

Experimental Study of Annular Two-phase Flow on 3x3 Rod-bundle Geometry with Spacers

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Pham Hong Son

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Pham Hong Son

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ACRONYMS AND ABBREVIATIONS

BWR	Boiling Water Reactor
CCF	Cross-correlation Function
CHF	Critical Heat Flux
DNS	Direct Numerical Simulation
DOF	Depth of Field
LFD	Laser Focus Displacement
PLIF	Planar Laser Induced Fluorescent
PSD	Power Spectral Density

Chapter 1 Introduction

Many heat transfer systems consist of the multiphase flow which includes the phase changing between the liquid (water) and gas (steam). The efficiency of the heat transfer processes strongly depend on the accompanied phenomena such as conduction, convection, boiling, and condensation. Furthermore, the safety of these systems could also be affected if the heated surfaces are not covered by the liquid phase due to the low heat removal capacity of the gas or steam phase. This concern is particularly important to the nuclear power plants using the boiling water reactors (BWRs) in which the dry-out situation could occur and damage the nuclear fuel core.

The flow patterns which can occur near the top of a BWR fuel core are described in Figure 1-1. Together with the increasing of the volume ratio of gas phase and liquid phase, called void fraction, there is a transition from single liquid-phase flow to bubbly flow, slug flow, annular flow, mist flow and finally single gas-phase flow (Todreas and Kazimi, 1990).

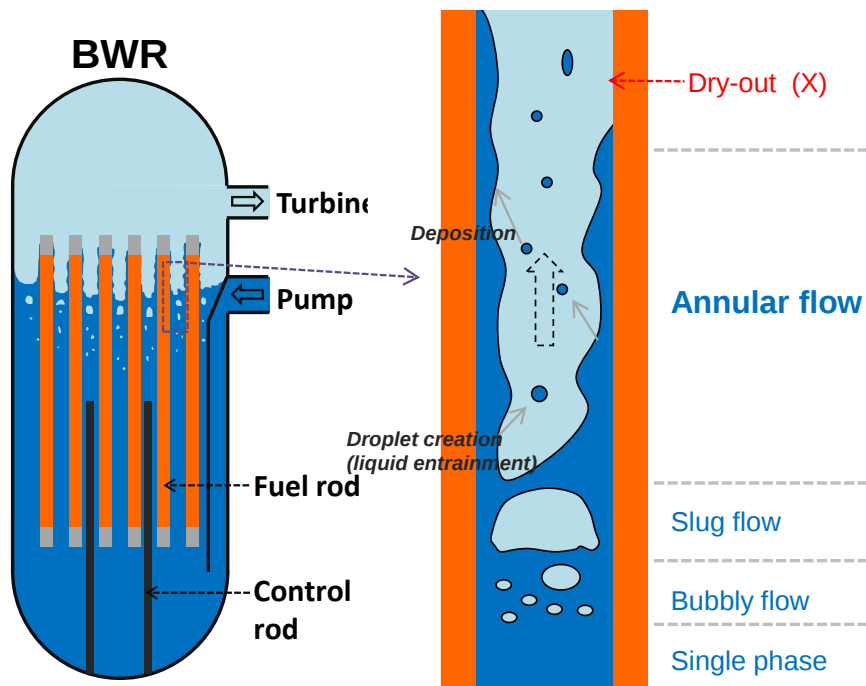


Figure 1-1 Possible flow patterns occurring near the top of BWR fuel core

It can be pointed out that the flow regime which directly leads to the dry-out situation is the annular flow. In other words, this flow regime is responsible for the momentum, heat, and mass transfer near the CHF (critical heat flux) condition. Because the systems are designed to avoid the dry-out, the characteristics of this regime plays very important roles in the consideration of maximum power of operation as well as the safety of the facilities. This is the reason why the annular flow has been the subject of many studies. The knowledge about this flow regime, however, is very limited due to many difficulties.

One of the most challenges comes from the complexity of the annular two-phase flow itself. This flow is characterized by the liquid films flowing on the fuel rod surfaces, the gas cores flowing through the gaps between these rods, and liquid droplets flying with the gas cores. The surfaces of the liquid films can consist of small waves, called ripples, and large-amplitude ones called disturbance waves. It has been widely known that the entrainment processes in which the liquid droplets are generated from the liquid film mostly occur at the disturbance waves.

Differing from the small ripples covering the base liquid film, the large amplitude-disturbance waves only exist in the flow regimes with the liquid flow rates higher than some critical values and they can affect the interfacial roughness as well as the momentum and heat transfers of the system (Hewitt and Hall Taylor, 1970; Ishii, M. Grolmes, 1975). Since the gas and liquid flows in the rod-bundle are highly turbulent, the experimental techniques have faced many difficulties to study the interfaces' behaviors as well as the characteristics of the entrained liquid droplets. This has kept the researchers from providing a detail description for the phenomena, especially about the wave shapes and entrainment processes.

The very unstable gas-liquid interfaces also affect the measurement of the liquid droplet flying in the gas core. Azzopardi (1997) suggested that optical techniques should be most suitable to perform this task. However, they all required the removal of the liquid film to measure the diameter and velocity of the liquid droplets when studying the annular flow with a circular pipe test-section. The removal obviously restricts the ability to obtain the information of both liquid film and droplet.

Beside the very unstable gas-liquid interfaces, the fuel rod-bundle is considered as a complicated geometry. A typical design of BWR fuel assembly is presented in Figure 1-2. The characteristics of the flow moving through this structure strongly depend on different mechanisms such as the effect of rod position (corner or center), the flow-spacer interaction, etc.



Figure 1-2 Schematic view of BWR fuel assembly (www.world-nuclear.org)

The spacers not only help to maintain the clearance between the fuel rods but also affect the performance of the flow moving through the assembly. In the view of the annular two-phase flow, it can modify the liquid film thickness, the generation and deposition of droplets so that the dry-out phenomena can be enhanced or delayed. Therefore, there have been the experiments which were dedicated to study these influences with different spacer designs. Damsohn(2011) developed a high-speed liquid-film sensor system to study the annular flow in a test section modeling the sub channels of BWR fuel rods. Feldhaus et al. (2002) also studied the annular flow in rod bundle geometry by using five pairs of conductance probes. Both the experiments were conducted with the sub-channel geometry. Another study conducted by Nishida et al. (1994) by using circular electrodes shown that the liquid film flowing on the corner rod was thicker than that on the center one. One of the few studies talking both liquid film and droplets into account was performed by Kraemer et al. (1995). Meanwhile the change of droplet's size across a spacer was observed by Cho et al. (2011).

As will be seen in the more detail reviewing of existing measurement techniques presented in Chapter 2, despite of much attention has been paid on studying the annular two-phase flow the following points are remained:

- The obtained visualization information has not been enough to describe the mechanisms of important phenomena occurring in annular two-phase.
- The time-space resolutions of many applied techniques were not enough to measure the very unstable wavy gas-liquid interfaces.
- The rod-bundle experiments which considered the wave characteristics are not available.
- In many experiments, the data including the characteristics of both the wavy liquid film and droplets were not available.
- The effects of spacer on the two-phase flow have not been considered adequately.

The last two points are particularly important because the wavy behaviors play a major role in the liquid entrainment and strongly affect whole the mass and heat transfer phenomena. Furthermore, the average liquid film thickness itself should not the only

key parameter of the interaction between the liquid film and the spacer structure. The disturbance waves which are much higher than the average liquid film would have more chance to interact with the spacer's structures.

The current work is an attempt to overcome these limitations. The high-speed camera technique has been applied to investigate the annular two-phase flow in a 3x3 simulating BWR fuel rod-bundle test-section including the spacers at micro-scale of time and space. The main targets include the followings:

- Achieve the clear side-view images of wavy gas-liquid interfaces' behaviors including the processes of liquid entrainment, droplet impingement, the side view images of disturbance waves,
- Determine the characteristics of the wavy liquid film flowing on the rod's surfaces at up- and downstrems of the spacer.
- Simultaneously, measure the characteristics of liquid droplets existing in the gas core between the rods.
- Obtain the close-up visualization of phenomena occurring at right up- and downstrems of the spacer to understand the influences of the spacers on the two-phase flow.

The contents presented in next chapters are structured as follows:

Chapter 2 provides the review of the existing experimental techniques applied to study the annular flow. Then the experimental facility including two-phase annular flow loop and image data acquisition system are described. The general descriptions of the methodologies for liquid film and droplet measurements techniques are also given.

Chapter 3 presents the visualization results which can be used to explain the mechanism of important processes such as liquid entrainment phenomena and the disturbance waves.

Chapter 4 is about the experimental methodology and the results of the quantitative measurement of the liquid film. The detail descriptions for image acquiring and image processing procedure developed with Matlab are given. The later parts show the results

of average values, probability density and power spectral density of the liquid film thickness for different positions and flow conditions. The data obtained up- and downstreams of the spacer reflect the effects of this structure on the film flow.

Chapter 5 is similar to Chapter 4 but the subject becomes the liquid droplets. The image processing technique to extract the information of droplets is demonstrated. The results consist of the diameter, velocity, space distribution of droplets for different positions and flow conditions. The influences of the liquid film characteristics and the spacer on liquid droplet distributions are discussed.

Chapter 6 presents the attempt to investigate the phenomena happening at right up- and downstreams of the spacer. The close-up visualization data shows how the large-amplitude waves enter the spacer structures as well as how droplets are generated right downstream of the spacer.

Finally, the conclusions and implementation to two-phase flow models are provided in Chapter 7.

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Chapter 2 Experimental apparatus and measuring techniques

As pointed out in Chapter 1, the annular two-phase flow is one of the most complicated flow regimes and has caused many difficulties for the experimental studies. Hence, the first parts of this chapter are dedicated to the reviewing on the existing techniques which have applied in these studies. The later parts then describe the current experimental apparatus and the general methodology to obtain image data of the annular two-phase flow on rod-bundle geometry.

2.1 Reviewing of existing experimental techniques

Various techniques have been applied to study the annular two-phase flow with different geometries of the test-section. Generally, each of them has the advantage in providing only one or more information such as visualization, liquid film thickness, wave characteristics, and the data of droplets. The remained aspects or parameters, however, could not be taken into account. For example, the both liquid film and droplets have not been measured simultaneously. Therefore, the applied experimental techniques can be classified by the following purposes.

2.1.1 Visualization of gas-liquid wavy interfaces

The visualization data is essentially to understand the mechanism behind the important processes occurring at the gas-liquid interfaces of the annular two-phase flow. However the very unstable interfaces do not only require the high time and space resolutions of the image data acquisition systems but also cause the light scatter and reflection which lead to significant distortions in the image data. Therefore, the wavy surfaces of the liquid film flowing on the wall of the test-section strongly affect the observation of the waves themselves, as well as further inside the flow.

To avoid these optical distortions, a popular method named as axial viewing technique (Hewitt and Whalley, 1980) was developed to provide the real-time observation inside the flow but in the axial direction. Being considered as a suitable method to observe the liquid-film and the droplets' behaviors within the image plane, this technique was improved by Fisher and Yu (1975) and Badie et al. (2001). A camera was placed in the axis of a circular pipe to look into it. The outlet of this test section was modified in order to allow the liquid film leaving it without disturbing the observation from the camera. A part of the pipe at the focus plane of the camera was illuminated during the image recording processes.

The recent data given by this technique were obtained by Lecoeur et al. (2010). The image series showed the cross section of the pipe with some like-bubble and ligament shapes corresponding to the two entrainment mechanisms proposed by Azzopardi (1983): bag break-up and ligament break-up. The former happens when the gas flow undercuts the disturbance wave crest to form a bag shape with a thick filament rim. The pressure is continuously accumulated inside the bag until the bursting occurs to generate many small droplets. Then the rim of the bag is also broken into several larger droplets. This was also mentioned as the undercut mechanism (Ishii and Grolmes, 1975). The second mechanism, ligament break-up, happens when the crest of roll waves is elongated by the gas flow to form a thin ligament and then breaks down into droplets. Although axial viewing technique provided good evidences for two proposed mechanisms, it has faced difficulties to provide the important information about the wavy interfaces' behaviors right before and after the event and the droplets' characteristics. The missing comes from the fact that the flow is generally high velocity in the axial direction, while the obtained image is a radial cross section.

It has been widely known that the entrainment processes mentioned above mostly occur at the disturbance waves. Differing from the small ripples presenting on the liquid film surfaces, the disturbance waves only exist in the flow regimes with the liquid flow rates higher than some critical values and can affect the interfacial roughness as well as the momentum and heat transfers of the system (Hewitt and Hall Taylor, 1970; Ishii, M. Grolmes, 1975). Because of these important roles, the disturbance waves have become

the subject of many studies with different experimental techniques. Taylor et al. (1963) used cine film technique to observe the disturbance waves in a transparent circular-pipe test-section. The disturbance waves were recognized by their “milky” appearance due to the light scattering effect occurring at their unstable surfaces. The data showed that the velocities of the disturbances waves were almost constant with some exception such as a wave can be decelerated and taken over by a next faster wave. Schubring et al. (2010a) also used a high speed camera with a back light arrangement to study the vertical annular flow in a pipe. The waves detected based on the dark areas in the images were classified into two types, the large waves traveling at high average velocity and smaller waves at lower velocity.

The lack of the side view data which can fully describe how the entrainment processes as well as the propagation of the disturbance waves has restricted the comprehensive understanding about these phenomena.

2.1.2 Measurement of liquid films

Generally, the liquid film thickness is measured by the techniques based on optical, ultrasound, electricity conduction, and sometime x-ray or neutron tomography as the followings.

Optical techniques:

One method is the laser focus displacement (LFD) meter which can be used to measure the liquid film thickness at very high resolutions of time and space. The displacement of the gas-liquid interface is detected basing on the continuous movement of an objective lens at a given frequency. Hazuku et al. (2008) applied this technique for a circular pipe of 3m long and found that the fully developed state of the annular flow would never be achieved. The technique, however, could not detect the surface having inclination larger than 33° , according to the authors. This limitation might restrict the detail investigation of the disturbance wave structures consisting of the very unstable surfaces.

The side viewing method which can locate the gas–liquid interfaces is the planar laser-induced fluorescent (PLIF) technique (Schubring et al., 2010b). A small amount of fluorescent dye was introduced into the liquid phase and then activated by a laser sheet during the image recording processes. The liquid film thickness was successfully measured and the data showed that most of models for annular flow under-predicted the effect of increasing liquid flow on pressure loss and interfacial shear. However, the data were in the form of separated images so that there was no real-time description of the interface behaviors and the liquid droplets flying in the gas core.

Another study by using PLIF with high speed camera was performed by Alekseenko et al. (2009) to measure the disturbance waves of a vertical downward annular flow in a circular pipe. From the intensity of the light captured by the camera, the authors inferred the liquid film thickness and found that both the surfaces of the base liquid film and the back slopes of disturbance waves are covered by small amplitude ripples. At the base film, these ripples can be decelerated and absorbed by successive disturbance waves or be accelerated to reach the front lobe before disappearing due to the entrainment processes. An extension to study the three-dimensional structures of these types of waves was also performed (Alekseenko et al., 2011). More recently, Farias et al. (2012) applied the PLIF not only to obtain the side view but also to develop a stereoscopic setting to visualize the cross section of annular flow in a horizontal circular pipe. To obtain the cross-section images, two high speed cameras were placed at both sides of the pipe and each one looked into the illuminated plane under an angle of 45° . Then, the data obtained by these cameras were used to reconstruct the cross-section image of the cross-section, basing on a calibration target and an image correction algorithm. The quantitative data of the liquid film were achieved at the equivalent accuracy compared to other techniques. The PLIF images, however, could not provide the detail descriptions of the interface behaviors such as the entrainment phenomena and the liquid droplets.

Ultrasound techniques

Also based on the reflection of the signal the gas liquid interface, Serizawa et al. (1994) applied the ultrasonic transmission techniques to measure the liquid film flowing over a

horizontal duct. Then this method was applied to study the liquid film flowing on the outer surface of a rod by Kamei and Serizawa (1998) and with a 3x3 rod bundle by Kamei (1998). The application of a rotation reflector provided the capacity of measuring the liquid film around the rod. The measurement was performed at distance 0.95 m from the inlet and it needed 0.4 ms for one round measurement. Chang et al (1990) also used ultrasonic technique to detect the gas-liquid interfaces for slug flow in a horizontal test-section.

Although being considered as a non-intrusive method, this technique faces difficulties to detect the large liquid interfaces. Similar to the case of LFD technique, the bouncing back sound-signal is hardly captured by the sensor so that the sharp waves or complex wave structures such as disturbance wave can be mistaken.

Electrical conductivity techniques

Overall, the most popular method is the conduction probe technique which can measure the liquid film thickness at high frequency and can be applied to the complicated geometries. Taylor and Nedderman (1968) used this technique to study the development of the disturbance waves and suggested that for the distances about 0.3 or 0.6 m from the injector, the probability of the coalescence of waves is high. After that the coalescence rate decreases and the velocities of adjacent waves are correlated. Azzopardi (1986) setup the conductance probes at several distances 0.31 to 5.17 m from the inlet to determine the frequency of the disturbance waves from the film-thickness data. The data also showed the decreasing tendency of the wave frequency due to the coalescences occurring downstream. The systems of multiple-point and multiple-ring electrode probes were used in the experiment of Sekoguchi and Takeishi (1989). They found a new type of wave (termed as “huge wave”) which has large amplitudes and travel faster than the disturbance waves. Sawant et al. (2008) performed the experiment to cover a wide range of pressure and flow conditions and found that the previous correlations failed to predict the variation of disturbance waves’ frequency on the pressure. The authors proposed a new correlation which could retrieve their results as well as the others’ data within 25% of deviation. More recently, a system of 320 conductivity sensors was developed by Belt et al. (2010) for a circle pipe of 5 cm in

diameter. The measurement region was performed at distance about 6.5 m from the inlet led the authors to the conclusion that the disturbance waves were three-dimensional structures and had a random spatial distribution due to the coalescence processes. Zhao et al. (2013) used four conduction probes equally placed around the periphery of the circular pipe test-section to obtain the data of the liquid film thickness. Beside the development in the axial direction, the authors also obtained an interesting conclusion that before becoming a ring-like disturbance waves downstream, the structure appeared at specific circumferential locations and then spread around.

It can be seen that the electric conductivity based measurement could be applied to a completed geometry such as rod bundle and achieves a very high frequency but its space resolution is quite low due to the limitation in the machinery. This disadvantage will be discussed in more detail in Chapter 3.

Others techniques

Beside above techniques, gas-liquid interfaces can also be detected basing on X-ray and neutron tomography which are recently applied by Fischer and Hampel (2010) and Zboray et al. (2011, 2013). These techniques present the advantage in applying for the complex geometry such as rod-bundle with spacer but are limited in the resolution. Furthermore, they are more complicated and expensive compared to other techniques.

In summary, each technique applied to measure the liquid film has some advantages such as the high resolution in time and/or space, ability to provide 2D or 3D data. However there is also limitation in one or more of these parameters or a problem of image distortion likes the optical techniques.

2.1.3 Measurement of liquid droplets

Keeping the important roles in the annular flow phenomena, the liquid droplets has also becomes the subject of many experimental studies. The total volume of liquid droplets of the annular flow can be determined by using the suction probes (Barbosa et al., 2002; Kraemer et al., 1995) but the detail information such as droplet's size and velocity

should be obtained by an optical based technique (Azzopardi, 1997). These optical methods consist of the followings:

Laser-diffraction technique

The laser-diffraction technique has been widely used (Azzopardi, 1985; Sarimeseli, 2009; Fore and Dukler, 1995) to determine droplet size distribution and the corresponding device was also produced commercially by Malvern Instruments. This technique is based on the formation of the diffraction pattern when a spherical droplet flies across the parallel beam of monochromatic light. This will result in the pattern of rings on the focal plane of the lens placed behind the droplet. These light patterns are detected by a detector and a computational procedure based on a given drop size distribution is performed to trace back the droplet size.

The technique can provide a high resolution measurement but the need of droplet size distribution could cause difficulty in some experiment conditions. Furthermore, the liquid film needs to be removed to be able to detect the droplets.

Laser anemometry

Fore and Dukler (1995) used a transparent Ronchi diffraction grating to create an interference pattern of a laser beam which includes bright and dark fringes. A droplet passing through these set of fringes will reflect the light and the detector receives a fluctuating light intensity. Based on the frequency of light fluctuation and the specification of the fringes, the velocity can be calculated. Another detector is used to detect the unscattered light to support the drop size measurement. The technique also needs to avoid the liquid film to detect the droplet and it is accomplished by using the acrylic tube to penetrate the film (Fore and Dukler, 1995). Yano et al. (2000) also applied the similar technique to study mist flow.

Photographic technique

The photographic technique was use by Cho et al. (2011) to study the change in size of droplet flow passing through a spacer grid while the application to annular flow

required the removal of liquid film (Hay et al., 1998) or be limited to the axial viewing arrangement (Hewitt and Whalley, 1980). This technique can only get the information for the flow cross-section, while the main direction of the flow is axial.

It can be seen that the droplet size distribution and velocity can be measured by optical based techniques but the requirement of removing the liquid film has restrict the experimental studies from an simultaneous measurement of both liquid film and droplets which is essential to understand the characteristic of the phenomena.

In summary, much attention has been paid on studying the annular two-phase flow and different techniques and geometries of the test-section were used. However, due to the inherence complexities of the flow and the limitation in each applied techniques the following problems are still remained:

- The obtained visualization information has not been enough to describe the mechanism of important phenomena occurring in annular two-phase flow such as liquid entrainment processes or the propagation of the disturbance waves.
- Most of the applied technique cannot maintain high resolutions for both time and spacer to measure the very unstable wavy gas-liquid interfaces.
- There has been few experiment designed to study annular flow on rod-bundles, especially when the disturbance waves are taken into account.
- In many experiments, the data including both droplet and wavy liquid film were not available. Some provided data of droplets plus average liquid film thickness only, not the wavy characteristics of the film surfaces.
- The effects of spacer on the two-phase flow have not been studied adequately. There has been no information about the interaction between the wavy liquid films and the spacers.

2.2 Experimental Apparatus

As an attempt to get over the difficulties mentioned above, the current studies is aimed at setting up an experimental arrangement which could provide a clear side view image of the liquid film surfaces as well as the liquid droplets flying in the gas core at the gap between two fuel rods. This installation will be used to obtain qualitative image data to describe the important phenomena occurring at the gas-liquid interfaces (Chapter 3) and near the spacer (Chapter 6). The quantitative image data are also recorded and processed to evaluate the characteristics of both the wavy liquid films (Chapter 3) and the liquid droplets (Chapter 5). The next subsections will present main points of the experimental apparatus and methodology while the more detail arrangement as well as the image processing procedures needed for each task will be given in the corresponding chapter.

2.2.1 Experimental Apparatus

The schematic diagram of the annular two-phase flow experiment is shown in Figure 2-1. The purified water in the water tank is pumped and divided into nine lines before reaching the 3x3 rod bundle test-section. Nine pairs of valve and water flow meter are used to control these water lines independently. The gas flow (normal air) from the gas compressor is controlled by one pair of valve and flow meter before entering the test section in four ways. The drag force caused by this gas flow will support the upward moving of the water to maintain the annular two-phase flow on the rods' surfaces. After leaving the test section, the two-phase flow goes to the separator where the gas is released to the environment and the water comes back to the water tank.

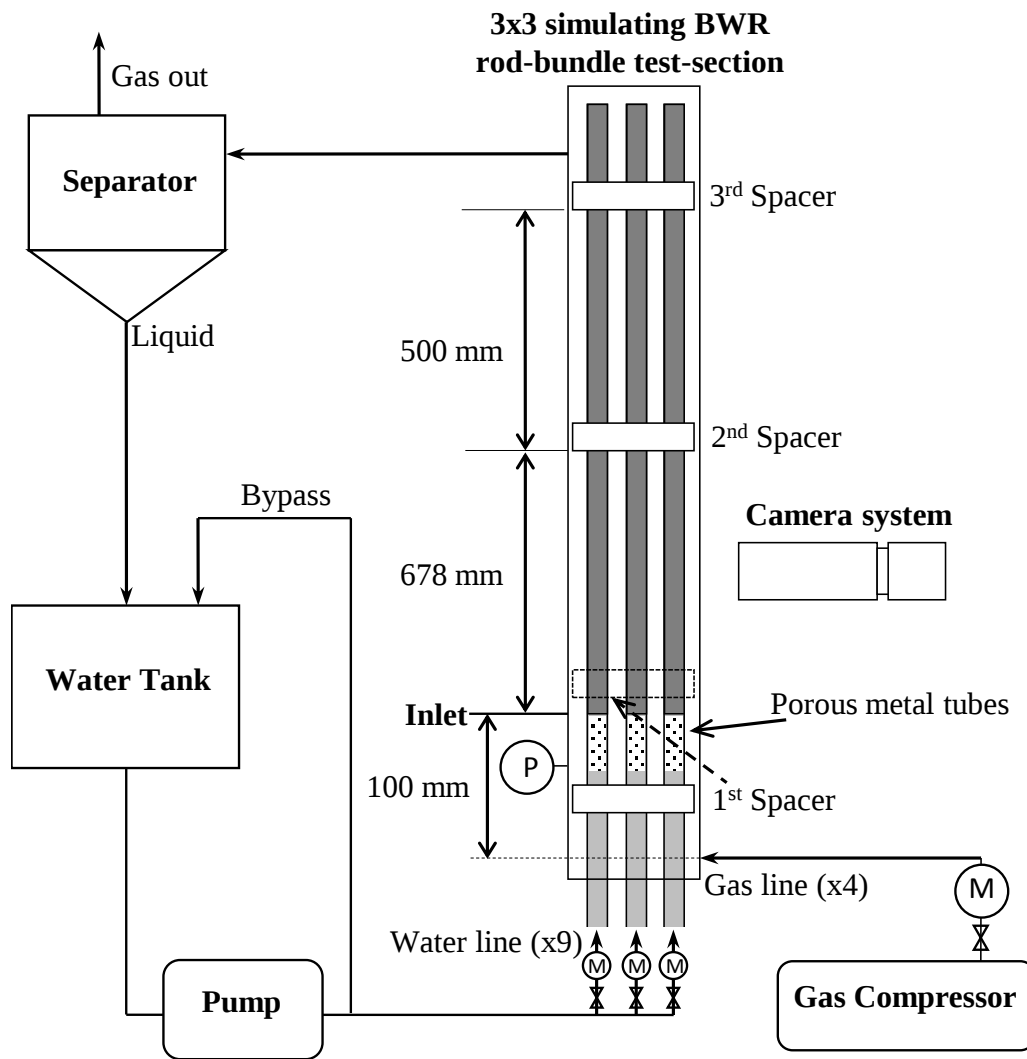


Figure 2-1 Schematic diagram of the experimental apparatus

The following key components of the experimental apparatus are shown in Figure 2-2:

- (1) The 3x3 simulating BWR rod bundle test section consists of a rectangular duct made of transparent acrylic resin and nine steel rods of OD 12mm (Figure 2-2a). The rods are fixed by three circular ferrule-type spacers to maintain the minimum distance between them as 3 mm. The image of a real spacer and its specification is presented in Figure 2-3. The position of the first spacer can be changed as indicated in the Figure 2-1 to support the study of the phenomena occurring near the inlet or more downstream. The observation or measuring points are located between the first and

the third spacers. Hence, the influence of the second spacer on the flow can be evaluated.

- (2) The porous inlet structure arrangement allows a clearer observation from the side of the test section. The porous material has been widely used to introduce the liquid into the test section. In the system, the lower part of each rod is made of the circular pipe which can let the water flowing inside it before penetrating through the porous part to reach the outer surface of the rod (Figure 2-2b). In this way, the water can be introduced and start to flow smoothly on the outer surface of the rods without creating droplet or distributing any amount of liquid on the duct wall. This requirement is confirmed by using the system of high speed camera and tele-microscope.
- (3) The optical system includes a high speed camera Phantom V7.1 (Vision Research Inc.); a Cassegrain tele-microscope (Seika Corporation); and a micro lens (Nikon). The maximum resolution of the camera used in the current study is 512x512 pixel but it can be changed to support the recording speed up to 32 kfps depend on each task. This recording speed equals to the maximum time resolution of 31.25 μ s. Because of the very high recording speeds, a huge amount of data is generated and costs much time for saving during the recording as well as for the image processing procedures.

Together with this camera, the two lenses are used in the backlight and reflected light arrangements, respectively (Figure 2-2c and d) as the followings.

