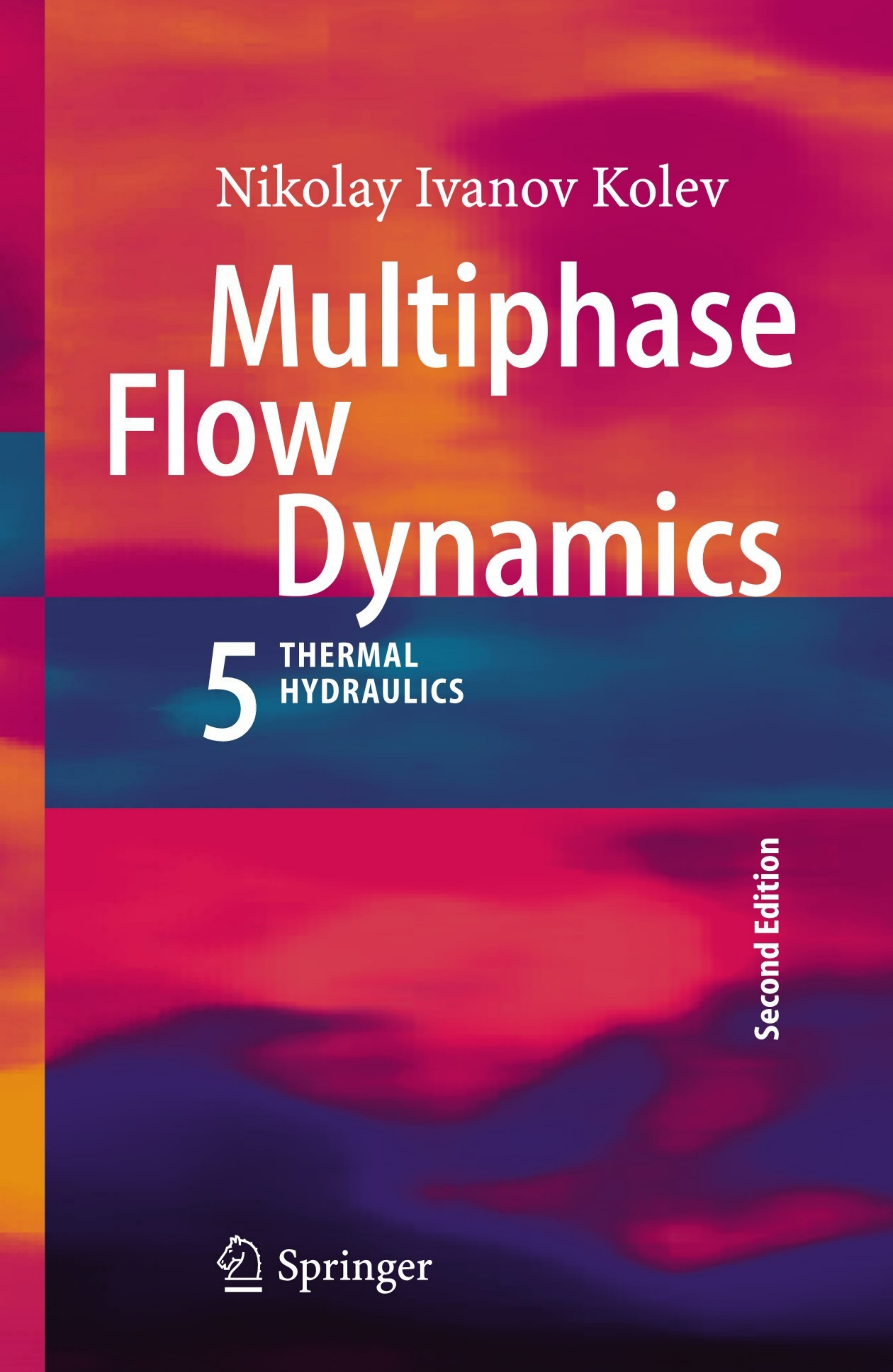

Nikolay Ivanov Kolev

Multiphase Flow Dynamics

5 THERMAL HYDRAULICS

Second Edition

Springer

Multiphase Flow Dynamics 5

Nikolay Ivanov Kolev

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Nuclear Thermal Hydraulics

Springer

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To my mother!

Nordsee, Oct. 2005, Nikolay Ivanov Kolev, oil on linen

Nikolay Ivanov Kolev, PhD, DrSc
Born 1.8.1951, Gabrowo, Bulgaria

A Few Words about the Second Edition

After a break of about 20 years the world started again to modernize the old nuclear power plants and to build new ones. Students, engineers, and scientists need modern books in this field, reflecting the world-wide engineering experience. This explains the considerable interest in this book, which came very much in time in 2008, and now needs a second edition. Several chapters have been updated and improved. I hope it will help young scientists and engineers in their professional life of designing better facilities than those created by my generation.

