Fluid Mechanics and Its Applications

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Heat Transfers and Related Effects in Supercritical Fluids

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Aims and Scope of the Series

The purpose of this series is to focus on subjects in which fluid mechanics plays a fundamental role.

As well as the more traditional applications of aeronautics, hydraulics, heat and mass transfer etc., books will be published dealing with topics which are currently in a state of rapid development, such as turbulence, suspensions and multiphase fluids, super and hypersonic flows and numerical modeling techniques.

It is a widely held view that it is the interdisciplinary subjects that will receive intense scientific attention, bringing them to the forefront of technological advancement. Fluids have the ability to transport matter and its properties as well as to transmit force, therefore fluid mechanics is a subject that is particularly open to cross fertilization with other sciences and disciplines of engineering. The subject of fluid mechanics will be highly relevant in domains such as chemical, metallurgical, biological and ecological engineering. This series is particularly open to such new multidisciplinary domains.

The median level of presentation is the first year graduate student. Some texts are monographs defining the current state of a field; others are accessible to final year undergraduates; but essentially the emphasis is on readability and clarity.

Preface

Over the past 50 years, the problem of supercritical or near-critical fluids has turned from a particular aspect of phase transitions described in books on thermodynamics to an active domain of research involving a variety of fundamental topics in statistical physics, fluid dynamics, chemistry, as well as many applications in different industrial processes. Supercritical fluids have provided a canonical example in the study of critical phenomena and anomalous exponents. They have displayed remarkable effects in out-of-equilibrium physics and hydrodynamics where they have made possible laboratory experiments in an extreme parameter range usually achieved only in geophysical or astrophysical flows. They also involve rapidly developing applications in engineering such as the ones taking benefit of the peculiar properties of chemical reactions in supercritical fluids.

Although there exist excellent books on each facet of the above subjects, a consistent account of the field is needed since it has become increasingly difficult to follow the literature on all these different topics. In addition, most books on supercritical fluids consider either the fundamental problems statistical of statistical physics or the aspects related to engineering processes in fluid dynamics or chemistry without making connection between these fields. This book will thus fill a gap in the existing literature. The authors have made a major effort to introduce the fundamental concepts, both in statistical physics and in hydrodynamics to readers who have no previous knowledge of these fields. They then present more specialized material on heat transfer, boiling, and hydrodynamic instabilities in supercritical fluids with emphasis on related microgravity experiments. The authors have been most actively engaged in various studies on supercritical fluids in a remarkable collaborative effort over the past 30 years. This book is a witness to this fruitful collaboration that provided many results. In particular, pioneering studies on the piston-effect that is a mechanism of heat transfer characteristic of near-critical fluids, fluids are widely described in the book.

I hope that this book will provide a profitable introductory text addressed to graduate students but will also be useful to researchers studying one of the many aspects of supercritical fluids.

Paris, February 2014 Stephan Fauve

Nomenclature

Latin Symbols

a or a_v	Oscillatory amplitude
a	Specific Helmhotz energy
a	van der Waals specific attractive parameter
$\bar{a}$	van der Waals molar attractive parameter
a_m	Modulus of the magnetic acceleration vector
A	Cross-sectional area
b	van der Waals specific covolume
$\bar{b}$	van der Waals molar covolume
B	Amplitude of the magnetic field vector
B_f	Dimensionless thermo-oscillatory number
c_S	Velocity of sound
$\overline{c_p}$	Molar heat capacity at constant pressure
c_p	Specific heat at constant pressure
$\overline{c_V}$	Molar heat capacity at constant volume
c_V	Specific heat at constant volume
CBL	Cooling boundary layer
C	Convective parameter
d	Inner diameter of an anisotropic thermal boundary layer
d	Dimension of the space
d_c	Upper critical dimension of space
d_0	Thermistor radius
D	Outer diameter of an anisotropic thermal boundary layer
D	Coefficient of diffusion
D_T	Thermal diffusivity
$\bar{e}$	Molar energy
e	Specific energy
e	Length, or thickness, of the system
E_{vdW}	van der Waals solid–liquid interaction energy (per unit area)
f	Frequency
HBL	Heating boundary layer
g	Specific Gibbs free energy

