Molecular Gas Dynamics
Yoshio Sone
(Birkhäuser, Boston, 2007)

Supplementary Notes and Errata
Yoshio Sone

Version 4-00 (8 January 2009)

Kyoto University Research Information Repository
http://hdl.handle.net/2433/66098

Bibliography

Update of bibliography

• [19] Arkeryd, L. and A. Nouri [2006]:
  (to be published) → 401–443
• [29] Bardos, C., F. Golse, and Y. Sone [2006]:
  (to be published) → 275–300
  [2006] → [2007]
  59, (to be published) → 60, 147–163
  [2006a] → [2006]
• [137] Liu, T.-P. and S.-H. Yu [2006b]:
  [2006b] → [2007]
  59, (to be published) → 60, 295–356

The corresponding corrections in the text

• p. 166, the first line in the third paragraph:
  [2004b, 2006a] → [2004b, 2006]
• p. 166, the last line in the third paragraph:
  [2006b] → [2007]
• p. 183, the second line:
  [2006] → [2007]
Errata

• p. 9, the 7th line:
  specular condition  →  specular reflection

• p. 27, the 3rd line of Footnote 26:
  Eq. (1.99)  →  a linear combination of Eqs. (1.99) and (1.101)

• p. 27, the 6th line of Footnote 26:
  except for a common constant factor  →  except for a common constant factor and additive functions
  (say, $f_a$ in $\hat{H}$ and $f_{b_i}$ in $\hat{H}_i$ in their second order) satisfying
  $\mathbf{Sh} \partial f_a / \partial \hat{t} + \partial f_{b_i} / \partial x_i = 0$

• p. 81, the 4th line in Footnote 7:
  $u_{iGm} \rightarrow u_{iGm} - u_{jGm} n_j n_i$
  or $\phi_{eGm} \rightarrow \phi_{eGm}$

• p. 83, the first line in Footnote 14:
  $u_{iGm} \rightarrow u_{iGm} - u_{jGm} n_j n_i$

• p. 504, the first line in Footnote 24:
  damin  →  domain

• p. 505, Eq. (A.60):
  \[
  \left| \frac{1}{\sin\theta_c} \frac{\partial \sin^2 \theta_c}{\partial \theta_c} \right| \rightarrow \left| \frac{1}{\sin\theta_c} \frac{d \sin^2 \theta_c}{d \theta_c} \right|
  \]
  \[
  \left| \frac{1}{\sin\theta_c} \frac{\partial^2}{\partial \theta_c^2} \right| \rightarrow \left| \frac{1}{\sin\theta_c} \frac{d^2}{d \theta_c^2} \right|
  \]

• p. 506, the 13th line [The line next to Eq. (M-A.63)]:
  with respect to $\theta_c$  →  with respect to $\theta_a$

• p. 639, the 3rd line in Ref. [262]:
  $gs \rightarrow gas$

Supplementary Notes

In the present supplementary notes, the letter M is attached to the labels of sections, equations, etc. in the book “Molecular Gas Dynamics” to avoid confusion.
1 Chapter M-1

1.1 Supplement to Foonote M-26 in Chapter M-1

Footnote M-26 is supplemented with more explicit mathematical expressions for the process given there. Take the non-dimensional form of the equation for the H function, i.e., Eq. (M-1.72):

\[ \text{Sh} \frac{\partial \hat{H}}{\partial t} + \frac{\partial \hat{H}_i}{\partial x_i} = \frac{1}{\bar{k}} \hat{G}, \]  

(1)

where

\[ \hat{H}(x_i, i) = \int \hat{f} \ln(\hat{f}/\bar{c}_0) d\zeta, \quad \hat{H}_i(x_i, i) = \int \zeta_i \hat{f} \ln(\hat{f}/\bar{c}_0) d\zeta, \]

\[ \hat{G} = -\frac{1}{4} \int (\hat{f}' \hat{f}'' - \hat{f} \hat{f}') \ln \left( \frac{\hat{f}' \hat{f}''}{\hat{f}^2} \right) d\zeta \]

(2)

with \( \bar{c}_0 = c_0(2RT_0)^{3/2}/\rho_0 \). The perturbed form of the velocity distribution function \( \hat{f} \) is defined by

\[ \hat{f} = E(1 + \phi), \]  

(3)

where

\[ E = \frac{1}{\pi^{1/2}} \exp(-\zeta^2). \]

Let \( \varepsilon \) be a small quantity. Here, we take the case in which \( \phi \) is of the order of \( \varepsilon \), and examine the terms of the order of \( \varepsilon^2 \) of Eq. (1). The perturbed function \( \phi \) is expressed as

\[ \phi = \phi_1 \varepsilon + \phi_2 \varepsilon^2 + \cdots. \]  

(4)

Corresponding to the expansion, the macroscopic variables, i.e., \( \omega, u_i, P \), etc., \( \hat{H}, \hat{H}_i \), and \( \hat{G} \) are also expressed as

\[ h = h_1 \varepsilon + h_2 \varepsilon^2 + \cdots, \]  

(5a)

\[ \hat{H} = \hat{H}_0 + \hat{H}_1 \varepsilon + \hat{H}_2 \varepsilon^2 + \cdots, \]  

(5b)

\[ \hat{H}_i = \hat{H}_{i0} + \hat{H}_{i1} \varepsilon + \hat{H}_{i2} \varepsilon^2 + \cdots, \]  

(5c)

\[ \hat{G} = \hat{G}_0 + \hat{G}_1 \varepsilon + \hat{G}_2 \varepsilon^2 + \cdots, \]  

(5d)

where \( h \) represents the perturbed macroscopic variables, \( \omega, u_i, P \), etc., and the quantities \( \phi_n, h_n, \hat{H}_n, \hat{H}_{in} \), and \( \hat{G}_n \) are of the order of unity. Then, with the aid of the expanded forms of Eqs. (M-1.78a)-(M-1.78f), \( \hat{H}_n, \hat{H}_{in} \), and \( \hat{G}_n \) are
expressed as

\[ \dot{H}_0 = -\frac{3}{2} - \ln \pi^{3/2} \dot{\epsilon}_0, \]  

(6a)

\[ \dot{H}_1 = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \int E \phi_1 d\zeta - \int \zeta^2 E \phi_1 d\zeta \]

\[ = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \omega_1 - \frac{3}{2} P_1, \]  

(6b)

\[ \dot{H}_2 = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \int E \phi_2 d\zeta - \int \zeta^2 E \phi_2 d\zeta + \frac{1}{2} \int E \phi_2^2 d\zeta \]

\[ = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \omega_2 - \left( \frac{3}{2} P_2 + u_1^2 \right) + \frac{1}{2} \int E \phi_2^2 d\zeta, \]  

(6c)

\[ \dot{H}_{10} = 0, \]

(7a)

\[ \dot{H}_{11} = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \int \zeta_1 \phi_0 d\zeta - \int \zeta_1 \zeta^2 E \phi_1 d\zeta \]

\[ = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) u_{11} - \left( Q_{11} + \frac{5}{2} u_{11} \right), \]  

(7b)

\[ \dot{H}_{12} = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \int \zeta_1 \phi_0 d\zeta - \int \zeta_1 \zeta^2 E \phi_2 d\zeta + \frac{1}{2} \int \zeta_1 E \phi_2^2 d\zeta \]

\[ = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \left( u_{12} + \omega_1 u_{11} \right) - \left( Q_{12} + \frac{5}{2} u_{12} + u_{11} P_{1j1} + \frac{3}{2} u_{11} P_1 \right) \]

\[ + \frac{1}{2} \int \zeta_1 E \phi_2^2 d\zeta, \]  

(7c)

\[ \dot{G}_0 = 0, \]

(8a)

\[ \dot{G}_1 = 0, \]

(8b)

\[ \dot{G}_2 = -\frac{1}{4} \int E \phi_1 \phi_1 \nu \left( \phi_1 - \phi_1 - \phi_{1s} \right)^2 \hat{B} \delta \Omega d\zeta, d\zeta \leq 0. \]  

(8c)

With the aid of these expressions, the \( \varepsilon \) and \( \varepsilon^2 \)-order expressions of Eq(1) are given as

\[ \frac{\partial \dot{H}_1}{\partial t} + \frac{\partial \dot{H}_{11}}{\partial x_i} = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \left( \frac{\partial \omega_1}{\partial t} + \frac{\partial u_{11}}{\partial x_i} \right) \]

\[- \left[ \frac{3}{2} \frac{\partial P_1}{\partial t} + \frac{\partial}{\partial x_i} \left( \frac{5}{2} u_{11} + Q_{11} \right) \right], \]  

(9a)

\[ \frac{\partial \dot{H}_2}{\partial t} + \frac{\partial \dot{H}_{12}}{\partial x_i} = (1 - \ln \pi^{3/2} \dot{\epsilon}_0) \left( \frac{\partial \omega_2}{\partial t} + \frac{\partial (u_{12} + \omega_1 u_{11})}{\partial x_i} \right) \]

\[- \frac{\partial}{\partial t} \left( \frac{3}{2} P_2 + u_1^2 \right) - \frac{\partial}{\partial x_i} \left( Q_{12} + \frac{5}{2} u_{12} + u_{11} P_{1j1} + \frac{3}{2} u_{11} P_1 \right) \]

\[ + \frac{1}{2} \left( \frac{\partial}{\partial t} \int E \phi_2^2 d\zeta + \frac{\partial}{\partial x_i} \int \zeta_1 E \phi_2^2 d\zeta \right). \]  

(9b)
Substituting the series expansion (5a) into the conservation equation (M-1.87), we have

\[ \text{Sh}_t \frac{\partial \omega_1}{\partial t} + \frac{\partial u_{1i}}{\partial x_i} = 0, \quad (10a) \]

\[ \text{Sh}_t \frac{\partial \omega_2}{\partial t} + \frac{\partial (u_{2i} + \omega_{1i}u_{1i})}{\partial x_i} = 0. \quad (10b) \]

Similarly, from the conservation equation (M-1.89), we have

\[ \frac{3}{2} \text{Sh}_t \frac{\partial P_i}{\partial t} + \frac{\partial}{\partial x_i} \left( \frac{5}{2} u_{1i} + Q_{1i} \right) = 0, \quad (11a) \]

\[ \text{Sh}_t \frac{\partial}{\partial t} \left( \frac{3}{2} P_2 + u_{1i}^2 \right) + \frac{\partial}{\partial x_i} \left( \frac{5}{2} u_{2i} + Q_{2j} + u_{1j} P_{1j} + \frac{3}{2} u_{1i} P_i \right) = 0. \quad (11b) \]

With the aid of the expanded forms (10a)–(11b) of the conservation equations (M-1.87) and (M-1.89), Eqs. (9a) and (9b) are reduced to, for the solution of the Boltzmann equation (M-1.47) or (M-1.75a),

\[ \text{Sh}_t \frac{\partial \hat{H}_1}{\partial t} + \frac{\partial \hat{H}_{1i}}{\partial x_i} = 0, \quad (12a) \]

\[ \text{Sh}_t \frac{\partial \hat{H}_2}{\partial t} + \frac{\partial \hat{H}_{2i}}{\partial x_i} = \frac{1}{2} \left( \text{Sh} \frac{\partial}{\partial x_i} \int E \phi^2_1 d\zeta + \frac{\partial}{\partial x_i} \int J_i E \phi^2_1 d\zeta \right). \quad (12b) \]

Thus, the \( o(\varepsilon^2) \) terms being neglected in Eq. (1), it is reduced to

\[ \text{Sh} \frac{\partial}{\partial t} \int E \phi^2_1 d\zeta + \frac{\partial}{\partial x_i} \int J_i E \phi^2_1 d\zeta \]
\[ = \frac{1}{2k} \int E \int (\phi_1' + \phi_1' - \phi_1 - \phi_1')^2 B d\Omega d\zeta, d\zeta \leq 0. \quad (13) \]

This expression does not contain \( \phi_2 \).

(Section 1.1: Version 4-00)

2 Chapter M-3

2.1 Processes of solution of the systems in Section M-3.7.2

(July 2007)

The processes of solutions of the fluid-dynamic-type equations derived in Section M-3.7.1 are straightforward and may not need explanation. For the equations in Section M-3.7.2, some explanation may be better to be given. The discussion will be made on the basis of the boundary conditions in Section M-3.7.3 for a simple boundary where the shape of the boundary is invariant and its velocity component normal to it is zero.
2.1.1 “Incompressible Navier–Stokes set”

Consider the initial and boundary-value problem of Eqs. (M-3.265)–(M-3.268), i.e.,

\[
\frac{\partial P_1}{\partial x_i} = 0, \quad (14)
\]

\[
\frac{\partial u_{i1}}{\partial x_i} = 0, \quad (15a)
\]

\[
\frac{\partial u_{i2}}{\partial t} + u_{j1} \frac{\partial u_{i1}}{\partial x_j} = -\frac{1}{2} \frac{\partial P_2}{\partial x_i} + \gamma_1 \frac{\partial^2 u_{i1}}{\partial x_j^2}, \quad (15b)
\]

\[
\frac{5}{2} \frac{\partial \tau_{11}}{\partial t} - \frac{\partial P_1}{\partial t} + 5 \frac{\partial \tau_{11}}{\partial x_j} = \frac{5 \gamma_2}{4} \frac{\partial^2 \tau_{11}}{\partial x_j^2}, \quad (15c)
\]

\[
\frac{\partial u_{i2}}{\partial x_i} = -\frac{\partial \omega_{11}}{\partial t} - \frac{\partial \omega_{1i} u_{i1}}{\partial x_i}, \quad (16a)
\]

\[
\frac{\partial u_{i2}}{\partial t} + u_{j1} \frac{\partial u_{i1}}{\partial x_j} + u_{j2} \frac{\partial u_{i1}}{\partial x_j} = -\frac{1}{2} \left( \frac{\partial P_3}{\partial x_i} - \omega_{11} \frac{\partial P_2}{\partial x_i} \right) + \gamma_1 \frac{\partial}{\partial x_j} \left( \frac{\partial u_{i2}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} - \frac{2}{3} \frac{\partial u_{i2}}{\partial x_k} \delta_{ij} \right) \nonumber \\
- \frac{\gamma_1 \omega_{11} \partial^2 u_{i1}}{2 \partial x_j^2} + \gamma_1 \frac{\partial}{\partial x_j} \left[ \tau_{11} \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} \right) \right] - \frac{\gamma_3}{2} \frac{\partial^2 \tau_{11}}{\partial x_j^2} \nonumber \\
+ 3 \frac{\partial P_2}{\partial t} + \frac{3}{2} \frac{u_{i1} \partial P_2}{\partial x_j} + \frac{5}{2} \left( \frac{\partial P_1 u_{j2}}{\partial x_j} - \frac{\partial \omega_{21} u_{i1}}{\partial x_j} - \frac{\partial (\omega_{21} u_{j1} + \omega_{11} u_{j2})}{\partial x_j} \right) \nonumber \\
= \frac{5 \gamma_2}{4} \frac{\partial^2 \tau_{11}}{\partial x_j^2} + \frac{5 \gamma_5}{4} \frac{\partial}{\partial x_j} \left( \tau_{11} \frac{\partial \tau_{11}}{\partial x_j} \right) + \frac{\gamma_1}{2} \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} \right)^2, \quad (16b)
\]

where

\[
P_{11} = \omega_{11} + \tau_{11}, \quad P_{22} = \omega_{22} + \omega_{11} \tau_{11} + \tau_{22}. \quad (17)
\]

