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APPLICATION OF THE PRINCIPLE OF SIMILARITY FLUID MECHANICS

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ABSTRACT

Possible applications of the principle of similarity to fluid mechanics is described and illustrated. In correlating thermophysical properties of fluids, the similarity principle transcends the traditional corresponding states principle. In fluid mechanics the similarity principle is useful in correlating flow processes that can be modeled adequately with one independent variable (i.e., one-dimensional flows). In this paper we explore the concept of transforming the conservation equations by combining similarity principles for thermophysical properties with those for fluid flow. We illustrate the usefulness of the procedure by applying such a transformation to calculate two phase critical mass flow through a nozzle.

KEYWORDS

Fluid mechanics; principles of similarity; thermophysical properties; corresponding states; thermodynamic critical point; two phase choked flows.

INTRODUCTION

Many dynamic processes can be modeled in terms of one physical coordinate dimension and the success of such modeling is well known. However, in doing so one must realize that not all boundary conditions associated with higher dimension coordinate spaces can be satisfied; implying the use of a set of suitable constraints, a priori, which "average" the dynamic character of the flow field. For example, in fluid mechanics the representative velocity, heat flux, and friction factor can be written as

\[
\bar{u} = \frac{1}{A_1 t_0} \int \vec{u}(A_1, t) \cdot \vec{n} \, dA \, dt; \quad \bar{q} = \frac{1}{A_1 t_0} \int \vec{q}(A_1, t) \cdot \vec{n} \, dA \, dt
\]

\[
\bar{f}_f = \frac{1}{A_1 t_0} \int f_f(A_1, t) \, dA \, dt
\]

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where $A_1$ is a surface and $t_o$ a specific time interval. In order to formulate a set of constraints, one postulates the existence of principles of similarity between the thermodynamic parameters and the conservation equations, such as constant or power law dependent fluid properties, or coordinates which behave in such a way as to satisfy separation of variables. Often such relations imply a "slug flow" velocity profile, or constant heat flux or an average friction factor based on the inlet and exit pressure differences. Under these conditions, only a limited number of boundary conditions can possibly be satisfied.

A family of functions of a number of physical variables is said to satisfy a similarity principle if the function can be made identical by reducing the functions and variables in terms of suitably chosen scale factors. Thus when such scale factors are found as units to nondimensionalize (normalize) other variables, the profiles plotted in these dimensionless coordinates become congruent. For instance, in fluid mechanics when the momentum equation, cited below, is made dimensionless using the fluid velocity ($u$), density ($\rho$), viscosity ($\eta$) and a characteristic length ($l$), it follows that two flows become similar when their Reynolds numbers are equal.

$$Re_1 = \frac{\rho_1 u_1^2 l}{\eta_1} = \frac{\rho_2 u_2^2 l}{\eta_2} = Re_2$$

and this is known as Reynolds principle of similarity. For thermophysical properties, van der Waals' principle of corresponding states assumes that property surfaces become similar when the variables describing these surfaces are properly scaled, in terms of the critical point parameters,

$$P_{R_1}(T_{R_1}, V_{R_1}) = P_{R_2}(T_{R_2}, V_{R_2})$$

where $P_R = P/P_c$, $T_R = T/T_c$ and $V_R = V/V_c$. And in mathematics, similarity solutions are based on suitable scale factors which stretch the coordinates and reduce the governing partial differential equations to ordinary ones. When confronted with a complex problem, it is often quite useful to determine the exact solution subject to restricted geometric conditions similar to those of the original problem. Boundary layer theory is rich in such an approach where most similarity solutions are also one dimensional (Bird and colleagues, 1960; Gebeci and Smith, 1974; Hansen, 1964; Hinze, 1975; Moore, 1964; Schlichting, 1968).

The reason for similarity and/or one dimensional modeling can be readily understood by considering the conservation equations of fluid mechanics (Bird and colleagues, 1960; Gebeci and Smith, 1974; Hinze, 1975; Schlichting, 1968; Zeleznik, 1976).

Continuity:

$$\frac{\partial \rho}{\partial t} + \frac{\partial \rho u_i}{\partial x_i} = 0$$

Momentum:

$$\frac{\partial \rho u_i}{\partial t} + \frac{\partial \rho u_i u_j}{\partial x_j} = \frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_i} + \rho g_i$$

Energy:

$$\frac{\partial \rho H_o}{\partial t} + \frac{\partial \rho u_j H_o}{\partial x_j} = \frac{\partial}{\partial x_j} (u_i \tau_{ij} - q_j) + \frac{\partial p}{\partial t}$$

State:

$$P = P(\rho, H, x)$$
where \[ H_0 = H + \frac{1}{2} u_1 u_1 \]

These equations are difficult to solve without some simplifying assumptions, even for potential flows. With added complexities, such as diabatic flows with real fluid properties and severe gradients, the mass and energy fluxes, \( \tau_{ij} \) and \( q_j \) respectively, become most difficult to determine as BOTH \( \tau_{ij} \) and \( q_j \) are related and yet constrained by some boundary. Much of our information for these related constraints is constructed from engineering data for the fluids water and air. Still our knowledge is limited and we are forced to make simplifying assumptions.

For the cases where tractable analytical and/or numerical treatments are available, regardless of simplifications, we must have accurate, consistent thermophysical property information to transform these solutions into physical reality. Sometimes this information is limited or unavailable, yet the success of the entire transformation depends on its accuracy. So we need to develop methods to predict thermophysical properties and techniques to relate these results to an experimental body of data for fluid \( \alpha \) to a similar experiment with fluid \( \beta \) without essentially reproducing the entire experiment.

Following van der Waals' principle of similarity, many thermophysical properties for several species seem to be correlated in the sense that one can introduce suitable scale factors in the dependent and independent variables so that properties so reduced are congruent to some universal curve (i.e., become universal). This applies to normal as well as near critical behavior. But since flow and heat transfer behavior depend on these properties, it seems reasonable to expect that for similar geometric arrangements it should be possible to describe flow and heat transfer in such a way as to be, more or less, congruent to some universal curves.

In general then, one would like to develop solutions which are independent of BOTH the physical nature of the coordinates and the thermodynamic character of the working fluid. As an attempt toward accomplishing this, we shall first review some similarity principles for the thermophysical properties of fluids in section A, with emphasis on the critical region in section B and cite some related computational programs in section C; second, we shall provide some examples of physical processes which have been related using similarity principles, in section D; and third, in section E we use these similarity principles to demonstrate that two-phase choked flows for a simple fluid \( \alpha \) can be computed using a simple fluid \( \beta \) independent of the thermodynamic character of the other fluids \( \alpha \) and \( \beta \) thereby demonstrating the process independence of BOTH coordinates and working fluid; our conclusions are summarized in section F.

A. THE PRINCIPLE OF SIMILARITY IN DESCRIBING THERMOPHYSICAL PROPERTIES OF FLUIDS

A1. Background

Most engineering texts on thermodynamics treat the subject of corresponding states to some degree for both single and multicomponent fluids, while some consider a possible formulation of corresponding states for transport properties. However, the actual practice of predicting such fluid properties as a function of the thermodynamic state variables requires a great deal of computing capability and accurate PVT data for developing fundamental equations. In this section, we will mention some approaches.
A2. Thermophysical Properties of One-Component Fluids

A2.1 Thermodynamic Properties

As an example of the traditional corresponding states methods, consider van der Waals' equation of state describing fluid \( \alpha \).

\[
P = \frac{RT}{v-b} - \frac{a}{v^2} \tag{A.1}
\]

In reduced form it becomes,

\[
P_R = \frac{T_R}{Z_c(V_R - \Omega_b/Z_c)} - \frac{\Omega_a}{Z^2 c v^2} \tag{A.2}
\]

where

\[
Z_c = \frac{1}{3}; \quad \Omega_b = \frac{1}{8}; \quad \Omega_a = \frac{27}{64}; \quad T_R = \frac{T_c}{T}; \quad V_R = \frac{V_c}{V}; \quad T_R = \frac{T}{T_c}
\]

and in this form it not only describes fluid \( \alpha \) but fluid \( \beta \) as well. This approach is correct for any system of molecules whose potential can be specified by two system-dependent parameters only.

