

Preface

This present book is concerned with two important aspects of non-equilibrium evaporation and condensation processes: the molecular kinetic theory of phase transition and the dynamics of a vapor bubble in a superheated liquid.

The problems pertaining to the processes of intense phase change (evaporation and condensation) are of great interest both from a theoretical and from a practical point of view. Exposure of materials to laser radiation may lead to strong evaporation from the heated sections, which is accompanied by active condensation on the cooled parts. Development of space hardware calls for the study of singularities of flows that may appear in the evaporation of a coolant or as a consequence of its leak. A hypothetical root cause may be the loss of leak integrity of the containment shell of a nuclear engine due to thermal overloads in the course of a spaceflight. Exposure to the solar radiation on a comet surface results in the evaporation of its ice nucleus with the formation of atmosphere. Depending on the distance to the Sun, the intensity of evaporation varies a great deal and may reach huge values. The process of evaporation, which is sharply varying with time, has a great effect on the density of the comet atmosphere and the character of its motion.

The majority of phase change problems are studied within the approximation to thermodynamic equilibrium. However, in a number of cases, one has to take into account gas-phase non-equilibrium phenomena on the phase interface consequent on molecular kinetic effects. Theoretical analysis of non-equilibrium phenomena depends on the Boltzmann equation, which for many years, due to its very involved structure, had been looked upon as a mathematical abstraction. Labuntsov [1] laid the foundation of the linear kinetic theory and studied for the first time the phase changes from the theoretical point of view on the basis of the Boltzmann equation. This theory was further developed by Loyalka [2] and Siewert [3].

A phase change in which the flow velocity is comparable with the sonic one is called the strong evaporation or strong condensation. Theoretical studies of such processes may be conventionally subdivided into two directions. In the strong (“microscopic”) approach, one solves numerically the Boltzmann equation (or its simplified “relaxation” analogues) to determine the distribution function of its molecules in velocities. Using the distribution function, one calculates the

distributions of the velocity, pressure, and temperature in the vapor near the phase interface. Among recent studies in this direction, we mention the papers by Gusarov and Smurov [4], Frezzotti and Ytrehus [5], and Frezzotti [6]. In turn, the approximation (“macroscopic”) approach calls for the solution of the system of mass, momentum, and energy conservation equations of the molecular fluxes, which is augmented by various approximations of the distribution function. As a result, one obtains general analytical expressions for the distributions of gas-dynamic parameters away from the phase interface. Here, one may mention the studies by Anisimov [7], Labuntsov and Kryukov [8], Ytrehus [9], Rose [10], as well as the studies by the author of this present book.

The phenomenon of gas (vapor) bubbles in a liquid, in spite of the fluctuation character of their nucleation and short lifetime, has a wide spectrum of manifestations: underwater acoustics, sonoluminescence, ultrasonic diagnostics, decreasing friction by surface nanobubbles, nucleate boiling, etc. The most important application of the bubble dynamics is the effervescence of a liquid superheated with respect to the saturation temperature. This results in the initiation and growth of nuclei of a new (vapor) phase in liquid. An ideal subject of investigation of this phenomenon is the spherically asymmetric growth of the vapor bubble in the volume of a uniformly superheated liquid.

Labuntsov proposed a systematic approach to the problem of the vapor bubble growth in a superheated liquid. The growth rate in the general case was shown as being dependent on four physical effects: (a) viscous resistance of the medium displaced by the bubble; (b) inertial reaction of the liquid to the swelling of the bubble in it; (c) non-equilibrium effects at the interface; and (d) the mechanism of heat transfer from the superheated liquid to the bubble boundary. Taking into account the action of each of the factors under the assumption that the influence of the others is absent leads to “limiting schemes” of the bubble growth.

In this present book, we perform the next step by changing to “binary” schemes of growth that describe the simultaneous effect of two principal factors on the growth of a bubble: inertial reaction of the liquid and heat transfer from the superheated liquid. We describe the effect of “pressure blocking” in the vapor phase, when the superheating enthalpy exceeds the phase transition heat.

The problem of non-equilibrium evaporation and condensation processes will be the underlying theme of this entire book. Moreover, each chapter, which will be concerned with some or other aspects of this general problem, is practically self-contained and can be studied independently. The author has deliberately followed this approach in the organization of this book, which leads to certain “self-intersection” of some chapters and, as a consequence, to some “overweighting” of this book. However, here I am convinced that in the present digital era the reader ought to be given a possibility of the independent familiarization with the chosen topic. Such a presentation of the material is aimed at releasing the reader from wearisome paging through this book in searching for references scattered over the entire volume of this book. This is why each chapter contains a separate reference list and a separate list of symbols (in case their number is fairly large).