Herzogenaurach
December 28, 2010

The Motivation to Write This Book

Nuclear thermal hydraulics is the science that provides knowledge and mathematical tools for adequate description of the process of transferring the fission heat released in materials due to nuclear reactions into its environment. Along its way to the environment the thermal energy is organized to provide useful mechanical work or useful heat. Properly arranged and controlled processes achieve this target. Improperly arranged processes or inappropriately controlled processes may lead to damage, losing the investment partially or totally. If power plants are designed so that in low-probability accidental processes only the investment is lost, we speak about safe nuclear power plants. Improperly designed power plants that contain the potential besides losing the investment to destroy the environment and human lives are not acceptable to human society. Nuclear thermal hydraulics is a substantial part of the engineering discipline called nuclear reactor safety. Nuclear reactor safety is not only a technical science. It contains the relations between society, with its mature and effective control mechanisms, and technology. Scientists and engineers alone cannot solve the problem of nuclear reactor safety. It is a technological and simultaneously a social problem, as is any problem associated with high-energy technologies. I will limit my attention in this work to the scientific part. After about 60 years research and practice we know how to build technically safe nuclear power plants. The public attitude to this subject has had its up and downs. Now the world faces the problem of dramatically increasing oil and energy prices, making nuclear energy inevitable. At the same time there is a generation change, and a large army of experienced nuclear engineers are retiring. The responsibility to transfer knowledge to the next generation is what drives me to write this book. I hope it will help young scientists and engineers in their professional life of designing better facilities than those created by my generation.

Herzogenaurach
May 22, 2006

Summary

This monograph contains theory, methods, and practical experience for describing complex transient multiphase processes in arbitrary geometrical configurations. It is intended to help applied scientists and practicing engineers to understand better natural and industrial processes containing dynamic evolutions of complex multiphase flows. The book is also intended to be a useful source of information for students in the high semesters and in PhD programs.

This monograph consists of five volumes:

Vol. 1 Fundamentals, 4th ed. (14 chapters and 2 appendices), 782 pages
Vol. 2 Mechanical Interactions, 4th ed. (11 chapters), 364 pages
Vol. 3 Thermal Interactions, 4th ed. (16 chapters), 678 pages
Vol. 4 Turbulence, Gas Absorption and Release by Liquid, Diesel Fuel Properties, 2nd ed. (13 chapters), 328 pages
Vol. 5 Nuclear Thermal Hydraulics, 2nd ed. (17 chapters), 848 pages

In Volume 1 the concept of three-fluid modeling is presented in detail "from the origin to the applications". This includes derivation of local volume- and time-averaged equations and their working forms, development of methods for their numerical integration, and finally finding a variety of solutions for different problems of practical interest.

Special attention is paid in Volume 1 to the link between the partial differential equations and the constitutive relations called closure laws without providing any information on the closure laws.

Volumes 2 and 3 are devoted to these important constitutive relations for mathematical description of the mechanical and thermal interactions. The structure of the volumes is in fact a state-of-the-art review and selection of the best available approaches for describing interfacial transfer processes. In many cases the original contribution of the author is incorporated in the overall presentation. The most important aspects of the presentation are that they stem from the author's long years of experience developing computer codes. The emphasis is on the practical use of these relationships: either as stand-alone estimation methods or within a framework of computer codes.

Volume 4 is devoted to the turbulence in multiphase flows.

Nuclear thermal hydraulics is the science providing knowledge about the physical processes occurring during the transferring the fission heat released in structural materials due to nuclear reactions into its environment. Along its way to the environment the thermal energy is organized to provide useful mechanical work or useful heat or both. Volume 5 is devoted to nuclear thermal hydraulics. In a way this is the most essential application of the multiphase fluid dynamics in analyzing steady and transient processes in nuclear power plants.

Volume 5 can be summarized as follows:

Chapter 1 contains introductory information about the heat release in the reactor core, the thermal power and thermal power density in the fuel, structures, and moderator, the influence of the thermal power density on the coolant temperature, and the spatial distribution of the thermal power density. Finally, some measures are introduced for equalizing the spatial distribution of the thermal power density.

Chapter 2 gives the methods for describing the steady and the transient temperature fields in the fuel elements. Some information is provided regarding influence of cladding oxidation, hydrogen diffusion, and corrosion product deposition on the temperature fields.

Didactically nuclear thermal hydraulics needs introductions at different levels of complexity, introducing step-by-step new features after the previous ones have been clearly presented. The following two chapters serve this purpose.

