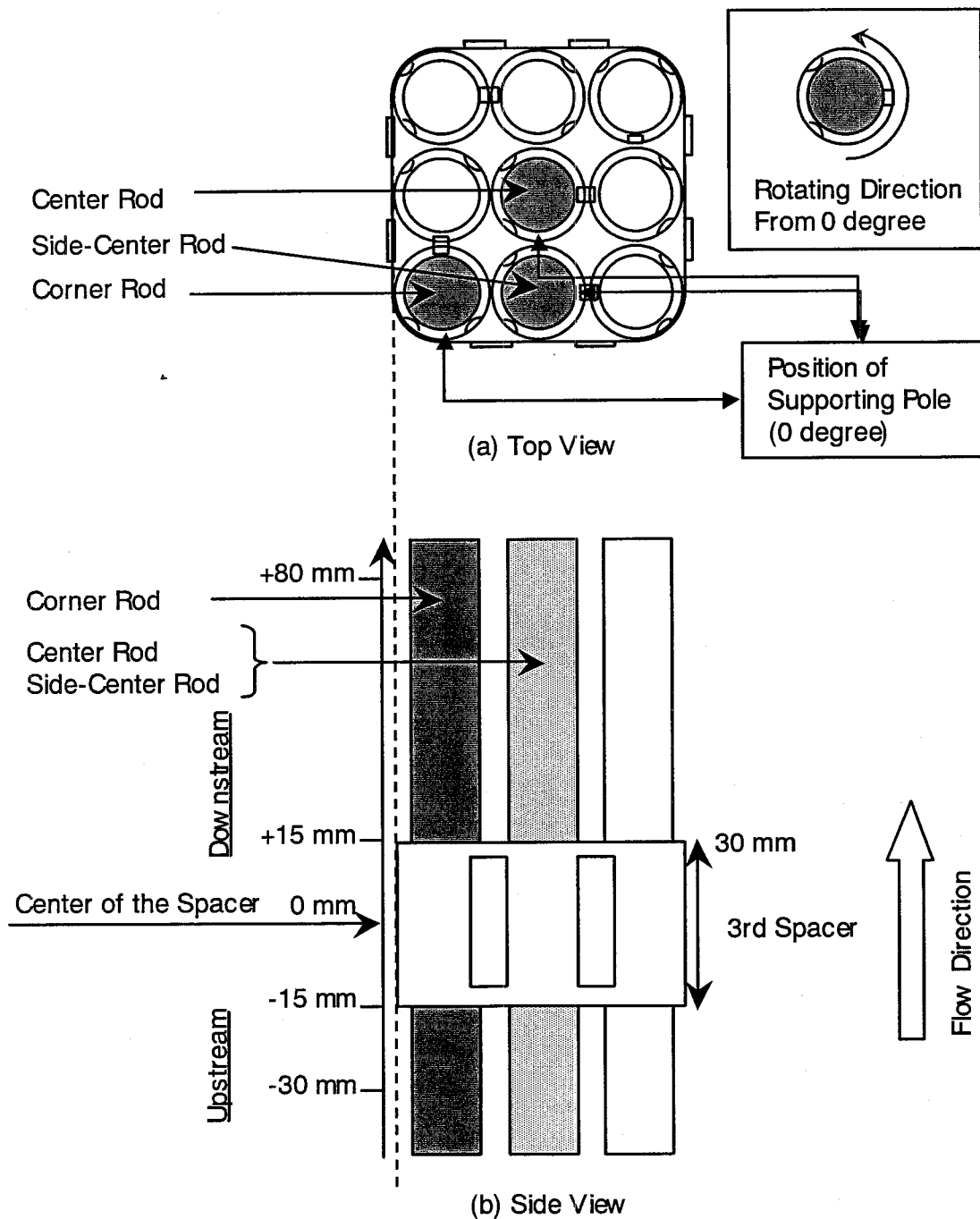


Figure 6.4 Measuring Location of the First Test

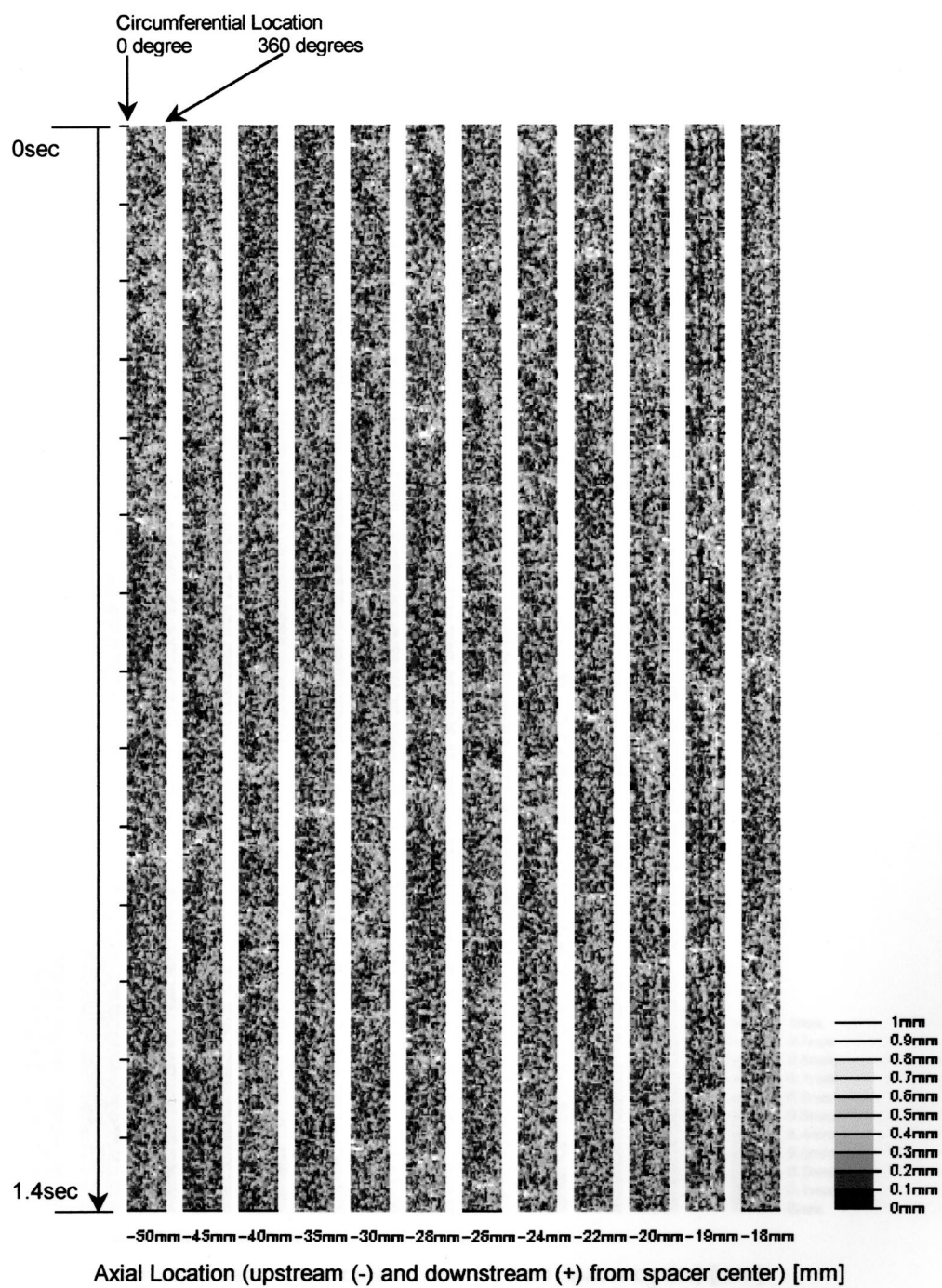


Figure 6.5 (1) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

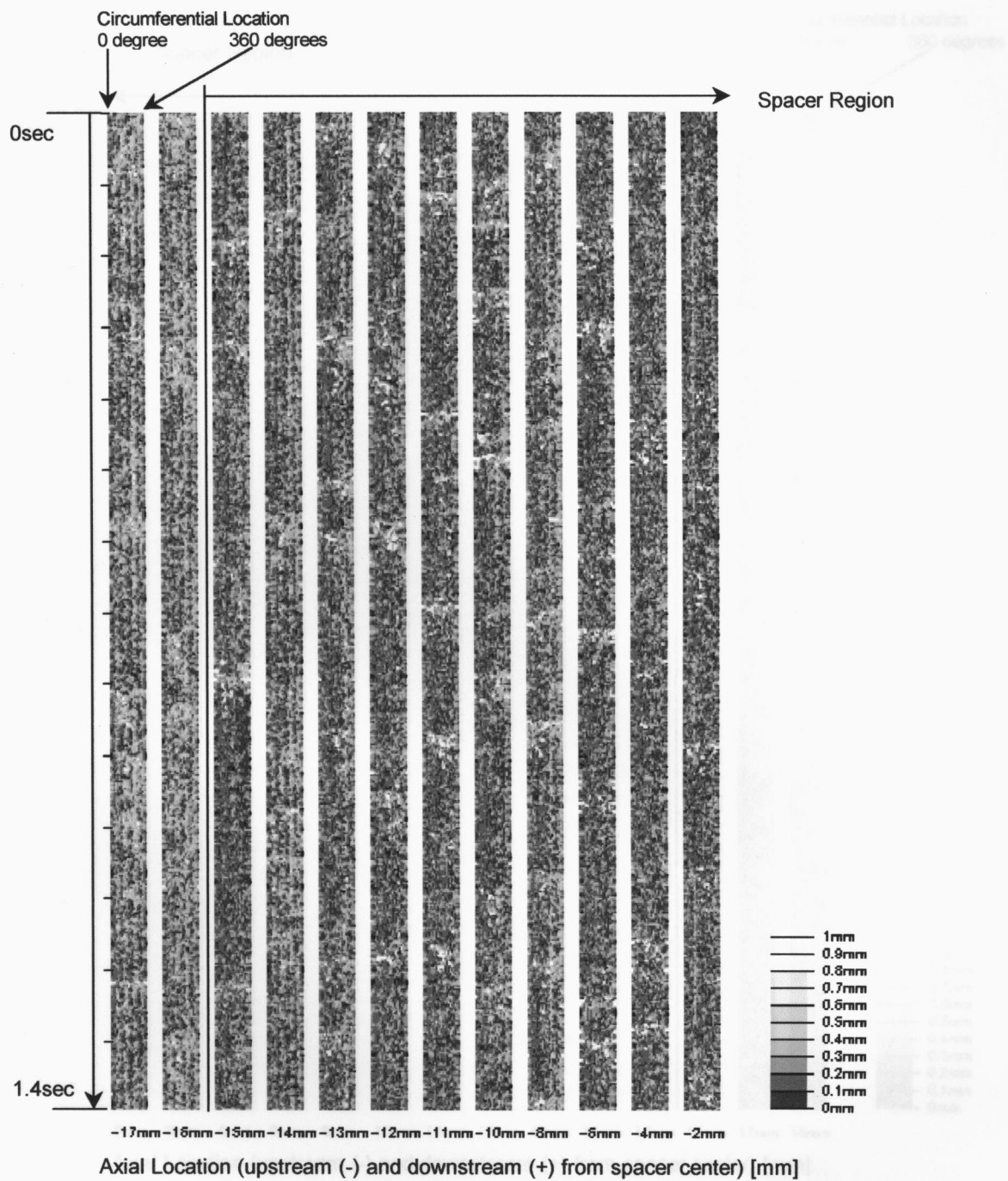


Figure 6.5 (2) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

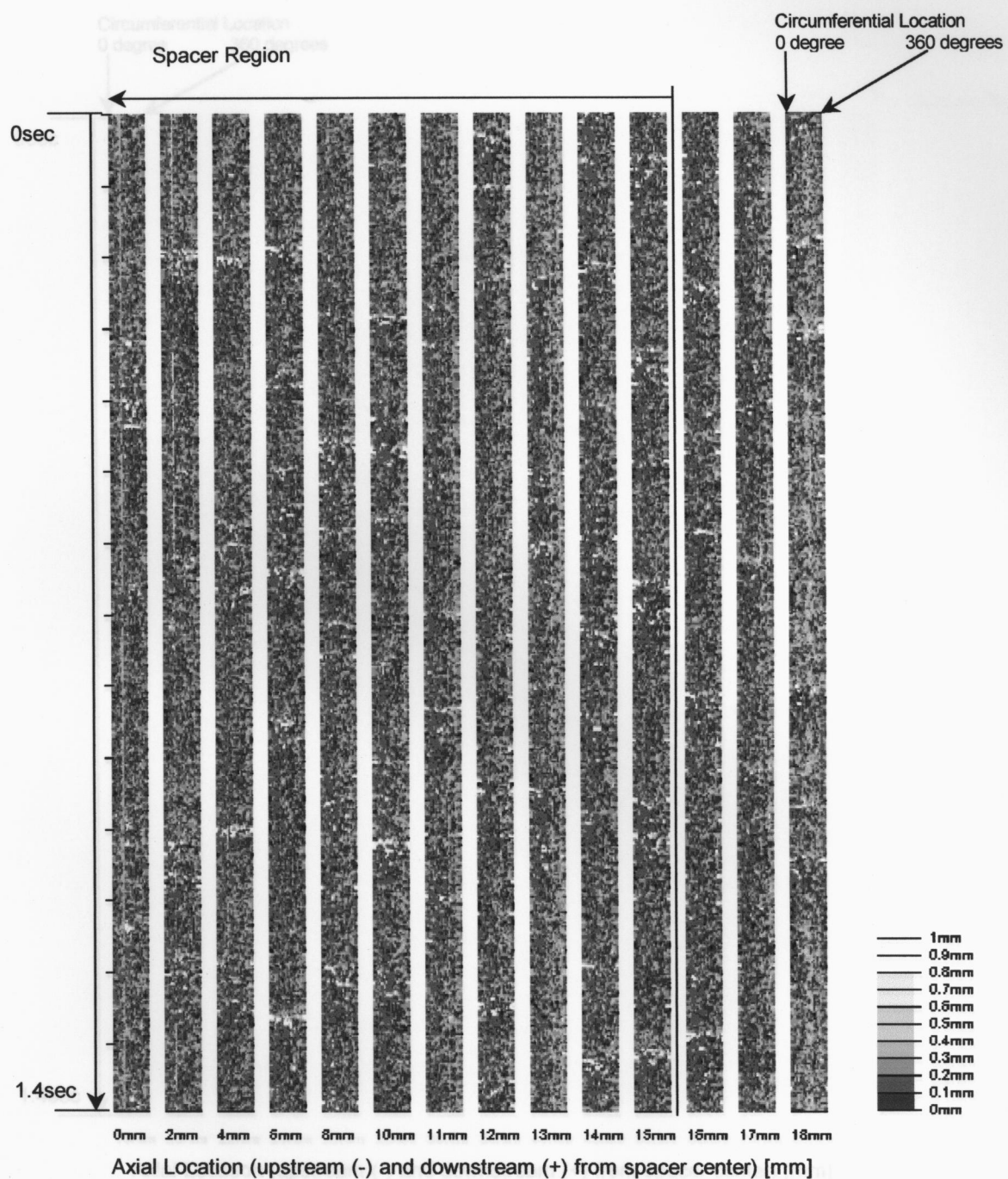


Figure 6.5 (3) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

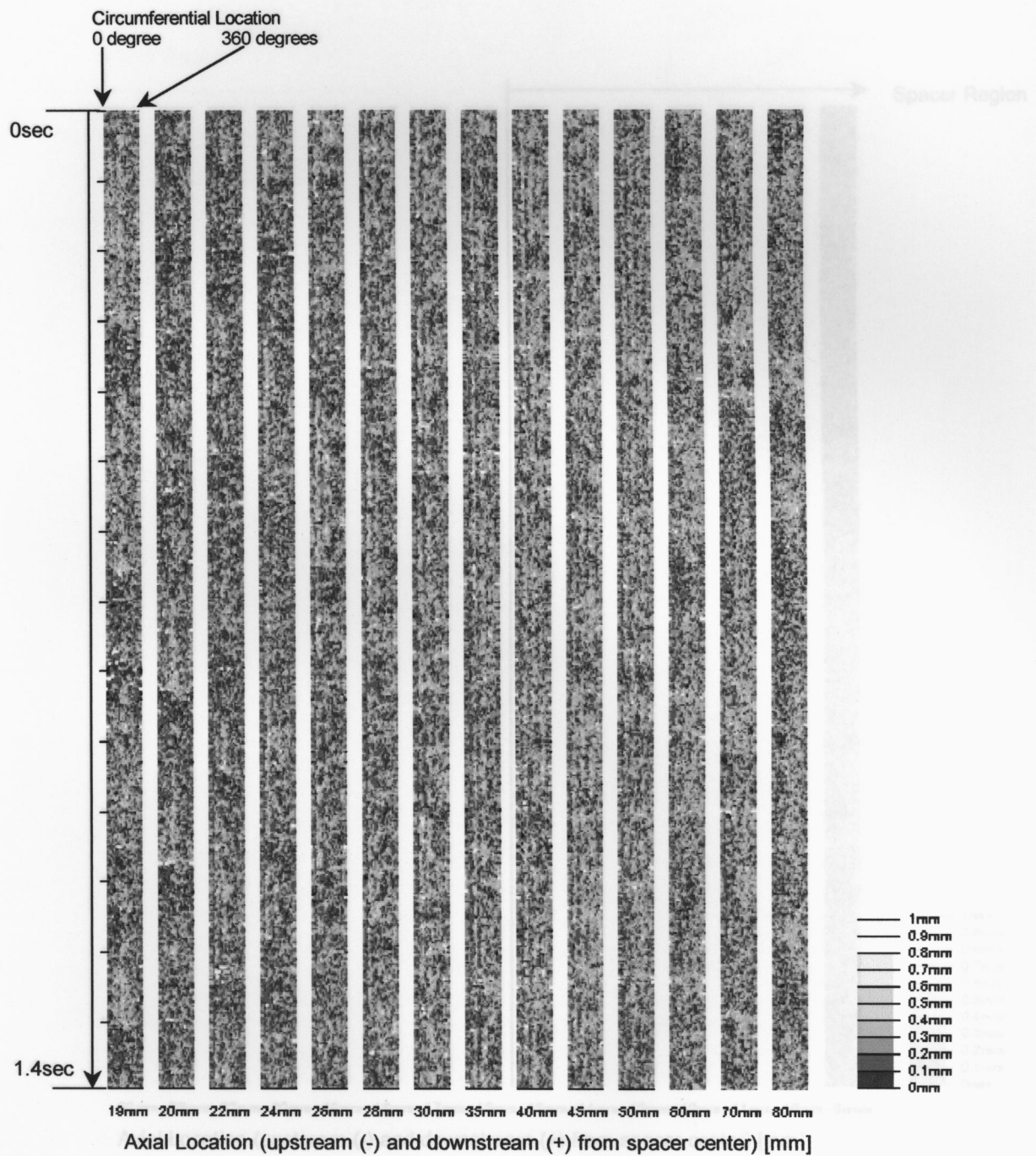


Figure 6.5 (4) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

Continued

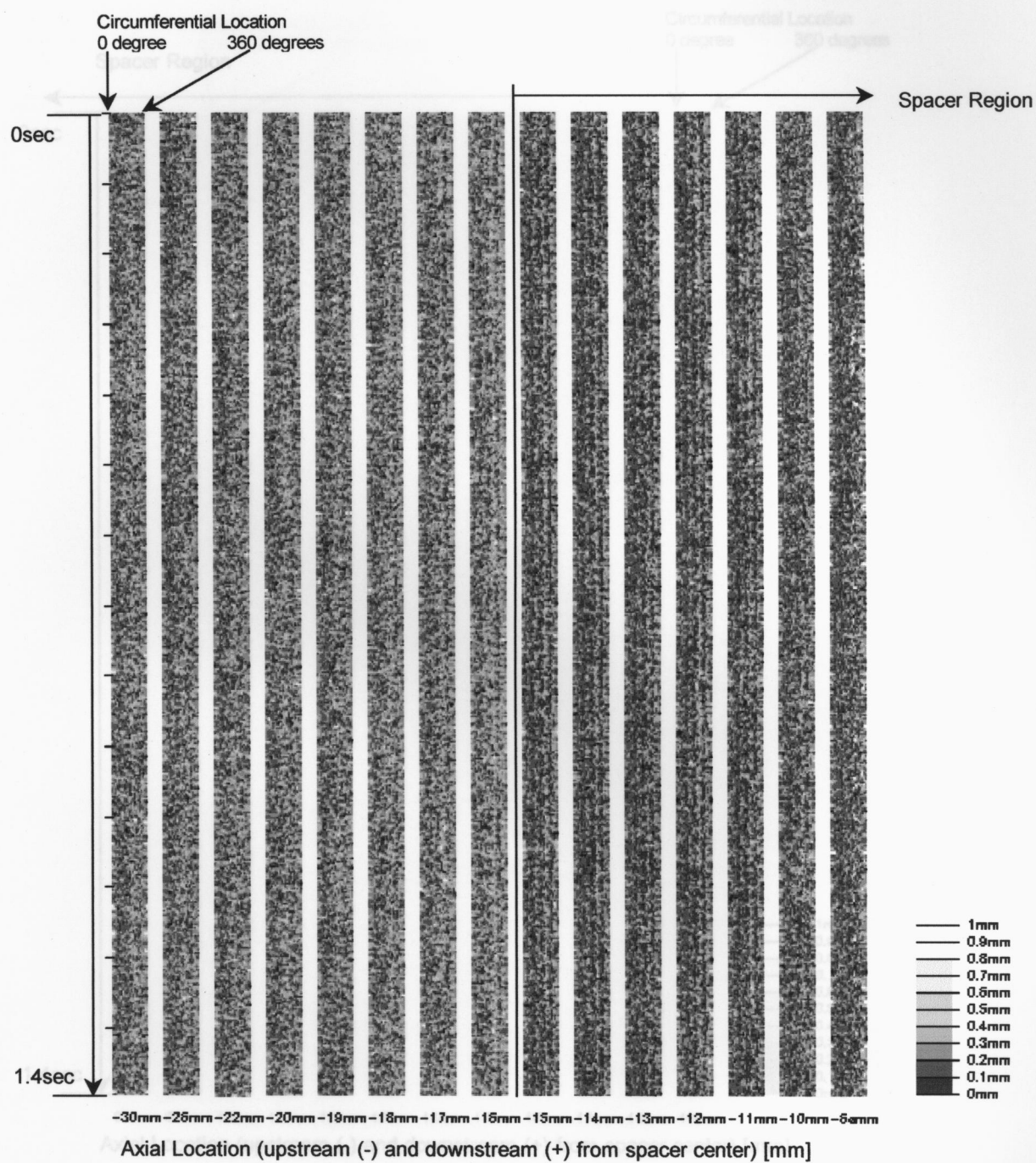


Figure 6.6 (1) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

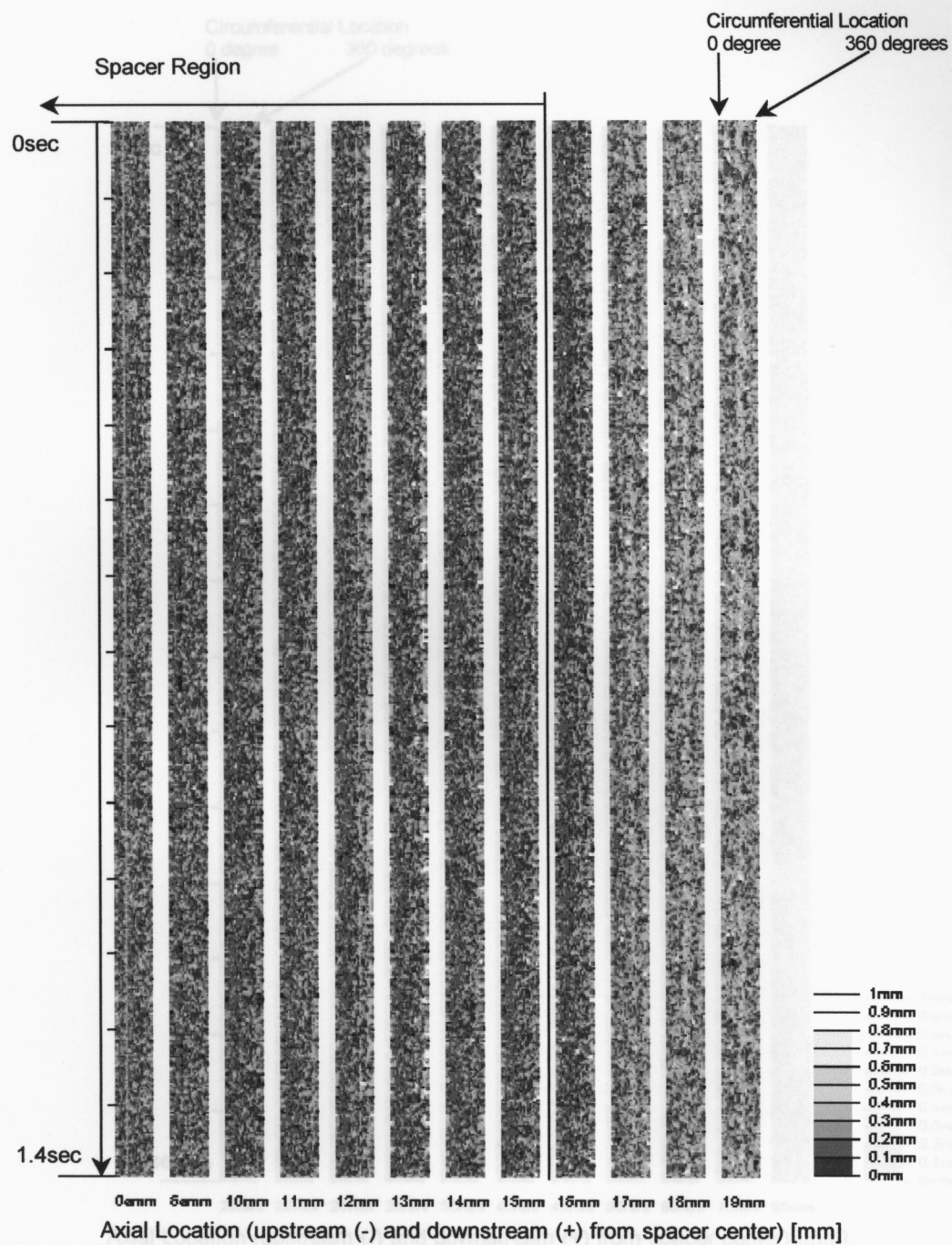


Figure 6.6 (2) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

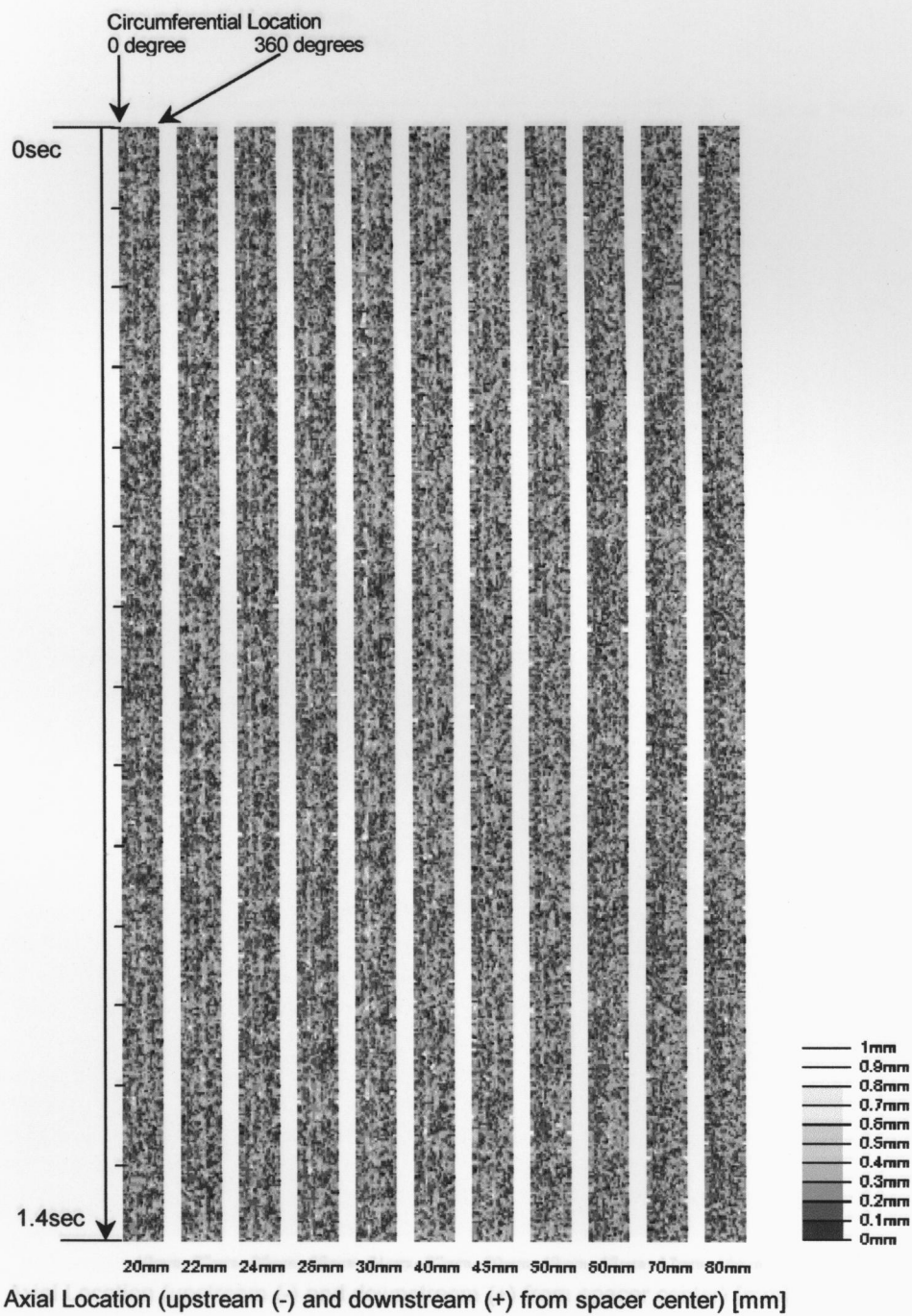


Figure 6.6 (3) Contour Plots of Liquid Film Thickness Distribution around Center Rod
(Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

