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INTRODUCTION

KAZUO AOKI

This article is to describe briefly the career and research of Professor Yoshio Sone. Since “Sone sensei” (Japanese polite form of address, more or less corresponding to “Teacher Sone”), rather than Prof. Sone, is used normally among three of the guest editors, we will adhere to this Japanese form throughout this Introduction.

Sone sensei has been an outstanding and leading scientist for more than four decades in the field of molecular gas dynamics (or kinetic theory of gases) and has made crucial contributions to the development of the field. His first papers ([2, 5, 6, 7] in the list of publications attached at the end of this Introduction) quickly impressed Harold Grad, who immediately invited him to visit Courant Institute of Mathematical Sciences, New York University for two years. Currently, he has published around 130 research papers, each of which contains new ideas, beautiful analysis and/or accurate numerical results, and deep physical insights. After retirement, he published two books ([145, 146]), consisting mostly of the results of his own research. These books contain many materials not found in any other books, and are becoming classics in physical and mathematical sciences. His deep knowledge in mathematics, physics, and engineering has facilitated his extensive cooperation and discussions with mathematicians, physicists, and engineers. In the last decade, he had stronger interaction with mathematicians, and many of them have been impressed and guided by his mathematical insight based on deep physical understanding. This is why three of the present guest editors are mathematicians, and a mathematical journal was selected for the present publication.

Sone sensei graduated from Kyoto University (Department of Aeronautical Engineering, Faculty of Engineering) in 1959 and finished the Master Course of the same university (Department of Aeronautical Engineering, Graduate School of Engineering) in 1961. After the positions of Research

Associate (1961), Lecturer (1963), Associate Professor (1966), he was appointed as Professor in 1979 in the same department. As a faculty member of Kyoto University, he received the degree of Doctor of Engineering in 1965. Retiring from Kyoto University in 2000, he is now Professor Emeritus. He was Research Fellow at Courant Institute of Mathematical Sciences, New York University (1966-1968), and subsequently Visiting Professor at many leading foreign universities (University of Paris 6, University of Paris 7, Politecnico di Milano, University of Parma, etc.). He was also invited to many international conferences and schools to give lectures and courses (Sectional Lecture at 15th ICTAM (Toronto, 1980), Harold Grad Lecture at 20th International Symposium on Rarefied Gas Dynamics (Beijing, 1996), David Enskog Memorial Lecture at Royal Institute of Technology (Stockholm, 1997), CIMPA School-Kinetic Equations: From Theory to Applications (Taipei, 2004) among others). Sone sensei was a member of International Advisory Committee, International Symposia on Rarefied Gas Dynamics (1984-2000) and is a member of Advisory Editorial Board of Modeling and Simulation in Science, Engineering and Technology, Birkhäuser. In 1991, he organized the 4th International Workshop on Mathematical Aspects of Fluid and Plasma Dynamics (MAFPD) in Kyoto, Japan. Through these activities, and by inviting numerous outstanding scientists from abroad, he has made significant contributions to international scientific exchanges.

Molecular gas dynamics (or kinetic theory of gases) deals with rarefied gas flows (gas flows in low-density circumstances or in micro scales), and its fundamental equation is the Boltzmann equation. In such flows, there is a key parameter, called the Knudsen number. It is defined by the ratio of the molecular mean free path (the average of the distance over which a molecule can move without collision with other molecules) to the characteristic length of the considered system, and can in principle take any positive value. In ordinary circumstances (i.e., in a system of ordinary size under the atmospheric pressure), the Knudsen number is practically zero. The mathematical limit of vanishing Knudsen number is called the continuum or fluid-dynamic limit, and the classical fluid dynamics is supposed to be valid there. Therefore, molecular gas dynamics is not a special branch of fluid dynamics, but covers much wider class of flows than the latter. We now give a brief summary of Sone sensei's work on molecular gas dynamics, focusing on several key topics.