Chapter 3 describes mathematically the “simple” steady boiling flow in a pipe. The steady mass-, momentum-, and energy-conservation equations are solved at different levels of complexity by removing, one after the other, simplifying assumptions. First the idea of mechanical and thermodynamic equilibrium is introduced. Then the assumption of mechanical equilibrium is relaxed. Then the assumption of thermodynamic equilibrium is relaxed in addition. In all cases comparison with experimental data gives the evidence of the level of adequacy of the different level of modeling complexity. The engineering relaxation methods are considered, followed by the more sophisticated boundary layer treatment without and with variable effective bubble size. Then an introduction to the saturated flow-boiling heat transfer is given and the accuracy of the methods is demonstrated by comparison with experiments. The hybrid method of combining the asymptotic method with boundary layer treatment allowing for variable effective bubble size is also presented. Finally, the idea of using separated momentum equations and bubble dynamics is introduced and again its adequacy is demonstrated by comparison with experiments.

While Chap. 3 essentially deals with the so-called two-fluid model, Chap. 3 demonstrates the real cases where a three-fluid model is mandatory. Chapter 3 is an introduction to the “simple” steady three-fluid boiling flow in a pipe. The flow regime transition from slug to churn turbulent flow is considered in addition to the already-available information from Chap. 3. The idea of the redistribution of the liquid between film and droplets is presented at two levels of complexity: the instantaneous and the transient liquid redistribution in film and droplets. The transient redistribution is in fact the introduction of the ideas of droplet entrainment and deposition. The idea for the description of the mechanical interaction of the velocity fields is again presented at two levels of complexity: by using drift flux correlations and by using separated momentum equations defining the forces among the fields. The next step of the sophistication is then introduced by using models for the dynamic evolution of the mean droplet size consisting of models for the droplet size stability limit, for droplet production rate due to fragmentation, for duration of the fragmentation, and for collision and coalescence of droplets.

Then the heat and mass transfer mechanisms in the film flow with droplet loading are introduced. Finally, comparisons with experimental data demonstrate the success of the different ideas and models.

To my view the reader will not understand the material of the following chapters if Chaps. 3 and 4 are not well understood. Chapter 5 describes the most powerful methods for describing the core thermal hydraulics these days. First an introduction of the design of the reactor pressure vessels for pressurized- and boiling-water reactors is given. Then by using a large number of experimental data sets for *steady* flows in heated bundles the accuracy of the modern methods is demonstrated. The experiments gathered for comparison are the NUPEC experiment, the SIEMENS void data for the ATRIUM 10 fuel bundle, the FRIGG experiment, and the THTF experiments: high pressure and low mass flow. Methods for prediction of the pressure drop for boiling flow in bundles are presented and compared with data. Then by using experimental data sets for *transient* flows in heated bundles the accuracy of the modern methods is demonstrated. The experiments gathered for comparison are the NUPEC transients in a channel simulating one subchannel of a pressurized-water reactor fuel assembly and the NUPEC transients in a pressurized-water reactor 5 × 5 fuel assembly. Actually avoiding a boiling crisis is the main target of a proper core design. That is why the methods for analyzing whether the critical heat flux is reached in the cores cooled by steady-state flows are presented in detail at different complexity levels: initial 0D guess and 3D critical heat flux analysis. Several uncertainties of the physical models are identified during this process and discussed in detail. New ideas for future progress in this field are presented: large-scale turbulence modeling in bundles, fine-resolution analysis, etc. Finally, an example is given of the most complex case subject in nuclear thermal hydraulics: the analysis of the thermal processes in a core of a boiling-water reactor using the methods presented in this monograph.

The stronger the driving forces for flow processes, the more stable are the resulting phenomena and vice versa. Many of the processes in nuclear thermal hydraulics are associated with low driving forces and tend to instability. This chapter presents a nonlinear stability analysis on some prominent examples in nuclear thermal hydraulics: flow boiling and condensation stability analysis. After a state-of-the-art review the AREVA boiling stability data for the ATRIUM 10B fuel bundle are compared with state-of-the-art predictions using the methods presented in this monograph. The classical boiling instability analysis is accomplished with the seldom-presented flow condensation stability analysis in a complex system of emergency condensers consisting of a large number of 1D condensing pipes submerged into a 3D pool. Condensation at the high-pressure side leads to all flow patterns for nearly horizontal pipes with all their instabilities. It is coupled with the 3D boiling of the secondary pool side. The complex picture is very informative for what can be expected and what has to be avoided in such designs.

