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<td>Supplement to Kinetic Theory and Fluid Dynamics - Yoshio Sone (Birkhäuser, Boston, 2002)</td>
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Supplement to
Kinetic Theory and Fluid Dynamics
Yoshio Sone
(Birkhäuser, Boston, 2002)

Yoshio Sone

Version 5-00 (10 December 2010)

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Bibliography

Update of bibliography

• [161] Sone, Y., M. Handa, and H. Sugimoto [2002]:
  (to be published) → 299–332
• p. 151, the eighth line from the bottom:
  Sone, Handa & Doi [unpublished] → Sone, Handa & Doi [2003]
  The following reference is to be added to Bibliography:
  Sone, Y., M. Handa, and T. Doi (2003), Ghost effect and bifurcation in a gas
  between coaxial circular cylinder with different temperatures, Phys. Fluids 15,
  2903–2915.
• p. 159, the sixth line
  Sone & Doi [unpublished] → Sone & Doi [2003]
  The following reference is to be added to Bibliography:
  Sone, Y. and T. Doi (2003), Bifurcation of and ghost effect on temperature
  field in the Bénard problem of a gas in the continuum limit, Phys. Fluids 15,
  1405–1423.

Errata

• p. 11, the 10th line
• p. 33, the first line in Eq. (3.31c):
\[
\frac{\partial S_{ijG0}}{\partial x_i} \rightarrow \frac{\partial S_{ijG0}}{\partial x_j}
\]
• p. 33, the first line in Eq. (3.31d):
\[
\frac{\partial S_{ijG1}}{\partial x_i} \rightarrow \frac{\partial S_{ijG1}}{\partial x_j}
\]
• p. 36, Footnote 7:
Footnote 7 should be replaced by the following statement:
In some cases, the boundary data \(u_{wi}, \tau_w, \) or \(\omega \) (thus, \(P_w \)) are unknown beforehand and may depend on the Knudsen number, for example, the surface temperature of a particle set freely in a gas. To include the case, the data \(u_{wi}, \tau_w, \omega \), and \(P_w \) also are expanded in power series of \(k \) in the following discussion. Even when they are independent of \(k \), the \(\phi_w \) generally depends on \( \phi (\zeta_i n_i < 0) \).
• p. 104, the second line in Footnote 18:
only \( \Omega \) and \( \Theta \) \(\rightarrow\) \((\Omega_8, \Theta_8), (\Omega_9, \Theta_9), \) and \((\Omega_{10}, \Theta_{10})\)
• p. 146, the fifth line:
\[
\hat{Y}_1(\tilde{\eta}) = Y_1(\tilde{\eta}) \rightarrow \hat{Y}_1(\tilde{\eta}) = Y_1(\tilde{\eta})
\]
• p. 177, Eq. (6.53):
The following note should be made to Eq. (6.53):
Equation (6.54), which is derived from Eqs. (6.50), (6.52), and \( \hat{v}_{wi} n_i = 0 \), is used in the derivation of Eq. (6.53) from the solvability condition. See the second paragraph in page 130 of Y. Sone, Molecular Gas Dynamics (Birkhäuser, Boston, 2007).
To improve the indefinite expression, the third paragraph on p. 177, which starts from its 9th line from the bottom and ends at the second line on p. 178, should be replaced by the following paragraph:\footnote{In the new paragraph, the numbering (6.54) comes earlier than (6.53) to avoid the correction of the quotations in the rest of the book.}
Now return to the discussion of \( \hat{f}_{V,m} \). The first relation of the solvability condition (6.48) with \( m = 1 \), where
\[
Ih_1 = \zeta_i n_i (\partial \hat{f}_{V0} / \partial y), \quad (6.51)
\]
reduces to
\[
\frac{\partial (\hat{\rho}_{V0} \hat{v}_{1V0} n_i)}{\partial y} = 0, \quad (6.52)
\]
from which with the aid of Eqs. (6.50) and \( \hat{v}_{wi} n_i = 0 \), we have
\[
\hat{v}_{1V0} n_i = 0. \quad (6.54)
\]
With the use of Eq. (6.54), the scalar product of the second relation of Eq. (6.48) and \( n_{1} \) reduces to

\[
\frac{\partial \hat{p}_{V0}}{\partial y} = 0. \tag{6.53}
\]

Thus, \( \hat{p}_{V0} \) is a function of \( \chi_{1} \) and \( \chi_{2} \) only, i.e.,

\[
\hat{p}_{V0} = \hat{p}_{V0}(\chi_{1}, \chi_{2}). \tag{6.55}
\]

The remaining three relations [or the remaining two of the second relation of Eq. (6.48) and its third relation] reduce to identities with the aid of Eq. (6.54).

- p.215, the third line in Footnote 6:
  \( M_{n} \rightarrow -M_{n} \)
- p. 220, the fifth line:
  \( F_{s} \rightarrow -M_{n}F_{s} \)
  \( F_{b} \rightarrow -M_{n}F_{b} \)

**Supplementary Notes**

In the present supplementary notes, the letter K is attached to the labels of equations and sections, etc. in the book *Kinetic Theory and Fluid Dynamics*, the letter M is attached to those in Y. Sone, *Molecular Gas Dynamics* (Birkhäuser, Boston, 2007), and the letter MS is attached to those in Y. Sone [2010] (Supplement to *Molecular Gas Dynamics*) to avoid confusion. The two books, *Kinetic Theory and Fluid Dynamics* and *Molecular Gas Dynamics*, and the supplement (Sone [2010]) themselves are, respectively, referred to as KF, MGD, and MS.²

1 Chapter K-2

1.1 Background of the Boltzmann equation (Sections K-2.1 and K-2.2)

The situation of a monatomic gas the description of which is the purpose of the Boltzmann equation is explained in more detail in the last half [the paragraphs after Eq. (MS-23)] of Section MS-1.5.2 (Version 9-00). This will serve as the supplement to Sections K-2.1 and K-2.2, though it is prepared for the discussion of the parameters in the nondimensional Boltzmann equation.

²Labels in MS depend on its version.
1.2 Bulk viscosity

The assumptions (K-2.14) and (K-2.15) for the stress tensor and heat-flow vector in classical gas dynamics are what is to be studied by kinetic theory (see KF). For a monatomic gas, consisting of identical molecules whose intermolecular potential is spherically symmetric, which is discussed in KF, the bulk viscosity is easily seen to vanish. From Eqs. (K-2.2d) and (K-2.2f),

\[ p_{ii} = 3p. \]  

(1)

On the other hand, the trace of the first relation of Eq. (K-2.15) is

\[ p_{ii} = 3p - 3\mu B \frac{\partial v_i}{\partial X_i}. \]

Thus, from the two relations, we have

\[ \mu B = 0. \]  

(2)

(Section 1.2: Version 3-00)

1.3 Nondimensional form of the Boltzmann equation for an infinite-range potential (Sections K-2.9)

As mentioned in Footnote K-10 in Section K-2.9, \( B_0 \) in Eq. (K-2.41d) is infinite for an intermolecular potential extending up to infinity. Therefore, the nondimensional formulas for the collision term there are useless for an infinite-range potential and so is the Boltzmann equation (K-2.40a) in nondimensional form. The nondimensional form of the Boltzmann equation for an infinite-range potential is derived in a natural way in Section MS-1.4 (Version 9-00) of the Supplement to MGD (Sone [2010]).