From Eq. (14), \( P_{11} \) is a function of \( \ddot{t} \), i.e.,

\[
P_{11} = f_{1}(\ddot{t}). \quad (18)
\]

In an unbounded-domain problem where the pressure at infinity is specified (or the pressure is specified at some point), \( P_{11} = f_{1}(\ddot{t}) \) is known, but in a bounded-domain problem of a simple boundary, \( f_{1}(\ddot{t}) \) is unknown at this moment and is determined later. Let \( u_{i1} \) and \( \tau_{11} \) as well as \( f_{1}(\ddot{t}) \) be given at time \( \ddot{t} \) in such a way that \( u_{i1} \) satisfies Eq. (15a). Taking the divergence of Eq. (15b) and using Eq. (15a), we have

\[
\frac{\partial^2 P_{22}}{\partial x_i^2} = -2 \frac{\partial u_{i1}}{\partial x_i} \frac{\partial u_{i1}}{\partial x_j}. \quad (19)
\]
On a simple boundary, the derivative of \( P_{2S} \) normal to it is found to be expressed with \( u_{iS1} \) and its space derivatives by multiplying Eq. (15b) by the normal vector to the boundary.\(^1\) In the unbounded-domain problem, where \( f_1(\tilde{t}) \) is known, \( P_{2S} \) is determined by Eq. (19). In the bounded-domain problem, \( P_{2S} \) is determined by Eq. (19) except for an additive function of \( \tilde{t} \) say, \( f_2(\tilde{t}) \). Anyway, \( \partial P_{2S}/\partial x_i \) is independent of this ambiguity. From Eq. (15b), \( \partial u_{iS1}/\partial \tilde{t} \) at \( \tilde{t} \) is determined, irrespective of \( f_2(\tilde{t}) \), in such a way that \( \partial(\partial u_{iS1}/\partial x_i)/\partial \tilde{t} = 0 \) for the above choice of \( P_{2S} \). Thus, the solution \( u_{iS1} \) of Eqs. (15a) and (15b) is determined by Eq. (15b) with the supplementary condition (19) instead of Eq. (15a). From Eq. (15c), \( (5/2)\partial \tau_{S1}/\partial \tilde{t} - \partial P_{S1}/\partial \tilde{t} \) or \( (5/2)\partial \tau_{S1}/\partial \tilde{t} - \partial f_1(\tilde{t})/\partial \tilde{t} \) is determined, i.e.,

\[
(5/2)\partial \tau_{S1}/\partial \tilde{t} - \partial f_1(\tilde{t})/\partial \tilde{t} = G(x_i, \tilde{t}),
\]

where

\[
G(x_i, \tilde{t}) = \frac{5}{2} u_{jS1} \frac{\partial \tau_{S1}}{\partial x_j} + \frac{5\gamma_2}{4} \frac{\partial^2 \tau_{S1}}{\partial x_j^2}.
\]

Thus, \( \tau_{S1} \) is determined in the unbounded-domain problem, but \( \tau_{S1} \) has ambiguity owing to \( f_1(\tilde{t}) \) in the bounded-domain problem. The undetermined function \( f_1(\tilde{t}) \) is determined in the following way.

In the bounded-domain problem whose boundary is a simple boundary, the mass of the gas in the domain is invariant with respect to \( \tilde{t} \). The condition at the leading order is

\[
\frac{d}{d\tilde{t}} \int_V \omega_{S1} d\mathbf{x} = 0,
\]

where \( V \) indicates the domain (or its volume in the later). With the aid of Eq. (17), we have

\[
\frac{d f_1(\tilde{t})}{d\tilde{t}} V = \frac{d}{d\tilde{t}} \int_V \tau_{S1} d\mathbf{x} = 0.
\]

On the other hand, from Eq. (20),

\[
-\frac{d f_1(\tilde{t})}{d\tilde{t}} V + \frac{5}{2} \frac{d}{d\tilde{t}} \int_V \tau_{S1} d\mathbf{x} = \int_V G(x_i, \tilde{t}) d\mathbf{x}.
\]

From Eqs. (23) and (24), we obtain \( \frac{d f_1(\tilde{t})}{d\tilde{t}} \) and \( \frac{d}{d\tilde{t}} \int_V \tau_{S1} d\mathbf{x} \) as

\[
\frac{d f_1(\tilde{t})}{d\tilde{t}} = \int_V G(x_i, \tilde{t}) d\mathbf{x},
\]

\[
\frac{d}{d\tilde{t}} \int_V \tau_{S1} d\mathbf{x} = \frac{2}{3} \int_V G(x_i, \tilde{t}) d\mathbf{x}.
\]

That is, \( f_1(\tilde{t}) \) in the bounded-domain problem [and thus the solution \( \tau_{S1} \) of Eq. (15c)] is determined.

\(^1\)The time-derivative term vanishes owing to the boundary condition mentioned in the first paragraph of Section 2.1.
The analysis of the higher-order equations is similar; for example, from Eqs. (16a)-(16c), $u_{iS2}, \tau_{S2}$, and $P_{S3}$ are determined in the unbounded-domain problem, but $f_{2}(\tilde{t})$, $u_{iS2}, \tau_{S2}$, and $P_{S3}$, except for an additive function of $\tilde{t}$ in $P_{S1}$, are determined in the bounded-domain problem.\(^2\) Let $u_{iS2}, \tau_{S2}$, and $f_{2}(\tilde{t})$ be given at $\tilde{t}$ in such a way that Eq. (16a) is satisfied.\(^3\) Taking the divergence of Eq. (16b) and using Eq. (16a) and the results obtained above, we find that $P_{S3}$ is governed by the Poisson equation

$$\frac{\partial^2 P_{S3}}{\partial x_i^2} = \text{Inhomogeneous term,} \quad (26)$$

where the inhomogeneous term consists of $u_{iS2}, P_{S2}$, and the functions determined in the preceding analysis. On a simple boundary, the derivative of $P_{S3}$ normal to it being known,\(^4\) $P_{S3}$ is determined by this equation, except for an additive function of $\tilde{t}$ [say, $f_{3}(\tilde{t})$] in the bounded-domain problem. Then, from Eq. (16b), $\partial u_{iS2}/\partial \tilde{t}$ at $\tilde{t}$ is determined irrespective of $f_{3}(\tilde{t})$. From Eq. (16c), $\partial (\partial P_{S2} - 5\omega_{S2})/\partial \tilde{t} \quad \text{or} \quad \partial (\partial \tau_{S2} - 2P_{S2})/\partial \tilde{t}$ at $\tilde{t}$ is determined. Thus, $u_{iS2}$ and $\tau_{S2}$ (except for the additive function $2f_{2}/5$ in the bounded-domain problem) [thus, $\omega_{S2}$ (except for the additive function $3f_{2}/5$)] are determined. In the bounded-domain problem, where the boundary is a simple boundary, the condition of invariance of the mass of the gas in the domain at the corresponding order is\(^5\)

$$\frac{d}{d\tilde{t}} \int_V \omega_{S2} d\mathbf{x} = 0. \quad (27)$$

With the aid of Eq. (17), $d f_{2}(\tilde{t})/d\tilde{t}$ at $\tilde{t}$ is determined as $d f_{1}(\tilde{t})/d\tilde{t}$ is done.

To summarize, the solution $(u_{iS1}, P_{S1}, \tau_{S1}, P_{S2})$ of the initial and boundary-value problem of Eqs. (14)-(15c) is determined, with an additive arbitrary function $f_{2}(\tilde{t})$ in $P_{S2}$ in a bounded-domain problem of a simple boundary, when the initial data of $u_{iS1}, P_{S1}, \tau_{S1}$, and $P_{S2}$ satisfy Eqs. (15a) and (19). The additive function $f_{2}(\tilde{t})$ does not affect the other variables. The function $f_{2}(\tilde{t})$ is determined in the next-order analysis. In other words, the solution $(u_{iS1}, P_{S1}, \tau_{S1})$ of Eqs. (14)-(15c) is determined consistently by Eqs. (14), (15b), and (15c) with the supplementary condition (19), instead of Eq. (15a), when the initial data of $u_{iS1}, P_{S1}$, and $\tau_{S1}$ satisfy Eq. (15a). Naturally, the initial $P_{S2}$ is required to satisfy Eq. (19). This process is natural for numerical computation.

\(^2\)Note that, with the aid of Eq. (17), the time-derivative term $\frac{d}{d\tilde{t}} P_{S2}/\partial \tilde{t} - \frac{d}{d\tilde{t}} \omega_{S2}/\partial \tilde{t}$ in Eq. (16c) is transformed into $\frac{d}{d\tilde{t}} P_{S2}/\partial \tilde{t} - \frac{d}{d\tilde{t}} \omega_{S2}/\partial \tilde{t} + \frac{1}{5} \partial \omega_{S1}/\partial \tilde{t}$.

\(^3\)The time derivative $\partial \omega_{S1}/\partial \tilde{t}$ is known from $\partial \tau_{S1}/\partial \tilde{t}, d f_{1}(\tilde{t})/d\tilde{t}$, and Eq. (17).

\(^4\)Shift the discussion of the boundary condition for $P_{S2}$ to the next order.

\(^5\)The contribution of the Knudsen-layer correction to the mass in the domain is of a higher order, though it is required to $\omega_{S2}$.
2.1.2 Ghost-effect equations (M-3.275)–(M-3.278b):

Consider the initial and boundary-value problem of Eqs. (M-3.275)–(M-3.278b), i.e.,

\[
\dot{\rho}_{SB0} = \dot{\rho}_0 (\tilde{t}), \\
\dot{\rho}_{SB1} = \dot{\rho}_1 (\tilde{t}), \\
\frac{\partial \rho_{SB0}}{\partial t} + \frac{\partial \rho_{SB0} \dot{v}_{SB1}}{\partial x_i} = 0, \\
\frac{\partial \rho_{SB0} \dot{v}_{SB1}}{\partial t} + \frac{\partial \rho_{SB0} \dot{v}_{SB1} \dot{v}_{SB1}}{\partial x_j} = 0,
\]

(30a)

\[
\frac{1}{2} \frac{\partial \rho_{SB0} \dot{v}_{SB1}}{\partial x_i} + \frac{1}{2} \frac{\partial \dot{\rho}_{SB0} \dot{v}_{SB1}}{\partial x_i} = \frac{1}{2} \frac{\partial \dot{\rho}_{SB0} \dot{v}_{SB1}}{\partial x_i} + \frac{1}{2} \frac{\partial \dot{\rho}_{SB0} \dot{v}_{SB1}}{\partial x_i}
\]

(30b)

\[
\frac{3}{2} \frac{\partial \rho_{SB0} \dot{T}_{SB0}}{\partial t} + \frac{5}{2} \frac{\partial \rho_{SB0} \dot{v}_{SB1} \dot{T}_{SB0}}{\partial x_i} = \frac{5}{4} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \left( \Gamma_2 (\dot{T}_{SB0}) \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right),
\]

(30c)

where \( \dot{\rho}_0 \) and \( \dot{\rho}_1 \) depend only on \( \tilde{t} \), and

\[
\dot{\rho}_{SB0} = \dot{\rho}_{SB0} \dot{T}_{SB0}, \\
\dot{\rho}_{SB1} = \dot{\rho}_{SB1} \dot{T}_{SB0} + \rho_{SB0} \dot{T}_{SB1}, \\
\dot{\rho}_{SB2} = \dot{\rho}_{SB2} \dot{T}_{SB0} + \rho_{SB0} \dot{T}_{SB1} + \rho_{SB0} \dot{T}_{SB2}, \\
\dot{\rho}_{SB2} = \dot{\rho}_{SB2} + \frac{2}{3 \rho_0} \frac{\partial}{\partial x_k} \left( \Gamma_2 (\dot{T}_{SB0}) \frac{\partial \dot{T}_{SB0}}{\partial x_k} \right).
\]

(31)

(32)

Let \( \dot{\rho}, \dot{v}, \) and \( \dot{T} \) (thus, \( \dot{\rho} = \dot{\rho} \dot{T} \)) at time \( \tilde{t} \) be given; thus, \( \dot{\rho}_{SB0}, \dot{v}_{SB1}, \dot{T}_{SB0} \) (\( \rho_{SB0} \)), etc., including \( \dot{\rho}_{SB2} \), are given. Then \( \partial \dot{\rho}_{SB0} / \partial \tilde{t}, \partial \dot{\rho}_{SB0} \dot{v}_{SB1} / \partial \tilde{t}, \) and \( \partial T_{SB0} / \partial \tilde{t} \) at \( \tilde{t} \) are given by Eqs. (30a)–(30c); thus, the future \( \dot{\rho}_{SB0}, \dot{v}_{SB1}, \) and \( T_{SB0} \) (also \( \rho_{SB0} \)) are determined. However, the future \( \dot{\rho}_{SB0}, \) as well as \( \dot{\rho}_{SB0} \) at \( \tilde{t} \), is required to be independent of \( x_i \) owing to Eq. (28). Taking this point into account, we discuss how the solution is determined. For convenience of the discussion, transform Eq. (30c) in the form

\[
\frac{\partial \rho_{SB0}}{\partial \tilde{t}} = \mathcal{P},
\]

(33)

where

\[
\mathcal{P} = - \frac{5}{3} \rho_{SB0} \frac{\partial \dot{v}_{SB1}}{\partial x_i} + \frac{5}{6} \frac{\partial}{\partial x_i} \left( \Gamma_2 (\dot{T}_{SB0}) \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right).
\]

First, consider the case where \( \dot{\rho} \) (thus, \( \dot{\rho}_{SB0}, \dot{\rho}_{SB1}, \) etc.) is specified at some point, e.g., at infinity. Then, from Eq. (28), \( \rho_0 (\tilde{t}) \) is a given function of \( \tilde{t} \), and
\( \dot{p}_{SB0} \) is determined. The initial value of \( \dot{p}_{SB0} \) is uniform, i.e., \( \dot{p}_{SB0} = \dot{p}_0(0) \).

On the other hand, from Eq. (33), the variation of \( \partial \dot{p}_{SB0} / \partial \tilde{t} \) is also determined by the data of \( \dot{p}_{SB0}, \dot{T}_{SB0}, \dot{v}_{SB1} \), and their space derivatives at \( \tilde{t} \). This must coincide with the corresponding data given by Eq. (28), i.e., \( \partial \dot{p}_{SB0} / \partial \tilde{t} = d \dot{p}_0 / d \tilde{t} \).

