

Advances in

HEAT
TRANSFER

Volume 7

Advances in

HEAT TRANSFER

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Volume 7



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TRANSFER

Contributors to Volume 7

W. O. BARBER

Edited by RICHARD S. GARG

W. D. W. WALL

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The Electrochemical Method in Transport Phenomena

T. MIZUSHINA

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PREFACE

The serial publication, "Advances in Heat Transfer," is designed to fill the information gap between the regularly scheduled journals and university level textbooks. The general purpose of this series is to present review articles or monographs on special topics of current interest. Each article starts from widely understood principles and in a logical fashion brings the reader up to the forefront of the topic. The favorable response to the first six volumes by the scientific and engineering community is an indication that our authors have competently fulfilled this purpose.

The editors are pleased to announce the publication of Volume 7 and wish to express their appreciation to the current authors who have so effectively maintained the spirit of the series.

The Influence of Electric and Magnetic Fields on Heat Transfer to Electrically Conducting Fluids

MARY F. ROMIO

Fluid Mechanics and Heat Transfer of Two-Phase Annular-Dispersed Flow

MARIO SILVETTI

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Chemically Reacting Nonequilibrium Boundary Layers

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Low Density Heat Transfer

F. M. DEVIZZINI

Heat Transfer in Non-Newtonian Fluids

A. B. MATZNER

Radiation Heat Transfer between Surfaces

E. M. SPARROW

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I. Introduction

The rapid growth of research activity in supercritical heat transfer over the past ten or fifteen years is a consequence of several trends in engineering. There has been a steady development of steam plant towards supercritical conditions, and supercritical water has been considered as a coolant for several types of nuclear reactors. Helium is used at near-critical conditions as a coolant for the conductors of electrical machines, and rocket motors are frequently cooled by pumping fuel through cooling pipes at supercritical pressure.

From a fundamental standpoint, the problem has been regarded as one in which the variation of physical properties with temperature becomes extremely important. Effects which, with most fluids, may be treated as small perturbations of the "constant property" idealization, sometimes become dominant, rendering existing theoretical models and empirical correlations useless. In some cases phenomena appear which have no counterpart with constant property fluids. At the same time experimental difficulties have hampered the investigation of these effects. These are not merely the difficulties of operating equipment at high pressures, but also the problems of compressibility (which becomes very high near the critical point and makes the density sensitive to relatively small pressure variations) and of specific heat (which also becomes large and hinders the accomplishment of thermal equilibrium).

It might be thought that heat transfer experiments of such complexity would have little to contribute to the understanding of basic mechanisms. It is true that in constructing models of the process one is forced to introduce additional assumptions which are difficult to test; nevertheless, there are some cases where extreme property variations afford a much more stringent test of some aspects of current theories than could be obtained in other ways. An example of this is the interaction between forced and free turbulent convection; with a supercritical fluid the trend of the results is in the opposite sense to that which one would expect. This may well lead to a reexamination of the same problem for fluids with small property variations.

The near-critical region may be thought of as that region in which boiling and convection merge. When the pressure is sufficiently sub-critical or supercritical, the problem tends towards either a boiling problem or a constant property convection problem; under such conditions existing theoretical and empirical methods are generally adequate. We shall concentrate on the region rather close to the critical point where the property variations are severe and where there are very significant heat transfer effects. Such effects are usually found in a range of pressures

from the critical up to about 1.2 times the critical; they are generally largest when the temperatures of the hotter surface and the fluid span the critical temperature.

We begin with a brief description of the behavior of thermodynamic and transport properties near the critical point. The equations of continuity, momentum, and energy are then examined with a view to revealing the effect of variable properties and deciding whether the same simplifications can be made as are common with a constant property fluid. A discussion of the various modes of heat transfer then follows, particular attention being given to the interaction between forced and free convection.

II. Physical Properties near the Critical Point

A. THERMODYNAMIC PROPERTIES

The properties of a fluid near its critical point have interested thermodynamicists for the past hundred years. This is hardly surprising in view of the singular behavior in this region: the classical description indicates, for example, that the compressibility and the specific heat at constant pressure both become infinite at the critical point. These factors make experimentation difficult; it is evident that as $(\partial V/\partial p)_T$ becomes large, the hydrostatic pressure variation in the fluid will lead to significant density variations even for small changes of height and also that the approach to thermal equilibrium will be slow as c_p becomes large.

The present state of knowledge of thermodynamic behavior is not entirely satisfactory, either from a theoretical or from an experimental standpoint; nevertheless, it is probably true to say that an understanding of heat transfer in the critical region is limited more by lack of knowledge of the heat transfer processes (e.g., turbulent diffusion, effect of buoyancy forces) than by uncertainties in the thermodynamic properties. In these circumstances, the classical description of the critical point may still be adequate.