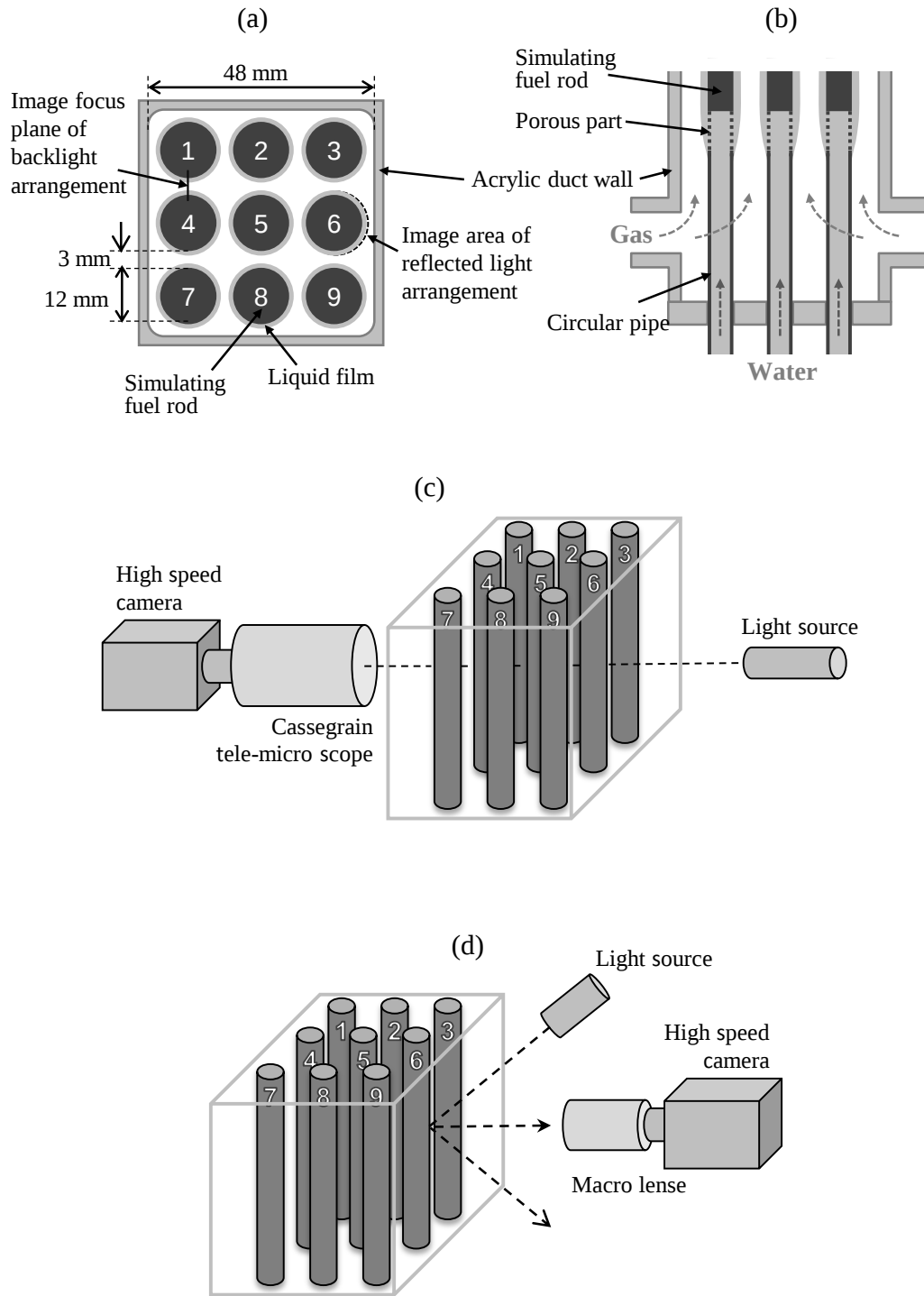


Figure 2-2 The key components of the xperimental apparatus: (a) test section' horizontal cross-section; (b) inlet structure; (c) optical sytem arrangement using backligh; and (d) optical sytem arrangement using reflected light.

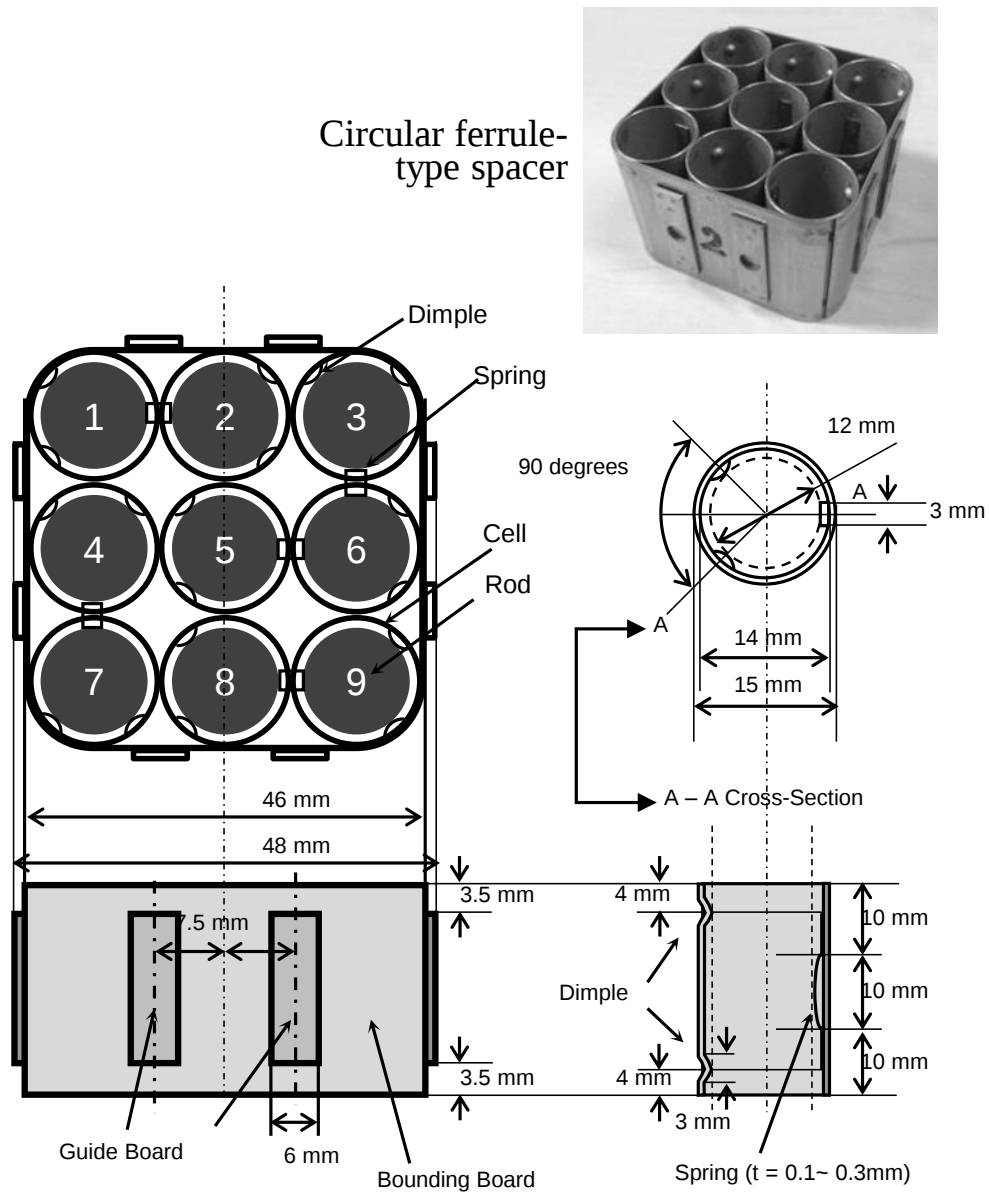


Figure 2-3 Technical specification of spacer

2.2.2 Methodology

Two arrangements of optical system with the backlight and reflected light sources are used. The main part of the current study uses the backlight arrangement to study different characteristics of the two-phase flow as well as the influences caused by the spacer while the backlight arrangement is used to evaluate the circumferential coherence of the disturbance waves around the rod.

Backlight arrangement

The backlight arrangement is used to obtain the images of the liquid film and the droplet at the focus plan indicated in Figure 2-2a. The obtained information consists of the side-view visualization of the gas-liquid interfaces' behaviors and the quantitative data of wavy liquid film thickness and the droplets. The Cassegrain lens is applied because of its ability to provide a high magnification at very low distortion. The calibration is performed by taking the photo of a scale placed at the focus point of the system. The data show that each dimension of the image pixel represents a length from 6.6 to 7.0 μm on the focus plan depending on the distance between the lens and the test-section used in each task. A strong light source (metal halide lamp – Nippon P.I. Co.) helps to reduce the exposure time to 2 μs to support the high recording speeds. With the deep of field (DOF) of the system is about 500 μm , only the parts of liquid film and droplets belong the spacer at the gap between the corner rod #1 and the side rod #4 are observed. The location a rod' surface can be determined by turn off the waterline corresponding to that rod.

Comparing to the previous experiments of annular two-phase flow it could be seen that this study is the first time the back light arrangement is applied to study the annular flow with the rod bundle geometry. Furthermore, the use of porous inlet structure to avoid the initial distribution of the liquid film on the acrylic duct wall will helps to reduce the optical distortion occur in the obtained images. The similar attempt cannot be done in the case of a circular pipe test-section in which the internal surface of the pipe is the only solid surface to support the liquid film.

One point should be noticed is that the method will hardly be suitable if the liquid entrainment rate is too high. In this circumstance, the accumulation of liquid droplets on the acrylic duct wall could be large enough to continuously form a thin film layer or a rivulet and they will strongly distort the optical observation is about the observation positions around the rods. The method cannot be applied to the locations through which the light source cannot be seen by the camera.

An example image obtained by the backlight arrangement is presented in Figure 2-4a. It can be seen that the gas-liquid interfaces is clearly located. Furthermore, a droplet flying in the gap can be captured. Therefore this arrangement could provide the information on both liquid film thickness and droplets at high time and space resolutions.

Reflected light arrangement

The reflected light arrangement is used to study the circumferential development of the disturbance waves which occur at the liquid film flowing on the side rod #6 as indicated in Figure 2-2a and d. The detection of the disturbance waves is based on the fact that the surfaces of these waves are very unstable so that the light has more chance to be reflected to the camera compared to the gentler surfaces covering other parts of the liquid film. As will be seen in the Chapter 1, by sampling the image areas independently the circumferential development of the disturbance waves can be evaluated. The data are also gathered at up and downstreams of the second spacer to study its influences on the flow.

The limitation of the reflected light arrangement is that it cannot achieve the information of liquid film thickness nor of droplets. Therefore, it is just used as a supplement for the backlight arrangement which cannot provide the circumferential information of the wavy liquid film.

Figure 2-4b shows an example of the image data obtained with reflected light arrangements. The brighter image area enclosed by a white dashed line represents the unstable surface cover the disturbance waves. In this image, this wave structure has not achieved a full-ring structure which is called as fully developed disturbance waves.

The information relating to these two arrangements in more details as well as the corresponding image data processing procedures will be presented in the subsequent chapters.

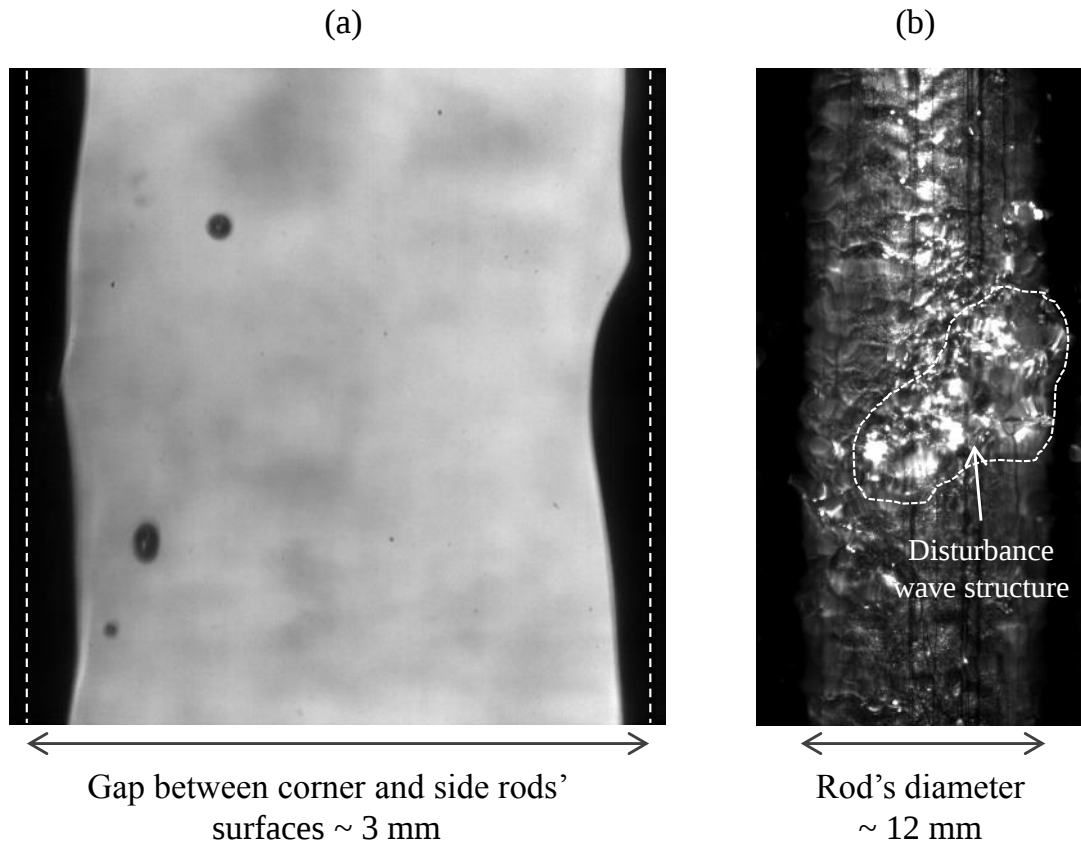


Figure 2-4 Examples of image data obtained by (a) backlight arrangement and (b) reflected light arrangement.

2.2.3 Flow conditions

Based on a survey using the system of high speed camera and tele-micro scope, the gas and liquid flow rates are mainly selected by the following criteria:

- The lowest gas velocity is strong enough to maintain the annular flow regime (there should not be any collapse or falling down of the liquid films).

- The lowest liquid flow rate is still large enough to maintain the continuously liquid film all the way downstream of the rod surfaces. It means that the liquid film is not broken into some rivulets.
- At the highest values of gas and liquid flow rates, the amount of liquid flowing on the duct wall surface are not enough to form a liquid rivulet crossing the image window or to cause strong distortion in the image data.

In addition, the recording and saving time needs to be reasonable especially in the case of obtaining visualization data (Chapter 3). This is necessary because the high recording speed of the camera generates huge amount of data (1.4 GB installed memory is enough for the recording time about 0.4 s only), while the image area is just about several square millimeters. Despite of the repetition of the shooting, the possibility to catch one of these processes occurring in such small area and short period of time is very low. Therefore, only the highest values of gas and liquid flow are used to obtain the visualization data which can describe the important processes of the phenomena.

The summary of the flow conditions of the current experiment is presented in Table 2-1. The criteria of choosing these flow conditions are described in more detail in each of the following chapters. All the water flow meters are calibrated and the error of the flow indicators is less than 2%.

Table 2-1 Flow conditions defined by superficial velocity (m/s)

$j_G \setminus j_L$	22.7	31.8	44.5	62.2
0.020	D+F	D+F+S	D+F+S	B+D+F+R+S
0.025	D+F	D+F+S	D+F+S	B+D+F+R+S
0.032	D+F	D+F+S	D+F+S	B+D+F+R+S

Where B stands for the visualization of the interface's behaviors; D - droplet measurement; F - liquid film measurement by backlight arrangement; R - circumferential coherence of disturbance wave by reflected light arrangement; S - close-up observation of phenomena happening just upstream and downstream of spacer.

The close-up observation of the phenomena occurring near the spacer (Chapter 6) needs some adjustments on the water lines and the corresponding flow conditions will be introduced later.

The temperature of the liquid and the gas at the inlet are maintained at $15 \pm 0.5^{\circ}\text{C}$ and $16 \pm 1^{\circ}\text{C}$, respectively. The gas gage pressure right after the inlet is about 40 kPa.

2.3 Summary

As an attempt to get over the limitations of the existing experimental techniques, the two-phase flow loop has been set up to study the annular flow on a 3x3 rod-bundle test-section with the high speed camera technique. The backlight arrangement provides a new method to obtain the clear side-view image of the phenomena. This allows not only the visualization of important processes occurring at the gas liquid-interfaces but also the qualitative measurement of the liquid film and droplets at high resolutions of time and space. In addition, the reflected light provides the information about the circumferential coherence of the disturbance waves. Basing on these experimental arrangements, the influences of the spacer on the flow can also be considered.

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Chapter 3 Detail observation of wavy interface behaviors

3.1 Introduction

The visualization information is essential to understand the important processes occurring in annular two-phase flow regime. They include the liquid entrainment in which a small amount of liquid is detached from the liquid film to form liquid droplets and travel with the gas core, and the droplet impingement which means a entrained liquid droplet collides with the film surfaces. These processes directly affect the transfer of mass, momentum, and energy in the heat exchange system.

The available observations of the gas-liquid interfaces, however, have been mostly provided by the axial-viewing technique which developed by Hewitt and Whalley (1980) as mentioned in Section 2.1.1. The obtained image series showed the cross section of the pipe with some bubble-like and ligament shapes corresponding to the two entrainment mechanisms proposed by Azzopardi (1983): bag break-up and ligament break-up. These two processes were also recalled in a review on the droplets involved in annular two-phase flow phenomena of Azzopardi (1997). Although axial viewing technique offered good evidences for two proposed mechanisms, it has faced difficulties to provide the important information about the wavy interfaces' behaviors right before and after the event and the droplets' characteristics. The missing comes from the fact that the flow is generally high velocity in the axial direction, while the obtained image is a radial cross section.

Another limitation in the existing data of the annular two-phase flow is about the development of the disturbance waves. Zhao et al. (2013) studied this development by using four conduction probes equally placed around the periphery of the circular pipe test-section to obtain the data of the liquid film thickness. Beside the development in the axial direction, the authors also obtained an interesting conclusion that before becoming a ring-like disturbance waves downstream, the structure appeared at specific

circumferential locations and then spread around. These processes continue and the fully-developed coherent disturbance-wave exists at the distance of 2m from the inlet. It can be seen that the closest measuring point in this study was located at 15 cm from the inlet and the corresponding data show the wave structures which have very small amplitude and distribute randomly. The obtained wave signals in this region are almost embedded to the liquid film. Therefore, it might be difficult to study these wave structures by using conductance probes or other techniques which have low resolution of time and/or space. It turns out that the information about the processes which can occur at region close to the inlet is still missing. Furthermore, despite the large attention paid to the disturbance waves which are fully developed, a direct side-view observation which can improve the understanding of their characteristics has not been available until today.

For a more comprehensive understanding of the interface behaviors related to the entrainment processes and the wave structures, the present work is aimed at achieving the clear side-view images of the phenomena at the micro-scale. The idea of avoiding the optical image distortion and the experimental setting are described in Section 3.2. Then section 3.3 presents the obtained image data together with the discussions on the formation of a singlet wave crest near the inlet, the images of disturbance waves downstream, and three types of entrainment mechanisms: bag break-up, ligament break-up, and droplet-impingement. Finally, the conclusions are given in Section 3.4.

3.2 Experimental methodology

From the above discussion, the lacking of a clear side-view image of the phenomena is undoubtedly due to the strong image distortions caused by the light scatter and reflection which happen at the unstable surface of the liquid film. It should be noted that most of the studies have been performed with the circular pipe test-section in which the liquid film flowing on the duct-wall and the distortions are unavoidable. Realizing this point, the current study performs an optical observation of annular two-phase flow with the rod-bundle geometry. The comparison between the optical observations conducted with circular pipe and rod-bundle test-sections are given in Figure 3-1. Being different

from the case of circular pipe, the objective liquid films are distributed on the rods' surfaces while acrylic duct-wall is covered by a smaller amount of liquid. As will be seen in next sections, this amount of liquid can be minimized or modified to maintain a clear image window on the acrylic duct-wall.

Taking this advantage, the current study uses the high speed camera with the Cassegrain tele-microscope to observe the wavy interface behaviors of the annular flow with 3x3 simulating BWR fuel rod-bundle test-section. It should be noticed that the liquid films in this study are distributed on the outer surfaces of the rods instead of the internal wall of the circular pipe as in many existing experiments. This difference, however, may not play a very important role in the phenomena which occur locally because the main flow is in the axial direction.

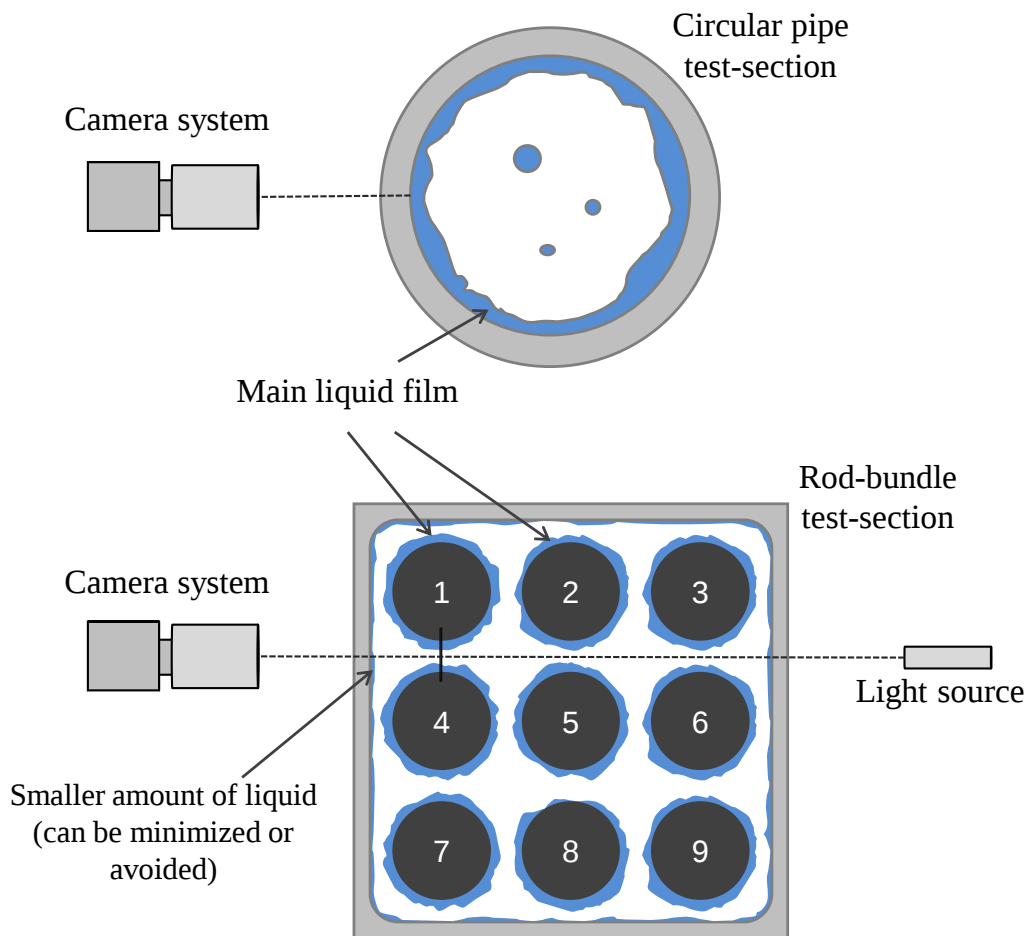


Figure 3-1 Comparison between the circular-pipe and rod-bundle test-sections

Because the current task does not take the influence of the spacers into account, the first spacer is located lower than the inlet and the observation is performed between this inlet and the second spacer as shown in Figure 3-2. This helps to isolate the parts including the inlet and observation locations of the rods from the wall. In other word, the liquid existing on the wall (if there is any) is from the entrainment phenomena occurring somewhere upstream. This amount of liquid can affect the optical observation but generally, the amount of the liquid entrained into the gas core is much smaller than that of the liquid film on the rods' surface. For the present flow condition and observation range lying between the first and the second spacers, the liquid does exist on the duct wall. However the area at the image window is not always covered by the liquid. Hence the data acquisition can be performed repeatedly then the images with low distortion are selected.

The observation was performed at the positions located at 5, 15, 40, and 60 cm from the inlet to investigate the phenomena occurring near the inlet as well as the different stages of development of the disturbance waves. Only the highest flow rates of gas and liquid which correspond to superficial velocities of 62.2 m/s and 0.032 m/s, respectively are used. These high values help to archive the high frequency of the interesting events. This is necessary because the high recording speed of the camera generates huge amount of data (1.4 GB installed memory is enough for the recording time about 0.4 s only), while the image area is just about several square millimeters. Despite of the repetition of the shooting, the possibility to catch one of these processes occurring in such small area and short period of time is very low so that the high frequency of occurrence will keep the recording time reasonable. According to the criteria given by Azzopardi (1983) to differentiate the bag break-up and the ligament break-up mechanisms, this flow condition is closed to the boundary between these two regimes. Therefore, both mechanisms are expected to occur.

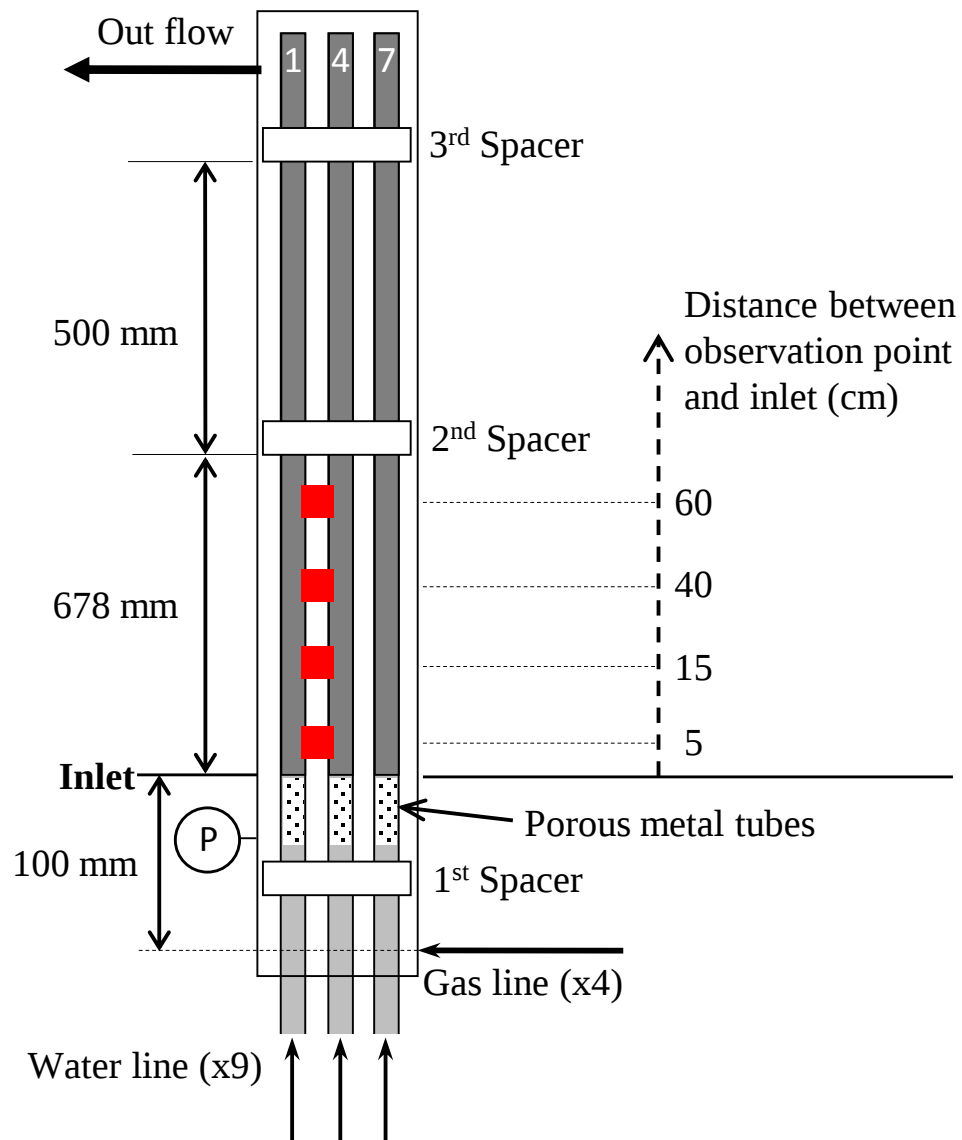


Figure 3-2 Experimental setting to obtain the visualization information

3.3 Results and discussion

The clear side-view images which can indicate the gas-liquid interfaces and droplets were successfully achieved. This section presents the image series extracted from the obtained video clips to provide the description of important processes of the annular two-phase flow.