Substituting this relation into Eq. (33), we have

\[
\frac{\partial}{\partial x_i} \left( \dot{p}_{SB0} \dot{v}_{SB1} - \frac{\Gamma_2(\dot{T}_{SB0})}{2} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right) = -\frac{3}{5} \frac{d \dot{p}_0}{d \tilde{t}} \tag{34}
\]

which requires a relation among \( \dot{p}_{SB0}, \dot{T}_{SB0}, \) and \( \dot{v}_{SB1} \) for all \( \tilde{t} \), since \( d \dot{p}_0 / d \tilde{t} \) is given. This condition is equivalently replaced by the following two conditions: The initial data of \( \dot{p}_{SB0}, \dot{T}_{SB0}, \) and \( \dot{v}_{SB1} \) are required to satisfy Eq. (34), and the time derivative of Eq. (34) has to be satisfied for all \( \tilde{t} \), i.e.,

\[
\frac{\partial^2}{\partial \tilde{t} \partial x_i} \left( \dot{p}_{SB0} \dot{v}_{SB1} - \frac{\Gamma_2(\dot{T}_{SB0})}{2} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right) = -\frac{3}{5} \frac{d^2 \dot{p}_0}{d \tilde{t}^2} \tag{35}
\]

With the aid of Eqs. (30a)-(30c) and (33), the left-hand side of Eq. (35) is expressed in the form without the time-derivative terms, i.e., \( \partial \dot{p}_{SB0} / \partial \tilde{t}, \partial \dot{T}_{SB0} / \partial \tilde{t}, \) and \( \partial \dot{v}_{SB1} / \partial \tilde{t} \), as follows:

\[
\frac{\partial^2}{\partial \tilde{t} \partial x_i} \left( \dot{p}_{SB0} \dot{v}_{SB1} - \frac{\Gamma_2(\dot{T}_{SB0})}{2} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right) = -\frac{1}{2} \dot{p}_{SB0} \frac{\partial}{\partial x_i} \left( \frac{1}{\dot{p}_{SB0}} \frac{\partial \dot{p}_{SB2}}{\partial x_i} \right) + f_n, \tag{36}
\]

where \( f_n \) is a given function of \( \dot{p}_{SB0}, \dot{v}_{SB1}, \dot{T}_{SB0}, \) and their space derivatives. Thus, the condition (35) is reduced to an equation for \( \ddot{p}_{SB2} \), i.e.,

\[
\frac{\partial}{\partial x_i} \left( \frac{1}{\dot{p}_{SB0}} \frac{\partial \dot{p}_{SB2}}{\partial x_i} \right) = F_n, \tag{36}
\]

where

\[
F_n = \frac{2}{\dot{p}_0} \left( f_n + \frac{3}{5} \frac{d^2 \dot{p}_0}{d \tilde{t}^2} \right). \tag{36}
\]

The boundary condition for \( \ddot{p}_{SB2} \) in Eq. (36) on a simple boundary is derived by multiplying Eq. (30b) by the normal \( n_i \) to the boundary. In this process, the contribution of its time-derivative terms vanishes.\(^6\) Thus, \( \ddot{p}_{SB2} \) (or \( \ddot{p}_{SB2} \)) is determined in the present case, where \( \ddot{p} \) (thus, \( \ddot{p}_{SB2} \)) is specified at some point. The solution \( \ddot{p}_{SB2} \) of Eq. (36) being substituted into Eq. (30b), Eqs. (30a)-(30c) with the first relation in Eq. (31) are reduced to the equations for \( \dot{p}_{SB0}, \dot{T}_{SB0}, \) and \( \dot{v}_{SB1} \) which naturally determine \( \partial \dot{p}_{SB0} / \partial \tilde{t}, \partial \dot{T}_{SB0} / \partial \tilde{t}, \) and \( \partial \dot{v}_{SB1} / \partial \tilde{t} \). Further, if the initial data of \( \dot{p}_{SB0}, \dot{T}_{SB0}, \) and \( \dot{v}_{SB1} \) being chosen in such a way that \( \dot{p}_{SB0} \dot{T}_{SB0} = \dot{p}_0 \) and that Eq. (34) is satisfied, the variation \( \partial \dot{p}_{SB0} / \partial \tilde{t} \) of \( \dot{p}_{SB0} = \dot{p}_{SB0} \dot{T}_{SB0} \) given by these equations is consistent with Eq. (28), since

\( \text{\footnote{The discussion is similar to that in Footnote 1.}} \)
Eq. (36) or (35) with the condition (34) at the initial state guarantees Eq. (34), i.e., \( \partial \hat{p}_{SB0}/\partial \hat{t} = \partial \hat{p}_0/\partial \hat{t} \), for all \( \hat{t} \).

Equations (28) and (30a)–(30c) with Eqs. (31) and (32) determine \( \hat{p}_{SB0}, \hat{T}_{SB0}, \hat{v}_{SB1}, \) and \( \hat{p}_{SB2} \) consistently for appropriately chosen initial data. However, these equations are the leading-order set of equations derived by the asymptotic analysis of the Boltzmann equation. In the above system, \( \hat{p}_{SB2} \) is determined. On the other hand, the variation \( \partial \hat{p}_{SB2}/\partial \hat{t} \) is determined independently by the counterpart of Eq. (33) at the order after next. The situation is similar to that at the leading order, where Eqs. (28), with a given \( \hat{p}_0 \), and (33) determine \( \hat{p}_{SB0} \) independently. The analysis can be carried out in a similar way. Let \( \hat{p}_{SB2} \) determined by Eq. (36) be indicated by \( (\hat{p}_{SB2})_0 \) and the equation for \( \partial \hat{p}_{SB2}/\partial \hat{t} \), or the counterpart of Eq. (33) at the order after next, be put in the form

\[
\frac{\partial \hat{p}_{SB2}}{\partial \hat{t}} = P_2,
\]

where \( P_2 \) is a given function of \( \hat{p}_{SBm}, \hat{v}_{SBm+1}, \hat{T}_{SBm} \) \((m \leq 2)\), and their space derivatives. For the consistency, \( \partial \hat{p}_{SB2}/\partial \hat{t} \) is substituted for \( \partial \hat{p}_{SB4}/\partial \hat{t} \) in Eq. (37), i.e.,

\[
P_2 = \frac{\partial (\hat{p}_{SB2})_0}{\partial \hat{t}},
\]

where \( \partial (\hat{p}_{SB2})_0/\partial \hat{t} \) is known. This requires a relation among \( \hat{p}_{SBm}, \hat{v}_{SBm+1}, \hat{T}_{SBm} \) \((m \leq 2)\), and their space derivatives. This condition is equivalently replaced by the following two conditions: Equation (38) is applied only for the initial state, and the time derivative of Eq. (38), i.e.,

\[
\frac{\partial P_2}{\partial \hat{t}} = \frac{\partial^2 (\hat{p}_{SB2})_0}{\partial \hat{t}^2},
\]

has to be satisfied for all \( \hat{t} \). The \( \partial \hat{p}_{SBm}/\partial \hat{t}, \partial \hat{v}_{SBm+1}/\partial \hat{t}, \partial \hat{T}_{SBm}/\partial \hat{t} \) \((m \leq 2)\) in \( \partial P_2/\partial \hat{t} \) being replaced by the counterparts of Eqs. (30a)–(30c) and (33) at the corresponding order, an equation for \( \hat{p}_{SB4} \) for all \( \hat{t} \) is derived.\(^7\) The conclusion is that an additional initial condition and the condition for \( \hat{p}_{SB4} \) are introduced and, instead, that the condition (36) for \( \hat{p}_{SB2} \) is required only for the initial data. The higher-order consideration does not affect the determination of the solution \( \hat{p}_{SB0}, \hat{T}_{SB0} \) and \( \hat{v}_{SB1} \) (thus also \( \hat{p}_{SB0} \)).

In this way, the solution of Eqs. (28), (30a)–(32) is determined consistently by Eqs. (30a)–(32) with the aid of the supplementary condition (36), instead of Eq. (28), when the initial data of \( \hat{p}_{SB0}, \hat{T}_{SB0}, \) and \( \hat{v}_{SB1} \) satisfy Eqs. (28) and (34), where \( \hat{p}_0(\hat{t}) \) is a known function of \( \hat{t} \) from the boundary condition.

Secondly, consider a bounded-domain problem of a simple boundary. In contrast to the first case, \( \partial \hat{p}_0/\partial \hat{t} \) is unknown because no condition is imposed on \( \hat{p}_{SB0} \) on a simple boundary. However, in a bounded-domain problem of a

\(^7\)The conditions on the odd-order \( \hat{p}_{SB2m+1} \) are derived by the analysis starting from the condition (29) that \( \hat{p}_{SB1} \) is independent of \( \hat{t} \).
simple boundary, the mass of the gas in the domain is invariant with respect to \( \tilde{t} \), i.e., at the leading order,

\[
\frac{d}{dt} \int_V \rho_{SB0} \, dx = 0,
\]

where \( V \) indicates the domain under consideration. Using the first relation of Eq. (31), i.e., \( \dot{\rho}_{SB0} = \rho_0 \dot{T}_{SB0} \), in Eq. (39), we have

\[
\frac{d \rho_0}{dt} \int_V \frac{1}{T_{SB0}} \, dx = \rho_0 \int_V \frac{1}{T_{SB0}^2} \frac{\partial T_{SB0}}{\partial t} \, dx.
\]

Using Eq. (30c) for \( \partial \dot{T}_{SB0}/\partial \tilde{t} \) in Eq. (40), we find that the variation \( d\rho_0/d\tilde{t} \) is expressed with \( \dot{\rho}_0, \dot{T}_{SB0}, \) and \( \dot{v}_{iSB1} \) as follows:

\[
\frac{d \rho_0}{d\tilde{t}} = P(\tilde{t}),
\]

where

\[
P(\tilde{t}) = \rho_0 \int_V \frac{1}{T_{SB0}^2} \left[ \frac{5}{6} \dot{\rho}_{SB0} \frac{\partial}{\partial x_1} \Gamma_2 (\dot{T}_{SB0}) \frac{\partial \dot{T}_{SB0}}{\partial x_1} \right] \, dx
\]

\[
\times \frac{1}{V} \left( \int_V \frac{1}{T_{SB0}} \, dx \right)^{-1}
\]

With this expression of \( d\rho_0/d\tilde{t} \), we can carry out the analysis in a similar way to that in the first case.

The variation \( d\rho_0/d\tilde{t} \) or \( \partial \dot{\rho}_{SB0}/\partial \tilde{t} \) is also determined by Eq. (33). The two \( \partial \dot{\rho}_{SB0}/\partial \tilde{t} \)’s given by Eq. (41) with Eq. (42) and Eq. (33) have to be consistent. Thus, substituting Eq. (41) with Eq. (42) into \( \partial \rho_{SB0}/\partial \tilde{t} \) in Eq. (33), we have

\[
\frac{\partial}{\partial x_i} \left( \rho_{SB0} \dot{v}_{iSB1} - \frac{\Gamma_2 (\dot{T}_{SB0})}{2} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right) = -\frac{3}{5} P(\tilde{t}),
\]

where \( P(\tilde{t}) \) is given by Eq. (42). This must hold for all \( \tilde{t} \) for consistency. This condition is equivalently replaced by the following two conditions: The initial data of \( \rho_{SB0}, \dot{T}_{SB0}, \dot{v}_{iSB1} \) are required to satisfy Eq. (43), and the time derivative of Eq. (43) has to be satisfied for all \( \tilde{t} \), i.e.,

\[
\frac{\partial^2}{\partial \tilde{t} \partial x_i} \left( \rho_{SB0} \dot{v}_{iSB1} - \frac{\Gamma_2 (\dot{T}_{SB0})}{2} \frac{\partial \dot{T}_{SB0}}{\partial x_i} \right) = -\frac{3}{5} \frac{dP(\tilde{t})}{d\tilde{t}}.
\]

Using Eqs. (30a), (30b), and (33) for the time derivatives \( \partial \dot{\rho}_{SB0}/\partial \tilde{t}, \partial \dot{v}_{iSB1}/\partial \tilde{t}, \) and \( \partial \rho_{SB0}/\partial \tilde{t} \) in Eq. (44), we find that \( \dot{\rho}_{SB2} \) at \( \tilde{t} \) is determined by the equation

\[
\frac{\partial}{\partial x_i} \left( \frac{1}{\rho_{SB0}} \frac{\partial \rho_{SB2}^*}{\partial x_i} \right) + L \left( \frac{\partial \rho_{SB2}^*}{\partial x_i} \right) = \mathbf{F}_n,
\]
where $F_n$ is a given functional of $\rho_{SB0}$, $\bar{v}_{SB1}$, $T_{SB0}$, and their space derivatives, and $L(\partial_\rho^\ast_{SB2}/\partial x_i)$ is a given linear functional of $\partial_\rho^\ast_{SB2}/\partial x_i$, i.e.,

$$L \left( \frac{\partial_\rho^\ast_{SB2}}{\partial x_i} \right) = -\frac{1}{p_0} \int_V \frac{1}{T_{SB0}} \frac{\partial T_{SB0}}{\partial x_i} \frac{\partial_\rho^\ast_{SB2}}{\partial x_i} \, dx \left( \int_V \frac{1}{T_{SB0}} \, dx \right)^{-1}.$$

On a simple boundary, the derivative of $\rho_{SB2}$ normal to the boundary is specified. Thus, $\rho_{SB2}$ is determined except for an additive function of $t$. The solution $\rho_{SB2}$ of Eq. (45) being substituted into Eq. (30b), the result is independent of the additive function. Thus, Eqs. (30a)-(30c) with the first relation in Eq. (31) and the above $\rho_{SB2}$ substituted are reduced to those for $\rho_{SB0}$, $T_{SB0}$, and $\bar{v}_{SB1}$, which naturally determine $\partial_\rho_{SB0}/\partial t$, $\partial T_{SB0}/\partial t$, and $\partial_\bar{v}_{SB1}/\partial t$. Further, if the initial data of $\rho_{SB0}$, $T_{SB0}$, and $\bar{v}_{SB1}$ being chosen in such a way that $\rho_{SB0}T_{SB0}(= \rho_{SB0}) = p_0$ and that Eq. (43) is satisfied, the variation $\partial_\rho_{SB0}/\partial t$ of $\rho_{SB0}(= \rho_{SB0}T_{SB0})$ given by these equations is consistent with Eq. (28), since Eq. (45) or (44) with the condition (43) at the initial state guarantees Eq. (43), i.e., $\partial_\rho_{SB0}/\partial t = \rho_{p0}/\partial t$, for all $t$.

Equations (28) and (30a)-(30c) with Eqs. (31) and (45) determine $\rho_{SB0}$, $T_{SB0}$, $\rho_{SB0}$, $\bar{v}_{SB1}$, and $\rho_{SB2}$, except for an additive function of $t$ in $\rho_{SB2}$, consistently for appropriately chosen initial data. However, these equations are the leading-order set of equations derived by the asymptotic analysis of the Boltzmann equation. The analysis of the higher-order equations not shown here is carried out in a similar way. First, the undetermined additive function in $\rho_{SB2}$ is determined by the condition of invariance of the mass of the gas in the domain at the order after next as $d\rho_0/\partial t$ is determined.