The title of the books suggests that it is concerned solely with analytical methods of solution. Analytical solutions of the fluid flow and heat transfer problems play a significant role even in the current computer age:

- The value of the analytical approach consists in the opportunity of the closed qualitative description of the process, revealing the full list of dimensionless characteristic parameters and their hierarchical classification based on the criteria of their importance.
- Analytical solutions possess a necessary generality, so that a variation of the boundary and inlet conditions allows one to carry out parametrical investigations.
- In order to validate numerical solutions of the full differential equations, it is necessary to have basic analytical solutions of the equations for some obviously simplified cases after an estimation and omission of negligible terms.

Chapter 1 provides a short introduction to the topic. We give a short history of the development of the molecular kinetic theory and the discussion around the Boltzmann equation. An exact solution of the Boltzmann equation is presented. Processes of intensive phase change are briefly discussed.

Chapter 2 is concerned with non-equilibrium effects on the phase interface. We give the conservation equations of molecular flows of mass, momentum, and energy and describe the classical problem of evaporation into a vacuum. We present the fundamentals of the linear kinetic theory and give a short introduction to the problem of strong evaporation.

Chapter 3 is devoted to the approximate kinetic analysis of strong evaporation. The author's mixing model is presented. On this basis, we give analytical solutions for temperatures, pressures, and mass velocities of vapor and match them with the available numerical and analytical solutions. We also calculate the evaporation limiting mass velocity.

Chapter 4 proposed a semiempirical model of strong evaporation based on the linear kinetic theory. Here, it proved possible to achieve a pretty good agreement with the results of numerical and approximate analytical solutions for monatomic and polyatomic gas and also for the limit mass flux.

In Chap. 5, the approximate kinetic analysis of strong condensation is considered. As in Chap. 3 we shall use the mixing model of strong condensation. We give solutions for the sonic and supersonic condensations. The analytical solution demonstrates a good agreement with available simulation data.

In Chap. 6, the mixing model is used for the analysis of linear kinetic problems of phase transition. The asymmetry of evaporation and condensation, which occurs for intensive processes, remains even for the case of linear approximation. The dependence of the vapor pressure on its temperature is shown as having a minimum near the margin between the anomalous and normal regimes of condensation.

Chapter 7 is concerned with the spherically symmetric growth of a vapor bubble in an infinite volume of a uniformly superheated liquid. Following Labuntsov, we considered the influence of each effect within the framework of the following four

“limiting schemes”: (a) dynamic viscous; (b) dynamic inertial; (c) energetic molecular kinetic (non-equilibrium); and (d) energetic thermal. A problem on the description of the limiting schemes of bubble growth is presented. As the next step, we come to “binary” schemes of growth that describe the simultaneous effect of two factors on the growth of a bubble.

Chapter 8 proposed a “pressure blocking effect” in the growing vapor bubble in a highly superheated liquid. The known Plesset–Zwick formula has been generalized to the region of strong superheating. The problem for the conditions of the experiment on the effervescence of the butane drop has been solved. An algorithm for calculating was proposed for constructing an approximate analytical solution under conditions when the enthalpy of the superheating of which exceeds the phase transition heat.

Chapter 9 provides an evaporating meniscus on the interface of three phases. An approximate solving method is presented capable of finding the influence of the molecular kinetic effects on the geometric parameter of the meniscus and on the heat transfer intensity. Analytical expressions for the evaporating meniscus parameters are obtained from the analysis of interaction of the intermolecular, capillary, and viscous forces, and the study of the molecular kinetic effects.

Chapter 10 is concerned with kinetic effects for a spheroidal state. The kinetic pressure with respect to a levitating droplet is shown to have either “repulsing” or “attracting” character depending on the value of the coefficient of evaporation/condensation. We also put forward an analytical dependence for the vapor film thickness with the consideration of molecular kinetic effects. The asymptotic formula for the solution is written down for the exotic case when the coefficient of evaporation/condensation tends to zero.

Chapter 11 provides a vapor condensation upon transversal flow around a cylinder. An analysis of the limiting heat exchange laws is given. Analytical solutions for the laws were obtained, which correspond to the effect of only one factor: gravity, longitudinal pressure gradient, interfacial friction. The results of the solution were presented as relative heat exchange laws with respect to the case of steady-state vapor.

Appendix A considers the problem of heat transfer under film boiling. We obtain analytical solutions capable of taking into account the effects of vapor superheat in a film and the influence of the convection on the effective values of thermal conductivity and heat of phase transition of superheated vapor.

Appendix B presents the results of experimental investigation of heat transfer in a pebble bed for flows of single-phase boiling liquid. Use was made of a method of processing of experimental data, which enables one to determine the coefficient of “pseudo-turbulent” thermal conductivity without differentiation of the experimentally obtained temperature profile. Temperature profiles were obtained for the case of boiling on the pebble bed wall, and qualitative analysis of these profiles was performed.

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In conclusion, I cannot but stress the most crucial role played in my career by the prominent Russian scientist Prof. Labuntsov who was my scientific advisor. I would consider my task accomplished if in this book I was able to develop some of Prof. Labuntsov's ideas that could lead to some new modest results.

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