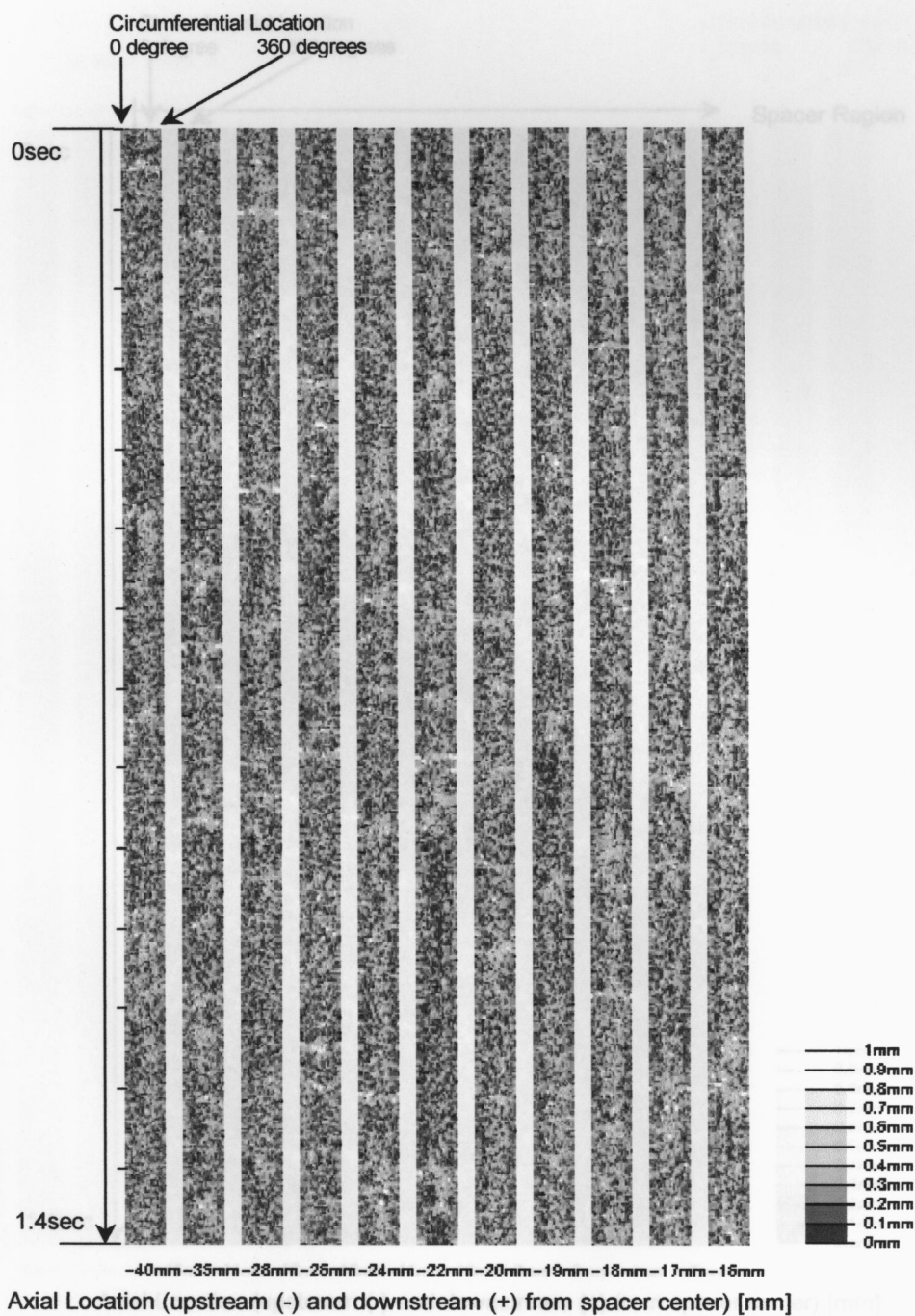


Figure 6.7 (1) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

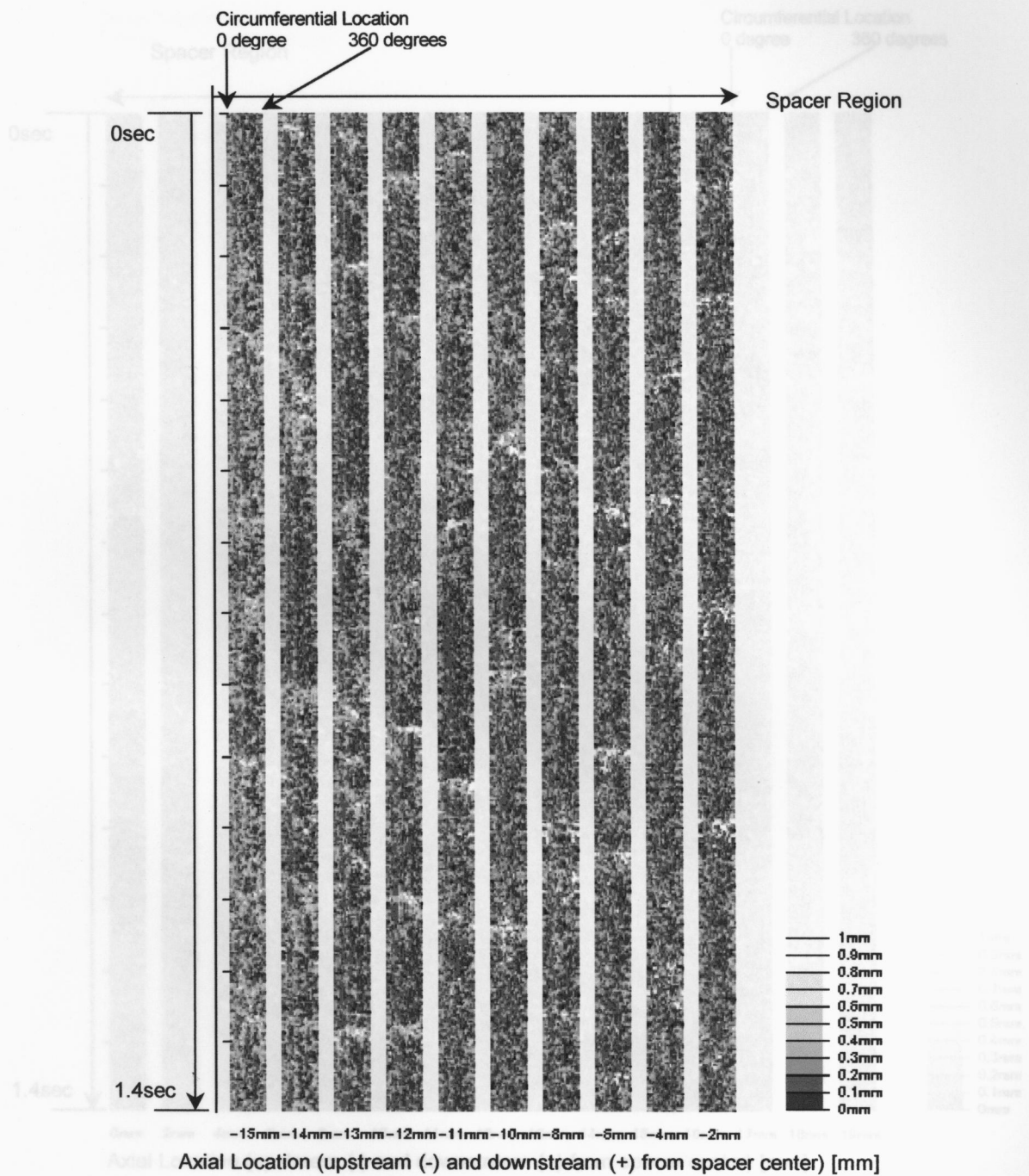


Figure 6.7 (2) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

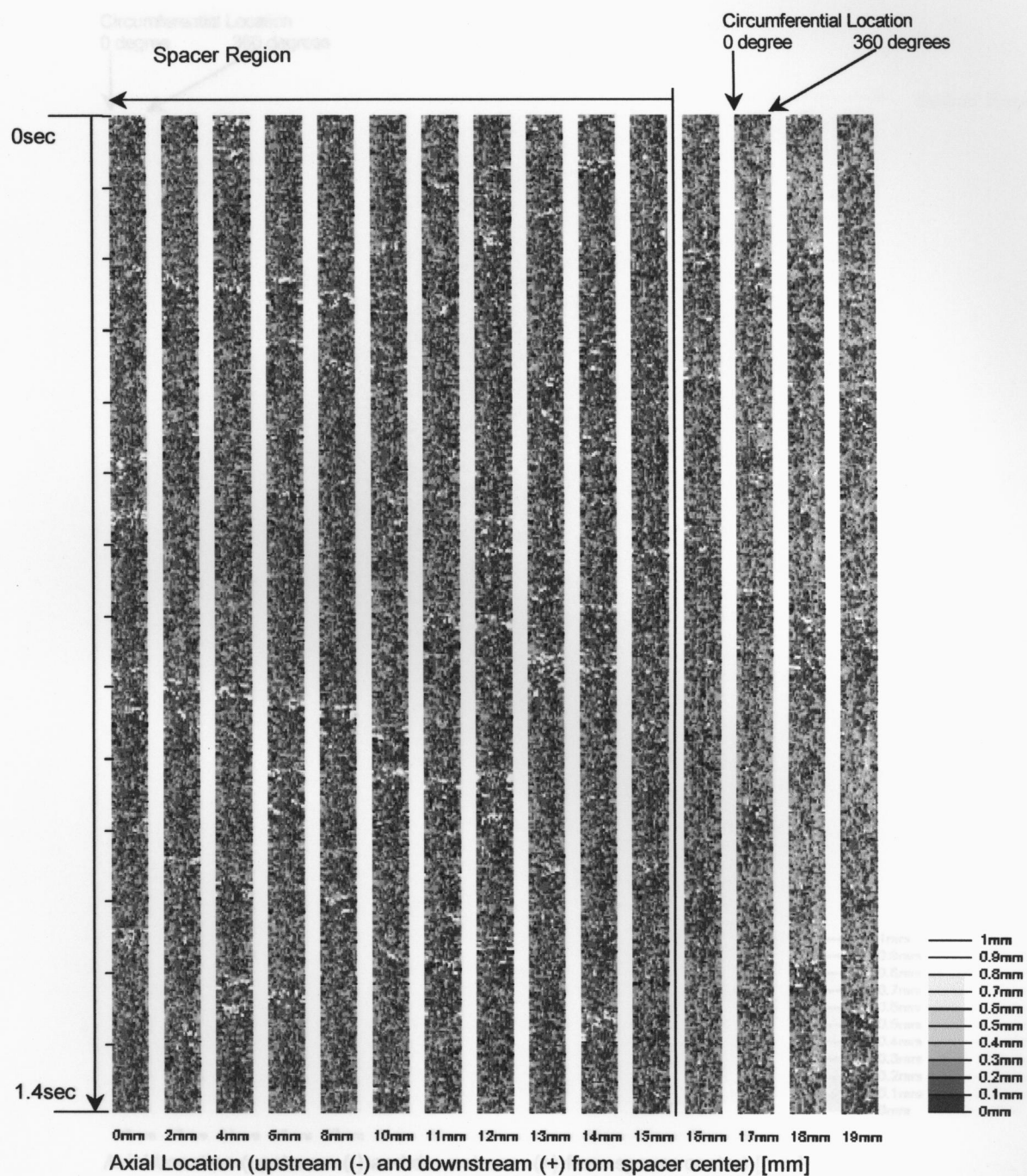


Figure 6.7 (3) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

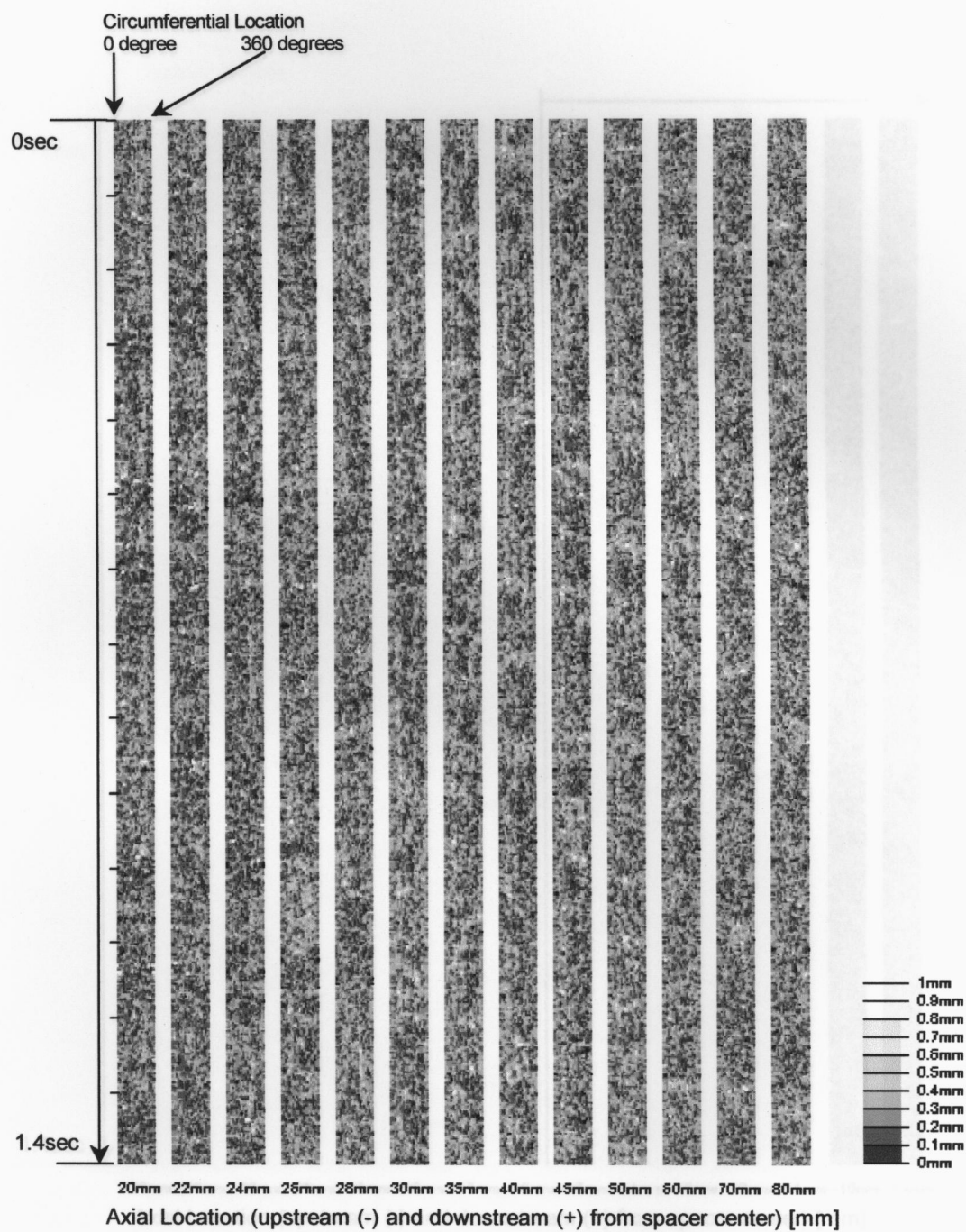


Figure 6.7 (4) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) *Continued*

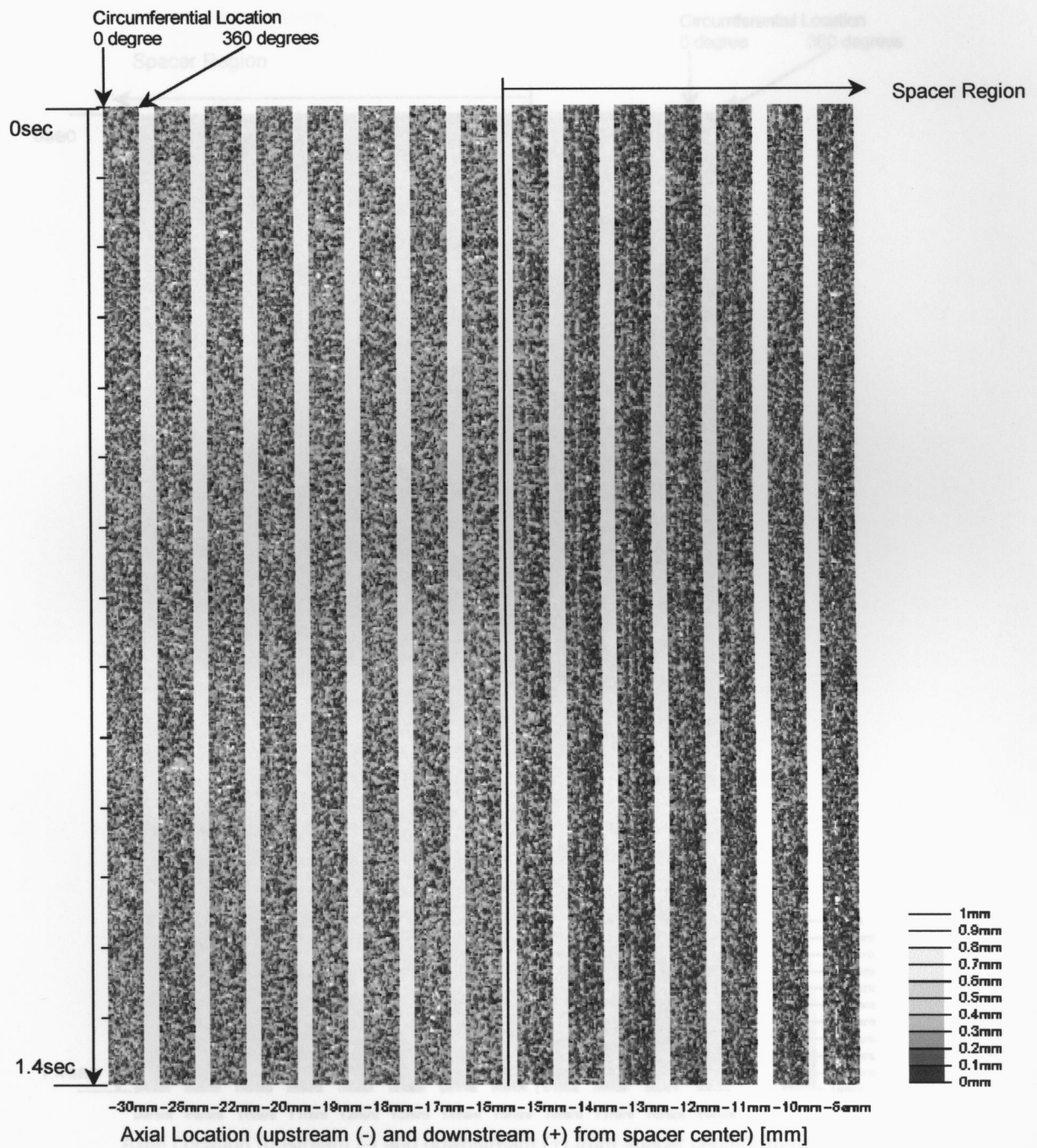


Figure 6.8 (1) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

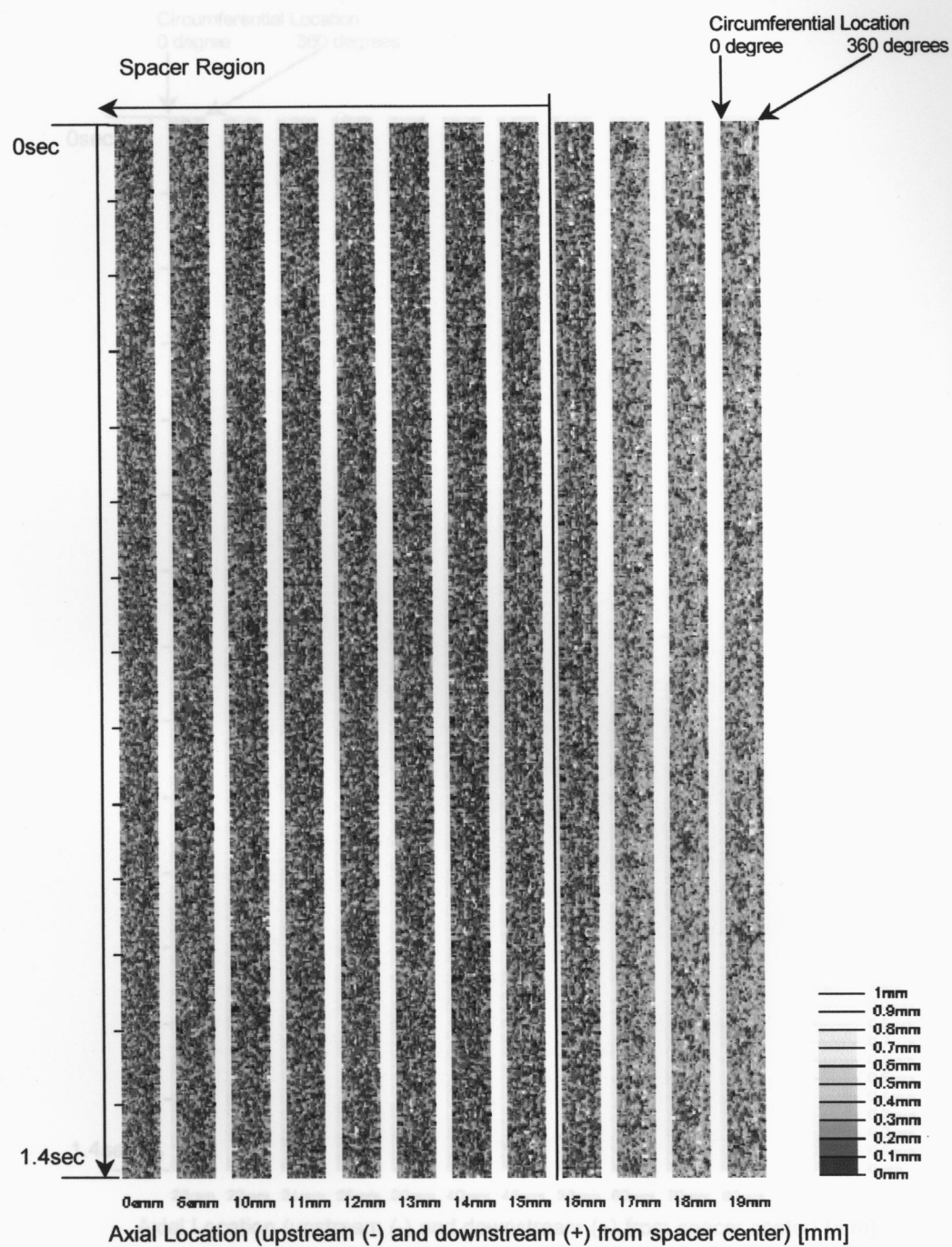


Figure 6.8 (2) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

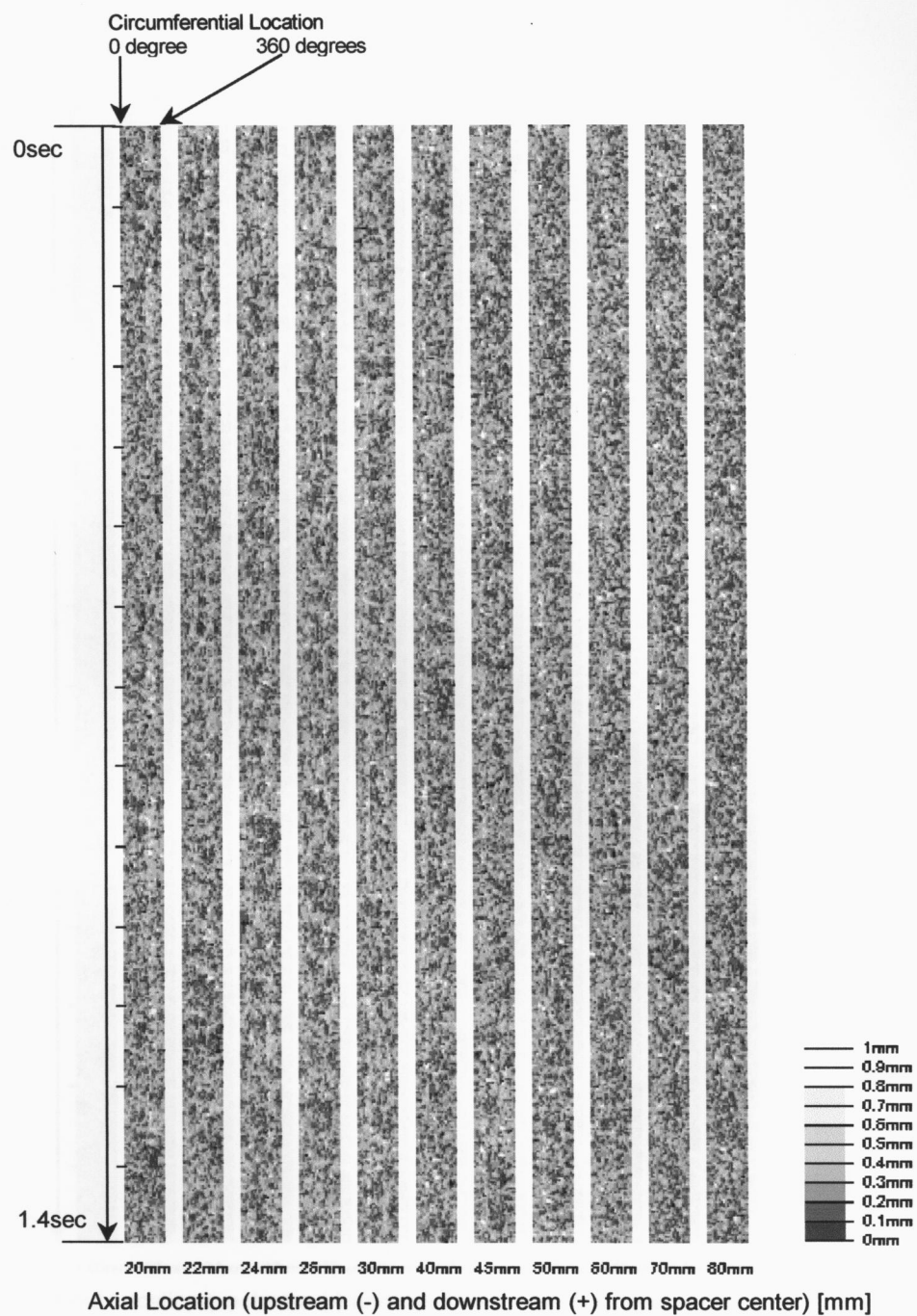


Figure 6.8 (3) Contour Plots of Liquid Film Thickness Distribution around Side-Center Rod (Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

