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A.Y. Varaksin

Turbulent Particle-Laden Gas Flows

With 105 Figures

Springer

Professor Dr. Aleksej Y. Varaksin
Institute for High Temperatures
Russian Academy of Sciences
13/19 Izhorskaya street, 125412 Moscow, Russia
E-mail: varaksin_a@mail.ru

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Preface

Turbulent air flows, which carry solid particles, occur widely in nature and find application in numerous fields of human activities. For several decades now, gas–solid heterogeneous flows have been attracting researchers' attention. Quite extensive theoretical and experimental data have been accumulated to date, which are devoted to diverse aspects of gas dynamics and thermophysics of such flows [1–34].

The presence of even an insignificant amount of a disperse impurity in flows of gas media may cause undesirable effects. As a result, the study of such flows and the development of mechanics of heterogeneous media become extremely urgent.

In spite of great interest shown by numerous teams of researchers the world over in studying heterogeneous flows and of the large number of papers on the subject, the currently available theory of multiphase turbulent flows is inadequate. This is apparently due to two reasons. First, the theory of single-phase turbulent flows of continuous media is at present far from being complete. Second, the addition of a disperse impurity in the form of particles to a turbulent flow (complex as this flow is) causes a serious complication of the flow pattern. This is first of all associated with the great diversity of the properties of particles being introduced, which results in the realization of numerous flow modes of the gas suspension. By varying the concentration of particles (which is the main extensive characteristic of heterogeneous flows), one can change both qualitatively the parameters of initial flow and of particle motion and accomplish qualitative restructuring of the flow (for example, the transition of laminar flow mode to turbulent, as well as inverse effect, i.e., relaminarization of flow). Because of this, the experimental and theoretical investigation techniques employed in the classical mechanics of single-phase continuous media more often than not are unfit for use in studying heterogeneous flows. The available experimental data are often fragmentary and contradictory, while the physical concepts and developed mathematical models cannot be recognized as adequate. The foregoing factors impede the development of the mechanics of heterogeneous media. Nevertheless, the practical needs and the logic of scientific development demand continuous perfection of the theory of heterogeneous flows.

This monograph deals with problems associated with the hydrodynamics of turbulent flows of air in the presence of solid particles in pipes (channels) and under conditions of flow past bodies. The closest in content to this book is the monograph by Shraiber et al. [22]. The problems treated there have found further development in this book.

The first, introductory, chapter contains brief information about turbulent single-phase wall flows, which is essential for the understanding of the problems treated in the book. This information is borrowed from the available literature sources and is in no way original. Also given in the first chapter are the main characteristics of gas flows with particles, and the suggested classification of heterogeneous turbulent flows is described.

Two subsequent chapters deal with basic approaches and methods of mathematical and physical simulation of heterogeneous flows. The entire history of development of natural science confirms the mutual importance and interdependence of theoretical and experimental investigation techniques. In constructing the theory of any physical phenomenon (however, complex or simple it might seem to be at first glance), one must not underestimate the importance of some or other methods of investigation. The foregoing is well supported by the entire history of development of the theory of turbulent single-phase and multiphase flows. In recent years, in view of rapid development of computer equipment, mathematical simulation techniques (numerical methods) have come to play an important part in the development of the theory of two-phase flows. The use of these methods enables one to solve systems of complex differential equations and obtain detailed information about the fine structure of heterogeneous flows. Rapid progress in computer development gave a powerful impetus to the development of experimental investigation techniques. The use of high-speed processors makes possible the measurement of fine structure characteristics of heterogeneous flows in real time.

The second chapter contains the description of presently available methods of mathematical simulation of gas flows with solid particles. Analysis is made of the validity of some or other approaches for studying particleladen flows of different classes in accordance with the classification given in the first chapter.