In this relation, it is better to make the dependence of \( U_0 \) (on the 2nd line of Footnote K-11 in Section K-2.9) on \( m \) explicit. That is,

\[ U_0 \rightarrow m\bar{U}_0, \]

(Section 1.2: Version 3-00)

3For molecules with internal degree of freedom (e.g., rotational and vibrational freedoms), this freedom contributes to the integrands of Eqs. (K-2.2c)-(K-2.2g). Thus, Eq. (1) does not generally hold. (More precisely, the velocity distribution function \( f \) depends also on the variables of the internal degree of freedom of a molecule. The integration with respect to these variables in Eqs. (K-2.2a)-(K-2.2g) has to be carried out. The angular momentum due to the rotation of molecules of infinitesimal size per unit mass is negligible even when the energy of rotation is not negligible.) The density \( \rho \) and the specific internal energy \( e \) can be clearly defined whether the gas is in an equilibrium state or not. The specific internal energy \( e/f \) per unit freedom of a molecule is taken as \( RT/2 \), i.e., \( e = i_f RT/2 \), where \( i_f \) is the degree of freedom of a molecule; thus, the relation between \( e \) and \( T \) is independent of the state of the gas (equilibrium or nonequilibrium). The pressure is defined by the equation of state, i.e., the perfect gas relation \( p = \rho RT \); thus, except for a monatomic gas without internal degree of freedom, the pressure differs generally from the isotropic part of stress tensor in a nonequilibrium state.

4What is called the Boltzmann equation for an infinite-range potential (see Footnote K-10 in Section K-2.5) is conventional one in the sense explained in (ii) of Footnote MS-19.
where $U_0$ has the dimension of $RT_0$. Correspondingly, $U_0/k_B T_0$ on the 3rd line of Footnote K-11 in Section K-2.9 should be replaced by $U_0/RT_0$ [see item (iii) of Footnote MS-19 (Version 9-00)]. Incidentally, some notes are added to Footnote K-11 in Section K-2.9 here: $U$ is better to be replaced by $\bar{U}$, which is used in Section M-A.2.4; only the value 1 is allowed as $m$ of $a^m$ on the 2nd line from below for the function $B$ [compare the 2nd and 3rd lines in Eq. (K-2.41d); see Section M-A.2.4 for $B(|\alpha \cdot (\xi_\ast - \xi)|/|\xi_\ast - \xi|, |\xi_\ast - \xi|)$].

(Section 1.3: Version 5-00)

2 Chapter K-3

2.1 Video files for experiments

2.1.1 Thermal creep flow

The video file of the simple experiment (K-Sone [1991b]) demonstrating thermal creep flow in Section K-3.11.1 can be downloaded from Sone [1991] at Kyoto University Research Information Repository.

(Section 2.1.1: Version 5-00)

2.1.2 Thermal edge flow

The video files of the simple experiment demonstrating thermal edge flow in Section K-3.11.4 (K-Sone & Yoshimoto [1997]) can be downloaded from Sone & Yoshimoto [1997] at Kyoto University Research Information Repository.

(Section 2.1.2: Version 5-00)

3 Chapter K-4

3.1 Notes on basic equations in classical fluid dynamics

3.1.1 Euler and Navier–Stokes sets

For the convenience of discussions, the basic equations in the classical fluid dynamics are summarized here.

The mass, momentum, and energy-conservation equations of fluid flow are given by

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial X_i} (\rho v_i) = 0, \quad (3)$$

$$\frac{\partial}{\partial t} (\rho v_i) + \frac{\partial}{\partial X_j} (\rho v_i v_j + p_{ij}) = 0, \quad (4)$$

$$\frac{\partial}{\partial t} \left[ \rho \left( e + \frac{1}{2} v_i^2 \right) \right] + \frac{\partial}{\partial X_j} \left[ \rho v_j \left( e + \frac{1}{2} v_i^2 \right) + v_i p_{ij} + q_j \right] = 0, \quad (5)$$

where $\rho$ is the density, $v_i$ is the flow velocity, $e$ is the internal energy per unit mass, $p_{ij}$, which is symmetric with respect to $i$ and $j$, is the stress tensor, and $q_i$
is the heat-flow vector. The pressure $p$ and the internal energy $e$ are given by the equations of state as functions of $T$ and $\rho$, i.e.,

$$p = p(T, \rho), \quad e = e(T, \rho). \quad (6)$$

Especially, for a perfect gas,

$$p = R\rho T, \quad e = e(T). \quad (7)$$

Equations (4) and (5) are rewritten with the aid of Eq. (3) in the form

$$\rho \frac{\partial v_i}{\partial t} + \rho v_j \frac{\partial v_i}{\partial X_j} + \frac{\partial p_{ij}}{\partial X_j} = 0, \quad (8)$$

$$\rho \frac{\partial}{\partial t} \left( e + \frac{1}{2} v_i^2 \right) + \rho v_j \frac{\partial}{\partial X_j} \left( e + \frac{1}{2} v_i^2 \right) + \frac{\partial}{\partial X_j} (\nu p_{ij} + q_j) = 0. \quad (9)$$

The operator $\partial/\partial t + v_j \partial/\partial x_j$, which expresses the time variation along the fluid particle, is denoted by $D/Dt$, i.e.,

$$\frac{D}{Dt} \equiv \frac{\partial}{\partial t} + v_j \frac{\partial}{\partial X_j}. \quad (10)$$

Multiplying Eq. (8) by $v_i$ we obtain the equation for the variation of kinetic energy as

$$\rho \frac{D}{Dt} \left( \frac{1}{2} v_i^2 \right) = -v_i \frac{\partial p_{ij}}{\partial X_j}. \quad (10)$$

Another form of Eq. (5), where Eq. (10) is subtracted from Eq. (9), is given as

$$\rho \frac{D e}{Dt} = -p_{ij} \frac{\partial v_i}{\partial X_j} - \frac{\partial q_j}{\partial X_j}. \quad (11)$$

Noting the thermodynamic relation

$$\frac{De}{Dt} = T \frac{Ds}{Dt} + \rho \frac{Dp}{Dt} \rho^2 \frac{Dt}{Dt}, \quad (12)$$

where $s$ is the entropy per unit mass, and Eq. (3), Eq. (11) is rewritten as

$$\rho \frac{Ds}{Dt} = -\frac{1}{T} \left[ (p_{ij} - p\delta_{ij}) \frac{\partial v_i}{\partial X_j} + \frac{\partial q_j}{\partial X_j} \right]. \quad (13)$$

Equation (13) expresses the variation of the entropy of a fluid particle.

Equations (3)–(6) contain more variables than the number of equations. Thus, in the classical fluid dynamics, the stress tensor $p_{ij}$ and the heat-flow vector $q_i$ are assumed in some ways. The Navier–Stokes set of equations (or the Navier–Stokes equations) is Eqs. (3)–(6) where $p_{ij}$ and $q_i$ are given by

$$p_{ij} = p\delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - \frac{2}{3} \frac{\partial \nu_k}{\partial X_k} \delta_{ij} \right) - \mu B \frac{\partial v_k}{\partial X_k} \delta_{ij}, \quad (14)$$

$$q_i = -\lambda \frac{\partial T}{\partial X_i}, \quad (15)$$
where $\mu$, $\mu_B$, and $\lambda$ are, respectively, called the viscosity, bulk viscosity, and thermal conductivity of the fluid. They are functions of $T$ and $\rho$. The *Euler set of equations* (or the *Euler equations*) is Eqs. (3)--(6) where $p_{ij}$ and $q_i$ are given by

$$p_{ij} = p\delta_{ij}, \quad q_i = 0,$$

or the Navier–Stokes equations with $\mu = \mu_B = \lambda = 0$.