3.3.1 Formation of singlet disturbance-crest

The first result is the observation performed at the distance 5 cm from the inlet using the recording speed 19 kfps of the camera. For the total recording time of about 10 s, image data shows that the large amplitude disturbance waves do not exist but there are some liquid droplets flying in the gas core (Figure 3-3a). The liquid film surface is covered by many small-scale waves which are formed through Kelvin–Helmholtz instability travel from the left to the right of the image area. The advancing of the wave structures occurs but the entrainment phenomena do not happen because of their small scale.

In particular, there are the situations in which a very sharp wave-crest is formed quickly in a local area as shown in Figure 3-3b. Because this formation occurs independently, the crest is called as “singlet disturbance-crest”. It can be seen that the process in the image series (b) can be started at the surface which is relative flat compared to the interface presented in the image series (a). Another point is that the top of the crest moves away from the liquid film in a quite large angle. This situation raises a question about the role of shear on the formation of the singlet wave-crest because generally the acting force caused by the shear is weaker when the surface is gentler and the direction of the force is almost parallel to the base film surface.

Unfortunately, the experimental data in the literatures have been too limited to provide a good estimation of this contribution. One of the few studies which showed the relation between the deformation of the gas–liquid interface and the shear is the direct numerical simulation (DNS) performed by Fulgosi et al. (2003). The study on the sheared air–water flow at the turbulent Reynolds number of 171 found that the deformation is in the range of capillary waves. Another one is the DNS work conducted by Yamamoto and

Kunugi (2011) for the high-Froude-number turbulent open-channel flow. The results also showed that the maximum interface fluctuation generated by the shear is small, approximates 4% of the water depth. Assuming the maximum height of the wave generated by shear in current experiment is somehow at the same level with these results. With the liquid film thickness is about several hundred μm , the maximum height of the wave due to the shear should be 10 - 20 μm . This value is much smaller than the height of the singlet disturbance-crest showed in the image ($\sim 330 \mu\text{m}$). In this sense, the shear may have little impact on the formation of the singlet-crest.

If the shear is not the main cause to form the singlet disturbance-crest, the unknown mechanism behind this process could relate to a special structure formed inside the liquid phase. One idea comes from an experiment of larger flow scale performed by Okuda et al. (1976) in which the hydrogen bubble technique was used to visualize the wind-exerted surface flow. Their obtained images confirmed the existence of the turbulence layer in the liquid region underneath the interface due to the downward-bursting. This occurred even at the initial stage of the acting of wind flow when the water surface was being still. From this point of view there could be is a down-burst existing in the process of the singlet-crest formation. But differing from the wind-exerted surface flow where the water depth is relative large, this down-burst toward the rod surface quickly leads to a bounce back because the liquid film is thin. The bounce back may push an amount of liquid to move into the gas core to form the singlet disturbance-crest.

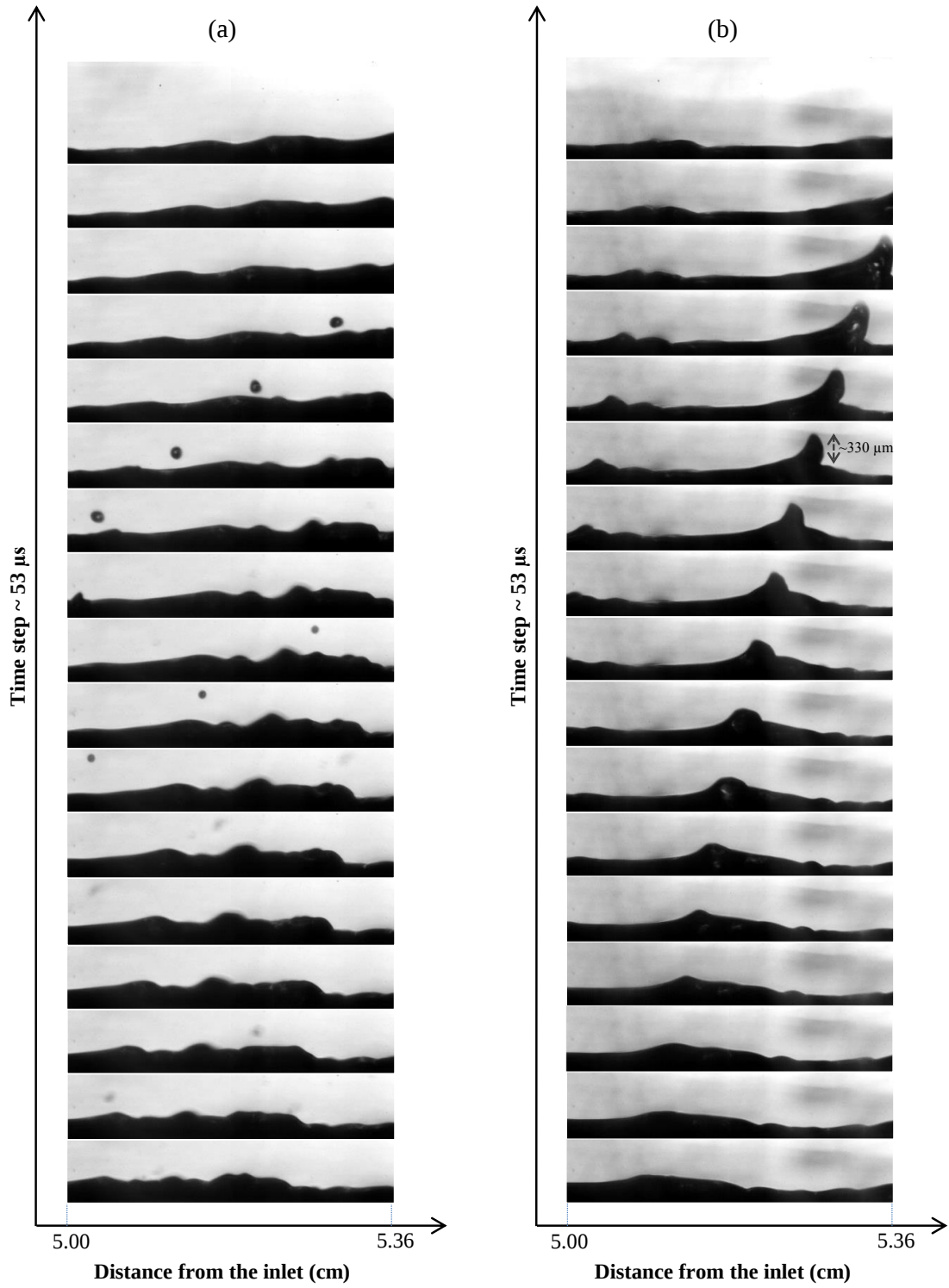


Figure 3-3 Image series obtained at distance 5 cm from the inlet: (a) typical interface behavior; and (b) the formation of a singlet disturbance-crest

From the obtained data that the formation processes did not happen frequently and the height of the crests was large which meant that the down-burst needed to be strong enough. This leads to an idea that the turbulent coherent structure (sweep motion) near the interface could be responsible for these phenomena. To summarize, the formation of a singlet disturbance-crest may be explained by the drawing presented in Figure 3-4 as follows: Because the gas flow is highly turbulent, there is the situation in which the sweep motion (1) of the turbulent coherent structure near the interface pushes this interface and generates a down-burst (2) in the region of liquid underneath it. The down-burst toward the rod surface quickly leads to a bounce back (3) pushing an amount of liquid to move into the gas core.

One important role of these singlet disturbance-crests shows up in the fact that the liquid droplets are observed at the positions close to the inlet. As mentioned in Section 2.2.1, the water is confirmed to be introduced smoothly into the test section and the disturbance waves have not been formed in the region. Therefore, they cannot be the sources for the observed liquid droplets. Actually, after being created, the singlet disturbance-crest can come back to the liquid film to generate a small fluctuation on the surface (without any droplet generation) or it can undergo an entrainment process as seen in Sections 3.3.2 to generate the first liquid droplets.

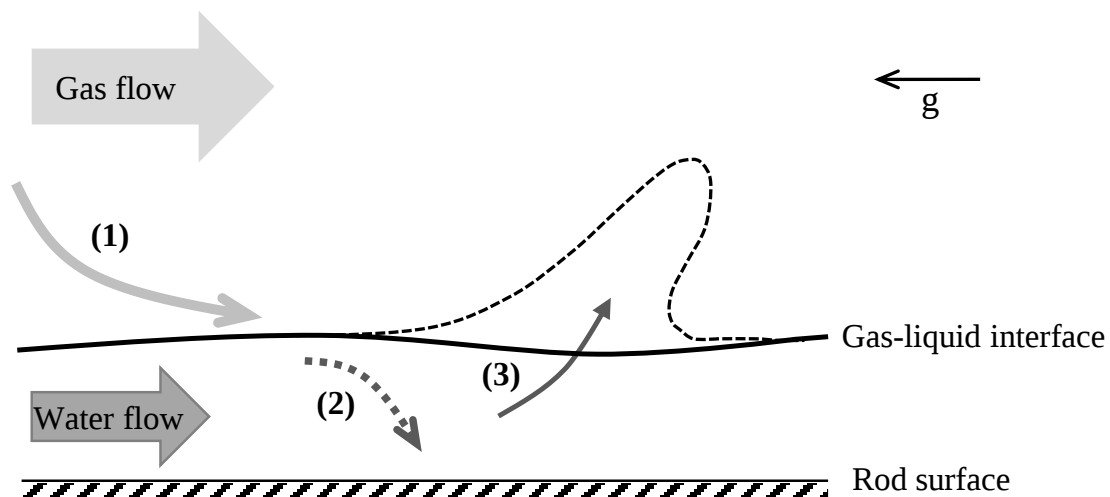


Figure 3-4 Proposing mechanism for the formation of the singlet disturbance-crest

Although the number of these droplets is generally small they can be accelerated and then impinge on the wave surfaces somewhere downstream to generate secondary droplets. This process is referred as the droplet impingement mechanism and also presented in Section 3.3.2.

Another important role of the singlet disturbance-crest relates to the formation of the disturbance waves and will be discussed together with the images obtained at further downstream in Section 3.3.3.

3.3.2 Entrainment phenomena

The entrainment processes occurring under different mechanisms were observed at the regions close to the inlet as well as further downstream. The side-view data provided the important information of interface behaviors right before and after their occurrences. Taking these advantages, the more comprehensive understanding about the starting point of the entrainment processes, their development along the axial direction over the times, and the new-born droplets were obtained.

Bag break-up mechanism

Figure 3-5 shows the bag break-up entrainment processes. The first image series (a) obtained at distance 5 cm from the inlet shows that starting point of the process is a singlet disturbance-crest. Exactly the same as the mechanism proposed by Azzopardi (1983), the gas flow causes an accumulation of the pressure inside the crest to open a bag shape. When the pressure is high enough, the thin layer of this bag is broken into tiny droplets before the breaking of the rim forms some larger droplets. The second series (b) describes a bag break-up process occurring at a disturbance wave structure in an early stage of its development at the distance 15 cm from the inlet. It is considered that the wave structure of starting point of this process is in the early stage because its amplitude is quite low and only one entrainment event occurs, while a more developed disturbance waves will generate the droplets continuously (as will be seen in Section 3.3.3).

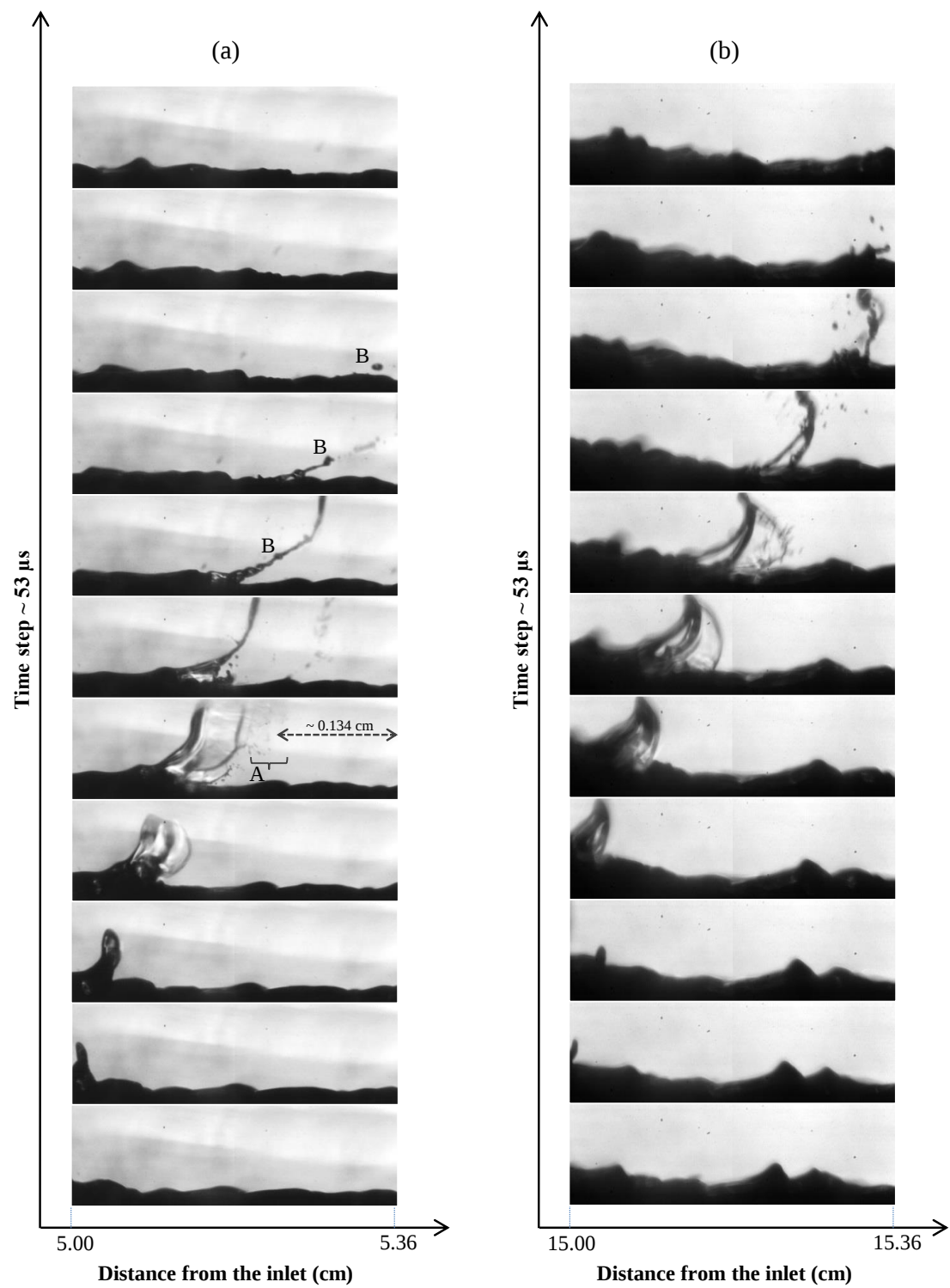


Figure 3-5 Bag break-up processes observed at distances: (a) 5 cm; and (b) 15 cm from the inlet

Paying attention on the droplets, it can be seen that the tiny droplets generated due to the breaking of the front part of the bag shape (indicated by letter A) disappear at the next time step. This is because their velocities are high enough to travel away from the image window in one time step. Using the values of the distance between the breaking point and the right boundary of the image frame and the time step it could be estimated that the velocity of these tiny droplets must be larger than ~ 25 m/s. This high velocity value could be reached by the acceleration coming from the following sources: the acting force caused by the pressure difference between inside and outside of the bag at the moment of breaking; the surface tension effect occurs when the instability generated at the thin liquid layer at the front part of the bag at the moment right before the breaking; and the drag force caused by the gas flow.

In the other hand, the velocity of the bigger droplets generated due to the instability occurring at the thick rim (as indicated by letter B) do not change much after the breaking. This could be explained not only by their larger weight but also by the fact that the breaking of front part of the bag due to the accumulation of pressure occurs earlier than the breaking of the rim. It means the high pressure inside the bag is released before the formation of these bigger droplets and the acceleration only comes from to the drag force caused by gas flow and surface tension effect related to the breaking of the rim. However, during the formation of the bag shape, the corresponding amount of liquid already receives some momentum and moves a little bit faster than the main disturbance wave structure as shown in the images. Therefore, the initial velocities of these big droplets are higher than the velocities of the disturbance waves.

Ligament break-up mechanism

The formation of a ligament occurring at a singlet disturbance-crest is shown in Figure 3-6a. The break-up process does not happen in this image series but it is a good example for the transition from the singlet disturbance-crest into the ligament. In the reality, the ligament has high possibility to return to the liquid film but it can also be broken into droplets due to the Rayleigh instability as shown in Figure 3-6c. Again, the data agree with the proposed ligament break-up mechanism in which the crest of waves is elongated by the gas flow to form a thin ligament and then this ligament is broken into

droplets. Another event observed at 15 cm from the inlet is presented in Figure 3-6b. The wave structure in this figure is also considered as the early stage of a disturbance wave.

Similar to the droplets generated at the rim of the bag shape, the droplets generated due to the instability occurring on the ligament also have the initial velocities higher than the bulk wave structures. However, because most part of the ligament has high possibility to return to the liquid film as mentioned above, these droplets also have many chances to deposit on the film surface. This contradicts to the bag break-up process where nearly all the crests volume is evacuated. Consequently, at the same magnitude of the wave crests the amount of entrained liquid in a process of bag break-up is higher than that of ligament break-up.

It can be seen that both bag break-up and ligament break-up mechanisms do occur in the present flow condition. As mentioned in the Section 3.2, the chosen flow condition is near the boundary between bag break-up and ligament break-up regimes. In the reality, the boundary is not a distinct thin line but a shadow region so that both mechanisms are expected to occur. Although the number of observed events has not been enough for a formal conclusion about the contribution of each mechanism but the frequency of occurrence of the bag break-up events seem to be about several times higher than that of the ligament break-up.

Droplet impingement

In addition to the entrainment processes caused by the interaction between gas flow and the liquid film, droplets are also generated due to the collision between a droplet flying in the gas core and the wave surface. This means that an entrained droplet can be the trigger for another entrainment process to generate secondary droplets. Figure 3-7 presents two impingement events happened at the distance 40 cm from the inlet. It should be noticed that the droplet impingement processes can occur at any kind of wave structures. Figure 3-7a shows that the amount of entrained liquid caused by this event can be significant.

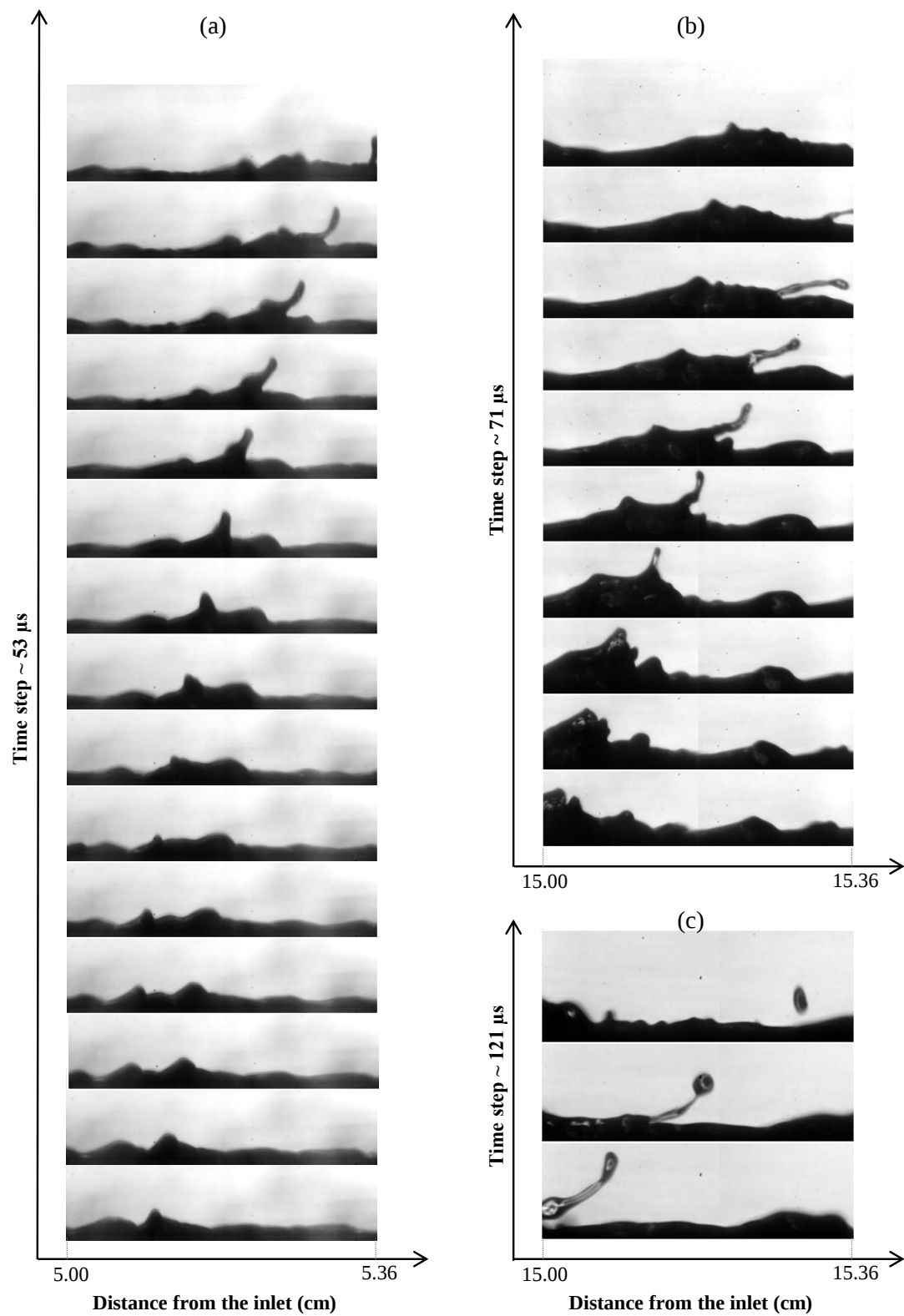


Figure 3-6 Ligament break-up processes observed at distances: (a) 5 cm; (b and c) 15 cm from the inlet.

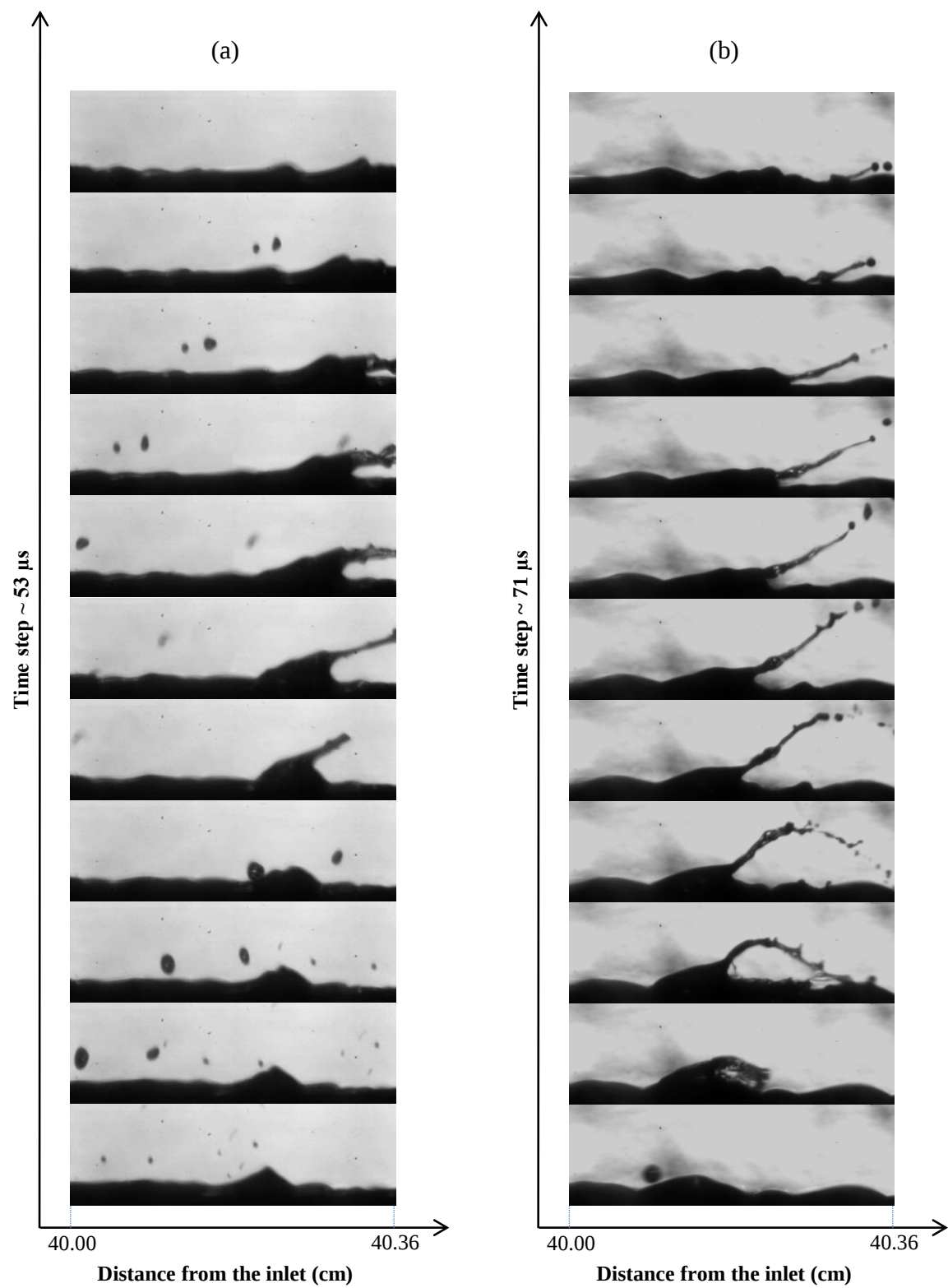


Figure 3-7 Droplet impingement processes observed at distance 40 cm from the inlet.

The obtained data shows in many impingement events (but not all) that there is the existence of a ligament at the last stages as showed in Figure 3-7b. The mechanism how this ligament was formed is not clear but its shape is quite similar to the ligament formed during the ligament break-up process showed in Figure 3-6b. The main difference between the two processes is the primary droplet coming at the high velocity in the impingement case. Hence, it is difficult to distinguish two mechanisms if this trigger droplet cannot be detected. This could be the reason why the impingement mechanism has not been emphasized in some literatures, especially when the authors used a low time and/or space resolution equipment or applied the axial viewing technique in which the droplet's velocity vector is perpendicular to the image plane.

3.3.3 Disturbance waves

The description of disturbance waves which are more developed compared to the early stages mentioned above and accompanied by multiple entrainment events are presented. Figure 3-8 shows that many droplets enter the image area right before the disturbance wave arrives. This point agrees with the observation from outside of the transparent pipe performed by Taylor et al. (1963) in which many droplet impingement events were detected before the arriving of the disturbance waves. The high frequency of impingement process directly relates to the high density of the droplet in the region. This huge number of droplets comes from the entrainment processes continuously happening at the complex surface of the disturbance waves.

The images of the disturbance waves with the appearance of both bag and ligament break-up processes are obtained at further downstream within the distance of 60 cm from the inlet. This length is small compared to the full-developed lengths presented in the literatures so that the disturbance waves are not fully-developed. It should be noticed that the time steps presented in this image series are much larger than that of previous data due to the large axial scale of the wave structure. Qualitatively, in the observation range from 5 to 60 cm from the inlet, the amplitudes of the disturbance waves observed downstream are also large compared to that of the waves upstream.

The most important point implied by the images is the relation between the singlet disturbance-crests and the disturbance waves. Figures 3-8 and 3-9 show that the starting points of the bag and ligament break-up processes are several wave-crests. Because the DOF of the optical system is about 500 μm , if these starting points were in the form of circumferential ripples, some parts of them would be out of focus and appear as shadow areas in the images. Furthermore, each of the entrainment events happens similarly to the bag break-up or ligament break-up process occurring at the singlet disturbance-crests presented in Section 3.3.2. This evidence suggests that the upper part of the disturbance wave structure may consist of several crests which share some common characteristics with the singlet disturbance-crests. Because the magnitude of the observed disturbance waves becomes larger at downstream, it could be said that there is the coherence in axial direction between the formations of these singlet crests to form a wave packet or what is called as a disturbance wave.