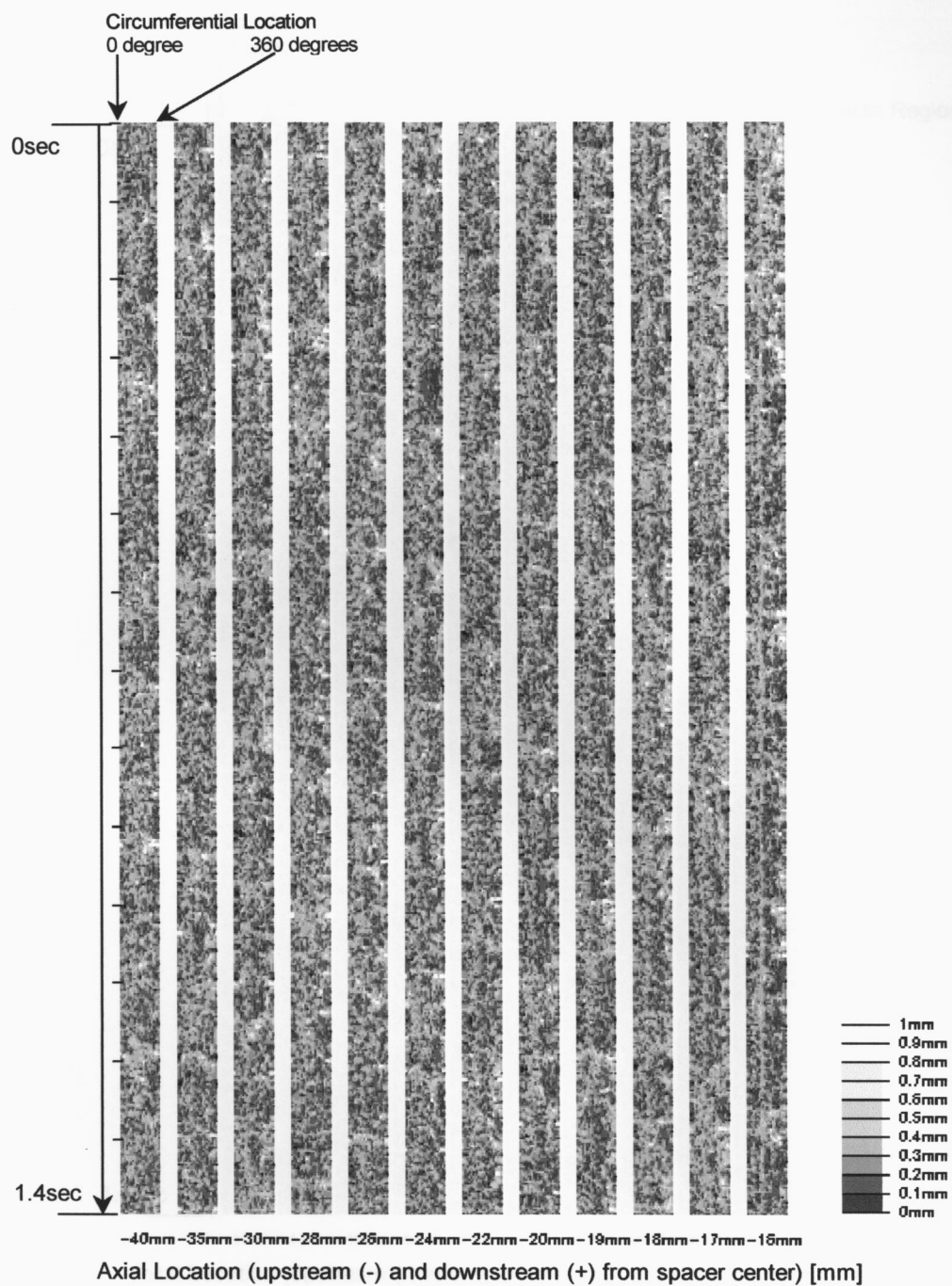


Figure 6.9 (1) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

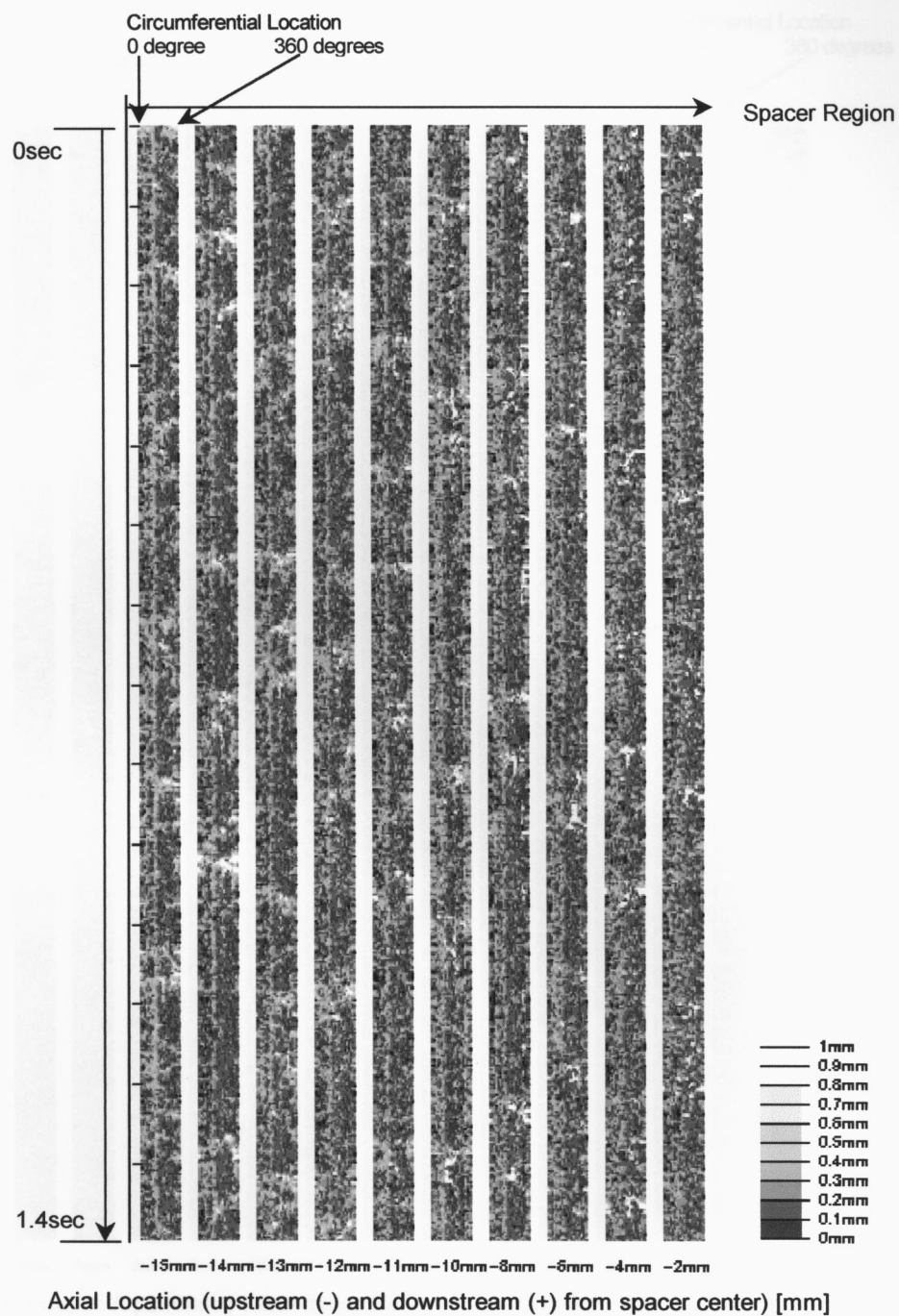


Figure 6.9 (2) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

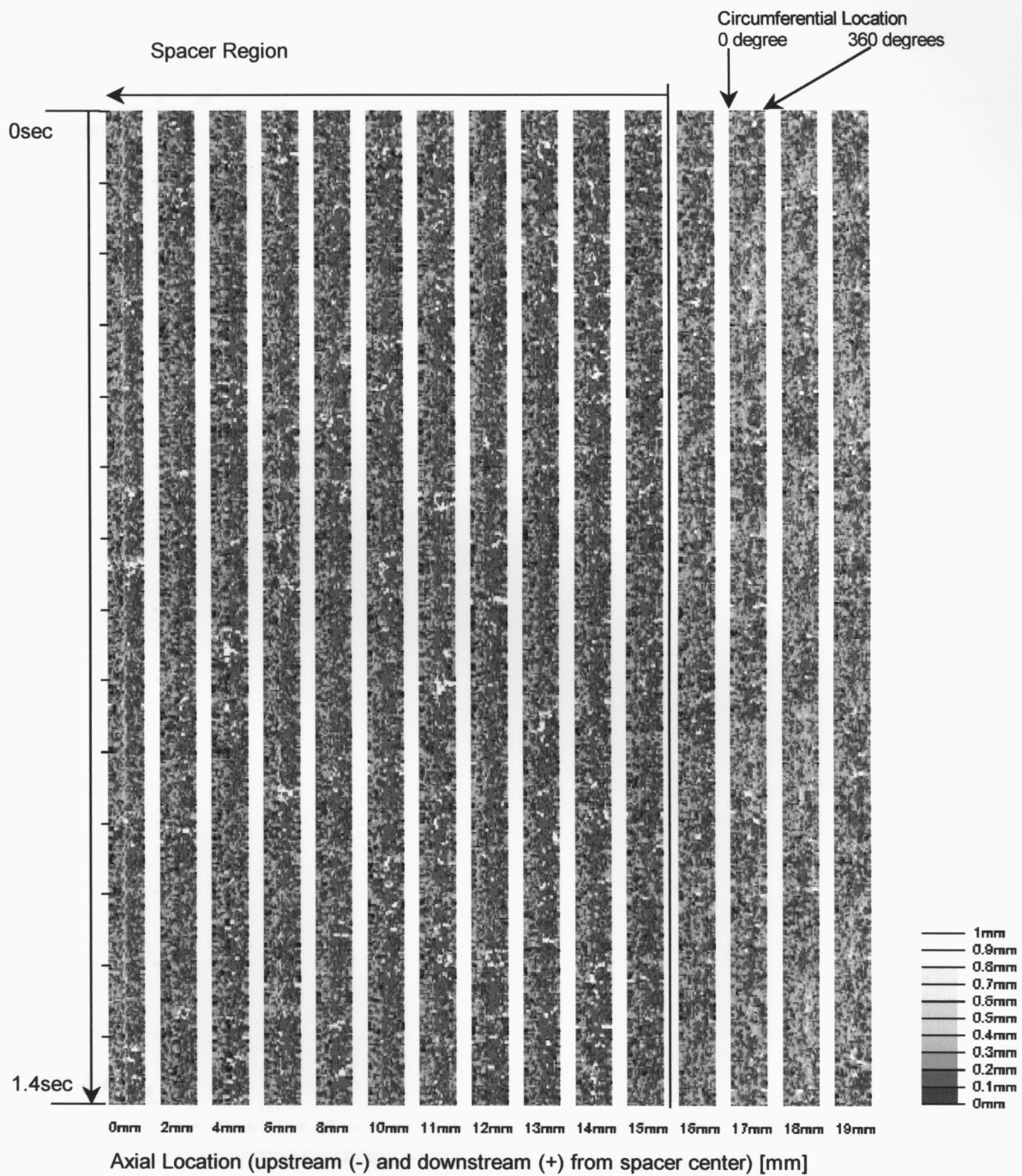


Figure 6.9 (3) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$) Continued

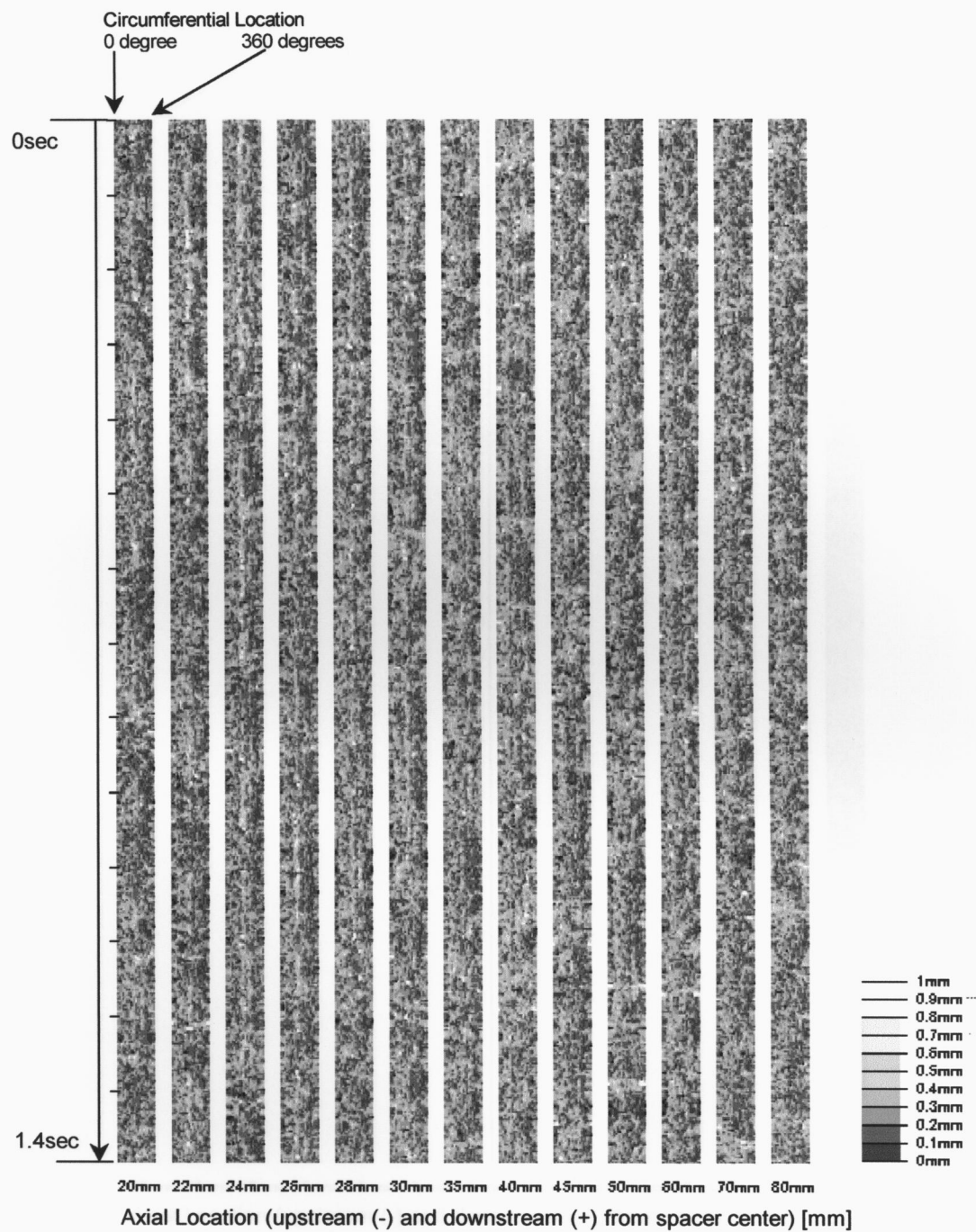


Figure 6.9 (4) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

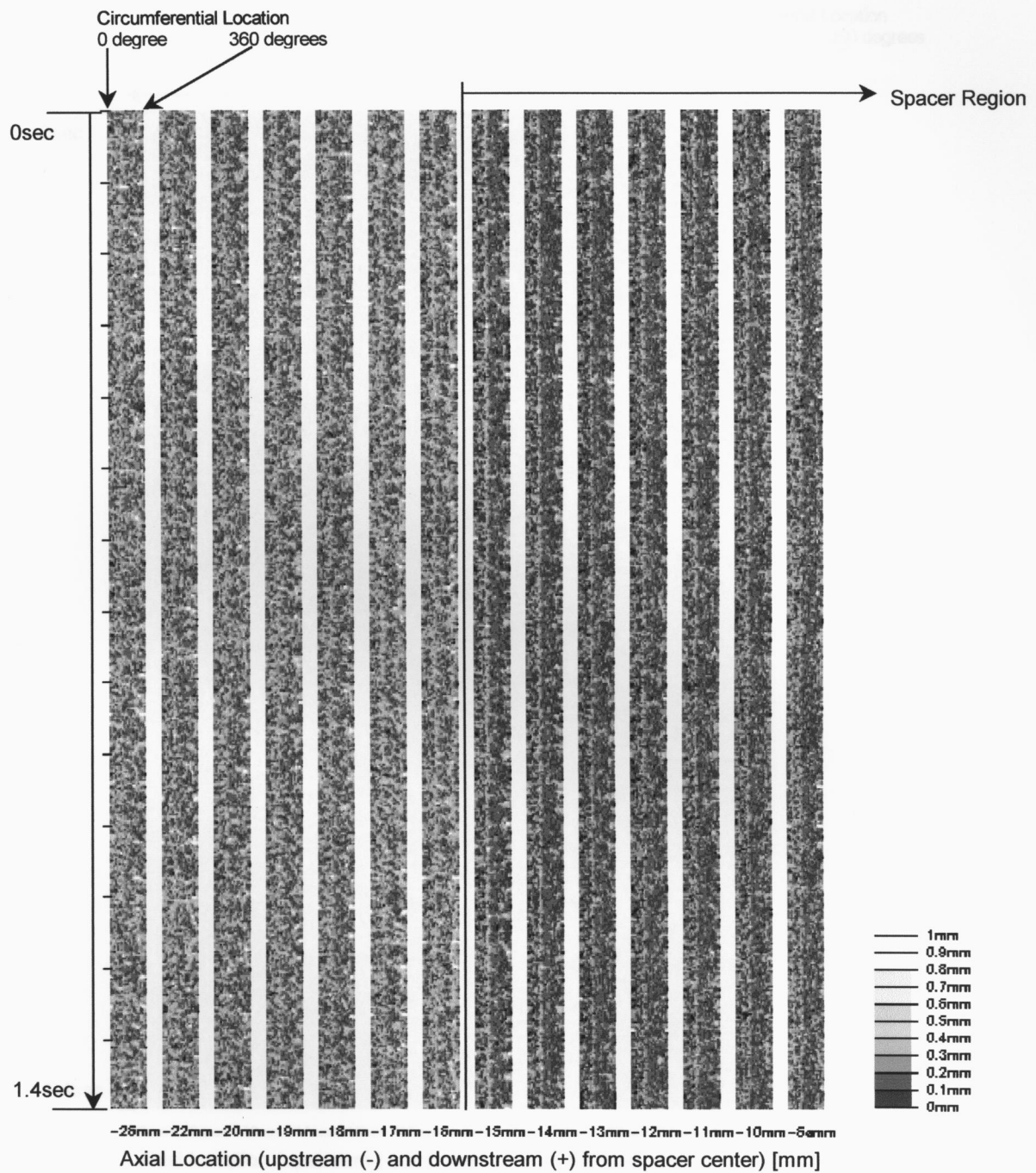


Figure 6.10 (1) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

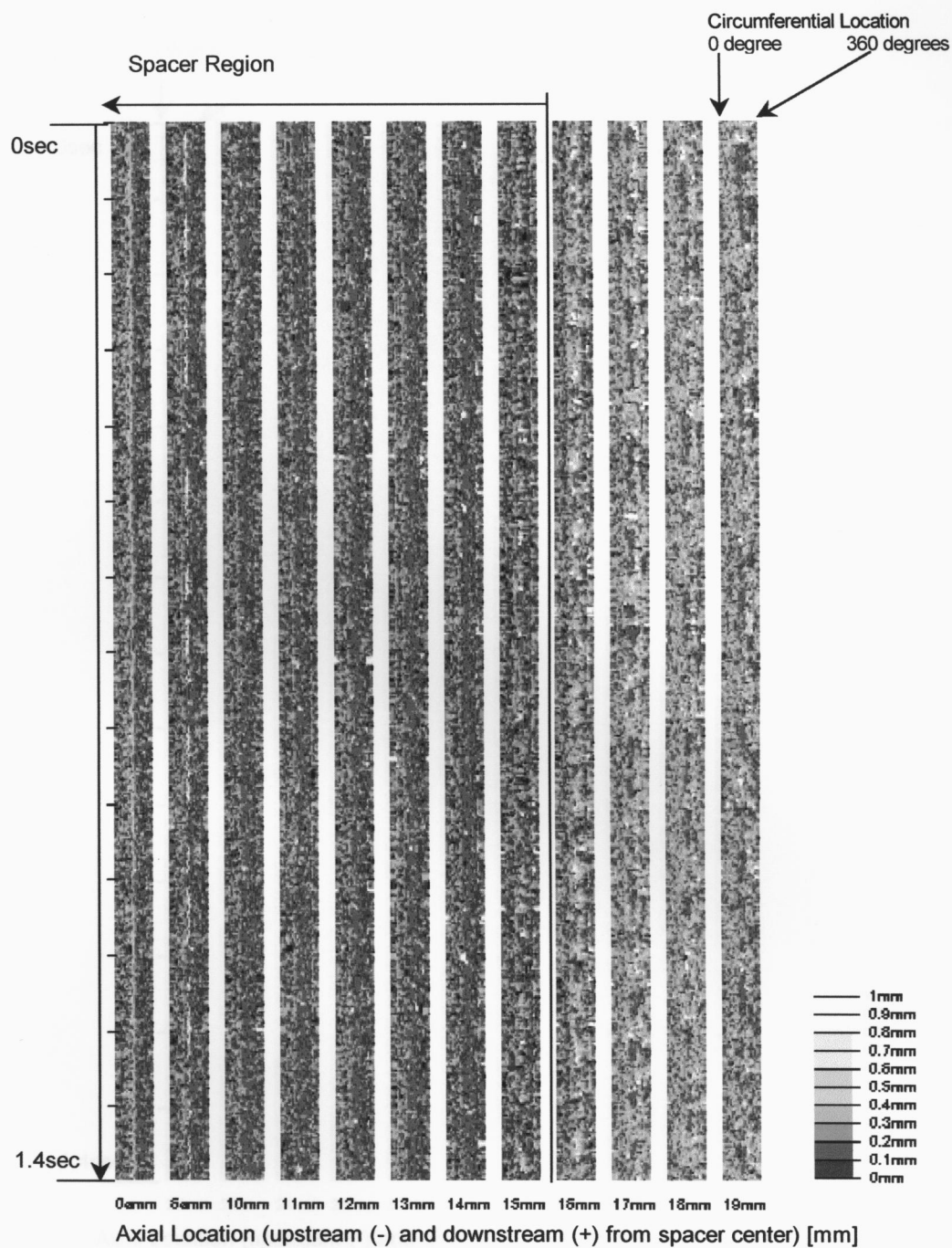


Figure 6.10 (2) Contour Plots of Liquid Film Thickness Distribution around Corner Rod
(Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$) Continued

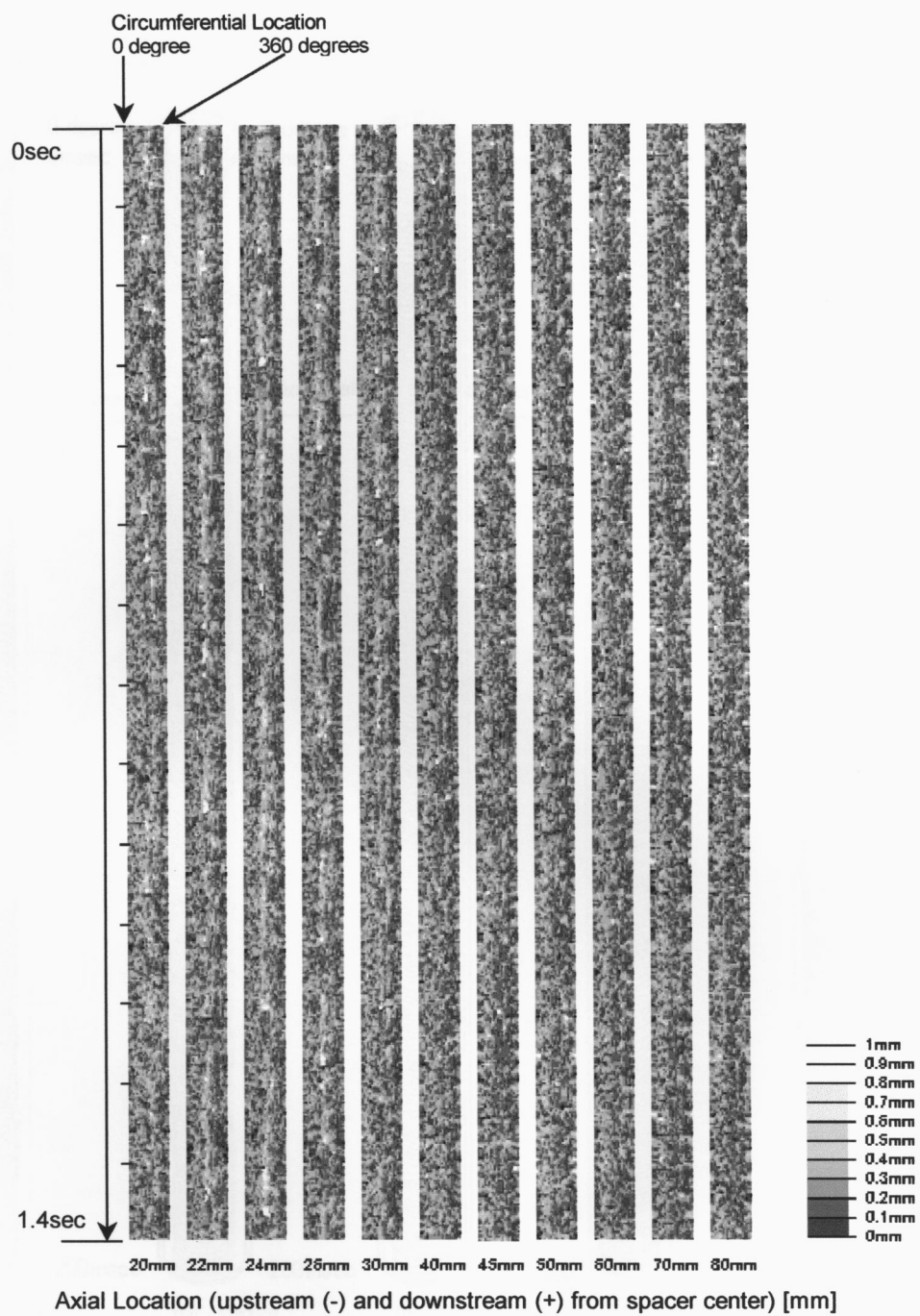


Figure 6.10 (3) Contour Plots of Liquid Film Thickness Distribution around Corner Rod (Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

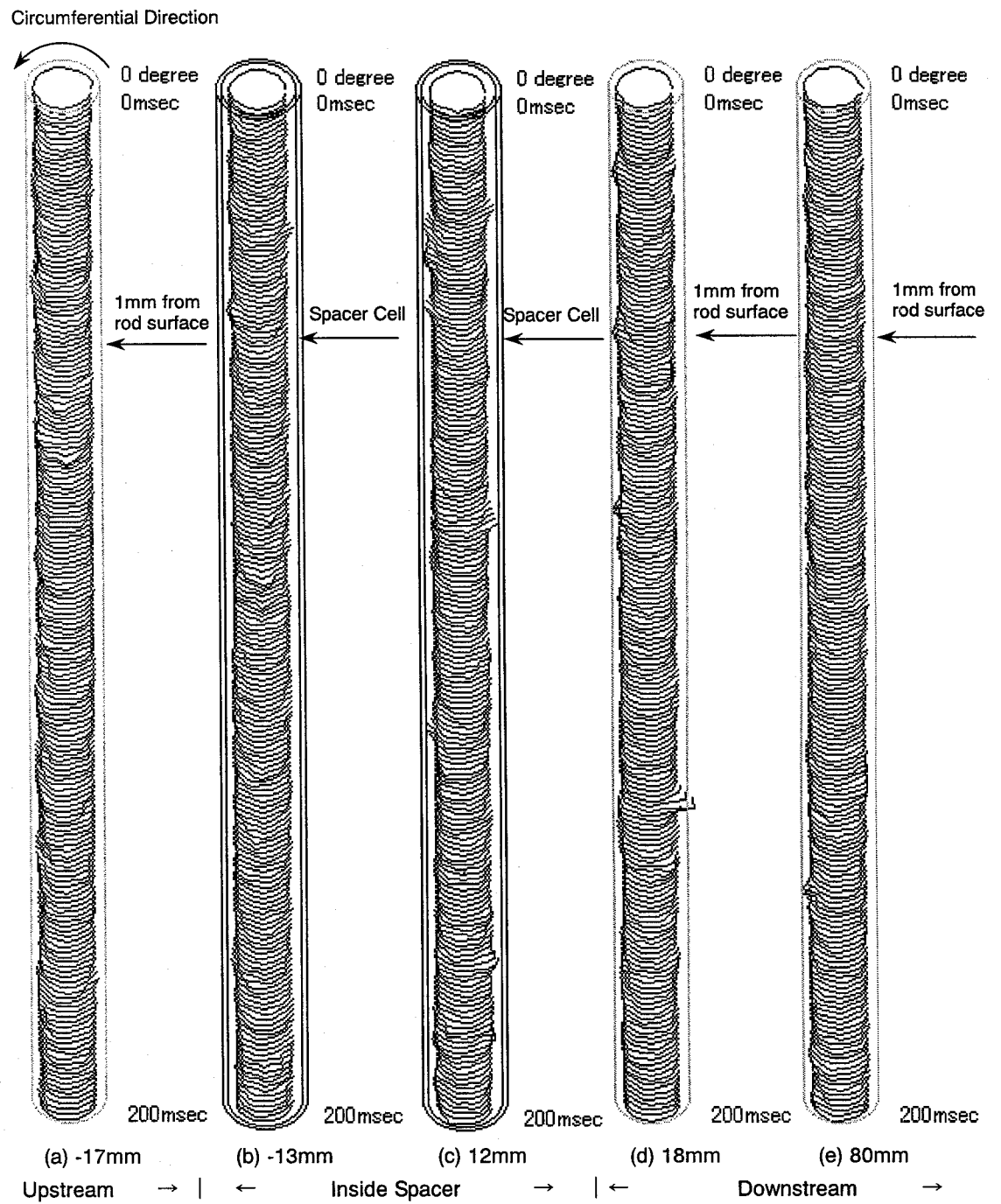


Figure 6.11 Bird's Eye View of Liquid Film Thickness Distribution around Center Rod
(Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

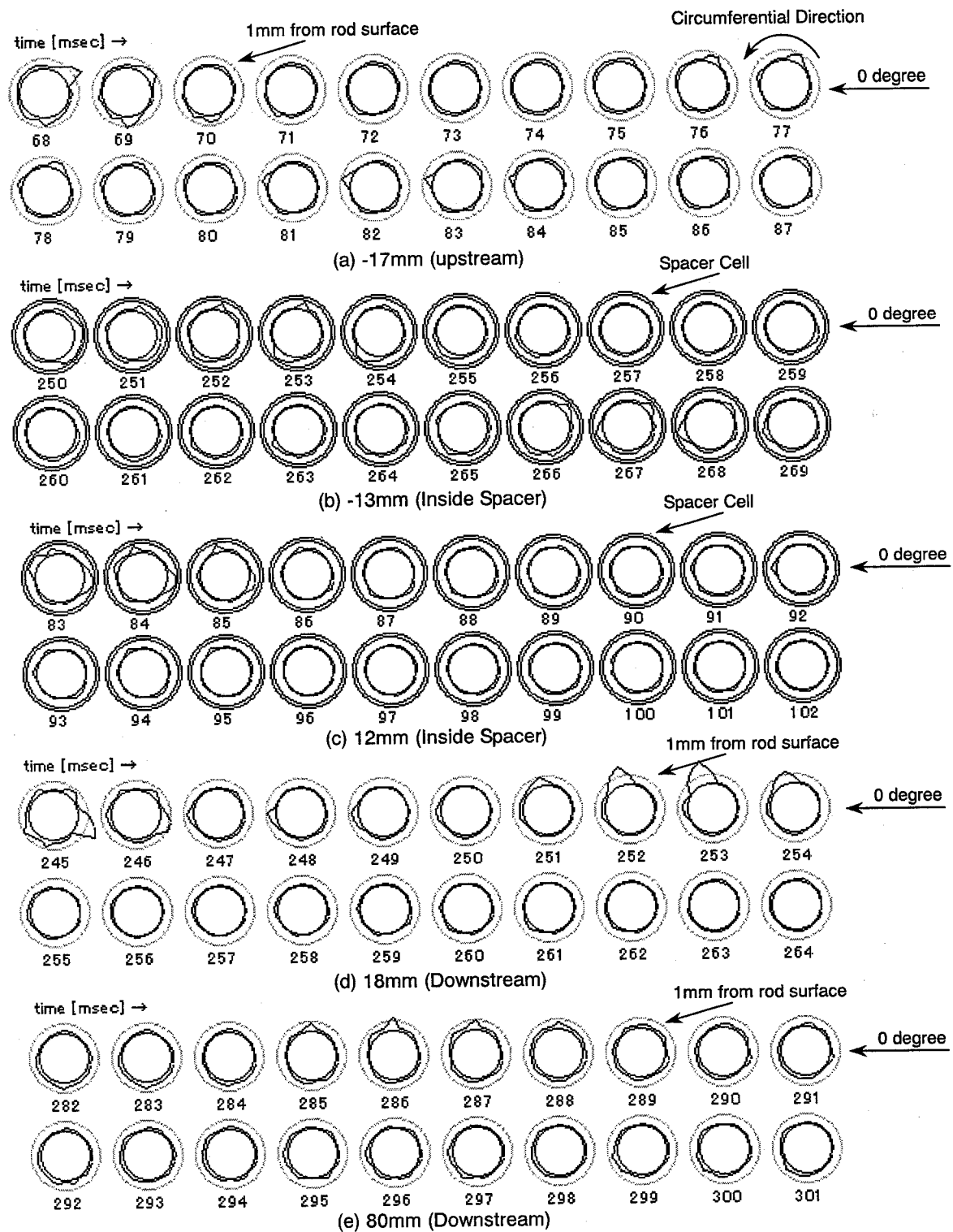
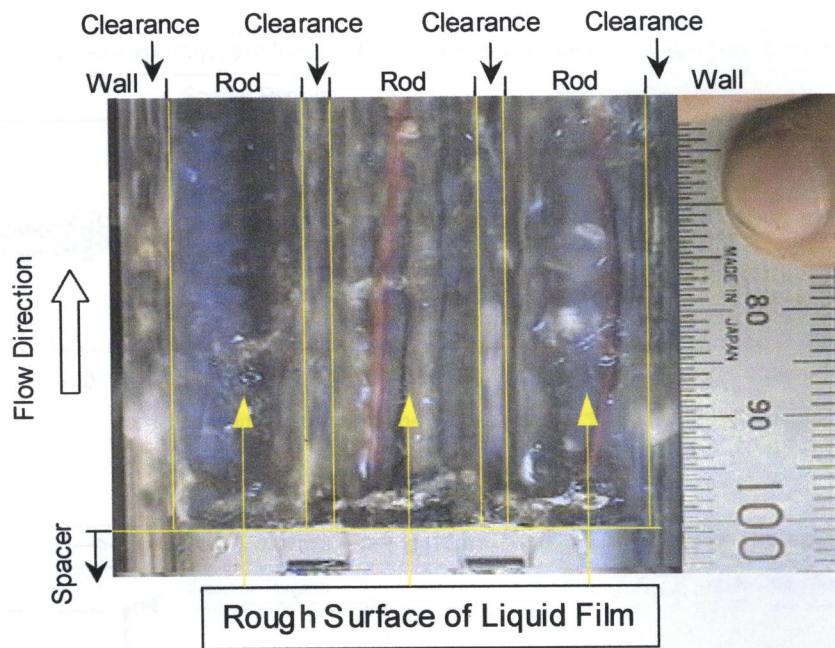
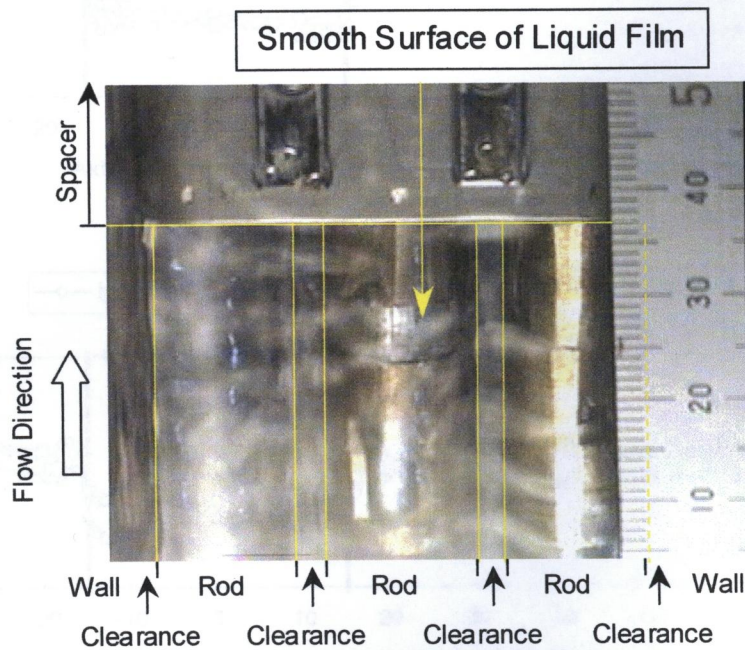


Figure 6.12 Cross-Sectional View of Liquid Film Thickness Distribution around Center Rod (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

