Critical Regimes of Two-Phase Flows with a Polydisperse Solid Phase

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Annotation

This book brings to light peculiarities of the formation of critical regimes of two-phase flows with a polydisperse solid phase. A definition of entropy is formulated on the basis of statistical analysis of these peculiarities. The physical meaning of entropy and its correlation with other parameters determining two-phase flows are clearly defined. The interrelations and main differences between this entropy and the thermodynamic one are revealed. The main regularities of two-phase flows both in critical and in other regimes are established using the notion of entropy. This parameter serves as a basis for a deeper insight into the physics of the process and for the development of exhaustive techniques of mass exchange estimation in such flows.

The book is meant for university students of engineering specialties studying two-phase flows. It can also be of use to those working for a doctor's degree, and to scientists and engineers engaged in specific problems of such fields as chemical technology, mineral dressing, modern ceramics, microelectronics, pharmacology, power engineering, thermal engineering, etc. using flows with solid particles in their respective production methods.

Introduction

Two-phase flows are widely used in applications of systems analysis to problems encountered in all segments of modern industry. A special category of systems is the one that contains discrete formations distributed in a continuum. These discrete formations consist of either solid particles of constant shape and size, or liquid drops or gas bubbles that can change their size in the course of a process, whereas the continuum in which they exist is either liquid or gaseous. Modern technology's concern with two-phase flows is caused by a large contact surface of dispersed and continuous phases ensuring high velocities of mass transfer and other processes. The simplest among them are dispersed systems containing a solid phase – in a certain sense, they can be used as simplified models of systems containing drops and gas bubbles.

As shown in Fig. 1, two-phase flows can be of various kinds depending on the correlations between the velocities of the continuum and the solid phase particles contained therein.

A so-called transport regime is realized at flow rates ensuring the ascent of the entire solid phase. Its velocity is limited from below by the value at which even the coarsest particles do not settle against the flow. The minimal value of this velocity is called the critical pneumatic or hydraulic transport velocity depending on the continuum used – air or water.

An opposite regime of two-phase flows with the formation of a so-called descending layer is also used in some technologies. In this regime, all solid particles settle against the flow. In this case, the flow velocity is limited from above. The maximal velocity at which even the finest particles of solid phase are not transported by the flow is called critical for the descending layer. A particular case of a descending layer is a so-called motionless layer; in this case, solid material lies motionless on a grating and is blown through from below.

The ratio of these critical velocities is of certain theoretical and practical interest from the point of view of mass exchange processes within their range. For instance, the velocity of a boiling bed process, which is widely used in present-day technology, lies within this range, which points to the importance of studying such flow regimes. Critical regimes of two-phase flows are most widely used in industry for

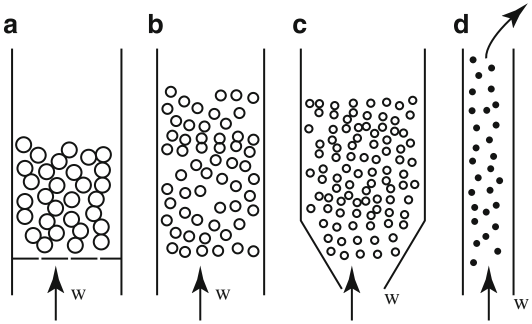

Fig. 1 Various regimes of two-phase critical flows: (**a**) motionless layer, (**b**) incident layer, (**c**) boiling layer, (**d**) pneumatic transport and separation regime

fractionating bulk materials according to particle sizes or densities. Only such regimes allow transportation of fine lightweight particles with the flow and a simultaneous motion of coarse heavy particles against the flow. Until now, these processes have not been sufficiently studied and formalized.

Critical regimes of two-phase flows can be realized not only in vertical flows, but also in a centrifugal field, fields of magnetic and electrostatic forces and in other situations with the solid phase motion directed differently with respect to the flow.