Chapter 7 is devoted to critical multiphase flow. It starts with the mathematical definition of the criticality condition, with the appropriate design of a numerical grid structure and numerical iteration strategy. Then the methods used in modern design are presented, starting from the simple models and gradually increasing the complexity. First the single-phase critical flow in a pipe is considered for the case with no-friction energy dissipation and constant cross-section. Then the general case is presented for a perfect gas. Then the same ideas are extended to simple two-phase cases for pipes and nozzles: subcooled critical mass flow rate in short pipes, orifices, and nozzles; frozen homogeneous nondeveloped flow; inhomogeneous developed flow without mass exchange; equilibrium homogeneous flow; equilibrium inhomogeneous flow; inhomogeneous developing flow in short pipes and nuzzles with infinitely fast heat exchange and with limited interfacial mass transfer. Then the recent state of the knowledge for describing critical flow is presented by considering physical details like: bubble origination; bubble fragmentation; bubble coalescence; droplet origination. Examples follow for application of the theory of the critical flow in real-scale analysis: blow-down of a closed pipe and blow-down of a vessel.

Chapter 8 is devoted to the basics of designing of steam generators.

Chapter 9 is devoted to the basics of designing of moisture separation. First the importance of knowing the characteristic spectra of the moisture is underlined for proper analysis. Then some simple methods for computation of the efficiency of the separation are given for cyclone-type and vane-type separators. Different ideas based on different complexity are presented for description of the velocity field: the *Kreith* and *Sonju* solution for the decay of turbulent swirl in a pipe, the potential gas flow in vanes; description of the trajectory of particles in a known continuum field; the computational fluid dynamics (CFD) analyses of cyclones; the CFD analyses of vane separators. Then several experiments are collected from the literature for boiling-water reactor cyclones, pressurized-water reactor steam-generator cyclones, other cyclone types, and vane dryers. In several cases the success of different methods is demonstrated by comparison with data.

The nuclear power plant consists not only of large and small components but also by a forest of interconnected pipes. Chapter 10 is devoted to the estimation of the accuracy of modeling of transient processes in pipe networks by using all the methods presented in this monograph. First some basic definitions are introduced of pipes, axes in space, knots, diameters of pipe sections, reductions, elbows, creating a library of pipes, creating a subsystem network, and discretization of pipe networks for numerical treatment. Then seven interesting experiments are simulated and a comparison with measurements is presented in order to derive conclusions about the accuracy of the methods derived in this monograph.

Not only are the main systems of interest for the practicing engineer. He or she will have to handle problems in real life in the so-called auxiliary systems. As one example of such a system the high-pressure reduction station is analyzed in Chapter 11. A single high-pressure pipe break is analyzed and the consequences of such an event are discussed. As a second example for processes in auxiliary systems an analysis of the physical and chemical processes of radiolysis gas production, air absorption, diffusion-controlled gas release, and transport in the coolant cleaning system of the research reactor FRM II is given.

The evolution of the safety philosophy in the last 30 years has led to the introduction of so-called passive safety systems. Such examples are so-called emergency condensers. Chapter 12 gives first a simple mathematical illustration of the operation of the system. Then the performance of the condenser as a function of the water level and pressure are analyzed with the methods introduced in this monograph. The important question of the condensate removal is discussed.

Chapter 13 is devoted to the core degradation during so-called severe accidents.

Chapter 14 is devoted to melt-water interaction, which is an important part of modern nuclear reactor thermal hydraulics.

Chapter 15 is devoted to the coolability of layers of molten nuclear reactor material. Such physics is important for designing stabilization of spread melt in reactor compartments. After defining the problem with its boundary conditions and some simplifying assumptions the system of differential equations describing the process is presented: mass and energy conservation. The following effects are taken into account: molten steel dropped in the melt or originating inside the melt; gas release from a sublayer; the viscous layer; crust formation; buoyancy-driven convection; film boiling; heat conduction through the structures; oxide crust formation on colder heat-conducting structures. The existence of a metallic layer is also considered. Some test cases are presented to make easy the application of the presented models: oxide over metal and oxide beside metal. A simple model for gravitational flooding of a hot solid horizontal surface by water leading to a hyperbolic system is also presented.

Chapter 16 is devoted to the so-called external cooling of reactor vessels during a severe accident. It is a technology allowing the arrest of the melt inside the vessel if some initial conditions are fulfilled. First the state of the art is presented. Then a brief description of the phenomenology leading to melt in the lower head is discussed: dry core melting scenario, melt relocation, wall attack, focusing effect. A brief mathematical model description is given appropriate for a set of model assumptions. The model describes: melt pool behavior, two-dimensional heat conduction through the vessel wall, total heat flow from the pools into the vessel wall, vessel wall ablation, heat fluxes, crust formation, and buoyancy-driven convection. A solution algorithm is provided for a set of boundary conditions adequate for real situations. A summary of the state of the art regarding the critical heat flux for externally flowing lower head geometry is provided. For several practical applications different effects are demonstrated: the effect of vessel diameter, of the lower head radius, of the relocation time, of the mass of the internal structures. Varying some important parameters characterizing the process the difference between high-powered pressurized- and boiling-water reactor vessel behavior is demonstrated.