For the Navier–Stokes equations, in view of the relations (14) and (15), the entropy variation is expressed in the form\(^5\)

$$\frac{D S}{D t} = \frac{1}{T} \left[ \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right)^2 + \mu_B \left( \frac{\partial v_k}{\partial X_k} \right)^2 + \frac{\partial}{\partial X_i} \left( \lambda \frac{\partial T}{\partial X_i} \right) \right].$$

(17)

For the Euler equations, for which $p_{ij}$ and $q_i$ are given by Eq. (16), the entropy of a fluid particle is invariant, i.e.,

$$\frac{D S}{D t} = 0.$$

(18)

For an *incompressible fluid*, the first relation of Eq. (6) is replaced by\(^6\)

$$\frac{D \rho}{D t} = 0 \quad \text{or} \quad \frac{\partial \rho}{\partial t} + v_j \frac{\partial \rho}{\partial X_j} = 0.$$  

(19)

Thus, from Eqs. (3) and (19),

$$\frac{\partial v_i}{\partial X_i} = 0.$$

(20)

Equation (14) for the Navier–Stokes-stress tensor reduces to

$$p_{ij} = p\delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right).$$

(21)

The first term on the right-hand side of Eq. (11) reduces to

$$-p_{ij} \frac{\partial v_i}{\partial X_j} = - \left[ p\delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right) \right] \frac{\partial v_i}{\partial X_j}$$

$$= \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2.$$ 

Note the following transformation:

$$\frac{\partial v_i}{\partial X_j} = \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij}$$

$$= \frac{1}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right) \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right)$$

$$= \frac{1}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right)^2 + \frac{1}{3} \frac{\partial v_l}{\partial X_l} \delta_{ij} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - 2 \frac{\partial v_k}{\partial X_k} \delta_{ij} \right).$$

The second term in the last expression is easily seen to vanish.

The density is invariant along fluid-particle paths. If $\rho$ is of uniform value $\rho_0$ initially, it is a constant, i.e.,

$$\rho = \rho_0.$$  

In a time-independent (or steady) problem, the density is constant along streamlines.
Thus, Eq. (11) reduces to

\[ \rho \frac{D e}{D t} = \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \lambda \frac{\partial T}{\partial X_j} \right). \]  

(22)

To summarize, the Navier–Stokes equations for incompressible fluid are

\[ \frac{\partial v_i}{\partial X_i} = 0, \]  

(23a)

\[ \rho \frac{\partial v_i}{\partial t} + \rho v_j \frac{\partial v_i}{\partial X_j} = - \frac{1}{\rho} \frac{\partial p}{\partial X_i} + \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \lambda \frac{\partial T}{\partial X_j} \right), \]  

(23b)

\[ \rho \frac{\partial e}{\partial t} + \rho v_j \frac{\partial e}{\partial X_j} = \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \lambda \frac{\partial T}{\partial X_j} \right), \]  

(23c)

with the incompressible condition (19) being supplemented, i.e.,

\[ \frac{\partial \rho}{\partial t} + v_j \frac{\partial \rho}{\partial X_j} = 0. \]  

(24)

### 3.1.2 Boundary condition for the Euler set

In Chapter K-7, we discussed the asymptotic behavior for small Knudsen numbers of a gas around its condensed phase where evaporation or condensation with a finite Mach number is taking place, and derived the Euler equations and their boundary conditions that describe the overall behavior of the gas in the limit that the Knudsen number tends to zero. The number of boundary conditions on the evaporating condensed phase is different from that on the condensing one. We will try to understand the structure of the Euler equations giving the non-symmetric feature of the boundary conditions by a simple but nontrivial case.

Consider, as a simple case, the two-dimensional boundary-value problem of the time-independent Euler equations in a bounded domain for an incompressible ideal fluid of uniform density. The mass and momentum-conservation equations of the Euler set are

\[ \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \]  

(25)

\[ u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = - \frac{1}{\rho} \frac{\partial p}{\partial x}, \]  

(26)

\[ u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = - \frac{1}{\rho} \frac{\partial p}{\partial y}, \]  

(27)

where \( \rho \) is the density, which is uniform, \((u, v)\) is the flow velocity, and \( p \) is the pressure. Owing to Eq. (25), the stream function \( \Psi \) can be introduced as

\[ u = \frac{\partial \Psi}{\partial y}, \quad v = - \frac{\partial \Psi}{\partial x}. \]  

(28)
Eliminating $p$ from Eqs. (26) and (27), we have\footnote{The following equation is formed from them: \[ \partial_x \text{Eq. (26)} - \partial_y \text{Eq. (27)} = 0. \]}
\begin{equation}
\frac{u}{\partial x} \frac{\partial \Omega}{\partial x} + \frac{v}{\partial y} \frac{\partial \Omega}{\partial y} = 0,
\end{equation}
where $\Omega$ is the vorticity, i.e.,
\begin{equation}
\Omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2}.
\end{equation}
From Eqs. (28) and (29),
\begin{equation}
\frac{\partial \Psi}{\partial y} \frac{\partial \Omega}{\partial x} - \frac{\partial \Psi}{\partial x} \frac{\partial \Omega}{\partial y} = 0.
\end{equation}
This equation shows that $\Omega$ is a function of $\Psi$, i.e.,
\begin{equation}
\Omega = F(\Psi).
\end{equation}
This can be seen with the aid of theorems on implicit functions (see Bronshtein & Semendyaye \cite{1997}, Buck \cite{1965}, Takagi \cite{1961}):\footnote{This can be seen with the aid of theorems on implicit functions (see Bronshtein & Semendyaye \cite{1997}, Buck \cite{1965}, Takagi \cite{1961}):}
\begin{equation}
\Omega(x, y), \quad \Psi = \Psi(x, y).
\end{equation}
Solving the second equation with respect to $x$, we have
\begin{equation}
x = \hat{x}(\Psi, y).
\end{equation}
With this relation into Eq. (\star),
\begin{equation}
\Omega = \Omega(\hat{x}(\Psi, y), y) = \hat{\Omega}(\Psi, y),
\end{equation}
\begin{equation}
\Psi = \Psi(\hat{x}(\Psi, y), y) = \hat{\Psi}(\Psi, y).
\end{equation}
That is, $\Omega$ is expressed as a function of $\Psi$ and $y$. From Eqs. (2a) and (2b),
\begin{equation}
\frac{\partial \hat{\Omega}(\Psi, y)}{\partial y} = \frac{\partial \hat{\Omega}(\hat{x}(\Psi, y), y)}{\partial y} = \frac{\partial \hat{\Omega}(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \hat{\Omega}(x, y)}{\partial y},
\end{equation}
\begin{equation}
\frac{\partial \hat{\Psi}(\Psi, y)}{\partial y} = 0.
\end{equation}
On the other hand,
\begin{equation}
\frac{\partial \hat{\Psi}(\Psi, y)}{\partial y} = \frac{\partial \hat{\Psi}(\hat{x}(\Psi, y), y)}{\partial y} = \frac{\partial \hat{\Psi}(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \hat{\Psi}(x, y)}{\partial y}.
\end{equation}
Thus,
\begin{equation}
\frac{\partial \hat{\Psi}(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \hat{\Psi}(x, y)}{\partial y} = 0.
\end{equation}
From Eqs. (31), (\S2a) and (\dagger), we have
\begin{equation}
\frac{\partial \hat{\Omega}(\Psi, y)}{\partial y} = 0, \text{ or } \Omega = \hat{\Omega}(\Psi).
\end{equation}
This functional relation between $\Omega$ and $\Psi$ is a local relation, and therefore $F$ may be a multivalued function of $\Psi$. From Eqs. (30) and (32),