As mentioned in Section 3.1, Zhao et al. (2013) confirmed the existence of not only the axial but also the circumferential development of the wave structure to become a fully-developed disturbance wave at downstream. Taking their view point about the circumferential development, it is expected that the coherence in peripheral direction between the formations of singlet crest could also exist. The coherence process, in both axial and circumferential directions, continues on the way downstream and the result is the formation of the larger amplitude disturbance-wave. In other words, the singlet crests could be considered as the precursors of the developed disturbance waves downstream.

Additionally, the direct observation data may work as the reference to evaluate other measuring techniques. Firstly, at least for the current flow condition, the complex wavy surfaces at the upper part of the disturbance waves are hardly captured by the laser focus displacement technique (Hazuku et al., 2008) in which the surface having inclination angle larger than 33° cannot be detected. The similar problem would occur in the application of the technique using an ultrasound transducer. Hence, the techniques based on the reflection of the signals at the interface are able to detect the flatter surfaces of lower parts but not the sharpened crests of the disturbance waves.

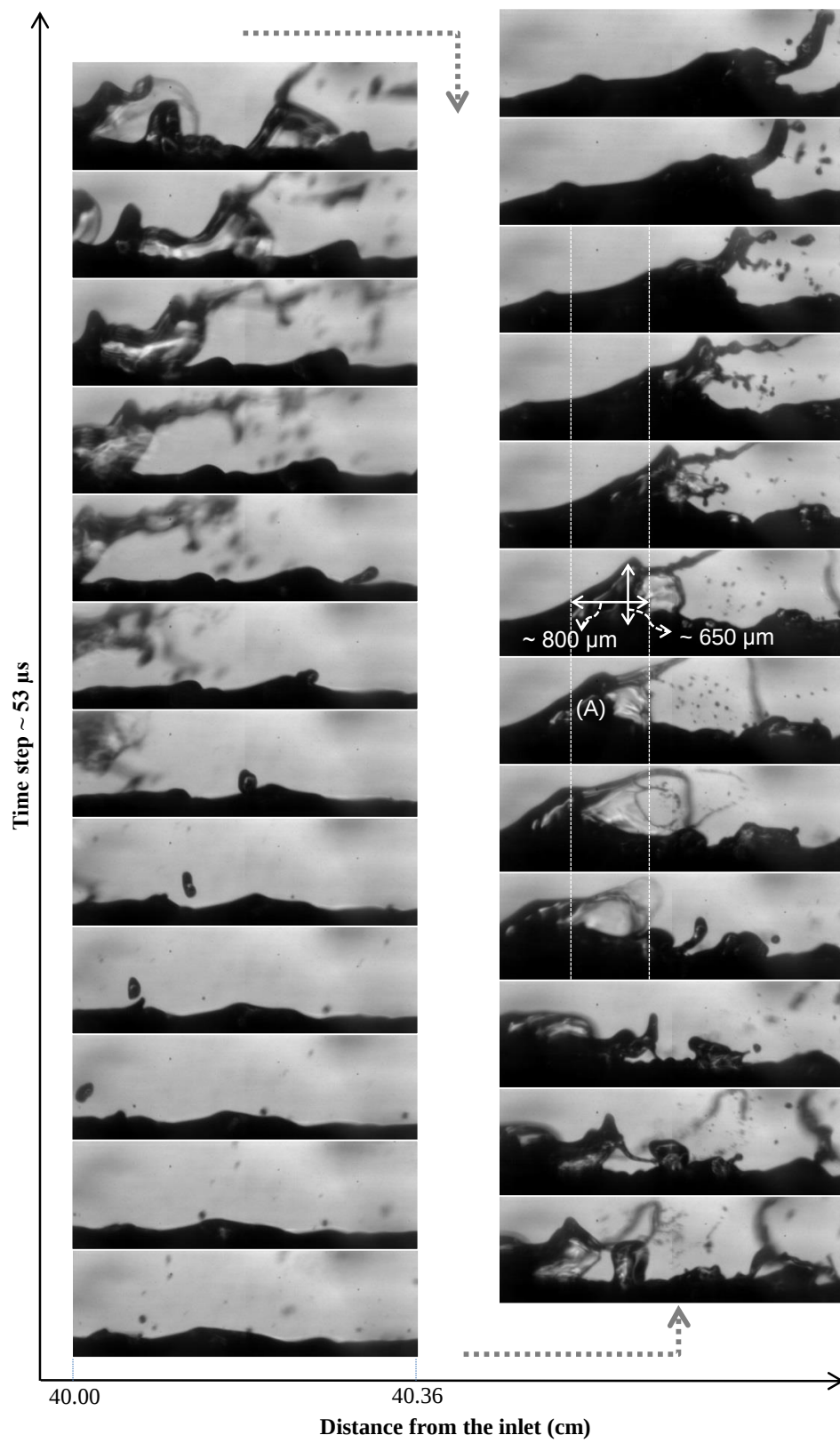


Figure 3-8 Disturbance waves observed at distance 40 cm from the inlet.

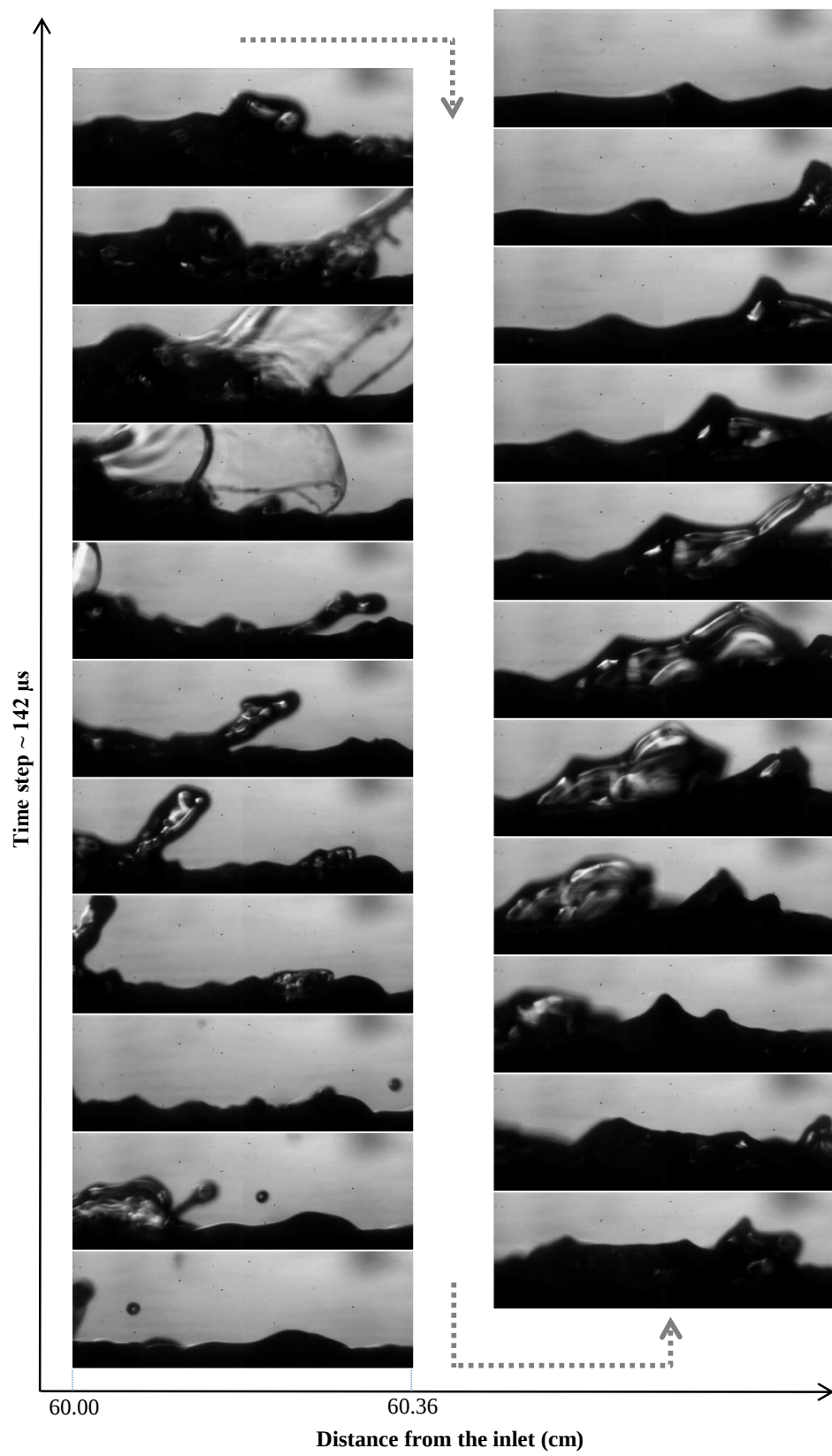


Figure 3-9 Disturbance waves observed at distance 60 cm from the inlet.

As an example, assuming that the crest (A) in Figure 3-8 needs to be detected to estimate the entrainment processes occurring at the disturbance wave. It can be seen that the applied techniques must be able to recognize the crest's height of $\sim 650\ \mu\text{m}$ within an axial length of $\sim 800\ \mu\text{m}$. If this axial length is considered as the measuring window, the crest needs about six time-steps or $\sim 318\ \mu\text{s}$ to pass by it. Moreover, the measurements at these resolutions face many challenges to maintain their accuracy because the crest adapts a three-dimension structure which is continuously changed due to the evolution of the disturbance waves and the entrainment phenomena. Therefore, both the validation and the calibration based on the comparison between the signal data obtained by one of those techniques and the images from the side-view observation as presented in this study are highly recommended.

3.4 Summary

The high speed camera technique with the backlight arrangement has been applied to study the annular two-phase flow on a 3x3 simulating BWR rod bundle test-section. The clear side-view images of the two-phase flow have been successfully achieved by keeping the base liquid film from flowing on the acrylic duct wall. The image data at micro-scale of time and space helped to evaluate other measuring techniques and provided the real-time description of the gas-liquid interfaces' behaviors which improve the understanding of the following important processes:

- (1) The singlet disturbance-crests are formed near the inlet. A mechanism for this process based on the turbulent characteristic of the gas flow was proposed. This crest can return to the liquid film or undergo an entrainment processes to generate the first droplets in the system.
- (2) Entrainment phenomena occur under the bag break-up, ligament break-up and droplet impingement mechanisms. The first two processes can happen at the singlet disturbance-crests as well as the disturbance waves. After the generation, the initial velocities of droplets are higher than the main wave structures. The droplet impingement can occur at the surface of any kind of wave and the

amount of the liquid ejected in the form of secondary droplets may be significant.

- (3) The disturbance waves are accompanied by multiple entrainment processes. The similarities between these processes and the entrainment events occurring at the singlet disturbance-crests suggested that the singlet disturbance-crest could be the first form of the disturbance waves.

The current task has focused on obtaining the clear side-view images of the phenomena occurring in the test section so that the quantitative data have not been available to support a full understanding of the development of disturbance waves. The next steps including the measurement of the liquid film thickness, the liquid droplets and the influences of the spacer on the flow in different the flow conditions will be presented in next chapters.

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Chapter 4 Quantitative measurement of wavy liquid films

4.1 Introduction

Being a main component of the two-phase flow, the liquid film keeps important roles in the momentum, mass and especially, the heat transfer from the system. The existence of the liquid film on the heated surface will assure the effective heat removal from it so that the safety of the system is retained. The important parameters under the consideration include not only the average liquid-film thickness but also the wavy characteristics of the gas-liquid interface, especially the disturbance waves. When the liquid flow rates higher than some critical values, these disturbance waves will be formed and can affect the interfacial roughness as well as the momentum and heat transfers of the system (Hewitt and Hall Taylor, 1970; Ishii, M. Grolmes, 1975).

It can be seen from the review presented in Section 2.1.2 that the liquid film thickness has been measured by several methods based on optical, ultrasound, electricity conduction, and sometime x-ray or neutron tomography. Each of them has some advantages such as the high resolution in time and/or space, the ability to provide 2D or 3D data but there is also limitation in one or more of these parameters. Among them, the visualization based technique has the ability to provide the best resolutions in both time and space by increasing the recording speed of the camera and using a microscope. Unfortunately, the strong image distortion caused by the scatter and reflection has limited the application of this technique.

In the case of the rod-bundle geometry, it can be seen that the interactions between the spacer and the wavy film, and the influence of the rod location (corner rod or not) have not been studied adequately. Actually, the number of annular flow experiments with rod-bundle is much smaller than that for the circular-pipe geometry. Moreover, the rod-bundle geometry is complex and causes difficulties to setting the measuring equipment so that the applied methods have been mostly restricted to the electric probe, ultrasound transducer, x-ray or neutron tomography techniques. As mentioned in Section 2.1.2,

these techniques can be applied to a complicated geometry but have low space resolution. Therefore the data of many important characteristics, especially the wavy parameters are not available.

Furthermore, the effects of the spacers which are used to maintain the clearances between the fuel rods on the performance of the flow moving through the assembly have not been considered adequately. The limitation in the applied techniques leads to the difficulties in providing information relating to the interactions between the wavy liquid film and the spacer.

From these points of view, the current task applies the side-view arrangement described in Chapter 2 to measure the liquid film thickness. The application of the high-speed camera technique for the rod bundle geometry with a backlight source has shown not only the very high time and space resolutions but also the ability to minimize or avoid the optical image distortions. The results include the average liquid film thickness, the thickness probability density, power spectrum density (PSD), and the wave velocity. These data are obtained at positions up and downstream of the spacer and at both corner and side rods to evaluate the influences of the spacer on the two-phase annular flow as well as the role of the rod's locations. In addition, the reflected-light arrangement mentioned in Chapter 2 is also used to evaluate the circumferential coherence of the disturbance waves' structure.

The next section will describe an additional modification made on the experimental system presented in Chapter 2 to support the measurement of the liquid film as well as the image-data acquiring and processing procedures. After that the results and discussions will be given.

4.2 Experimental methodology

During this task, the first spacer is located after the inlet section to increase the rod-fixing capacity of the three spacers. This is necessary to perform the measurement of

film thickness at the micro-scale. The data are obtained at four axial positions located at up and downstreams of the second spacer (Figure 4-1).

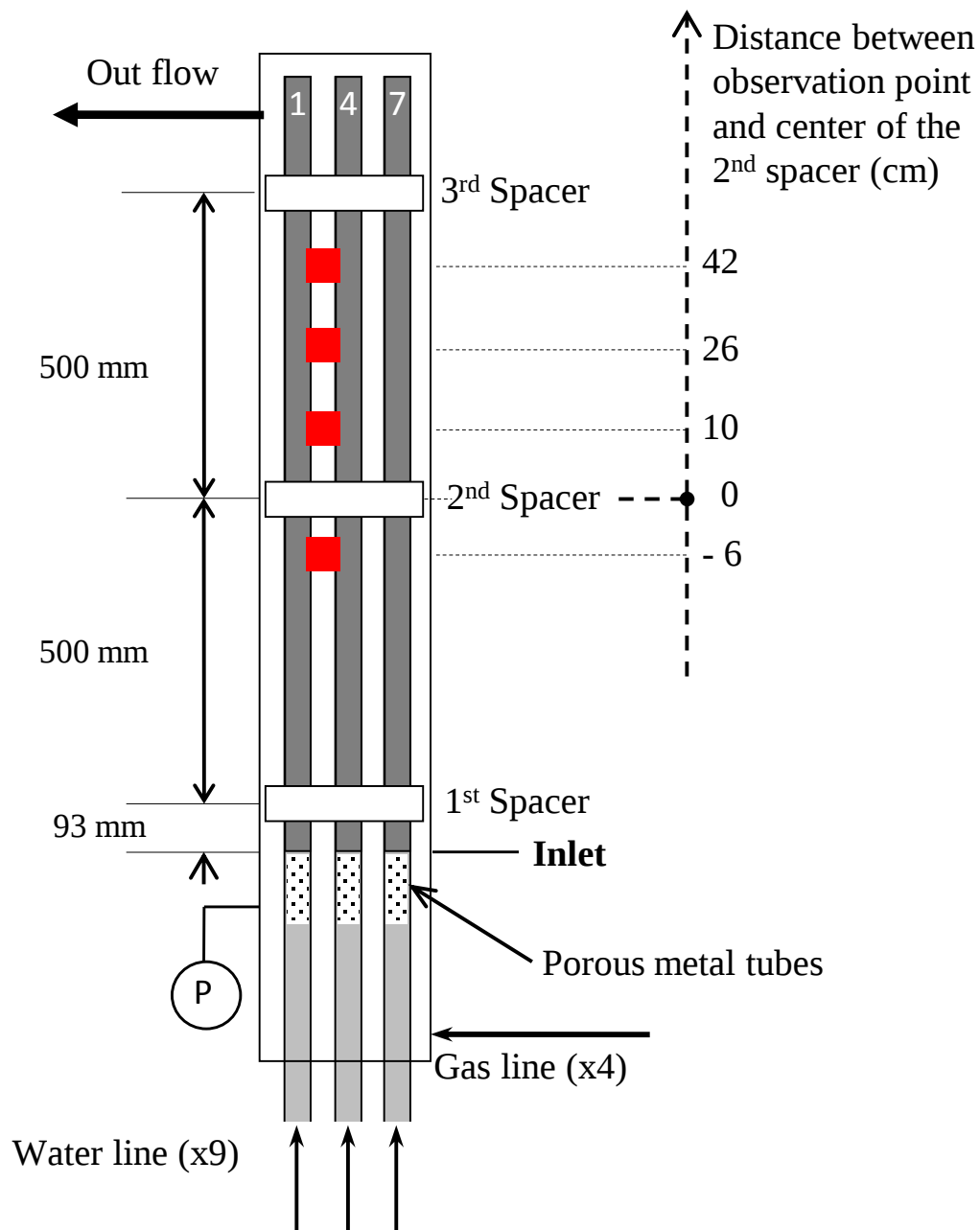


Figure 4-1 Experimental setting to study liquid film

The image-data acquisition devices include a high speed camera Phantom V7.1 (Vision Research Inc.), a Cassegrain tele-microscope (Seika Corporation), and a Micro lens F2.8 (Canon). Image processing procedures are developed basing on Matlab software and its tool boxes. The tele-microscope and the macro lens are used in back-light and reflected-light arrangements, respectively as the followings.

4.2.1 Measurement with backlight arrangement

Using the Cassegrain lens, the physical length represented by each pixel in the image data is determined by taking the photo of a 200- μm scale placed at the image focus plane. Then it shows that the dimension of an image pixel equals to 6.6 μm . The influence of light condition on this calibration is also performed by using a layer made of fluorinated ethylene propylene (FEP) which has the same refractive index as the water to simulate the liquid film. After being setup around a rod, the thickness of this layer is about 0.4 mm. The images captured in the same optical setting of the data recording show the agreement within 4% with the measurement by a micrometer. The location of a rod's surface in the image data is calibrated by turning off the valve of corresponding water line.

A challenge must be overcome is that the images taken through the acrylic duct wall can be distorted by the amount of liquid possibly distributed on this surface, especially when the entrainment rate is high or there is a spacer placed between the inlet and measuring point. To minimize these distortions, an oval-shape obstacle made of the commercial tape and silicon is setup onto the inner surface of the duct wall to guide the liquid (if there is any) around the image windows (Figure 4-2). The thickness of this obstacle is quite small (~ 0.8 mm) and it is placed locally at the image window so its influences on the two-phase flow from the inlet to the measuring point is expected to be negligible. It should be noticed that this modification affects the amount of liquid distributed on the duct wall, not the liquid films flowing on the rods' surfaces which are under the consideration. The similar attempt would not be accomplished for the case of circular-pipe test-section in which the main liquid film flows on the duct wall.

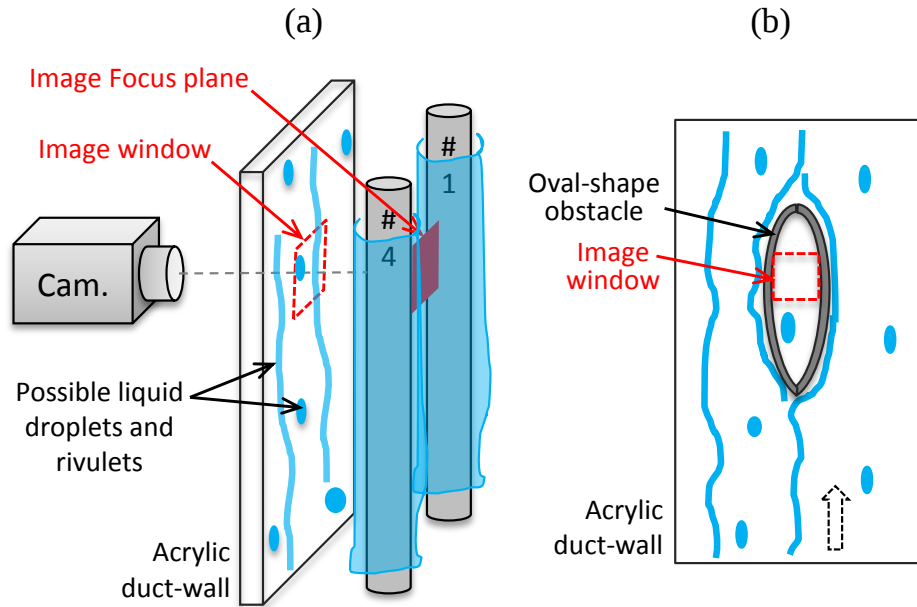


Figure 4-2 Problem of image distortion (a); and attempt to modify the liquid flowing on duct-wall (b).

An example of the image data and the image processing procedure are shown in Figure 4-3. The 64 x 512 pixels window is used to trace the gas-liquid interface at recording speeds from 17 to 32 kfps, according to the increase of the gas flow rates. These setting are decided after a survey to make sure that the recording speed is enough to detect all wave crests passing by the image window. Due to the large amount of image data generated at the high recording speed, the total recording time of each flow condition and measuring position is limited to 5 sec. Depending on the recording speed, from four to eight shots are taken in each case.

Figure 4-3a presents the image-data processing procedure developed with Matlab software and its tool boxes as follows:

- (1) The integrated Canny's edge-detection operator (Canny, 1986) is used to detect the edges where the sharp changes of intensity occur in the original image. The small values of both lower and upper thresholds of this operator are chosen to detect not only the strong edges but also the weaker ones.

- (2) The detected edges belonging to the droplets are removed. The method used to locate the droplets' image area is presented in Chapter 5.
- (3) Among remaining edges, the strongest one of each side is selected by comparing the gradient of image intensity across them to represent the corresponding film surface.
- (4) The liquid film thickness is determined by the distance between the rod surface and the interface point located on the middle pixel-row of the image.

It can be seen in the image of step (1) that the weak edges (indicated by several short lines) are included in the Canny's edge detection. Then the selection of strongest edge for each side at step (3) will require additional computational time. However, it is necessary to use the small thresholds of this operator because the background of the image continuously changes with time and will also be different for each flow condition or measuring position. Hence, there are the cases in which the real film surface belongs to a weak edge. By covering these situations, one couple of thresholds can be applied for the wide range of light and background condition.

While the determination of film thickness considers the middle pixel-row of the image as indicated in Figure 4-3, the wave velocity measurement uses 7th and 57th rows. The cross-correlation between the time-resolved thickness series obtained at these two locations is calculated. The time-lag corresponding to the peak of the correlation (as shown in Figure 4-4) is the average period of time needed for the waves travel between these pixel-rows. Then the wavy velocity is determined by using the real distance of 330 μm and the time-lag (calculated from the number of lag-frames and recording speed). Previously, this method was also used by Farias et al. (2012) with the laser-induced fluorescence technique. In the current experiment, the time-lag equivalents to about 5 to 10 image frames depending on the flow condition and recording speed so that the error of the velocity measurement which mostly comes from the time-interval between two image frames is less than 20%.

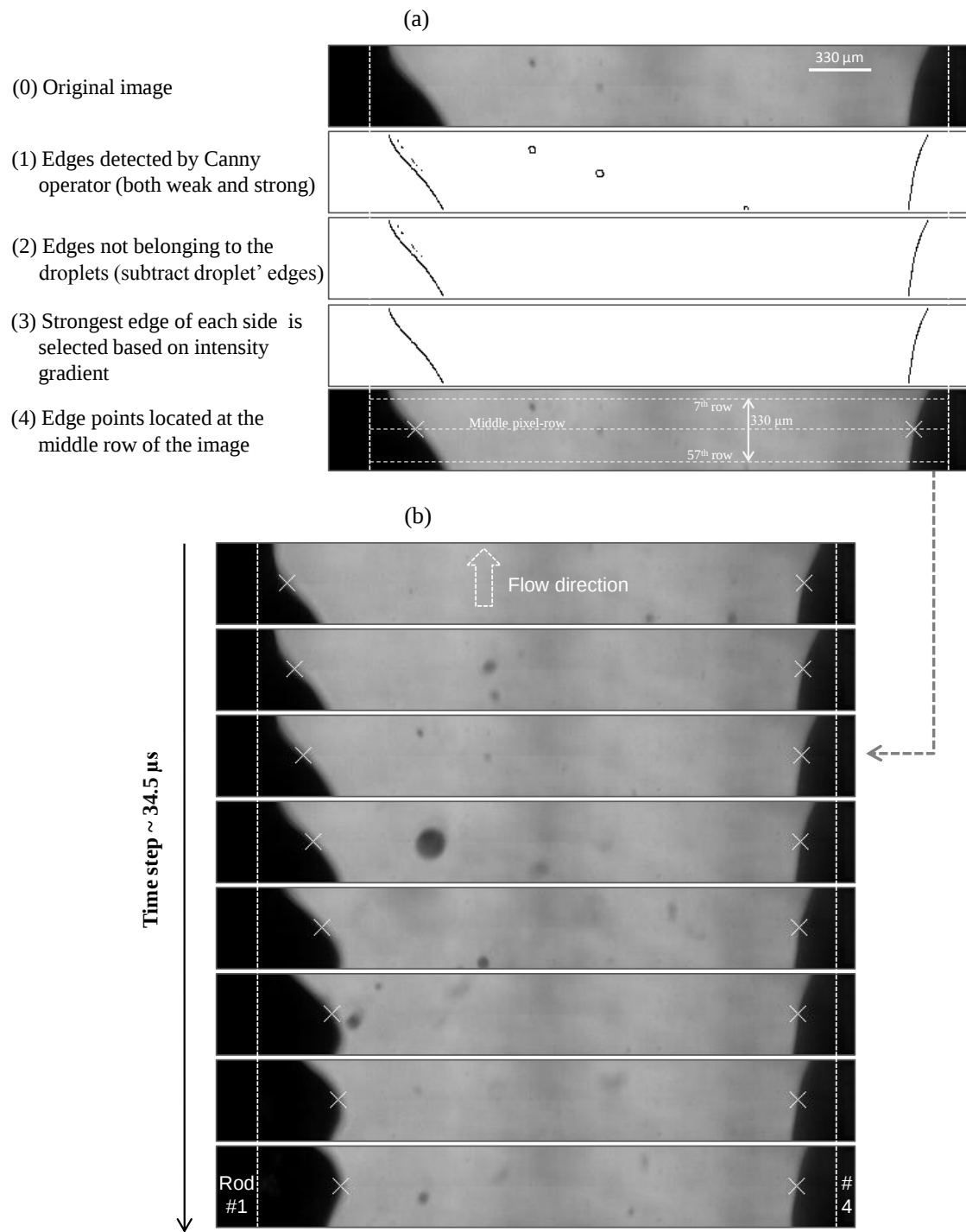


Figure 4-3 (a) Image processing procedure and (b) Example result. Images were capture at 42 cm for $j_G = 44.5 \text{ m/s}$ and $j_L = 0.025 \text{ m/s}$.

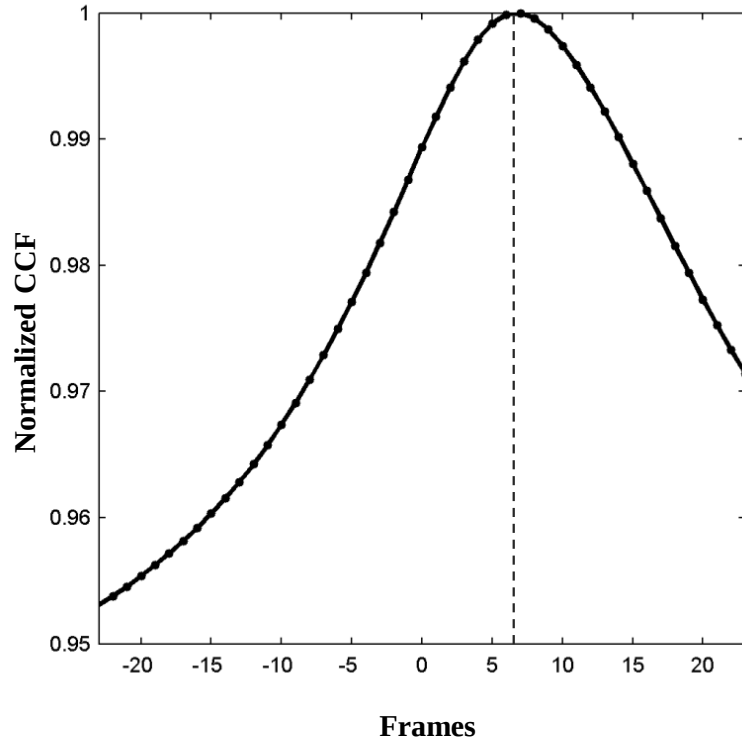


Figure 4-4 Normalized cross-correlation function (CCF) of time-resolved thickness series at 5th and 57th pixel-rows of image. The data is obtained for the corner rod at -6 cm and $j_G = 44.5$ m/s and $j_L = 0.02$ m/s

Comparing to the techniques which uses two sensors such as the conductance probes (Azzopardi, 1986) or the photo cells (Hurlburt and Newell, 1996) the current velocity measurement method presents a better approaching because the shape of waves is changed very little when they move between two pixel-rows as seen in Figure 4-3b. Meanwhile, the physical probes cannot be so small to put closely together due to the limitation in the machinery. This advantage becomes important for the case of high gas flow rates in which the wavy surfaces become more unstable.