Mollerup (1975 and 1977) proposes to relate the properties of two pure substances by the equations:

\[
z_a(V,T) = z_o(V/T) \tag{A.4}
\]

\[
G_a(V,T) = G_o(V/T) - RT \ln h \tag{A.5}
\]

where \( \alpha \) denotes the reference fluid and the properties are termed configurational because they evolve from the configurational part of the partition function and are conformal in that they have similar molecular potentials and obey the principle of corresponding states; for example, both are adequately described by a two parameter Lennard-Jones type potential. The functions \( f \) and \( h \) are dependent on the ratio of the critical temperature and volume.

\[
f = f_o \left( \frac{\nu}{\nu_c} \right)^\delta \quad h = h_o \left( \frac{\nu}{\nu_c} \right)^\phi \tag{A.6}
\]

while \( \delta \) and \( \phi \) are shape factor functions that depend on the eccentric factors of fluid \( \alpha \) and fluid \( \alpha \) and that are weakly dependent on temperature and volume. (See Leach, 1966, 1967; and Eqs. (E.5) and (E.6)).

Mollerup (1978) has used the Ping-Robinson equation to predict properties of the quantum fluids hydrogen and helium using eccentric factors of approximately -0.2187 and -0.3897 for hydrogen and helium respectively along with the extended corre-

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1 Note that the related forms become

\[
P_o - \frac{P_h}{T}; \quad V_o - \frac{V}{h}; \quad \rho_o - \rho h; \quad T_o - \frac{T}{h}
\]
spending states theory. Mollerup finds that the shape factor can be represented by

$$\theta = \frac{1 + m_i + (m_o - m_i) \sqrt{TR}}{1 + m_o}$$  \hspace{1cm} (A.7)

for quantum fluids, where $m_i$ is a quadratic function in eccentric factor $\omega_i$. He has verified this representation at reduced temperatures up to $TR \leq 26$ for hydrogen and $TR \leq 40$ for helium.

### 42.2 Transport

Dimensional analysis\(^2\) and corresponding states can be combined to determine suitable scale factors for transport coefficients.

1. Viscosity data for many fluids can be grouped over a large range in experimental conditions (Dean and Stiel, 1965; Jossi Stiel, and Thodos, 1962; Stiel and Thodos, 1962) using the parameters

$$\left(\eta - \eta_{0,0}\right)\xi_1 = f(TR, \rho_R)$$  \hspace{1cm} (A.8)

where

$$\xi_1 = \frac{T_c^{1/6}}{P_c^{2/3} M^{1/2}}$$  \hspace{1cm} (A.9)

as illustrated in Fig. 1.

2. Thermal conductivity data were grouped using a similar parameter (Misic and Thodos, 1961; Schaefer and Thodos, 1959)

$$\left(\lambda - \lambda_{0,0}\right)\xi_2 = f(TR, \rho_R)$$  \hspace{1cm} (A.10)

where

$$\xi_2 = M \xi_1$$  and  $$Z_c = \frac{P_c V_c}{RT_c}$$  \hspace{1cm} (A.11)

3. Binary diffusion coefficients were grouped using the parameter (Stattery and Bird, 1958)

$$D_{12} \xi_3 = f(TR, P_R)$$  \hspace{1cm} (A.12)

where

$$\xi_3 = \frac{P_c^{1/3} M_{1/2}}{T_c^{5/6}}$$  \hspace{1cm} (A.13)

\(^2\)Dynamically similar processes based on the observation that physical laws are independent of the particular system of units employed.
4. Surface tension data can be grouped with the parameter (Brock and Bird, 1955)

\[ \sigma_{\xi_4} = f(T_R) \]  

(A.14)

where

\[ \xi_4^{-1} = \frac{p_c}{T_c} \]  

(A.15)

Hanley (1977) and Rainwater (1977) applied these configuration functions to thermal conductivity and viscosity and proposed that the thermal conductivity and viscosity of pure components could be related as

\[ \lambda_\alpha(\rho, T) = \lambda_0(\Phi h, \frac{T}{T_c}) F_\lambda \]  

(A.16)

\[ \eta_\alpha(\rho, T) = \eta_0(\Phi h, \frac{T}{T_c}) F_\eta \]  

(A.17)

where

\[ F_\lambda = \left( \frac{M_\alpha}{M_\alpha} f \right)^{1/2} h^{2/3} \]

\[ F_\eta = \left( \frac{M_\alpha}{M_\alpha} f \right) \]  

(A.18)

The use of configurational functions \( f \) and \( h \) along with an accurate reference equation of state greatly enhances the users capability to accurately relate thermophysical properties. It does however have the disadvantage of being more complex and one needs to determine the configuration factors.

More recent representations of the viscosity surface (in terms of density virials with temperature dependent coefficients) are given by Hanley, McCarty and Haynes (1974a) using a corresponding states approach to correlate the results for several simple fluids. The procedure is more accurate but can not be applied to as many different fluids as some more conventional principles which have been successfully applied not only to simple fluids but to long chain hydrocarbons and polar molecules (Dean and Stiel, 1965; Jossi, Stiel, and Thodos, 1962; Stiel and Thodos, 1962).

A3. Thermophysical Properties of Multicomponent Fluids (Fluid Mixtures)

A3.1 Perfect Gases

Gordon and McBride (1971), Zeleznik and Gordon (1968), and Svhela (1962) have formulated a program which calculates the chemical equilibrium composition and mixing properties of multicomponent fluids. The program can handle fuels and oxidants constructed from 15 different chemical elements. There are some 600 different products of combustion whose data are stored in the computer program, and any given

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Using the related forms of Eq. (A.4)-footnote, we can relate traditional parameters and the extended corresponding states parameters

\[ \xi_1 = F_\eta; \xi_2 = \left( \frac{M_0}{M_\alpha} f \right)^{1/2} h^{1/3}; \xi_4^{-1} = \frac{f}{h^{2/3}} \]
computation can handle any 200 of them. The program includes solid and liquid condensed phases and ionization. Bittker and Scullin (1972) have a code for reaction kinetics. These programs represent a major contribution to combustion computations and are based on free energy functions. The thermodynamic and transport property contributions of Kestin (1979) and collaborators in formulating accurate representations of the thermodynamic and transport properties of pure component fluids and fluid mixtures are well known. Most recently they have developed a formula for the transport properties of natural gas (Abe and Kestin, 1979).

A3.2 Extended Principle-Multicomponent Fluids

A3.2.1 Thermodynamic Properties

Mollerup (1975, 1977, 1978) used an extended corresponding states principle to correlate and predict properties of some fluid mixtures with considerable accuracy. In this procedure, a reference substance is chosen, usually the most dominant of the mixture with the most accurate PVT surface description.

\[ Z_m(V,T,x) = Z_o(V,T) \]  
(A.19)

\[ G_m(V,T,x) = G_o(V,T) + RT \left( \sum x x \ln x - \ln h \right) \]  
(A.20)

The form is similar to that for pure substances except that we need to account for the energy of mixing and introduce some "mixing rules" which for our case are van der Waals' two component rules. While there are certainly other potentially applicable versions, these appear to be the simplest and most effective. We must now redefine the functions \( f \) and \( h \):

\[ h = \sum x x x \]  
(A.21)

\[ f = \sum x x x \]  
(A.22)

where

\[ f_{\alpha\beta} = \xi_{\alpha\beta} (f_{\alpha\alpha} f_{\beta\beta})^{1/2} \]  
(A.23)

\[ h_{\alpha\beta} = \phi_{\alpha\beta} \left( \frac{h_{\alpha\alpha}^{1/3} + h_{\beta\beta}^{1/3}}{2} \right)^3 \]  
(A.24)

and where \( \xi_{\alpha\beta} \) and \( \phi_{\alpha\beta} \) are binary interaction parameters. While the procedure is complex, Mollerup has already determined many interaction parameters of practical interest, for LNG, and has written a computer program to predict these properties.
A3.2.2 Transport Properties

Hanley and Rainwater (1977) applies these configuration functions and proposed that thermal conductivity and viscosity of mixtures could be related in a manner similar to pure components, Eqs. (A.16) and (A.17),

\[ \lambda(\rho, T, x_\alpha) = \lambda_0 (\phi h f_{T}) F_\lambda \]  
\[ \eta(\rho, T, x_\alpha) = \eta_0 (\phi h f_{T}) F_\eta \]

where \( f \) and \( h \) are defined as above, but \( F_\lambda, F_\eta \) are redefined.\(^4\) For the thermal conductivity, Hanley proposed an expression based on the theory of Enskog

\[ \chi^\lambda_{\alpha,0} = Q_{\alpha,0}^\lambda c_{\alpha,0}^\lambda \]  
\[ \chi^\eta_{\alpha,0} = Q_{\alpha,0}^\eta c_{\alpha,0}^\eta \]

where

\[ Q_{\alpha,0} = \left[ \frac{(b_p)_{\alpha}}{(b_p)_{o}} \right]^{1 - 1/\exp(p_c/\rho)} \]  
\[ C_{\alpha,0} = \frac{\kappa_{\alpha}^\lambda}{\kappa_{\alpha}^o} \]

\[ \kappa^\lambda = \frac{1}{\rho bX} + 1.2 + 0.775 bX \]  
\[ \kappa^\eta = \frac{1}{\rho bX} + 0.8 + 0.761 bX \]