The $\partial_\rho_{SB2}/\partial t$ or $\rho_{SB2}$ determined in this way is indicated by $\partial(\rho_{SB2})_0/\partial t$ or $(\rho_{SB2})_0$. On the other hand, the variation $\partial_\rho_{SB2}/\partial t$ is determined independently by Eq. (37) or the counterpart of Eq. (33) at the order after next. The two results must coincide. The discussion from here is the same as that given from the sentence starting from Eq. (37) to the end of the paragraph. The results are that an additional initial condition and the condition for $\rho_{SB4}$ are introduced, and that the condition (45) for $\rho_{SB2}$ is required only for the initial data. The higher-order consideration does not affect the determination of the solution $\rho_{SB0}$, $T_{SB0}$, and $\bar{v}_{SB1}$ (thus also $\rho_{SB0}$).

In this way, the solution of Eqs. (28), (30a)-(30c) is determined consistently by Eqs. (30a)-(30c) with the aid of the supplementary condition (45), instead of Eq. (28), when the initial data of $\rho_{SB0}$, $T_{SB0}$, and $\bar{v}_{SB1}$ satisfy Eqs. (28) and (43).

### 2.2 Notes on basic equations in classical fluid dynamics

#### 2.2.1 Euler and Navier–Stokes sets

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

---

8The Knudsen-layer correction to $\rho_{SB1}$, already determined (see Footnote 7), contributes to the mass at this order.
The mass, momentum, and energy-conservation equations of fluid flow are given by

\[
\begin{align*}
\frac{\partial p}{\partial t} + \frac{\partial }{\partial X_i} \left( \rho v_i \right) &= 0, \\
\frac{\partial }{\partial t} \left( \rho v_i \right) + \frac{\partial }{\partial X_j} \left( \rho v_i v_j + p_{ij} \right) &= 0, \\
\frac{\partial }{\partial t} \left[ \rho \left( e + \frac{1}{2} v_i^2 \right) \right] + \frac{\partial }{\partial X_j} \left[ \rho v_j \left( e + \frac{1}{2} v_i^2 \right) + v_i p_{ij} + q_j \right] &= 0,
\end{align*}
\]

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.,

\[
p = p(T, \rho), \quad e = e(T, \rho).
\]

Especially, for a perfect gas,

\[
p = R \rho T, \quad e = e(T).
\]

Equations (47) and (48) are rewritten with the aid of Eq. (46) in the form

\[
\begin{align*}
\frac{\partial v_i}{\partial t} + p v_j \frac{\partial v_i}{\partial X_j} + \frac{\partial p_{ij}}{\partial X_j} &= 0, \\
\frac{\partial }{\partial t} \left( e + \frac{1}{2} v_i^2 \right) + p v_j \frac{\partial }{\partial X_j} \left( e + \frac{1}{2} v_i^2 \right) + \frac{\partial }{\partial X_j} \left( v_i p_{ij} + q_j \right) &= 0.
\end{align*}
\]

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

\[
\frac{D}{\!\!\!t} = \frac{\partial }{\partial t} + v_j \frac{\partial }{\partial X_j}.
\]

Multiplying Eq. (51) by \( v_i \) we obtain the equation for the variation of kinetic energy as

\[
\frac{\partial }{\partial t} \left( \frac{1}{2} v_i^2 \right) = -v_i \frac{\partial p_{ij}}{\partial X_j}.
\]

Another form of Eq. (48), where Eq. (53) is subtracted from Eq. (52), is given as

\[
\frac{\partial }{\partial t} \left( e + \frac{1}{2} v_i^2 \right) = -p v_i \frac{\partial v_i}{\partial X_j} - \frac{\partial q_j}{\partial X_j}.
\]

Noting the thermodynamic relation

\[
\frac{D e}{\!\!\!t} = T \frac{D s}{\!\!\!t} + \frac{p}{\rho^2} \frac{D p}{\!\!\!t},
\]

14
where $s$ is the entropy per unit mass, and Eq. (46). Eq. (54) is rewritten as

$$\frac{\rho Ds}{Dt} = -\frac{1}{T} \left[ (p_{ij} - \rho \delta_{ij}) \frac{\partial v_i}{\partial X_j} + \frac{\partial q_i}{\partial X_j} \right]. \quad (56)$$

Equation (56) expresses the variation of the entropy of a fluid particle.

Equations (46)–(49) 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. (46)–(49) where $p_{ij}$ and $q_i$ are given by

$$p_{ij} = \rho \delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - \frac{2}{3} \frac{\partial v_k}{\partial X_k} \delta_{ij} \right) - \frac{\mu_B}{\partial X_k} \delta_{ij}, \quad (57)$$

$$q_i = -\lambda \frac{\partial T}{\partial X_i}, \quad (58)$$

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. (46)–(49) where $p_{ij}$ and $q_i$ are given by

$$p_{ij} = \rho \delta_{ij}, \quad q_i = 0, \quad (59)$$

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

For the Navier–Stokes equations, in view of the relations (57) and (58), the entropy variation is expressed in the form

$$\frac{\rho Ds}{Dt} = \frac{1}{T} \left[ \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - \frac{2}{3} \frac{\partial v_k}{\partial X_k} \delta_{ij} \right)^2 + \mu_B \left( \frac{\partial v_k}{\partial X_k} \right)^2 + \frac{\partial}{\partial X_i} \left( \frac{\lambda}{3} \frac{\partial T}{\partial X_i} \right) \right]. \quad (60)$$

For the Euler equations, for which $p_{ij}$ and $q_i$ are given by Eq.(59), the entropy of a fluid particle is invariant, i.e.,

$$\rho \frac{Ds}{Dt} = 0. \quad (61)$$

9Note the following transformation:

$$\begin{align*}
\frac{\partial v_i}{\partial X_j} & \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - \frac{2}{3} \frac{\partial v_k}{\partial X_k} \delta_{ij} \right) \\
& = \frac{1}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} - \frac{2}{3} \frac{\partial v_k}{\partial X_k} \delta_{ij} \right)^2 + \frac{1}{3} \frac{\partial v_i}{\partial X_j} \delta_{ij} + \frac{1}{3} \frac{\partial v_j}{\partial X_i} \delta_{ij}.
\end{align*}$$

The second term in the last expression is easily seen to vanish.
For an incompressible fluid, the first relation of Eq. (49) is replaced by\(^{10}\)
\[
\frac{D\rho}{Dt} = 0 \text{ or } \frac{\partial \rho}{\partial t} + v_j \frac{\partial \rho}{\partial X_j} = 0.
\]
(62)

Thus, from Eqs. (46) and (62),
\[
\frac{\partial v_i}{\partial X_i} = 0.
\]
(63)

Equation (57) for the Navier–Stokes-stress tensor reduces to
\[
p_{ij} = p\delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right).
\]
(64)

The first term on the right-hand side of Eq. (54) reduces to
\[
-\rho v_j \frac{\partial v_i}{\partial X_j} = - \left[ p\delta_{ij} - \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right) \right] \frac{\partial v_i}{\partial X_j}
= \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2.
\]

Thus, Eq. (54) reduces to
\[
\frac{D\rho}{Dt} = \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \frac{\lambda}{\partial X_j} \right).
\]
(65)

To summarize, the Navier–Stokes equations for incompressible fluid are
\[
\frac{\partial v_i}{\partial X_i} = 0,
\]
(66a)
\[
\rho \frac{Dv_j}{Dt} + \rho v_j \frac{\partial v_i}{\partial X_j} = - \frac{\partial p}{\partial X_i} + \frac{\partial}{\partial X_j} \left[ \mu \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right) \right],
\]
(66b)
\[
\rho \frac{De}{Dt} + \rho v_j \frac{De}{\partial X_j} = \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \frac{\lambda}{\partial X_j} \right).
\]
(66c)

with the incompressible condition (62) being supplemented, i.e.,
\[
\frac{\partial \rho}{\partial t} + v_j \frac{\partial \rho}{\partial X_j} = 0.
\]
(67)

\(^{10}\)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.
2.2.2 Boundary condition for the Euler set

In Section M-3.5, 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

\[
\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} = 0, \tag{68}
\]

\[
u \frac{\partial u}{\partial x} + v \frac{\partial u}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial x}, \tag{69}
\]

\[
u \frac{\partial v}{\partial x} + v \frac{\partial v}{\partial y} = -\frac{1}{\rho} \frac{\partial p}{\partial y}. \tag{70}
\]

where \(\rho\) is the density, which is uniform, \((u, v)\) is the flow velocity, and \(p\) is the pressure. Owing to Eq. (68), the stream function \(\Psi\) can be introduced as

\[
u = \frac{\partial \Psi}{\partial y}, \quad v = -\frac{\partial \Psi}{\partial x}. \tag{71}
\]

Eliminating \(p\) from Eqs. (69) and (70), we have\(^{11}\)

\[
u \frac{\partial \Omega}{\partial x} + v \frac{\partial \Omega}{\partial y} = 0, \tag{72}
\]

where \(\Omega\) is the vorticity, i.e.,

\[
\Omega = \frac{\partial u}{\partial y} - \frac{\partial v}{\partial x} = \frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2}. \tag{73}
\]

From Eqs. (71) and (72),

\[
\frac{\partial \Psi}{\partial y} \frac{\partial \Omega}{\partial x} - \frac{\partial \Psi}{\partial x} \frac{\partial \Omega}{\partial y} = 0. \tag{74}
\]

\(^{11}\)The following equation is formed from them:

\[
\partial \Omega / \partial y - \partial \Omega / \partial x = 0.
\]
This equation shows that $\Omega$ is a function of $\Psi$,
\begin{equation}
\Omega = F(\Psi),
\end{equation}
\(\text{(75)}\)

This functional relation between $\Omega$ and $\Psi$ is a local relation, and therefore $F$ may be a multivalued function of $\Psi$. From Eqs. (73) and (75),
\begin{equation}
\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = F(\Psi).
\end{equation}
\(\text{(76)}\)

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

\begin{equation}
\Omega = \Omega(x, y), \quad \Psi = \Psi(x, y).
\end{equation}
\(\text{(*)}\)

Solving the second equation with respect to $x$, we have
\begin{equation}
x = \hat{x}(\Psi, y).
\end{equation}
\(\text{(**)}\)

With this relation into Eq. (*),
\begin{equation}
\begin{aligned}
\Omega &= \Omega(\hat{x}(\Psi, y), y) = \hat{\Omega}(\Psi, y), \\
\Psi &= \Psi(\hat{x}(\Psi, y), y) = \hat{\Psi}(\Psi, y).
\end{aligned}
\end{equation}
\(\text{(2a) and (2b)}\)

That is, $\Omega$ is expressed as a function of $\Psi$ and $y$. From Eqs. (2a) and (2b),
\begin{equation}
\begin{aligned}
\frac{\partial \hat{\Omega}(\Psi, y)}{\partial y} &= \frac{\partial \Omega(\hat{x}(\Psi, y), y)}{\partial y} = \frac{\partial \Omega(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \Omega(x, y)}{\partial y}, \\
\frac{\partial \hat{\Psi}(\Psi, y)}{\partial y} &= 0.
\end{aligned}
\end{equation}
\(\text{(22a) and (22b)}\)

On the other hand,
\begin{equation}
\begin{aligned}
\frac{\partial \hat{\Psi}(\Psi, y)}{\partial y} &= \frac{\partial \Psi(\hat{x}(\Psi, y), y)}{\partial y} = \frac{\partial \Psi(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \Psi(x, y)}{\partial y}.
\end{aligned}
\end{equation}
\(\text{(4)}\)

Thus,
\begin{equation}
\frac{\partial \Psi(x, y)}{\partial x} \frac{\partial \hat{x}(\Psi, y)}{\partial y} + \frac{\partial \Psi(x, y)}{\partial y} = 0.
\end{equation}
\(\text{(4)}\)

From Eqs. (74), (22a) and (4), we have
\begin{equation}
\frac{\partial \hat{\Omega}(\Psi, y)}{\partial y} = 0, \quad \text{or} \quad \Omega = \hat{\Omega}(\Psi).
\end{equation}
\( \Psi \) and \( s \) on the part \( 0 < s < S_m \), i.e., \( s(\Psi) \), and noting the relation (75), we find that \( F \) is given by

\[
F(\Psi) = \Omega_B(s(\Psi)).
\] (77)

Then, the boundary-value problem is fixed. That is, Eq. (76) is fixed as\(^{13}\)

\[
\frac{\partial^2 \Psi}{\partial x^2} + \frac{\partial^2 \Psi}{\partial y^2} = \Omega_B(s(\Psi)),
\] (78)

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. (73), 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. (65) with \( \mu = \lambda = 0 \), i.e.,

\[
u \frac{\partial c}{\partial x} + v \frac{\partial c}{\partial y} = 0, \quad \text{or} \quad \frac{\partial \Psi}{\partial x} \frac{\partial c}{\partial x} + \frac{\partial \Psi}{\partial y} \frac{\partial c}{\partial y} = 0,
\] (79)

where \( c \) is the internal energy. Thus, \( c \) is a function of \( \Psi \), i.e.,

\[
ce = F_1(\Psi).
\] (80)

In the above boundary-value problem, therefore, \( c \) 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.\(^{14}\)

To summarize, we can specify three conditions for \( \Psi, \Omega \), and \( c \) 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.

### 2.2.3 Ambiguity of pressure in the incompressible Navier–Stokes system

It may be better to note ambiguity of the solution of the initial and boundary-value problem of the incompressible Navier–Stokes equations in a bounded domain of simple boundaries.

\(^{13}\)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.

\(^{14}\)From the second relation on \( c \) of Eq. (49) and the uniform-density condition, the condition on \( c \) can be replaced by the condition on the temperature \( T \).
Consider the Navier–Stokes equations for an incompressible fluid, i.e.,

\[
\frac{\partial v_i}{\partial x_i} = 0, \quad (81a)
\]
\[
\rho \frac{\partial v_i}{\partial t} + \rho v_j \frac{\partial v_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j} \left( \mu \frac{\partial v_i}{\partial x_j} + \frac{\partial v_j}{\partial x_i} \right), \quad (81b)
\]
\[
\rho \frac{\partial e}{\partial t} + \rho v_j \frac{\partial e}{\partial x_j} = \frac{\mu}{2} \left( \frac{\partial v_i}{\partial X_j} + \frac{\partial v_j}{\partial X_i} \right)^2 + \frac{\partial}{\partial X_j} \left( \lambda \frac{\partial T}{\partial X_j} \right), \quad (81c)
\]
\[
\frac{\partial \rho}{\partial t} + v_i \frac{\partial \rho}{\partial x_i} = 0. \quad (81d)
\]

where \(e, \mu, \text{ and } \lambda\) are functions of \(T \text{ and } \rho\).