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = F(\Psi). \quad (33)$$

Consider a boundary-value problem in a simply-connected bounded domain, where $\Psi$ is given on the boundary ($\Psi = \Psi_B$). Introduce a coordinate $s$ ($0 \leq s < S$) along the boundary in the direction encircling the domain counterclockwise. Then, the fluid flows into the domain on the boundary where $\partial \Psi_B / \partial s < 0$, and the fluid flows out from the domain on the boundary where $\partial \Psi_B / \partial s > 0$. When $F$ is given, the problem is a standard boundary-value problem. In the present problem, we have a freedom to choose $F$ on the part where $\partial \Psi_B / \partial s < 0$ or $\partial \Psi_B / \partial s > 0$. For example, take the case where $\partial \Psi_B / \partial s < 0$ for $0 < s < S_m$ and $\partial \Psi_B / \partial s > 0$ for $S_m < s < S$, and choose the distribution $\Omega_B(s)$ of $\Omega$ along the boundary for the part $0 < s < S_m$. By the choice of $\Omega_B$, the function $F(\Psi)$ is determined in the following way. Inverting the relation $\Psi = \Psi_B(s)$ between $\Psi$ and $s$ on the part $0 < s < S_m$, i.e., $s(\Psi)$, and noting the relation (32), we find that $F$ is given by

$$F(\Psi) = \Omega_B(s(\Psi)). \quad (34)$$

Then, the boundary-value problem is fixed. That is, Eq. (33) is fixed as

$$\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = \Omega_B(s(\Psi)), \quad (35)$$

and the boundary condition is given as $\Psi = \Psi_B(s)$. This system is a standard from the point of counting of the number of boundary conditions. Obviously, from Eq. (30), the solution of the above system automatically satisfies condition $\Omega = \Omega_B(s)$ along the boundary for $0 < s < S_m$. We cannot choose the distribution of $\Omega$ on the boundary for $S_m < s < S$.

The energy-conservation equation of the incompressible Euler set is given by Eq. (22) with $\mu = \lambda = 0$, i.e.,

$$u \frac{\partial e}{\partial x} + v \frac{\partial e}{\partial y} = 0, \quad \text{or} \quad \frac{\partial \Psi}{\partial y} \frac{\partial e}{\partial x} - \frac{\partial \Psi}{\partial x} \frac{\partial e}{\partial y} = 0, \quad (36)$$

where $e$ is the internal energy. Thus, $e$ is a function of $\Psi$, i.e.,

$$e = F_1(\Psi). \quad (37)$$

In the above boundary-value problem, therefore, $e$ can be specified on the the part $(0 < s < S_m)$ of the boundary, but no condition can be specified on other part $(S_m < s < S)$ and vice versa.\(^{10}\)

\(^{9}\)There is still some ambiguity. The case where there is a region with closed stream lines $\Psi(x, y) = \text{const inside the domain is not excluded.}

\(^{10}\)From the second relation on $e$ of Eq. (6) and the uniform-density condition, the condition on $e$ can be replaced by the condition on the temperature $T$. 

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To summarize, we can specify three conditions for $\Psi$, $\Omega$, and $e$ on the part $\partial\Psi_B/\partial s < 0$ ($\partial\Psi_B/\partial s > 0$) of boundary but one condition for $\Psi$ on the other part $\partial\Psi_B/\partial s > 0$ ($\partial\Psi_B/\partial s < 0$). The number of the boundary conditions is not symmetric and consistent with that derived by the asymptotic theory.

3.1.3 Equations derived from the compressible Navier–Stokes set when the Mach number and the temperature variation are small

It is widely said that the set of equations derived from the compressible Navier–Stokes set when the Mach number and the temperature variation are small is the incompressible Navier–Stokes set. This statement should be made precise. The difference is briefly explained in the book “Kinetic Theory and Fluid Dynamics” in connection with the equations derived by the $S$ expansion from the Boltzmann equation in Section K-4.3. Here, we explicitly show the process of analysis from the compressible Navier–Stokes set. In Section K-4.3, the time-independent case is discussed. Here, we discuss the problem without this restriction. The following discussion is applied to the former case simply by eliminating the time-derivative terms.

Take a monatomic perfect gas, for which the internal energy per unit mass is $3RT/2$. The corresponding Navier–Stokes set of equations is written in the nondimensional variables introduced by Eq. (K-2.57) in Section K-2.10 as follows:

\begin{align}
    \text{Sh} \frac{\partial \omega}{\partial t} + \frac{\partial (1 + \omega) u_i}{\partial x_i} &= 0, \quad (38),
    \\
    \text{Sh} \frac{\partial (1 + \omega) u_i}{\partial t} + \frac{\partial}{\partial x_j} \left( (1 + \omega) u_i u_j + \frac{1}{2} P_{ij} \right) &= 0, \quad (39),
    \\
    \text{Sh} \frac{\partial}{\partial t} \left[ (1 + \omega) \left( \frac{3}{2} (1 + \tau) + u_i^2 \right) \right] + \frac{\partial}{\partial x_j} \left[ (1 + \omega) u_j \left( \frac{3}{2} (1 + \tau) + u_i^2 \right) + u_i (\delta_{ij} + P_{ij}) + Q_j \right] &= 0. \quad (40).
\end{align}

The nondimensional stress tensor $P_{ij}$, and heat-flow vector $Q_i$ are expressed as

\begin{align}
    P_{ij} &= P \delta_{ij} - \frac{\mu_0 (2RT_0)^{1/2}}{p_0 L} (1 + \bar{\mu}) \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right), \quad (41a),
    \\
    Q_i &= - \frac{\lambda_0 T_0}{L p_0 (2RT_0)^{1/2}} (1 + \bar{\lambda}) \frac{\partial \tau}{\partial x_i}. \quad (41b)
\end{align}

Here, $\bar{\mu}$ and $\bar{\lambda}$ are, respectively, the nondimensional perturbed viscosity and thermal conductivity defined by

$$
    \mu = \mu_0 (1 + \bar{\mu}), \quad \lambda = \lambda_0 (1 + \bar{\lambda}),
$$

\footnote{For a monatomic gas, the bulk viscosity vanishes, i.e., $\mu_B = 0$ (see Section 1.2).}
where $\mu_0$ and $\lambda_0$ are, respectively, the values of the viscosity $\mu$ and the thermal conductivity $\lambda$ at the reference state. The $\bar{\mu}$ and $\bar{\lambda}$ are functions of $\tau$ and $\omega$. The first relation of the equation of state [Eq. (7)] is expressed as

$$P = \omega + \tau + \omega \tau. \quad (42)$$

Take a small parameter $\varepsilon$, and consider the case where

$$u_i = O(\varepsilon), \quad \omega = O(\varepsilon), \quad \tau = O(\varepsilon), \quad \text{Sh} = O(\varepsilon), \quad (43a)$$

$$\frac{\mu_0(2RT_0)^{1/2}}{p_0L} = \gamma_1\varepsilon, \quad \frac{\lambda_0T_0}{LP_0(2RT_0)^{1/2}} = \frac{5}{4}\gamma_2\varepsilon, \quad (43b)$$

thus,

$$P = O(\varepsilon), \quad \bar{\mu} = O(\varepsilon), \quad \bar{\lambda} = O(\varepsilon).$$