Separation of bulk materials in critical regimes of two-phase flows is an extremely complicated physical process. Its complicated character is caused by oppositely directed motions and mutual influence of an enormous quantity of particles of various sizes in the carrier medium flows, whose structure is extremely inhomogeneous. Such motions give rise to a broad range of various random factors. The most important among them are hydrodynamic and contact interactions of particles in the flow and with the walls confining the flow; unpredictable non-uniformity of the flow velocity and pressure fields; solid phase distribution within the flow; nature of the interactions between the phases; as well as the discrete component effect on the continuum motions. Among these factors are also principal parameters of real bulk materials, such as particle size, shape, weight, density, size grade distribution, all of which are random values.

All these complexities make any attempt to formulate a rigorous analytical description of the process completely hopeless. As well known, there is no acceptable analytical theory as yet even for a single-phase turbulent flow. The more so, there are no analytical solutions for two-phase flows. Thus researchers have usually studied the main regularities of such processes and then formalized the experimental data obtained from them at a semi-empirical theoretical level. This follows the usual pattern in science of dealing with the evolution from simpler to more complicated notions.

Initially, the study of the process under consideration in this book started from the analysis of the behavior of isolated particles. The first works on the topic were published in the second half of the nineteenth century. Rittinger established the regularities of simple deposition of isolated particles of spherical shape in an unbounded motionless liquid. In many subsequent works related to deposition, the influence of various factors was revealed, such as medium and material density, final velocities of particles deposition, their resistance coefficients, etc.

At the same time, the transition to working with real materials consisting of particles of irregular shape proved to have additional complications. Articles are still being published nowadays reflecting a variety of approaches to these problems. We have ample evidence that even the phenomena occurring during a simple deposition of particles of real materials in a motionless medium are very complicated.

Attempts to apply the main regularities obtained in the studies of isolated particles in a flow to actual processes have not provided generalized results. In fact, proceeding from this standpoint, one has to admit that an ascending flow can carry out of the separation zone only those particles whose deposition velocity is below the flow velocity. On the contrary, all the particles with deposition velocity exceeding the flow velocity are deposited against the flow.

However, experience shows that in bulk materials fractionating, this is not the case. Thus, we have to admit that although the problem of, e.g., powders separation in flows has been studied for more than a century, it has not reached the theoretical level suitable for solving practical problems. Therefore, commercial needs often continue to be satisfied by extensive empirical studies. Usually, the principal characteristics of a separation process under industrial conditions will be obtained on a laboratory model or a pilot plant. The obtained parameters are then extended to a working industrial unit. Because of imperfect modeling, it is not always successful.

An enormous number of experimental studies performed in recent years have made it possible to develop many empirical methods of estimating principal parameters for specific units. Beyond any doubt, these studies are important. However, researchers do not always realize that empirical methods influence only slightly the development of the theory of the process.

Empirical dependencies differ from theoretical ones; they do not naturally follow from the regularities of the phenomena under study, but only quantitatively reflect them. Even a carefully conducted experiment does not allow taking into account various permanent and random factors, both quantitative and qualitative ones. One can manage to specify, to some extent, the average effect of quantitative factors only by increasing the number of experiments. As for qualitative factors, their effect is mainly beyond all estimations.

Even the best and the most grounded empirical formula can be applied with a satisfactory result only within a limited range determined by the conditions of its derivation. Rather often, extrapolation beyond the limits of the experimental range is carried out on the basis of such dependencies, but it can result in gross errors. Application of empirical dependencies is also limited in time, since they cannot take into account the forthcoming development of science and technology. Some attempts have been made to refine calculated relationships from previous research and adjust them to present-day knowledge by introducing various correction factors. However, application of a large number of more or less arbitrarily chosen factors leads to the accumulation of errors, as well known in the effects of multiple round-off in even simple calculations.