Consider the initial and boundary-value problem of Eqs. (81a)–(81d) in a bounded domain \(D\) on the boundary \(\partial D\) of which \(v_i\) and \(T\) are specified as \(v_i = v_{wi}\) and \(T = T_w\) \((v_{wi} \text{ and } T_w\) are, respectively, the surface velocity and temperature of the boundary satisfying \(\int_{\partial D} v_{wi} n_i dS = 0, n_i : \text{the unit normal vector to the boundary}\) and no condition is imposed on \(\rho \text{ and } p\). Let \((v_i^{(s)}, \rho^{(s)}, T^{(s)}, p^{(s)})\) be a solution of the initial and boundary-value problem. Let \(P^{(s)}\) be an arbitrary function of \(t\), independent of \(x_i\), that vanishes at initial time \(t = 0\), i.e., \(P^{(s)} = f(t) \text{ with } f(0) = 0\). Put

\[
(v_i, \rho, T, p) = (v_i^{(s)}, \rho^{(s)}, T^{(s)}, p^{(s)} + P^{(s)}).
\]

Then, \(e, \mu, \text{ and } \lambda\) corresponding to the new \((v_i, \rho, T, p)\) are equal to \(e^{(s)}, \mu^{(s)}, \text{ and } \lambda^{(s)}\) respectively, because they are determined by \(\rho \text{ and } T\). The new \((v_i, \rho, T, p)\) satisfy the equations (81a)–(81d) and the initial and boundary conditions.

### 2.2.4 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 “Molecular Gas Dynamics” in connection with the equations derived by the S expansion from the Boltzmann equation in Sections M-3.2.4 and M-3.7.2. Here, we explicitly show the process of analysis from the compressible Navier–Stokes set. The resulting set of equations no longer has ambiguity of pressure in contrast to the incompressible Navier–Stokes set. 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. (M-1.74) in Section M-1.10 as
\( \text{follows:} \)

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

The nondimensional stress tensor \( P_{ij} \), and heat-flow vector \( Q_{ij} \) are expressed as

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

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

\[
\begin{align*}
\mu &= \mu_0 (1 + \bar{\mu}), & \lambda &= \lambda_0 (1 + \bar{\lambda}),
\end{align*}
\]

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. (50)] is expressed as

\[ P = \omega + \tau + \omega \tau. \tag{86} \]

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

\[
\begin{align*}
u_i &= O(\varepsilon), & \omega &= O(\varepsilon), & \tau &= O(\varepsilon), & \text{Sh} &= O(\varepsilon), \\
\frac{\mu_0 (2RT_0)^{1/2}}{p_0 L} &= \gamma_1 \varepsilon, & \frac{\lambda_0 T_0}{L p_0 (2RT_0)^{1/2}} &= \frac{5}{4} \gamma_2 \varepsilon.
\end{align*}
\]

thus,

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

According to the definition of \( u_i \) in Eq. (M-1.74), \( \varepsilon \) is of the order of the Mach number. In view of this and the definition of the Prandtl number \( \text{Pr} = 5R \mu / 2 \lambda \) (see Section M-3.1.9), \( \gamma_1 \) and \( \gamma_2 \) are, respectively, of the orders of \( 1/\text{Re} \) and \( 1/\text{PrRe} \) (\( \text{Re} \): the Reynolds number). According to Eq. (M-1.48a), the condition \( \text{Sh} = O(\varepsilon) \) in Eq. (87a) 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

\[ \text{For a monatomic gas, the bulk viscosity vanishes, i.e., } \mu_B = 0. \]
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 \( t_0 = L/(2RT_0)^{1/2} \) without loss of generality. Then,

\[ \text{Sh} = \varepsilon. \]  

(88)

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

\[ u_i = u_{i1}\varepsilon + u_{i2}\varepsilon^2 + \cdots, \]  

(89a)

\[ \omega = \omega_1\varepsilon + \omega_2\varepsilon^2 + \cdots, \]  

(89b)

\[ P = P_1\varepsilon + P_2\varepsilon^2 + \cdots, \]  

(89c)

\[ \tau = \tau_1\varepsilon + \tau_2\varepsilon^2 + \cdots, \]  

(89d)

\[ \bar{\mu} = \bar{\mu}_1\varepsilon + \bar{\mu}_2\varepsilon^2 + \cdots, \]  

(89e)

\[ \bar{\lambda} = \bar{\lambda}_1\varepsilon + \bar{\lambda}_2\varepsilon^2 + \cdots, \]  

(89f)

\[ P_{ij} = P_{i1}\delta_{ij} + P_{i2}\varepsilon^2 + \cdots, \]  

(89g)

\[ Q_i = Q_{i2}\varepsilon^2 + \cdots. \]  

(89h)

Substituting Eqs. (89a)–(89h) with Eqs. (87b) and (88) into Eqs. (82)–(84) with Eqs. (85a) and (85b), and arranging the same-order terms of \( \varepsilon \), we have

\[ \frac{\partial u_{i1}}{\partial x_i} = 0, \quad \frac{\partial P_1}{\partial x_i} = 0, \quad \frac{\partial u_{i1}}{\partial x_i} = 0, \]

\[ \frac{\partial \omega_1}{\partial t} + \frac{\partial \omega_{1u_{i1}}}{\partial x_i} + \frac{\partial u_{i2}}{\partial x_i} = 0, \]

\[ \frac{\partial u_{i1}}{\partial t} + \frac{\partial u_{i1}u_{j1}}{\partial x_j} + \frac{1}{2} \frac{\partial P_2}{\partial x_i} - \frac{\gamma_1}{2} \frac{\partial}{\partial x_j} \left( \frac{\partial u_{i1}}{\partial x_i} + \frac{\partial u_{j1}}{\partial x_j} - \frac{2}{3} \frac{\partial u_{k1}}{\partial x_k} \delta_{ij} \right) = 0, \]

\[ \frac{3}{2} \frac{\partial P_1}{\partial t} + \frac{\partial}{\partial x_j} \left( \frac{5}{2} u_{i2} + \frac{5}{2} P_{1u_{j1}} - \frac{5}{4} \frac{\partial \tau_1}{\partial x_j} \right) = 0, \]

and so on. At the leading order, the equations derived from Eqs. (82) and (84) degenerate into the same equation \( \partial u_{i1}/\partial x_i = 0 \). 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:

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

(90)
\[
\frac{\partial u_{i1}}{\partial x_i} = 0,
\]
(91a)
\[
\frac{\partial u_{i1}}{\partial t} + u_{j1} \frac{\partial u_{i1}}{\partial x_j} = -\frac{1}{2} \frac{\partial P_2}{\partial x_i} + \frac{\gamma_1}{2} \frac{\partial^2 u_{i1}}{\partial x_j^2},
\]
(91b)
\[
\frac{5}{2} \frac{\partial \tau_1}{\partial t} = \frac{\partial P_1}{\partial t} + 5 \frac{\partial u_{i1}}{\partial x_i} = \frac{5}{4} \gamma_2 \frac{\partial^2 \tau_1}{\partial x_j^2},
\]
(91c)
\[
\frac{\partial u_{i2}}{\partial x_i} = -\frac{\partial \omega_1}{\partial t} - \frac{\partial \omega_1 u_{i1}}{\partial x_i},
\]
(92a)
\[
\frac{\partial u_{i2}}{\partial t} + u_{j1} \frac{\partial u_{i2}}{\partial x_j} + u_{j2} \frac{\partial u_{i1}}{\partial x_j}
\]
\[
= -\frac{1}{2} \left( \frac{\partial P_3}{\partial x_i} - \omega_1 \frac{\partial P_2}{\partial x_i} \right) + \frac{\gamma_1}{2} \frac{\partial}{\partial x_j} \left( \frac{\partial u_{i2}}{\partial x_j} + \frac{\partial u_{i1}}{\partial x_j} + \frac{2}{3} \frac{\partial u_{2j}}{\partial x_k} \delta_{ij} \right)
\]
\[
- \frac{\gamma_1}{2} \frac{\partial^2 u_{i1}}{\partial x_j^2} + \frac{\gamma_1}{2} \frac{\partial}{\partial x_j} \left[ \frac{\mu_1}{2} \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} \right) \right],
\]
(92b)
\[
\frac{3}{2} \frac{\partial P_2}{\partial t} + \frac{3}{2} \frac{\partial u_{i1}}{\partial t} + \frac{3}{2} \frac{\partial P_2}{\partial x_j} + \frac{5}{2} \left( P_1 \frac{\partial u_{i2}}{\partial x_j} - \frac{\partial \omega_1}{\partial t} + \frac{\partial (\omega_1 u_{i2} + \omega_2 u_{j1})}{\partial x_j} \right)
\]
\[
= \frac{5 \gamma_2}{4} \frac{\partial}{\partial x_i} \left( \frac{\partial \tau_2}{\partial x_i} + \lambda_1 \frac{\partial \tau_1}{\partial x_i} \right) + \frac{\gamma_1}{2} \left( \frac{\partial u_{i1}}{\partial x_j} + \frac{\partial u_{j1}}{\partial x_i} \right)^2,
\]
(92c)
where
\[
P_1 = \omega_1 + \tau_1, \quad P_2 = \omega_2 + \tau_2 + \omega_1 \tau_1.
\]
(93)

These equations are very similar to Eqs. (M-3.265)–(M-3.268) [or Eqs. (14)–(17)] obtained by the S expansion of the Boltzmann equation in Section M-3.7.2 (or Section 2.1.1). The solution is determined in the same way as the solution of the S-expansion system is done in Section 2.1.1. What should be noted is the determination of $P_1, P_2, \cdots$ in a bounded-domain problem. They are determined by the condition of invariance of the mass of the gas in the domain with the aid of higher-order equations in the same way as $P_{S1}, P_{S2}, \cdots$ in the S-expansion system (see Section 2.1.1).

In order to compare Eqs. (91a)–(91c) and (93) with the incompressible Navier-Stokes equations (81a)–(81d), we will rewrite the latter equations for the situation where the former equations are derived. The starting equations are Eqs. (82)–(85b)\textsuperscript{16} and the nondimensional form of Eq. (62), i.e.,
\[
\frac{\text{Sh}}{\partial \omega}{\partial t} + u_{i1} \frac{\partial \omega}{\partial x_i} = 0,
\]
(94)
instead of Eq. (86)\textsuperscript{17}. The analysis is carried out in a similar way and the

\textsuperscript{16} As the internal energy $e$, $3RT/2 = 3RT_0(1 + \gamma)/2$ is chosen for consistency.

\textsuperscript{17} From Eqs. (82) and (94), we have $\frac{\partial u_{i1}}{\partial x_i} = 0$. 

23
equations corresponding to Eqs. (91a)–(91c) are:

\begin{align}
\frac{\partial u_{i1}}{\partial x_i} &= 0, \\
\frac{\partial u_{i1}}{\partial t} + u_j \frac{\partial u_{i1}}{\partial x_j} &= -\frac{1}{2} \frac{\partial P_2}{\partial x_i} + \frac{\gamma_1}{2} \frac{\partial^2 u_{i1}}{\partial x_j^2}, \\
3 \frac{\partial \tau_1}{\partial t} + \frac{3}{2} u_{i1} \frac{\partial \tau_1}{\partial x_i} &= \frac{5}{4} \gamma_2 \frac{\partial^2 \tau_1}{\partial x_j^2}.
\end{align}

Equations (95a) and (95b) are, respectively, of the same form as Eqs. (91a) and (91b). Equation (91c) is rewritten with the aid of Eqs. (90) and (93) as

\[
3 \frac{\partial \tau_1}{\partial t} + \frac{3}{2} u_{i1} \frac{\partial \tau_1}{\partial x_i} \left( \frac{\partial \omega_1}{\partial t} + u_i \frac{\partial \omega_1}{\partial x_i} \right) = \frac{5}{4} \gamma_2 \frac{\partial^2 \tau_1}{\partial x_j^2}.
\]

The difference of Eq. (91c) or (96) from Eq. (95c) is

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

which vanishes for an incompressible fluid. The work \( W \) done on unit volume of fluid by pressure, given by \(-p_0(2RT_0)^{1/2}(1 + P)u_i / \partial x_i\), is transformed with the aid of Eq. (92a) in the following way:

\[
\frac{W}{p_0(2RT_0)^{1/2}} = -\frac{\partial (1 + P)u_i}{\partial x_i} = -\frac{\partial u_{i1}}{\partial x_i} \varepsilon - \left( P_1 \frac{\partial u_{i1}}{\partial x_i} + \frac{\partial u_{i2}}{\partial x_i} \right) \varepsilon^2 + \cdots
\]

\[
= -\frac{\partial u_{i2}}{\partial x_i} \varepsilon^2 + \cdots
\]

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

The work vanishes up to the order considered here for an incompressible fluid, because \( \partial u_i / \partial x_i = 0 \) and \( \partial P_j / \partial x_i = 0 \) (see Footnote 18). That is, Eq. (91c) differs from Eq. (95c) by the amount of the work done by pressure.

To summarize, the mass and momentum-conservation equations of the set derived from the compressible Navier–Stokes set when the Mach number and the temperature variation are small are of the same form as the corresponding equations for the incompressible Navier–Stokes set, but the energy-conservation equation differs by the work done by pressure.\(^{19}\) Incidentally, we have already

\(^{18}\)We also obtain \( \partial P_j / \partial x_i = 0 \).

\(^{19}\)When the density \( \rho \) is uniform initially, for which \( \rho \) is a constant for an incompressible fluid, the viscosity and thermal conductivity are constants, and heat production by viscosity is neglected, Eqs. (95a)–(95c) can be compared directly with Eqs. (91a)–(91c) and (98), without carrying expansion, and the same results are obtained.
seen that the pressure in the incompressible Navier–Stokes set has ambiguity of
an additive function of time irrespective of the size of the parameters in contrast
to the pressure in the former set derived from the compressible Navier–Stokes
set.

3 Chapter M-9

3.1 Processes of solution of the equations with the ghost
effect of infinitesimal curvature (July 2007)

The way in which Eqs. (M-9.33)–(M-9.39b) or Eqs. (M-9.49a)–(M-9.50e), including
the time-dependent case with the additional time-derivative terms given
by Eq. (M-9.42) or the mathematical expressions next to Eq. (M-9.59), contain
the pressure terms, \( \dot{p}_{00}, \dot{p}_{02} \) or \( (P_{01}, P_{02}, P_{00}) \), is different from the way
in which the Navier–Stokes equations (M-3.265)–(M-3.266e) do the pressure
terms, \( (P_{31}, P_{32}) \). In Section M-9.4, we consider the time-independent solution
of Eqs. (M-9.49a)–(M-9.50e) [Eqs. (M-9.56)–(M-9.57d)] that is uniform with
respect to \( \chi \). Here, it may be better to explain how a solution of Eqs. (M-9.33)–
(M-9.39b) or Eqs. (M-9.49a)–(M-9.50e) in a general case or a time-dependent
solution that depends on \( \chi \) or \( \chi \) is obtained. Incidentally, the boundary con-
ditions for the time-dependent case are derived in the same way as in Section
M-3.7.3. Naturally from the derivation of the equations, the domain of a gas
is in a straight pipe or channel of infinite length whose axis is in the \( x \) or \( \chi \)
direction.