According to the definition of $u_i$ in Eq. (K-2.57), $\varepsilon$ is of the order of the Mach number. In view of this and the definition of the Prandtl number $Pr = 5R\mu/2\lambda$ (see Section K-3.9), $\gamma_1$ and $\gamma_2$ are, respectively, of the orders of $1/\text{Re}$ and $1/\text{PrRe}$ ($\text{Re}$: the Reynolds number). According to Eq. (K-2.41a), the condition $\text{Sh} = O(\varepsilon)$ in Eq. (43a) means that the time scale $t_0$ of the variation of variables is of the order of $L/(2RT_0)^{1/2}\varepsilon$, which is of the order of time scale of viscous diffusion. Thus, we are considering the case where the Mach number is small, the Reynolds and Prandtl numbers are of the order of unity, and the time scale of variation of the system is of the order of the time scale of viscous diffusion. We can take $t_0 = L/(2RT_0)^{1/2}\varepsilon$ without loss of generality. Then,

$$\text{Sh} = \varepsilon. \quad (44)$$

Corresponding to the above situation, $u_i$, $\omega$, $P$, and $\tau$ are expanded in power series of $\varepsilon$, i.e.,

$$u_i = u_{i1}\varepsilon + u_{i2}\varepsilon^2 + \cdots, \quad (45a)$$

$$\omega = \omega_1\varepsilon + \omega_2\varepsilon^2 + \cdots, \quad (45b)$$

$$P = P_{11}\varepsilon + P_{21}\varepsilon^2 + \cdots, \quad (45c)$$

$$\tau = \tau_1\varepsilon + \tau_2\varepsilon^2 + \cdots, \quad (45d)$$

$$\bar{\mu} = \bar{\mu}_1\varepsilon + \bar{\mu}_2\varepsilon^2 + \cdots, \quad (45e)$$

$$\bar{\lambda} = \bar{\lambda}_1\varepsilon + \bar{\lambda}_2\varepsilon^2 + \cdots, \quad (45f)$$

$$P_{ij} = P_{ij1}\varepsilon + P_{ij2}\varepsilon^2 + \cdots, \quad (45g)$$

$$Q_i = Q_{i1}\varepsilon^2 + \cdots. \quad (45h)$$

Substituting Eqs. (45a)-(45h) with Eqs. (43b) and (44) into Eqs. (38)-(40) with Eqs. (41a) and (41b), and arranging the same order terms of $\varepsilon$, we have

$$\frac{\partial u_{i1}}{\partial x_i} = 0, \quad \frac{\partial P_{11}}{\partial x_i} = 0, \quad \frac{\partial u_{i2}}{\partial x_i} = 0,$$
\[
\frac{\partial \omega_1}{\partial t} + \frac{\partial \omega_1 u_{1i}}{\partial x_i} + \frac{\partial u_{i2}}{\partial x_i} = 0, \\
\frac{\partial u_{i1}}{\partial t} + \frac{\partial u_{1i} u_{j1}}{\partial x_j} + \frac{1}{2} \frac{\partial P_2}{\partial x_i} - \gamma_1 \frac{\partial}{\partial x_j} \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} - \frac{2}{3} \frac{\partial u_{i1}}{\partial x_k} \delta_{ij} \right) = 0, \\
3 \frac{\partial P_1}{\partial t} + \frac{\partial}{\partial x_j} \left( \frac{5}{2} u_{j2} + \frac{5}{2} P_1 u_{j1} - \frac{5}{4} \gamma \frac{\partial \tau_1}{\partial x_j} \right) = 0,
\]
and so on. At the leading order, the equations derived from Eqs. (38) and (40) degenerate into the same equation \( \frac{\partial u_{i1}}{\partial x_i} = 0 \). Owing to this degeneracy, in order to solve the variables from the lowest order successively, the equations should be rearranged by combination of equations of staggered orders. Thus, we rearrange the equations as follows:

\[
\frac{\partial P_1}{\partial x_i} = 0, 
\]

(46)

\[
\frac{\partial u_{i1}}{\partial x_i} = 0, 
\]

(47a)

\[
\frac{\partial u_{i1}}{\partial t} + \frac{u_{j1} \partial u_{i1}}{\partial x_j} = - \frac{1}{2} \frac{\partial P_2}{\partial x_i} + \gamma \frac{\partial^2 u_{i1}}{\partial x_i}, 
\]

(47b)

\[
5 \frac{\partial \tau_1}{\partial t} - \frac{\partial P_1}{\partial x_i} + 5 \frac{\partial \tau_1}{\partial x_i} = 5 \frac{\partial^2 \tau_1}{\partial x_i}, 
\]

(47c)

\[
\frac{\partial u_{i2}}{\partial x_i} = \frac{\partial \omega_1}{\partial t} - \frac{\partial \omega_1 u_{i1}}{\partial x_i}, 
\]

(48a)

\[
\frac{\partial u_{i2}}{\partial t} + \frac{\partial u_{i1}}{\partial x_j} \frac{\partial u_{i2}}{\partial x_j} + \frac{u_{j1}}{2} \frac{\partial u_{i1}}{\partial x_j} \frac{\partial u_{i2}}{\partial x_j} \\
= - \frac{1}{2} \left( \frac{\partial P_3}{\partial x_i} - \omega_1 \frac{\partial P_2}{\partial x_j} \right) + \gamma_1 \frac{\partial}{\partial x_j} \left( \frac{\partial u_{i2}}{\partial x_j} + \frac{\partial u_{i1}}{\partial x_i} - \frac{2}{3} \frac{\partial u_{i1}}{\partial x_k} \delta_{ij} \right) \\
- \frac{1}{2} \frac{\partial }{\partial x_i} \left( \omega_1 \frac{\partial^2 u_{i2}}{\partial x_i} \right) + \gamma \frac{\partial}{\partial x_j} \left[ \mu \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} \right) \right], 
\]

(48b)

\[
3 \frac{\partial P_2}{\partial t} + \frac{3}{2} u_{j1} \frac{\partial P_2}{\partial x_j} + \frac{5}{2} \left( P_1 \frac{\partial u_{j2}}{\partial x_j} - \frac{\partial \omega_2}{\partial x_j} - \frac{\partial (\omega_1 u_{j2} + \omega_2 u_{j1})}{\partial x_j} \right) \\
= 5 \gamma \frac{\partial}{\partial x_i} \left( \frac{\partial \tau_2}{\partial x_i} + \lambda \frac{\partial \tau_1}{\partial x_i} \right) + \gamma_1 \left( \frac{\partial u_{i1}}{\partial x_i} + \frac{\partial u_{j1}}{\partial x_j} \right)^2, 
\]

(48c)

where

\[
P_1 = \omega_1 + \tau_1, \quad P_2 = \omega_2 + \tau_2 + \omega_1 \tau_1. 
\]

These equations are very similar to Eqs. (M-3.265)-(M-3.268) [or Eqs. (K-3.87)-(K-3.90) for the time-independent case] obtained by the S expansion of
the Boltzmann equation in Section M-3.7.2 (or Section K-3.2.2 for the time independent case).\footnote{12}

In order to compare Eqs. (47a)-(47c) and (49) with the incompressible Navier–Stokes equations (23a)-(24), we will rewrite the latter equations for the situation where the former equations are derived. The starting equations are Eqs. (38)-(41b)\footnote{13} and the nondimensional form of Eq. (19), i.e.,

\[ \frac{\partial \omega}{\partial t} + u_i \frac{\partial \omega}{\partial x_i} = 0, \] (50)

instead of Eq. (42).\footnote{14} The analysis is carried out in a similar way and the equations corresponding to Eqs. (47a)-(47c) are\footnote{15}

\[ \frac{\partial u_i}{\partial x_i} = 0, \] (51a)

\[ \frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{1}{2} \frac{\partial P_2}{\partial x_i} + \frac{\gamma_1}{2} \frac{\partial^2 u_i}{\partial x_i^2}, \] (51b)

\[ 3 \frac{\partial \tau_1}{\partial t} + 3 \frac{\partial u_1}{\partial x_i} = \frac{5}{4} \frac{\partial^2 \tau_1}{\partial x_i^2}. \] (51c)