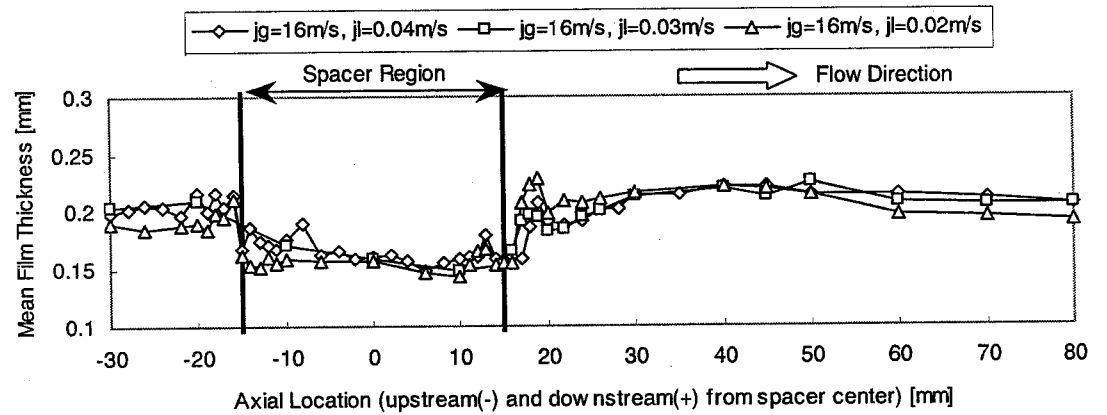


(b) Downstream of the Spacer

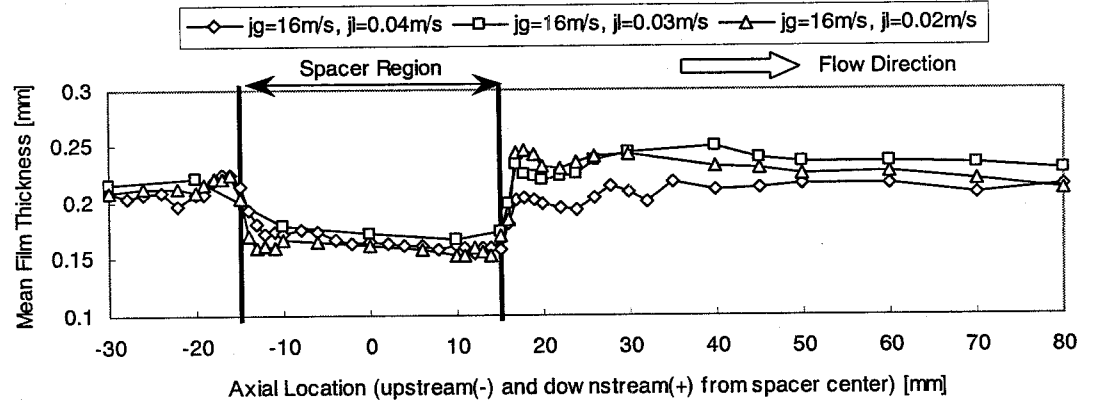


(a) Upstream of the Spacer

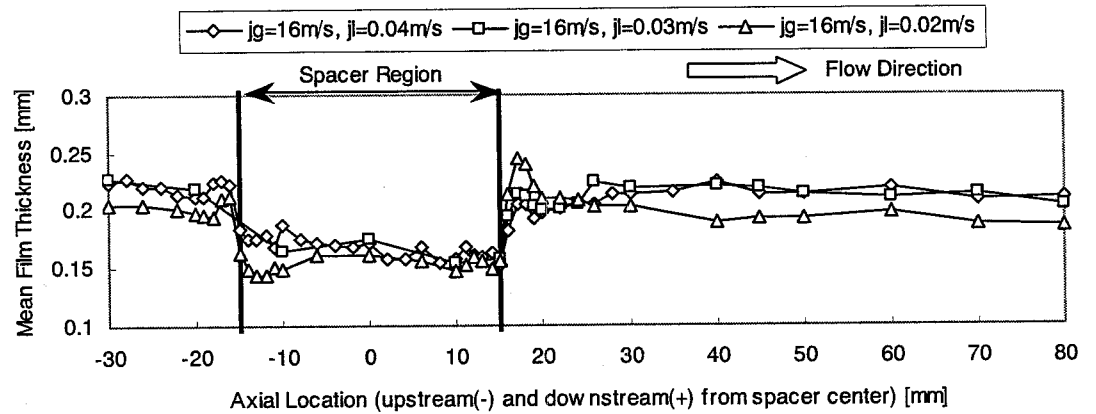
Figure 6.13 Photographic images of Liquid Film Flow in Rod-Bundle ($j_g=10\text{m/s}$, $j_l=0.017\text{m/s}$)



(a) Center Rod

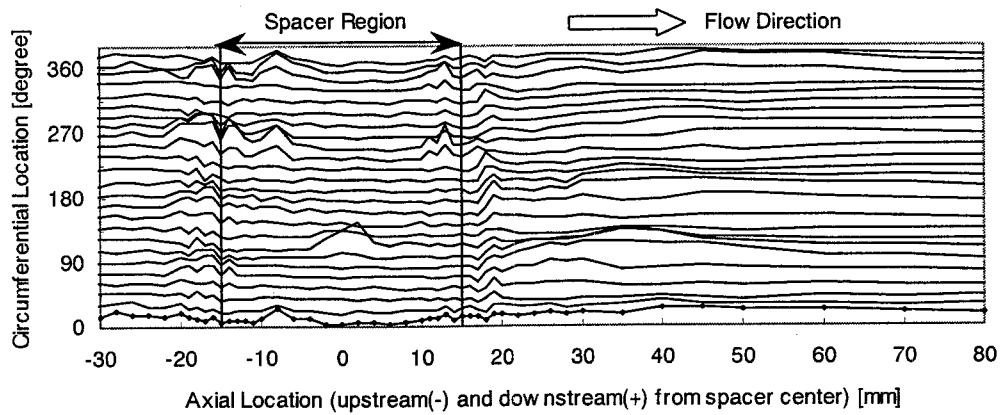


(b) Side-Center Rod

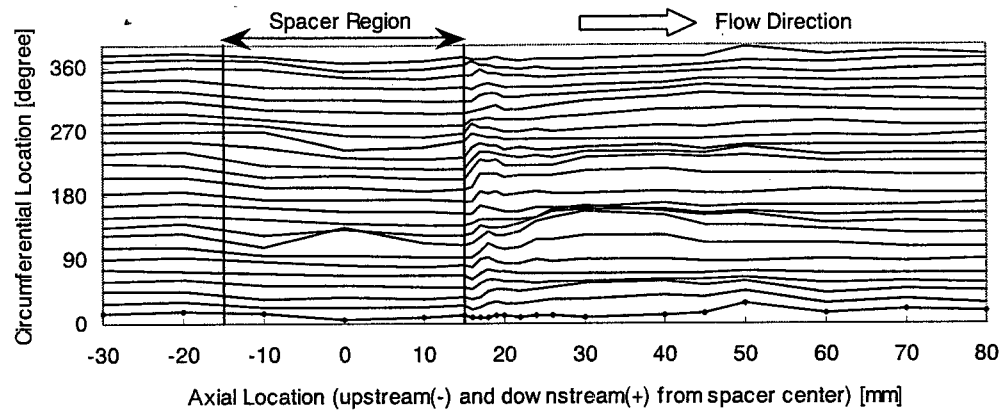


(c) Corner Rod

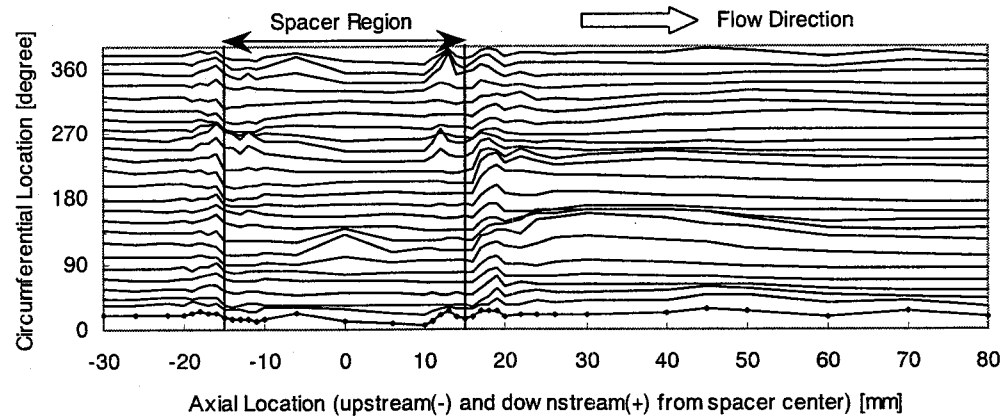
Figure 6.14 Cross-Sectional Averaged Mean Liquid Film Thickness



(a) Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$



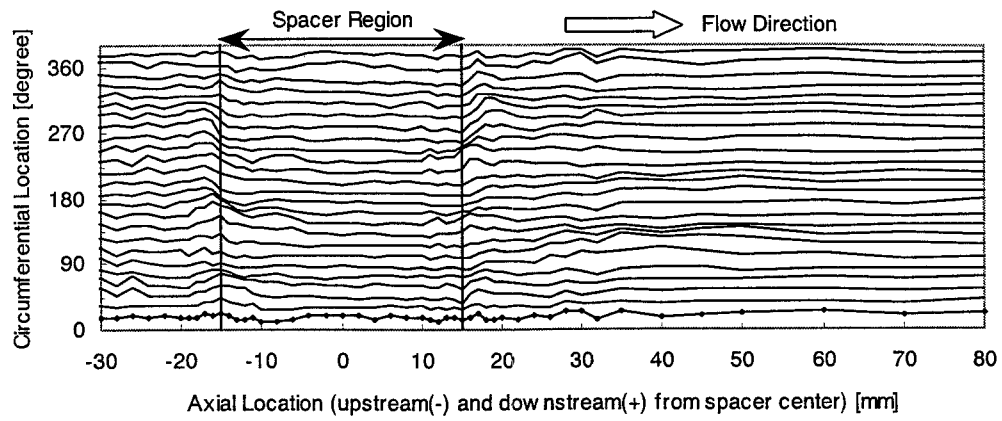
(b) Set2: $j_g=16\text{m/s}$, $j_l=0.03\text{m/s}$



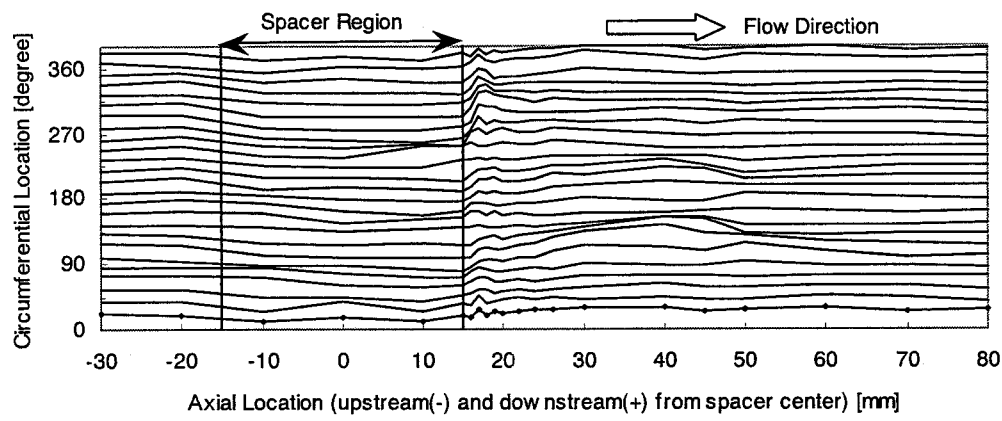
(c) Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$

Figure 6.15 Mean Liquid Film Thickness at Circumferential Locations (Center Rod)

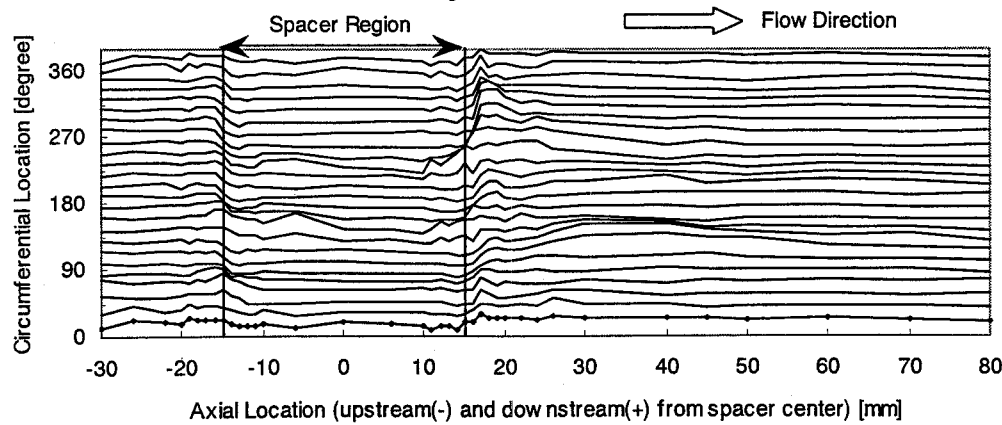
♦ : Measured Positions in Longitudinal Direction



(a) Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$



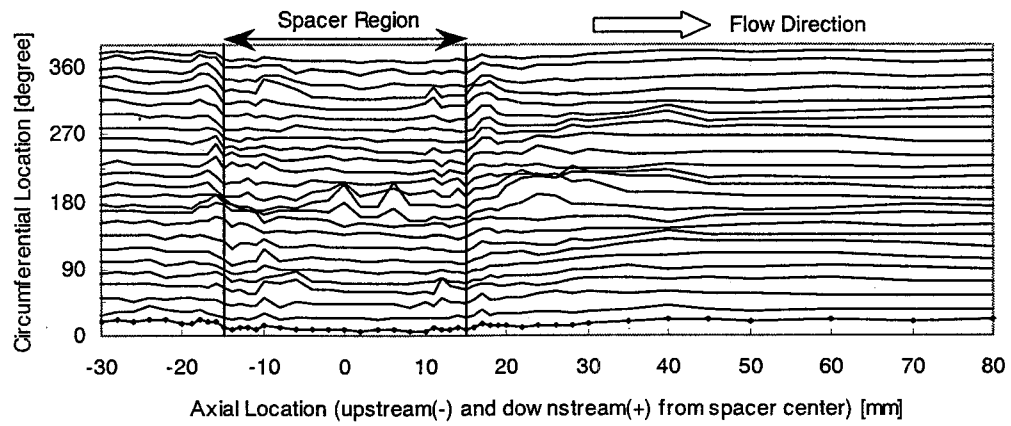
(b) Set2: $j_g=16\text{m/s}$, $j_l=0.03\text{m/s}$



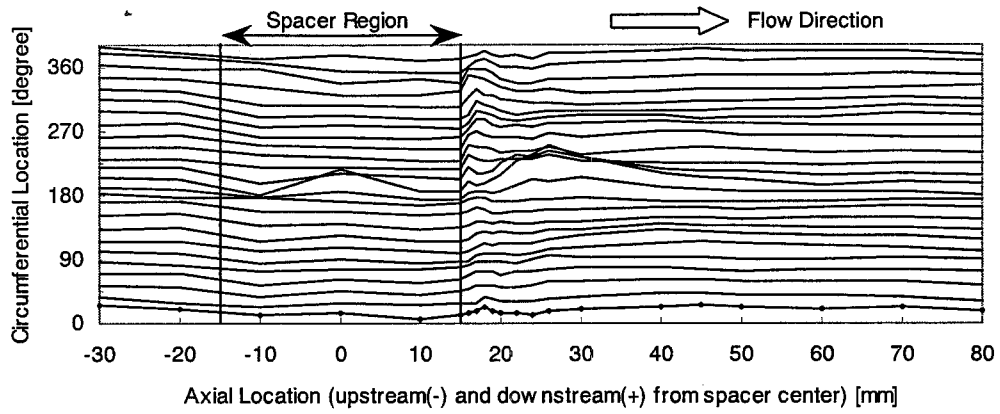
(c) Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$

Figure 6.16 Mean Liquid Film Thickness at Circumferential Locations (Side-Center Rod)

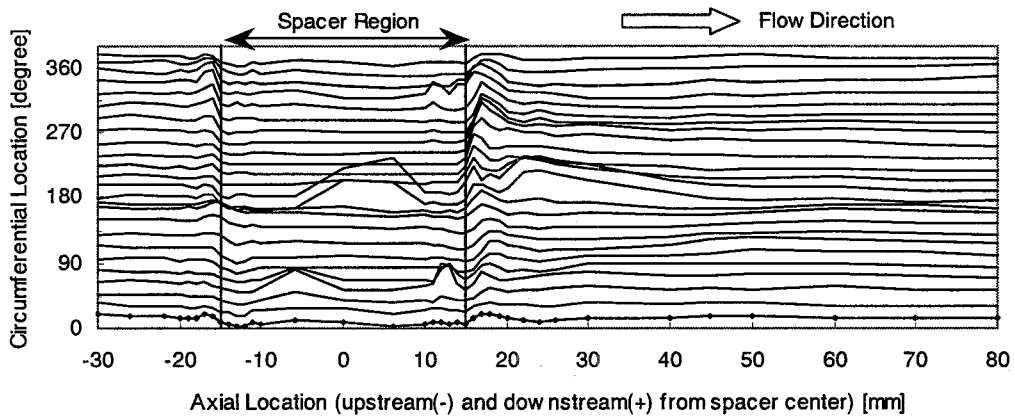
♦ : Measured Positions in Longitudinal Direction



(a) Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$



(b) Set2: $j_g=16\text{m/s}$, $j_l=0.03\text{m/s}$

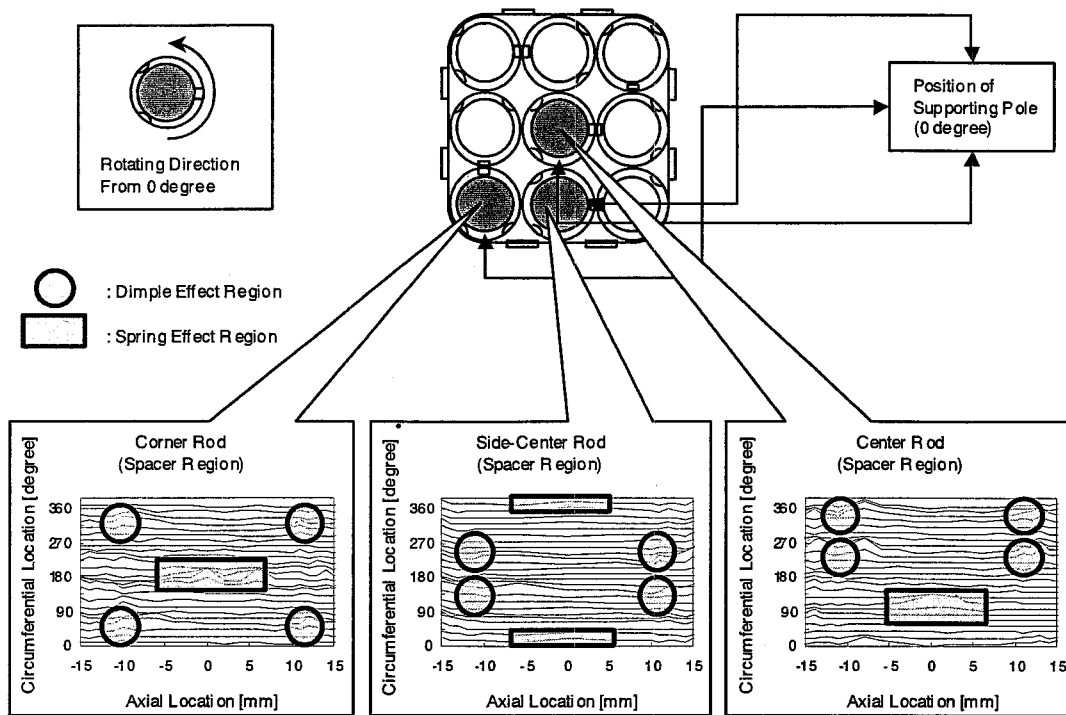


(c) Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$

Figure 6.17 Mean Liquid Film Thickness at Circumferential Locations (Corner Rod)

• : Measured Positions in Longitudinal Direction

(a) Appearance of Dimple Effect and Spring Effect in Spacer Region



(b) Formation of "Liquid Streak" around Dimple and Spring

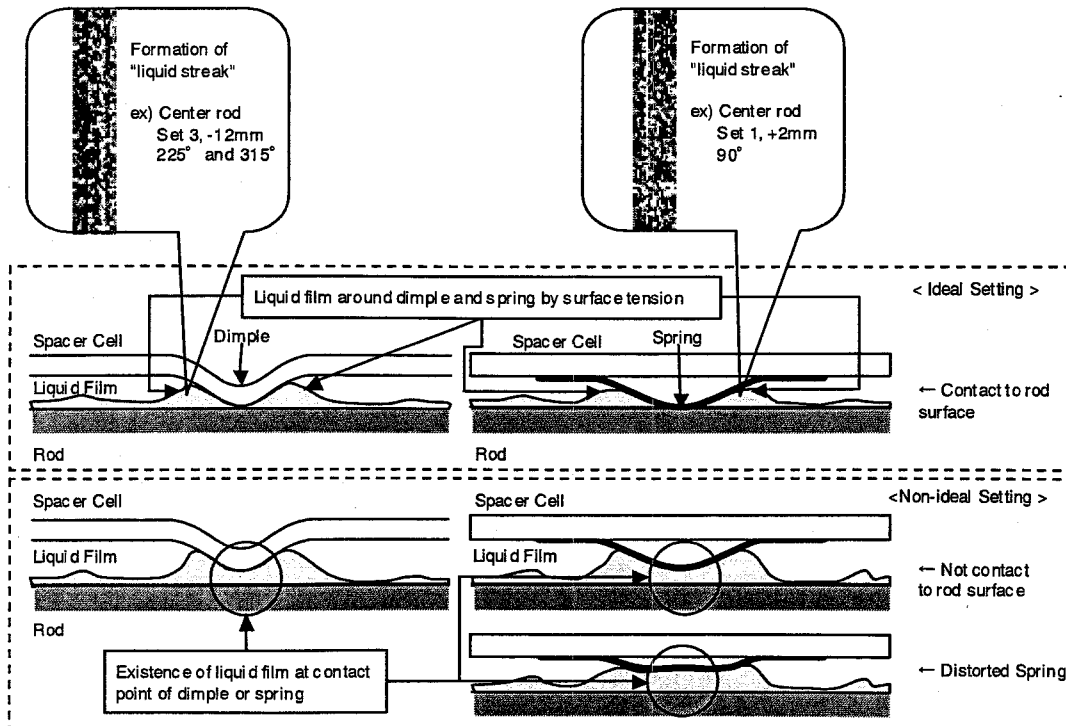
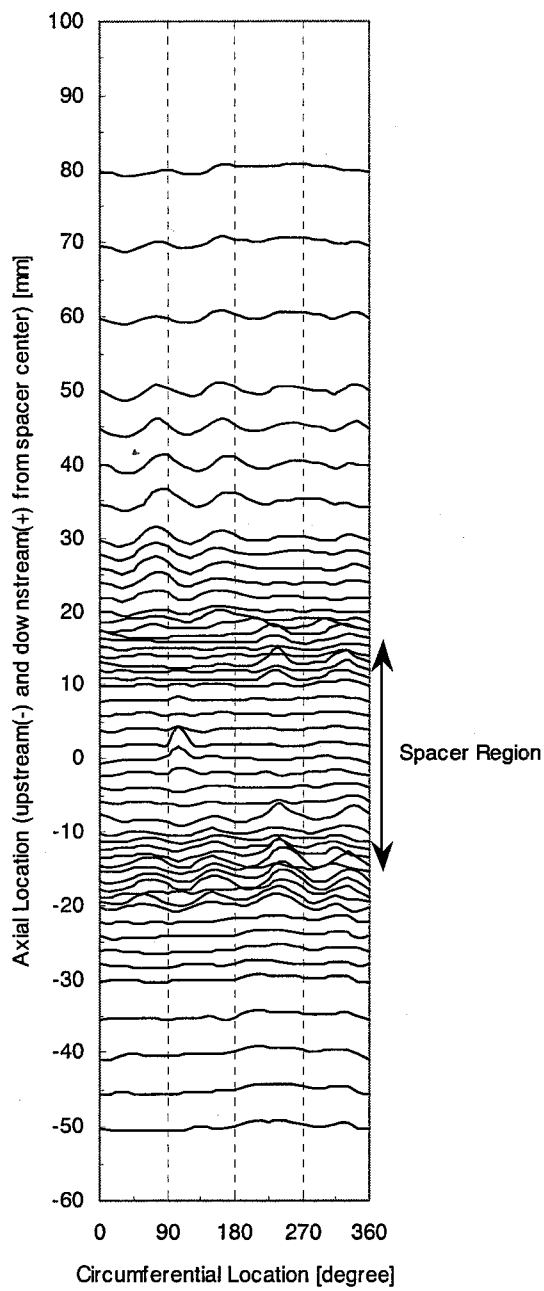
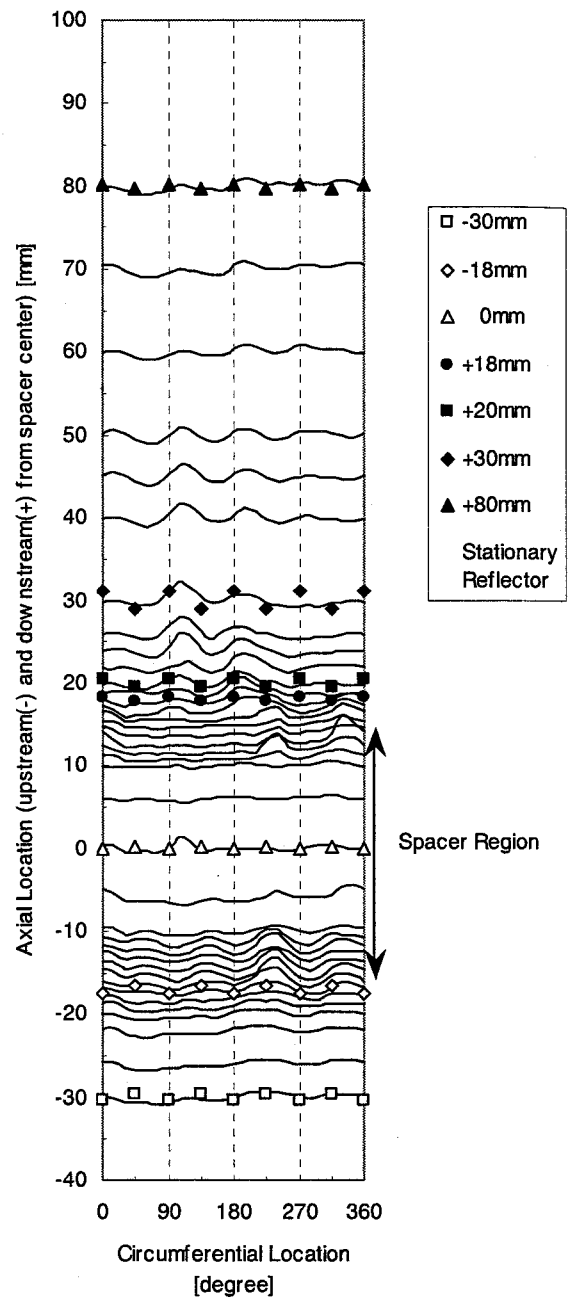


Figure 6.18 Effect of Dimple and Spring on Liquid Film in Spacer Region



(a) Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$



(b) Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$

Figure 6.19 Circumferential Distribution of Mean Liquid Film Thickness (Center rod)