Several modern aspects of the severe accident analysis cannot be understood if the engineer does not have accurate information on the material properties for the participating structural materials in solid, in liquid, and in some cases in gaseous states. Chapter 17 contains valuable sets of thermophysical and transport properties for severe accident analysis for the following materials: uranium dioxide, zirconium dioxide, stainless steel, zirconium, aluminum, aluminum oxide, silicon dioxide, iron oxide, molybdenum, boron oxide, reactor corium, sodium, lead, bismuth, and lead–bismuth eutectic alloy. The emphasis is on the complete and consistent thermodynamic sets of analytical approximations appropriate for computational analysis.

December 29, 2010 Nikolay Ivanov Kolev
Herzogenaurach

Nomenclature

Latin

A	cross-section, m²
$\mathbf{A}$	surface vector
a	speed of sound, $\mathrm{m/s}$
a_{lw}	surface of the field l wetting the wall w per unit flow volume $\sum_{l=1}^{l_{\max}} Vol_l$ belonging to control volume Vol (local volume interface area density of the structure w), m^{-1}
$a_{l\sigma}$	surface of the velocity field l contacting the neighboring fields per unit flow volume $\sum_{l=1}^{l_{\max}} Vol_l$ belonging to control volume Vol (local volume interface area density of the velocity field l), m^{-1}
a_l	total surface of the velocity field l per unit flow volume $\sum_{l=1}^{l_{\max}} Vol_l$ belonging to control volume Vol (local volume interface area density of the velocity field l), m^{-1}
Cu_i	Courant criterion corresponding to each eigenvalue, *dimensionless*
C_{il}	mass concentration of the inert component i in the velocity field l
c	coefficients, *dimensionless*
C_m	mass concentration of the component m in the velocity field, *dimensionless*
C_i	mass concentration of the component i in the velocity field, *dimensionless*
c_p	specific heat at constant pressure, $\mathrm{J/(kgK)}$
c^{vm}	virtual mass force coefficient, *dimensionless*
c^d	drag force coefficient, *dimensionless*
c^L	lift force coefficient, *dimensionless*
D_{hy}	hydraulic diameter (four times cross-sectional area / perimeter), m
D_{3E}	diameter of the entrained droplets, m
D_{ld}	size of the bubbles produced after one nucleation cycle on the solid structure, bubble departure diameter, m

D_{1dm}	size of bubbles produced after one nucleation cycle on the inert solid particles of field $m = 2, 3$
D_{lch}	critical size for homogeneous nucleation, m
D_{lcd}	critical size in presence of dissolved gases, m
D_l'	most probable particle size, m
D_l	characteristic length of the velocity field *l*, particle size in case of fragmented field, m
D_{il}^l	coefficient of molecular diffusion for species i into the field *l*, m^2/s
D_{il}^t	coefficient of turbulent diffusion, m^2/s
D_{il}^*	total diffusion coefficient, m^2/s
DC_{il}	right-hand side of the nonconservative conservation equation for the inert component, $\mathrm{kg}/\left(\mathrm{sm}^3\right)$
D	diffusivity, m^2/s
d	total differential
E	total energy, J
e	specific internal energy, J/kg
$F, f(...$	function of (...
f	force per unit flow volume, N/m^3
f	fraction of entrained melt or water in the detonation theory
F_{lw}	surfaces separating the velocity field *l* from the neighboring structure within *Vol*, m^2
$F_{l\sigma}$	surfaces separating the velocity field *l* from the neighboring velocity field within *Vol*, m^2
F	surface defining the control volume *Vol*, m^2
f_{im}	frequency of the nuclei generated from one activated seed on the particle belonging to the donor velocity field *m*, s^{-1}
f_{lw}	frequency of the bubble generation from one activated seed on the channel wall, s^{-1}
$f_{l,coal}$	coalescence frequency, s^{-1}
$\mathbf{g}$	acceleration due to gravity, m/s^2
H	height, m
h	specific enthalpy, J/kg
h_i	eigenvectors corresponding to each eigenvalue
$\mathbf{I}$	unit matrix, *dimensionless*
$\mathbf{i}$	unit vector along the *x*-axis
$\mathbf{J}$	matrix, *Jacobian*
$\mathbf{j}$	unit vector along the *y*-axis
$\mathbf{k}$	unit vector along the *k*-axis
k	cell number