Equations (51a) and (51b) are, respectively, of the same form as Eqs. (47a) and (47b). Equation (47c) is rewritten with the aid of Eqs. (46) and (49) as

\[ \frac{3}{2} \frac{\partial \tau_1}{\partial t} + 3 \frac{\partial u_1}{\partial x_i} - \left( \frac{\partial \omega_1}{\partial t} + u_1 \frac{\partial \omega_1}{\partial x_i} \right) = \frac{5}{4} \gamma_2 \frac{\partial^2 \tau_1}{\partial x_i^2}. \] (52)

The difference of Eq. (47c) or (52) from Eq. (51c) is

\[ \frac{\partial \omega_1}{\partial t} + u_1 \frac{\partial \omega_1}{\partial x_i}, \]

which vanishes for an incompressible fluid. The work \( W \) done per unit time on unit volume of fluid by pressure, given by \(-p_0(2RT_0)^{1/2}L^{-1} \partial (1 + P) u_i / \partial x_i\), is transformed with the aid of Eqs. (46), (47a), and (48a) in the following way:

\[
\frac{W}{p_0(2RT_0)^{1/2}L^{-1}} = -\frac{\partial (1 + P) u_i}{\partial x_i} = -\frac{\partial u_1}{\partial x_i} \varepsilon - \left( \frac{\partial u_1}{\partial x_i} + u_1 \frac{\partial P_1}{\partial x_i} + \frac{\partial u_2}{\partial x_i} \right) \varepsilon^2 + \cdots
\]

\[
= -\frac{\partial u_2}{\partial x_i} \varepsilon^2 + \cdots
\]

\[
= \left( \frac{\partial \omega_1}{\partial t} + u_1 \frac{\partial \omega_1}{\partial x_i} \right) \varepsilon^2 + \cdots.
\]

\footnote{12}{Equations (46)-(48a) and (49) are of the same form as Eqs. (M-3.265)-(M-3.267a) and (M-3.268). Thus the following discussion applies to the two systems. Naturally, it applies to the \( S \) expansion in Sections K-4.9 and K-4.10.3.}

\footnote{13}{As the internal energy \( \varepsilon = 3RT/2 \approx 3RT_0(1 + \tau)/2 \) is chosen for consistency.}

\footnote{14}{From Eqs. (38) and (50), we have \( \partial u_i / \partial x_i = 0 \).

\footnote{15}{We also obtain \( \partial P_1 / \partial x_i = 0 \).}
The work vanishes up to the order considered here for an incompressible fluid, because \( \partial u_i / \partial x_i = 0 \) and \( \partial P_1 / \partial x_i = 0 \) (see Footnotes 14 and 15).

That is, Eq. (47c) differs from Eq. (51c) by the amount of the work done by pressure. Thus, naturally, the temperature \( \tau_1 \) fields in the two cases are different owing to this difference.

To summarize, the mass and momentum-conservation equations (47a) and (47b) of the set derived from the compressible Navier–Stokes set [Eqs. (38)–(41b) and (42)] under the situation given by Eqs. (43a) and (43b) with small \( \varepsilon \) are of the same form as those equations (51a) and (51b) of the corresponding set derived from the incompressible Navier–Stokes set [Eqs. (38)–(41b) and (50)], but the energy-conservation equations (47c) and (51c) of the two sets differ by the work done by pressure.\(^{16}\)

The density \( \omega_1 \) obtained from Eqs. (46)–(47c) with the first relation of Eq. (49) does not generally satisfy the incompressible condition (50) with \( \omega = \omega_1 \) and \( u_i = u_{i1} \).\(^{17}\) Both the density and temperature fields \( (\omega_1, \tau_1) \) are different in the two sets. The variation of the density \( \omega_1 \) along a particle path is due to the first relation of Eq. (49).

Finally, it may be noted that under the situation (43a), the solenoidal condition for \( u_{i1} \), i.e., Eq. (47a) or (51a), is derived only from the mass conservation equation (38) without the help of the incompressible condition (50).

### 3.1.4 Equations derived from the compressible Euler set when the Mach number and the temperature variation are small

Take the Euler set of equations for a monatomic gas, which is derived from the Boltzmann equation in the limit \( k \to 0 \) (see Section M-3.71). Its nondimensional form with the notation (K-2.36) is given as follows [see Eqs. (M-3.250a)–(M-3.250c)]:

\[^{16}\text{When the density } \rho \text{ is uniform initially, for which } \rho \text{ is a constant for an incompressible fluid, the viscosity and thermal conductivity are constants, and heat production by viscosity is neglected, Eqs. (51a)–(51c) can be compared directly with Eqs. (47a)–(47c) and (49), without carrying expansion, and the same results are obtained.}\]

\[^{17}\text{It is easily seen that the velocity } u_{i1} \text{ vanishes, the pressure } P_1 \text{ is a constant, and the temperature } \tau_1 \text{ (thus, the density } \omega_1 \text{) varies with time in initial-value problems where the velocity is zero and the temperature is nonuniform (strictly, non-harmonic) initially, and the pressure is time-independent at infinity. Thus, the incompressible condition is not satisfied. See also the example given in Section K-4.10.3, where the velocity vanishes and the density varies with time, and further, the temperature field is quite different from the incompressible case owing to the time-dependent boundary condition on } P_0, \text{ corresponding to } P_1 \text{ here (note Footnote 12).}\]
3.250c) and the equation of state:

\[ \frac{\partial \hat{\rho}}{\partial t} + \frac{\partial \hat{\rho} \hat{v}_j}{\partial x_j} = 0, \]  
(53a)

\[ \frac{\partial \hat{\rho} \hat{v}_j}{\partial t} + \frac{\partial \hat{\rho} \hat{v}_j \hat{v}_i}{\partial x_j} + \frac{1}{2} \frac{\partial \hat{p}}{\partial x_i} = 0, \]  
(53b)

\[ \frac{\partial}{\partial t} \left[ \hat{\rho} \left( \hat{v}_i^2 + \frac{3}{2} \hat{T} \right) \right] + \frac{\partial}{\partial x_j} \left[ \hat{\rho} \hat{v}_j \left( \hat{v}_i^2 + \frac{5}{2} \hat{T} \right) \right] = 0, \]  
(53c)

\[ \hat{p} = \hat{\rho} \hat{T}, \]  
(53d)

where Strouhal number \( \text{Sh} \) is taken to be unity without loss of generality. We consider the situation where the state of the gas deviates slightly from a uniform equilibrium state at rest. That is,

\[ \hat{\rho} = 1 + \hat{\omega}, \quad \hat{p} = 1 + \hat{P}, \quad T = 1 + \hat{\tau}, \quad \hat{v}_i = \hat{u}_i, \]  
(54)

where the perturbed quantities \( \hat{\omega}, \hat{P}, \hat{\tau}, \) and \( \hat{u}_i \) are small, say of the order of \( \varepsilon \). They are expanded as

\[ \hat{h} = \hat{h}_1 \varepsilon + \hat{h}_2 \varepsilon^2 + \cdots, \]  
(55)

where \( \hat{h} = \hat{\omega}, \hat{P}, \hat{\tau}, \) or \( \hat{u}_i \).

We discuss the two cases with different time scale. The first case is

\[ \frac{\partial \hat{h}}{\partial t} = O(\hat{h}). \]  
(56)

Substituting the expansions (55) of the variables \( \hat{\omega}, \hat{P}, \hat{\tau}, \) and \( \hat{u}_i \) into the Euler equations (53a)-(53d) and arranging the same-order terms with Eq. (56) in mind, we find that the leading-order variables are governed by the following set of equations:

\[ \frac{\partial \hat{\omega}_1}{\partial t} + \frac{\partial \hat{u}_{1j}}{\partial x_j} = 0, \]  
(57a)

\[ \frac{\partial \hat{u}_{1j}}{\partial t} + \frac{1}{2} \frac{\partial \hat{P}_1}{\partial x_i} = 0, \]  
(57b)

\[ \frac{\partial \hat{P}_1}{\partial t} + \frac{5}{3} \frac{\partial \hat{u}_j}{\partial x_j} = 0, \]  
(57c)

\[ \hat{P}_1 = \hat{\omega}_1 + \hat{\tau}_1. \]  
(57d)

This set is the well-known acoustic equations, which are explained in a standard textbook of gas dynamics, e.g., K-Liepmann & Roshko [1957].