g	Modulus of the residual gravitational acceleration
g or $1g$	Residual gravitational acceleration expressed in unit of g_0
g_0	Modulus of the Earth's gravitational acceleration
g^*	Effective gravitational acceleration
h	Specific enthalpy
I	Current intensity
j	Specific heat flux (or heat flux per area unit)
K_m	Typical wave vector of phase-separating domains
K_m^*	Reduced typical wave vector of phase-separating domains
ℓ_c	Capillary length
l_v	Viscous boundary layer
L	Latent heat
L_m	Pseudo-wavelength between phase-separating domains
m	Mass
$\overline{m}$	Molar mass
$m_{\bar{p}}$	Molecular (or particle) mass
M	Order parameter
$M^{+,-}$	Order parameter in the inhomogeneous region
n	Dimension of the order parameter
n	Refractive index
n	Number density
$\bar{n}$	Molar number
p	Pressure
P_r	Prandtl number
q or $\dot{q}$	Heating power per unit volume or surface
q or Q	Heating power or heat flux
q or Q	Energy
Q	Heating power
r	Radius of the system
r	Spatial variable
r	Space variable
r	Specific gas constant
R	Universal constant of ideal gases
R_D	Universal ratio for thermal diffusivity
R_0	Typical cell radius
Ra_v	Vibrational Rayleigh number
Ra or Ra_0	Rayleigh number
Re or Re_0	Reynolds number
$\bar{s}$	Molal entropy
s	Specific entropy
S	Entropy
t	Time
t_D	Heat diffusion time
t_{eq}	Adiabatic temperature equilibrium timescale

t'_c or t_0 or t_{PE}	Piston effect time
t_ξ	Typical critical fluctuation time
t^*	Time reduced by the typical critical fluctuation time
t_{PE}	Piston-effect timescale
T	Temperature
T_c	Critical temperature
T_{cx}	Coexistence temperature
u	Specific internal energy
u	Molal internal energy
u, v, w	Velocity components on Cartesian axes
v	Specific volume
$\bar{v}$	Molar volume
V	Volume
x, y, z	Cartesian coordinates
x_η	Critical exponent for the shear dynamic viscosity
x_λ	Critical exponent for the thermal conductivity
$Y_\eta(=\nu x_\eta)$	Critical exponent of the shear dynamic viscosity

Greek Symbols

ϵ or ε	Small parameter of asymptotic expansions
α	Angle of vibration with respect to the direction of the temperature gradient
β_p	Isobaric thermal expansion coefficient
v	Molar volume
ρ	Density
ρ_c	Critical density
$\bar{\rho}$	Molar density
κ_T	Isothermal compressibility
χ_B	Magnetic susceptibility
χ_T	Isothermal susceptibility
ϕ	Volume fraction
Λ	Thermal conductivity
ξ	Correlation length of fluctuations
γ	Ratio of specific heats at constant pressure and constant volume
$\dot{\gamma}$	Acceleration
τ	Reduced temperature
ν	Kinematic viscosity
Ξ	Amplitude of vibration
μ	Shear dynamic viscosity
μ_B	Bulk dynamic viscosity
Π	Disjoining pressure
η_b	Bulk viscosity
η	Shear viscosity

σ	Gas–liquid surface tension
Ω	$=0.5\ \left(\beta'_P a' \omega'\right)^2$ Vibration parameter
Ra	Rayleigh number
Θ	Time reduced by the piston effect time
θ	Time reduced by heat diffusion time
μ^*	Chemical potential
μ_0	Magnetic permeability of vacuum
δ	Thickness of the thermal boundary layer
ζ	Distance
α	Critical exponent of the critical isochore for the specific heat at constant volume
β	Critical exponent of the critical isochore of the coexistence curve
γ	Critical exponent of the critical isochore of the isothermal susceptibility
ν	Critical exponent of the critical isochore of the correlation length
$\tilde{\delta}$	Critical exponent of the critical isotherm of the susceptibility (χ)
η	Fisher's critical exponent of the correlation function for order parameter fluctuations at the CP
Δ	Corrections-to-scaling exponent
ψ	Generic critical exponent
Ψ	Generic critical amplitude
ω	Angular frequency
$\tilde{x}$	Generic exponent of the spatial evolution of the thermal boundary layer
ϑ	Period of vibration

Vectors and Tensors

$\mathbf{u}$	Fluid velocity vector
$X(x, y, z)$	Spatial location vector
∇	Gradient operator
$\mathbf{n}$	Unit vector for the direction of vibration
$\vec{\tau}$	Viscosity stress vector
$\bar{\bar{\tau}}$	Viscosity stress tensor
Ξ	Vibration vector
$\mathbf{o}$	Rotational part of vector

General

$\Delta\ldots, \delta\ldots$	Difference (e.g., ΔT, δT are temperature differences)

Subscripts and Superscripts

a	Averaged quantity
b	Background quantity
b	Boundary layer quantity
b	Bulk quantity
c	Critical quantity
cx	Coexistence quantity
exp	Experimental quantity
g	Gas phase quantity
IG	Ideal gas quantity
l	Liquid phase quantity
MF	Mean field approximation
mod	Model quantity
p	Pulsating quantity
p	Quantity at constant pressure
V	Quantity at constant volume
v	Saturated vapor quantity
vdW	van der Waals quantity
w	Value at the sample wall
$-$	Cold part, below T_c
$+$	Hot part, above T_c
$\parallel$	Parallel
$\perp$	Perpendicular
0	Leading amplitude

Contents