k	kinetic energy of turbulent pulsation, $\mathrm{m}^2/\mathrm{s}^2$
k_{il}^{T}	coefficient of thermodiffusion, *dimensionless*
k_{il}^{p}	coefficient of barodiffusion, *dimensionless*
L	length, m
M_i	kg-mole mass of the species i, kg/mol
m	total mass, kg
$\mathbf{n}_{\Delta \mathbf{V}}$	unit vector pointing along $\Delta \mathbf{V}_{ml}$, *dimensionless*
$\mathbf{n}$	unit vector pointing outward from the control volume *Vol*, *dimensionless*
$\mathbf{n}_{le}$	unit surface vector pointing outward from the control volume *Vol*
$\mathbf{n}_{l\sigma}$	unit interface vector pointing outward from the velocity field l
n_{il}	number of the particle from species i per unit flow volume, m^{-3}
n_l	number of particles of field i per unit flow volume, particle number density of the velocity field l, m^{-3}
$\dot{n}_{coal}$	number of particles disappearing due to coalescence per unit time and unit volume, m^{-3}
$\dot{n}_{l,kin}$	particle production rate due to nucleation during evaporation or condensation, $1/\left(\mathrm{m}^3\mathrm{s}\right)$
n''_{lw}	number of the activated seeds on unit area of the wall, m^{-2}
$\dot{n}_{lh}$	number of the nuclei generated by homogeneous nucleation in the donor velocity field per unit time and unit volume of the flow, $1/\left(\mathrm{m}^3\mathrm{s}\right)$
$\dot{n}_{l,dis}$	number of the nuclei generated from dissolved gases in the donor velocity field per unit time and unit volume of the flow, $1/\left(\mathrm{m}^3\mathrm{s}\right)$
$\dot{n}_{l,sp}$	number of particles of the velocity field l arising due to hydrodynamic disintegration per unit time and unit volume of the flow, $1/\left(\mathrm{m}^3\mathrm{s}\right)$
P	probability
P	irreversibly dissipated power from the viscous forces due to deformation of the local volume and time-averaged velocities in space, $\mathrm{W/kg}$
Per	perimeter, m
p_{li}	l = 1: partial pressure inside the velocity field l l = 2, 3: pressure of the velocity field l
p	pressure, Pa
$\dot{q}'''$	thermal power per unit flow volume introduced into the fluid, $\mathrm{W/m}^3$
$\dot{q}'''_{\sigma l}$	l = 1, 2, 3. Thermal power per unit flow volume introduced from the interface into the velocity field l, $\mathrm{W/m}^3$
$\dot{q}'''_{w\sigma l}$	thermal power per unit flow volume introduced from the structure interface into the velocity field l, $\mathrm{W/m}^3$

R	mean radius of the interface curvature, m
$\mathbf{r}(x,y,z)$	position vector, m
R	(with indexes) gas constant, J/(kg K)
$\mathbf{s}$	arc length vector, m
S	total entropy, J/K
s	specific entropy, J/(kg K)
Sc^t	turbulent *Schmidt* number, *dimensionless*
Sc^{tn}	turbulent *Schmidt* number for particle diffusion, *dimensionless*
T	temperature, K
T_l	temperature of the velocity field *l*, K
$\mathbf{T}$	shear stress tensor, $\mathrm{N/m^2}$
$\mathbf{t}$	unit tangent vector
U	dependent variables vector
Vol	control volume, $\mathrm{m^3}$
$Vol^{1/3}$	size of the control volume, m
Vol_l	volume available for the field *l* inside the control volume, $\mathrm{m^3}$
$\sum_{l=1}^{l_{\max}} Vol_l$	volume available for the flow inside the control volume, $\mathrm{m^3}$
$\mathbf{V}$	instantaneous fluid velocity with components, *u*, *v*, *w* in $r, \theta,$ and z direction, m/s
$\mathbf{V}_l^\tau$	instantaneous field velocity with components, $u_l^\vartheta, v_l^\tau, w_l^\tau$ in $r, \theta,$ and z directions, m/s
$\mathbf{V}_l$	time-averaged velocity, m/s
$\mathbf{V}_l'$	pulsation component of the instantaneous velocity field, m/s
$\Delta\mathbf{V}_{lm}$	$\mathbf{V}_l - \mathbf{V}_m$, velocity difference, disperse phase *l*, continuous phase *m* carrying *l*, m/s
$\delta_i V_l^\tau$	diffusion velocity, m/s
$\mathbf{V}_{l\sigma}^\tau$	interface velocity vector, m/s
$\mathbf{V}_l^\tau \gamma$	instantaneous vector with components, $u_l^\vartheta \gamma_r, v_l^\tau \gamma_\theta, w_l^\tau \gamma_z$ in $r, \theta,$ and z directions, m/s
v	specific volume, $\mathrm{m^3/kg}$
x	mass fraction, *dimensionless*
y	distance between the bottom of the pipe and the center of mass of the liquid, m
$\times$	vector product