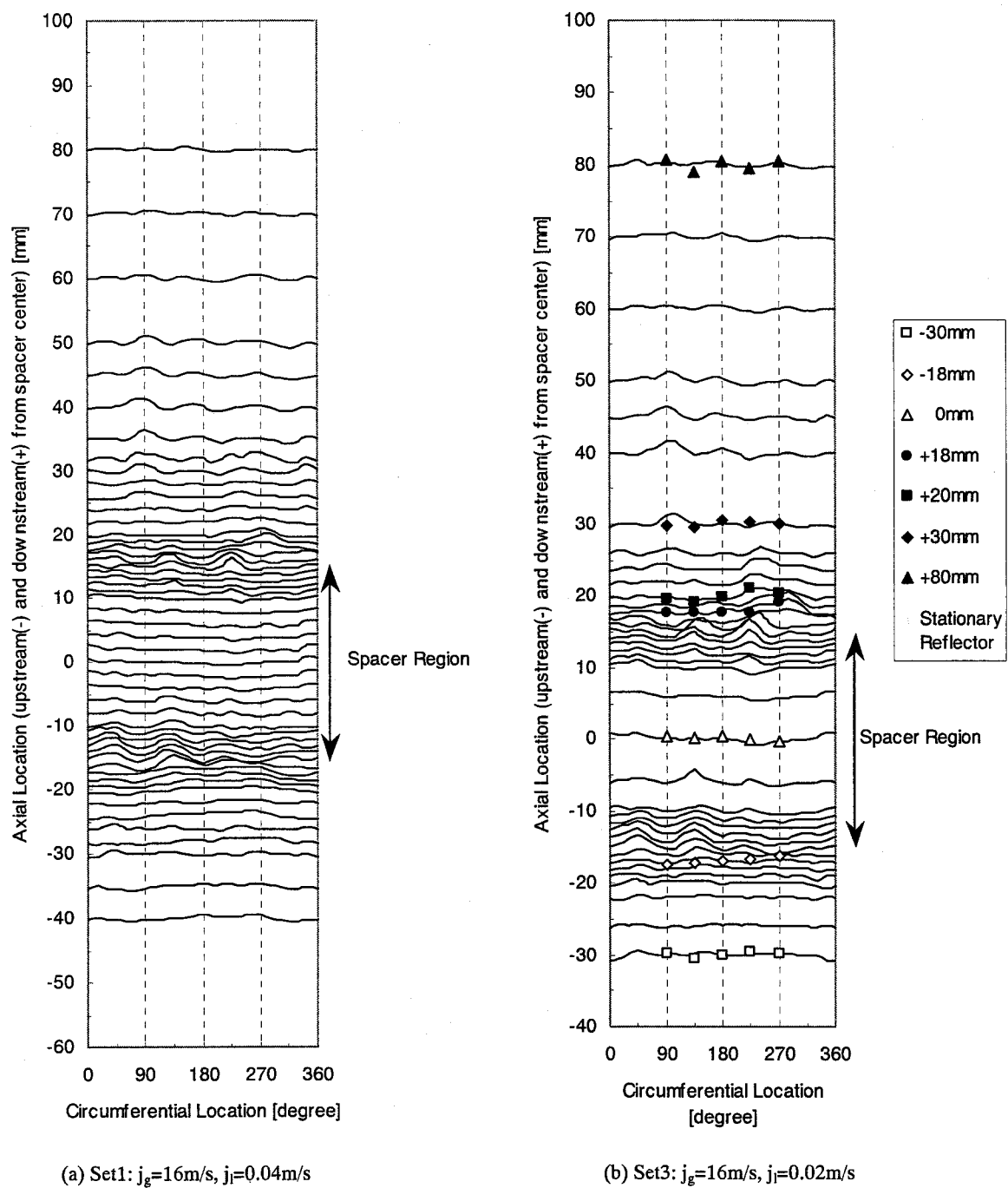
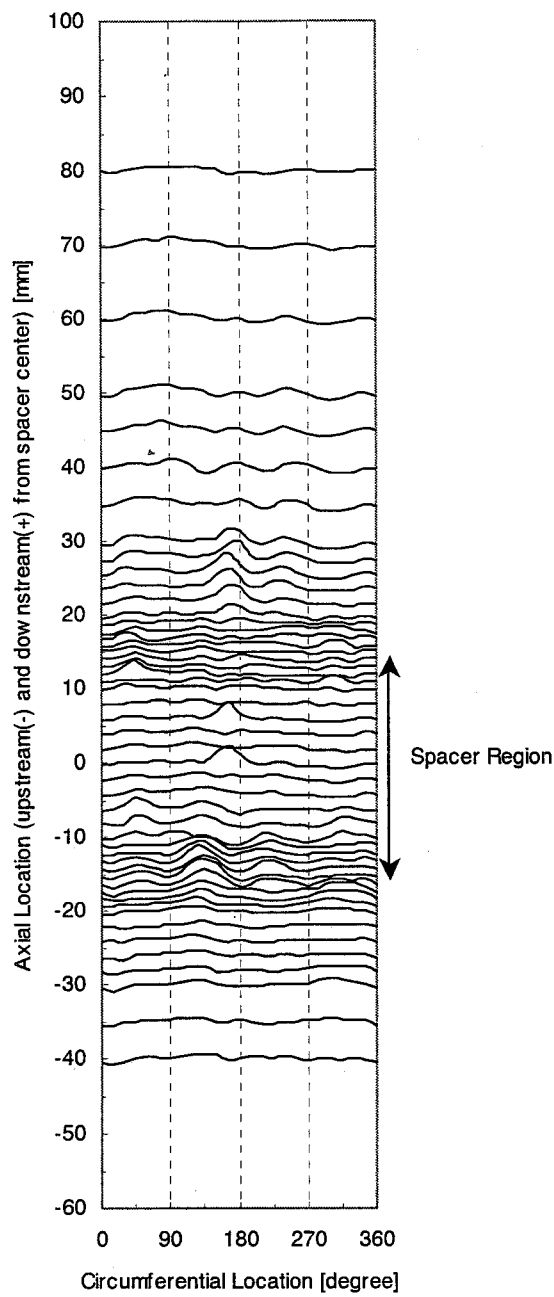
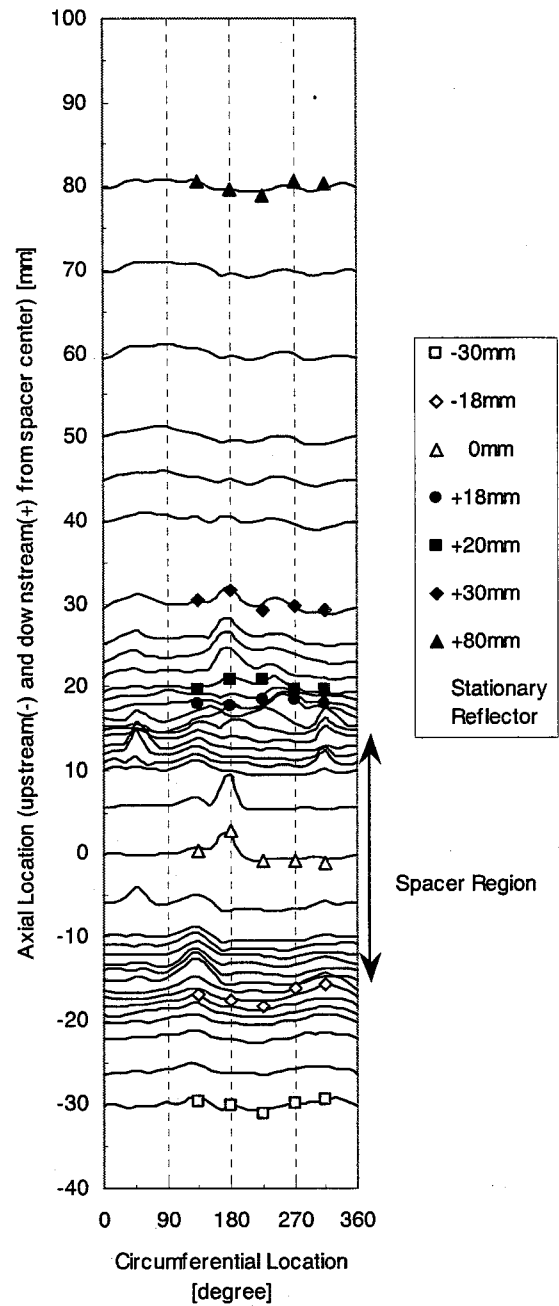


Figure 6.20 Circumferential Distribution of Mean Liquid Film Thickness (Side-Center Rod)

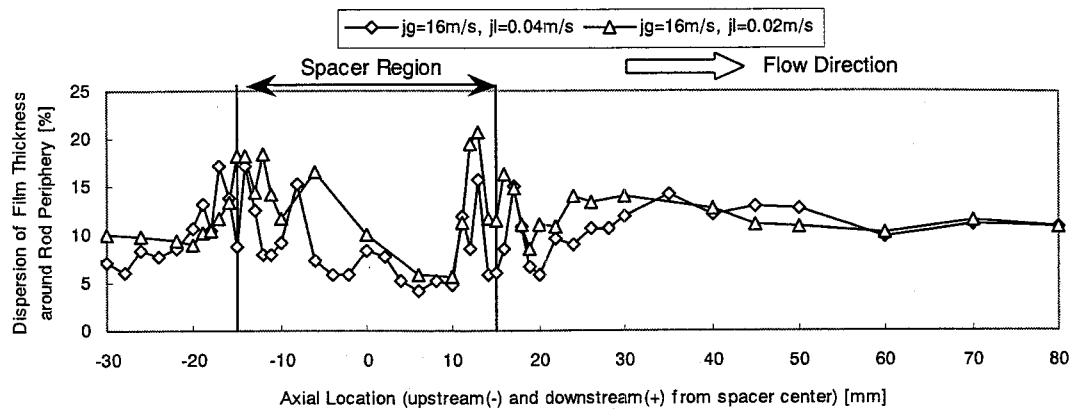


(a) Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$

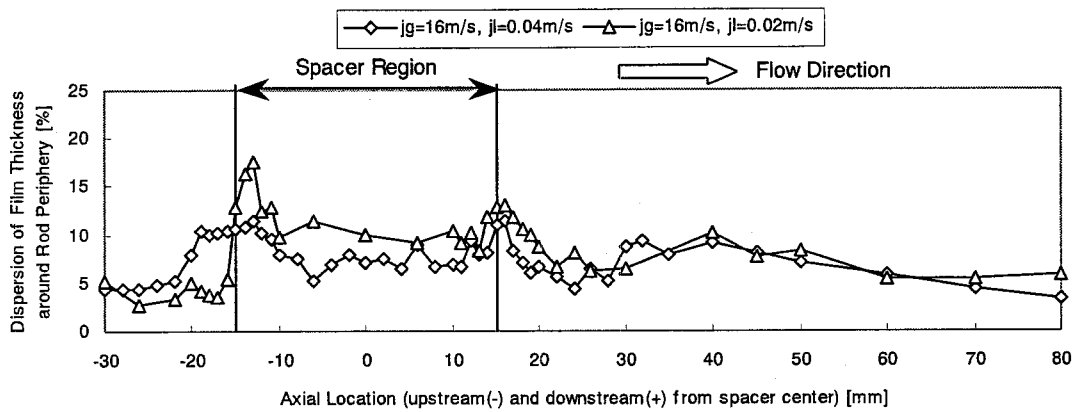


(b) Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$

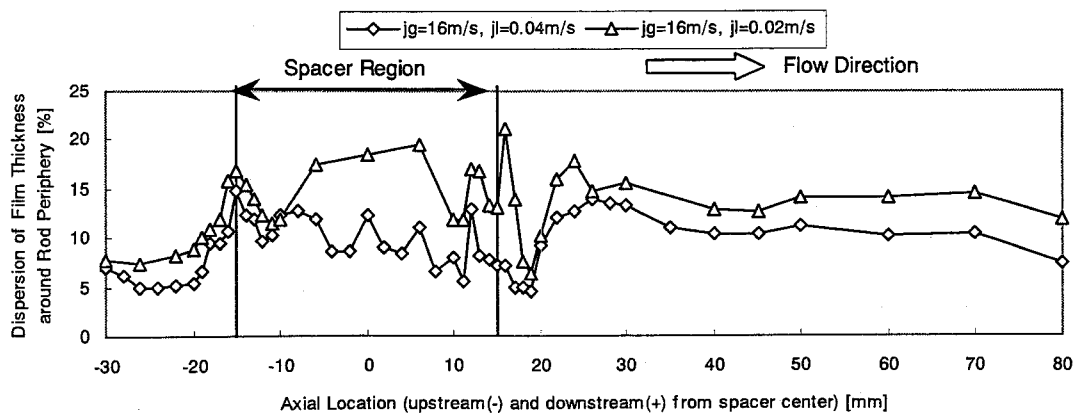
Figure 6.21 Circumferential Distribution of Mean Liquid Film Thickness (Corner rod)



(a) Center Rod

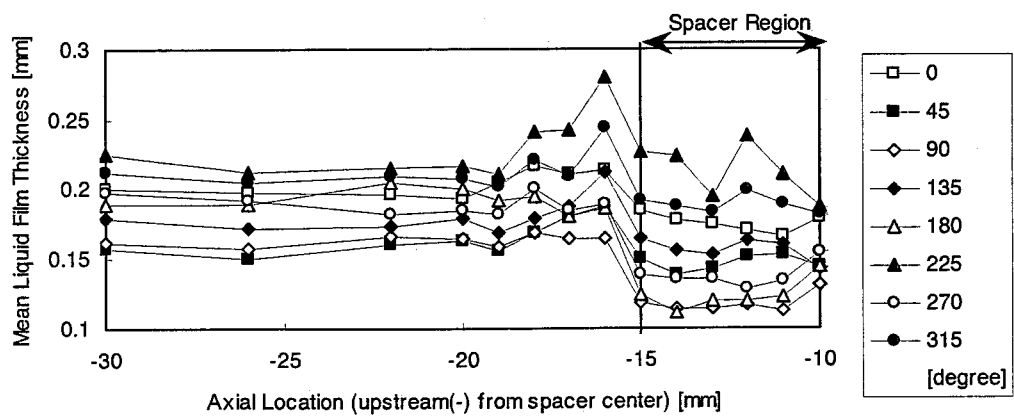


(b) Side-Center Rod

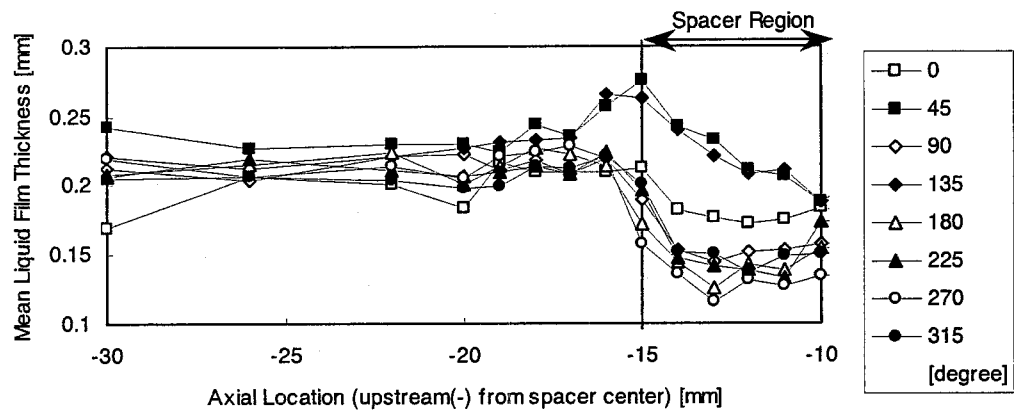


(c) Corner Rod

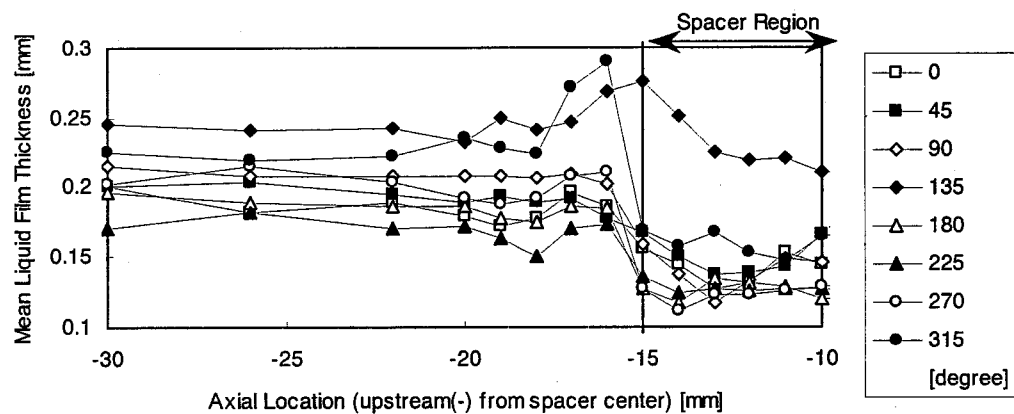
Figure 6.22 Dispersion of Liquid Film Thickness around Rod Periphery



(a) Center Rod



(b) Side-Center Rod



(c) Corner Rod

Figure 6.23 Mean Liquid Film Thickness in the upstream of Spacer (Set3: $j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

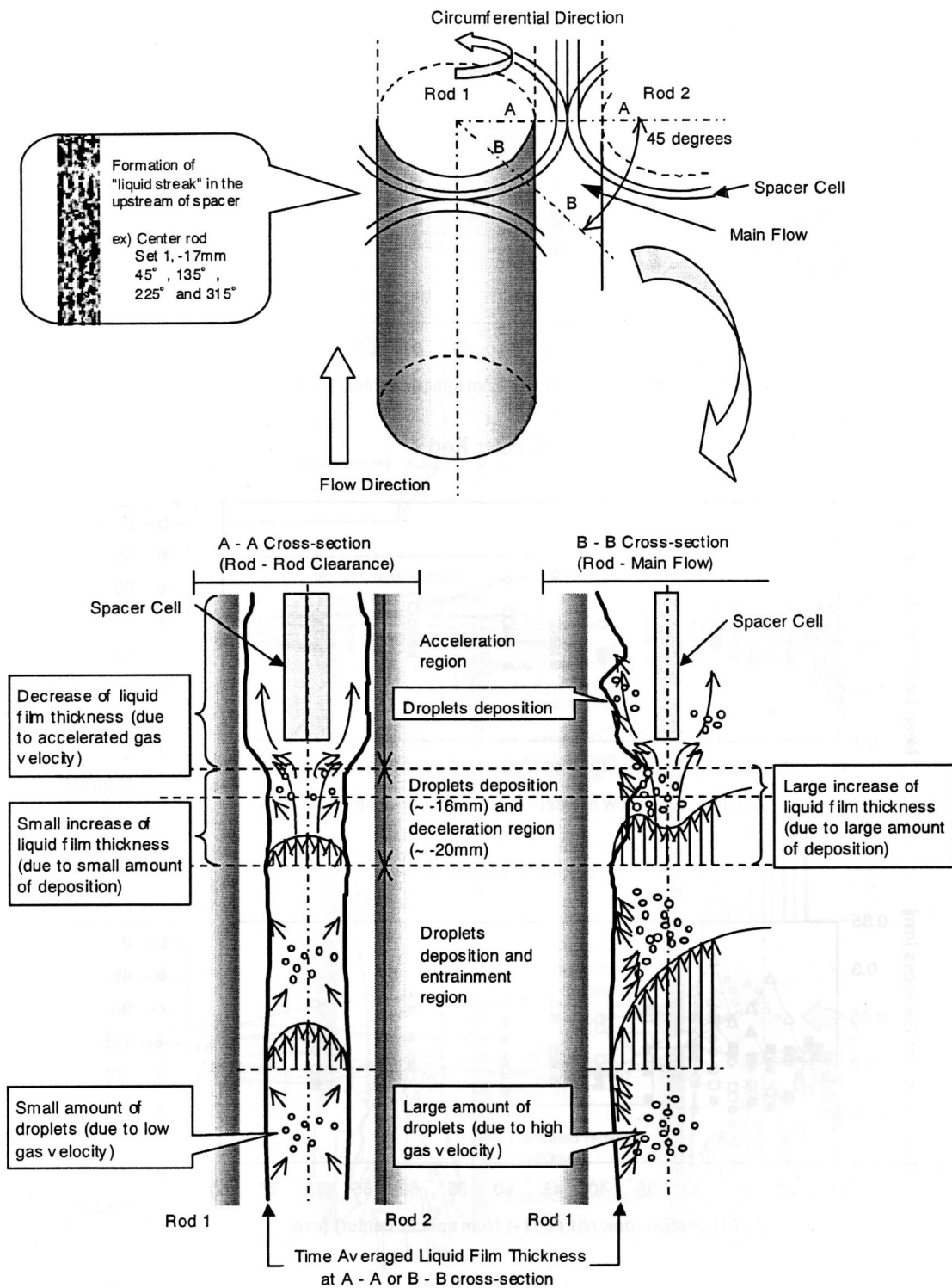
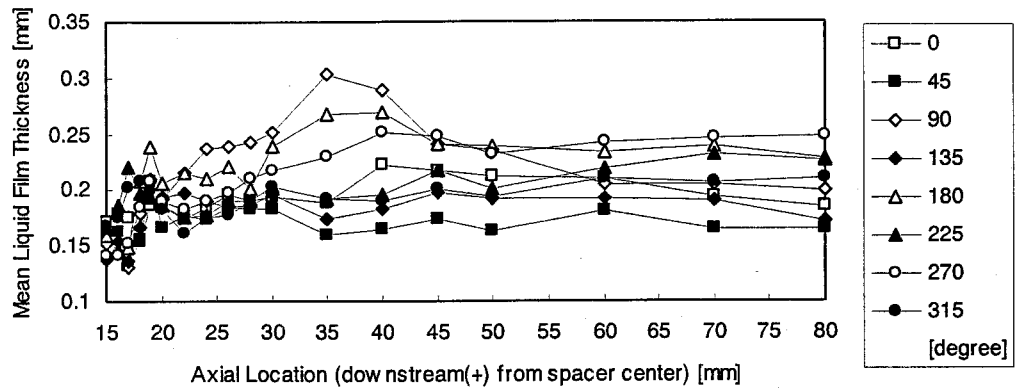
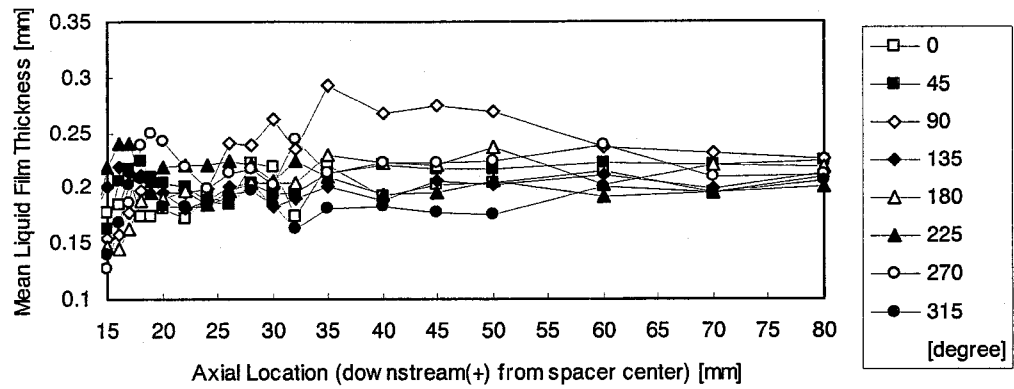


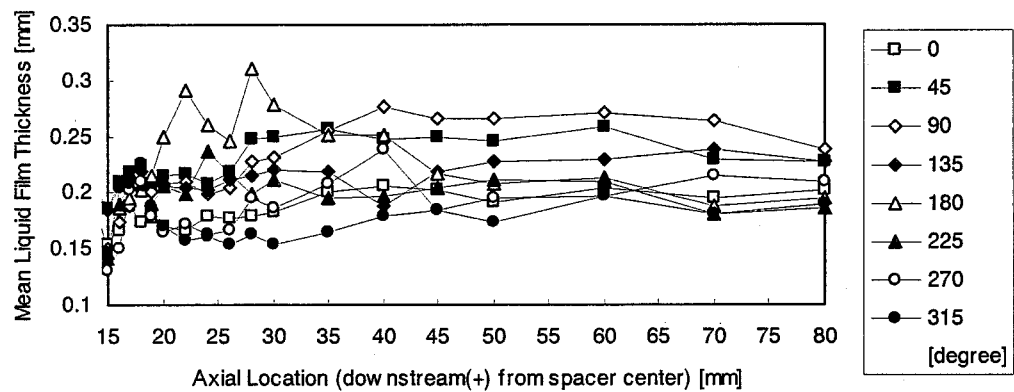
Figure 6.24 Evolution of Liquid Film Thickness at Different Circumferential Location (upstream)



(a) Center Rod



(b) Side-Center Rod



(c) Corner Rod

Figure 6.25 Mean Liquid Film Thickness in the downstream of Spacer (Set1: $j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

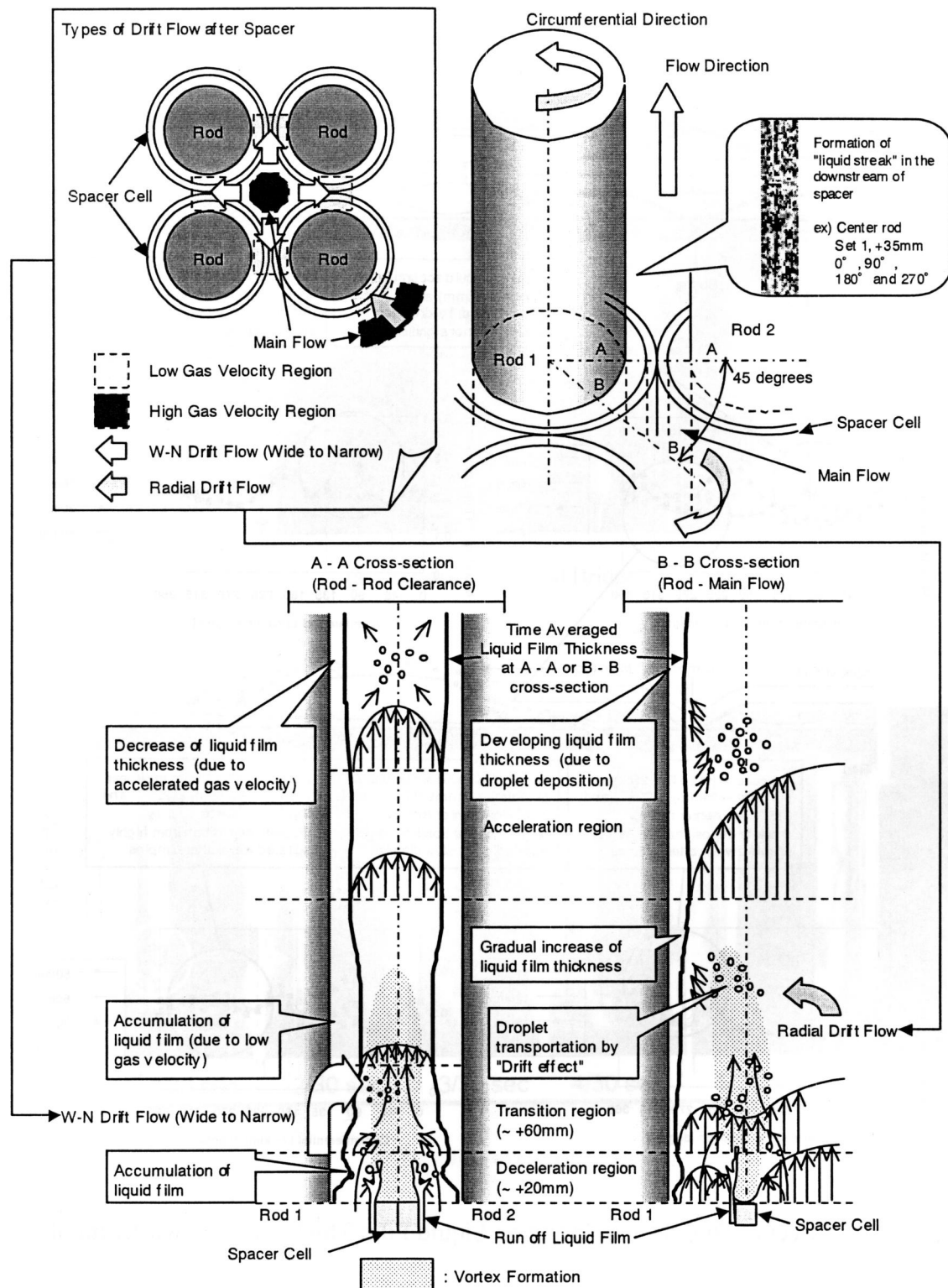


Figure 6.26 Evolution of Liquid Film Thickness at Different Circumferential Location (downstream)

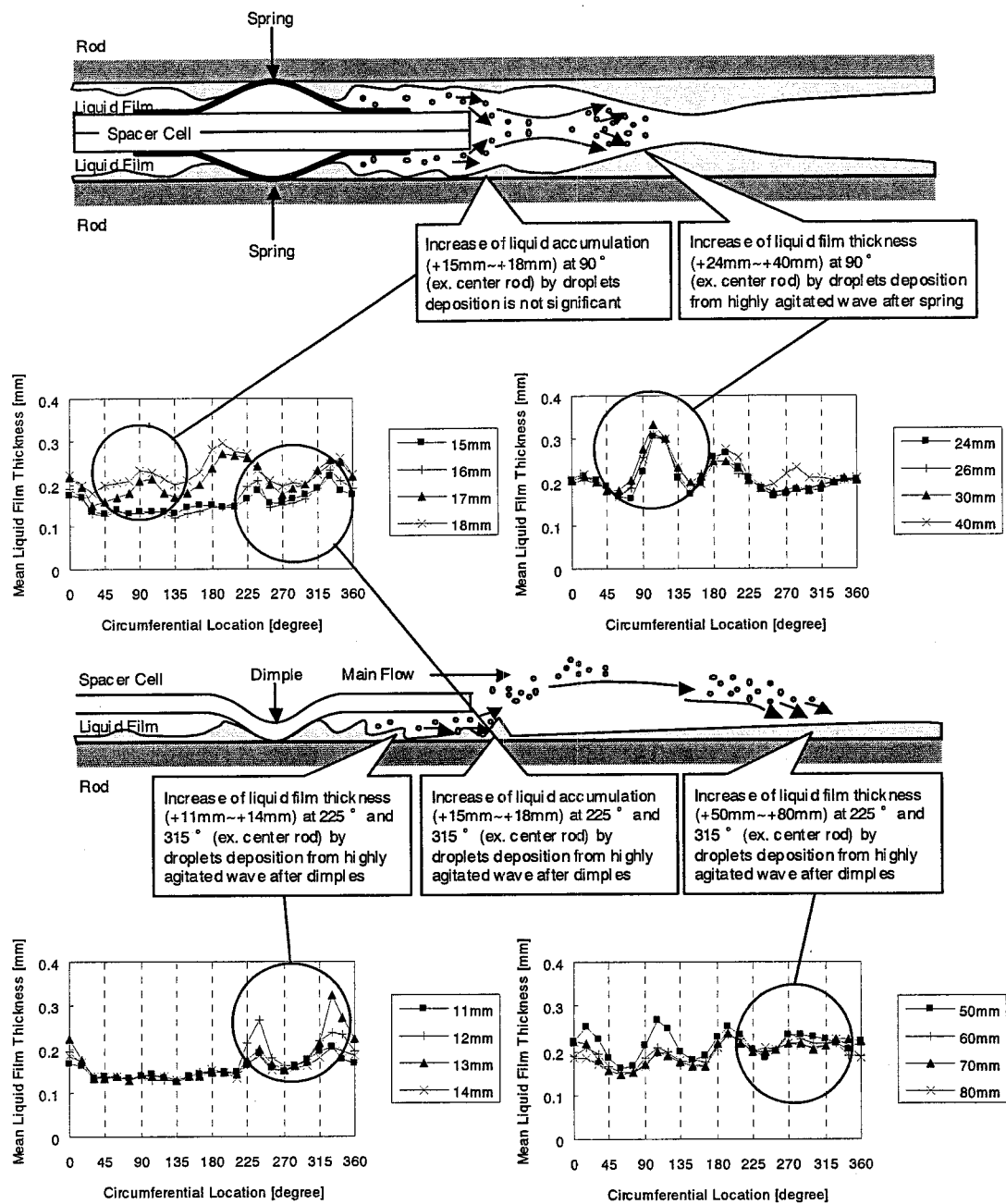
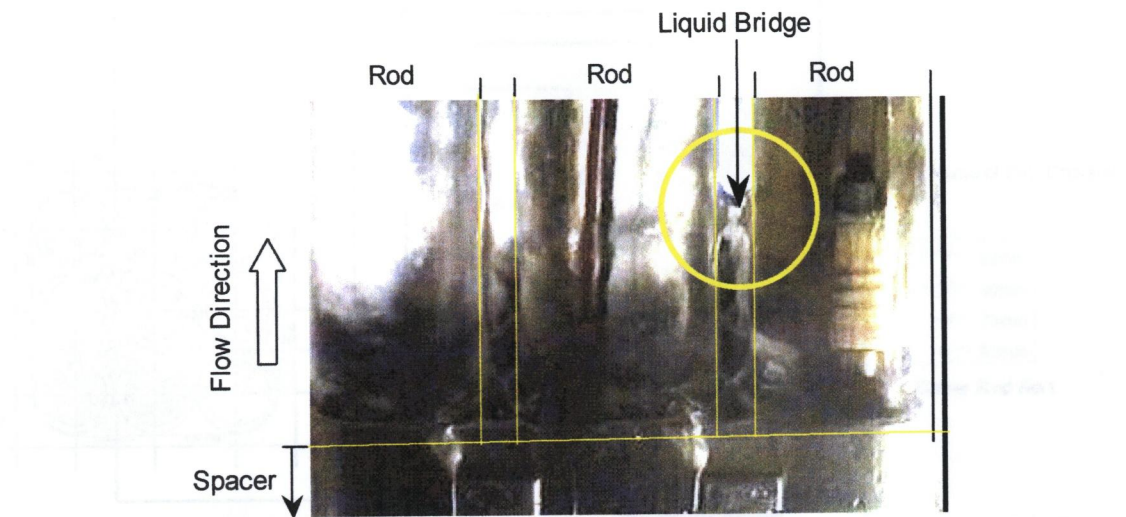
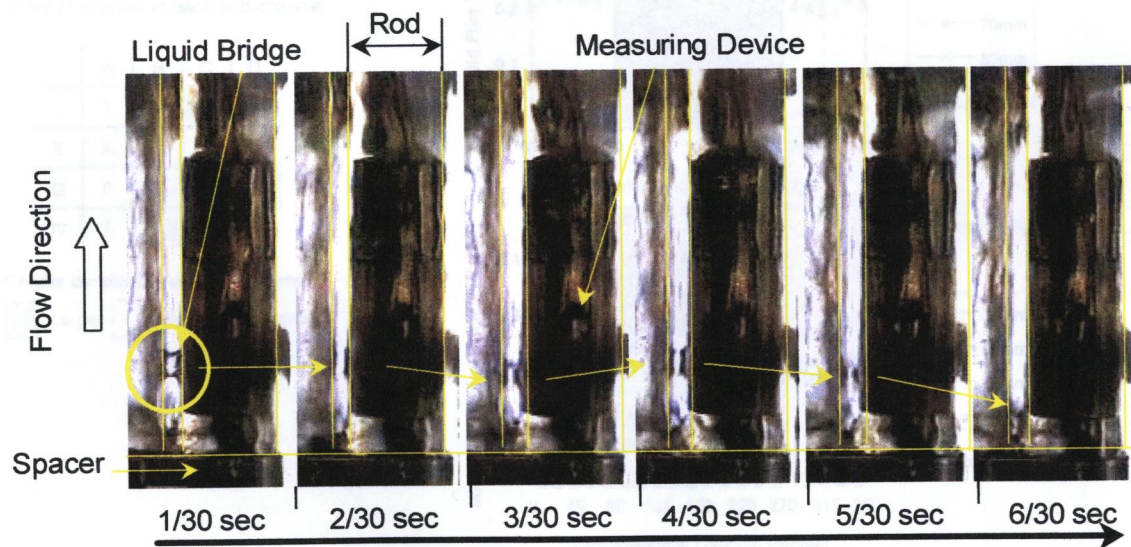