One limitation of the current backlight arrangement is that it cannot be applied to measure the liquid film at locations around the rod through which the light source cannot be seen by the camera. Therefore, the data of the average variables for whole flow area are not available. Another comes from the image distortions mentioned above which cannot be absolutely avoided by using the oval-shape obstacle. This is because

the entrained droplets still have a possibility to deposit on the acrylic duct-wall area located inside this structure. If this situation happens, it usually leads to strange values in the data such as very large or minus thickness. Hence, the outputs of the image auto-processing procedure need to be plotted and reviewed manually to find these strange points (if there are any) and correct them based on the observation of corresponding video frames. Due to the large amount of data generated by the high speed camera, this task costs time.

It should be also noted that because the measurement is performed at the micro-scale of resolutions, a relative displacement, even very small, between the camera system and the rods' surface can affect the accuracy of film thickness data. With the current apparatus, these rods' surfaces are seen to move up to four image pixels or $\sim 27\text{ }\mu\text{m}$ and the measured thickness would include this distance (adding or subtraction). Therefore, the current data can be used to study the average film thickness and the disturbance waves which have large amplitudes but they are not suitable to make the discussion on the minimum liquid film thickness. This problem, however, would be solved in the next version of the system by improving the fixing of the camera system and the test-section.

4.2.2 Reflected-light arrangement

The reflected-light arrangement with the system of high speed camera and macro lens is used to study the circumferential coherence of the disturbance waves which can exist on the surface of side-rod #6. The detection of disturbance waves' structure is based on the fact that their surfaces are much more unstable than remaining parts of the liquid film so that light has more chance to be reflected to the camera. Using a threshold to convert the reflected light images to the binary format, the bright area corresponding to the disturbance waves will be proportional to the white area in the output image. To consider the circumferential coherence of the disturbance waves, two virtual sensors are used to sample the independent small image areas as indicated in Figure 4-5. Then the cross-correlation between the signals obtained by them will be calculated. The stronger peak observed at the zero-time lag, the disturbance waves are considered as more developed.

It should be noticed that this method is suitable for the high gas superficial velocity only because the gentle ripples existing on the film surface of the low gas velocity cases also form a strong peak at the zero-time lags. Therefore, the current task considers only the highest gas velocity, $j_G = 62.2$ m/s. The camera setting includes 512 x 256 pixel image window and recording speed of 5 kfps is used. The photo of a scale put at the focus point of the camera system shows that each pixel represents a length of 54.5 μm in the axial direction.

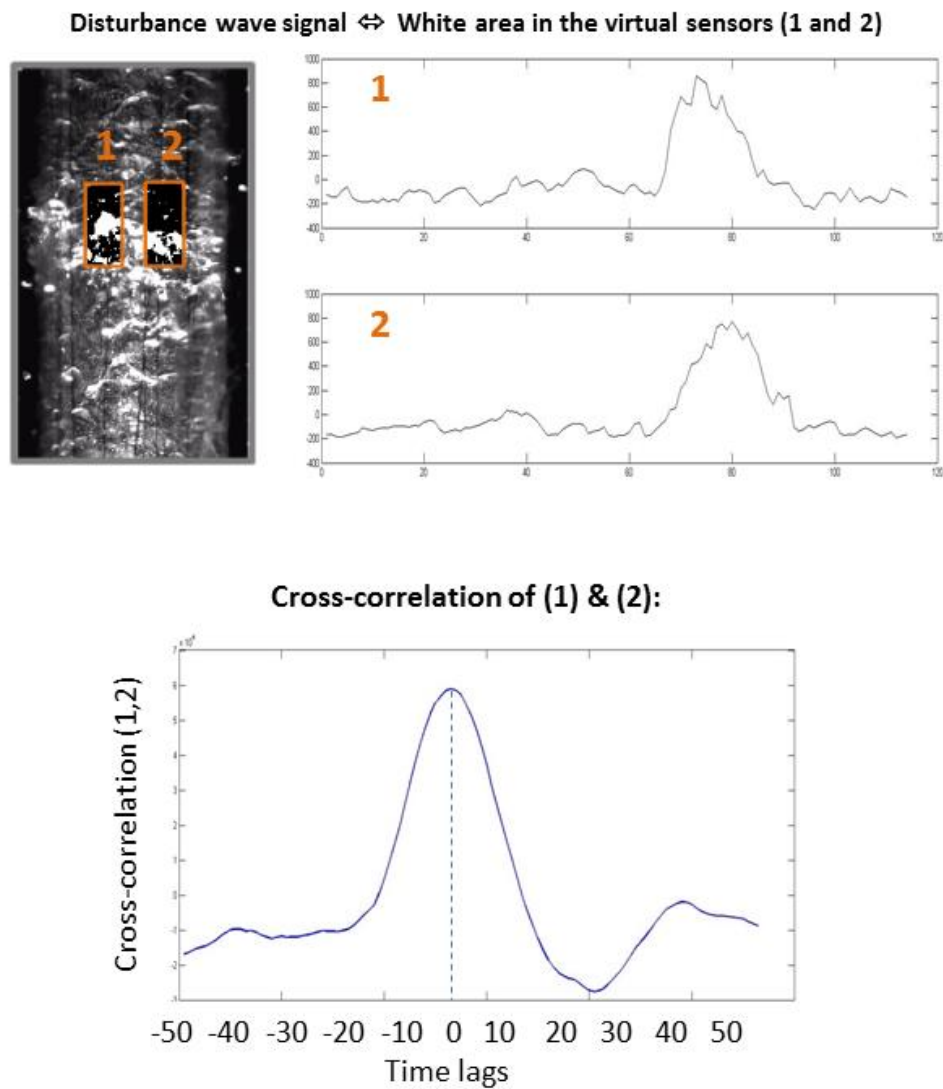


Figure 4-5 Evaluation of circumferential coherence of disturbance waves

4.3 Results and discussion

This section presents the obtained data to describe the characteristics of the liquid-film flow on rod-bundle geometry and the spacer's influences. Firstly, the examples of the disturbance waves' signals obtained at different gas flow rates are presented in Figure 4-6. These thickness time-series are confirmed to correspond to the disturbances waves by visualization data in which the waves possess the large amplitudes and generate the liquid droplets continuously through the entrainment mechanisms mentioned in Pham et al. (2014). Qualitatively, both the height and time scale of the disturbance waves decrease and the gas-liquid interface becomes less gentle as j_G increases. It can also be seen that the disturbance waves appear as the batch of many crests so that the using of wave height determined by local maxima (Farias et al., 2012) or large wave counting (Zhao et al., 2013) to analyze the wavy characteristics might not be suitable for the current flow conditions and measuring resolutions. The quantitative data including average values, probability density, and power spectral density of liquid film thickness as well as the wave velocity are given in the next subsections.

4.3.1 Liquid film thickness

The data of average values and probability density functions of liquid film thickness obtained in all flow conditions and measuring positions are presented in Figures 4-7 and 4-8, respectively. Both of them show the well-known tendency in which the mean film thickness increases with the increasing of j_L but it will decrease if the j_G increases.

Another point is that the liquid film flowing on the corner rod is thicker than that on the side rod. This trend agrees well with the data obtained by Nishida et al. (1994) and can be explained based on a typical gas velocity profile in which the gas velocity is smallest at the regions next to the corner of the test-section. This smaller gas velocity around the corner rod leads to a thicker film thickness as the trend mentioned above.

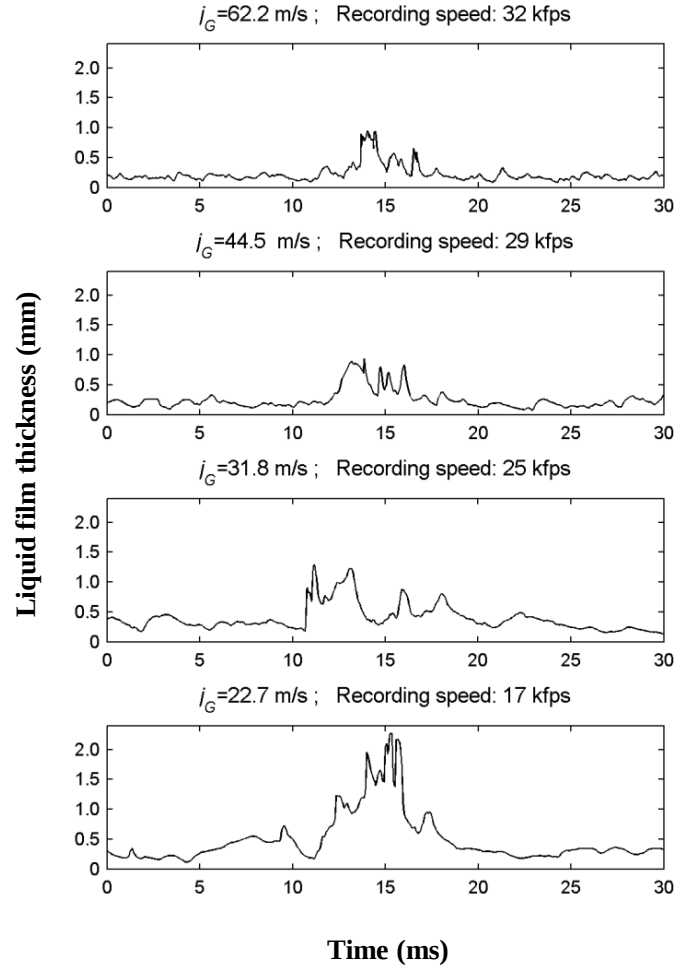


Figure 4-6 Liquid thickness signal of disturbance waves observed at corner rod at different j_G .

When the two-phase flow passes through the spacer region, both the gas core and the liquid film will interact with the spacer structure and the obtained data show different trends for the lower values (22.7 and 31.8 m/s) and the higher values (44.5 and 62.2 m/s) of j_G as shown in Figure 4-7. This difference can be explained by considering phenomena affecting the film thickness measured at the gap as the followings:

- (1) Due to the interaction between the liquid film and the spacer, an amount of liquid is separated from the film and flows along the spacer's structure to the duct wall or to the top of this structure and forms liquid droplets. This

separation reduces the liquid film thickness and will be more important at higher gas flow rates because the momentum of liquid becomes larger.

- (2) The spacer causes the lower gas velocity in several regions behind this structure, especially at each gap between two rods. This also leads to the higher velocity regions at the neighbored subchannels. In turn, the distribution of liquid around each rod right after the spacer is modified due to the change of gas velocity nearby. The portion of liquid film located at the gap become thicker while the others are thinner. At further downstream, the recovering of gas velocity profile occurs and a more uniform liquid distribution can be achieved. If the measuring point is located inside this recover region, the large thickness values at the gap will be recorded. Naturally, the recovering process will be faster at the higher gas flow rate.
- (3) Liquid film thickness is increased on the way downstream because the droplets generated by separation effect as mentioned in (1) deposit on the film surface or due to the friction loss of the flow.

For the data of the lower values of j_G , the thickness measured at 10 cm is larger than that at -6 cm because the modification of the liquid film as mentioned in (2) is more important than the separation effect. Then the lower values at 26 cm expresses that the recovering process can be accomplished before this point and the decrease compared to values at -6 cm is caused by the loss of water in separation effect (1). From 26 to 42 cm, the thickness is increased mostly by the processes presented by (3).

These are not the cases of higher values of j_G in which the modification and recovering processes mentioned in (2) are quickly accomplished. The measured thickness at 10 cm is mostly determined by separation effect and becomes smaller than that at -6 cm. Then the thickness is increased due to the droplet deposition and friction loss on the way downstream. It can be stated that for the current range of j_L and test-section, there is a transitions point of gas superficial velocity, falling between 31.8 and 44.5 m/s. For the convenience in the later discussions, the values of $j_G \leq 31.8$ m/s and $j_G \geq 44.5$ m/s will be classified as low and high superficial gas velocities, respectively.

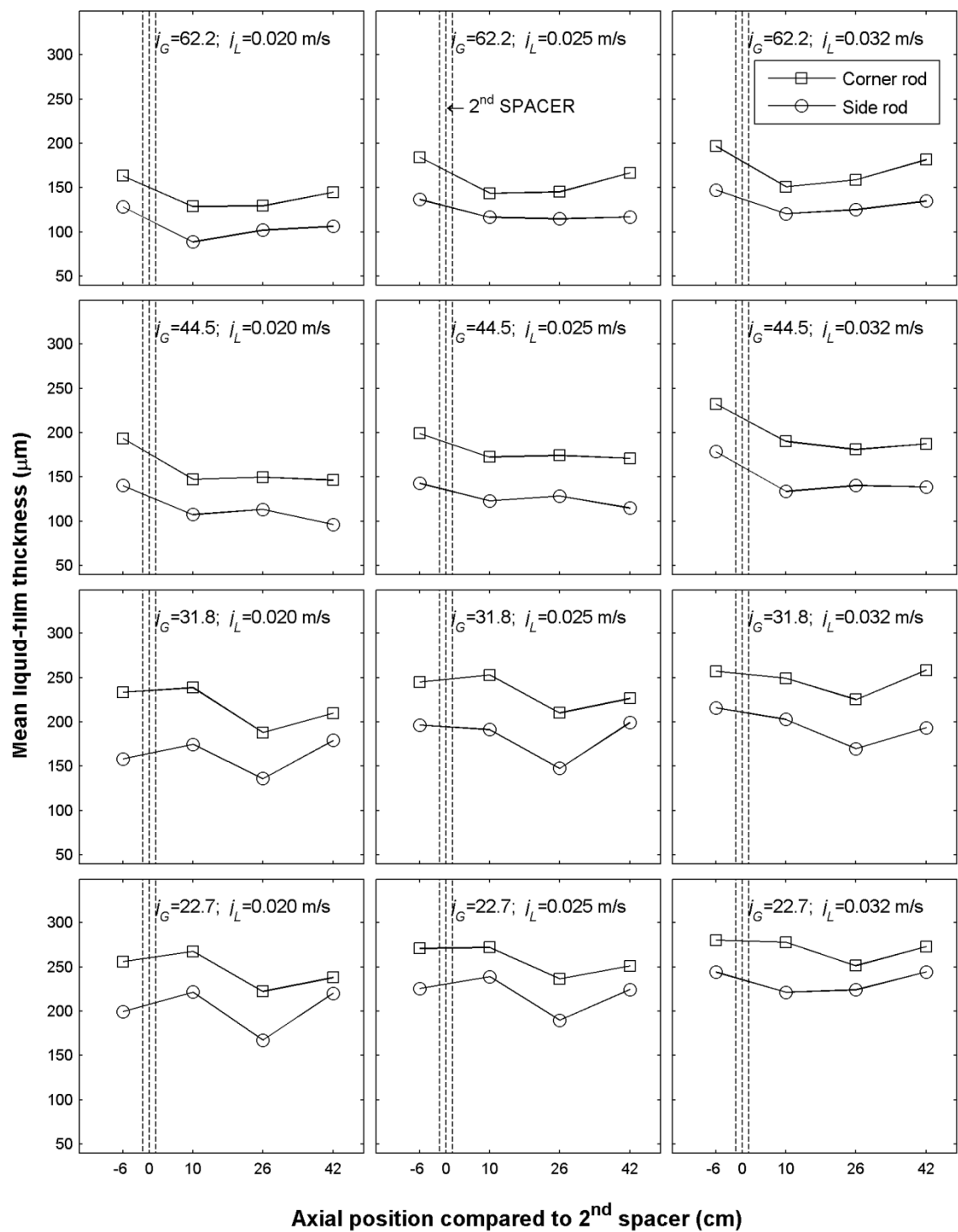


Figure 4-7 Time-averaged liquid film thickness

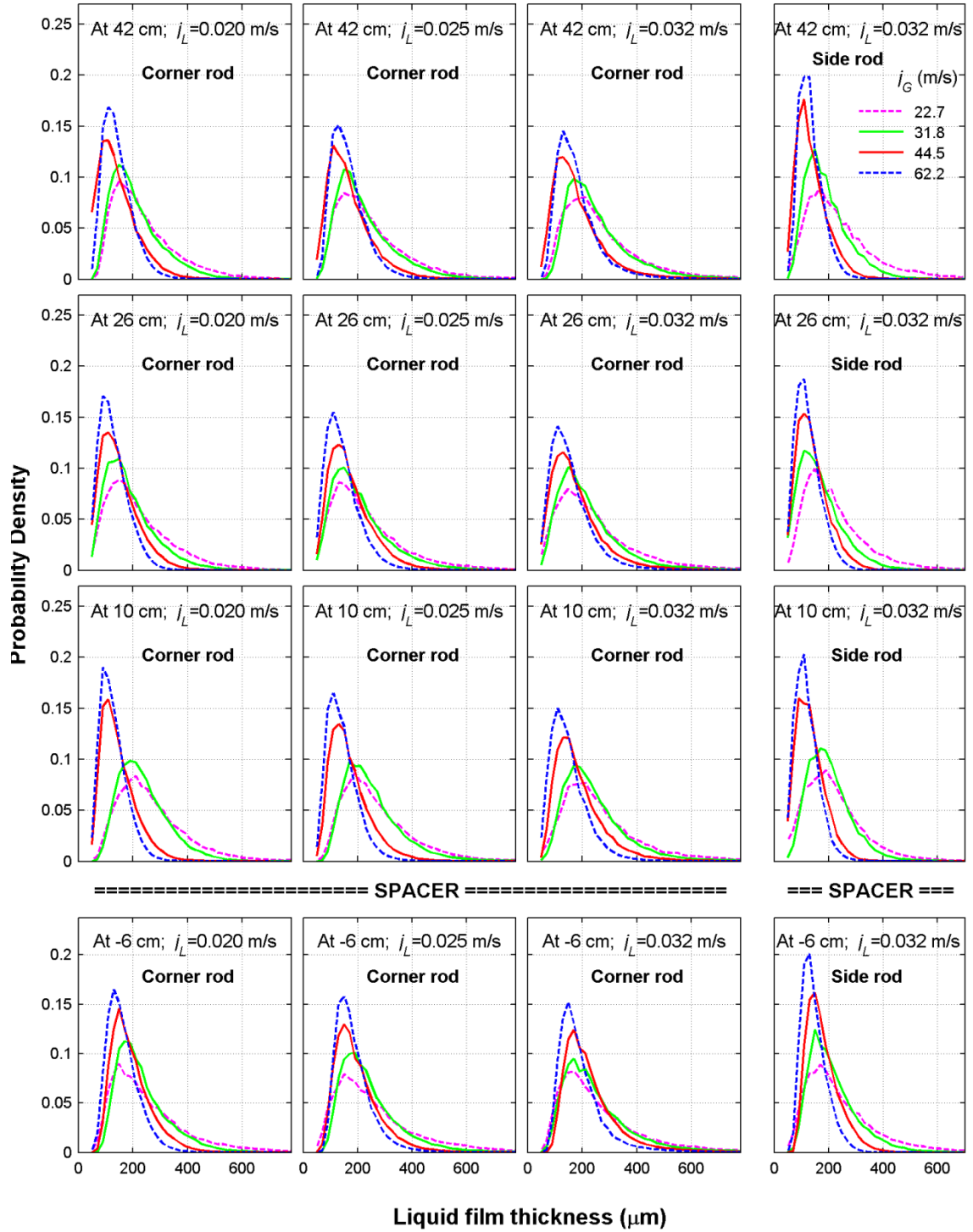


Figure 4-8 Film-thickness probability density

4.3.2 Power spectral density

The power spectral density (PSD) of time-resolved film thickness is obtained by using Matlab's functions. The presenting cases are selected among the entire data on the purpose of showing the influences of the changing in gas, liquid superficial velocities and measurement position on the wavy characteristics. Figure 4-9 shows the PSDs obtained in all the flow conditions at -6 cm. It should be noticed that the scale of the vertical axis is different for each j_G . In the same tendency of liquid film thickness mentioned in Section 3.1, the power scale decreases with the increasing of j_G and/or j_L . This trend was also observed by Farias et al. (2012) with a horizontal test-section. With an increasing of j_G , the peak frequency is seen to move to the higher region and the spectral becomes flatter because the energy is distributed in a broader range of frequency as the explanation of Paras et al. (1991). On the other hand, the increase of j_L seems to cause the lower peak frequency due to the appearance of larger wave structure at lower frequency.

The PSDs obtained at different axial positions on the corner and side rods for low and high gas superficial gas velocities are presented in Figure 4-10. It can be seen that the spectral obtained at the side rod for all measuring points and gas flow rates are at lower scale than those at the corner rod. The lower spectral of the side rod relates to the fact that its film thickness is smaller, as seen in Section 4.3.1.

Considering the PSDs obtained at the corner rod, the changing of the spectral scale from -6 cm to 42 cm at low j_G shows a quite similar tendency to the change in average thickness (Section 4.3.1). However, at high j_G , the peak region of PSD observed at -6 cm firstly disappears at 10 cm due to the interaction between the film and the spacer. Simultaneously, the average film thickness decreases across the spacer. Then, the PSD peak region is seen to appear again at 26 cm but the average thickness does not change. The difference between two cases of low and high gas superficial velocities could come from the variance in the nature of the large-amplitude waves as follows: at low j_G , the gas-liquid interface are more gentle and the agreement between PSD and average thickness data expresses the important role of the amount of liquid distributed on the

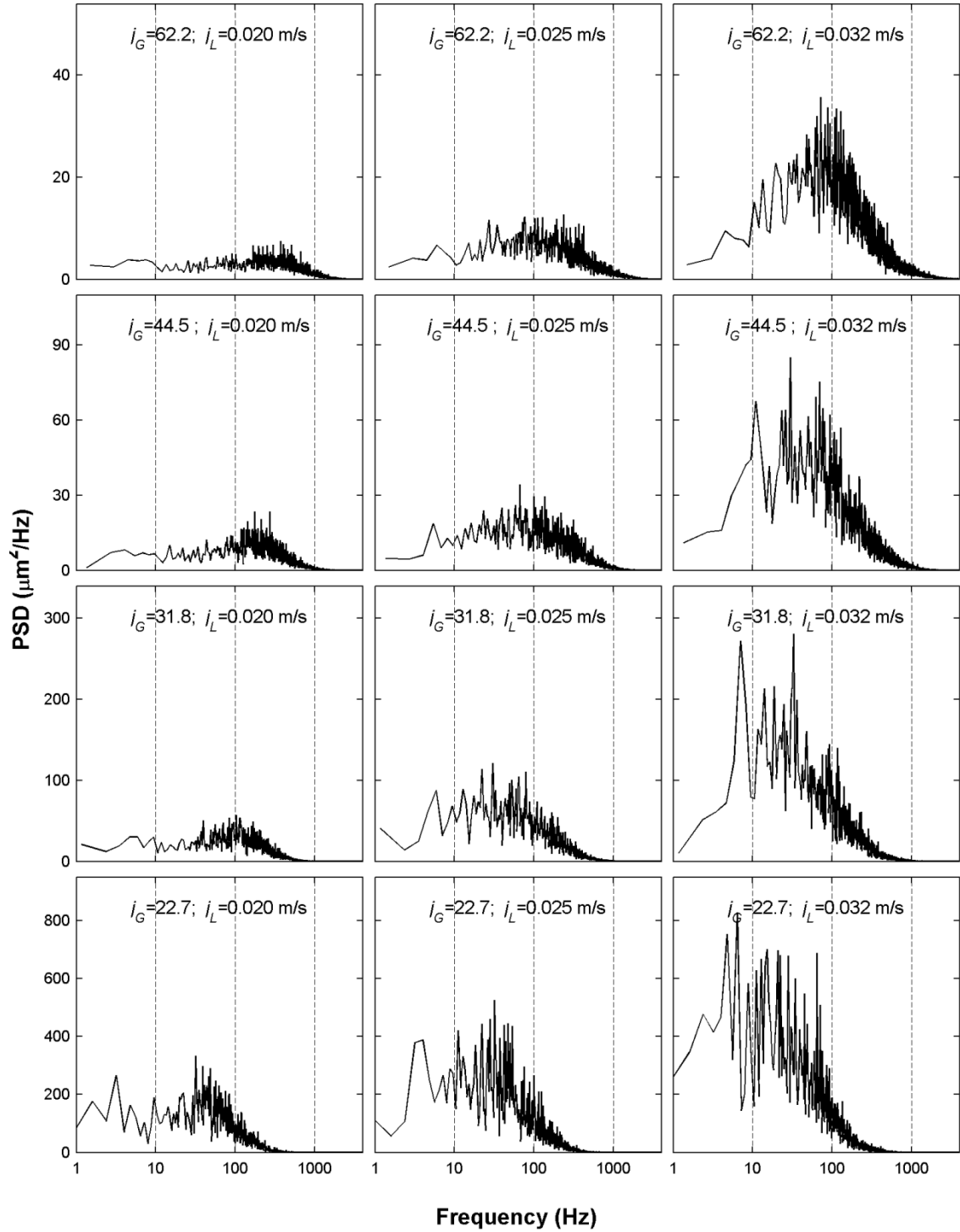


Figure 4-9 Power spectral density (PSD) of film thickness obtained at position -6 cm of corner rod for all flow conditions

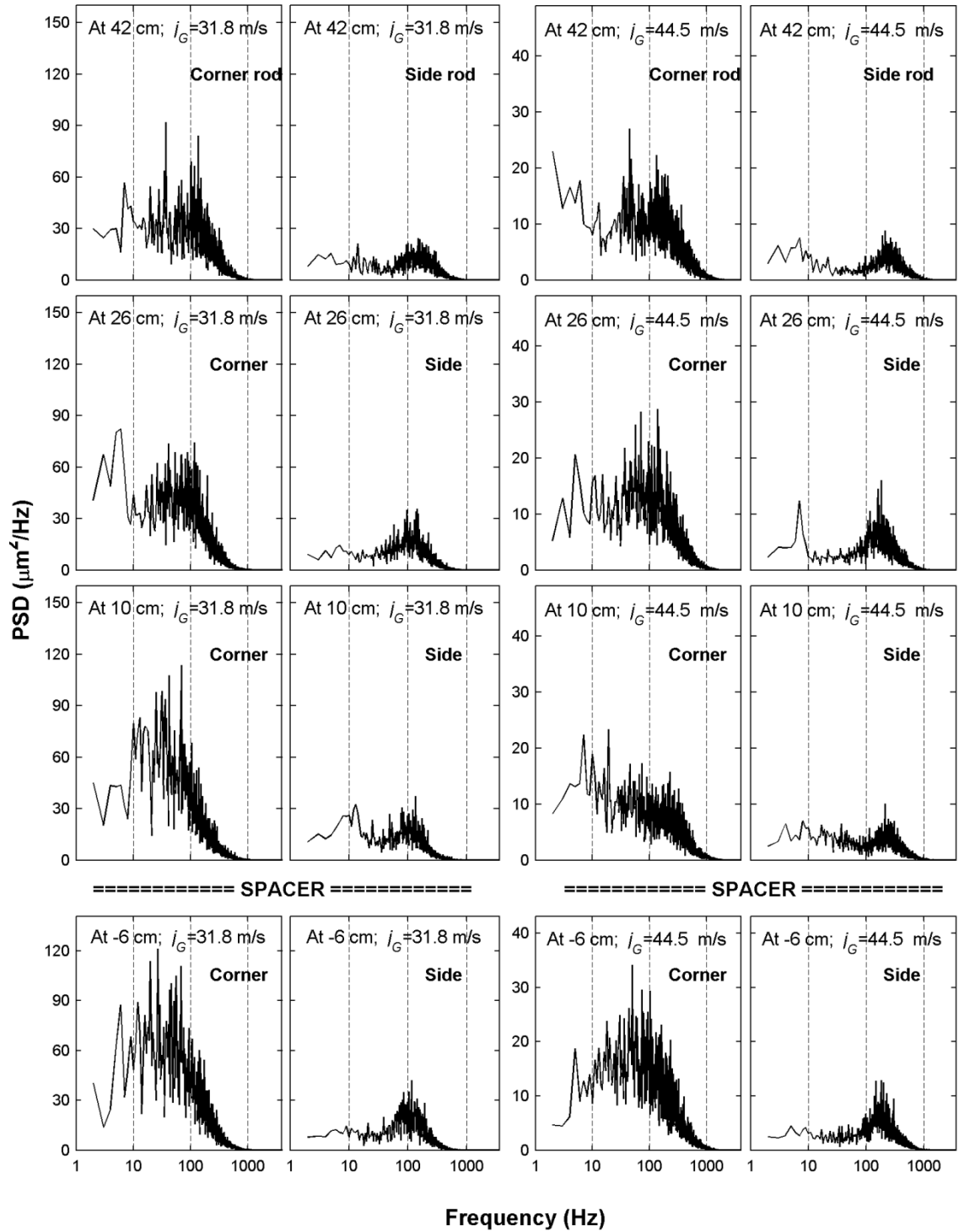


Figure 4-10 PSD of film thickness obtained at different axial positions for low and high gas superficial velocities

rod's surface to the formation of the wave. On the other hand, the early recover of PSD compared to the average thickness at high j_G seems to relate to the development of the disturbance waves in which the coherence of smaller disturbance wave structures happens to form the larger waves (Zhao et al., 2013; Pham et al., 2014).