1. Asymptotic Theory of the Boltzmann System for Slightly Rarefied Gases

This subject has always been the mainstream of Sone sensei's research. For slightly rarefied gas flows, i.e., for gas flows at small Knudsen numbers, Sone sensei established a method of systematic asymptotic analysis of the steady boundary-value problem of the Boltzmann equation for arbitrary geometry (with smooth boundaries). The method consists of a Hilbert-type expansion for the overall solution and the analysis of its correction in a thin layer with thickness of several mean free paths adjacent to the boundary (the so-called Knudsen layer). The asymptotic analysis provides the fluid-dynamic-type equations, their appropriate boundary conditions, and the corrections to the solution of the fluid-dynamic-type system in the Knudsen layer. This sophisticated thinking yields a recipe, by which one can solve the boundary-value problems of the Boltzmann equation with the same tractability as the classical fluid dynamics. In two important papers in the early stage [14, 20], he considered the case of small Reynolds numbers as well as that of finite Reynolds numbers. For small Reynolds numbers, he was able to derive the so-called slip boundary conditions for the Stokes system of equations up to the second order in Knudsen number. He showed that the first-order condition consists of the shear slip, thermal creep, and temperature jump and that the second-order condition contains the effects of boundary curvature and a velocity slip caused by imbalance of the thermal stress. It should be noted that seminal ideas for this general work were already contained in his earlier papers [2, 5, 6, 10]. For finite Reynold numbers, he showed that the leading-order equations are the so-called incompressible Navier–Stokes equations by the expansion, the Sone expansion, based on a crucial parameter setting, which was rediscovered by mathematicians more than a decade later. However, he also pointed out in his books [145, 146] the subtle but definite difference between these equations and the true incompressible Navier–Stokes equations. As always, the consideration of Sone sensei is more than analytical, and this is an example of his deep physical insight. The publication of the paper [112] for the remaining case of high Reynolds numbers completed the study of the asymptotic theory. In the process of its development, the theory has been extended to other physical situations and led to the creation of new types of fluid dynamics, which will be mentioned later. It also brought new discoveries, such as the presence of the thermal stress slip flow [20, 22, 25, 39] and the sub layer, the Sone layer, at the bottom of the Knudsen layer [23, 83]. The details of the asymptotic theory, together with its extension, are found in Sone sensei's two books [145, 146].

2. Flows of a Vapor with Phase Transition at the Interfaces between the Vapor and Its Condensed Phases

When flows of a vapor around its condensed phases are considered, phase transition (evaporation and condensation) of the vapor may take place at the interface between the vapor and the condensed phase. In such flows, the classical fluid dynamics are not valid anymore even for small or vanishing Knudsen numbers, since the gas deviates significantly from a local equilibrium state near the interface. Sone sensei applied the asymptotic theory described above to such flows at small Knudsen numbers. He derived correct fluid-dynamic-type systems (consisting of fluid-dynamic type equations, their boundary conditions, and the corrections in the Knudsen layers) for different Reynolds numbers [33, 37, 76, 77]. In particular, if one considers the continuum limit of the vanishing Knudsen number, the limiting systems provide new types of fluid dynamics for the vapor flows with phase transition, which cannot be derived within the framework of classical fluid dynamics. In the process of this research, he has clarified physical mechanisms of several fundamental phenomena, such as the negative temperature gradient [33] and the difference between evaporation and condensation in a half space [34, 111].

In the mid-1980's, Sone sensei started extensive numerical analysis in addition to his analytical approach. It was timely because the computer capability had then reached the level that enabled accurate computation of solutions of the Boltzmann and its model equations. In fact, by extensive numerical computation, he has clarified many fundamental properties of vapor flows with evaporation and condensation, such as evaporation from and condensation onto a plane condensed phase [51, 57, 58, 69, 78], strong evaporation from a spherical and a cylindrical condensed phase [79, 85, 93].

Here, special mention should be made of the half-space problem. The above-mentioned works [34, 51, 57, 58, 69, 78] revealed that there is a parameter relationship that allows a steady solution, and its form differs depending on whether the gas evaporates or condenses and whether the condensation speed is subsonic or supersonic in the case of condensation. That is, bifurcation of solution takes place at zero and sonic condensation speed. This finding has interested several leading mathematicians and motivated their mathematical study of the problem. This was also the start of Sone sensei's close interaction and collaboration with these and other mathematicians (see, e.g., [86, 105, 112, 115, 127, 128]). The mathematical study of the half-space problem has continued to this day.

3. Finding of New Types of Flow and Their Experimental Verification

One of the key subjects throughout Sone sensei's research is the coupling between velocity and temperature fields in rarefied gases, in particular, gas flows induced by the temperature fields. An example is the thermal creep flow, which is induced along the boundary from a cold to a hot part. In fact, in a short paper early in his career [11], he gave its first formulation based on the Boltzmann equation and solved it numerically. This paper was the origin of several papers on related subjects published later [12,18,64,65,128]. Sone sensei also found some new types of flow with the help of the asymptotic theory and numerical analysis. Examples include the flow induced by the second-order slip due to the imbalance of the thermal stress there (thermal stress slip flow) [20,22,25,39,81] and the flow caused by a heated (or cooled) sharp edge (thermal edge flow) [96,101]. Remarkably, he was able to perform experiments to observe the latter flow [101], as well as the thermal creep flow [73,90], using very simple facilities. In addition, he devised an arrangement to cause a one-way flow with pumping effect in a channel without average temperature or pressure gradient [98,117] and confirmed it experimentally [113,116]. Subsequently, he constructed vacuum pumps without any moving parts using this arrangement [118] and the above-mentioned thermal edge flow [126]. One of the manifestations of the thermally driven rarefied gas flows is the thermophoresis, i.e., the motion of an aerosol particle in a stationary gas with a temperature gradient. After he found the unusual negative thermophoresis [22], this became another important subject of Sone sensei's research [30, 40, 91, 94].