The second case is the case where the variables are slowly varying or the time scale of variation of the variables is long and of the order \( 1/\varepsilon \):

\[ \frac{\partial \hat{h}}{\partial t} = \varepsilon O(\hat{h}). \]  
(58)
Here, we introduce the shrunk time $\hat{t}_\varepsilon$:

$$\hat{t}_\varepsilon = \varepsilon t.$$  \hfill (59)

Then,

$$\frac{\partial \hat{h}}{\partial \hat{t}_\varepsilon} = O(\hat{h}).$$ \hfill (60)

Substituting the expansion (55) of the variables $\hat{\omega}$, $\hat{P}$, $\hat{\tau}$, and $\hat{u}_i$ into the Euler equations (53a)-(53d) and arranging the same-order terms with Eq. (60) in mind, we obtain the equations that determine the leading-order variables as\textsuperscript{18}

$$\frac{\partial \hat{P}_1}{\partial x_i} = 0,$$ \hfill (61a)

$$\frac{\partial \hat{u}_{j1}}{\partial x_j} = 0,$$ \hfill (61b)

$$\frac{\partial \hat{u}_{i1}}{\partial \hat{t}_\varepsilon} + \hat{u}_{j1} \frac{\partial \hat{u}_{i1}}{\partial x_j} + \frac{1}{2} \frac{\partial \hat{P}_1}{\partial x_i} = 0,$$ \hfill (61c)

$$\frac{5}{2} \frac{\partial \hat{\tau}_1}{\partial \hat{t}_\varepsilon} - \frac{\partial \hat{\omega}_1}{\partial \hat{t}_\varepsilon} + \frac{5}{2} \hat{u}_{j1} \frac{\partial \hat{\tau}_1}{\partial x_j} = 0,$$ \hfill (61d)

$$\hat{P}_1 = \hat{\omega}_1 + \hat{\tau}_1.$$ \hfill (61e)

From Eq. (61a), $\hat{P}_1$ is a function of $\hat{t}_\varepsilon$ only, and thus is determined by the boundary condition.$^9$ The relation

$$\frac{\partial \hat{P}_1}{\partial \hat{t}_\varepsilon} = \frac{\partial \hat{P}_1}{\partial \hat{t}_\varepsilon} + \hat{u}_{j1} \frac{\partial \hat{P}_1}{\partial x_j},$$ \hfill (62)

obvious from Eq. (61a), is conveniently used in the following discussion. The energy equation (61d) is transformed as

$$\frac{3}{2} \left( \frac{\partial \hat{\tau}_1}{\partial \hat{t}_\varepsilon} + \hat{u}_{j1} \frac{\partial \hat{\tau}_1}{\partial x_j} \right) - \frac{\partial \hat{\omega}_1}{\partial \hat{t}_\varepsilon} \hat{u}_{j1} \frac{\partial \hat{\omega}_1}{\partial x_j} = 0,$$ \hfill (63)

by using Eqs. (61e) and (62) for $\partial \hat{P}_1/\partial \hat{t}_\varepsilon$. From Eqs. (63) and (61e), the variation of $\hat{\omega}_1$ along the fluid-particle path is expressed as follows:

$$\frac{\partial \hat{\omega}_1}{\partial \hat{t}_\varepsilon} + \hat{u}_{j1} \frac{\partial \hat{\omega}_1}{\partial x_j} = \frac{3}{5} \left( \frac{\partial \hat{P}_1}{\partial \hat{t}_\varepsilon} + \hat{u}_{j1} \frac{\partial \hat{P}_1}{\partial x_j} \right) = \frac{3}{5} \frac{d \hat{P}_1}{d \hat{t}_\varepsilon}.$$ \hfill (64)

Eqs. (63) and (64) are the linearized forms of the isentropic variations of $\hat{\omega}_1$ versus $\hat{\tau}_1$ and $\hat{P}_1$ along the fluid-particle path. The energy equation (63) is

$^{18}$Under the assumptions (54) and (58) or (60), the solenoidal condition (61b) for $\hat{u}_{i1}$ is derived solely from the mass conservation equation (53a). It should not be confused with the incompressible condition.

$^{19}$For example, the pressure is specified at infinity in an unbounded problem.
conveniently compared with the energy equation of incompressible fluid. For the latter, the last two terms are absent and the temperature is invariant along the fluid-particle path. The difference is the work done by pressure, which can be shown as is done in Section 3.1.3.

The behavior of the gas governed by Eqs. (61a)-(61e) is summarized as follows:

(1): Equations (61b) and (61c) for the velocity field are of the same form as those of incompressible fluid.

(2): Depending on the condition of the boundary, \( \dot{P}_1 \) can be time dependent or independent. (i) If \( \dot{P}_1 \) is time dependent, the density \( \dot{\omega}_1 \) varies along the fluid-particle path owing to Eq. (64). (ii) If \( \dot{P}_1 \) is time independent, the temperature \( \dot{\tau}_1 \) and the density \( \dot{\omega}_1 \) are invariant along the fluid-particle path owing to Eqs. (61d) and (64).

(Section 3.1.4: Version 4-00)

4 Appendix K-A

4.1 Boundary condition for Euler equations

In Appendix K-A.10, we discussed the boundary condition for the linearized Euler equations for simple examples. Related discussion is given in Section 3.1.2 in this notes.

5 Appendix K-C

5.1 Numerical procedure for discrete \( \xi_i \) and \( \eta \) (Supplement to Sections K-C.2 and K-C.3)

In Appendix K-C, a numerical method of solution of conservation equations, e.g., fluid-dynamic equations, by a kinetic equation is discussed. As noted there, the range of the variables \( \xi_i \) and \( \eta \) may be a set of discrete points. Obviously, the integrals with respect to \( \xi_i \) and \( \eta \) in the discussion in Section K-C.2 are taken to be the summation over the discrete points because the velocity distribution function \( f \) is the collection of delta functions of \( \xi_i \) and \( \eta \) with their center at the discrete points. To solve the conservation equations by kinetic-equation approach, a finite number of discrete \( \xi_i \)'s and \( \eta \)'s are sufficient. The number depends on the size of the conservation equations. Here, we will describe the procedure of solution of conservation equations by a kinetic equation with the formulas expressed in discrete \( \xi_i \) and \( \eta \).