Figure 6.27 Effect of Dimple and Spring on Liquid Film Thickness in downstream of Spacer



(a) Formation of Liquid Bridge



(b) Traveling of Liquid Bridge

Figure 6.28 Behavior of Liquid Bridge ($j_g=10\text{m/s}$, $j_l=0.017\text{m/s}$)

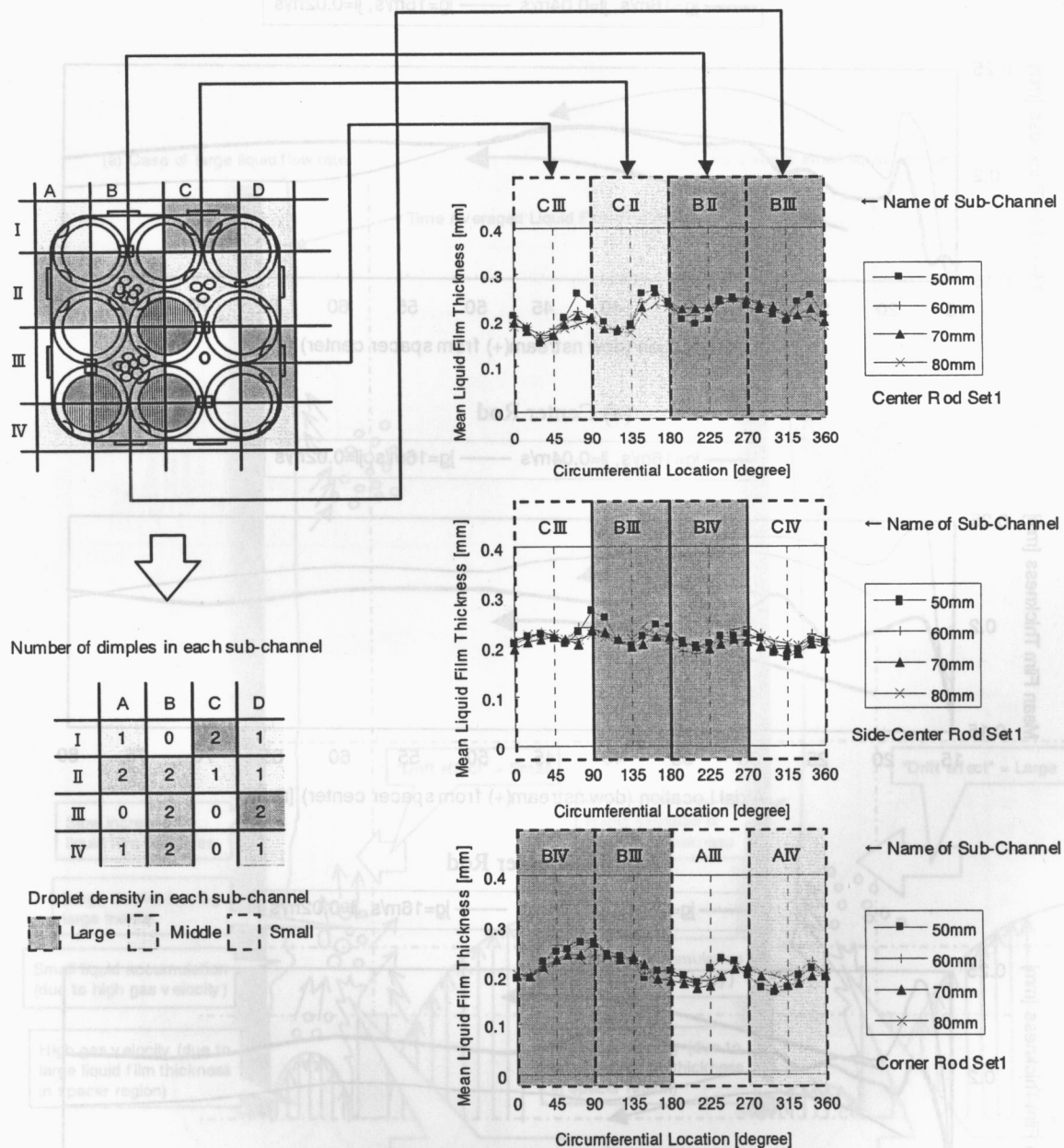
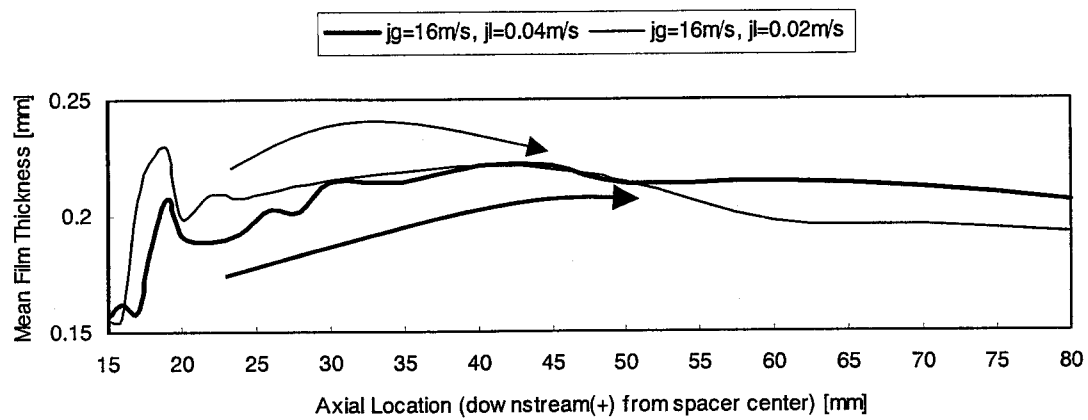
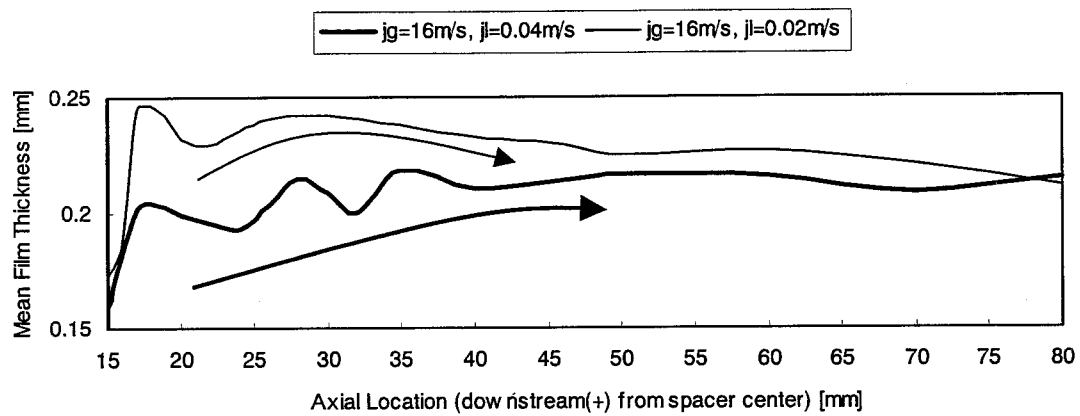


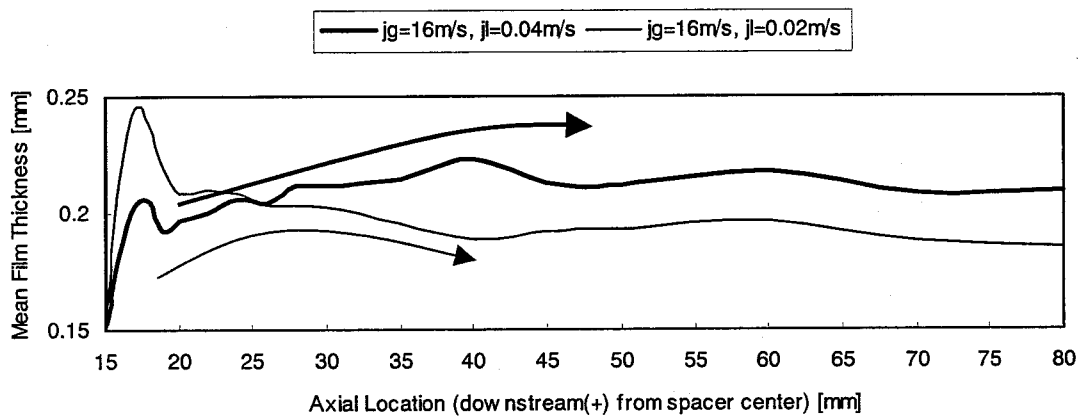
Figure 6.29 Effect of Dimple on Liquid Film Thickness in further downstream of Spacer



(a) Center Rod



(b) Side-Center Rod



(c) Corner Rod

Figure 6.30 Dependency of Liquid Flow Rate on Liquid Film Thickness in downstream of Spacer

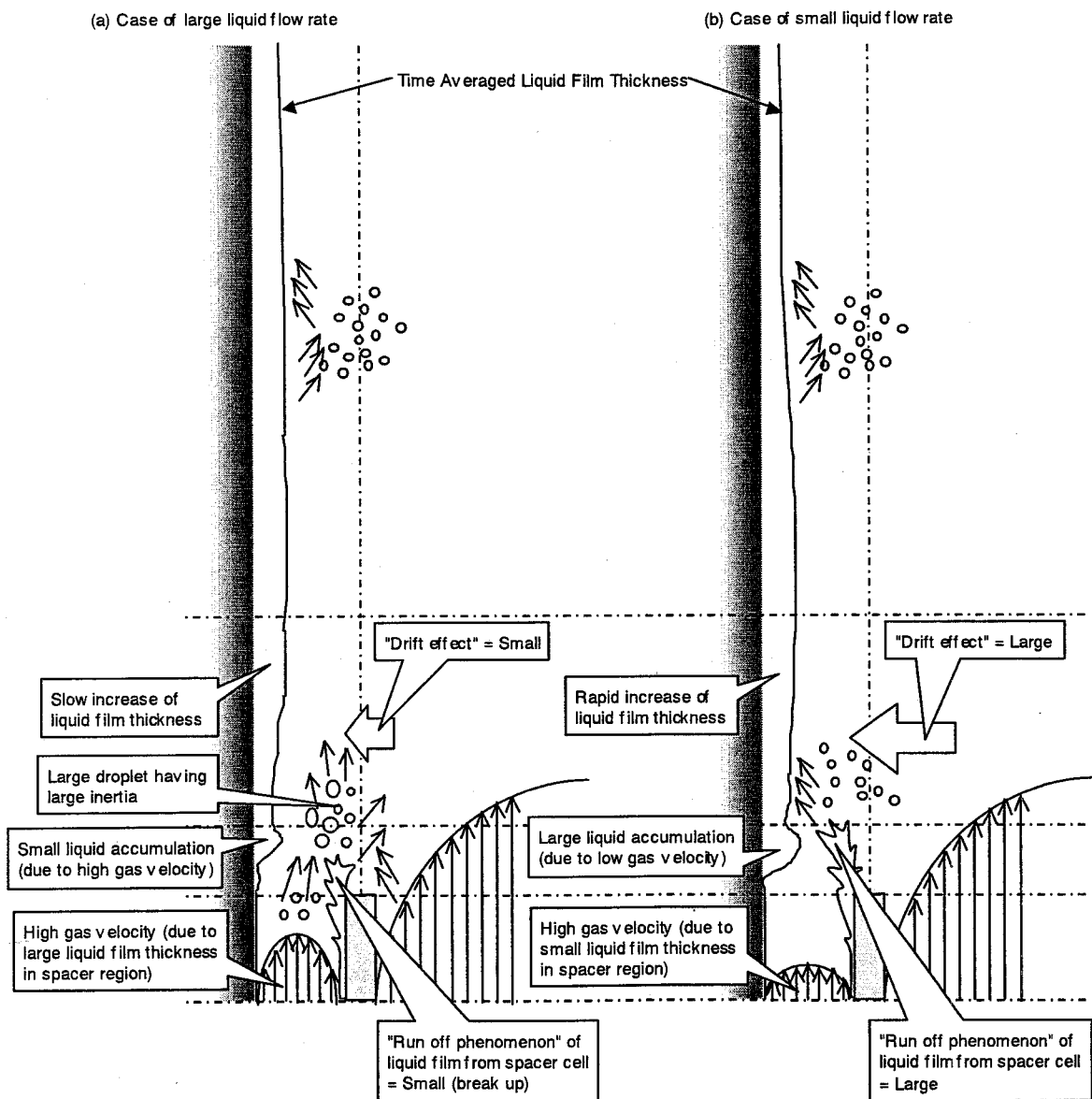
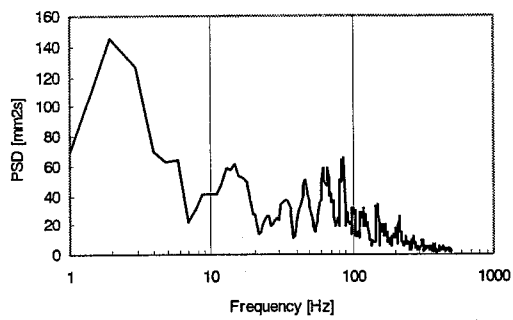
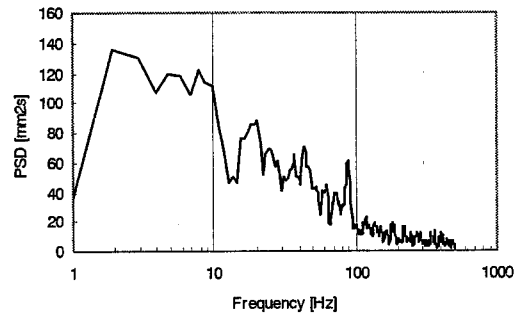


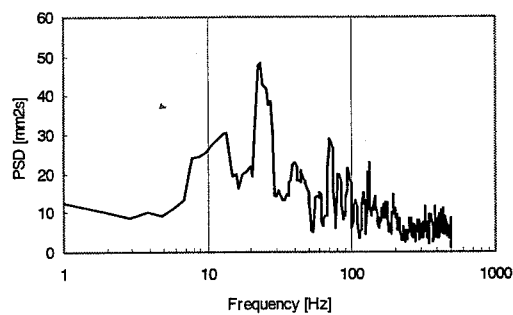
Figure 6.31 Effect of Liquid Flow Rate on Forming Liquid Film after Spacer



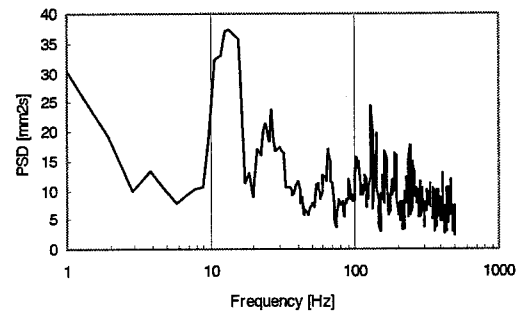
(a) -30mm (Side-Center Rod)



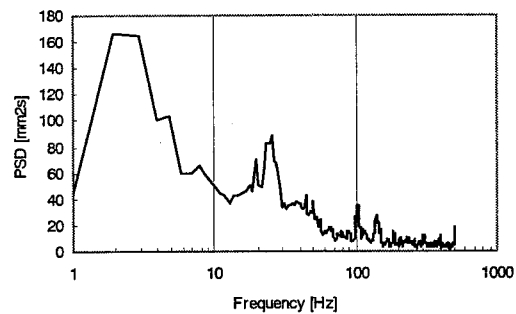
(e) -17mm (Corner Rod)



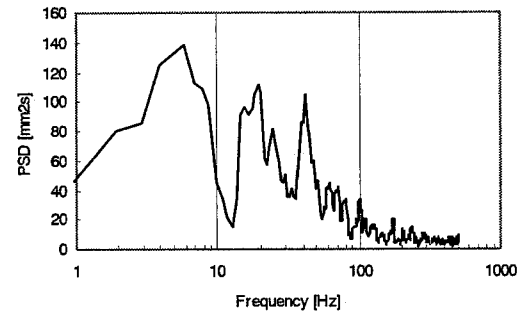
(b) 0mm (Side-Center Rod)



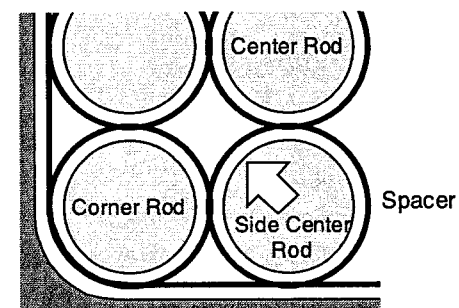
(f) 0mm (Corner Rod)



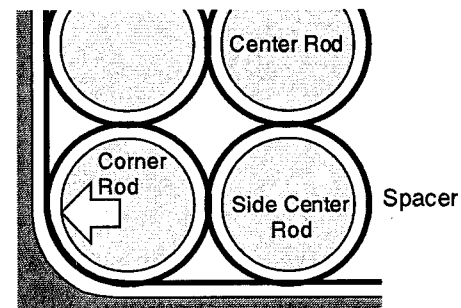
(c) 20mm (Side-Center Rod)



(g) 30mm (Corner Rod)

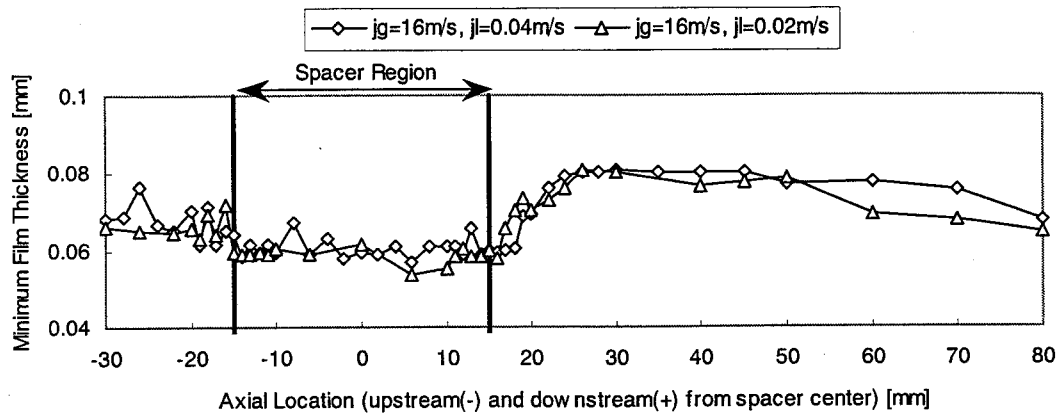


(d) Measuring Position Around Rod
(at 135 degrees of Side-Center Rod)

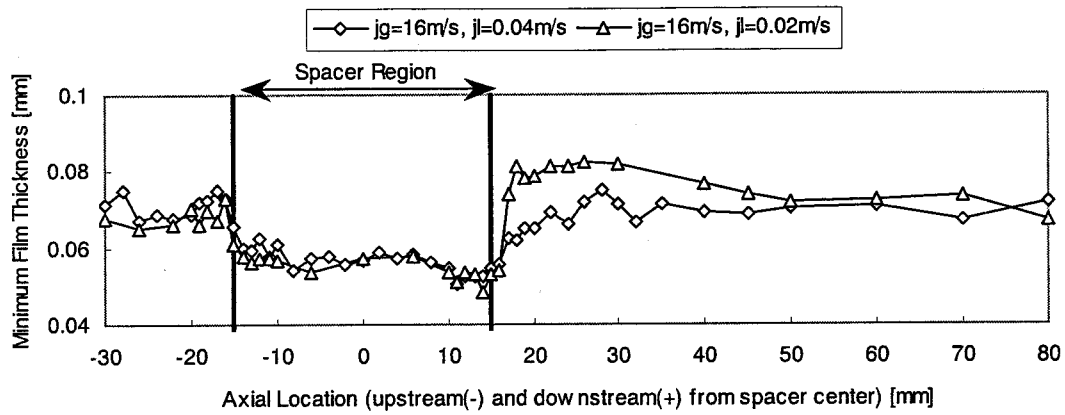


(h) Measuring Position Around Rod
(at 270 degrees of Corner Rod)

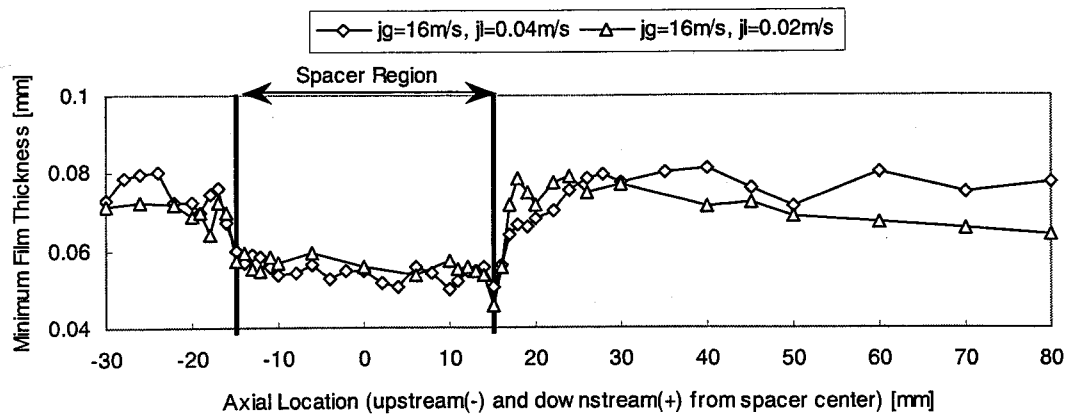
Figure 6.32 Power Spectral Density of Liquid Film Thickness ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



(a) Center Rod

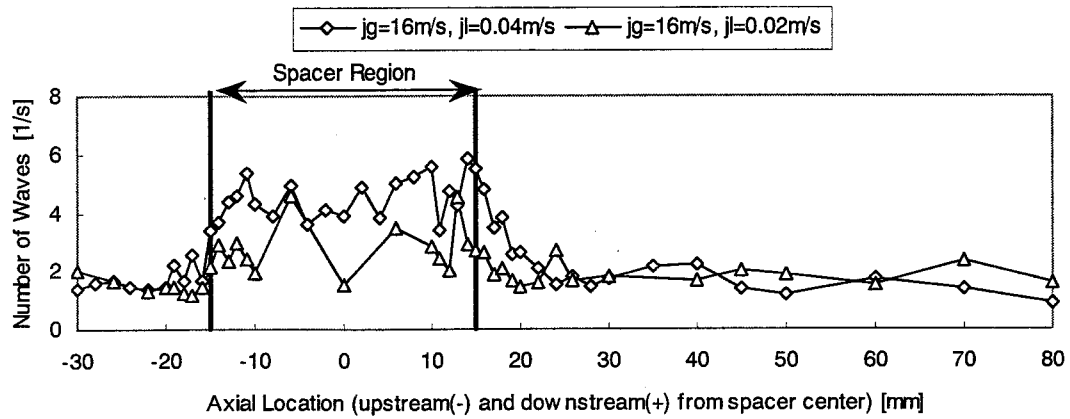


(b) Side-Center Rod

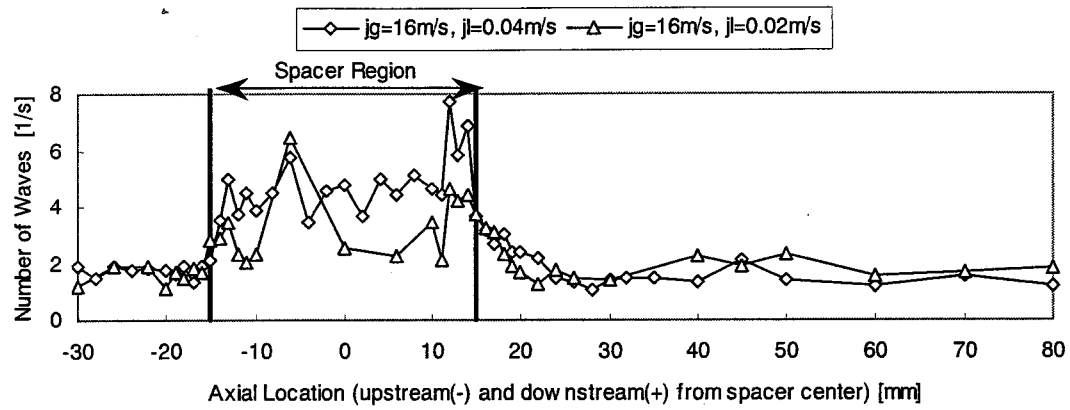


(c) Corner Rod

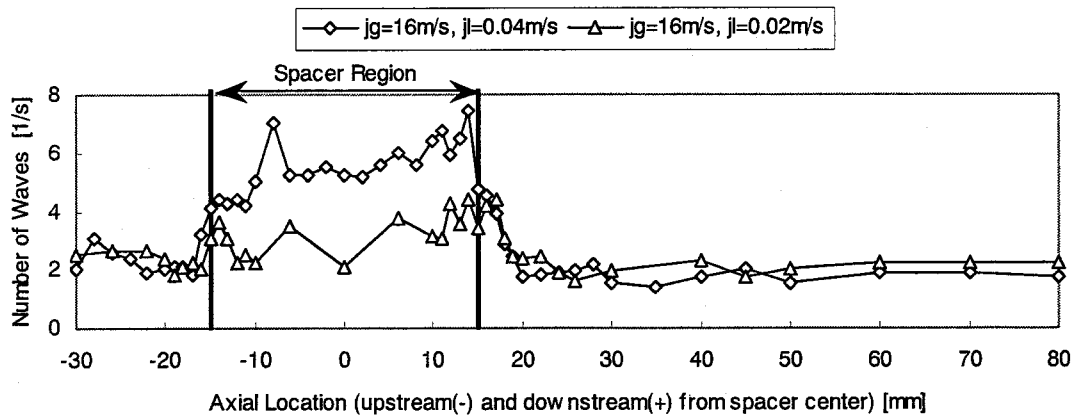
Figure 6.33 Cross-Sectional Averaged Minimum Film Thickness



(a) Center Rod

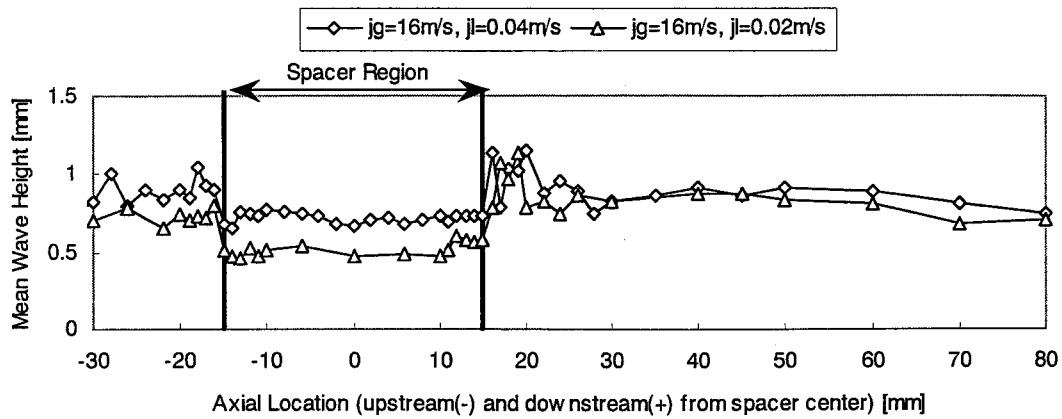


(b) Side-Center Rod

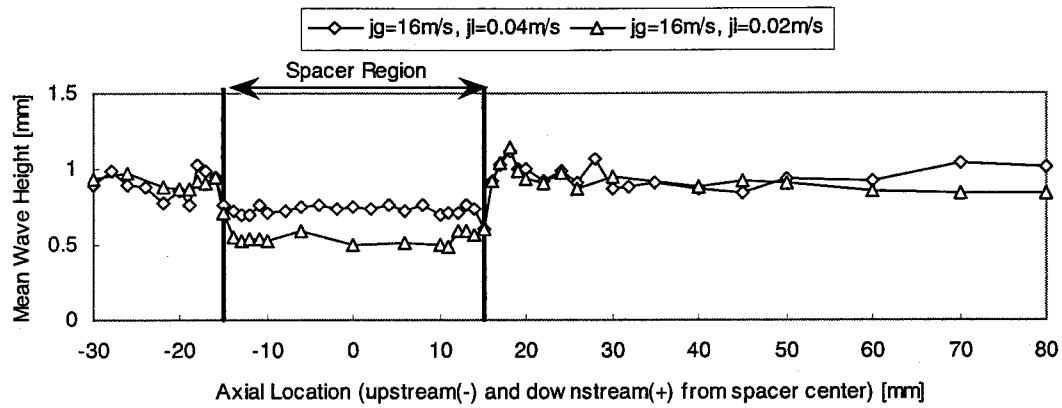


(c) Corner Rod

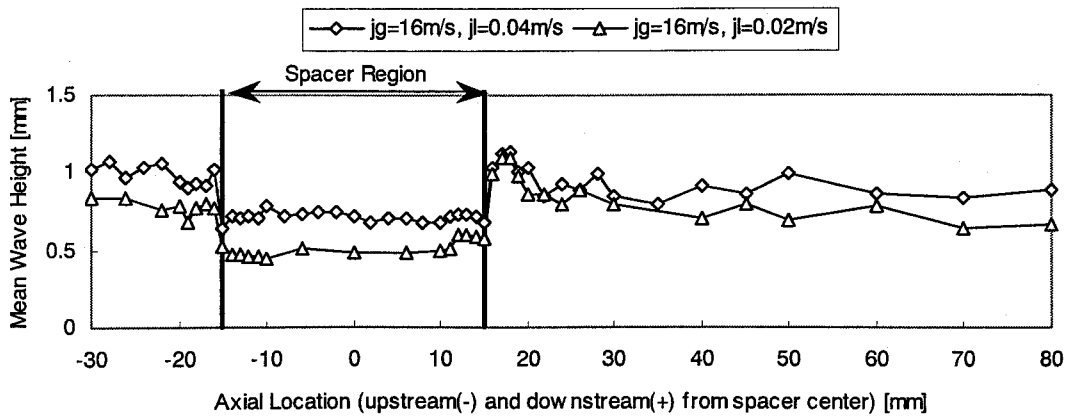
Figure 6.34 Cross-Sectional Averaged Number of Passing Waves (Large Wave)