4. Statics of a Highly Rarefied Gas

If the gas is so rarefied that the Knudsen number can be assumed to be infinitely large, one can neglect the collision term of the Boltzmann equation. Such a gas is called free molecular gas or Knudsen gas. Since this simplification is dramatic, most of the fundamental properties of the gas had been clarified in the early stage of the modern kinetic theory. Nevertheless, Sone sensei found an exact solution that describes the behavior of a stationary free molecular gas (i.e., a free molecular gas without macroscopic flow) around bodies of arbitrary shape, with arbitrary temperature distribution, and with arbitrary accommodation coefficients [44, 46, 47, 48]. From this very surprising finding, the statics of the free-molecular gas was established. He applied this exact solution to compute forces acting on the heated or cooled bodies in complicated configurations and heat transfer from the gas to the bodies [43, 49, 50, 52].

5. Ghost Effect and Defects of Classical Fluid Dynamics

It had been commonly accepted that the behavior of a gas in the continuum limit, where the Knudsen number vanishes, is described correctly by the classical fluid dynamics. However, Sone sensei pointed out that in some common situations, the classical fluid dynamics fails to describe the behavior of the gas even in the continuum limit. For example, the temperature field in a stationary gas (e.g., a gas in a stationary container with arbitrary temperature distribution along the wall) is commonly considered to be described by the steady heat-conduction equation. If one considers the same situation for small Knudsen numbers, a flow with Mach number of the order of the Knudsen number occurs in general. This flow, which vanishes in the continuum limit, has a finite effect on the temperature distribution in the gas. Therefore, the temperature field is not given by the heat-conduction equation. Sone sensei pointed out this fact and gave the correct fluid-dynamic type equations and their boundary conditions by the asymptotic analysis mentioned in the first Section [97]. This finding, which he named the ghost effect [100], was a shocking discovery that reveals an essential defect contained in the classical fluid dynamics. By calling it the ghost effect, Sone sensei warned if we live only in the narrow world of continuum theory, we cannot see the essence of physical phenomena.

The ghost effect is a manifestation of the fact that the continuum limit is a singular limit of the Boltzmann equation. The solution of the Boltzmann equation in the limit is not unique and depends on the limiting process. The problems of rarefied gas dynamics generally contain various parameters, such as the Mach number, Froude number, and accommodation coefficients, in addition to the Knudsen number. If we consider the continuum limit in the situation where one of the other parameters vanishes together with the

Knudsen number, then the effect of the parameter may remain finite in the continuum limit though the parameter itself vanishes. The vanishing parameter can be chosen either artificially by ourselves or naturally by the problem. In the above example of the temperature distribution in the stationary gas, the other vanishing parameter, which is naturally chosen by the problem, is the Mach number. The ghost effect has been investigated extensively in the subsequent papers by Sone sensei, and several interesting and non-intuitive phenomena have been clarified [99, 100, 110, 122, 123]. Among them are the deformation of the temperature field caused by the vanishing Bénard convection [122] and by the vanishing Taylor vortices [123]. The most recent discovery is an effect caused by an infinitesimal curvature of the boundary in plane Couette flow [124]. The solutions bifurcate from the conventional plane Couette flow by the effect of infinitesimal curvature. This was obtained analytically as well as numerically. In particular, Sone sensei pointed out that, in the case of the incompressible Navier–Stokes equations, the bifurcation takes place at infinite Reynolds number. This finding clinched one of the long-lasting problems in classical fluid dynamics. The instability of the plane Couette flow as well as that of the plane Poiseuille flow caused by the effect of infinitesimal curvature has been studied in Sone sensei's recent papers [125, 129]. It should be emphasized that all these studies have been performed along the line of the asymptotic theory described in Section One.

6. Stability and Bifurcation of Rarefied Gases

Sone sensei has also been interested in the stability and bifurcation of rarefied gas flows. Already in the 1990's, he studied the basic stability problem, such as Bénard problem and Taylor–Couette problem, for a rarefied gas numerically [95, 102, 107, 109]. On the other hand, bifurcation analysis of the fluid-dynamic type systems derived by the asymptotic theory played a crucial role in the analysis of the ghost effect in [122, 123, 124] mentioned above. Prior to these works, he showed that cylindrical Couette flow of a vapor, which is uniform in the axial and circumferential directions, exhibits flow bifurcation when evaporation and condensation take place on the cylinders through numerics [106, 108, 119] and analysis [114]. The bifurcations obtained by the asymptotic theory in the latter paper have motivated the current rigorous mathematical studies of the phenomena.

Future scientists will find it fruitful to continue the research field of molecular gas dynamics by reading Sone sensei's two books.

List of Publication of Sone Sensei

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