According to (Azzopardi, 1986), the peak of PSD corresponds to the frequency of the disturbance waves if the flow feature is dominated by these structures. Taking this point of view, if the disturbance waves pass by the spacer region, their structures will be broken, as indicated by comparing the PSDs observed at -6 and 10 cm for the high j_G . It can actually be imagined that at high j_G the larger-amplitude disturbance waves have not only the large amplitudes but also the high momentum. Therefore they hardly survive through the interaction with the spacer structure.

4.3.3 Average wave velocity

The mean wave velocities obtained by processing the time-resolved data are presented in Figure 4-11. As a general trend which was also perceived by Jayanti et al. (1990) and Farias et al. (2012) for the horizontal test-sections, the data indicate that the wave velocity increases with the increasing of j_G and/or j_L . The faster gas flow transfers more momentum to the liquid film surface and leads to a faster wave velocity. The increase of liquid flow rate results in the higher film thickness which supports the generation of more waves with the higher the wave velocities. However, both the spacer and axial position do not present a clear influence on the mean wave velocity. Taking the measurement error of about 20%, the wave velocity seems to be not changed much when the film passes by the spacer and flows in further downstream.

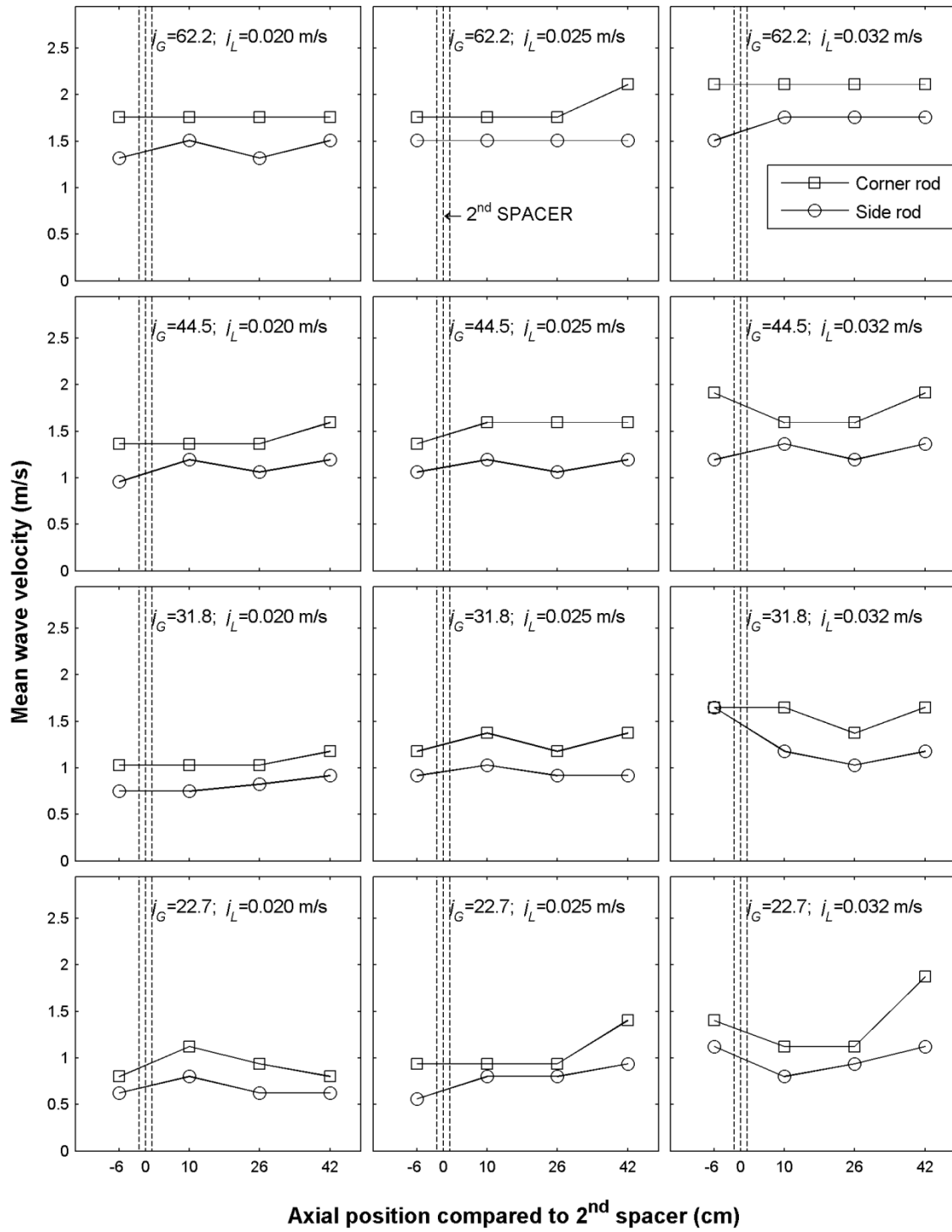


Figure 4-11 Average wave velocity obtained for all flow conditions and measuring points

4.3.4 Circumferential coherence of disturbance wave

The evaluation of the circumferential coherence of the disturbance waves is given in Figure 4-12. At lower water superficial velocity, there are no disturbance waves so that the peak at zero-time lag does not exist. For the highest value of j_L , there is a strong peak at -6 cm but this peak becomes weaker at 10 cm. This is the evidence leads to a conclusion that the spacer not only break the portion of disturbance waves belonging to the gap between the rods but also the circumferential coherence of the waves. In further downstream, the peak is seen to develop again. This point agrees with the discussion on the wave-amplitude provided in Section 4.3.2.

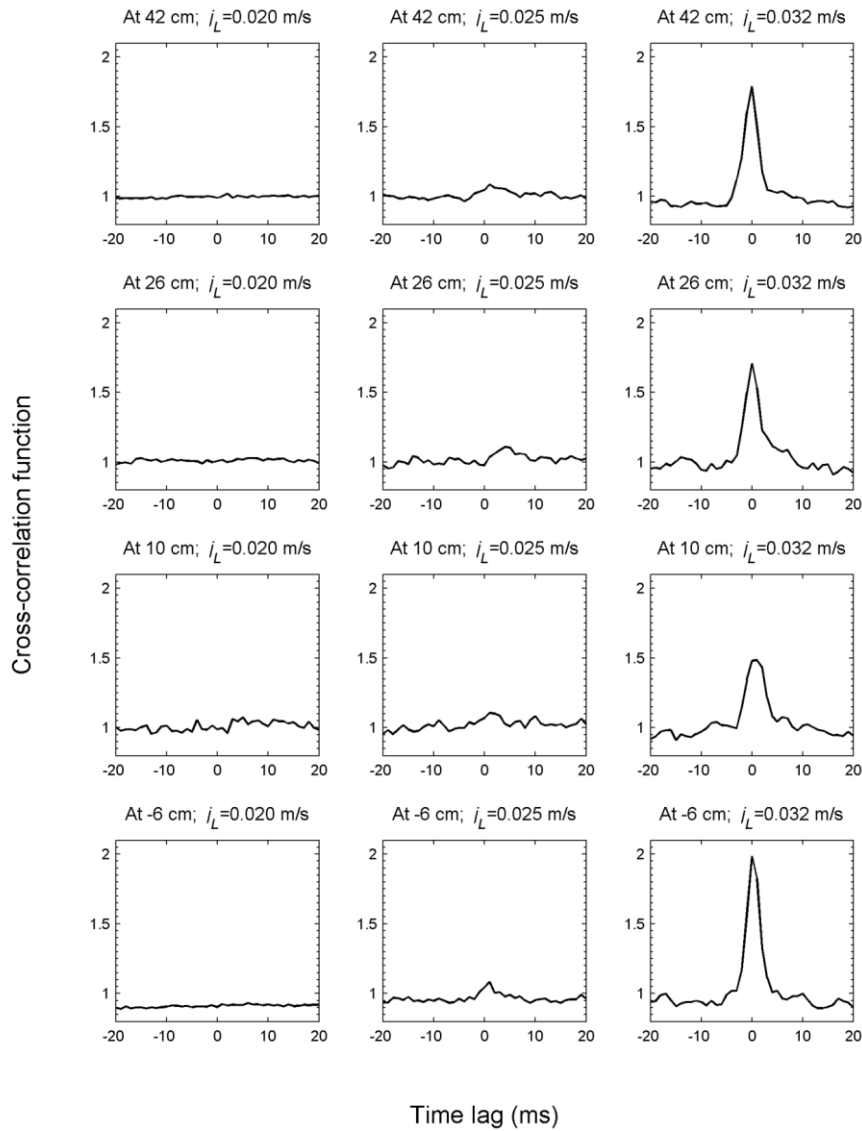


Figure 4-12 Cross-correlation of the reflected light signals

4.4 Summary

The backlight arrangement of high speed camera technique has been applied to measure the wavy liquid film at high time and space resolutions. Basing on the obtained data, the liquid-film flow on the rod-bundle geometry with the spacer can be characterized by the following main points:

- The average liquid film thickness, wave amplitude, and wave velocity measured at the corner rod is higher than those at the side rod.
- The influences of the spacer on the film thickness and wave amplitude are different for low and high values of j_G due to the contributions of the phenomena occurring at this structure in each case.
- The mean wave velocity does not change much on the way through the spacer and in the further downstream.

From the data obtained by using the reflected light arrangement in high gas superficial velocity cases, the disturbance waves' structure is seen to be broken when they pass by the spacer.

As mentioned at the beginning, the current experiment is also aimed at measurement of liquid droplets flying in the gas core and the corresponding results will be presented in Chapter 5. The discussion on how the characteristics of the wavy liquid-film affect the droplets' features will be included in that chapter.

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Chapter 5 Quantitative measurement of liquid droplets

5.1 Introduction

Beside the wavy liquid film flowing on the rods' surfaces, the existence of the liquid droplets which travel with the gas core in the space between the rods keeps the important role in mass, momentum and heat transfer in the system. The continuous interchange between the amounts of liquid distributed in the films and the droplets occurring in the means of the droplet entrainment and deposition phenomena point out the necessity of an investigation considering both of these components.

As mentioned in Section 2.1, however, the existing experimental techniques have not been able to satisfy this requirement. The total volume of liquid droplets of the annular flow can be determined by using the suction probes but the detail information such as droplet's size and velocity should be obtained by an optical based technique. These optical methods include the laser-diffraction technique, the laser-grating technique, phase-Doppler, and photography (for droplet flow). Most of them were applied for the annular flow in a circular pipe and their measuring devices required the removal of the liquid film to detect the droplets flying in the gas core. This was accomplished by extracting the liquid film before the measuring point or using cylinder tubes to penetrate the film in the direction perpendicular with the duct wall. In other words, the droplet's diameter and velocity could be determined but the wavy characteristics of the liquid film were out of the consideration.

It can be seen in the Chapter 2 and Chapter 3 that the current application of high speed camera technique using backlight arrangement can detect not only the liquid film surface but also the droplets flying in the gas core. Taking this advantage, beside the liquid film measurement presented in Chapter 1, the current study is also aimed at obtaining the quantitative data of liquid droplets. This chapter is dedicated to present the image data acquiring and processing and the results of this task. The obtained diameter,

velocity and spacer distribution of the droplets indicate not only the contribution of the liquid film characteristics (Chapter 1) but also the influences of the spacer.

5.2 Experimental methodology

Because the measurement of liquid droplets is conducted together with the measurement of liquid films (Chapter 1), the experimental apparatus and the flow conditions are the same with that task. The next subsections will present the examination of the image calibration, the image data acquiring and processing procedures for the droplet measurement.

The influence of the light condition on the image-pixel calibration is conducted by using a 1 mm transparent spherical particle to simulate the liquid droplet (Figure 5-1). The diameters determined by processing the obtained images agree with the value measured by micrometer within 5%.

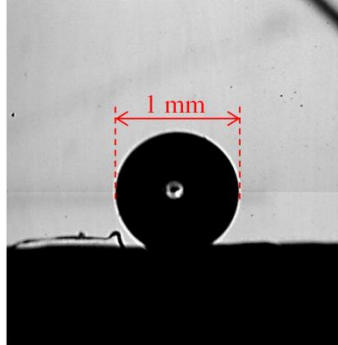


Figure 5-1 Image of spherical transparent-plastic particle used to simulate liquid droplet

5.2.1 Image data acquiring and processing

Image data of the liquid droplets' diameter and spatial distribution are acquired by using 512 x 512 pixels image window of the high speed camera. The low recording speed of 200 fps is used to avoid the situation in which a low-speed droplet appears in more than one image frame. With the height of the image ~ 3.38 mm, this requirement is satisfied for droplets traveling at the speed higher than 0.68 m/s. Because this value

approximates the lower limit of the mean wave velocity of the liquid film presented in Chapter 1, all droplets flying in the gas core is expected to have a velocity higher than 0.68 m/s. Five shots are taken for each flow condition and measuring point to obtain the total recording time of 10 sec.

Figure 5-2 presents an example of the obtained image data and the image processing procedure developed with Matlab software and its tool box as follows:

- (0) The original 512 x 512 pixels image taken just after a droplet impingement event is selected as an example to show the ability to detect small-diameter droplets of the current method.
- (1) The integrated Canny's edge-detection operator (Canny, 1986) is used to detect the edges where the sharp changes of intensity occur in the original image. A couple of lower and higher thresholds of this operator are chosen after a survey with data of different flow conditions and then they are used for all flow conditions and measuring points. It should be noticed that the thickness of the edge detected by Canny's algorithm is one pixel.
- (2) All image areas bounded by a closed edge line are determined and marked as droplets. This means that if a droplet is partly or fully out of the depth of field (DOF) then its full boundary cannot be detected and it will not be included in the data.
- (3) A removal of single-open lines in the image is performed so that only droplets' image areas remain.
- (4) The equivalent diameter and the distance from the centerline of the gap are calculated for each droplet's image area to represent the corresponding droplet. The points marked by the letter D appearing in most of the image frames correspond to the dust-points in the optical system and will be removed by a comparison between the frames.

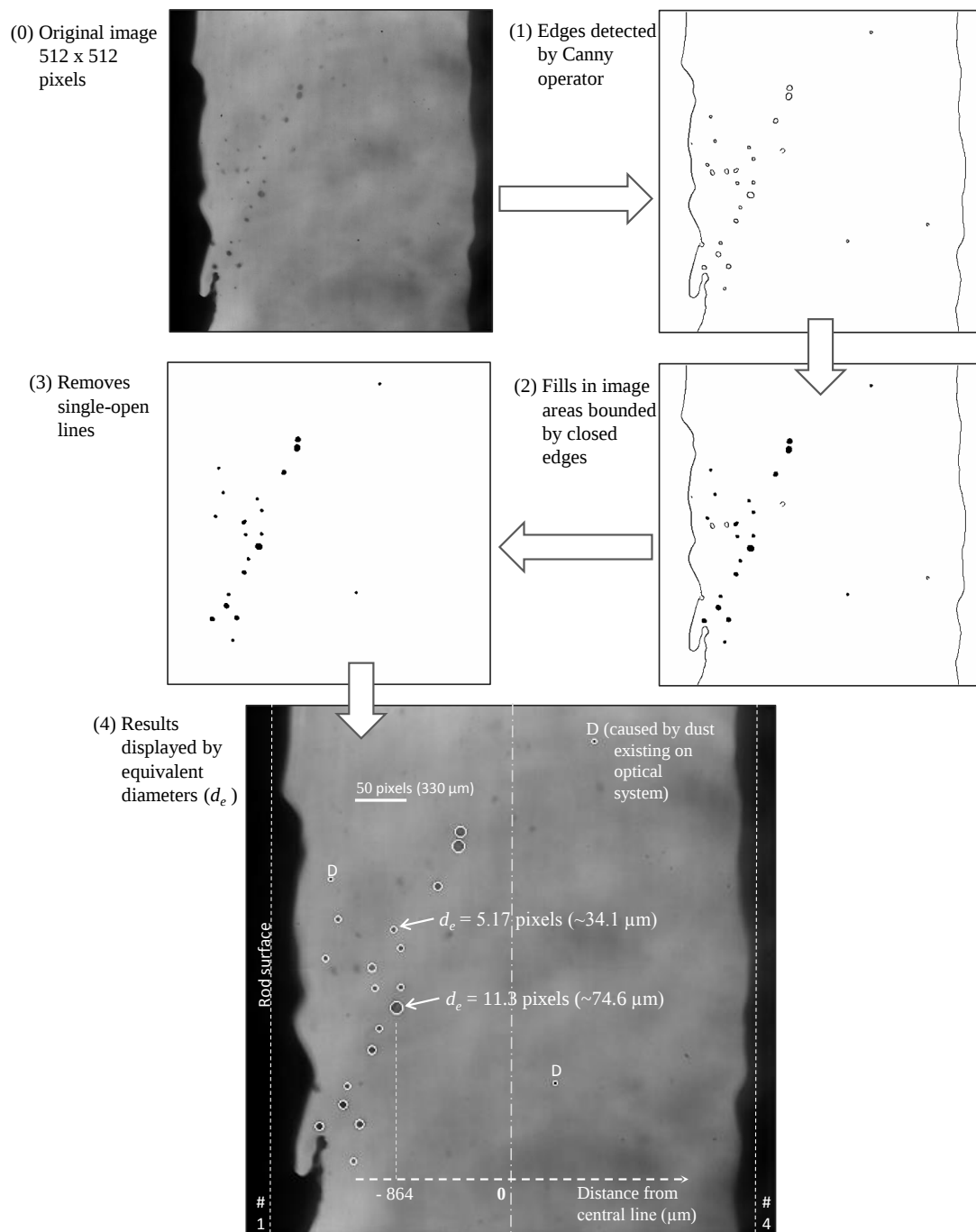


Figure 5-2 Image processing procedure with data obtained at position 42 cm for $j_G = 62.2$ m/s and $j_L = 0.025$ m/s.

The droplet velocity measuring method also uses the same procedure to detect the droplets in all image frames but it requires a much higher recording speed because each droplet needs to be detected at least two times. Due to the memory limitation of the camera, a narrower image window must be used. Based on the distribution of droplet size obtained with 512x512 pixels image-window, various width values are chosen to balance between the recording speed and the width of the image window. Keeping the image height of 512 pixels, the width is set between 144 and 64 pixels – corresponding to the increasing of gas superficial velocity – to archive the recording speed from 17 to 32 kfps. About 10 shots are taken for each flow condition and measuring point to obtain the recording time of 5 sec.

After detecting all droplets in the obtained image series, the existence of a droplet in two successive frames is determined by comparing the equivalent diameter, distance from the central line of the gap, and average image intensity of each droplet found in these two frame. This study considers only droplets flying almost parallel to the central line (the difference between the radial positions in two frames is less than five image pixels). The droplet velocity is calculated from the difference between its axial positions in the two frames and the image recording speed. If the same droplet is detected several times, the first two frames are used.

5.2.2 Limitations of droplet measurement

Mathematically, the definition that a droplet is the image area bounded by a closed boundary edge allows the detecting droplet whose equivalent diameter is as small as three pixels. However, the detection of these small droplets can be affected by the image background. With this study's backlight condition, the small droplets are hardly able to cause clear dark image areas which can be distinguished from the background so as to be detected by the detection operator. For this study, the lower limit of equivalent droplet diameter needs to be set at four pixels to remove this uncertainty. This limitation, however, can be improved by adding another oval-shape obstacle onto the duct wall behind the focus plane to guide the liquid distributed on this surface around the image

window at each measuring point (the current design of the test-section has not allowed this modification).

For the measurement of droplet velocity, the algorithm of finding the same droplet in two successive frames cannot recognize the case in which a droplet detected in the current frame disappears in the next frame (due to non-vertical velocity component) and another one is detected instead due to similarities in diameter, image intensity, and radial position. Then an incorrect velocity will be calculated based on the difference between their axial positions and the obtained value can be unreasonably lower or higher. However, the possibility of this situation is small due to the thin DOF and the small image area, therefore it does not affect the statistical point of view, but the information for the minimum and maximum droplet velocities cannot be obtained. Instead, the current study uses the liquid film wave velocity obtained in Chapter 1 and $1.5j_G$ as the lower and upper limits of the droplet velocity, respectively.

It also needs to be pointed out that the backlight arrangement only allows for measurement at positions through which the light source can be seen by the camera only. This limitation restricts the current method from providing the data of average variables for the whole flow area.

5.3 Results and discussion

5.3.1 Droplet size distribution

Figure 5-3 presents the droplet size distribution for all flow conditions and measuring points. It should be noticed that the generation of droplet caused by the first spacer is smaller than that of the second one because it is located near the inlet where the waves on the liquid film surfaces are in the early stages of development (Zhao et al., 2013; Pham et al., 2014). Therefore, the effect of flow conditions on the data of droplets is clearest at -6 cm. The data show a common tendency in which the number of droplets is increased with the increasing of j_G and/or j_L . Because most of the droplets are generated through the entrainment processes described in Pham et al. (2014), this tendency thus

directly relates to the magnitude of waves existing at the liquid film surface (Chapter 1)
 – which displays the same trend.

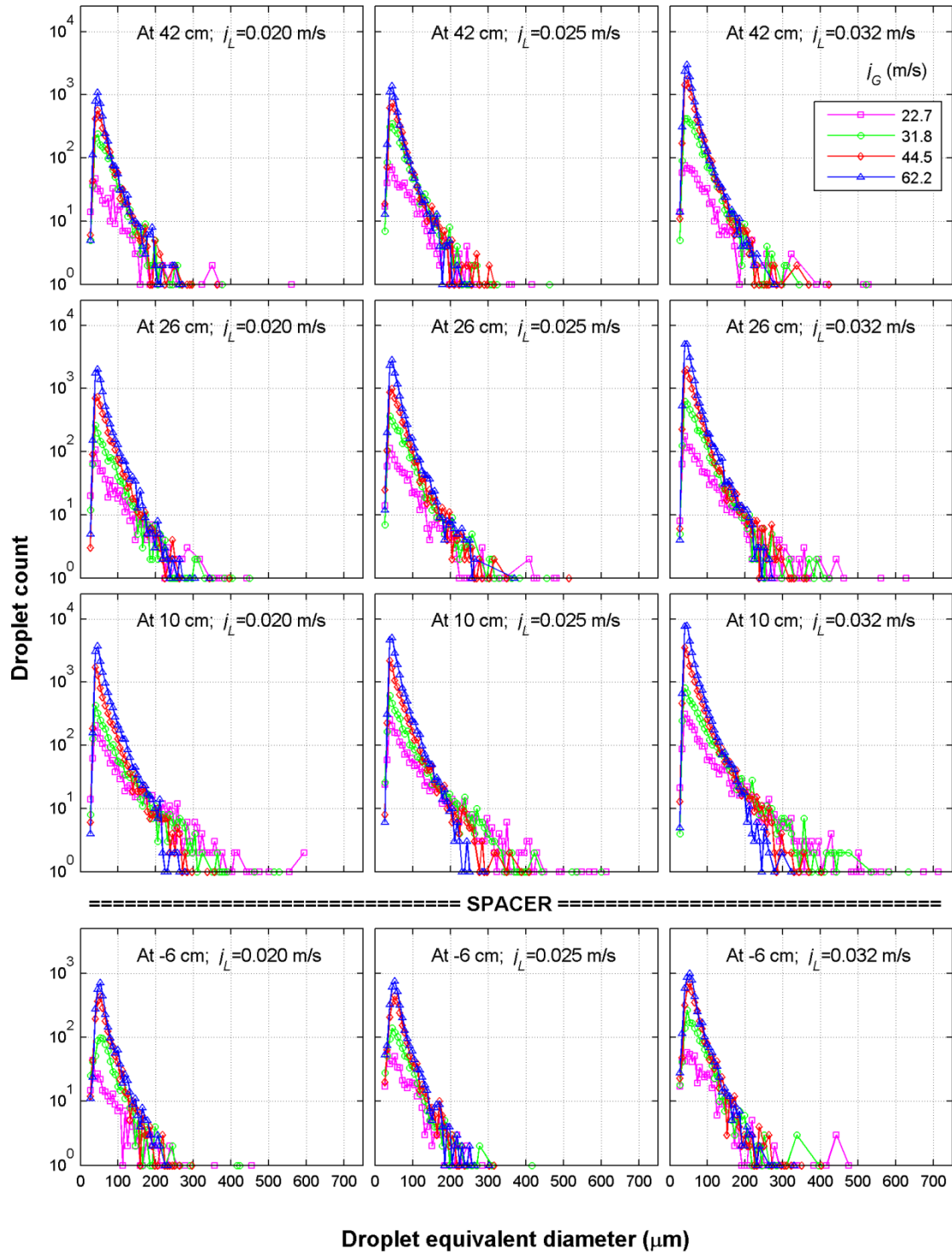


Figure 5-3 Droplet size distribution

Generally, the size distribution of entrained droplets is determined by the competition between the bag and ligament break-up processes. According to Azzopardi (1997), the occurrence possibility of ligament break-up event is increased as j_G decreases or j_L increases. This mechanism generates smaller number of droplets but with larger sizes compared to the bag-breakup process (Pham et al., 2014). Therefore, there are more big droplets flowing in the gas core as j_G decreases or j_L increases as shown in the figure.

The influence of the spacer is clearly indicated by comparing the data obtained at -6 and 10 cm. In all flow conditions, the spacer generates not only several droplets whose diameters exceed the maximum values at upstream but also a huge number of small droplets which cause a slight moving of the counting peak towards the smaller diameters. The appearance of these large size droplets can be linked to the theoretical “run-off” effect in which the liquid distributed on the spacer surface flows upward and leaves this structure (Yano et al., 2001a). The generation of small droplets was considered a result of the interaction between the droplets existing upstream and the spacer grid by Cho et al. (2011) but in a study for mist flow regime. It actually requires more information on the phenomena happening at the spacer to understand the mechanism controlling the droplet size distribution. Therefore, a discussion on this point in more detail will be given in Chapter 6 along with the visualization data.

5.3.2 Spatial distribution of droplets

The distribution of liquid droplets in the gap between the corner and side rods is provided in Figure 5-4. At upstream of the spacer, the droplets are distributed quite uniformly in the gap. Then the spacer introduces a large number of droplets into the gas core as indicated by the data at 10 cm. At further downstream, the droplet count decreases, suggesting that the rate at which droplets deposit or leave the DOF of the image window is larger than that of the droplet generation.

The most interesting point indicated by the data is the asymmetric distribution of the droplet count in further downstream of the spacer. The data obtained at 10 cm for all flow conditions are still almost axisymmetry, but shortly after the peaks are clearly seen to move into the corner rod in the left hand side of the figure, especially at higher gas

superficial velocities. One possible explanation is the interaction between the gas flow and the liquid films at both sides of the gap. The data of the liquid film (Chapter 1) show that both average film thickness and wave height are larger at the corner rod. In this sense, the frequency of the bag and ligament break-up events (Azzopardi, 1997, 1983; Pham et al., 2014) caused by the gas flow is higher at the corner rod and therefore more droplets are generated at this side. This argument, however, does not hold with the data at -6 cm where the difference between the wave magnitudes at both sides clearly exists but the droplet distribution is quite homogenized.