3.1.1 Equations (M-9.33)–(M-9.39b):

Take Eqs. (M-9.33)–(M-9.39b) with the additional time-derivative terms given
by Eq. (M-9.42), i.e.,

\[
\frac{\partial \dot{p}_{00}}{\partial t} = \frac{\partial \dot{p}_{00}}{\partial y} = 0, \tag{97}
\]

\[
\frac{\partial \dot{p}_{00}}{\partial t} + \frac{\partial \dot{p}_{00} {\hat{v}}_{x0}}{\partial y} + \frac{\partial \dot{p}_{00} {\hat{v}}_{y0}}{\partial y} + \frac{\partial \dot{p}_{00} {\hat{v}}_{z0}}{\partial z} = 0, \tag{98}
\]

\[
\frac{\partial {\hat{v}}_{x0}}{\partial t} + \dot{p}_{00} \left( \frac{\partial {\hat{v}}_{x0}}{\partial y} + \frac{\partial {\hat{v}}_{y0}}{\partial x} + \frac{\partial {\hat{v}}_{z0}}{\partial z} \right) = - \frac{1}{2} \frac{\partial \dot{p}_{00}}{\partial \chi} + \frac{1}{2} \frac{\partial}{\partial y} \left( \Gamma^1 \frac{\partial \hat{v}_{x0}}{\partial y} \right) + \frac{1}{2} \frac{\partial}{\partial z} \left( \Gamma^1 \frac{\partial \hat{v}_{x0}}{\partial z} \right), \tag{99}
\]

\(^{20}\)Equation (M-9.33) is replaced by its equivalent form (97).
\[
\dot{\rho}_{\Theta_0} \frac{\partial \dot{v}_{x\Theta_1}}{\partial t} + \dot{\rho}_{\Theta_0} \left( \ddot{v}_{x\Theta_0} \frac{\partial \dot{v}_{y\Theta_1}}{\partial x} + \ddot{v}_{y\Theta_1} + \dot{v}_{y\Theta_1} \frac{\partial \dot{v}_{y\Theta_1}}{\partial y} + \dot{v}_{z\Theta_1} \frac{\partial \dot{v}_{y\Theta_1}}{\partial z} - \frac{1}{c^2} \dot{v}_{x\Theta_0}^2 \right)
\]

\[
= -\frac{1}{2} \frac{\partial \dot{\rho}_{\Theta_0}^2}{\partial y} + \frac{1}{2} \frac{\partial}{\partial x} \left( \Gamma_1 \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right)
\]

\[
+ \frac{\partial}{\partial y} \left( \Gamma_1 \frac{\partial \dot{v}_{y\Theta_1}}{\partial y} \right) + \frac{1}{2} \frac{\partial}{\partial z} \left[ \Gamma_1 \left( \frac{\partial \dot{v}_{y\Theta_1}}{\partial z} + \frac{\partial \dot{v}_{z\Theta_1}}{\partial y} \right) \right]
\]

\[
+ \frac{1}{2 \rho_{\Theta_0}} \left\{ \frac{\partial}{\partial y} \left[ \Gamma_7 \left( \frac{\partial \dot{T}_{\Theta_0}}{\partial y} \right)^2 \right] + \frac{\partial}{\partial z} \left[ \Gamma_7 \left( \frac{\partial \dot{T}_{\Theta_0}}{\partial y} \right) \right] \right\}
\]

\[
+ \frac{1}{\rho_{\Theta_0}} \left\{ \frac{\partial}{\partial y} \left[ \Gamma_8 \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right)^2 \right] + \frac{\partial}{\partial z} \left[ \Gamma_8 \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right) \right] \right\},
\] (100)

\[
\dot{\rho}_{\Theta_0} \frac{\partial \dot{v}_{y\Theta_1}}{\partial t} + \dot{\rho}_{\Theta_0} \left( \ddot{v}_{x\Theta_0} \frac{\partial \dot{v}_{y\Theta_1}}{\partial x} + \ddot{v}_{y\Theta_1} + \dot{v}_{y\Theta_1} \frac{\partial \dot{v}_{y\Theta_1}}{\partial y} + \dot{v}_{z\Theta_1} \frac{\partial \dot{v}_{y\Theta_1}}{\partial z} \right)
\]

\[
= -\frac{1}{2} \frac{\partial \dot{\rho}_{\Theta_0}^2}{\partial z} + \frac{1}{2} \frac{\partial}{\partial x} \left( \Gamma_1 \frac{\partial \dot{v}_{x\Theta_0}}{\partial z} \right)
\]

\[
+ \frac{1}{2} \frac{\partial}{\partial y} \left[ \Gamma_1 \left( \frac{\partial \dot{v}_{y\Theta_1}}{\partial z} + \frac{\partial \dot{v}_{z\Theta_1}}{\partial y} \right) \right] + \frac{\partial}{\partial z} \left( \Gamma_1 \frac{\partial \dot{v}_{z\Theta_1}}{\partial z} \right)
\]

\[
+ \frac{1}{2 \rho_{\Theta_0}} \left\{ \frac{\partial}{\partial y} \left[ \Gamma_7 \left( \frac{\partial \dot{T}_{\Theta_0}}{\partial y} \right)^2 \right] + \frac{\partial}{\partial z} \left[ \Gamma_7 \left( \frac{\partial \dot{T}_{\Theta_0}}{\partial y} \right) \right] \right\}
\]

\[
+ \frac{1}{\rho_{\Theta_0}} \left\{ \frac{\partial}{\partial y} \left[ \Gamma_8 \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right)^2 \right] + \frac{\partial}{\partial z} \left[ \Gamma_8 \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right) \right] \right\},
\] (101)

\[
\frac{5 \dot{\rho}_{\Theta_0}}{2} \frac{\partial \dot{T}_{\Theta_0}}{\partial t} + \frac{5 \dot{\rho}_{\Theta_0}}{2} \left( \ddot{v}_{x\Theta_0} \frac{\partial \dot{T}_{\Theta_0}}{\partial x} + \ddot{v}_{y\Theta_1} \frac{\partial \dot{T}_{\Theta_0}}{\partial y} + \ddot{v}_{z\Theta_1} \frac{\partial \dot{T}_{\Theta_0}}{\partial z} \right)
\]

\[
- \frac{\partial \dot{\rho}_{\Theta_0}}{\partial t} - \ddot{v}_{x\Theta_0} \frac{\partial \dot{\rho}_{\Theta_0}}{\partial x}
\]

\[
= \frac{5}{4} \frac{\partial}{\partial y} \left( \Gamma_2 \frac{\partial \dot{T}_{\Theta_0}}{\partial y} \right) + \frac{5}{4} \frac{\partial}{\partial z} \left( \Gamma_2 \frac{\partial \dot{T}_{\Theta_0}}{\partial z} \right) + \frac{1}{\rho_{\Theta_0}} \left[ \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial y} \right)^2 + \left( \frac{\partial \dot{v}_{x\Theta_0}}{\partial z} \right)^2 \right],
\] (102)

and the subsidiary relations

\[
\dot{\rho}_{\Theta_0}(\chi, t) = \dot{\rho}_{\Theta_0} \dot{\rho}_{\Theta_0},
\] (103a)
\( \dot{\rho}_{e2} = \dot{\rho}_{e2} + \frac{2\Gamma_1}{3} \left( \frac{\partial \dot{v}_{x e0}}{\partial x} + \frac{\partial \dot{v}_{y e1}}{\partial y} + \frac{\partial \dot{v}_{z e1}}{\partial z} \right) + \frac{\Gamma_7}{3\rho_{e0}} \left[ \left( \frac{\partial \dot{T}_{e0}}{\partial y} \right)^2 + \left( \frac{\partial \dot{T}_{e0}}{\partial z} \right)^2 \right] \)

\[ + \frac{2}{3\rho_{e0}} \left[ \frac{\partial}{\partial y} \left( \Gamma_3 \frac{\partial T_{e0}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_3 \frac{\partial T_{e0}}{\partial z} \right) \right] \]

\[ - \frac{2\Gamma_9}{3\rho_{e0}} \left[ \left( \frac{\partial \dot{v}_{x e0}}{\partial y} \right)^2 + \left( \frac{\partial \dot{v}_{x e0}}{\partial z} \right)^2 \right], \quad (103b) \]

where \( \Gamma_1, \Gamma_2, \Gamma_3, \Gamma_7, \Gamma_8, \) and \( \Gamma_9 \) are short forms of the functions \( \Gamma_1(T_{e0}), \Gamma_2(T_{e0}), \ldots, \Gamma_9(T_{e0}) \) of \( T_{e0} \) defined in Section M-A 2.9.

Consider the solution of the initial and boundary-value problem of Eqs. (97)–(103b).

Let \( \dot{\rho}, \dot{v}, \) and \( \dot{T} \) (thus, \( \dot{\rho} = \dot{\rho}T \)) at time \( t = 0 \) be given; thus, \( \dot{\rho}_{e0}, \dot{v}_{x e0}, \dot{v}_{y e1}, \dot{v}_{z e1}, \dot{T}_{e0} \) etc., including \( \dot{\rho}_{e2} \), are given. Then \( \partial \dot{\rho}_{e0}/\partial t, \partial \dot{v}_{x e0}/\partial t, \partial \dot{v}_{y e1}/\partial t, \partial \dot{v}_{z e1}/\partial t, \) and \( \partial \dot{T}_{e0}/\partial t \) at \( t = 0 \) are given by Eqs. (98)–(103b); thus, the future \( \dot{\rho}_{e0}, \dot{v}_{x e0}, \dot{v}_{y e1}, \dot{v}_{z e1}, \) and \( \dot{T}_{e0} \) (also \( \dot{\rho}_{e0} \)) are determined. However, the future \( \dot{\rho}_{e0} \) is required to be independent of \( y \) and \( z \), as well as \( \dot{\rho}_{e0} \) at \( t = 0 \); owing to Eq. (97). Taking this into account, we will discuss how the solution is obtained by this system consistently.

First, transform Eq. (102) with the aid of Eqs. (98) and (103a) in the following form:

\[ \frac{\partial \dot{\rho}_{e0}}{\partial t} = \mathcal{P}, \quad (104) \]

where

\[ \mathcal{P} = \frac{5}{3} \dot{\rho}_{e0} \left( \frac{\partial \dot{v}_{x e0}}{\partial x} + \frac{\partial \dot{v}_{y e1}}{\partial y} + \frac{\partial \dot{v}_{z e1}}{\partial z} \right) - \dot{v}_{x e0} \frac{\partial \dot{\rho}_{e0}}{\partial x} \]

\[ + \frac{5}{6} \left[ \frac{\partial}{\partial y} \left( \Gamma_2 \frac{\partial \dot{T}_{e0}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_2 \frac{\partial \dot{T}_{e0}}{\partial z} \right) \right] + \frac{2}{3} \Gamma_1 \left[ \left( \frac{\partial \dot{v}_{x e0}}{\partial y} \right)^2 + \left( \frac{\partial \dot{v}_{x e0}}{\partial z} \right)^2 \right], \quad (105) \]

For \( \dot{\rho}_{e0} \) to be independent of \( y \) and \( z \) [see Eq. (97)], \( \mathcal{P} \) as well as the initial data of \( \dot{\rho}_{e0} \) is required to be independent of \( y \) and \( z \). Noting that \( \dot{\rho}_{e0} \) is independent of \( y \) and \( z \), and taking the average of Eq. (105) over the cross section \( S \) of the pipe or channel,\(^21\) we have another expression \( \mathcal{P} \) of \( \mathcal{P} \), explicitly uniform with

\(^{21}\) (i) In a channel, where the gas extends from \( z = -\infty \) to \( z = \infty \), the integral \( \int \mathcal{P} \, dy \, dz \) per unit length in \( z \), per a period in \( z \), etc., should be considered. Otherwise, it can be infinite.

(ii) Note that \( \dot{v}_{y e1} n_y + \dot{v}_{z e1} n_z = 0 \) on a simple boundary where \( n_i = (0, n_y, n_z) \) is the normal to the boundary.
respect to $y$ and $z$, i.e.,

\[
\mathcal{P} = -\frac{5}{3} \frac{\partial \tilde{v}_z \rho_0}{\partial y} \rho_0 - \frac{\partial \tilde{v}_z \rho_0}{\partial y} + \frac{5}{6} \left[ \frac{\partial}{\partial y} \left( \Gamma_2 \frac{\partial \tilde{T}_z \rho_0}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_2 \frac{\partial \tilde{T}_z \rho_0}{\partial z} \right) \right] + 2 \frac{\Gamma_1}{3} \left[ \left( \frac{\partial \tilde{v}_z \rho_0}{\partial y} \right)^2 + \left( \frac{\partial \tilde{v}_z \rho_0}{\partial z} \right)^2 \right],
\]

where

\[ \mathcal{A} = \int_S \mathcal{A} d\rho d\zeta. \]

The expression (106) is noted to be independent of $\dot{v}_y \dot{y}$ and $\dot{v}_z \dot{z}$. The two expressions (105) and (106) must give the same result, i.e.,

\[ \mathcal{P} = \mathcal{P}, \]

or

\[
-\frac{5}{3} \rho_0 \left( \frac{\partial \dot{v}_z \rho_0}{\partial y} + \frac{\partial \dot{v}_y \rho_0}{\partial z} \right) - \dot{v}_z \rho_0 \frac{\partial \tilde{v}_z \rho_0}{\partial y} + \frac{5}{6} \left[ \frac{\partial}{\partial y} \left( \Gamma_2 \frac{\partial \tilde{T}_z \rho_0}{\partial y} \right) + \frac{\partial}{\partial z} \left( \Gamma_2 \frac{\partial \tilde{T}_z \rho_0}{\partial z} \right) \right] + 2 \frac{\Gamma_1}{3} \left[ \left( \frac{\partial \dot{v}_z \rho_0}{\partial y} \right)^2 + \left( \frac{\partial \dot{v}_z \rho_0}{\partial z} \right)^2 \right] = \mathcal{P},
\]

when Eq. (97) holds, and vice versa. The condition (107) for all $\ell$ is equivalently replaced by the two conditions that the initial data of $\dot{p}_0, \tilde{T}_0, \dot{v}_z \rho_0, \tilde{v}_y \dot{y}, \tilde{v}_z \dot{z}$, and $\dot{v}_z \dot{z}$ satisfy Eqs. (97) and (107) and that the time derivative of Eq. (107) holds for all $\ell$, i.e.,

\[ \frac{\partial \mathcal{P}}{\partial \ell} = \frac{\partial \mathcal{P}_0}{\partial \ell}. \]