(a) Center Rod

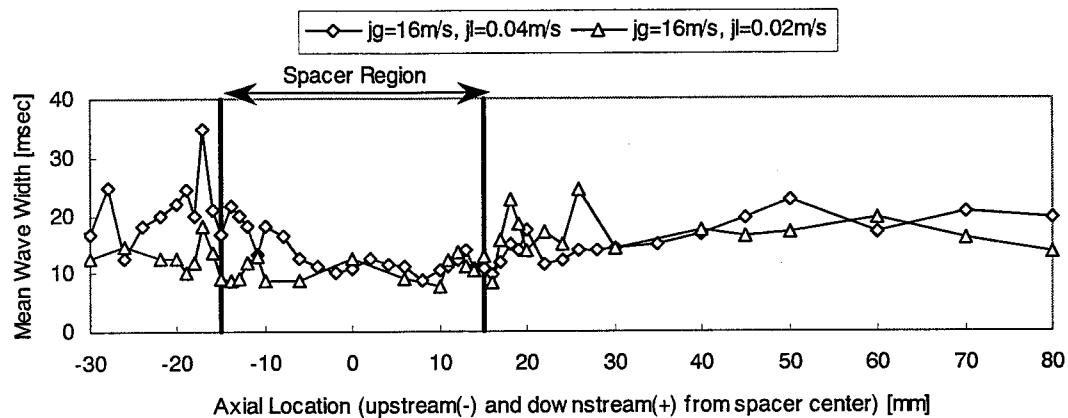


(b) Side-Center Rod

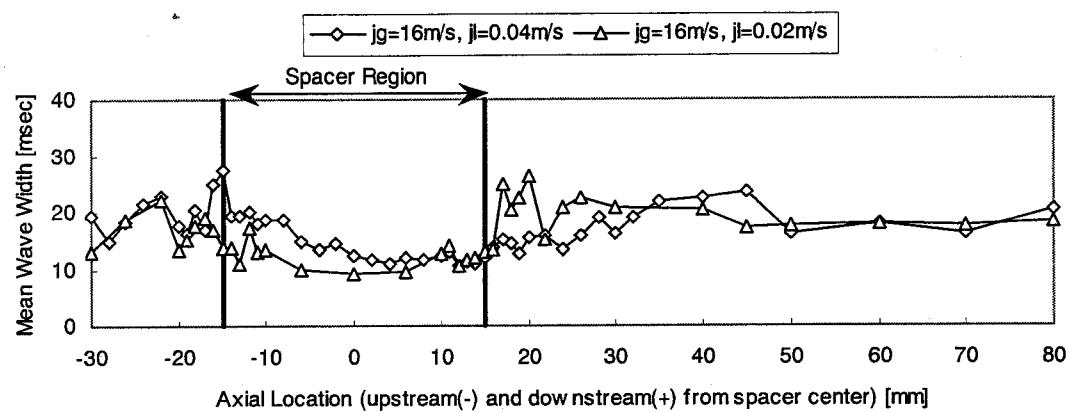


(c) Corner Rod

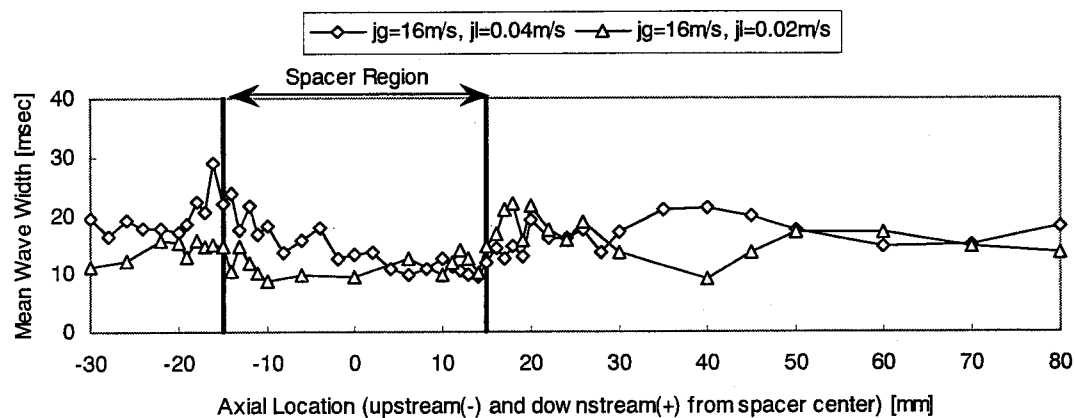
Figure 6.35 Cross-Sectional Averaged Wave Height (Large Wave)



(a) Center Rod

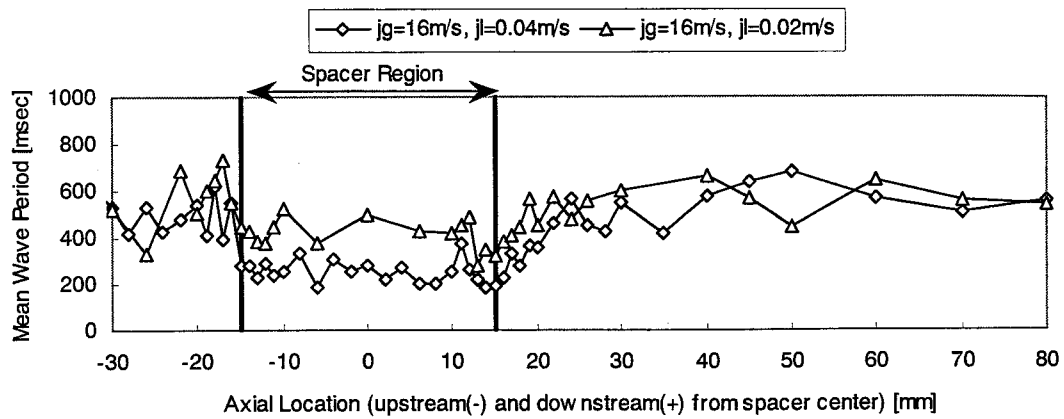


(b) Side-Center Rod

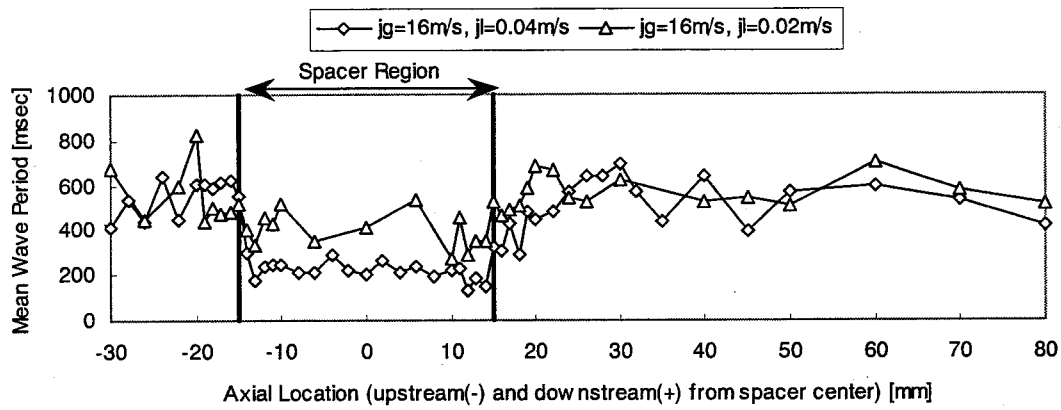


(c) Corner Rod

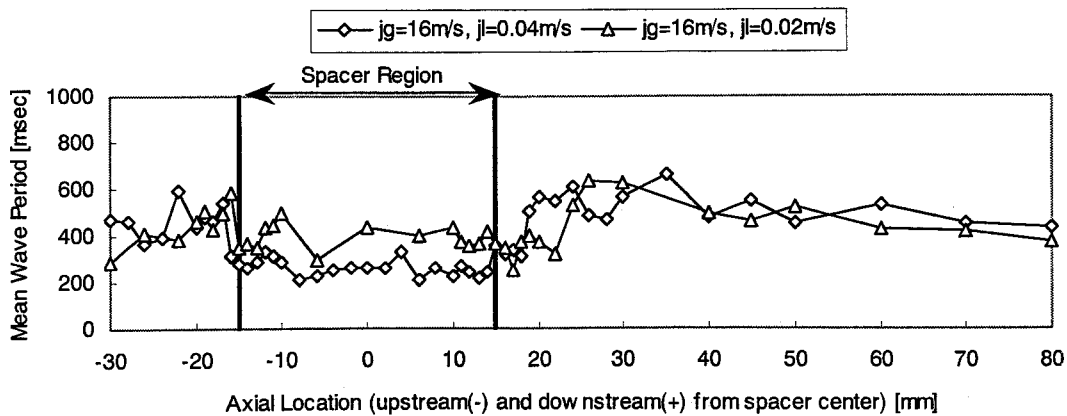
Figure 6.36 Cross-Sectional Averaged Wave Width (Large Wave)



(a) Center Rod

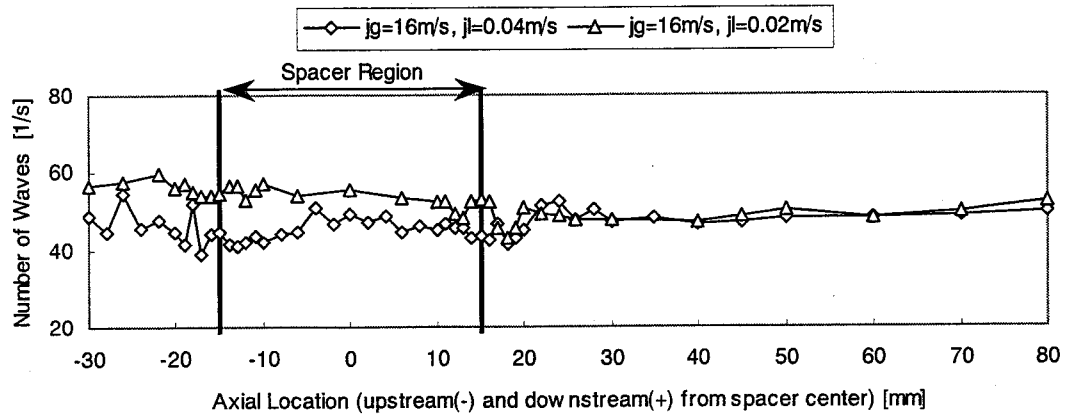


(b) Side-Center Rod

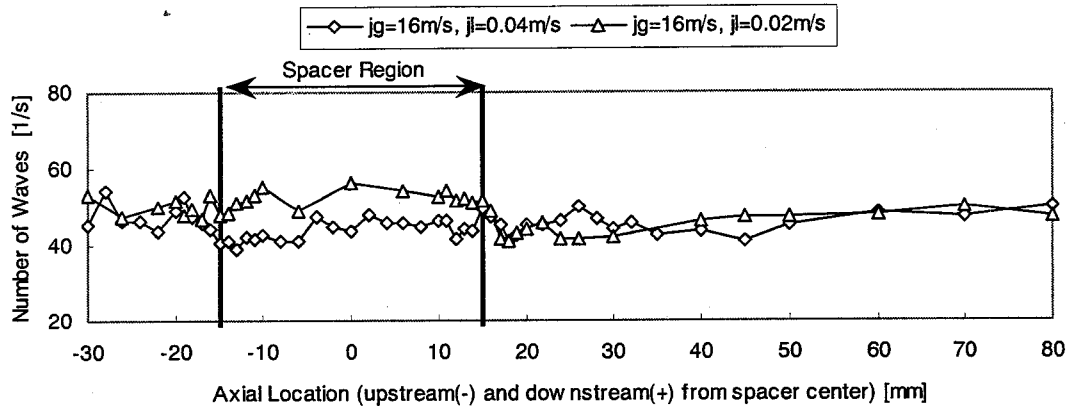


(c) Corner Rod

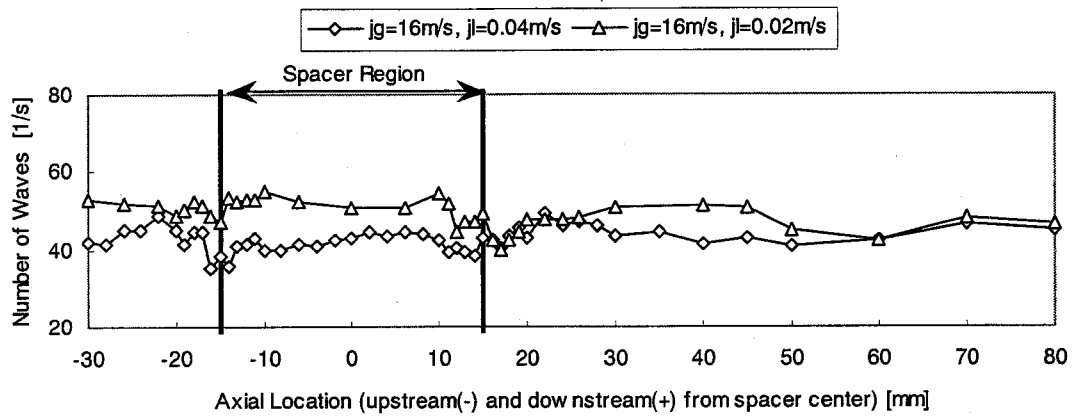
Figure 6.37 Cross-Sectional Averaged Wave Period (Large Wave)



(a) Center Rod

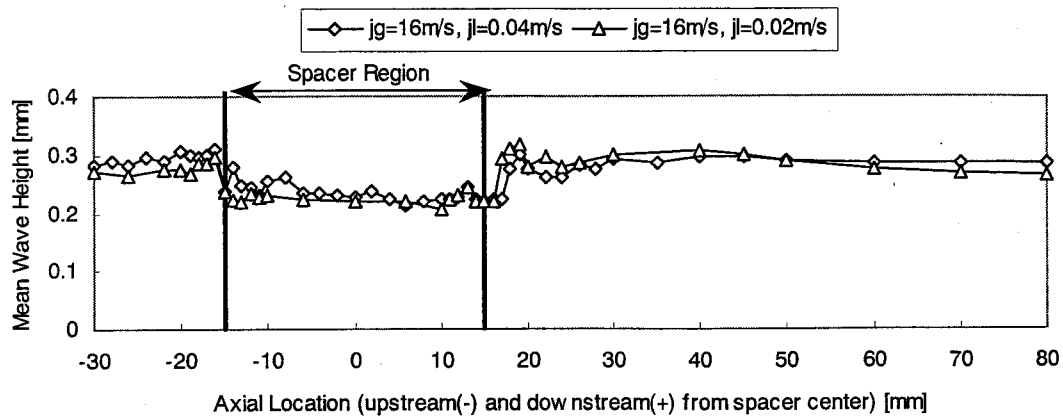


(b) Side-Center Rod

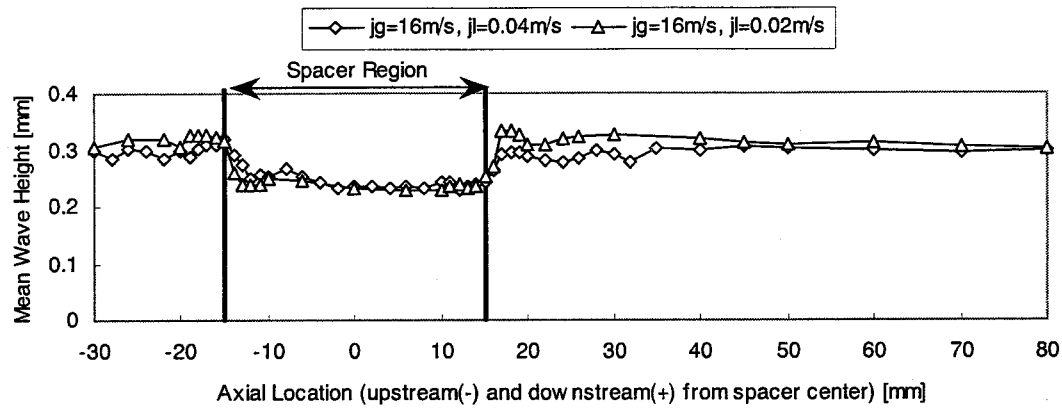


(c) Corner Rod

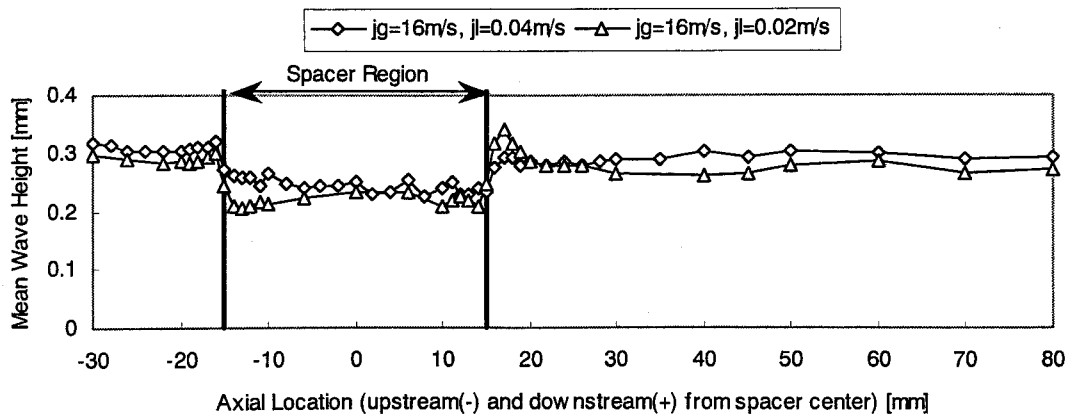
Figure 6.38 Cross-Sectional Averaged Number of Passing Waves (Ripple)



(a) Center Rod

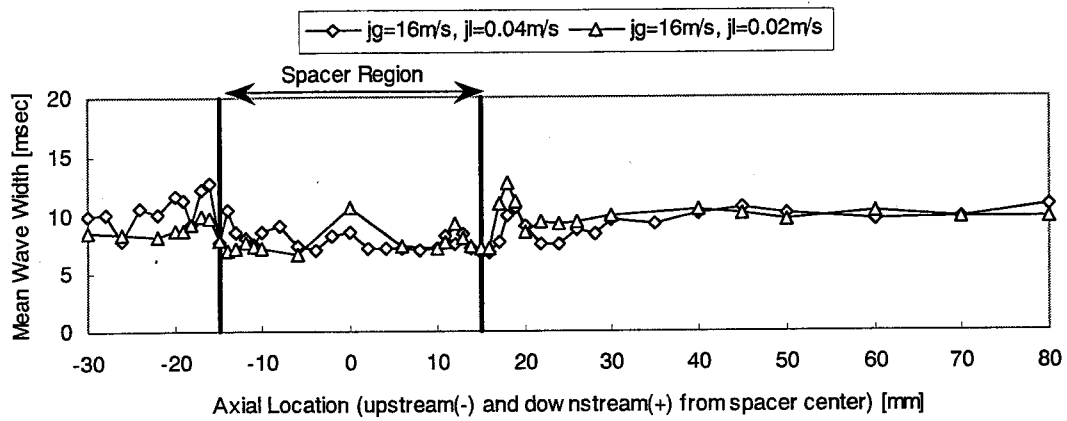


(b) Side-Center Rod

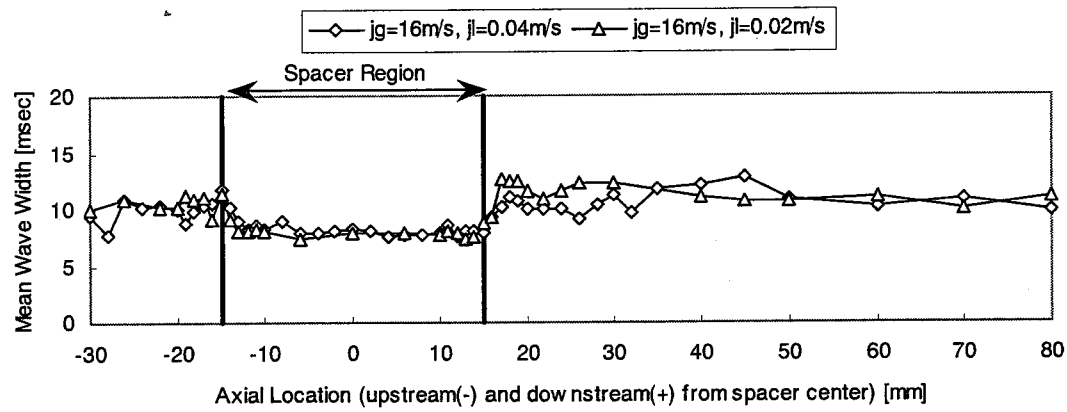


(c) Corner Rod

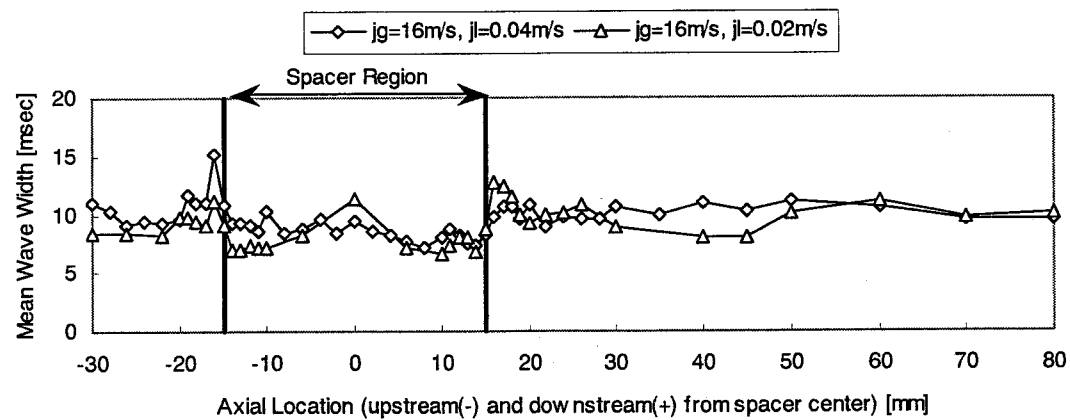
Figure 6.39 Cross-Sectional Averaged Wave Height (Ripple)



(a) Center Rod

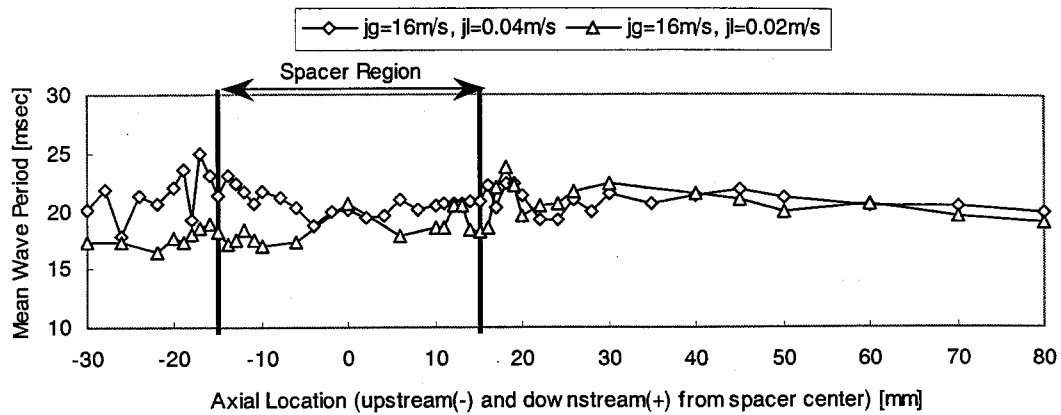


(b) Side-Center Rod

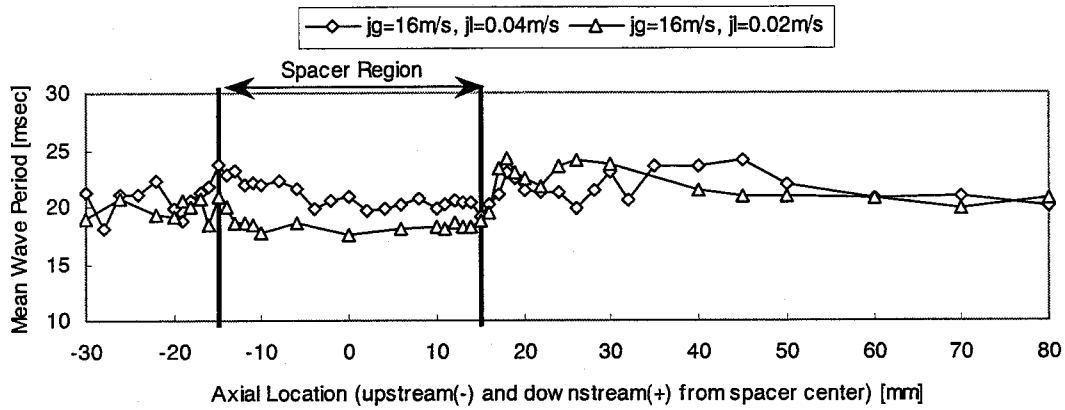


(c) Corner Rod

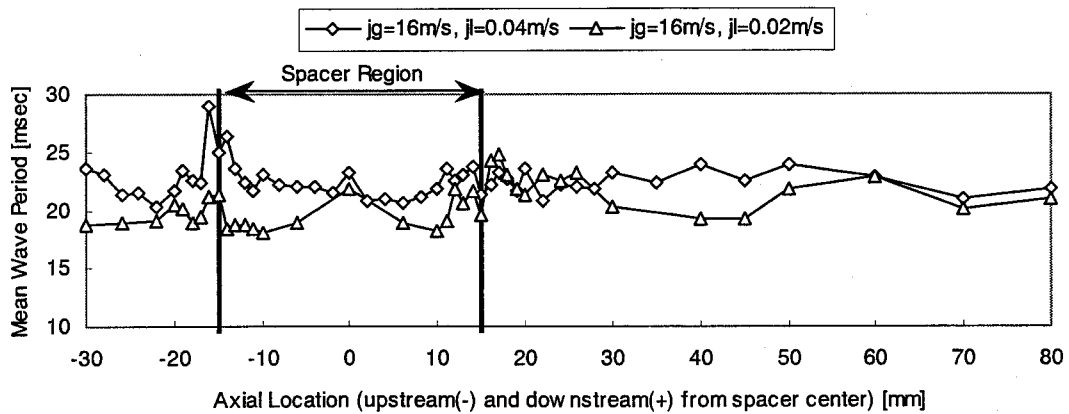
Figure 6.40 Cross-Sectional Averaged Wave Width (Ripple)



(a) Center Rod



(b) Side-Center Rod



(c) Corner Rod

Figure 6.41 Cross-Sectional Averaged Wave Period (Ripple)

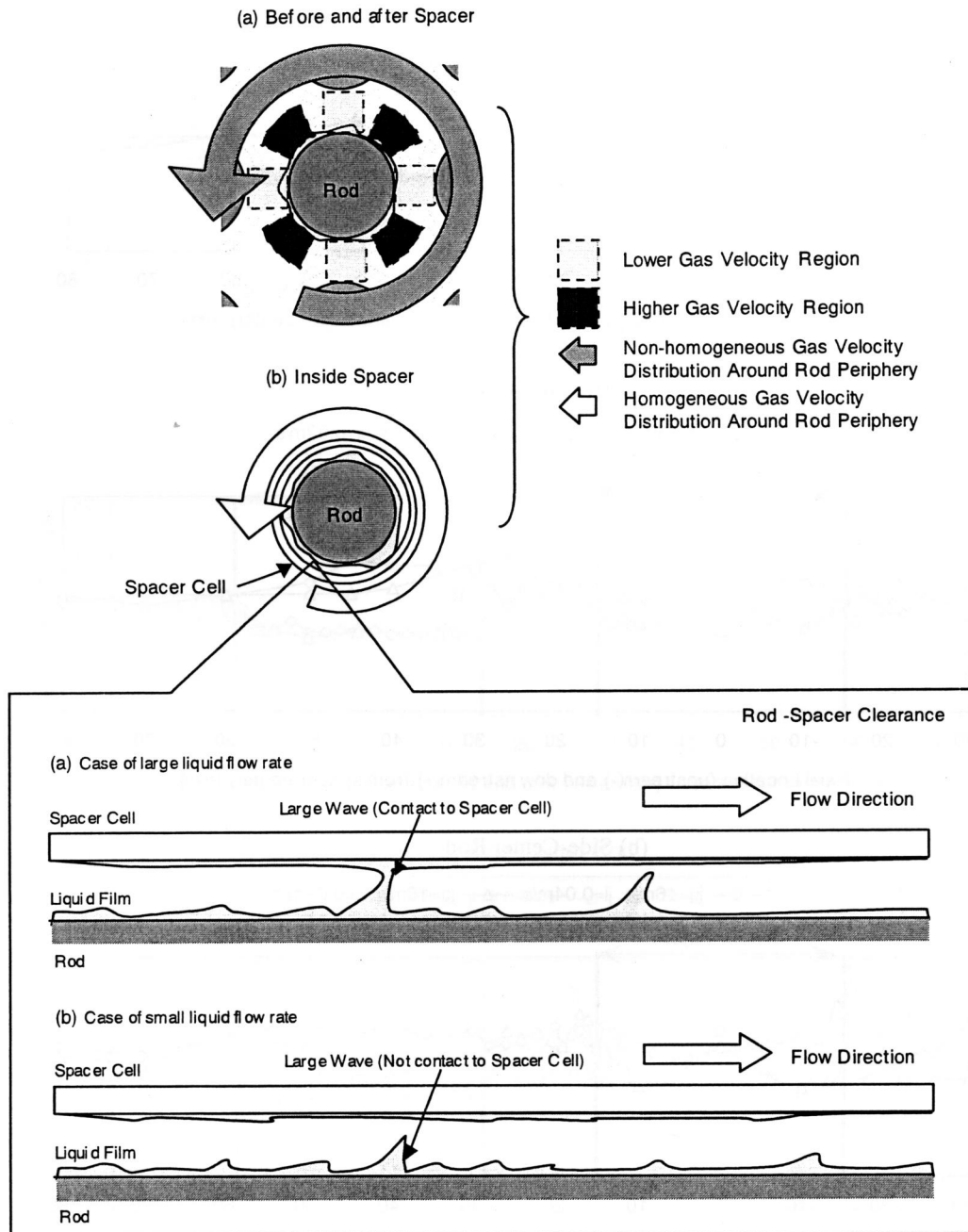
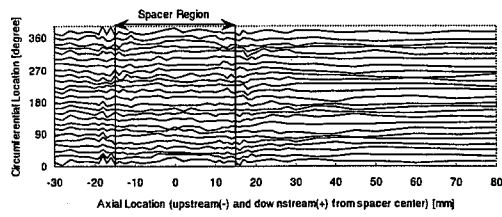
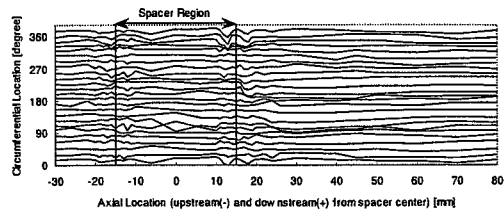


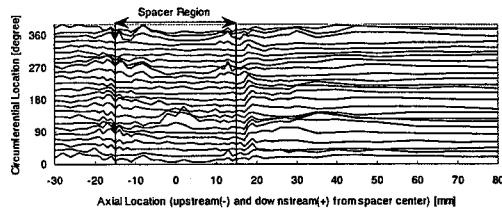
Figure 6.42 Formation of Two-Dimensional Large Wave inside Spacer



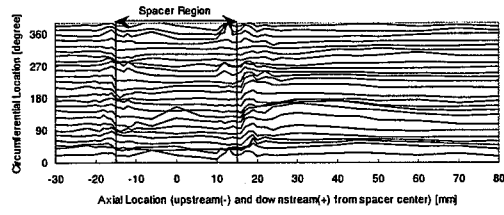
(a) Number of Passing Waves
($j_g=16\text{m/s}$, $j_i=0.04\text{m/s}$)