\( F_\lambda, F_\eta \) now can be written as

\[ F_\lambda = \left[ \left( \frac{M_o}{M_{\alpha}} \right)^{1/2} \right] \left[ \frac{n^2}{2} \right] \chi^\lambda_{\alpha,0} \]  
\[ F_\eta = \frac{M_o c_{\alpha,0}^\eta}{M_o c_{\alpha,0}^\lambda} \frac{F_\lambda}{F_\eta} \]

\(^4\) It should be noted that Prandtl number could be related using these principles.

\[ Pr = \frac{\text{mass diffusion/thermal diffusion}}{\nu/\alpha} \]  
(for const. properties, \( Pr = c_p (\eta/\lambda) \))

\[ Pr(\rho, T)_{\alpha} = Pr(\rho h, T/\alpha_0) \]

or

\[ [Pr(\rho, T) - Pr(T)]_{\alpha} = (\Delta Pr)_0 \]
B. SIMILARITY OF THERMOPHYSICAL PROPERTIES OF FLUIDS IN THE CRITICAL REGION

B.1 Background

Many thermophysical properties exhibit anomalous behavior in the vicinity of the critical point. For instance, the isothermal compressibility, the thermal expansion coefficient and the specific heat of fluids all diverge at the critical point. Critical enhancement effects are also encountered in the behavior of the thermal conductivity and the viscosity near the critical point.

It has always been difficult to formulate correlating equations that accurately incorporate the singular behavior of the various thermophysical properties near the critical point. However, in recent years considerable progress has been made in the art of developing representative equations for the thermodynamic and transport properties of fluids in the critical region.

The critical point is a point of marginal thermodynamic stability. In the vicinity of the critical point, large-scale density fluctuations are present in the fluid. The spatial extent of these fluctuations may be characterized by a coherence or correlation length $\xi$. Near the critical point, this correlation length becomes much larger than the intermolecular interaction range. One can imagine that the critical enhancement effects are caused by the static and dynamic behavior of a system of clusters. Different states in the vicinity of the critical point correspond to different cluster sizes and the thermodynamic states can be interrelated by scaling laws. Moreover, the properties of a system of clusters become independent of the nature of the individual molecules. This principle is currently known as critical-point universality (A. Sengers and J. V. Sengers, 1977).

Recent developments have demonstrated that these principles become rigorously valid only in an asymptotic small region around the critical point, a region too small to be of interest in engineering applications. However, using some semi-empirical adaptations, the approach can nevertheless be fruitfully used to formulate representations that can be used in practice in a larger range around the critical point (J. V. Sengers and J. M. H. Sengers, 1978). In this section we consider these somewhat empirical generalizations of the principles of scaling and universality for representing thermophysical properties of fluids in the critical region.

B.2 Thermophysical Properties

B.2.1 Power Laws

Let $F$ be the Helmholtz free energy, $S$ the entropy, $\mu$ the chemical potential per unit mass and $C_v$ the heat capacity at constant volume. We also find it convenient to introduce a symmetrized isothermal compressibility defined as

$$ \chi_T = \frac{\langle \partial S \rangle}{\partial N/T} = \rho^2 k_T \quad (B.1) $$

The thermodynamic properties are made dimensionless by expressing them in terms of the critical temperature $T_c$, the critical density $\rho_c$, and the critical pressure $P_c$. 
\[ T^* = T/T_c, \rho^* = \rho/\rho_c, P^* = P/P_c, F^* = F/F_c V, \]
\[ \mu^* = \mu_\rho/P_c, X^*_T = X_\rho P_c/\rho_c^2, S^* = ST_c/P_c V, C^*_V = C_v T_c/P_c V \]  \( (B.2) \)

Note that the reduced extensive properties \( F^*, S^* \) and \( C^*_V \) are all taken per unit volume rather than unit mass. The reason is that the singular part of the extensive thermodynamic properties per unit volume appears to be symmetric functions (Vincent-Missoni, Sengers, and Green, 1969; J. M. H. Sengers, 1974) of \( \rho - \rho_c \). As a consequence, \( X_T \) is also a symmetric function of \( \rho - \rho_c \), while the compressibility \( \kappa_T = P^{-1}\partial \rho/\partial T \) is not (J. V. Sengers, 1973). We also define the reduced differences

\[ \Delta T^* = (T - T_c)/T_c \]
\[ \Delta \rho^* = (\rho - \rho_c)/\rho_c \]
\[ \Delta \mu^* = [\mu(\rho, T) - \mu(\rho_c, T)]\rho_c/P_c \]  \( (B.3) \)

To represent the singular thermodynamic behavior of fluids in the vicinity of the critical point, one first defines critical power laws (Fisher, 1967). The exponents of these power laws depend on the property considered and the path along which the critical point is approached. The special paths in the \( \Delta T^* - \Delta \rho^* \) plane commonly considered are the coexistence curve or phase boundary \( (CXC) \), the critical isochore \( (CIC) \Delta \rho = 0 \) and the critical isotherm \( (CIT) \Delta T^* = 0 \). These paths are schematically indicated in Fig. 2. The critical power laws defined along these paths are summarized in Table I. The critical exponents of the different thermodynamic properties are not independent. The scaling laws to be discussed below imply the exponent relations

\[ \alpha = 2 - \beta(5 + 1) \]
\[ \gamma = \beta(5 - 1) \]  \( (B.4) \)

### 2.2 Scaling Laws

In order to formulate scaling laws for the critical region, we introduce a scaling variable \( x \) defined as

\[ x = \Delta T^*/[\Delta \rho^*]^{1/\beta} \]  \( (B.5) \)

This scaling variable is chosen such that the coexistence boundary corresponds to a constant value of the scaling variable \( x \):

\[ x_{CXC} = x_o, \quad x_o = B^{-1/\beta} \]  \( (B.6) \)

Instead of \( x \), it is slightly more convenient to use the variable

\[ y = \frac{x + x_o}{x_o} \]  \( (B.7) \)
Curves of constant \( y \) are schematically indicated in Fig. 3. The coexistence curve corresponds to \( y = 0 \), the critical isotherm to \( y = 1 \) and the critical isochore to \( y = \infty \).

In the critical region the thermodynamic properties are considered as a sum of two types of contributions, namely one type of contribution that represents the singular behavior at the critical point and satisfies scaling laws and another type of contribution that is a regular or "background" contribution. The scaled expressions for a number of thermodynamic functions are summarized in Table 2 (J. V. Sengers and J. M. H. Sengers, 1978). Here the singular behavior of the thermodynamic properties is expressed in terms of two scaling functions \( h(y) \) and \( a(y) \) which are related by the differential equation (J. M. H. Sengers, Greer, and J. V. Sengers, 1976)

\[
\beta h(y) = \beta (1 + 1)a(y) + (1 - y) \frac{da(y)}{dy}
\]  

(B.8)

The function \( h(y) \) is normalized such that \( h(1) = 1 \).

As an example, we consider the scaling law for the chemical potential

\[
\Delta \mu^c = \Delta \mu^c |\Delta \mu^c|^{\theta - 1} dh(y)
\]  

(B.9)

Normally, the chemical potential is a function of two variables, density and temperature. The scaling law (B.9) implies that when the data for \( \Delta \mu^c \) are divided by \( \Delta \mu^c |\Delta \mu^c|^{\theta - 1} \), the data should collapse onto a single curve as a function of the scaling variable \( y \). In Fig. 4 we show such a scaled plot for steam (J. M. H. Sengers, Greer, and J. V. Sengers, 1976).