Using Eqs. (98)–(101) and (104) for $\frac{\partial \tilde{p}_0}{\partial \ell}, \frac{\partial \dot{v}_z \rho_0}{\partial \ell}, \frac{\partial \dot{v}_z \rho_0}{\partial \ell}, \frac{\partial \dot{v}_z \rho_0}{\partial \ell}, \frac{\partial \dot{v}_z \rho_0}{\partial \ell},$ and $\frac{\partial \tilde{p}_0}{\partial \ell}$, we find that $\frac{\partial \mathcal{P}}{\partial \ell}$ is expressed with $\dot{\rho}_0, \tilde{v}_z \rho_0, \tilde{v}_y \dot{y}, \tilde{v}_z \dot{z}, \dot{p}_0,$ and $\tilde{p}_0^2$ in the form

\[
\frac{\partial \mathcal{P}}{\partial \ell} = \frac{5}{6} \dot{\rho}_0 \left[ \frac{\partial}{\partial \dot{y}} \left( \frac{1}{\rho_0} \frac{\partial \tilde{p}_0^2}{\partial \dot{y}} \right) + \frac{\partial}{\partial \dot{z}} \left( \frac{1}{\rho_0} \frac{\partial \tilde{p}_0^2}{\partial \dot{z}} \right) \right] + \text{F}_1, \]

where $\text{F}_1$ is a given function of $\dot{\rho}_0, \tilde{v}_z \rho_0, \tilde{v}_y \dot{y}, \tilde{v}_z \dot{z}, \dot{p}_0$, and their space derivatives. The expression (106) of $\mathcal{P}$ being independent of $\tilde{v}_z \dot{z}$, its time derivative $\frac{\partial \mathcal{P}}{\partial \ell}$ does not contain $\frac{\partial \tilde{v}_y \dot{y}}{\partial \ell}$ and $\frac{\partial \tilde{v}_z \dot{z}}{\partial \ell}$. Therefore, with the aid of Eqs. (98), (99), and (102), $\frac{\partial \mathcal{P}}{\partial \ell}$ is expressed with $\dot{\rho}_0, \tilde{v}_z \rho_0, \tilde{v}_y \dot{y}, \tilde{v}_z \dot{z}, \dot{p}_0$, and their space derivatives, i.e.,

\[
\frac{\partial \mathcal{P}}{\partial \ell} = \text{F}_2(\dot{\rho}_0, \tilde{v}_z \rho_0, \tilde{v}_y \dot{y}, \tilde{v}_z \dot{z}, \dot{p}_0, \text{and their space derivatives}),
\]

28
where $F_{n2}$ is a given functional of its arguments. From Eqs. (108), (109), and (110), we have

$$\frac{\partial}{\partial y} \left( \frac{1}{\rho_{\Theta_0}} \frac{\partial \hat{p}_{\Theta_2}}{\partial y} \right) + \frac{\partial}{\partial z} \left( \frac{1}{\rho_{\Theta_0}} \frac{\partial \hat{p}_{\Theta_2}}{\partial z} \right) = F_n,$$  \hspace{1cm} (111)

where $F_n = 6(F_{n2} - F_{n1})/5\rho_{\Theta_0}$, and therefore, $F_n$ is a given functional of $\rho_{\Theta_0}$, $\hat{v}_{x\Theta_0}$, $\hat{v}_{y\Theta_1}$, $\hat{v}_{z\Theta_1}$, $\rho_{\Theta_0}$, and their space derivatives. This is the equation for $\hat{p}_{\Theta_2}$ over a cross section of the pipe or channel.

The boundary condition for $\hat{p}_{\Theta_2}$ on a simple boundary is obtained by multiplying Eqs. (99)–(101) by the normal $n_t = (0, n_y, n_z)$ to the boundary; in this process, the contribution of their time-derivative terms vanishes because $\hat{v}_{y\Theta_1} n_y + \hat{v}_{z\Theta_1} n_z = 0$; then, the $n_y \partial \hat{p}_{\Theta_2} / \partial y + n_z \partial \hat{p}_{\Theta_2} / \partial z$ is imposed as the boundary condition. Thus, $\hat{p}_{\Theta_2}$ is determined by Eq. (111) except for an additive function of $\bar{t}$ and $\chi$. With this $\hat{p}_{\Theta_2}$ substituted into Eqs. (100) and (101), $\partial \hat{p}_{\Theta_0} / \partial \bar{t}$, $\partial \hat{v}_{x\Theta_0} / \partial \bar{t}$, $\partial \hat{v}_{y\Theta_1} / \partial \bar{t}$, $\partial \hat{v}_{z\Theta_1} / \partial \bar{t}$, and $\partial \rho_{\Theta_0} / \partial \bar{t}$ are determined by Eqs. (98)–(103b) independently of the additive function in $\hat{p}_{\Theta_2}$ in such a way that $\partial (\partial \hat{p}_{\Theta_0} / \partial y) / \partial \bar{t} = 0$, $\partial (\partial \hat{p}_{\Theta_0} / \partial z) / \partial \bar{t} = 0$, and $\partial (\partial \bar{P} / \partial y) / \partial \bar{t} = 0$, $\partial (\partial \bar{P} / \partial z) / \partial \bar{t} = 0$. That is, the solution $(\hat{p}_{\Theta_0}, \hat{v}_{x\Theta_0}, \hat{v}_{y\Theta_1}, \hat{v}_{z\Theta_1}, \bar{T}_{\Theta_0})$ of Eqs. (97)–(103b) is determined by Eqs. (98)–(103b) with the aid of the supplementary condition (111), instead of Eq. (97), when the initial condition for $\rho_{\Theta_0}$, $\hat{v}_{x\Theta_0}$, $\hat{v}_{y\Theta_1}$, $\hat{v}_{z\Theta_1}$, and $\bar{T}_{\Theta_0}$ is given in such a way that $\hat{p}_{\Theta_0} = \rho_{\Theta_0} \bar{T}_{\Theta_0}$ and $\bar{P}$ are independent of $y$ and $z$.

Equations (97)–(103b) are the leading-order set of equations derived by the asymptotic analysis of the Boltzmann equation. The analysis of the higher-order equations not shown here is carried out in a similar way. The equation for $\partial \hat{p}_{\Theta_2} / \partial \bar{t}$, corresponding to Eq. (104), is derived at the order after next. However, owing to the consistency of $\hat{p}_{\Theta_0}$, $\hat{p}_{\Theta_2}$ is already determined by Eq. (111) except for an additive function of $\chi$ and $\bar{t}$. The situation is similar to that at the leading order. That is, $\hat{p}_{\Theta_0}$ and $\hat{p}_{\Theta_2}$ are, respectively, determined by Eqs. (97) and (111), each with an additive function of $\chi$ and $\bar{t}$ and also by Eqs. (104) and the counterpart of Eq. (104) at the order after next. Thus, the higher-order analysis can be carried out in a similar way. The results are that an additional initial condition and an equation for $\hat{p}_{\Theta_2}$, the counterpart of Eq. (111), are introduced and that the condition (111) is required only for the initial data. The higher-order consideration does not affect the determination of the solution $\hat{p}_{\Theta_0}$, $\bar{T}_{\Theta_0}$, $\hat{v}_{x\Theta_0}$, $\hat{v}_{y\Theta_1}$, and $\hat{v}_{z\Theta_1}$ (thus also $\rho_{\Theta_0}$).

To summarize, the solution $(\hat{p}_{\Theta_0}, \hat{v}_{x\Theta_0}, \hat{v}_{y\Theta_1}, \hat{v}_{z\Theta_1}, \bar{T}_{\Theta_0})$ of Eqs. (97)–(103b) is determined by Eqs. (98)–(103b) with the aid of the supplementary condition (111), instead of Eq. (97), when the initial data of $\hat{p}_{\Theta_0}$, $\hat{v}_{x\Theta_0}$, $\hat{v}_{y\Theta_1}$, $\hat{v}_{z\Theta_1}$, and $\bar{T}_{\Theta_0}$ are given in such a way that $\hat{p}_{\Theta_0} = \rho_{\Theta_0} \bar{T}_{\Theta_0}$ and $\bar{P}$ are independent of $y$ and $z$.\textsuperscript{22} The results are not affected by the higher-order analysis.

\textsuperscript{22}If $\bar{P}$ is independent of $y$ and $z$, $\bar{P} = \Psi$ by definition.
3.1.2 Equations (M-9.49a)–(M-9.50e):

Take Eqs. (M-9.49a)–(M-9.50e) with the additional time-derivative terms given in the first mathematical expressions after Eq. (M-9.59), i.e.,

\[
\frac{\partial P_{01}}{\partial x} = \frac{\partial P_{01}}{\partial y} = \frac{\partial P_{01}}{\partial z} = 0, \quad P_{01} = \omega + \tau, \quad \text{(112a)}
\]

\[
\frac{\partial P_{02}}{\partial y} = \frac{\partial P_{02}}{\partial z} = 0, \quad \text{(112b)}
\]

\[
\frac{\partial u_x}{\partial t} + \frac{\partial u_y}{\partial y} + \frac{\partial u_z}{\partial z} = 0, \quad \text{(113a)}
\]

\[
\frac{\partial u_x}{\partial t} + u_x \frac{\partial u_x}{\partial x} + u_y \frac{\partial u_x}{\partial y} + u_z \frac{\partial u_x}{\partial z} = -\frac{1}{2} \frac{\partial P_{02}}{\partial x} + \frac{\gamma_1}{2} \left( \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right), \quad \text{(113b)}
\]

\[
\frac{\partial u_y}{\partial t} + u_x \frac{\partial u_y}{\partial x} + u_y \frac{\partial u_y}{\partial y} + u_z \frac{\partial u_y}{\partial z} = -\frac{1}{2} \frac{\partial P_{02}}{\partial y} + \frac{\gamma_1}{2} \left( \frac{\partial^2 u_y}{\partial y^2} + \frac{\partial^2 u_y}{\partial z^2} \right), \quad \text{(113c)}
\]

\[
\frac{\partial u_z}{\partial t} + u_x \frac{\partial u_z}{\partial x} + u_y \frac{\partial u_z}{\partial y} + u_z \frac{\partial u_z}{\partial z} = -\frac{1}{2} \frac{\partial P_{02}}{\partial z} + \frac{\gamma_1}{2} \left( \frac{\partial^2 u_z}{\partial y^2} + \frac{\partial^2 u_z}{\partial z^2} \right), \quad \text{(113d)}
\]

\[
\frac{\partial \tau}{\partial t} = \frac{2}{5} \frac{\partial P_{01}}{\partial t} + u_x \frac{\partial \tau}{\partial x} + u_y \frac{\partial \tau}{\partial y} + u_z \frac{\partial \tau}{\partial z} = \gamma_2 \left( \frac{\partial^2 \tau}{\partial y^2} + \frac{\partial^2 \tau}{\partial z^2} \right). \quad \text{(113e)}
\]

The qualitative difference of this set of equations from the set (97)–(103b) is the absence of the time-derivative term in Eq. (113a) that corresponds to Eq. (98).

Consider the solution of the initial and boundary-value problem of Eqs. (112a)–(113e). Let \( u_x, u_y, u_z, \) and \( \tau \) at \( t \) be given in such a way that Eq. (113a) is satisfied. Integrating Eq. (113a) over the cross section of the channel or pipe \( \int_S \text{d}y \text{d}z \), we find that \( \int_S u_x \text{d}y \text{d}z \) depends only on \( t \),\(^2\) i.e.,

\[
\int_S \left( \frac{\partial u_x}{\partial x} \right) \text{d}y \text{d}z = 0, \quad \text{(114)}
\]

where \( S \) indicates the cross section. Applying Eqs. (112b), (113a), and (114) to the equation \( \partial \int_S \text{d}y \text{d}z / \partial \chi \), we have \( \partial^2 P_{02} / \partial \chi^2 \) as

\[
\frac{\partial^2 P_{02}}{\partial \chi^2} = \frac{\partial}{\partial \chi} \left[ -\frac{2}{\partial \chi} \left( \frac{\partial^2 u_x}{\partial y^2} + \frac{\partial^2 u_x}{\partial z^2} \right) \right], \quad \text{(115)}
\]

where

\[
\mathcal{A} = \int_S \text{Ad}y \text{d}z / \int_S \text{d}y \text{d}z.
\]

Thus, \( \partial P_{02} / \partial \chi \) and \( P_{02} \) are determined if they are specified at a point in the gas. Here, we consider this case.\(^2\) Using Eq. (113a) in the sum of \( \partial |\text{Eqs. (113b)}| / \partial \chi \),

\(^2\)See Footnote 21, with \( \bar{v}_{y1} \) and \( \bar{v}_{z1} \) being replaced by \( u_y \) and \( u_z \).

\(^2\)\( \text{(i)} \) Imagine the case of the Poiseuille flow.

\(^2\)\( \text{(ii)} \) Here, \( P \) (thus, \( P_{01} \)) is specified at some point. Then, \( P_{01} \) is a given function of \( t \).
\[ \partial \text{[Eqs. (113)]}/\partial y, \text{ and } \partial \text{[Eqs. (113d)]}/\partial z, \text{ we obtain the equation for } P_{20} \text{ in the form} \]
\[
\frac{\partial^2 P_{20}}{\partial y^2} + \frac{\partial^2 P_{20}}{\partial z^2} = F_n(u_x, u_y, u_z, \text{ and their space derivatives}), \tag{116}
\]

where \( F_n \) is a given functional of the variables in the parentheses, and the time derivatives are absent owing to Eq. (113a). Thus, the right-hand side of Eq. (116) is known. This equation is the Poisson equation for \( P_{20} \) over the cross section \( S \). Its boundary condition is obtained in a way similar to how the condition for \( \rho_{\phi 2} \) in Eq. (111) is derived. Thus, \( P_{20} \) over each cross section is determined except for an additive function of \( t \) and \( \tilde{\chi} \). This ambiguity does not influence \( \partial P_{20}/\partial y \) and \( \partial P_{20}/\partial z \).

With \( P_{02} \) and \( P_{20} \) prepared above into Eqs. (113b)–(113e), the time derivatives \( \partial u_x/\partial t, \partial u_y/\partial t, \partial u_z/\partial t, \) and \( \partial \tau/\partial t \) are determined in such a way that \( \partial(\partial u_x/\partial \tilde{\chi} + \partial u_y/\partial y + \partial u_z/\partial z)/\partial t = 0 \) owing to the above choice of \( P_{20} \).\(^{25}\)

Thus, the solution \( (u_x, u_y, u_z, \tau) \) of Eqs. (112b), (113a)–(113e) is determined by Eqs. (113b)–(113e) with the aid of the supplementary conditions (115) and (116) for \( P_{02} \) and \( P_{20} \), instead of Eqs. (112b) and (113a). This process is natural for numerical computation. The undetermined additive function of \( \tilde{\chi} \) and \( \tilde{t} \) in \( P_{20} \), which does not affect the solution \( (u_x, u_y, u_z, \tau) \), is determined by the higher-order equation derived from that for \( \partial \tilde{\psi}_{\phi 2}/\partial \tilde{t} \) (see Section 3.1.1), in a way similar to that in which \( P_{02} \) is determined by Eq. (113b). In the higher-order equation, \( P_{20} \) plays the same role as \( P_{02} \) in Eq. (113b); Equation (116) corresponds to Eq. (112b), and \( P_{20} \) and \( P_{02} \) are determined by these equations, each with an additive function of \( \tilde{\chi} \) and \( \tilde{t} \).