In the third chapter, the problems of physical simulation of heterogeneous flows are treated. The fundamentals of laser Doppler anemometry (LDA) are described: during the last several decades, this method has become one of the most extensively used means of fine diagnostics of single-phase flows. A wide range of metrological problems, which arise during investigations of heterogeneous flows using this method are discussed. Such problems include the optimization of the parameters of the optoelectronic system of laser Doppler anemometers for measuring the instantaneous velocity of large particles of the dispersed phase, the development of the procedure for correct measurement of the velocity of substantially polydisperse particles, the elaboration of the principles of signal selection required for studying the inverse effect of particles on the characteristics of carrier air flow, the development of the procedure for measurement of the concentration of particles, and so on. Along with the description of the techniques employed in the LDA diagnostics of heterogeneous flows, much attention is given to the problems associated with the theoretical and experimental monitoring of the measurement results. Examples of experimental apparatuses for studying flows of air with particles are given at the end of the chapter, as well as the description of the principle of selection of characteristics of solid particles which are used in the investigation of heterogeneous flows as the disperse phase.

The fourth chapter treats the motion of disperse phase and characteristic features of interphase processes under conditions of gas flow with solid particles in channels (pipes). The results of experimental investigations of gas-solid flows in channels are described for heterogeneous flows of different classes. Analysis is made of the data of measurements of distributions of averaged and fluctuation velocities of particles in a wide range of the particle concentration. Special attention is given to the experimental and theoretical study of one of the fundamental problems in the mechanics of multiphase media, namely, the problem of modification by the particles of the turbulent energy of the carrier phase. Analysis is made of the results of experimental investigation involving, for the first time in the “pure” state (the presence of particles did not affect the profile of averaged velocity of the carrier phase), a study of the process of additional dissipation of turbulence in a flow with relatively low-inertia particles. The modification of the turbulent energy by particles is studied theoretically. The mathematical model, which enables one to determine the values of additional generation and dissipation of turbulence in flows with particles is described. The calculations involving the use of this model made possible the generalization of the available data on the modification of the turbulent energy of carrier gas by particles in a wide range of variation of the concentration and inertia of these particles.

In the fifth chapter, the characteristic features of gas flows with particles past bodies are described. Analysis is made of the available data on the behavior of particles in the vicinity of the critical point of bodies of different shapes subjected to flow, as well as on the effect of particles on the characteristics of the carrier phase. The effect of various factors (particle inertia, Saffman force, etc.) on the deposition of particles is treated. Much attention is given to the description of singular features of heterogeneous flow in the boundary layer developing along the surface of a body. The experimental data on the distribution of velocities of “pure” air, air with particles, and solid particles proper in all regions of the boundary layer developing along the surface of the model, i.e., laminar, transition, and turbulent regions, are treated and analyzed. It is demonstrated that the presence of particles in the flow precipitates the beginning of the laminar–turbulent transition. The effect of the particles on the intensity of turbulence of carrier air in the turbulent boundary layer is treated. The experimental data on the distribution of the velocities of incident particles and particles reflected from the body surface are described and analyzed. The size of the region of existence of the "phase" of reflected particles is determined for the inertia of the dispersed phase varying in a wide range. The behavior of particles repeatedly interacting with the body surface is studied.

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Moscow, April 2007 *Aleksei Y. Varaksin*