Instead, the high droplet populations themselves can be responsible for the asymmetry. Beside the bag and ligament break-up processes, the liquid droplets can be generated through the droplet impingement mechanism in which a droplet flying in the gas core impinges on the film surface, creating secondary droplets (Ishii and Grolmes 1975). The occurring frequency of this process becomes larger as the droplet count increases. According to the side-view images obtained by Pham et al. (2014), the amount of entrained liquid in the form of secondary droplets can be significant. Similar to a typical droplet impact event, this amount is proportional to the momentum of the primary droplet and determined by the impact angle. Because the velocity vector of the primary droplet is almost parallel to the rod surface, the high-amplitude waves will present the larger impact angle, hence the portion of liquid confronted by them can receive more kinetic energy and have more chance to be entrained into the gas core. In contrast, small impact angles in the case of small waves or smooth surfaces restrict this entrainment process.

Therefore, the impingement processes between high-density droplet flow and the wavy film surface on the corner rod will generate a larger number of secondary droplets than the smoother surface on the side rod. The asymmetry is clearer at higher j_G (meaning higher droplet momentum) and further downstream, where more and more droplets generated at the spacer have taken part in the impinging or deposition processes. The data obtained at small values of j_G , on the other hand, do not possess the clear asymmetry due to the low density and momentum of the droplets. This new information quantitatively points out the important contribution of the droplet impingement

mechanism in the entrainment phenomena of the annular two phase flow which has not been emphasized in previous literatures.

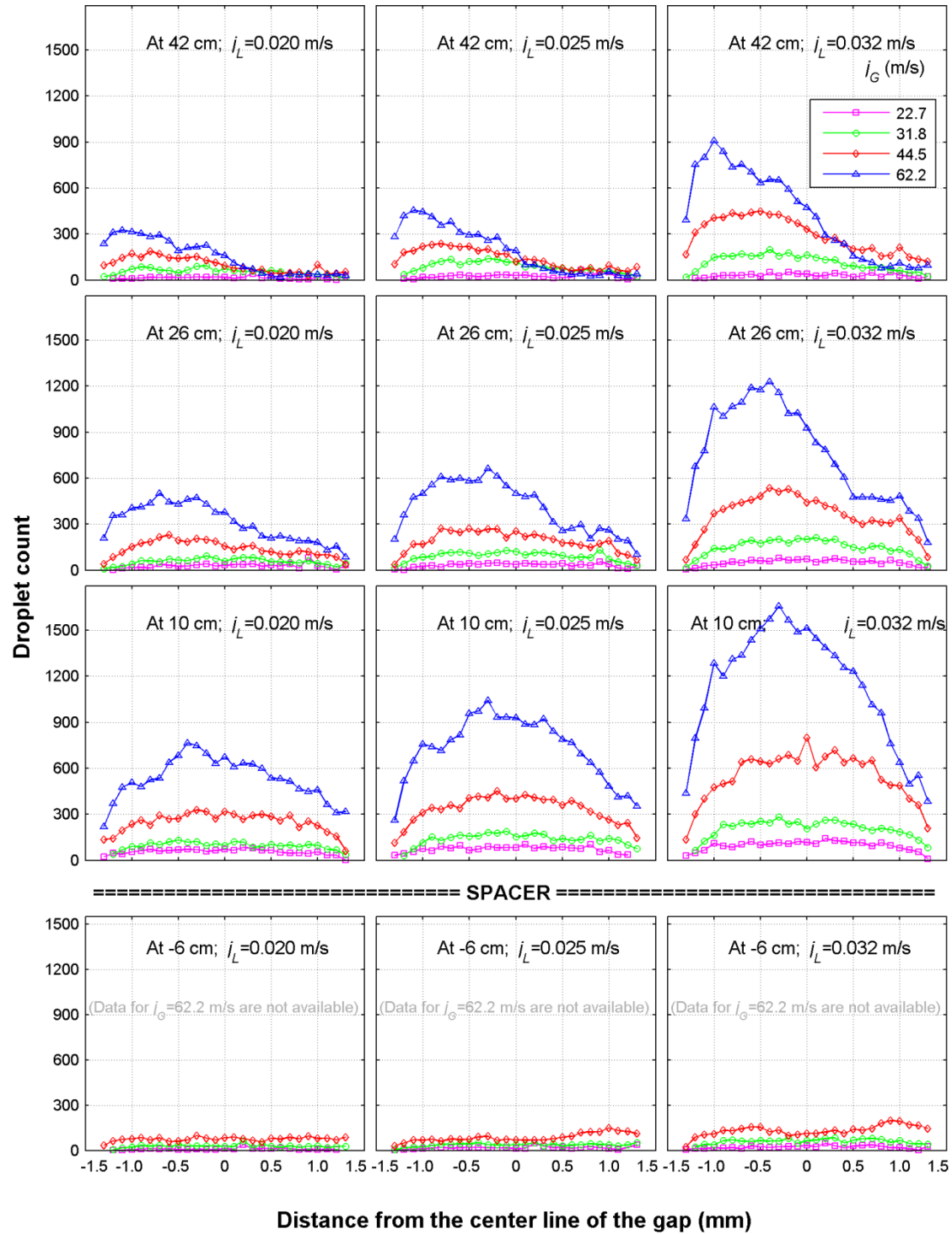


Figure 5-4 Space distribution of liquid droplets

The spatial distributions of droplet diameter are given in the Figures 5-5 to 5-8. It can be seen that the average diameters are quite uniform in the gap between two rods. The spacers generated not only small droplets but also the large diameter ones. The phenomena corresponding to these processes will be seen in Chapter 6.

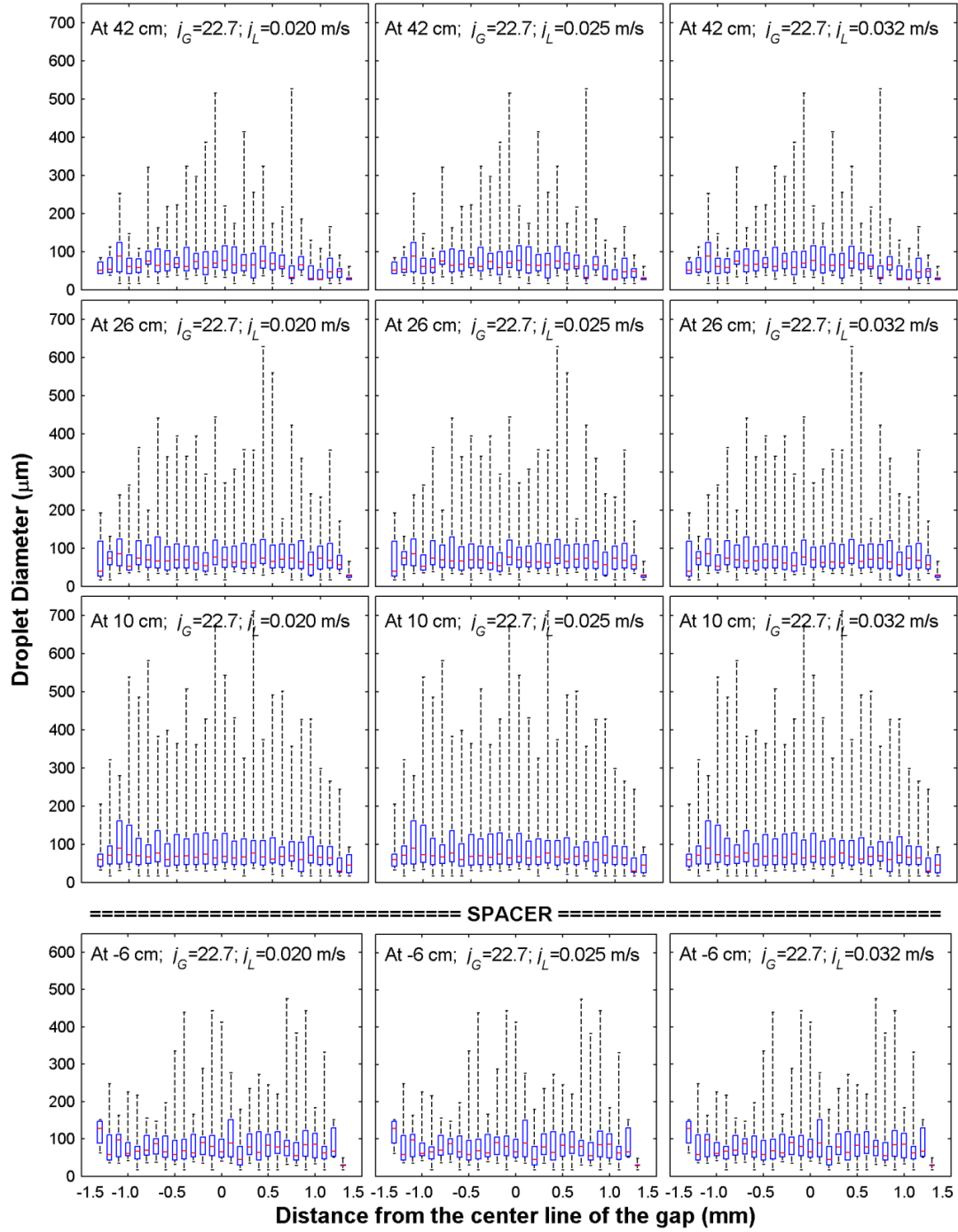


Figure 5-5 Space distribution of droplet diameter ($j_G = 22.7$ m/s)

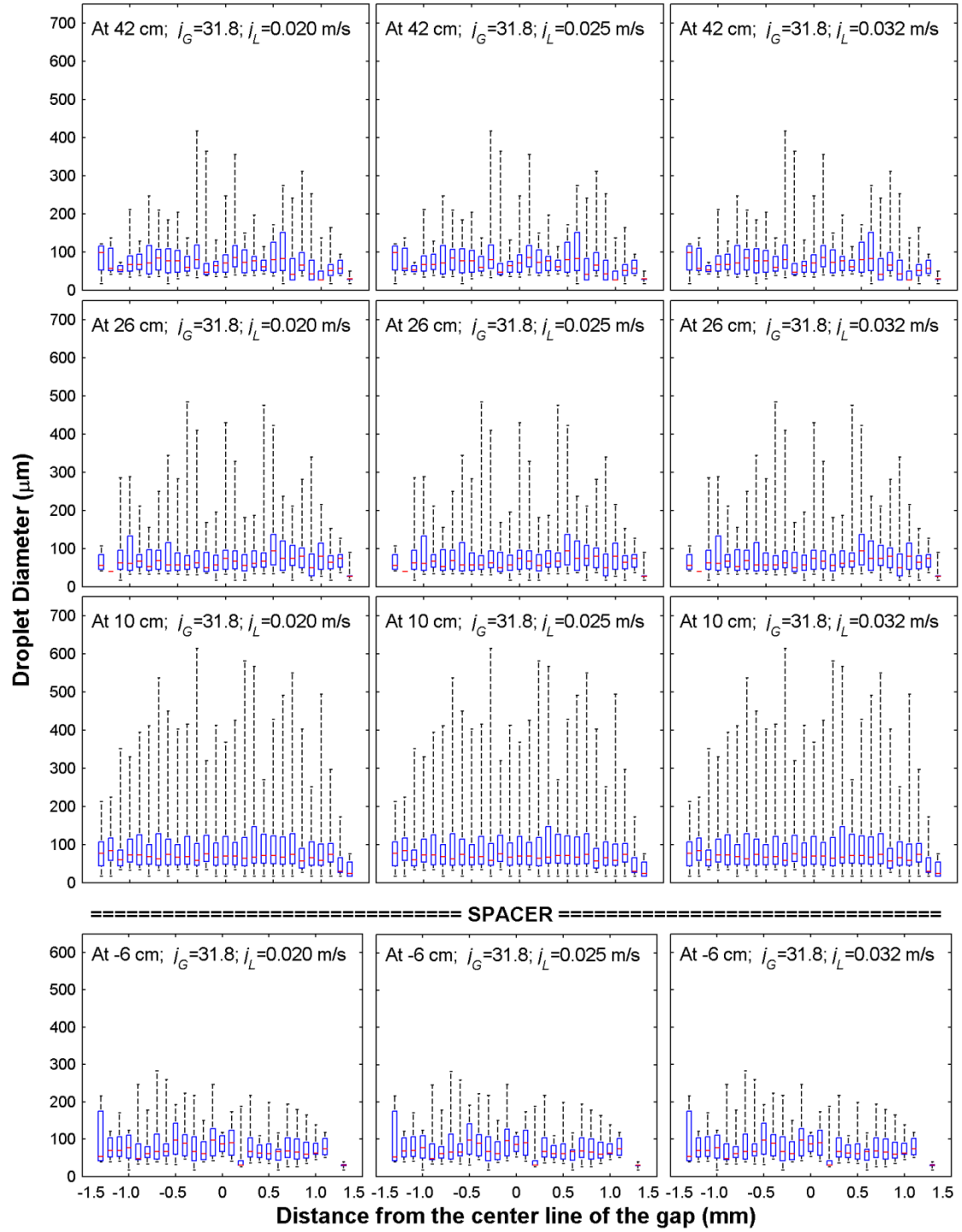


Figure 5-6 Space distribution of droplet diameter ($j_G = 31.8$ m/s)

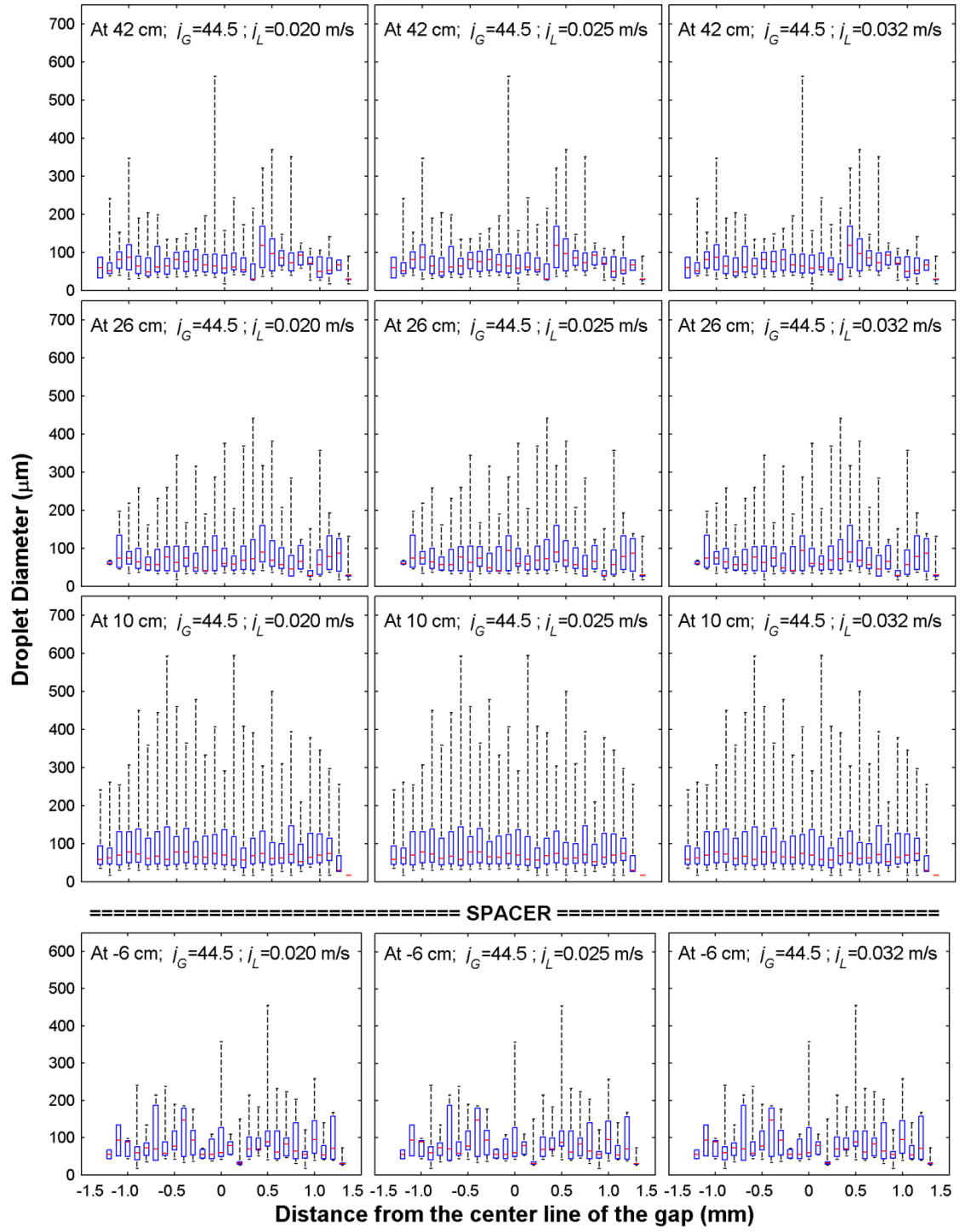


Figure 5-7 Space distribution of droplet diameter ($j_G = 44.5$ m/s)

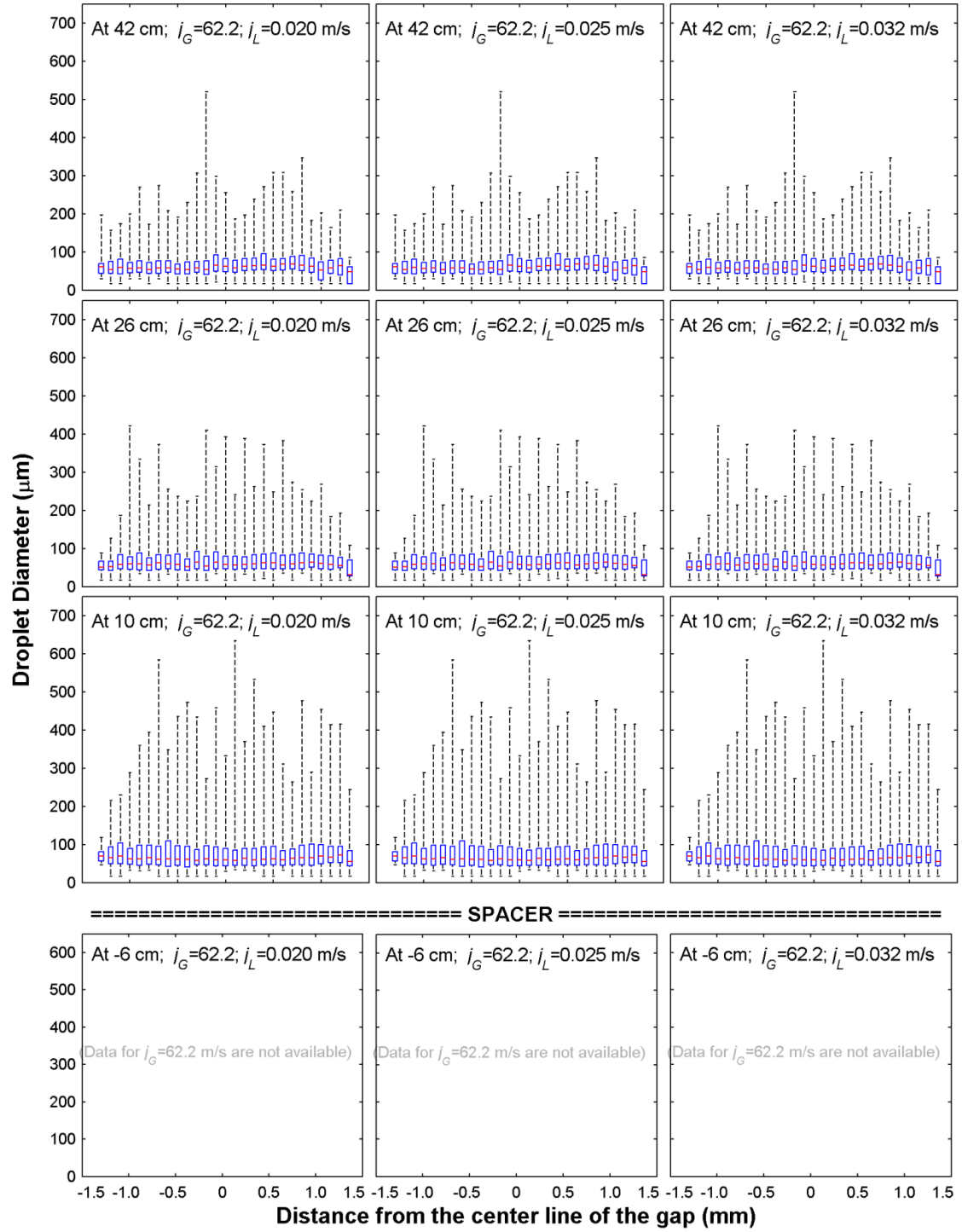


Figure 5-8 Space distribution of droplet diameter ($j_G = 62.2$ m/s)

5.3.3 Droplet velocity

The probability density functions of droplet velocity and the dependence of the velocity on diameter for all flow conditions and measuring points are presented in Figure 5-9 and Figure 5-10, respectively. It is necessary to point out that the number of successful droplet velocity detections for low gas velocities or at upstream of the spacer is not enough for a statistical consideration. However the effects of the flow conditions on the velocity distribution can still be observed. Unlike the results obtained at the centerline of a circular pipe test-section by Fore and Dukler (1995), the droplet velocity in current experiment does not really exceed the superficial gas velocity. It is because the gas velocity at the gap between two rods does not belong to the highest values of the gas velocity profile as in the case of their experiment.

Further downstream of the spacer, there is a general trend in which the peak velocity is slightly increased due to the droplet acceleration caused by the gas flow. On the other hand, the existence of small velocity values should correspond to the droplets which were generated near the measuring point and have not accelerated.

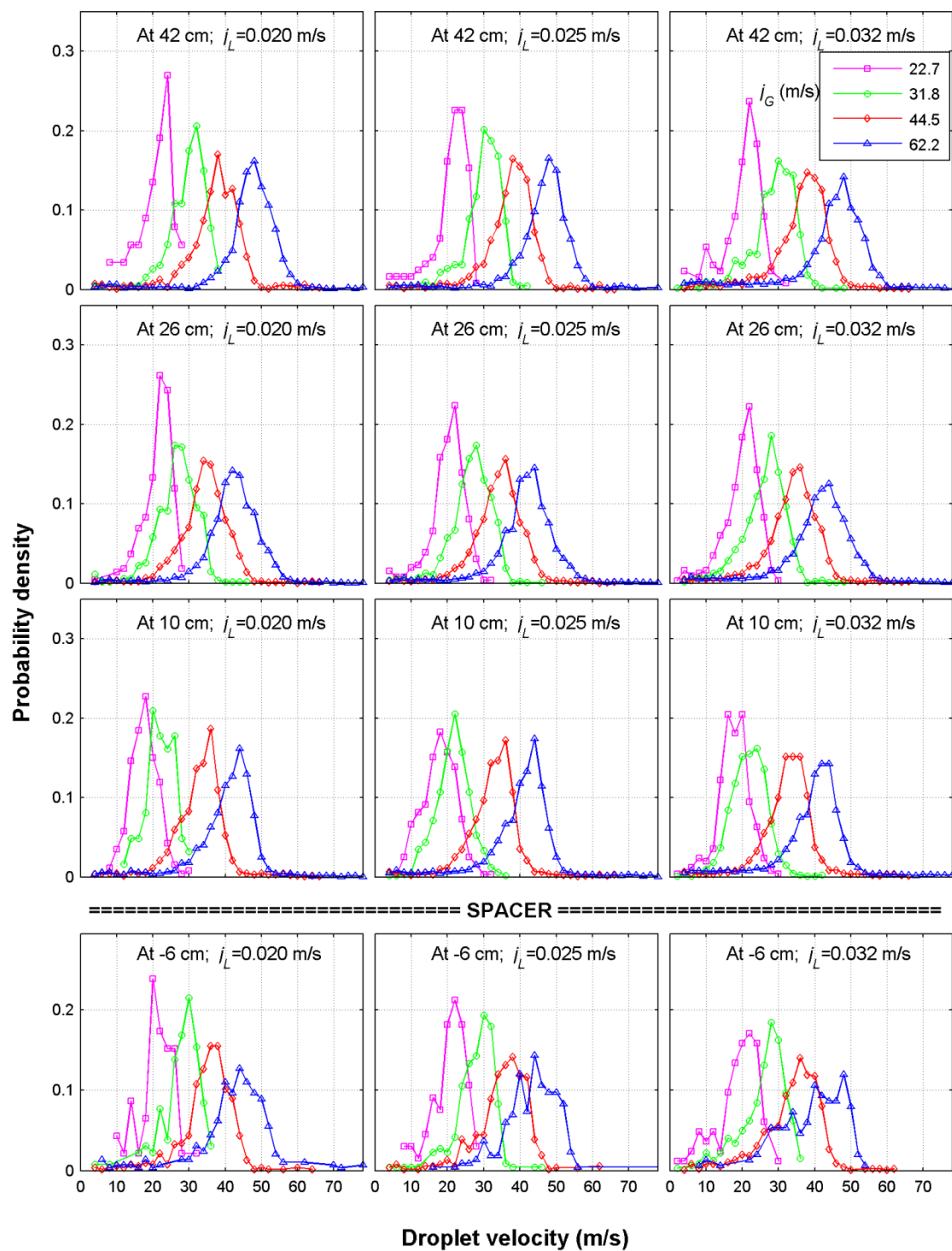


Figure 5-9 Probability density functions of droplet velocity

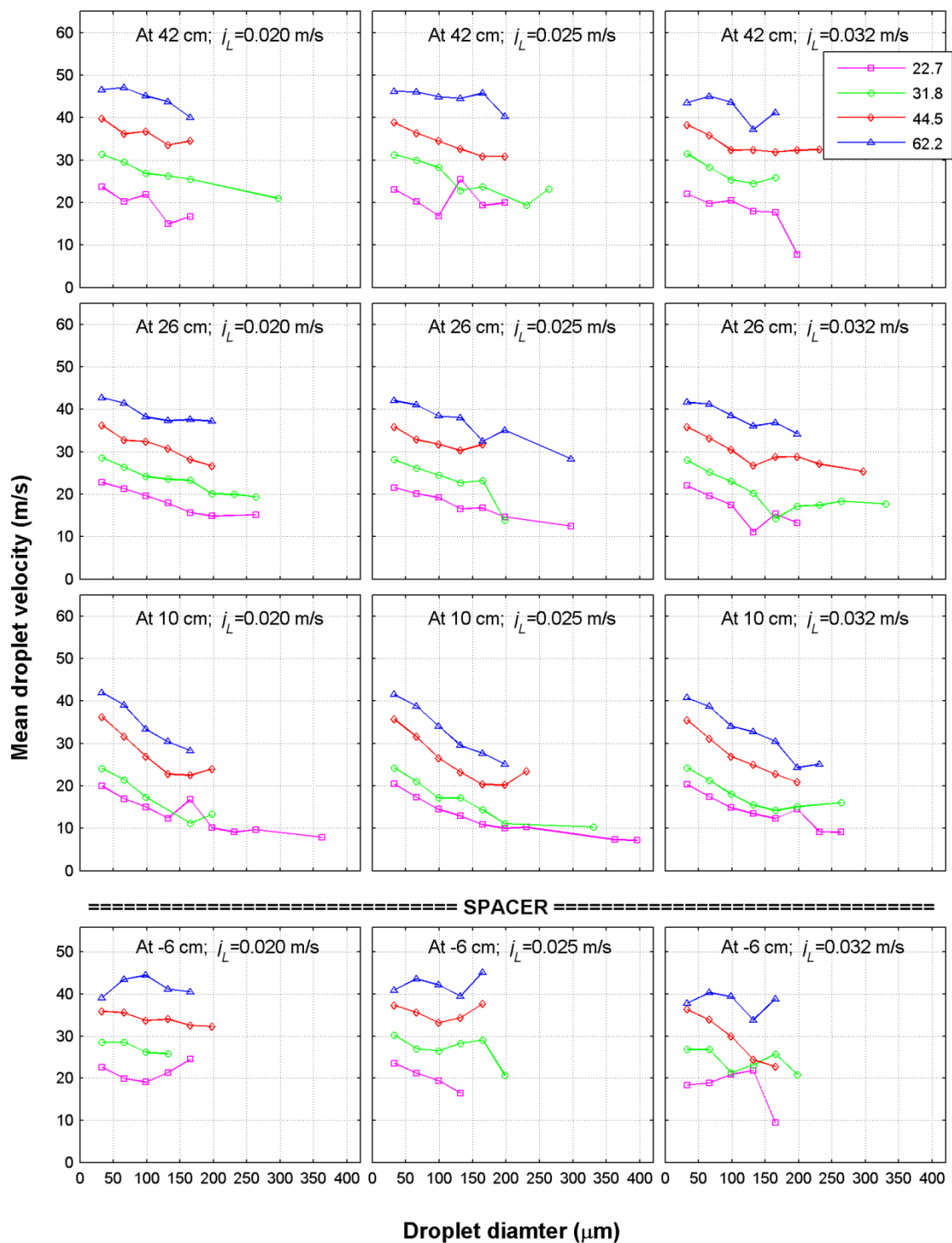


Figure 5-10 Dependence of droplet velocity on diameter

5.4 Summary

Together with the results presented in Chapter 1, the obtained data provided in this chapter have confirmed the advantages of the high speed camera technique with back light arrangement in measuring both the liquid film and droplets of the annular flow on rod-bundle geometry. The main results made from the obtained data of liquid droplets are as follows:

- At upstream of the spacer, most of droplets are generated through the entrainment processes, therefore the droplet's population and size distribution directly relate to the magnitude of waves existing on the liquid films.
- Spacer generates a huge number of small-size droplets. In the cases of lower gas superficial velocities, it also generates several droplets whose diameters exceed the maximum values at upstream.
- The asymmetrical spatial distribution of the droplets at downstream of spacer emphasizes the importance contribution of the droplets impingement processes occurring on the wavy film surface to the liquid entrainment phenomena.
- Because the gas velocity is not at the highest in the gap between two rods, the obtained droplet velocity distribution does not significantly surpass the gas superficial velocity compared to the data obtained at the center line of a circular test-section.