1. *The van der Waals Model*

In 1873, van der Waals proposed an explanation of thermodynamic behavior near the critical point. His model, in which an allowance is made for the attractive and repulsive forces between molecules, leads to an equation of state of the following form:

$$(p + \{a/\bar{V}^2\})(\bar{V} - b) = RT \quad (1)$$

The physical arguments underlying the equation are well known and need not be repeated here; it is sufficient to note that the constant b accounts for the strong, short range repulsive forces (imposing a limit to the reduction of volume as pressure is increased), and the term a/\bar{V}^2 represents the long range attractive forces between molecules. Figure 1 illustrates the shape of isotherms on a p, V diagram, according to van der Waals equation.

Consider a particular isotherm, marked $abcdef$ in Fig. 1. The fluid

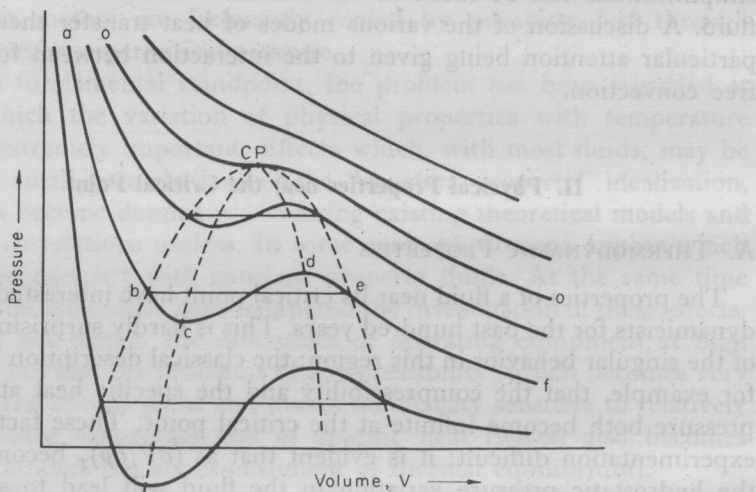


FIG. 1. The van der Waals isotherms.

can exist in a homogeneous state along the section of the isotherm marked abc and def ; the section cd represents conditions in which the thermodynamic inequality

$$(\partial p / \partial \bar{V})_T < 0$$

is not satisfied, and the fluid would separate into two distinct phases. The regions bc and de represent, respectively, superheated liquid and subcooled vapor; the extent of these metastable regions is indicated by broken lines in Fig. 1. Equilibrium between the liquid and vapor phases (with a plane interface between them) is achieved with states marked b and e . (Note that unstable equilibrium between liquid and vapor can be achieved with a curved interface along bc and de . In these cases, surface tension forces at the bubble or droplet surface lead to a difference between the liquid and vapor pressures.)

The isotherm marked o in Fig. 1 is known as the critical isotherm and

passes through the critical point. It represents the isotherm for which the points bcd and e all coincide, thus giving a point of inflection at the critical point (CP on Fig. 1), so that

$$(\partial p / \partial \tilde{V})_T^c = 0 \quad (2)$$

$$(\partial^2 p / \partial \tilde{V}^2)_T^c = 0 \quad (3)$$

2. The Law of Corresponding States

The behavior of the critical isotherm, as embodied in Eqs. (2) and (3), can be used to eliminate the constants a and b in the van der Waals equation as follows: Equation (1) may be written as

$$p = RT/(\tilde{V} - b) - a/\tilde{V}^2$$

and, using Eqs. (2) and (3),

$$\left(\frac{\partial p}{\partial \tilde{V}}\right)_T^c = 0 = \frac{-RT^c}{(\tilde{V}^c - b)^2} + \frac{2a}{(\tilde{V}^c)^3}$$

$$\left(\frac{\partial^2 p}{\partial \tilde{V}^2}\right)_T^c = 0 = \frac{2RT^c}{(\tilde{V}^c - b)^3} - \frac{6a}{(\tilde{V}^c)^4}$$

from which we find that

$$\tilde{V}^c = 3b; \quad p^c = \frac{1}{27} a/b^2; \quad T^c = 8a/27bR$$

Introducing the "reduced" quantities,

$$V^* = \tilde{V}/\tilde{V}^c; \quad p^* = p/p^c; \quad T^* = T/T^c$$

the van der Waals equation becomes

$$(p^* + 3/(V^*)^2)(3V^* - 1) = 8T^* \quad (4)$$

An interesting aspect of this equation is the fact that it involves only p^* , V^* , and T^* and not any quantities that are characteristic of a particular substance. In the above form it applies only to substances for which the van der Waals equation is true; however, the same principle may be stated in more general terms by asserting that there is a unique relationship between p^* , V^* , and T^* for all substances. This is known as the *principle of corresponding states* and is frequently stated in the form

$$Z = Z(p^*, T^*) \quad (5)$$