To use the scaling laws in practice, one needs an explicit expression for the scaling function \( h(y) \). An expression proposed for this purpose is the so-called NBS- or NBSG-equation (Sengers, Greer, and Sengers, 1976; Sengers and Sengers, 1977; Vincentini-Missoni, Sengers, and Green, 1969)

\[
h(y) = y \left( \frac{1 + Ex^2 \beta}{1 + E} \right)^{(y-1)/2\beta}
\]  

(B.10)

where \( E \) is a constant to be discussed below. The advantage of this expression is that it enables one to calculate the compressibility \( \chi^c \) directly as a function of density and temperature in the critical region. The disadvantage is that it cannot be analytically integrated to yield an explicit expression for \( a(y) \) and, hence, for the pressure. This problem is solved by introducing two auxiliary ("parametric") variables, replacing the variables \( \Delta T^c \) \( \Delta \mu^c \). For a discussion of the parametric equations for the thermodynamic properties in the critical region, the reader is referred to a review published elsewhere (Sengers and Sengers, 1978).

It follows from (B.5) and (B.9), that all critical exponents for the power laws in Table 1 are related to the exponents \( \beta \) and \( \theta \). These relations were earlier given in (B.4). The amplitudes \( B \), \( \Gamma \) and \( \Gamma' \) of the critical power laws for the coexistence curve and the compressibility are related to \( D \) and \( \chi_o \) by

\[
B = \chi_o^{-\beta}
\]  

(B.11a)
\[ \Gamma = \frac{x^Y}{D} \left( \frac{1 + E}{E} \right)^{(\gamma-1)/2\beta} \] (B.11b)

\[ \Gamma' = \frac{3x^Y}{D} (1 + E)^{(\gamma-1)/2\beta} \] (B.11c)

### 2.3 Universality

The principle of universality asserts that the critical exponents and the scaling function \( h(y) \) should be universal, that is, the same for all 3-dimensional systems with short range forces. The universal values for the critical exponents of this universality class have been calculated theoretically (Baker, Nickel, and Meiron, 1978; Guillon and Zinn-Justin, 1977). The only system dependent constants in the scaling laws are the coefficients \( D \) and \( x_0 \) which specify the amplitude of the critical isotherm and the coexistence curve, respectively.

It turns out that the principle of universality in its strict sense applies in a small region \( \Delta T \leq 10^{-4} \) near the critical point which is insignificantly small for engineering applications (Sengers and Sengers, 1977). However, an empirical extension of the universality principle as applied to fluids near the critical point is obtained by introducing effective fluid exponents and an effective value for the constant \( \alpha \) (B.10) (Sengers, Greer, and Sengers, 1976; Sengers and Sengers, 1976; Sengers and Sengers, 1978)

\[ \alpha = 0.100, \beta = 0.355, \gamma = 1.19, \delta = 4.352, E = 0.287 \] (B.12)

As an illustration of this practical application of universality, we show in Fig. 5 scaled chemical potential data (Sengers, Greer, and Sengers, 1976; Sengers and Sengers, 1978) for \( \text{He}, \text{Ne}, \text{Xe}, \text{CO}_2 \), and \( \text{H}_2\text{O} \). The data can approximately be represented by a single function of the scaling variable \( y = (x + x_0)/x_0 \). The data cover a range in temperature and density corresponding to

\[ 5 \times 10^{-4} \leq |\Delta T| \leq 3 \times 10^{-2}, |\Delta \rho| \leq 0.25 \] (B.13)

The principle of corresponding states would imply identical behavior when the thermodynamic properties are reduced using the critical parameters \( T_c, P_c, \rho_c \). The fluids included in Fig. 5 do not satisfy corresponding states. However, the universality hypothesis is a generalization of corresponding states, saying that universal critical behavior is obtained using only two additional constants, \( D \) and \( x_0 \), besides the critical parameters themselves. In Table 3, taken from an earlier review (Sengers and Sengers, 1978), we have listed these parameters for a large number of fluids.

The principle of universality applies to the compressibility \( X_T \) and to the singular contributions of the other thermodynamic properties (see Table 2). It may be noted that \( (\partial P/\partial T)_\rho \) is finite at the critical point, while the compressibility \( X_T \) diverges strongly. It has been found in some practical applications that already a significant improvement is obtained if \( X_T \) is calculated from the scaling laws even if the equation of state and, hence \( (\partial P/\partial T)_\rho \) are represented by more conventional equations.
3. Correlation Length

An important quantity in the critical region is the correlation length $\xi$, which measures the size of the clusters. In practice, this correlation length may be estimated from (Sengers and Sengers, 1978)

$$\xi = \xi_0 \left(\frac{r}{T}\right)^{\nu/\gamma}$$  \hspace{1cm} (B.14)

where $\Gamma$ is given by (B.11b). The critical exponent $\nu$ for the correlation length is related to the thermodynamic exponents $\beta$ and $\gamma$ by the hyperscaling relation

$$\nu = (2\beta + \gamma)/3$$  \hspace{1cm} (B.15)

Using the values adopted in (B.12) one finds $\nu = 0.633$. The scale factor $\xi_0$ for the correlation length can be related to the critical power amplitudes $B$ and $\Gamma$ by (Sengers and Sengers, 1978)

$$\xi_0 \left(\frac{B^2T_c}{\Gamma k_B T_c}\right)^{1/3} = R_1$$  \hspace{1cm} (B.16)

where $R_1$ is a universal constant whose value is approximately equal to 0.7. Values of the correlation length scale factor $\xi_0$ for a number of fluids are also included in Table 3.

4. Transport Properties

4.1 Thermal Conductivity

The thermal conductivity of fluids shows a pronounced critical enhancement in a large range of temperatures and densities around the critical point (Sengers, 1972, 1973). To account for this behavior, the total thermal conductivity $\lambda$ is decomposed as the sum of a normal part $\bar{\lambda}$ and a critical part $\Delta \lambda$

$$\lambda = \bar{\lambda} + \Delta \lambda$$  \hspace{1cm} (B.17)

The idea is that the normal part $\bar{\lambda} = \bar{\lambda} + \lambda_0 \rho$ represents the thermal conductivity without the extra contributions due to the critical fluctuations. This part, therefore, can be represented by customary correlating procedures, section section A.

The theory of dynamical critical phenomena predicts that the critical enhancement $\Delta \lambda$ will diverge asymptotically at the critical point as (Hohenberg and Halperin, 1967; Kawasaki, 1970; Sengers, 1973)

$$\Delta \lambda \sim \Delta \lambda_c = \frac{\Lambda}{2n\eta} \frac{k_B T^2}{\rho^2} \left(\frac{\partial P}{\partial T}\right)_\rho \chi_T = \frac{\Lambda k_B T}{6n\eta^2} \frac{T^2}{\rho} \left(\frac{\partial P}{\partial T}\right)_\rho \chi_T$$  \hspace{1cm} (B.18)

where $k_B$ is Boltzmann’s constant, $\eta$ the shear viscosity, and $\Lambda$ a universal constant of order unity. Values predicted theoretically for this constant $\Lambda$ span the range $1.0 \leq \Lambda \leq 1.2$.

An empirical generalization of (B.18) to cover the entire range of temperatures and densities of the thermal conductivity enhancement, is obtained by writing (Hanley, McCarty, and Sengers, 1974; Hanley, Sengers, and Ely, 1976),
\[ \Delta \lambda = \Delta \lambda_c f_1(\Delta T^*,\Delta \rho^*) \]  
(B.19)

where \( \Delta \lambda_c \) is given by (B.18) and where \( f(\Delta T^*,\Delta \rho^*) \) is an empirical damping function such that

\[
\lim_{\Delta T^* \to 0, \Delta \rho^* \to 0} f_1(\Delta T^*,\Delta \rho^*) = 1
\]

and

\[
\lim_{\Delta T^* \to \infty, \Delta \rho^* \to \infty} f_1(\Delta T^*,\Delta \rho^*) = 0
\]

An example of a suitable damping function is (Hanley, McCarty, and Sengers, 1974; Hanley, Sengers, and Ely, 1978)

\[
f_1(\Delta T^*,\Delta \rho^*) = \exp \left\{ - \left[ c_T (\Delta T^*)^2 + c_\rho (\Delta \rho^*)^4 \right] \right\}
\]  
(B.20)

with \( c_T = 18.66 \) and \( c_\rho = 4.25 \). Equations of the type given in (B.19) have been used to represent the thermal conductivity of a variety of fluids (Hanley and colleagues, 1974a, 1974b, 1976, 1977a, 1977b) including steam (Basu and Sengers, 1979).