Greek

α_l	part of $\gamma_v Vol$ available to the velocity field *l*, local instantaneous volume fraction of the velocity field *l*, *dimensionless*
α_{il}	the same as α_l in the case of gas mixtures; in the case of mixtures consisting of liquid and macroscopic solid particles, the part of $\gamma_v Vol$ available to the inert component *i* of the velocity field *l*, local instantaneous volume fraction of the inert component *i* of the velocity field *l*, *dimensionless*
$\alpha_{l,\max}$	≈ 0.62, limit for the closest possible packing of particles, *dimensionless*
γ_v	the part of *dVol* available for the flow, volumetric porosity, *dimensionless*
γ	surface permeability, *dimensionless*
$\vec{\gamma}$	directional surface permeability with components $\gamma_r, \gamma_\theta, \gamma_z$, *dimensionless*
Δ	finite difference
δ	small deviation with respect to a given value
δ_l	= 1 for continuous field; = 0 for disperse field, *dimensionless*
∂	partial differential
ε	dissipation rate for kinetic energy from turbulent fluctuation, power irreversibly dissipated by the viscous forces due to turbulent fluctuations, $\mathrm{W/kg}$
η	dynamic viscosity, kg/(m s)
θ	θ-coordinate in the cylindrical or spherical coordinate systems, rad
κ	= 0 for *Cartesian* coordinates; = 1 for cylindrical coordinates
κ	isentropic exponent
κ_l	curvature of the surface of the velocity field *l*, m
λ	thermal conductivity, W/(m K)
λ	eigenvalue
μ_l^τ	local volume-averaged mass transferred into the velocity field *l* per unit time and unit mixture flow volume, local volume-averaged instantaneous mass source density of the velocity field *l*, $\mathrm{kg/\left(m^3 s\right)}$
μ_l	time average of μ_l^τ, $\mathrm{kg/\left(m^3 s\right)}$
μ_{wl}	mass transport from exterior source into the velocity field *l*, $\mathrm{kg/\left(m^3 s\right)}$
μ_{il}^τ	local volume-averaged inert mass from species *i* transferred into the velocity field *l* per unit time and unit mixture flow volume, local volume-averaged instantaneous mass source density of the inert component *i* of the velocity field *l*, $\mathrm{kg/\left(m^3 s\right)}$

μ_{il}	time average of μ_{il}^{τ}, $\mathrm{kg/(m^3s)}$
μ_{iml}^{τ}	local volume-averaged instantaneous mass source density of the inert component *i* of the velocity field *l* due to mass transfer from field *m*, $\mathrm{kg/(m^3s)}$
μ_{iml}	time average of μ_{iml}^{τ}, $\mathrm{kg/(m^3s)}$
μ_{ilm}^{τ}	local volume-averaged instantaneous mass source density of the inert component *i* of the velocity field *l* due to mass transfer from field *l* into velocity field *m*, $\mathrm{kg/(m^3s)}$
μ_{ilm}	time average of μ_{ilm}^{τ}, $\mathrm{kg/(m^3s)}$
ν	kinematic viscosity, $\mathrm{m^2/s}$
ν_l^t	coefficient of turbulent kinematic viscosity, $\mathrm{m^2/s}$
ν_l^{tn}	coefficient of turbulent particle diffusion, $\mathrm{m^2/s}$
ξ	angle between $\mathbf{n}_{l\sigma}$ and $\Delta\mathbf{V}_{lm}$, rad
ρ	density, $\mathrm{kg/m^3}$
ρ	instantaneous density, density; without indexes, mixture density, $\mathrm{kg/m^3}$
ρ_l	instantaneous field density, $\mathrm{kg/m^3}$
ρ_{il}	instantaneous inert component density of the velocity field *l*, $\mathrm{kg/m^3}$
$\langle\rho_l\rangle^l$	intrinsic local volume-averaged phase density, $\mathrm{kg/m^3}$
$(\rho w)_{23}$	entrainment mass flow rate, $\mathrm{kg/(m^2s)}$
$(\rho w)_{32}$	deposition mass flow rate, $\mathrm{kg/(m^2s)}$
$(\rho_l \mathbf{V}_l^{\tau})^{le}$	local intrinsic surface mass flow rate, $\mathrm{kg/(m^2s)}$
σ, σ_{12}	surface tension between phases 1 and 2, N/m
τ	time, s
φ	angle giving the projection of the position of the surface point in the plane normal to $\Delta\mathbf{V}_{lm}$, rad
$\chi_l^{m\sigma}$	the product of the effective heat transfer coefficient and the interfacial area density, $\mathrm{W/(m^3K)}$. The subscript *l* denotes inside the velocity field *l*. The superscript $m\sigma$ denotes location at the interface σ dividing field *m* from field *l*. The superscript is only used if the interfacial heat transfer is associated with mass transfer. If there is heat transfer only, the linearized interaction coefficient is assigned the subscript *ml* only, indicating the interface at which the heat transfer takes place.

