1 Introduction

Two-phase flow is generally understood as being a simultaneous flow of two different immiscible phases separated by an infinitesimal thin interface. Phases are identified as “homogeneous” parts of the fluid for which unique local state and transport properties can be defined. In most cases, phases are simply referred to as the state of matter, e.g. gas/vapor, liquid, or solid. Typical examples are the flow of liquid carrying vapor or gas bubbles, or the flow of gas carrying liquid droplets or solid particles. However, more complex flow processes may exist where the phase distribution is less well defined.

Two-phase flow is of large relevance for many scientific/technical disciplines ranging from environmental research to the modeling of normal operation or accident conditions in nuclear, chemical, or process engineering installations. For a long time, the analysis of two-phase flow processes was limited to mostly empirical correlations or to largely simplified engineering models and, therefore, two-phase flow was considered as a rather “dirty” branch of fluid dynamics. This situation has changed significantly during the last two decades when a large effort was spent for the analysis of two-phase flow systems and for the development of related numerical simulation methods. Much of this work was stimulated by the specific requirements for the safety analysis of pressurized water reactors which, for obvious reasons, relies largely on the prediction capability of computer codes for complex two-phase flow and heat transfer processes.

Many of the present advanced models for the description of nonhomogeneous nonequilibrium two-phase flow are related to the two-fluid approach using separate mass, momentum, and energy equations for the two phases. These separate conservation equations are obtained in a volume and/or time averaging process starting from the local instantaneous conservation equations of the individual phases. In the averaging procedure important information on local flow processes is lost and, consequently, additional correlations are needed in order to close the system of equations. Most of these closure relations are of empirical nature or include some heuristic elements which cannot be deduced completely from first principles.

The correct formulation of the basic two-fluid equations and the appropriate form of the closure laws have been controversially discussed during the past, and up to now, there does not exist a commonly agreed approach. A specific concern has been that most models presently used in the large computer codes are based on governing equations having complex eigenvalues and, therefore, do not represent a mathematically “well-posed” initial-boundary value problem. Nevertheless, there seems to be a common agreement that the pure transport or Euler part of the governing system of equations should be of hyperbolic nature. The necessity

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for the hyperbolicity of the governing equations of the two-fluid model has several aspects, including the following:

- any transient flow process might be seen as a response to perturbations manifesting themselves in wave propagation phenomena as characterized by the hyperbolic nature of the governing equations,
- nonhyperbolic models suffer from high wave-number instabilities and, therefore, require explicit damping mechanisms in the numerical algorithms with the consequence of excessive numerical diffusion and artificial viscosity effects,
- the existence of a hyperbolic system of equations is an essential condition for the application of advanced numerical methods such as Approximate Riemann Solver or Flux Vector Spitting techniques which make explicit use of the eigenstructure of the flow equations.

There have been various tentative proposals for a “hyperbolic two-fluid model” characterized by the existence of only real eigenvalues and a corresponding set of independent eigenvectors. The hyperbolicity is usually obtained by adding interfacial momentum coupling terms having time and/or spatial derivatives of governing parameters. Often, these terms cannot be deduced completely from first principles and, therefore, can be verified only indirectly. This approach might be justified as long as (1) there is a clear physical background for these additional closure terms, and (2) the effect of these terms on the predicted results is fully plausible. For all the present investigations of wave propagation processes a newly developed hyperbolic two-fluid model will be used which will be described in detail in Chapter 5.

Before dealing with complex two-phase flow conditions, it was felt worthwhile to recall a few facts about single-phase gasdynamics. This is done in Chapter 2, which also introduces the basic methodology for the characteristic analysis of the flow equations as used throughout the book.

The basic features and limitations of the two-fluid approach for two-phase flow are summarized in Chapter 3. A more detailed derivation of the corresponding balance equations for the two-fluid model is provided in Appendix A, based on the concept of a phasic distribution function and its differential form having the property of the Dirac delta function at the interface.

In Chapter 4, simplified two-phase models, based on the assumption of mechanical equilibrium (equal phase velocities) and thermal equilibrium (equal phasic temperatures), are analyzed. Although these models have only a limited value for practical applications, they are of interest as limiting cases for detailed two-phase models dealing with more complex flow conditions.

Chapter 5 is devoted to the development of an improved “hyperbolic” two-fluid model for nonhomogeneous, nonequilibrium flow conditions as forming the basis for the subsequent analysis of wave propagation phenomena in two-phase media. A specific feature of the model is the presence of explicit algebraic formulations for the complete eigenspectrum of the flow equations including eigenvalues and related right and left eigenvectors. A complete reference for the hyperbolic model is provided in Appendix B, including all relevant information on the coefficient matrices, various forms of the source term vector, right and left eigenvectors, and the characteristic form of basic flow equations.

Chapter 6 deals with the propagation and attenuation of sound waves in two-phase media. Based on the acoustic approximation a dispersion relation is derived describing the dependence of sound velocity and attenuation on the frequency of sound waves. Although the results of the dispersion analysis do not directly enter into the numerical simulation, they are of large importance for the understanding of pressure wave propagation processes in two-phase flow and the occurrence of shock waves and critical flow conditions.

Chapter 7 summarizes some basic features of numerical methods for hyperbolic conservation laws and their adaptation for two-phase flow processes.

The numerical results as presented in Chapter 9 cover a wide spectrum of typical two-phase flow phenomena at low and high Mach numbers. Where appropriate, a comparison with analytical solutions or existing experimental data is included. All results shown have been obtained with the Advanced Two-Phase Flow Module (ATFM), a computer code developed at the European Commission's Joint Research Centre in Ispra, based on the hyperbolic two-phase flow model and related numerical methods as described in Chapters 5 and 7. The basic physical modeling and applied numerical features of the ATFM code are briefly outlined in Chapter 8.

In Chapter 10 summarizing conclusions are given together with an perspective with regard to future developments for two-phase flow modeling and related numerical simulation strategies.