Recent decades have produced certain achievements in the development of various aspects of two-phase flow theory. However, for the solid phase distribution in critical regimes of two-phase flows, the situation is different. Beyond any doubt, it is one of the most complicated and intricate theoretical issues, and it is, as a rule, either left out or examined on the basis of empirical relationships only. This practice can be easily observed in recent review monographs and handbooks.

In the present book, we attempt to solve this problem from a somewhat different standpoint. Usually, two-phase flows are considered, in the first place taking into account peculiar properties of a continuum motion altered by solid particles placed into this continuum. We are making an attempt to use the laws of solid phase mass motion as a basis of critical regimes of motion.

It is practically impossible to describe simultaneous mass motion of solid particles in a non-uniform continuum flow from the standpoint of classical mechanics. It is well known that classical mechanics developed by Newton, Lagrange and Hamilton can predict the behavior of either an ordered system of bodies or a system with a moderate number of elements. On this basis, one can obtain an exact solution of a celestial mechanics problem easily enough, but the three-body problem has not yet been solved in a general form.

Meanwhile, there exists a statistical approach to the study of mass continuum phenomena that has been developing for more than 100 years. The works of Boltzmann and Gibbs, which have already become classical, laid the basis of this approach. Its principal ideas were widely used and developed in quantum mechanics and its applications to optics, theory of magnetism, solid state theory and other fields of science. They have become corner stones in the foundations of the state-of-the-art knowledge in these fields. The principal distinctive feature of this approach is that it is based on a definition of the state of the entire system, no matter whether one examines a large or a small system comprising an infinite number of particles or a single particle.

Here the methods of analyzing mass processes (involving a large number of particles) are considered as essentially statistical ones. Data obtained as a result of such analysis should be considered as averaged over an ensemble, but not as absolutely rigorous in each case. This inevitably follows from the nature of a statistical approach, which is applicable either in the absence of the necessary initial data or when practical solutions are very complicated. To justify statistical methods, it should be emphasized that they should finally lead to conclusions consistent with experimental data.

Here the basic point is how to determine average values. Instead of time averaging within a single system, it is possible to examine a set of a large number of respectively organized systems. An ensemble of systems represents a mental structure reflecting the properties of a real system. It consists of a large number of similarly organized systems, each system of the ensemble being equivalent to a real system.

The theory of L. Boltzmann was based on the notion that a molecule of gas consists of ideal balls of the same diameter placed into a closed volume, and their velocity is determined by the temperature of the medium. Such a simplified model allowed Boltzmann to develop a well-composed statistical theory of gases, which in many respects agrees with experimental data.

In recent decades, interest in this theory has been growing in two aspects. On the one hand, a large number of researches expanding Boltzmann's theory have appeared. On the other hand, principal ideas and methods of this theory have been successfully applied to other non-gaseous systems, such as solid-state theory, nuclear matter, magnetism, polymerization, etc.

These efforts have given additional support to the well-known principle that the physically grounded method of analogies is extremely fruitful for the development of science. We make an attempt in this book to apply certain ideas of this theory to the problem under study. Critical regimes of solid phase flow form the basis of this problem. Therefore we start with the analysis of solid particle characteristics and dynamics, as well as with the analysis of all achievements in the empirical study of two-phase critical flows.

We make one additional remark. Physics, hydraulics, mineralogy, etc. provide a conceptual tool and phenomenological approach to the analysis of the phenomena under study. Mathematics is not only a tool for the analysis of these processes. It determines, in many respects, ways and methods of this analysis, constituting the main line of scientific thought. Therefore, mathematical transformations are presented in the book in detail, so that the problem setting, derivation and analysis of the obtained results are clear. It is not always reasonable to give a final result without its derivation, because in the course of solving a particular problem, one often comes across instructive techniques and even intermediate results.

The book is intended for a broad circle of research specialists including students of respective specialties. Therefore, the mathematical apparatus is intentionally used in its simplest version, corresponding to the level of students of the first degree in engineering sciences.

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