4 Appendix M-A

4.1 Parity of the collision integral: Supplement to M-A 2.7

In Appendix M-A 2.7, we discussed the parity of the linearized collision integral. It may be better to explain a similar property of the collision integral defined by Eq. (M-1.9), i.e.,
\[
J(\hat{f}, \hat{g}) = \frac{1}{2} \int (\hat{f}' \hat{g}' + \hat{f} \hat{g}' - \hat{f}' \hat{g} - \hat{f} \hat{g}') B d\Omega(\alpha) d\zeta, \tag{117}
\]
\[
\hat{B} = \hat{B}(|\alpha V|/|V|, |V|),
\hat{f} = \hat{f}(\zeta), \hat{f}' = \hat{f}(\zeta'), \hat{f} = \hat{f}(\zeta), \hat{f}' = \hat{f}(\zeta'),
\text{ and a similar notation for } \hat{g}, \hat{g}', \text{ and } \zeta',
\zeta = \zeta + \alpha V_j a_i, \zeta' = \zeta - \alpha V_j a_i; \zeta = V_i + \zeta_i.
\]

\(^{25}\)Note that \( P_{01} \) is known [Footnote 24].
Here, we discuss the relation of the parity of \( J(f, g) \) with respect to a component \((\zeta_1, \zeta_2, \text{ or } \zeta_3)\) of the variable \( \zeta \) to that of \( f \) and \( g \). Put the integral (117) in the sum
\[
J(f, g) = \frac{1}{2} (IV + III - II - I),
\]
where
\[
I = \int \hat{f}_s \hat{g} \hat{B} d\Omega(\alpha) dV,
\]
\[
II = \int \hat{f}_s \hat{g} \hat{B} d\Omega(\alpha) dV,
\]
\[
III = \int \hat{f}_s \hat{g} \hat{B} d\Omega(\alpha) dV,
\]
\[
IV = \int \hat{f}_s \hat{g} \hat{B} d\Omega(\alpha) dV,
\]
and discuss each term separately.\(^{26}\) In Eqs. (119a)-(119d), the variable of integration is changed from \( \zeta \) to \( \hat{\nu} (= \zeta - \zeta) \). The following change of the variables
\[
\hat{\nu}_1 = -V_1, \quad \hat{\nu}_s = V_s, \quad \tilde{\alpha}_1 = -\alpha_1, \quad \tilde{\alpha}_s = \alpha_s \quad (s = 2, 3)
\]
is performed in the integrals \( I, II, III \), and \( IV \). Noting that
\[
\zeta_{is} = V_i + \zeta_i, \quad |\hat{\nu}_i| = |V_i|, \quad \tilde{\alpha}_i \hat{\nu}_i = \alpha_i V_i,
\]
we can transform the integrals \( I, II, III, \) and \( IV \) in the following way, where the subscript \( s \) indicates \( s = 2 \) and \( 3 \):
\[
I(\zeta_1, \zeta_s) = \int \hat{f}(V_1 + \zeta_1, V_s + \zeta_s) \hat{g}(\zeta_1, \zeta_s) \hat{B} |\alpha_i V_i| |\hat{\nu}_i| |\nu_i| d\Omega(\alpha) dV
\]
\[
= \int \hat{f}(-\hat{\nu}_1 + \zeta_1, \hat{\nu}_s + \zeta_s) \hat{g}(\zeta_1, \zeta_s) \hat{B} |\tilde{\alpha}_i \hat{\nu}_i| |\hat{\nu}_i| |\nu_i| d\Omega(\tilde{\alpha}) d\hat{\nu}_i;
\]
(122a)

Interchanging the arguments of \( \hat{f} \) and \( \hat{g} \) in \( I \), we have
\[
II(\zeta_1, \zeta_s) = \int \hat{f}(\zeta_1, \zeta_s) \hat{g}(-\hat{\nu}_1 + \zeta_1, \hat{\nu}_s + \zeta_s) \hat{B} |\tilde{\alpha}_i \hat{\nu}_i| |\hat{\nu}_i| |\nu_i| d\Omega(\tilde{\alpha}) d\hat{\nu}_i;
\]
(122b)

\[
III(\zeta_1, \zeta_s) = \int \hat{f}(V_1 + \zeta_1 - \alpha_j V_j \alpha_i) \hat{g}(\zeta_i + \alpha_j V_j \alpha_i) \hat{B} |\alpha_i V_i| |\nu_i| |\nu_i| d\Omega(\alpha) dV
\]
\[
= \int \hat{f}(-\hat{\nu}_1 + \zeta_1 + \tilde{\alpha}_j \hat{\nu}_j \tilde{\alpha}_1, \hat{\nu}_s + \zeta_s - \tilde{\alpha}_j \hat{\nu}_j \tilde{\alpha}_s)
\]
\[
\times \hat{g}(\zeta_1 - \tilde{\alpha}_j \hat{\nu}_j \tilde{\alpha}_1, \zeta_s + \tilde{\alpha}_j \hat{\nu}_j \tilde{\alpha}_s) \hat{B} |\tilde{\alpha}_i \hat{\nu}_i| |\hat{\nu}_i| |\nu_i| d\Omega(\tilde{\alpha}) d\hat{\nu}_i;
\]
(122c)

\(^{26}\)The separation is made only for convenience of explanation.
Interchanging the arguments of \( \hat{f} \) and \( \hat{g} \) in III, we have

\[
IV(\zeta_1, \zeta_s) = \int \hat{f}(\zeta_1 - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \zeta_s + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \\
\times \hat{g}(-\tilde{V}_1 + \zeta_1 + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \tilde{V}_s + \zeta_s - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \\
\times \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V}.
\]  

(122d)

Now we examine the parity of the integrals I, II, III, and IV with respect to \( \zeta_1 \) on the basis of Eqs. (122a)–(122d). Here, we introduce the notation: (i) the parity of \( \hat{f} \) (or \( \hat{g} \)) is indicated by the subscript attached to it, i.e., the subscript \( E \) is attached when it is even and the subscript \( O \) when it is odd; (ii) the first subscript of I, II, III, and IV indicates the parity of \( \hat{f} \) in them and the second indicates the parity of \( \hat{g} \). First, when \( \hat{f} \) and \( \hat{g} \) are even functions of \( \zeta_1 \),

\[
I_{EE}(\zeta_1, \zeta_s) = \int \hat{f}_E(-\tilde{V}_1 + \zeta_1, \tilde{V}_s + \zeta_s) \hat{g}_E(\zeta_1, \zeta_s) \\
\times \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= \int \hat{f}_E(\tilde{V}_1 - \zeta_1, \tilde{V}_s + \zeta_s) \hat{g}_E(-\zeta_1, \zeta_s) \\
\times \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= I_{EE}(-\zeta_1, \zeta_s),
\]  

(123a)

where the last relation holds owing to the first relation of Eq. (122a). Interchanging the arguments of \( \hat{f}_E \) and \( \hat{g}_E \) in \( I_{EE} \), we have

\[
II_{EE}(\zeta_1, \zeta_s) = II_{EE}(-\zeta_1, \zeta_s):
\]  

(123b)

\[
III_{EE}(\zeta_1, \zeta_s) = \int \hat{f}_E(-\tilde{V}_1 + \zeta_1 + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \tilde{V}_s + \zeta_s - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \\
\times \hat{g}_E(\zeta_1 - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \zeta_s + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= \int \hat{f}_E(\tilde{V}_1 - \zeta_1 - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \tilde{V}_s + \zeta_s - \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \\
\times \hat{g}_E(-\zeta_1 + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_1, \zeta_s + \tilde{a}_j \tilde{V}_j \tilde{\alpha}_s) \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= III_{EE}(-\zeta_1, \zeta_s):
\]  

(123c)

Interchanging the arguments of \( \hat{f}_E \) and \( \hat{g}_E \) in \( III_{EE} \), we have

\[
IV_{EE}(\zeta_1, \zeta_s) = IV_{EE}(-\zeta_1, \zeta_s).
\]  

(123d)

When both \( \hat{f} \) and \( \hat{g} \) are odd with respect to \( \zeta_1 \),

\[
I_{OO}(\zeta_1, \zeta_s) = \int \hat{f}_O(-\tilde{V}_1 + \zeta_1, \tilde{V}_s + \zeta_s) \hat{g}_O(\zeta_1, \zeta_s) \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= \int \hat{f}_O(\tilde{V}_1 - \zeta_1, \tilde{V}_s + \zeta_s) \hat{g}_O(-\zeta_1, \zeta_s) \hat{B}(|\tilde{a}_1 \tilde{V}_1|, |\tilde{V}_1|) d\Omega(\tilde{a}) d\tilde{V} \\
= I_{OO}(-\zeta_1, \zeta_s):
\]  

(124a)

33
Interchanging the arguments of \( f_o \) and \( g_o \) in II_{OO}, we have

\[
II_{OO}(\zeta_1, \zeta_s) = II_{OO}(-\zeta_1, \zeta_s); \tag{124b}
\]

\[
III_{OO}(\zeta_1, \zeta_s) = \int f_o(\vec{V}_1 + \zeta_1 + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \vec{V}_s + \zeta_s - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)
\]
\[
\times g_o(\zeta_1 - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \zeta_s + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)
\]
\[
\times \bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= \int f_o(\vec{V}_1 - \zeta_1 - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \vec{V}_s + \zeta_s - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)
\]
\[
\times g_o(-\zeta_1 + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \zeta_s + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= III_{OO}(-\zeta_1, \zeta_s); \tag{124c}
\]

Interchanging the arguments of \( \hat{f} \) and \( \hat{g} \) in III_{OO}, we have

\[
IV_{OO}(\zeta_1, \zeta_s) = IV_{OO}(-\zeta_1, \zeta_s). \tag{124d}
\]

When \( \hat{f} \) is even and \( \hat{g} \) is odd with respect to \( \zeta_1 \),

\[
I_{EO}(\zeta_1, \zeta_s) = \int \hat{f}(\vec{V}_1 + \zeta_1, \vec{V}_s + \zeta_s)\hat{g}(\zeta_1, \zeta_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= - \int \hat{f}(\vec{V}_1 - \zeta_1, \vec{V}_s + \zeta_s)\hat{g}(-\zeta_1, \zeta_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= -I_{EO}(-\zeta_1, \zeta_s); \tag{125a}
\]

\[
II_{EO}(\zeta_1, \zeta_s) = \int \hat{f}(\vec{V}_1, \zeta_s)\hat{g}(-\zeta_1 + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \vec{V}_s + \zeta_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= - \int \hat{f}(-\zeta_1, \zeta_s)\hat{g}(\vec{V}_1 - \zeta_1, \vec{V}_s + \zeta_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= -II_{EO}(-\zeta_1, \zeta_s); \tag{125b}
\]

\[
III_{EO}(\zeta_1, \zeta_s) = \int \hat{f}(\vec{V}_1 + \zeta_1 + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \vec{V}_s + \zeta_s - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)
\]
\[
\times \hat{g}(\zeta_1 - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \zeta_s + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= - \int \hat{f}(\vec{V}_1 - \zeta_1 - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \vec{V}_s + \zeta_s - \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)
\]
\[
\times \hat{g}(-\zeta_1 + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_1, \zeta_s + \vec{\alpha}_j \vec{V}_j \vec{\alpha}_s)\bar{B}(|\vec{\alpha}_i \vec{V}_i|/|\vec{V}_i|, |\vec{V}_i|) d\Omega(\vec{\alpha}) d\vec{V}
\]
\[
= -III_{EO}(-\zeta_1, \zeta_s); \tag{125c}
\]

34
\[ I_{EO}(\zeta_1, \zeta_s) = \int \hat{f}_E(\zeta_1 - \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_1, \zeta_s + \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_s) \]
\[ \times \hat{g}_O(-\tilde{V}_1 + \zeta_1 + \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_1, \tilde{V}_s + \zeta_s - \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_s) \]
\[ \times \hat{B}(|\tilde{\alpha}_1|/|\tilde{V}_1|, |\tilde{V}_s|) d\Omega(\tilde{\alpha}) d\tilde{V} \]

\[ = - \int \hat{f}_E(-\zeta_1 + \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_1, \zeta_s - \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_s) \]
\[ \times \hat{g}_O(-\tilde{V}_1 + \zeta_1 - \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_1, \tilde{V}_s + \zeta_s - \tilde{\alpha}_j \tilde{V}_j \tilde{\alpha}_s) \]
\[ \times \hat{B}(|\tilde{\alpha}_1|/|\tilde{V}_1|, |\tilde{V}_s|) d\Omega(\tilde{\alpha}) d\tilde{V} \]

\[ = -I_{EO}(-\zeta_1, \zeta_s). \quad (125d) \]

For \( I_{IE}, II_{OE}, III_{OE}, \) and \( IV_{OE}, \) interchanging the role of \( \hat{f} \) and \( \hat{g}, \) respectively, in \( II_{EO}, I_{EO}, IV_{EO}, \) and \( III_{EO}, \) we have

\[ I_{OE}(\zeta_1, \zeta_s) = -I_{OE}(\zeta_1, \zeta_s), \quad (126a) \]
\[ II_{OE}(\zeta_1, \zeta_s) = -II_{OE}(\zeta_1, \zeta_s), \quad (126b) \]
\[ III_{OE}(\zeta_1, \zeta_s) = -III_{OE}(\zeta_1, \zeta_s), \quad (126c) \]
\[ IV_{OE}(\zeta_1, \zeta_s) = -IV_{OE}(\zeta_1, \zeta_s). \quad (126d) \]

The parity is common to \( I, II, III, \) and \( IV. \) Therefore, the parity of \( \hat{J}(\hat{f}, \hat{g}) \)

is the same as \( I, \) i.e.,

\[ \hat{J}(\hat{f}_E, \hat{g}_E)(\zeta_1, \zeta_s) = \hat{J}(\hat{f}_E, \hat{g}_E)(-\zeta_1, \zeta_s), \quad (127a) \]
\[ \hat{J}(\hat{f}_O, \hat{g}_O)(\zeta_1, \zeta_s) = \hat{J}(\hat{f}_O, \hat{g}_O)(-\zeta_1, \zeta_s), \quad (127b) \]
\[ \hat{J}(\hat{f}_E, \hat{g}_O)(\zeta_1, \zeta_s) = -\hat{J}(\hat{f}_E, \hat{g}_O)(-\zeta_1, \zeta_s), \quad (127c) \]
\[ \hat{J}(\hat{f}_O, \hat{g}_E)(\zeta_1, \zeta_s) = -\hat{J}(\hat{f}_O, \hat{g}_E)(-\zeta_1, \zeta_s). \quad (127d) \]

Obviously, the same parity holds for the other components, i.e., \( \zeta_2, \zeta_3, \) of \( \zeta. \)

(Section 4.1: Version 4-00)