Contents

Symbols

Dimensional quantities

D – pipe diameter, m
R – pipe radius, m
r – distance from the pipe axis, m
l – Prandtl–Nikuradse mixing length, m
ρ – density of gas, $\mathrm{kg\,m^{-3}}$
ρ_p – density of the particle material, $\mathrm{kg\,m^{-3}}$
d_p – particle diameter, m
x, y, z – axial, radial, and azimuthal Cartesian coordinates, m
x, r, φ – axial, radial, and azimuthal cylindrical coordinates, m
N – numerical concentration of particles, $\mathrm{m^{-3}}$
u_i – components of instantaneous velocity of gas, $\mathrm{m\,s^{-1}}$
v_i – components of instantaneous velocity of particle, $\mathrm{m\,s^{-1}}$
U_i – components of averaged velocity of gas, $\mathrm{m\,s^{-1}}$
V_i – components of averaged velocity of particle, $\mathrm{m\,s^{-1}}$
u'_i – components of fluctuation velocity of gas, $\mathrm{m\,s^{-1}}$
v'_i – components of fluctuation velocity of particle, $\mathrm{m\,s^{-1}}$
u_* – dynamic velocity, $\mathrm{m\,s^{-1}}$
t – instantaneous temperature of gas, K
t_p – instantaneous temperature of particle, K
T – averaged temperature of gas, K
T_p – averaged temperature of particle, K
t' – fluctuation temperature of gas, K
t'_p – fluctuation temperature of particle, K
p – instantaneous pressure, Pa
P – averaged pressure, Pa
p' – fluctuation pressure, Pa
μ – coefficient of dynamic viscosity, $\mathrm{Ns\,m^{-2}}$
ν – coefficient of kinematic viscosity, $\mathrm{m^{2}\,s^{-1}}$
λ – thermal conductivity coefficient of gas, $\mathrm{W\,m^{-1}K^{-1}}$

λ_{p} – thermal conductivity coefficient of the particle material, $\mathrm{W\,m^{-1}K^{-1}}$
C_p – heat capacity of gas, $\mathrm{J\,kg^{-1}K^{-1}}$
$C_{p_{\mathrm{p}}}$ – heat capacity of the particle material, $\mathrm{J\,kg^{-1}K^{-1}}$
a – thermal diffusivity of gas, $\mathrm{m^2\,s^{-1}}$
g – acceleration of gravity, $\mathrm{m\,s^{-2}}$
k – turbulent energy of gas, $\mathrm{m^2\,s^{-2}}$
k_0 – turbulent energy of gas in the absence of particles, $\mathrm{m^2\,s^{-2}}$
k_p – energy of velocity fluctuations of particles, $\mathrm{m^2s^{-2}}$
ε – rate of dissipation of turbulent energy, $\mathrm{m^2\,s^{-3}}$
τ – time, s
τ_{p} – time of dynamic relaxation of particle, s
$\tau_{\mathrm{p_0}}$ – time of dynamic relaxation of Stokesian particle, s
τ_{t} – time of thermal relaxation of particle, s
$\tau_{\mathrm{t_0}}$ – time of thermal relaxation of Stokesian particle, s
T_{f} – characteristic time of gas in averaged motion, s
T_{L} – characteristic time of gas in large-scale fluctuation motion, s
τ_{K} – characteristic time of gas in small-scale fluctuation motion (Kolmogorov timescale of turbulence), s
τ_{w} – shear stress on the wall, Pa

Dimensionless quantities

m – instantaneous mass concentration of particles
M – averaged mass concentration of particles
m' – fluctuation mass concentration of particles
φ – instantaneous volume concentration of particles
$\varPhi$ – averaged volume concentration of particles
φ' – fluctuation volume concentration of particles
Re_{D} – Reynolds number
Re_{x} – local value of the Reynolds number, calculated by longitudinal coordinate
$\widetilde{Re}_{\mathrm{p}}$ – instantaneous value of the Reynolds number of particle
Re_{p} – averaged value of the Reynolds number of particle
Re'_{p} – fluctuation value of the Reynolds number of particle
Stk_{f} – Stokes number in averaged motion
Stk_{L} – Stokes number in large-scale fluctuation motion
Stk_{K} – Stokes number in small-scale fluctuation motion
γ – Karman constant
C_{D} – coefficient of aerodynamic drag of particle
C_{x0} – body drag coefficient
$C_{x_{\mathrm{p}}}$ – coefficient of body drag due to the effect of particles
C_{f} – coefficient of friction

Indexes

$\langle\cdots\rangle$ – averaging over the cross-sectional area of the pipe (channel)
$(\overline{\cdots})$ – time averaging, relative value
$(\cdots)'$ – fluctuation value

Subscripts

c – value on the pipe (channel) axis
w – value on the pipe (channel) wall
0 – value in external flow, value in the absence of particles
m – modified value