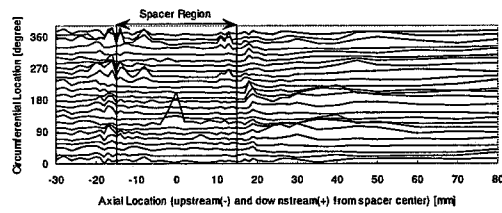
(e) Number of Passing Waves
($j_g=16\text{m/s}$, $j_i=0.02\text{m/s}$)



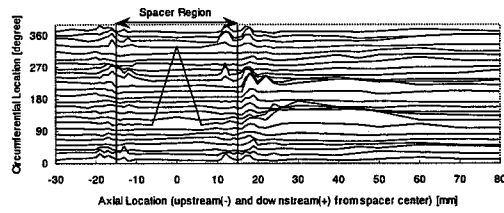
(b) Mean Wave Height ($j_g=16\text{m/s}$, $j_i=0.04\text{m/s}$)



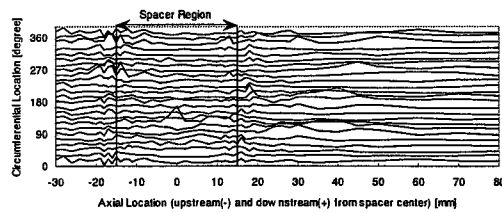
(f) Mean Wave Height ($j_g=16\text{m/s}$, $j_i=0.02\text{m/s}$)



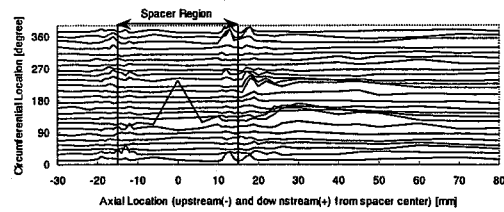
(c) Mean Wave Width ($j_g=16\text{m/s}$, $j_i=0.04\text{m/s}$)



(g) Mean Wave Width ($j_g=16\text{m/s}$, $j_i=0.02\text{m/s}$)

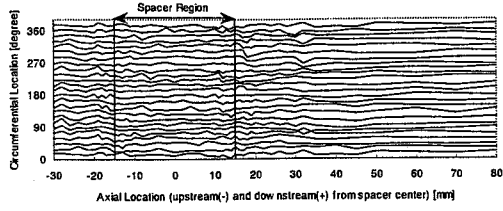


(d) Mean Wave Period ($j_g=16\text{m/s}$, $j_i=0.04\text{m/s}$)

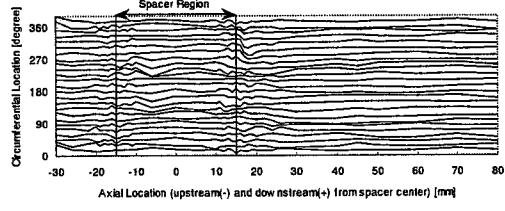


(h) Mean Wave Period ($j_g=16\text{m/s}$, $j_i=0.02\text{m/s}$)

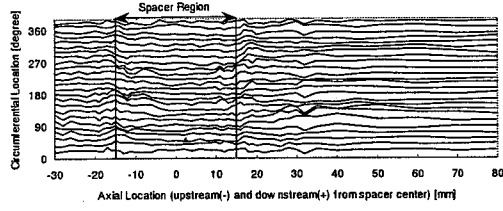
Figure 6.43 Characteristics of Ripple (Center Rod)



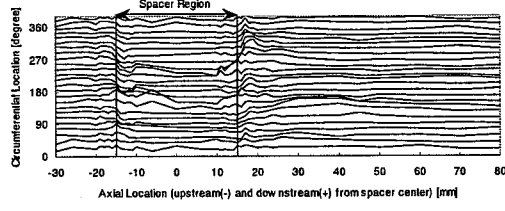
(a) Number of Passing Waves
($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



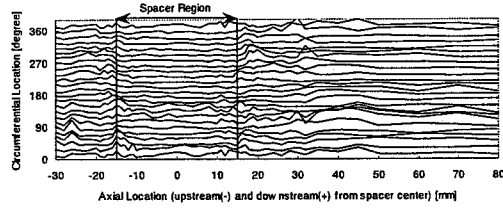
(e) Number of Passing Waves
($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



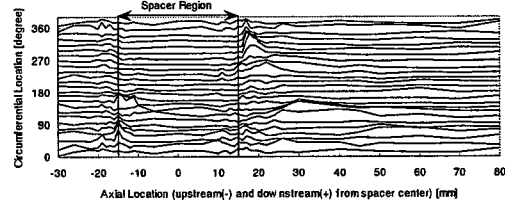
(b) Mean Wave Height ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



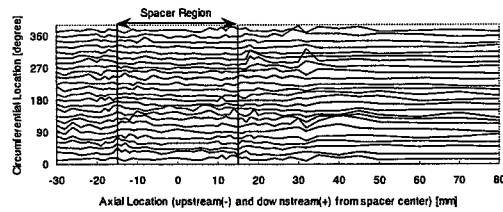
(f) Mean Wave Height ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



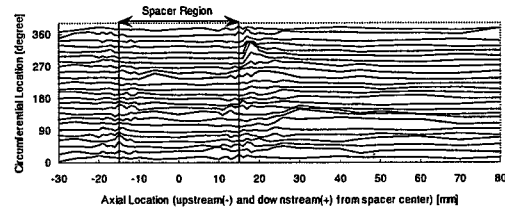
(c) Mean Wave Width ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



(g) Mean Wave Width ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

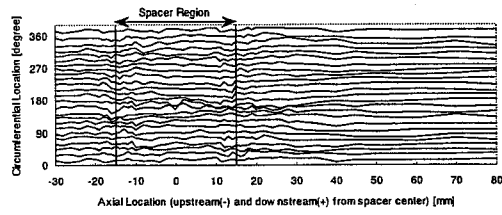


(d) Mean Wave Period ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)

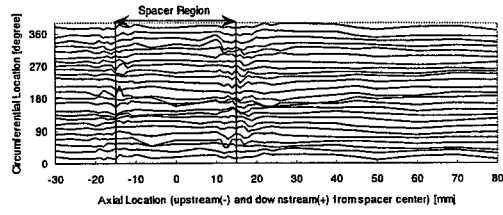


(h) Mean Wave Period ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

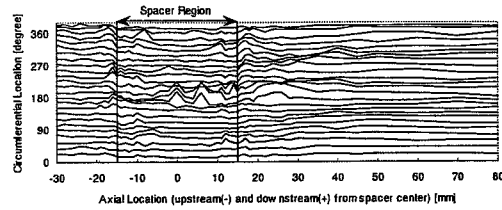
Figure 6.44 Characteristics of Ripple (Side-Center Rod)



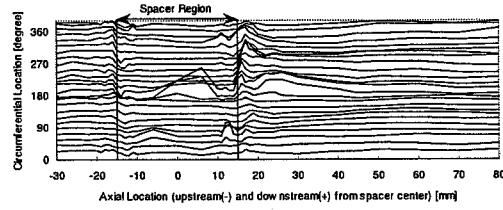
(a) Number of Passing Waves
($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



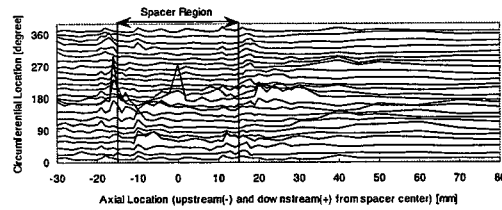
(e) Number of Passing Waves
($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



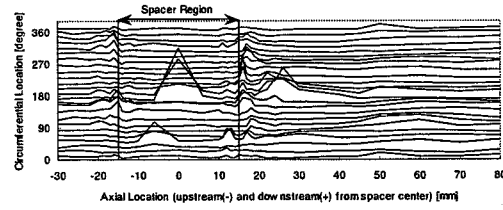
(b) Mean Wave Height ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



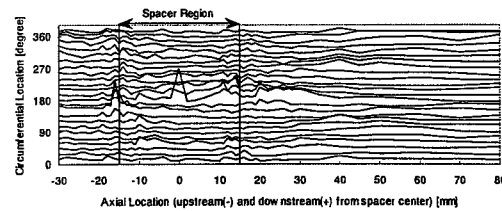
(f) Mean Wave Height ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



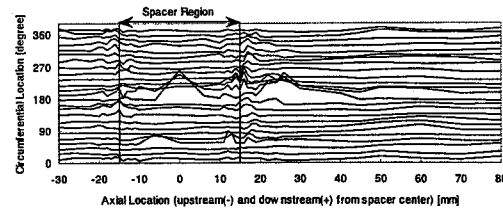
(c) Mean Wave Width ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



(g) Mean Wave Width ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)



(d) Mean Wave Period ($j_g=16\text{m/s}$, $j_l=0.04\text{m/s}$)



(h) Mean Wave Period ($j_g=16\text{m/s}$, $j_l=0.02\text{m/s}$)

Figure 6.45 Characteristics of Ripple (Corner Rod)

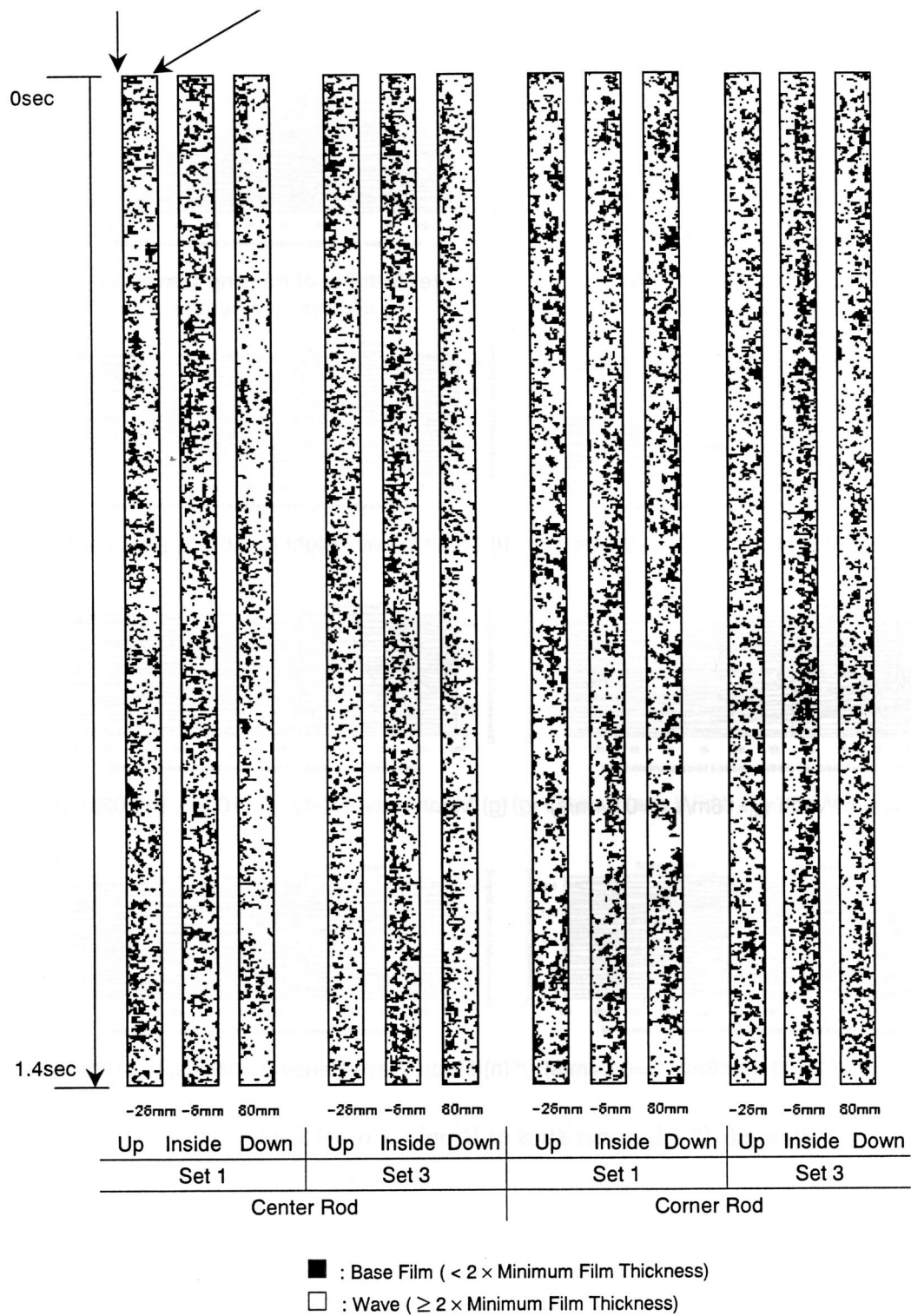
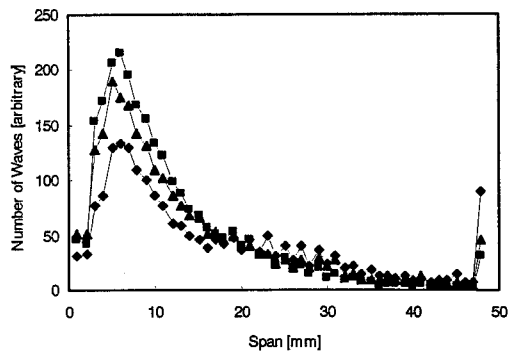
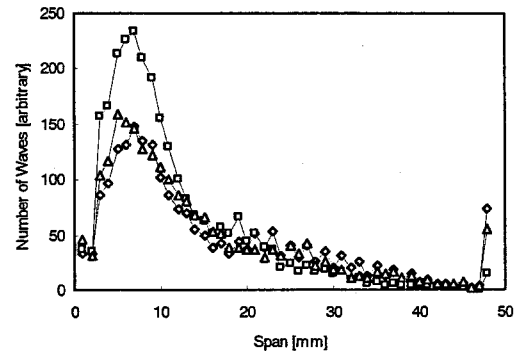


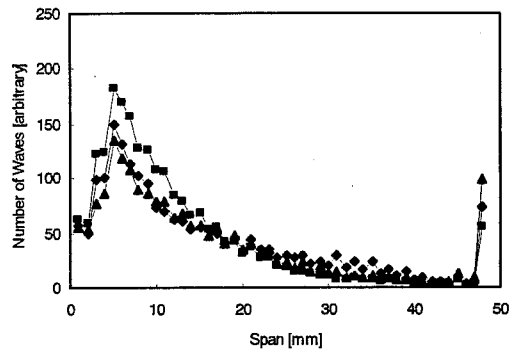
Figure 6.46 Binary Plots of Liquid Film Thickness



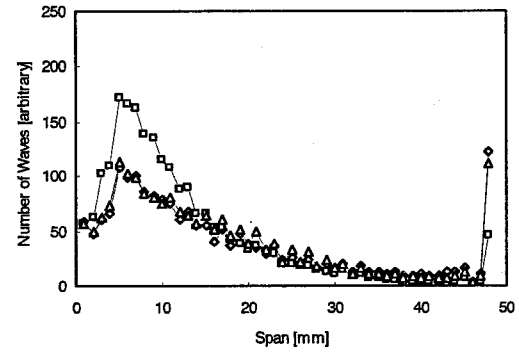
(a) Set 1 (Center Rod)



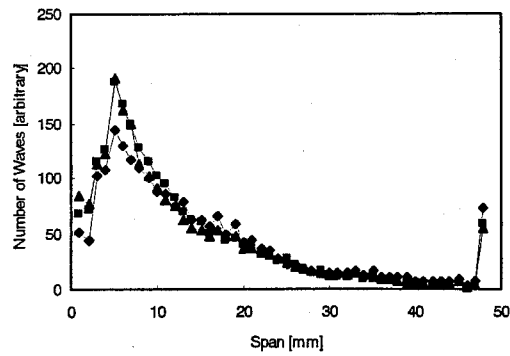
(d) Set 3 (Center Rod)



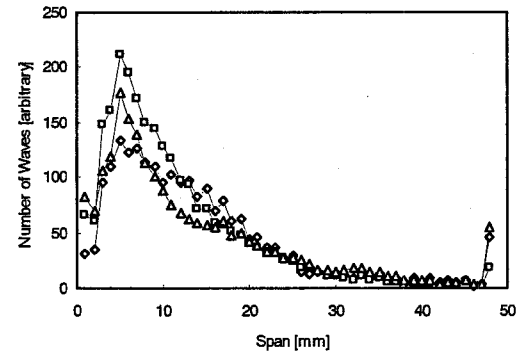
(b) Set 1 (Side-Center Rod)



(e) Set 3 (Side-Center Rod)



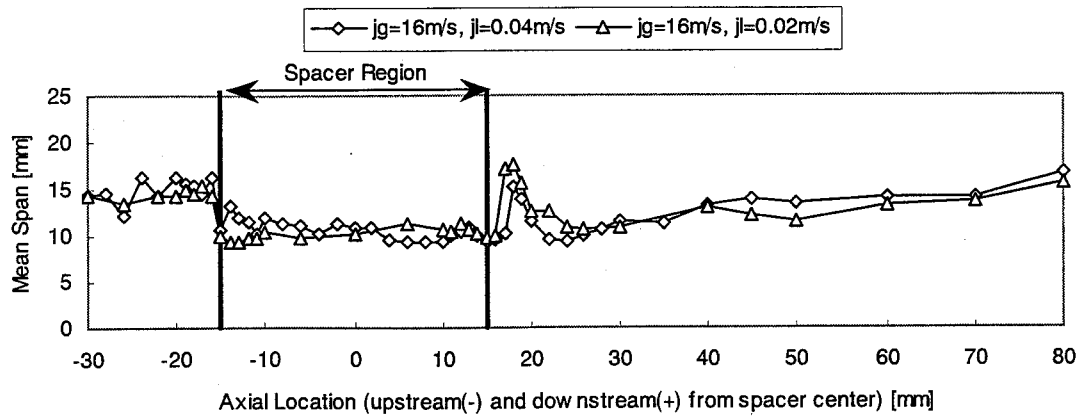
(c) Set 1 (Corner Rod)



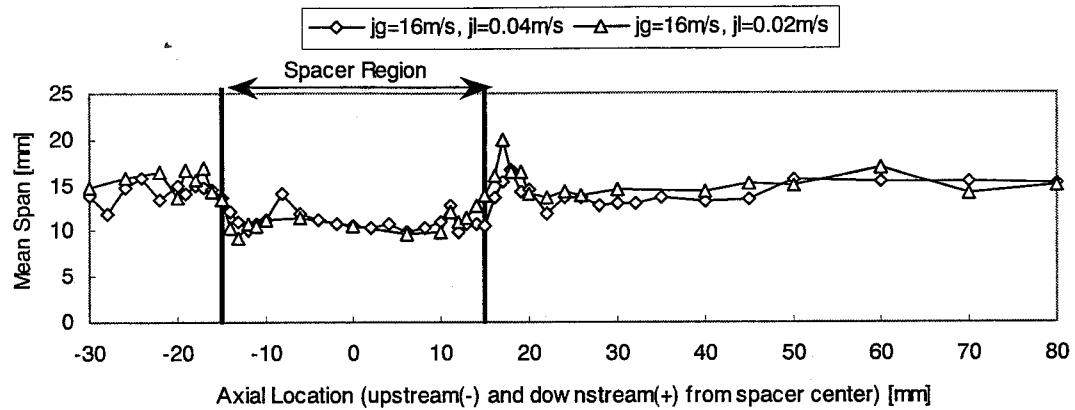
(f) Set 3 (Corner Rod)

Set 1 ($j_g=16\text{m/s}$, $j_i=0.04\text{m/s}$)	Set 3 ($j_g=16\text{m/s}$, $j_i=0.02\text{m/s}$)
◆ : Upstream of Spacer	◇ : Upstream of Spacer
■ : Inside of Spacer	□ : Inside of Spacer
▲ : Downstream of Spacer	△ : Downstream of Spacer

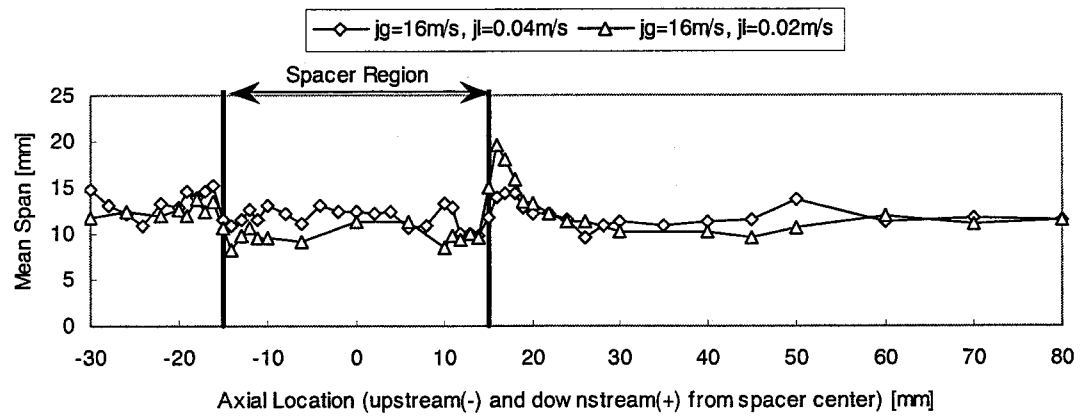
Figure 6.47 Number Histogram of Waves



(a) Center Rod



(b) Side-Center Rod



(c) Corner Rod

Figure 6.48 Mean Span of Waves

7. Conclusion

Liquid film behavior in near dryout region that required for safety analysis of nuclear reactor core was experimentally studied in this research. Concerning multi-dimensional behavior of liquid film flow and sensitiveness against external agitation, non-intrusive and multi-dimensional measuring techniques were developed at first. Then, effects of spacer on liquid film flow were investigated since spacers supporting fuel rods strongly affect on liquid film on fuel rods. The results obtained in this thesis are summarized as follows.

7.1. Development of Non-Intrusive and Multi-Dimensional Measuring Techniques

The FDM visualizes instantaneous liquid film cross-sectional shapes by detecting fluorescence coming from the luminous material accompanied in liquid phase excited by a sheet wise laser light. Rhodamine B and an argon gas laser were applied for the purpose. Spatial resolution of the FDM is about $80\mu\text{m}$ due to the size of the viewing area and digitization. The time resolution to detect time sequence of liquid film behavior is 1msec depending on the high-speed video camera at moment.

Liquid film flow in a horizontal rectangular channel was visualized by the FDM and characteristics of liquid film flow were clarified. Time-dependent two-dimensional film thickness distribution was reconstructed in bird's eye view graphics and contour plots providing excellent understandings of liquid film behavior.

It was observed by perpendicular incidence type of the FDM that large disturbance waves had several peaks on their crest in the span wise direction. A lot of interesting features of waves, i.e., number of passing waves, wave height, wave velocity, wave axial width and wave steepness, were obtained by parallel incidence type of the FDM.

Waves were also classified into three types by using the above features, to say, conducted value of wave longitudinal cross-sectional area as a product of wave height, axial width and velocity. "Huge wave" was determined having larger value of wave cross-sectional area than 100mm^2 , "ripple" having smaller than 10mm^2 and the rest for "disturbance wave". Huge wave was observed in relatively low gas velocity and relatively large liquid flow rate. Huge wave had a severely rough surface compare to

disturbance wave. Their appearing frequency was less than about 2Hz. The traveling velocity was somewhat larger than that of disturbance wave. The wave height was about twice of disturbance wave height and four times of ripple.

From the results of averaged wave steepness, it was found that waves lean toward flow direction and the steepness decreases with increasing gas velocity. It was also seen that wave steepness increases with increasing liquid flow rate.

Ultrasonic transmission technique that has been used for local measurement of instantaneous liquid film thickness formed on internal surface of channel was improved to measure multi-dimensional distribution of film thickness formed on external surface of tube adopting a high-speed rotating reflector and interpolation processing. The accuracy of the film thickness measurement is 75 μm assuming the sound velocity in water being 1,500m/s. Since the USEM employs couple of one transducer and reflector, scanning time of reflector becomes major factor to reconstruct multi-dimensional image of liquid film flow precisely. The scanning time is about 3msec at moment.

Liquid film thickness formed on outer surface of a vertically upward annulus tube simulating a nuclear fuel rod was measured by the USEM. The reconstructed three-dimensional images such as contour plots and bird's eye view graphics showed better understandings of liquid film behavior around tube. The results obtained by a rotating reflector agreed well with the results of a stationary reflector calibrated finely with electrical probe method. The images clearly revealed that large disturbance wave keep stretch around tube periphery while it passes measuring position. More over, film thickness of disturbance wave is not necessarily constant in the span wise direction so as to have several crests.

Characteristics of waves, such as power spectral density distribution of the liquid film thickness fluctuations, wave height, wave width (duration time), wave period and number of passing waves, were obtained from time-trace of film thickness both for disturbance wave and ripple. Reasonable properties were indicated for wave height and wave width, however, number of passing disturbance wave showed somewhat different dependency of gas velocity due to the experimental setup, i.e., in the developing region of liquid film flow. The USEM will be improved in the scanning time to more precisely detect disturbance wave that sometimes passes in short time less than scanning time.

7.2. Effects of Obstacle on Liquid Film Flow

Effects of obstacle having three different cross-sectional shapes, to say rectangle, trapezoid and inverted trapezoid, on liquid film flow were clarified by using parallel incidence type of the FDM. Reconstructed images showed that the clearance between

obstacle and channel bottom becomes to be occupied by the liquid film with decrease of clearance. Flow reversal and bubbles contained in the liquid film were observed.

In upstream region of obstacle, liquid film thickness was locally, within about 5mm, increased with decrease of clearance. This trend was caused due to deceleration of gas flow in turn to reduce interfacial shear stress, and droplets deposition. Increase of liquid film thickness before the obstacle had the largest value with Type C obstacle having downward chamfer since lots of droplets were transported to liquid film by its chamfer, and had the smallest for Type B obstacle having upward chamfer enabling to transport liquid droplets to main gas flow.

Liquid film structure was changed when liquid flow rate was enlarged enough for the liquid film to occupy the clearance between the obstacle and channel bottom, and then liquid film stagnates before the obstacle. This was observed only with Type A obstacle under the present experimental conditions.

In downstream region of obstacle, liquid film thickness also increased with decrease of clearance due to deceleration of gas flow coming through the narrow clearance between obstacle and bottom of channel. This tendency was remarkably seen with Type A obstacle showing no dependency on liquid flow rate since turbulence was generated after the obstacle. Namely, gas velocity is strongly reduced by the turbulence and the turbulence also transports a lot of droplets to the liquid film. It was seen that the peak after the obstacle was located near to it for Type B obstacle because high-speed gas flow was conducted to the liquid film in a short distance. In contrast with this, the peak after the obstacle was located relatively far from the obstacle for Type C because high-speed gas takes long distance to reach the liquid film, and also because gas flow coming through the narrow clearance drag the liquid film.

Liquid film thickness on simulated fuel rods in a 3×3 rod bundle was measured by the USEM. Effects of geometrical structures such as spacer and rod bundle on liquid film flow were clarified.

Time-dependent liquid film thickness distribution around rod was reconstructed as contour plots, bird's eye view graphics and peripheral plots. Excellent understandings of the liquid film behavior affected by spacer were obtained. Cross-sectional averaged liquid film thickness indicated a general trend, that is to say, liquid film thickness has a small peak in front of spacer, decreases in spacer region, has another peak just behind the spacer and recovers in downstream region of spacer. Film thickness is slightly small at center rod since its surrounding gas velocity is relatively high.

Decreasing of cross-sectional averaged liquid film thickness in spacer region is due to acceleration of gas velocity caused by reduction of flow area. In spacer region, liquid

film thickness distributes almost uniformly around rod since constant rod-spacer clearance forms homogeneous gas velocity distribution, however, locally increases at dimples and spring.

Peak of liquid film thickness before the spacer seems to occur by obstruction of liquid film flow due to an increase of gas pressure before the spacer cell and also by liquid droplet deposition. Droplet entrainment is large at where rod surface faces to fast gas flow, thus the peak is enlarged at this direction and also film thickness in spacer region is thickened due to remaining droplets. Liquid film thickness also becomes large at channel corner because of large spacer thickness and low gas velocity. Therefore, ununiformity of liquid film thickness around rod strongly appears in a limited area within about 5mm from spacer front edge.

Liquid accumulation behind the spacer seems to be created by decelerated gas velocity and deposition of liquid droplets or liquid lumps departing from spacer cell by run off effect. Liquid film leaving from spacer cell easily becomes liquid lump and deposit near of spacer for small liquid flow rate, however liquid accumulation is small for large liquid flow rate since liquid film from spacer cell is destroyed into droplets which are transported toward downstream.

In downstream region of spacer, inhomogeneous liquid film thickness distribution is formed by several factors, such as different gas velocity profile, droplet entrainment after the dimples and spring, different droplet concentration in sub-channels due to number of dimples in upstream region. Excluding effects of projections, liquid film thickness seems to be thick at rod-rod clearance where gas velocity is small and be thin at where rod surface faces to gas main flow since interfacial shear stress is increased and drift effect is small.

Liquid film thickness rapidly recovers and has large peak after the spacer with low liquid flow rate. This is because gas velocity from rod-spacer clearance is small enough to form liquid stagnation and also to enhance drift effect. Liquid bridge is sometimes formed in downstream region of spacer at corner rod because of large liquid film thickness due to reduced gas velocity.

Power spectral density distribution of liquid film thickness fluctuation in external region of spacer has a large peak in low frequency region and has several peaks between 10Hz and 100Hz. On the other hand, in spacer region, the power spectral density distribution do not have significant peak in lower frequency and frequencies distribute continuously to higher region being about 200Hz.

Though two-dimensional large waves do not often appear in external region of spacer compare to the experiments in annulus channel but frequently occur in spacer

region with relatively large liquid flow rate. This is because that gas velocity profile in external region of spacer is inhomogeneous around rod so as to disable to create two-dimensional large wave, but becomes uniform in spacer region due to constant clearance between rod and spacer cell and then liquid film is uniformly dragged to develop large waves. Such large waves often contact spacer cell forming liquid bridge.

Characteristics of ripples such as number of passing waves, wave height, wave width (duration time) and wave period changes with gas velocity profiles around rod as expected from time- averaged liquid film thickness distribution. To say, number of passing waves decreases and the rests increase at where liquid film thickness is large due to small gas velocity.

7.3. Recommendations for Future Work

Time- and spatial resolutions of the FDM are expected to be precise with improvement of applied systems such as image capture device (video camera, etc.) and suitable optical accessories. Ephemeral waves that change their traveling velocities in a long distance will be distinguished by using plural system of parallel type of the FDM in axial directions. Additional optical device will be needed when the FDM is applied to a circular channel, because refraction of fluorescence should be eliminated for observation. The USEM will be improved its spatial resolution by adopting higher rotating reflector and emitting frequency of ultrasound.

It is reported that obstacle thickness also affects on liquid film flow thus, more experiments using other obstacle shape will give better understandings. Border of changing film structure by obstacle will be clarified with carrying more experiments of different flow conditions.

More information of spacer effect will be obtained by changing parameters of spacer (shape, dimensions, interval etc.) in a rod bundle experiments. In the present work, dimples and spring were considered as projections giving a lot of effects on liquid film, in addition, guide board is also seen to be a source of liquid droplets. Thus, Liquid film thickness on channel wall should be measured, too. To study the relation between rods, measurements on plural rods should be carried out simultaneously. This will be possible by using two or three measuring systems, or using a multiplexer.

In this research, we supposed several mechanisms to form liquid film around simulating nuclear fuel rods in a complex geometry; it will be strongly required to clarify gas velocity distribution that participates with liquid film formation.

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