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Chapter 6 Close-up visualization of phenomena happening near spacer

6.1 Introduction

The data of liquid film droplet obtained in the last two chapters have pointed out the influences of the spacer on the annular two-phase flow. In the literature, the spacer has also received much attention from both the experimental and simulation works. However, it can be seen that most of the applied techniques such as conductance probes (Damsohn, 2011; Feldhaus et al., 2002; Nishida et al., 1994) or suction probes (Kraemer et al., 1995) could not provide a good description on the interaction between the wavy liquid film surface as well as the generation of droplets caused by the spacer.

Because the visualization information of the phenomena is essential for the establishment of the related two-phase flow models, the current task is aimed at taking the clear images at right up- and downstreams of this structure. The obtained data improve the understanding of the film-spacer interaction and the mechanisms behind the generation of the liquid droplets as well as their behaviors near spacer.

6.2 Experimental methodology

The attempt to avoid the image distortions by using an oval-shape obstacle mentioned above cannot be accomplished for the observation conducted near the spacer. This is because the existence of this structure itself offers a pathway for the liquid to flow from the rod surface onto the duct wall and cover the image window. Therefore the task requires the first spacer to be removed and the water lines at six rods (#1, 3, 4, 6, 7, and 9) to be turned off as indicated in Figure 6-1 and Figure 6-2, respectively in order to minimize the amount of liquid distribution on the duct wall. The j_G conditions are the same as the settings of droplet measurement. The water flow rates at the inlets of each of the three working rods (#2, 5, and 8) are also the same as that of each of the nine rods in the droplet measurement experiment, therefore the water superficial velocity in this

observation will be denoted as $j_{L \times 3}$ to hold the same values as before. The image focus plane is setup at the gap between the side (#2) and the center (#5) rods (Figure 6-2), and the axial locations of the observation are as indicated in Figure 6-1. The camera's recording speed and image windows are changed depending on the process under consideration.

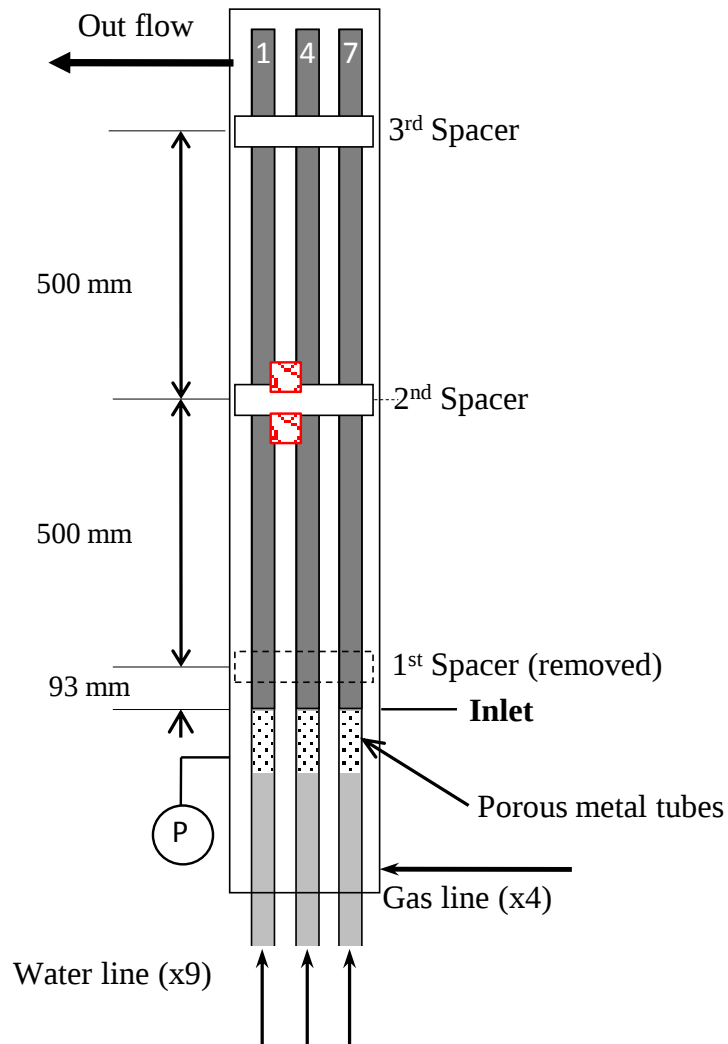


Figure 6-1 Schematic of experimental system

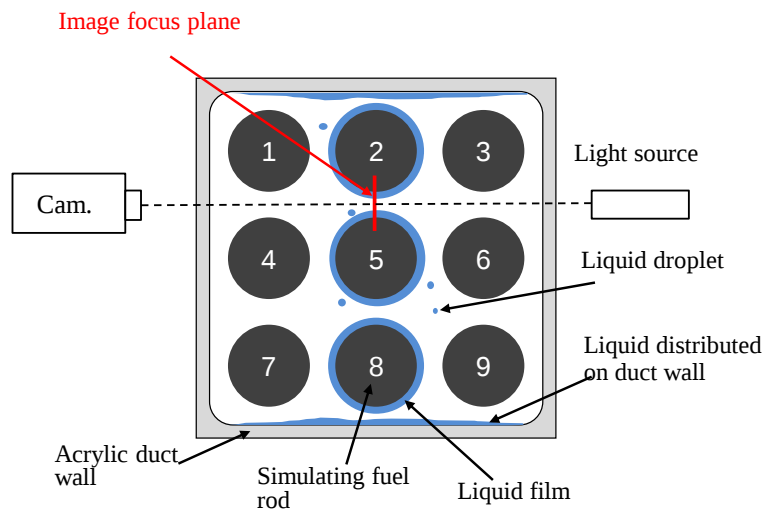


Figure 6-2 Experimental setting used for the observation of phenomena occurring at the spacer

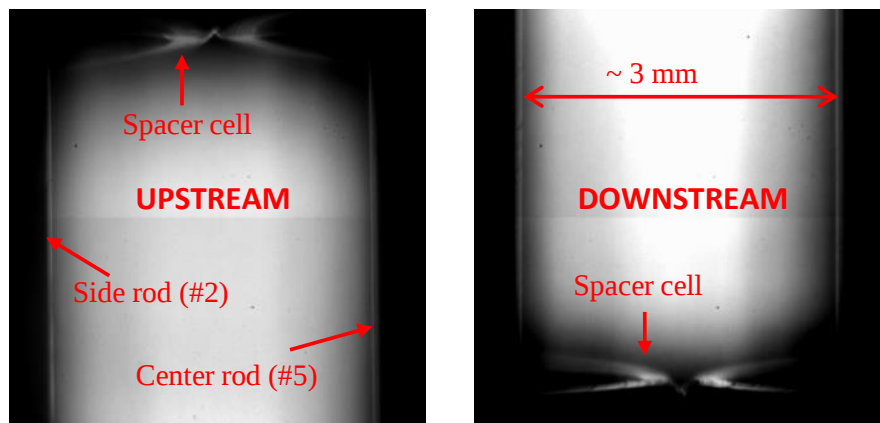


Figure 6-3 Images taken right up- and downstream of the second spacer when all water input lines are closed

6.3 Results and discussion

Figure 6-3 shows the images taken right up- and downstreams of the second spacer when all the water valves are closed. The angle of the optical system is slightly adjusted to allow the visualization of not only the surfaces of the side and corner rods but also the portions of the spacer-cells holding them. The image data presented below are subjectively selected to show typical situations of the interactions between the two-phase flow and the spacer cells. In this manner, the time-step of each image series is chosen based on the speed of progression of the phenomenon being considered. The brightness and sharpness of most of the images are slightly adjusted to enhance visual quality.

6.3.1 Wavy liquid film entering spacer region

Firstly, the situations in which the large-amplitude waves approaching the spacer are shown in Figure 6-4. In both cases of low and high values of j_G the wavy films can smoothly enter the spacer region even when there are some wave crests excess the rod-spacer clearance. In other words, the interruption of the spacer hardly causes any separation in which an amount of liquid in the film is immediately detached and put into the gas core. Hence, the increase of liquid entrainment upstream of the spacer as mentioned in the model of “narrow channel effect” (Yano et al., 2001a, 2001b) could not be held for the current study’s image data. Instead, some amount of liquid leaves the liquid film and moves onto the spacer’s surfaces to flow on.

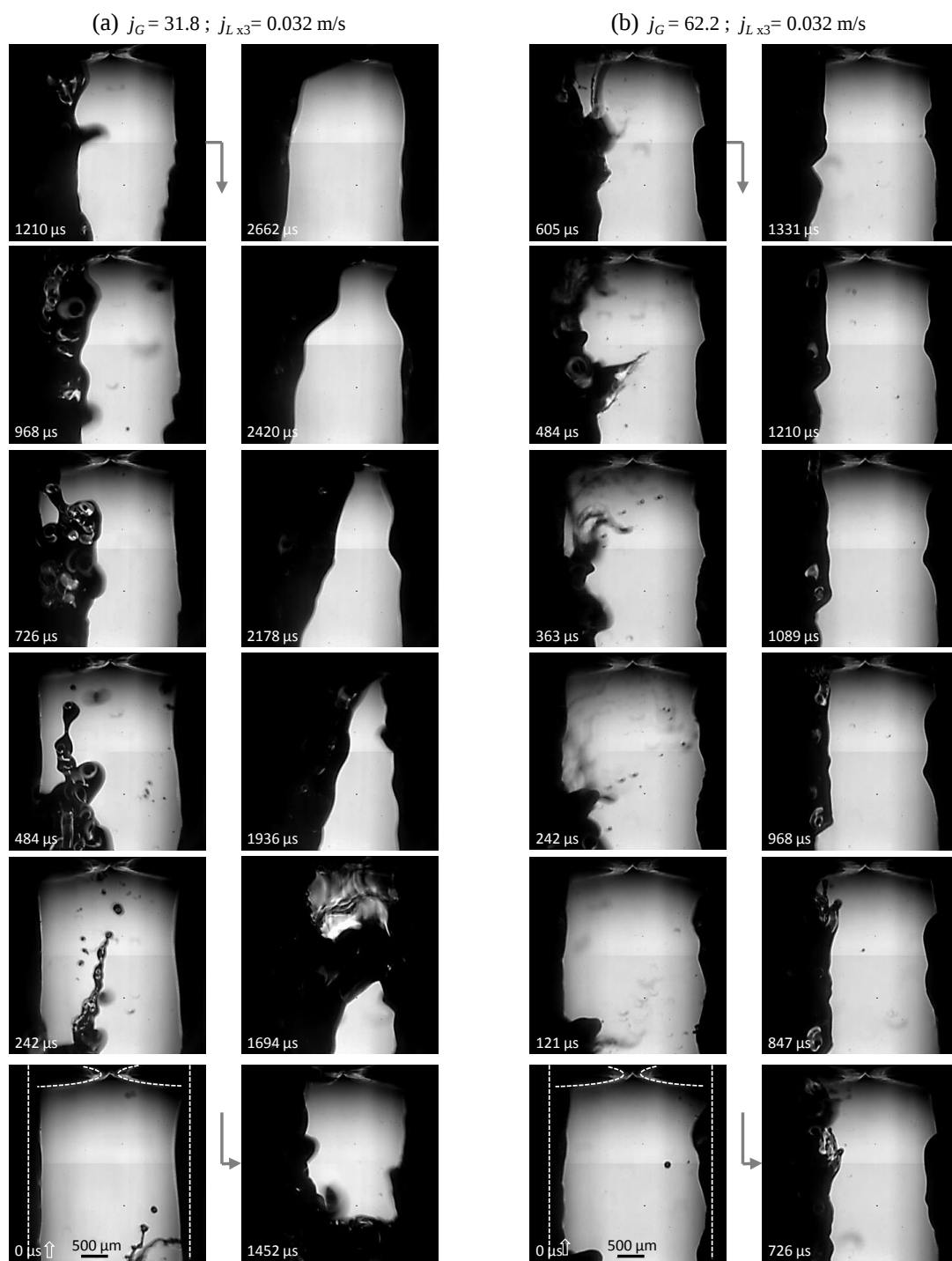


Figure 6-4 Large-amplitude waves enter spacer region

6.3.2 Generations of liquid droplets

When the liquid flowing on the spacer's surface reaches the end of this structure, the generation of liquid droplets happens as shown in Figure 6-5. From the obtained visualization data, the frequency of these droplet generations is clearly seen to be much higher than that of large-amplitude waves entering the spacer (Figure 6-4). This is because of the existence of the dimples and springs (Figure 2-3) which provide pathways from the rod surface to the spacer cells. Following these pathways, some portions of liquid belonging to the base film (not necessary the large-amplitude waves) can easily move to the spacer surface. Therefore, it can be concluded that the amount of liquid distributed in the droplets at downstream of the spacer mostly comes from the base liquid films.

At low j_G (Figure 6-5a), the process similar to bag break-up mechanism does happen to the liquid block attached to the top of spacer structure and small-size droplets are generated but there is more frequently the formation of thick ligaments which are subsequently broken into large-size droplets. Meanwhile the image series for high j_G (Figure 6-5b) shows that the bag break-up mechanism dominate the droplets generation. Large amount of small-size droplets are formed as the bag-shapes are broken while the larger ones formed in the breaking of the rims. Because the rims are similar to a thin ligament, the droplets of the latter group are small compared to the droplets generated in the case of low j_G . This is the main reason why the droplet-size distribution of low j_G consists of large droplets which are not found in the high j_G cases in Figure 5-3.

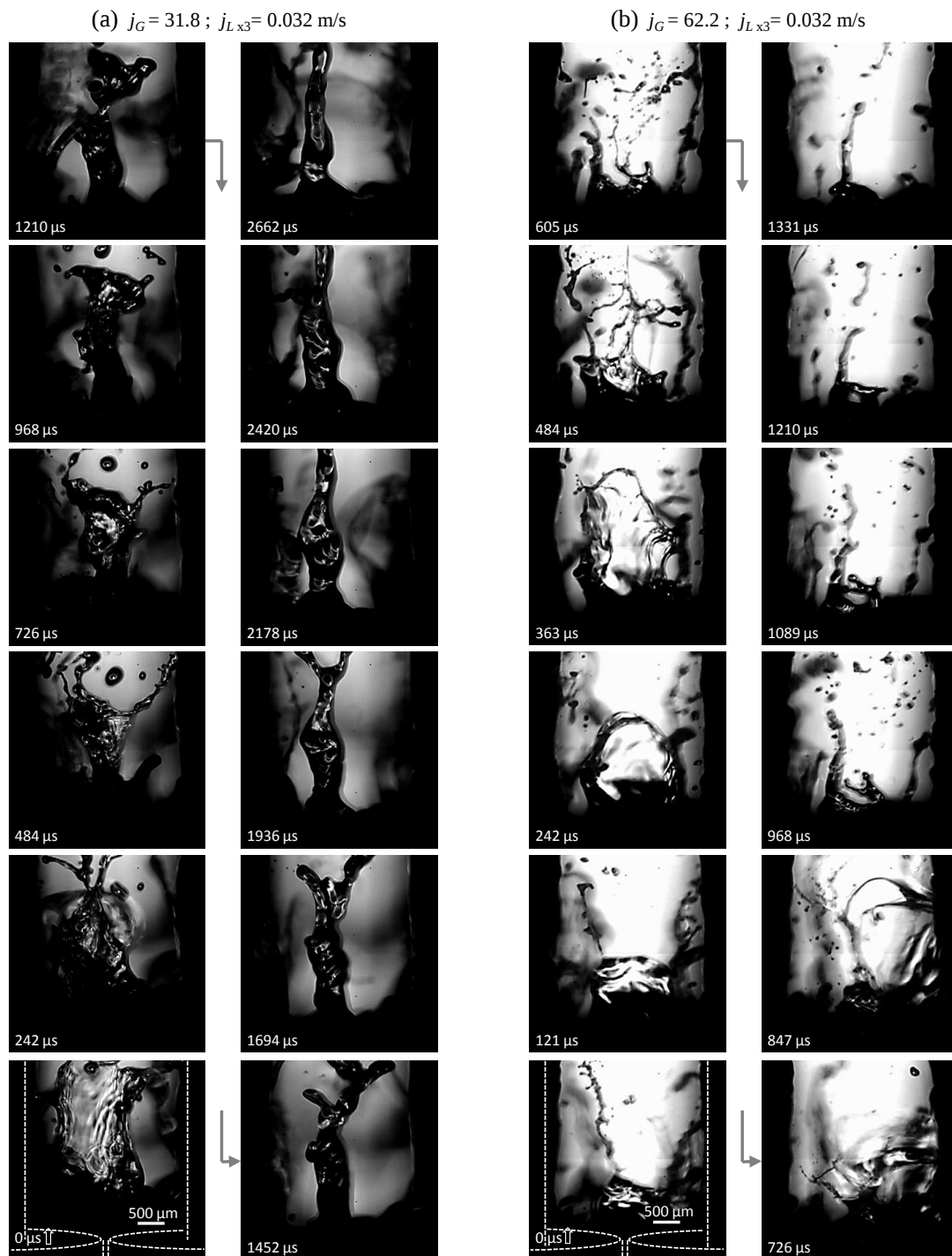


Figure 6-5 Generations of liquid droplets at the top of the spacer

6.3.3 Droplet behaviors

The typical behaviors of liquid droplets in the regions up- and downstreams of the spacer are also observed. Figure 6-6a shows a collision between a droplet and the spacer cell. Despite the small thickness of the spacer cell (500 μm), impacts like this are frequently found in the image data, during which splashing occurs and the primary droplet is broken into many tiny secondary ones. These small-size droplets even bounce back till the next two frames (at time = 78 μs) before being pushed up by the gas flow. This large number of small droplets can keep a role in the size distribution of the droplet at downstream of the spacer.

An interesting situation commonly observed at right downstream of the spacer is when a droplet keeps rotating at the same elevation or even falling down despite of the high gas superficial velocity flowing in the system. As seen in the Figure 6-6b, several droplets hold their axial position or fall down for a while before one of them undergoes the bag break-up process. This indicates that some flow areas in the spacer region are temporarily blocked due to the formation of liquid bridge. When these flow areas are opened again, the exposing of a zero-velocity droplet to a local high-velocity gas flow easily leads to a droplet break-up process.

Figure 6-6c also describes the case of a droplet falling down but after that it undergoes the ligament break-up process. It is well known that the type of break-up which the droplet will go through is determined by the local gas velocity and its size. Because the local gas velocity continuously changes with time, both mechanisms are expected to occur in this region. While the ligament break-up processes generate several droplets of smaller size compared to the original one, the bag break-up events can add a large number of tiny droplets into the gas core. Therefore, beside the collisions between upstream-droplet with the spacer-cell mentioned above, the bag break-up processes happening to the droplets are also responsible for the huge number of small-size droplets at further downstream of the spacer, as seen in Figure 5-3.

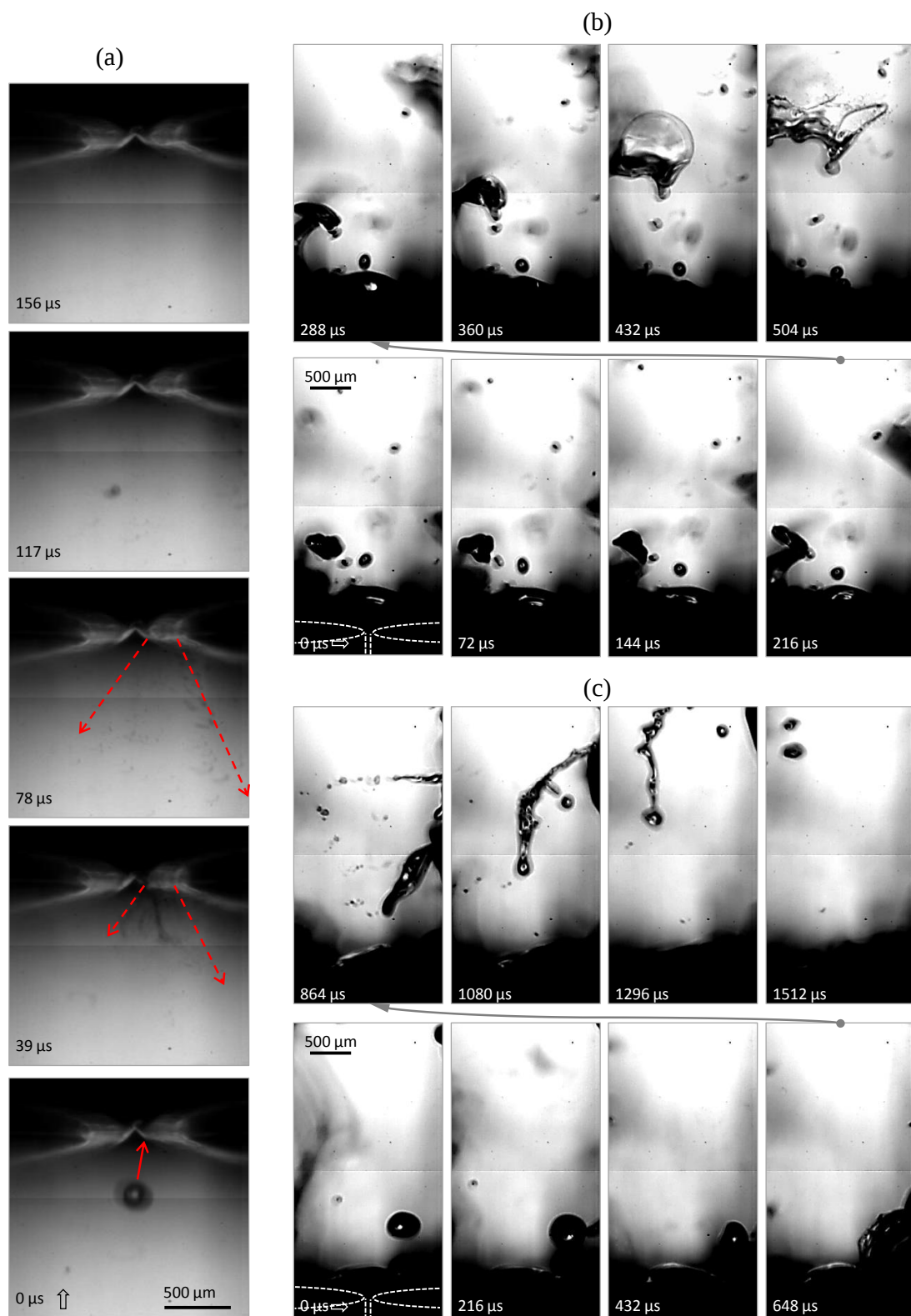


Figure 6-6 Droplet behaviors at regions located right up- and downstreams of spacer

6.4 Summary

The close-up visualization conducted near the spacer has successfully provided the detailed descriptions of the local phenomena. The interaction between the coming waves and the spacer cell is seen to be not strong enough to entrain some amount of liquid into the gas core as mentioned in the “narrow channel” effect. The obtained images of the generation of droplets and their behaviors right upstream of this structure explained well the mechanisms behind the size distribution obtained in Chapter 5.

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Chapter 7 Conclusion and Implementation

7.1 Conclusion

The high speed camera technique has been applied to study the annular two-phase flow on rod bundle with spacers. By keeping the base liquid film from flowing on the acrylic duct wall, the experimental arrangement has successfully provided not only the clear side-view observation of the phenomena but also the measurement at high temporal resolutions of both liquid film and droplets. The obtained qualitative data reflect the influences of the spacer on the two-phase flow.

7.1.1 Visualization of gas-liquid interface's behavior

The image data at micro-scale of time and space provided the real-time description of the gas-liquid interfaces' behaviors which improve the understanding of the following important processes:

- (1) The singlet disturbance-crests are formed near the inlet. A mechanism for this process based on the turbulent characteristic of the gas flow was proposed. This crest can return to the liquid film or undergo an entrainment processes to generate the first droplets in the system.
- (2) Entrainment phenomena include the bag break-up, ligament break-up, and droplet impingement mechanisms. The first two processes can happen at the singlet disturbance-crests as well as the disturbance waves. After the generation, the initial velocities of droplets are higher than the main wave structures. The droplet impingement can occur at the surface of any kind of wave and the amount of the liquid ejected in the form of secondary droplets may be significant.
- (3) The disturbance waves are accompanied by multiple entrainment processes. They are formed and developed on the way downstream due to the coherences of the formation of the singlet disturbance-crests.

7.1.2 Quantitative measurement of liquid film and droplets

The current work has presented a new experimental method which can evaluate the characteristics of both liquid film and droplets of the annular flow on rod-bundle geometry. This advantage allows a more comprehensive investigation of the phenomena which consist of the continuous interchange between the liquid film and droplets.

The obtained data for liquid film showed that the average liquid film thickness, wave amplitude and wave velocity measured at the corner rod is higher than those at the side rod. The influences of the spacer on the film thickness and wavy scale are different for low and high values of j_G due to the contribution of different phenomena occurring at this structure in each case. In high gas superficial velocity cases, the disturbance waves are broken when they pass by the spacer.

These characteristics are reflected in the data of liquid droplets. At upstream of the spacer, most of droplet are generated through the entrainment and therefore the droplet population and size distribution directly related to the magnitude of waves existing on the liquid films proportional to the scale of the waves on the liquid films. Spacer generates huge amount of small droplets. In the cases of low gas superficial velocities, several droplets of larger diameter compared to upstream ones are generated. At further downstream, the droplet spatial distribution possesses an interesting asymmetry which emphasizes the importance of the liquid entrainment cause by the droplets impinging on the large-amplitude waves existing at the corner rod.

7.1.3 Close-up investigation near spacer

The influences of the spacer were indicated by the quantitative data of the liquid film and droplets obtained at up and downstreams of this structure. To achieve a more comprehensive understanding which can help to explain the mechanisms behind these influences, a close-up investigation has been conducted. The clear side-view images have provided the detail description of the local phenomena. The interaction between the coming wave and the spacer cell is seen to be not strong enough to entrain an amount liquid to the gas core as mentioned in existing model even in the case of high

gas superficial velocity. The images of the generation of droplets and their behaviors in the regions also provide the mechanism behind the droplet size distribution with the large droplets and huge number of small-size ones.

7.1.4 Remark and future works

The next work would include the improvement in background reducing by setting-up two oval-shape obstacles onto the walls at both side of the test-section. Also, the fixing capacity of the test-section and the camera system needs to be enhanced to minimize the error caused by the relative movement between them and to allow the discussion on the minimum liquid film thickness.

The close-up visualization would be applied to study the influences of other designs of the spacer on the annular flow on rod bundle geometry. Moreover, the using of a heated rod-surface will also be considered in the next steps.

Due to the lack of ability to obtain the circumferential information of the flow, the combination between the current measurement method and other techniques such as conductance probe or ultrasound transducer is highly expected.

7.2 Implementation to two-phase flow models

From the obtained visualization information as well as the quantitative results of the measurement of both liquid film thickness and droplets, the following points are expected to be considered in the work of two-phase flow simulations:

- The entrainment phenomena (bag, ligament break-up, and droplet impingement) might not be modeled based on force analysis only. Instead, the parameters such as wave shape and droplet population should be taken into account.
- The subchannel analysis needs to consider the gap between two rods to take the influences of the spacer into account.
- The “wall effect” needs to consider not only the average liquid film thickness but also the differences in the wavy characteristics between the rods.

- The enhancement of the liquid entrainment at region just upstream of the spacer in the “narrow channel” effects seems to not occur. Instead, the large amount of liquid from the film will be redistributed on the spacer surface.
- In the case of high droplet density, the droplet impingement mechanism does keep an important role in the liquid entrainment phenomena and so the droplet distribution in the rod bundle geometry.