4.2 Viscosity

Theory predicts that the shear viscosity \( \eta \) of fluids also diverges at the critical point (Hohenberg and Halperin, 1967; Ohta and Kawasaki, 1976; Perl and Ferrell, 1972). Hence, we write in analogy to (B.17)

\[
\eta = \tilde{\eta} + \Delta \eta
\]  
(B.21)

where \( \tilde{\eta} = \tilde{\eta} + \eta_0,0 \) is the normal viscosity and \( \Delta \eta \) the critical viscosity enhancement. It turns out that the critical viscosity enhancement is a multiplicative enhancement, that is, \( \Delta \eta \) is itself proportional to \( \tilde{\eta} \) (Ohta, 1977). Therefore, in practice, we prefer to consider the viscosity ratio \( \Delta \eta/\tilde{\eta} \) or \( \eta/\tilde{\eta} \) (Basu and Sengers, 1979).

Unlike the critical thermal conductivity enhancement, the critical viscosity enhancement is weak and limited to a small range of temperatures and densities around the critical point (Basu and Sengers, 1979). Hence, the enhancement may be neglected for many applications as was done in the viscosity equation recently adopted by IAPS for steam (Hendricks, McClintock, and Silvestri, 1977; Nagashima, 1977; Schleffer and colleagues, 1978).

A more detailed discussion of the critical viscosity enhancement of fluids near the gas-liquid critical point is presented elsewhere (Basu and Sengers, 1979; Basu, Sengers, and Watson, unpublished). It can be estimated as

\[
\eta = \tilde{\eta}(q_1^*)^{q_1} \quad \text{for} \quad q_1^* \geq 1 \]

where \( q_1 \) is a universal critical exponent and \( q_1^* \) a parameter depending on the fluid. The effect of the critical enhancement is small and accurate knowledge of
\(\varphi_1\) and \(q_1\) is not needed for practical applications. As a guide, we recommended an effective exponent value (Basu and Sengers, 1979)

\[
\varphi_1 = \frac{8}{15\pi^2} \approx 0.054
\]  \hspace{1cm} (B.23)

while the parameter \(q_1\) may be estimated from (Basu and Sengers, 1979; Oxtoby and Gelbart, 1974)

\[
q_1 = \frac{k_B T^2}{8\pi \eta \lambda \rho} \left( \frac{\partial P}{\partial T} \right)^2 \frac{\chi^2}{\xi^2} \approx \frac{k_B c_p}{8\pi \eta \lambda \xi o^2} \left( \frac{\partial P^*}{\partial T^*} \right)^2
\]  \hspace{1cm} (B.24)

while, as "a rule of thumb," \(\left( \frac{\partial P^*}{\partial T^*} \right)_P \approx 6\), see Eq. (D.4).

C. NUMERICAL PLOTTING CODES

Before proceeding, we must caution the reader that accurate representations of the PVT surfaces are a requirement for a meaningful transformation of any solution to physical reality.

Equations of state (EOS) are available from NBS, IUPAC, HTFS, NASA, Tech. Univ. Munich, etc. and mixtures from Mollerup Tech. Univ. of Denmark, AGA, NBS, NASA and the Petro Chem. Ind., API.5

With the advent of the computer and plotting programs, such as those developed by Trivisonno and Hendricks (1977), and the thermophysical properties routines for several fluids (Hendricks and colleagues, 1973, 1975), or any of those supplied from the organizations list above, thermophysical properties may be accurately and quickly compared on such complex charts as T-S, H-S, H-P, F-T, G-T, etc., see Fig. 6. These charts, which are useful in cycle analysis, also serve to rapidly assess descriptions of the PVT surface and its derivatives which, in turn, can establish corresponding states reduction parameters as required. The recent work of Mollerup extends the input parameter options of his mixtures program to \((\rho, \varphi, \chi_o)\) where \(\varphi = T, V, H, S\) and \((H, S, \chi_o)\).

D. EXAMPLES OF THERMOPHYSICAL PROPERTIES RELATED TO DYNAMIC PROCESSES

D1. Thermophysical Properties

D1.1 A classic example of a thermodynamic property related to a dynamic process is sonic velocity. The dynamic wave motion is described completely and entirely by curvature of the PVT surface representing the fluid through which the wave is passing.

\[c_s^2 = \left( \frac{\partial P}{\partial ho} \right)_s \]  \hspace{1cm} (D.1)

Thus sonic velocity is fixed by state and not process. This concept is modified somewhat at high frequencies.

5NBS - Gaithersburg, MD and Boulder, CO; IUPAC - Imperial College, London; HTFS - AERE Harwell, England; NASA - COMSIC U. of Georgia, Athens, GA; AGA - Arlington, VA; API - Washington, D.C.
D1.2 Joule-Thomson coefficients are also thermodynamic properties which are related to an expansion process. For an isenthalpic expansion,

\[
\mu_o = \left( \frac{\partial P}{\partial T} \right)_H = \frac{1}{\rho_o c_T} \left[ \frac{T}{P} \left( \frac{\partial P}{\partial T} \right)_T \right] - 1 \quad (D.2)
\]

D1.3 Hendricks, Baron, and Peller (1972) demonstrated that for engineering purposes the reduced Joule-Thomson coefficient, see Fig. 7, was useful in grouping results for various simple fluids

\[
\mu_{oR} = \frac{\mu_o}{\mu_{o,c}} \quad (D.3)
\]

where

\[
\mu_{o,c} = \left[ \left( \frac{\partial P}{\partial T} \right)_p \right]^{-1} \approx \frac{T_c}{\delta P_c} \quad (D.4)
\]

Figure 7 illustrates a reduced Joule-Thomson coefficient plot.

D1.4 Leinhard and Karimi (1977) and Alamgir applied the corresponding states principle to van der Waals spinodal locus (Leinhard and Karimi, 1977) and surface tension (Leinhard and Alamgir) for several fluids, see Fig. 8.6.

D1.5 Simoneau and Hendricks (1977) used the principle to extend the calculations for equilibrium fluid properties into the metastable regions to the equivalent van der Waals minimum pressure locus or vapor spinodal, for use in two phase choked flow computations, see Fig. 9.

D1.6 Parameters such as \( \beta_j = \frac{\partial \ln \rho}{\partial \Phi} \) where \( \Phi_j = T, H, E, A, \) or can be reduced to a single plot of sufficient accuracy for most heat transfer calculations. This has been demonstrated by Hendricks (1979). Figure 10 represents a reduced volumetric expansion factor plot \( \beta_R = \beta_j / (2c_T c_H) \). These few examples serve to illustrate some of the principles of similarity.

D2. Heat and Mass Transfer Processes Related through the Principle

D2.1 Choked Flows

Hendricks (1973, 1974) has shown that two-phase choked flow rates of several simple fluids can be grouped using the reduced mass flux (see Fig. 11(a))

\[
W_R = \frac{W}{\rho c_T} \quad (D.5)
\]

where

\[\sigma_\alpha(\rho, T) = \sigma_\alpha(c_T, f, e)(f/h)^{2/3}\]

It should follow that from Eq. (A.4)-footnote the extended corresponding states relation is:
also in good agreement are the reduced pressure profiles of Fig. 11(b) where the ordinate represents the ratio of the nozzle throat pressure to that of an isentropic gas expansion.

The parameter \( W^* \) has been useful in grouping and predicting mass flux for several geometries in addition to multiple fluids, see Simoneau and Hendricks (1979).

Hendricks (1979a, 1979b) and Poolos (1979) have used this normalization procedure to group data for free jet flows through tubes with Borda and sharp edge inlets. For (Hendricks and Poolos, 1979) the tube was short, \( L/D = 2 \), but four inlet geometries were used; circular, square, rectangular and triangular.

More recently, Hendricks (1979c) has shown that for gases flowing through a simulated shaft seal configuration, a modified form

\[
\frac{V_R \sqrt{T_{Ro}}}{P_{Ro}} = c \quad (D.7)
\]

reduces to a universal curve for simple gases; for this simulated shaft seal geometry, \( c \) is nearly constant at 0.16. For a nozzle, \( c = 1/5 \).

In convergent tapered passages, the mass flux rate is reduced using the area \( \bar{A}_1 \)

\[
\bar{A}_1 = \frac{2A_{exit} + A_{inlet}}{3} \quad (D.8)
\]

\[
W = \dot{m}/A_1 \quad (D.9)
\]

With this modification, the above relations are valid for convergent tapered passages as well.