Subscripts

c	continuous
d	disperse
lm	from l to m or l acting on m
w	region "outside of the flow"
e	entrances and exits for control volume Vol
l	velocity field l, intrinsic field average
i	inert components inside the field l, noncondensable gases in the gas field $l = 1$, or microscopic particles in water in field 2 or 3
i	corresponding to the eigenvalue λ_i in Chapter 4
M	noninert component
m	mixture of entrained coolant and entrained melt debris that is in thermal and mechanical equilibrium behind the shock front
ml	from m into l
iml	from im into il
max	maximum number of points
n	inert component
0	beginning of the time step
E	entrainment
$coal$	coalescence
sp	splitting, fragmentation
σ	interface
τ	old time level
$\tau + \Delta\tau$	new time level
$*$	initial
0	reference conditions
p, v, s	at constant p, v, s, respectively
L	left
R	right
1	vapor or in front of the shock wave
2	water or behind the shock wave
3	melt
4	entrained coolant behind the front – entrained coolant
5	microparticles after the thermal interaction – entrained melt

Superscripts

´	time fluctuation
$'$	saturated steam
$''$	saturated liquid
$'''$	saturated solid phase
A	air
d	drag
e	heterogeneous

i	component (either gas or solid particles) of the velocity field
$i_{\max}$	maximum for the number of the components inside the velocity field
L	lift
l	intrinsic field average
le	intrinsic surface average
$l\sigma$	averaged over the surface of the sphere
m	component
n	normal
n	old iteration
$n+1$	new iteration
t	turbulent, tangential
vm	virtual mass
τ	temporal, instantaneous
$\overline{}$	averaging sign

Operators

$\nabla\cdot$	divergence
∇	gradient
∇_n	normal component of the gradient
∇_t	tangential component of the gradient
∇_l	surface gradient operator, 1/*m*
∇^2	*Laplacian*
$\langle\ \rangle$	local volume average
$\langle\ \rangle^l$	local intrinsic volume average
$\langle\ \rangle^{le}$	local intrinsic surface average

Nomenclature required for coordinate transformations

(x, y, z)	coordinates of a *Cartesian,* left-oriented coordinate system (*Euclidean* space). Another notation which is simultaneously used is x_i $(i = 1, 2, 3)$: x_1, x_2, x_3
(ξ, η, ζ)	coordinates of the curvilinear coordinate system called transformed coordinate system. Another notation which is simultaneously used is ξ^i $(i = 1, 2, 3)$: ξ^1, ξ^2, ξ^3
$\mathbf{V}_{cs}$	the velocity of the curvilinear coordinate system
$\sqrt{g}$	*Jacobian* determinant or *Jacobian* of the coordinate transformation $x = f(\xi, \eta, \zeta)$, $y = g(\xi, \eta, \zeta)$, $z = h(\xi, \eta, \zeta)$

a_{ij}	elements of the *Jacobian* determinant
a^{ij}	elements of the determinant transferring the partial derivatives with respect to the transformed coordinates into partial derivatives with respect to the physical coordinates. The second superscript indicates the *Cartesian* components of the contravariant vectors
$\left(\mathbf{a}_1, \mathbf{a}_2, \mathbf{a}_3\right)$	covariant base vectors of the curvilinear coordinate system tangent vectors to the three curvilinear coordinate lines represented by (ξ, η, ζ)
$\left(\mathbf{a}^1, \mathbf{a}^2, \mathbf{a}^3\right)$	contravariant base vectors, normal to a coordinate surface on which the coordinates ξ, η, and ζ are constant, respectively
g_{ij}	covariant metric tensor (symmetric)
g^{ij}	contravariant metric tensor (symmetric)
$\left(\mathbf{e}^1, \mathbf{e}^2, \mathbf{e}^3\right)$	unit vectors normal to a coordinate surface on which the coordinates ξ, η, and ζ are constant, respectively
$\mathbf{V}^i$	$= \mathbf{a}^i \cdot \mathbf{V}$, contravariant components of the vector $\mathbf{V}$
$\mathbf{V}_i$	$= \mathbf{a}_i \cdot \mathbf{V}$, covariant components of the vector $\mathbf{V}$
$\left(\gamma_\xi, \gamma_\eta, \gamma_\zeta\right)$	permeabilities of coordinate surfaces on which the coordinates ξ, η, and ζ are constant, respectively

Greek

A, α	Alpha
B, β	Beta
Γ, γ	Gamma
Δ, δ	Delta
E, ε	Epsilon
Z, ζ	Zeta
H, η	Eta
Θ, ϑ	Theta
I, ι	Iota
K, κ	Kappa
Λ, λ	Lambda
M, μ	Mu
N, ν	Nu
Ξ, ξ	Xi
O, o	Omikron
Π, π	Pi
P, ρ	Rho
Σ, σ	Sigma
T, τ	Tau
Φ, φ	Phi
X, χ	Chi
Υ, υ	Ypsilon
Ψ, ψ	Psi
Ω, ω	Omega

Table of Contents