The Navier-Stokes equations (K-C.34a)-(K-C.34c) are taken as an example. In this case, \( r = 0, 1, \ldots, 4 \), or \( j = 1, 2, 3 \), and \( \gamma_r \)'s are chosen as

\[
\gamma_0 = 1, \quad \gamma_i = \xi_i, \quad \gamma_4 = \xi_i^2 + (\alpha - 3)\eta^2,
\]

(65)
where $\alpha \geq 3$ is a constant.\footnote{The constant $\alpha$ is the freedom of a molecule of the gas under consideration. For a monatomic gas without internal degree of freedom, $\alpha = 3$.} From the Navier–Stokes equations (K-C.34a)–(K-C.34c), we can identify $\rho_r$ and $\hat{H}_r^i$ as follows:

\begin{align*}
\rho_0 &= \rho, \\
\rho_i &= \rho u_i, \\
\rho_4 &= \rho (u_i^2 + 2e), \\
\hat{H}_0^i &= \rho u_i, \\
\hat{H}_i^j &= \rho u_i u_j + p_{ij}, \\
\hat{H}_4^i &= \rho u_i (u_j^2 + 2e) + 2u_j p_{ij} + 2q_i,
\end{align*}

where

\begin{align*}
e &= \frac{\alpha RT}{2}, \\
p &= \rho RT, \\
p_{ij} &= p \delta_{ij} - \mu \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3} \frac{\partial u_k}{\partial x_k} \delta_{ij} \right) - \mu_B \frac{\partial u_k}{\partial x_k} \delta_{ij}, \\
q_i &= -\lambda \frac{\partial T}{\partial x_i}.
\end{align*}

The velocity distribution function $f^{(m,n)}$ of Chapman–Enskog type that gives a given set $(\rho_r, \hat{H}_r^i)$ is obtained by the following simultaneous linear algebraic equations, which correspond to Eqs. (K-C.1) and (K-C.5):\footnote{Note that the relation between $\rho_i$ and $f^{(m,n)}$ and that between $\hat{H}_r^i$ and $f^{(m,n)}$ are the same. That is, these relations are commonly expressed by Eq. (69b).}

\begin{align*}
\sum_{m,n} f^{(m,n)} &= \rho_0, \\
\sum_{m,n} \xi_i^{(m)} f^{(m,n)} &= \rho_i, \\
\sum_{m,n} [\xi_i^{(m)}]^2 + (\alpha - 3)(\eta^{(n)})^2] f^{(m,n)} &= \rho_4, \\
\sum_{m,n} \xi_i^{(m)} \eta_j^{(n)} f^{(m,n)} &= \hat{H}_i^j \quad (j \leq i), \\
\sum_{m,n} \xi_i^{(m)} [(\xi_j^{(m)})^2 + (\alpha - 3)(\eta^{(n)})^2] f^{(m,n)} &= \hat{H}_4^i.
\end{align*}
the points is 14 [5 for \( \rho_r \), 6 for \( \bar{H}_i^j \) (\( j \leq i \)), and 3 for \( \bar{H}_i^i \)] in the present case.\(^{22}\) If one chooses more points for one’s convenience, one should impose some extra conditions to make \( f^{(m,n)} \) unique.\(^{23}\)

Once the way to determine the velocity distribution function \( f^{(m,n)} \) of the Chapman–Enskog type is fixed, we can proceed to the next procedure described in Section K-C.3. That is, (i) for given initial data \( \rho_r \), \( u_i \), and \( T \), compute \( \bar{H}_i^j \) by Eqs. (67b)–(68d); (ii) construct the corresponding velocity distribution function \( f^{(m,n)} \) of Chapman–Enskog type by Eqs. (69a)–(69e); (iii) determine the solution of the free-molecular equation (K-C.35) at the next time step with the velocity distribution function constructed in the step (ii) as the initial condition; (iv) compute \( \rho_r \) from the resulting velocity distribution function by Eqs. (69a)–(69e); (v) return to the step (i) and repeat the process. Then, we can obtain the solution of the Navier–Stokes equations (K-C.34a)–(K-C.34e).

To determine the solution of the free-molecular equation in the step (iii) of the preceding paragraph, we need the boundary condition compatible with the solution of Chapman–Enskog type. For the Navier–Stokes equations, \( u_i \) and \( T \) are generally specified on the boundary of bodies, but \( \rho \) is not specified. The boundary value of \( \rho \) is determined with \( \rho_r \) and \( u_i \) at the previous time step by Eq. (K-C.34a). Then, we know the boundary data \( \rho_r \). Together with the \( \rho \), \( u_i \), and \( T \) inside gas obtained by the free-molecular solution starting at the preceding time step, we can determine the boundary data of \( H_i^j \) by Eqs. (67b)–(68d). Then, the boundary data \( f^{(m,n)} \) compatible with the solution of Chapman–Enskog type are determined by Eqs. (69a)–(69e).

In the process of solution of the free-molecular equation (K-C.35) by a finite difference method, one can make use of a simplifying process introduced in the lattice-Boltzmann-equation approach. Then, the step (iii) in the above procedure is simplified. Let \( X \) be a lattice point in \( x \) space, and let \( \Delta t \) be the time step of computation. We arrange the lattice points \( \sum X \)'s and \( \xi^{(m)} \)'s in such a way that \( X + \xi^{(m)} \Delta t \) is also some lattice point in \( x \). Then, \( f^{(m,n)} \) at \( t+\Delta t \) is obtained by shifting \( f^{(m,n)} \) at \( t \) among the lattice points \( X \)'s. For example, take rectangular lattices for \( x_i \), where the lattice points \( X \)'s are expressed as \( X = (m_1, m_2, m_3) \Delta x \) with \( m_i \) being an integer \((0, \pm 1, 2, \cdots)\). Then, we choose \( \xi^{(m)} = (k_1, k_2, k_3) \Delta x / \Delta t \), where \( k_i \) is, for example, \( k_i = 0, \pm 1 \). Then,

\[
f(m_i \Delta x, k_i \xi, t + \Delta t) = f((m_i - k_i) \Delta x, k_i \xi, t),
\]

where \( \xi = \Delta x / \Delta t \).\(^24\) With the above choice of \( \xi^{(m)} \), \((m_i - k_i) \Delta x \) is a lattice

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\(^{22}\) When the determinant vanishes, we cannot obtain the solution for arbitrary data on the right-hand side.

\(^{23}\) In the case of \( \alpha = 3 \) (monatomic gas), the left-hand side of Eq. (69c) is derived from Eq. (69d) with \( i = j \). The right-hand side of Eq. (69c) is obtained in the same way because the bulk viscosity vanishes \((\mu_B = 0)\) for a monatomic gas. Thus, Eq. (69c) is unnecessary in the analysis.

\(^{24}\) Sometimes, it is convenient to choose more \((\xi^{(m)}, \eta^{(m)})\) than required to avoid awkward distribution \( f^{(m,n)} \).

The appropriate lattice ratio of \( \Delta x \) and \( \Delta t \) (thus, \( \xi \)) depends on the conservation equations (i.e., the Navier–Stokes equations) under consideration.

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point of \( x_i \) or \( X \). Other examples of the lattice point system are found, for example, in Qian, Succi & Orszag [1995], and Kataoka [submitted].

In Section K-C.3, we discussed the process and validity of solving the conservation equations, or the validity of the procedure of solution given in this section, by making use of the free molecule equation on the basis of the discussion in Section K-C.2. In this discussion, we implicitly assumed the stability of solution of Eq. (K-C.6) with Eq. (K-C.7). Further, it is also assumed that 
\[
|\hat{H}_r(x, \nabla \rho_r) - \hat{H}_r(x, \nabla \rho_c)| = O((\Delta t)^2)
\]
for \( \hat{H}_r \) at the step (i) after step (iv) (or at time \( t + \Delta t \)) when 
\[
|\rho_r - \rho_c| = O((\Delta t)^2)
\]
[Eq. (K-C.40)] for the present Navier–Stokes equations. More rigorously, the condition about the size used in the discussions in Section K-C.3 should be uniformly bounded in some neighborhood of the solution of Eq. (K-C.6). The conditions are mainly determined by the property of solution of the Navier–Stokes equations [generally, Eqs (K-C.12) and (K-C.13)]. Some examples of the numerical computation of the Navier–Stokes equations by the present method are carried out by Kataoka [submitted].

(Section 5.1: Version 3-00)

References


\[25\] This assumption corresponds to the assumption on the space variation of \( \rho_r \) and \( \rho_c \). For the Euler equations, this assumption is not required because the space-derivative terms are absent in \( \hat{H}_r \).