D2.2 Heat Transfer

Hendricks (1977) has shown that there is good evidence that the transposed critical temperature, \( T^*_P \) used in near critical heat transfer problems, can be related through the corresponding states principles.

\[ W^*_a = \psi a \sqrt{\frac{E}{R}} \quad (D.6) \]

\[ \psi^2_a = \text{Const.} \frac{k}{k+1} \left( \frac{2}{k+1} \right)^{(k+1)/k} \]

where \( k \) is the isentropic expansion coefficient.

\[ T^*_P \]

represents the loci of maximum specific heats.
The transposed critical temperature locus $T^*$ has been used by several investigators to classify heat transfer data where behavior was more gas like $T > T^*$ or more liquid like $T < T^*$ and processes which crossed the $T^*$ locus could possess either a maximum or a minimum heat transport. This phenomenon is more fully discussed by Hendricks and colleagues (1962, 1966, 1970). The point is, that $T^*$ appears to be a corresponding states parameter, some heat transfer data can be classified using this criteria and consequently the grouping of heat transfer and hydrodynamic data in this manner could also follow a similarity principle.

Two component models are commonly used to represent heat transfer and hydrodynamic data where distinct phase transitions occur (e.g., liquid-vapor). However, two component models are also used to represent HcII and HeII transitions below the temperature (Lee and colleagues, 1978), and in grouping data of classical fluids in the subcritical and supercritical pressure states (Hendricks and colleagues, 1962, 1970). Similarities in wall temperature profiles and flow stability between the subcritical and supercritical pressure heat transfer data for forced convection and the wall temperature-heat flux profiles and stability in "pool boiling" have been noted by several investigators (Graham, Hendricks, and Ehlers, 1964; Hendricks and colleagues, 1962; Sabersky and Hauptmann, 1967).

**D2.2.2 Subcritical Convection**

Hendricks and Papell (1977) used the principle to group forced convection subcooled nucleate boiling data for neon, nitrogen and water. The reduced temperature difference was expressed as

$$
\Delta T_R = \left( \frac{Z_c - \frac{\omega}{4}}{3} \right)^{1/4} q_R \exp \left[ - \frac{4P_R}{7 \left( Z_c - \frac{\omega}{4} \right)} \right]
$$

where

$$
q_R = \frac{q}{q^*}
$$

$$
\omega = -1 - \log P_v \bigg|_{T_R=0.7}
$$

and

$$
q^*_k = 0.16 h_{fg} \left( g \sigma \frac{\rho_f^2}{\rho_g \rho_f} \right)^{1/4}
$$

is the Kutateladze expression for critical heat flux.

**D2.2.3 Volumetric Expansion**

Yaskin and colleagues (1977) used the volumetric expansion parameter in the form of $(1 + \beta_1 \Delta T)$ in successfully grouping heat transfer data for fluid helium including the near critical region. A similar parameter $\left[ 1 + \frac{(\partial \ln \rho)}{(\partial \Delta H)} P \Delta H \right]$ was used by Hendricks (1977), to group fluid nitrogen and fluid oxygen data. However it did not group the data as well as the work of Yaskin and colleagues (1977). Here $\Delta T = T_w - T_B$ and $\Delta H = H_w - H_B$. 

Hendricks (1977) showed that heat transfer data for fluids nitrogen and oxygen were qualitatively related using the principle; however, assessment of the effects of buoyancy, relative velocity parameters, etc., which also grouped these data, must be made before the simulation can be made quantitative.

It was shown by Simoneau and Hendricks (1964), that for gases, the heat transfer coefficient can be written

\[ h_t = CG^{0.8} d^{-0.2} \frac{V_T}{T_W} \quad (D.14) \]

and it can be shown that for an ideal gas

\[ \left[ 1 + \beta_1(T_W - T_B) \right]^{1/2} = \frac{V_T}{T_W} \quad (D.15) \]

(Note: C related to \( M_1 \)) This work was reviewed (Hendricks, 1979d), and many sets of heat transfer data can be grouped using volumetric expansion parameters \( \psi_k \) and the reduced Nusselt number \( \text{Nu}_R \), see Fig. 12:

\[ \text{Nu}_R = \frac{\text{Nu}_{\exp}}{\text{Nu}_{\text{calc}}} \sim \psi_m \quad m = \frac{1}{2} \quad (D.16) \]

where

\[ \text{Nu}_{\text{calc}} = 0.023 \text{Re}^{0.8} \text{Pr}^{0.4} \quad (D.17) \]

\[ \psi_k = 1 + \beta_k \Delta \psi_k = 1 + \beta_k (\psi_W - \psi_B) \quad \text{no sum on } k \quad (D.18) \]

\[ \beta_k = -\left( \frac{\partial \ln \psi_k}{\partial \psi_k} \right) \quad (D.19) \]

and

\[ \begin{align*}
\psi_1 &= T \\
\psi_2 &= F \\
\psi_3 &= G \\
\psi_4 &= \psi_5 = E \\
\psi_6 &= \mu_1
\end{align*} \quad (D.20) \]

Using the Gibbs energy parameter \( \psi_4 \), the data group well indicating that if the process were constructed using Gibbs potential, a better understanding would ensue. Recall that the scaled equation of state in the critical region is based on chemical potential which reduces to Gibbs potential for pure fluids.

The coefficient, \( \beta_k \), has been shown (D.6), to obey the principle of corresponding states; for \( k = 1 \) the normalizing parameter \( (Z_c T_c)^{-1} \), as noted before, is suitable for engineering calculations.

**D2.2.4 Volumetric Expansion and Density Fluctuations**

Hendricks and colleagues (1979) have demonstrated that the parameter \( \beta_j \) is related to density fluctuations and in turn to turbulent flows with substantial temperature and or pressure gradients. Further, the fluctuation components are related through the equations of state where the density can be written
where the "primed" terms represent the fluctuating terms. Introducing fluctuation density \( \rho' = \bar{\rho} + \rho' \), pressure \( P' = \bar{P} + P' \), enthalpy \( H' = \bar{H} + H' \), and velocity \( u' = \bar{u} + u' \) into the conservation equations cited in the INTRODUCTION, the turbulent momentum and energy transport, for developed pipe flow, were written (Hendricks and colleagues, 1979),

\[
\begin{align*}
-T_t &= \bar{\rho} \bar{u}'v' + \bar{v} \bar{p}'u' + \bar{p}'u'v' \\
-q_t &= \bar{\rho} \bar{v}'H' + \bar{v} \bar{\rho}'H' + \bar{p}'v'H'
\end{align*}
\]  \hspace{1cm} (D.22)  \hspace{1cm} (D.23)

At very small temperature differences, the convective heat transfer is enhanced and it follows that the Rayleigh number would be an important parameter

\[ g \bar{c}_p \beta \Delta T \frac{d^3}{\nu \lambda} \]

See for example (Hendricks, Simoneau, and Smith, 1970) and the careful work of Irie and colleagues (1978), which would follow more closely the scaling laws; compare also the work of Lee and colleagues (1978) and Klipping.

E. POSSIBLE GENERALIZATIONS

El. Background

The usefulness of the similarity principles in grouping results for processes with heat and momentum transport has been demonstrated in the previous sections. The fact that the results obtained with cryogenic fluids can also be applied to a widely different fluid such as water is extremely useful.

Following the extended corresponding states principles of sections A and B, in this section we propose to "scale" fluids as

\[ P_o = Ph/f; \eta_o = \eta F\eta; T_o = T/f; \lambda_o = \lambda F\lambda; V_o = Vh \]

and transform thermophysical properties as

\[ \varphi^T = \varphi(h, f, \phi, \theta, \eta, F, F\eta, \ldots) \]

such that solutions of the fundamental equations of motion could be transformed independent of fluid characteristics.\(^9\)

\(^9\)To assign a characteristic length common to both molecular and continuum mechanics, it will be necessary to separate the effects of \( h, F, \eta, F\eta \) (Eqs. (A.4)-(A.16-17)). Then perhaps one could assign

\[ L_o = L_o \left( \frac{c^e}{h_o} \right) \Psi \]

however the assessment of \( L_o \) is difficult as transport property measurements themselves represent solutions of the conservation equations and the character of \( \Psi \) must be such as to give \( L_o \) independent of cluster size where appropriate; its definition is beyond the scope of this paper.
E2. Calculation of Critical Mass Flux Using the Generalized Transform

The thermophysical properties program of Hendricks and colleagues (1975), which was based on the work of Btnder (1970), was used to both compute the properties of the reference fluid and the necessary constants for the transform. The analytical program used by Simoneau and Hendricks (1979) was adapted to calculate the flow rates and pressure ratios for two-phase choked flow through a nozzle. The pressure and temperature of the working fluid were converted to the pressure and temperature of the reference fluid; computations then proceeded as usual for a single component reference fluid.

The conversion of pressure and temperature follows

\[
P_R = P_R^0 \quad T_R = T_R^0
\]

\[
P = P^0 \frac{Z c f}{Z c 0 h} \quad T = T^0 f
\]

where

\[
h = \frac{N c}{M c} \frac{c c^0}{c c 0} \phi \quad f = \frac{T c^0}{T c^0}
\]

\[
\phi = 1 + \left(\omega_c - \omega_o\right)
\]

\[
\theta = 1 + \left(\omega_c - \omega_o\right)
\]

Some calculated reduced critical mass flux values are given in Table 4 for oxygen or nitrogen flowing through a nozzle. The computed values of reduced mass flux are in good agreement, as can be seen in Tables 5 and 6 which were constructed using the various reference fluids methane, nitrogen, oxygen. The calculated values are compared to the experimental data, Fig. 12, of Hendricks, Simoneau, and Barrows (1976) in Figs. 13 to 19. In general the nitrogen and oxygen data points are in excellent agreement, independent of the working fluid, providing they are normalized (Hendricks, Simoneau, and Barrows, 1976), see Fig. 12. The theoretical calculations are for the most part, in good agreement independent of the working fluid and the reference fluid used to calculate the results. The agreement between oxygen data and theory using oxygen properties is in general quite good for this complex flow and the same comment can be made for nitrogen.

These results lend credence to the similarity principles delineated earlier and in part substantiate their validity. The work for the thermophysical properties people is extensive as application of the similarity principles requires accurate data bases for classes of fluids. In fluid mechanics and heat transfer accurate definitive experiments will be required.

\[10\]The homogeneous equilibrium fluid model of the nozzle with no slip between phases was chosen because of its relative simplicity and agreement with experimental results.
F. SUMMARY

The principle of similarity as applied to thermophysical properties with emphasis on the critical region and fluid mechanics, has been reviewed and shown, qualitatively, to group the experimental results of several physical processes. Using these principles, it is proposed that solutions can be developed which are independent of both the fluid characteristics and the physical nature of the coordinates. To illustrate this proposal, two phase choked flow of fluid \( \alpha \) was computed using fluid \( \beta \); where \( \alpha \) and \( \beta \) were either methane, nitrogen or oxygen; the results are in good agreement with extensive oxygen and nitrogen data.

SYMBOLS

- \( A_l \): area
- \( a, b, e, f, \alpha, \beta, m \): constants
- \( \beta \): scaling parameter, Eq. (B.6)
- \( C_p \): specific heat, constant pressure
- \( C_v \): specific heat, constant volume
- \( c \): constant
- \( c_s \): speed of sound
- \( c_{\alpha}, c_{\beta} \): coefficients of temperature and density difference terms, Eq. (B.20)
- \( D \): diffusion coefficient
- \( D, E \): constants, Eqs. (B.9), (B.10), and (B.12)
- \( d \): diameter
- \( F \): free energy, Helmholtz
- \( F_\alpha \): scale function for thermal conductivity
- \( F_\eta \): scale function for viscosity
- \( f \): scale function, fluid \( \alpha \) to reference fluid
- \( f_f \): friction factor
- \( f_1 \): bounding function, Eq. (B.19)
- \( G_m \): configurational Gibbs free energy; mixture
- \( G_0 \): configurational Gibbs free energy, reference fluid
- \( G_\alpha \): configurational Gibbs free energy, fluid \( \alpha \)
- \( G \): Gibbs free energy
- \( G_{a, o} \): scale parameter, Eqs. (A.30), (A.27), and (A.28)
$s$  body force
$H$  static enthalpy
$H_0$  total enthalpy
$h$  scale function, fluid $\alpha$ to reference fluid
$h_t$  heat transfer coefficient
$h(y)$  scaling function, Eq. (B.8)
$k$  isentropic expansion coefficient
$k_B$  Boltzmann's constant
$k_T$  isothermal compressibility
$M$  molecular weight
$m$  mass flow rate
$Pr$  Prandtl number
$P$  pressure
$Q_{\alpha,0}$  scale parameter, Eq. (A.29)
$q$  heat flux
$q_{k}$  reference heat flux, Kutateladze, Eq. (D.13)
$q_{1}$  fluid scale parameter, Eq. (B.22)
$R$  gas constant
$S$  entropy
$T$  temperature
$T^*$  transposed critical temperature (pseudo critical temperature)
$t$  time
$t_0$  reference time
$u,v$  velocity components
$V$  specific volume
$W = \rho u$  mass flux
$W^* = \sqrt{\frac{P c}{\rho c} / Z_c}$  flow normalizing parameter
$x$  coordinate scale
$x^*$  scaling variable, Eq. (B.5)
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<td>$\nu$</td>
<td>critical exponent, Eq. (B.14)</td>
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<tr>
<td>$\nu_a$</td>
<td>dynamic viscosity</td>
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<td>$\xi$</td>
<td>correlation length, Eq. (B.14)</td>
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<td>$\xi_1$</td>
<td>viscosity normalization parameter, Eq. (A.5)</td>
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<tr>
<td>$\xi_2$</td>
<td>thermal conductivity normalization parameter, Eq. (A.7)</td>
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<td>$\xi_3$</td>
<td>diffusion normalization parameter, Eq. (A.9)</td>
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<td>$\xi_4$</td>
<td>surface tension normalization parameter, Eq. (A.11)</td>
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<td>$\xi_{\alpha, \beta}$</td>
<td>binary interaction parameter</td>
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<tr>
<td>$\rho$</td>
<td>density</td>
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<tr>
<td>$\sigma_s$</td>
<td>surface tension</td>
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<td>$\tau$</td>
<td>shear force</td>
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<tr>
<td>$\phi$</td>
<td>shape factor</td>
</tr>
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</table>
\( \varphi \) property parameter, Eqs. (D.19) and (E.2)

\( \phi_{a, \beta} \) binary interaction parameter

\( \phi_1 \) constant, Eq. (B.23)

\( \chi \) scale parameter, Eqs. (A.27), (A.28), and (A.33)

\( \chi_T \) symmetrized isothermal compressibility

\( \psi \) correction parameter, Eq. (D.6)

\( \psi_k \) volumetric or energy expansion parameter, Eq. (D.17)

\( \omega = -1 - \log_{10} \frac{R}{T_R} \bigg|_{T_R = 0.7} \) accentric factor, Eq. (D.12)

**Subscripts:**

B bulk

CIC critical isochore

CIT critical isotherm

CXC coexistence curve

c critical

m mixture

o reference fluid

R reduced

T throat of nozzle

w wall

0,0 "zero-density" reference state

a working fluid

\( a, \beta \) binary interaction

\( \alpha_{a, \beta} \) pure component interactions

**Superscripts:**

c critical

\( \bar{\cdot} \) average

\( \sim \) background or "normal conditions"

\( \cdot \) fluctuating

* normalized
REFERENCES

Alamgir, Md., and J. H. Lienhard. The Temperature Dependence of Surface Tension of Pure Fluids. To be published.


Acknowledgement: The assistance of J. R. Hendricks in preparing this document is hereby acknowledged.


Acknowledgement: The assistance of J. R. Hendricks in preparing this document is hereby acknowledged.
**TABLE 1** Critical Power Laws

<table>
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<th>Property</th>
<th>Path</th>
<th>Power law</th>
</tr>
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<td>$C_v^* / T^*$</td>
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<td>$A</td>
</tr>
<tr>
<td>$C_v^* / T^*$</td>
<td>CIC, $\Delta T^* \leq 0$</td>
<td>$A'</td>
</tr>
<tr>
<td>$\Delta H^*$</td>
<td>CXC</td>
<td>$B</td>
</tr>
<tr>
<td>$\chi^*_T$</td>
<td>CIC, $\Delta T^* \geq 0$</td>
<td>$\Gamma</td>
</tr>
<tr>
<td>$\chi^*_T$</td>
<td>CXC</td>
<td>$\Gamma'</td>
</tr>
<tr>
<td>$\Delta u^*$</td>
<td>CIT</td>
<td>$\Delta D</td>
</tr>
</tbody>
</table>

**TABLE 2** Scaled Expressions for Thermodynamic Functions

Chemical potential

$$\mu^* = \mu^*(\rho_c^*, T^*) + \Delta \phi^* | \Delta T^* |^6 \cdot \delta h(y)$$

Compressibility

$$\chi_{T-1}^* = | \Delta \phi^* |^{6-1} D \left[ \delta h(y) + \frac{1}{\beta} (1 - y) \frac{\delta h(y)}{\delta y} \right]$$

Helmholtz free energy density

$$F^* = A_o^*(T^*) + \rho^* \mu^*(\rho_c^*, T^*) + | \Delta \phi^* |^{6+1} \delta a(y)$$

Entropy density

$$-S = \frac{dA_o^*(T^*)}{dT^*} + \rho^* \frac{d\mu^*(\rho_c^*, T^*)}{dT^*} + | \Delta \phi^* |^{1-\alpha} \frac{D}{\delta a(y)} \frac{d\delta a(y)}{dy}$$

Heat capacity

$$- \frac{C_v^*}{T^*} = \frac{d^2 A_o^*(T^*)}{dT^*^2} + \rho^* \frac{d^2 \mu^*(\rho_c^*, T^*)}{dT^*^2} + | \Delta \phi^* |^{-\alpha/\beta} \frac{D}{\delta a(y)} \frac{d^2 \delta a(y)}{dy^2}$$

Pressure

$$P^* = -A_o^*(T^*) + D \left[ \Delta \phi^* | \Delta T^* |^5 \cdot h(y) + | \Delta \phi^* |^{6+1} \left[ h(y) - a(y) \right] \right]$$

$A_o^*(T^*)$ and $\mu^*(\rho_c^*, T^*)$ are analytic functions of $T^*$; $\rho_c^* = 1.$
### TABLE 3 Critical Region Parameters for a Number of Fluids Assuming Effective Universal Exponents

<table>
<thead>
<tr>
<th>Fluid</th>
<th>$P_c^*$ (MPa)</th>
<th>$\rho_c^*$ (kg/m$^3$)</th>
<th>$T_c^*$ (K)</th>
<th>$x_o$</th>
<th>$D$</th>
<th>$\xi_o \times 10^6$ (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>$^3\text{He}$</td>
<td>0.11678</td>
<td>41.45</td>
<td>3.3099</td>
<td>0.489</td>
<td>3.16</td>
<td>2.7</td>
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<tr>
<td>$^4\text{He}$</td>
<td>2.2742</td>
<td>69.6</td>
<td>5.1895</td>
<td>0.369</td>
<td>2.86</td>
<td>2.2</td>
</tr>
<tr>
<td>Ar</td>
<td>4.865</td>
<td>535</td>
<td>150.725</td>
<td>0.83</td>
<td>2.43</td>
<td>1.6</td>
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<tr>
<td>Kr</td>
<td>5.4931</td>
<td>908</td>
<td>209.286</td>
<td>0.83</td>
<td>2.43</td>
<td>1.7</td>
</tr>
<tr>
<td>Xe</td>
<td>5.8400</td>
<td>1110</td>
<td>289.734</td>
<td>0.83</td>
<td>2.43</td>
<td>1.9</td>
</tr>
<tr>
<td>p-H$_2$</td>
<td>1.285</td>
<td>31.39</td>
<td>32.935</td>
<td>0.260</td>
<td>2.50</td>
<td>1.9</td>
</tr>
<tr>
<td>H$_2$</td>
<td>3.398</td>
<td>313.9</td>
<td>126.24</td>
<td>0.164</td>
<td>2.32</td>
<td>1.6</td>
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<td>O$_2$</td>
<td>5.043</td>
<td>1136.2</td>
<td>154.580</td>
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<td>1.6</td>
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<tr>
<td>H$_2$O</td>
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<td>322.2</td>
<td>647.13</td>
<td>0.100</td>
<td>1.28</td>
<td>1.3</td>
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<tr>
<td>D$_2$O</td>
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<td>357</td>
<td>643.89</td>
<td>0.100</td>
<td>1.28</td>
<td>1.3</td>
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<td>CO$_2$</td>
<td>7.3753</td>
<td>467.8</td>
<td>304.127</td>
<td>0.141</td>
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<td>1.6</td>
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<td>NH$_3$</td>
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<td>0.109</td>
<td>1.47</td>
<td>1.4</td>
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<tr>
<td>SF$_6$</td>
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Notes: $\alpha = 0.100$, $\beta = 0.355$, $\gamma = 1.190$, $\delta = 4.352$, $\nu = 0.633$, $E = 0.287$. 
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<th>( T, K )</th>
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<td>( x ) CH(_4)</td>
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### Reproducibility of the Original Data is Poor

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<th>(T_R = 0.942)</th>
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<td>1.27</td>
<td>.854</td>
<td>.35</td>
<td>.93</td>
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</table>

1st index = reference fluid used to calculate values.
2nd index = working fluid flowing through nozzle.
**TABLE 6** Calculated Throat to Stagnation Pressure Ratios for Critical Flow using the Principle of Similarity and the Homogeneous Equilibrium Model, Reference 65

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<th>$P_R$</th>
<th>$P_{o_2}$</th>
<th>$P_N_2$</th>
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<th>$T_R = 0.945$</th>
<th>$T_R = 1.025$</th>
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<td>$P_{o_2}$</td>
<td>$P_{o_2}$</td>
<td>$P_{CH_4-o_2}$</td>
<td>$P_{CH_4-N_2}$</td>
<td>$P_{CH_4-o_2}$</td>
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<tr>
<td>.25</td>
<td>1.27</td>
<td>.854</td>
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<td></td>
</tr>
</tbody>
</table>

1st index = reference fluid used to calculate values.
2nd index = working fluid flowing through nozzle.
$P_T$ represents the pressure at the nozzle throat.
Fig. 1. Relationship between the residual viscosity modulus $\bar{\eta} - \eta_{0,0}^{E}$ and reduced density $\rho_R$ for normally behaving substances, Jossi, Stiel, and Thodos (1962).
Fig. 2. Special paths in the \( \Delta T^* \) versus \( \Delta \rho^* \) plane for the definition of critical power laws.

Fig. 3. Curves of constant \( y \) in the \( \Delta T^* - \Delta \rho^* \) plane.
Fig. 4. Scaled chemical potential data for steam as a function of $\gamma = \frac{x + x_0}{x_0}$. Reduction parameters are taken from Table III.

Fig. 5. Scaled chemical potential data for $^3$He, $^4$He, Xe, CO$_2$, and H$_2$O as a function of $\gamma = \frac{x + x_0}{x_0}$. Reduction parameters are taken from Table III.
Fig. 7. Reduced Joule-Thomson coefficients as function of reduced temperature for selected isobars, Hendricks, Peller, and Baron (1972).

Fig. 8. Temperature dependence function for surface tension: low and moderate temperatures, Lienhard and Amir (1977).
Fig. 9. Temperature-entropy chart with metastable locus, Simoneau and Hendricks (1977).
Fig. 10. Reduced volumetric expansion factor as a function of reduced temperature at selected reduced isobars. Hendricks (1979).
Fig. 11(a). Comparison of nitrogen and methane critical flow rate data on corresponding states basis, ref. 64.

Fig. 11(b). Comparison of nitrogen and methane critical flow pressure ratio data on corresponding states basis, Hendricks and Simoneau (1973).
Fig. 12. Reduced Nusselt number as a function of Gifford energy expansion factor for gaseous data from Hendrick (1971).

PRODUCIBILITY OF THE
REPRODUCIBILITY OF THE ORIGINAL PAGE IS POOR

Fig. 14. Comparisons of choked flow rates as a function of reduced pressure for reduced temperature of -0.750.

Fig. 15. Comparisons of choked flow rates as a function of reduced pressure for reduced temperature of -0.942.
Fig. 16. Comparisons of choked flow rates as a function of reduced pressure for reduced temperature of -1.025.

Fig. 17. Comparison of pressure ratio as a function of reduced pressure for reduced temperature of -0.750.
Fig. 18. Comparison of pressure ratio as a function of reduced pressure for reduced temperature of 0.942.

Fig. 19. Comparison of pressure ratio as a function of reduced pressure for reduced temperature of 1.025.

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APPLICATION OF THE PRINCIPLE OF SIMILARITY
FLUID MECHANICS

R. C. Hendricks, Lewis Research Center, Cleveland, Ohio and J. V. Sengers, University of Maryland, College Park, Maryland

Possible applications of the principle of similarity to fluid mechanics is described and illustrated. In correlating thermophysical properties of fluids, the similarity principle transcends the traditional corresponding states principle. In fluid mechanics the similarity principle is useful in correlating flow processes that can be modeled adequately with one independent variable (i.e., one-dimensional flows). In this paper we explore the concept of transforming the conservation equations by combining similarity principles for thermophysical properties with those for fluid flow. We illustrate the usefulness of the procedure by applying such a transformation to calculate two phase critical mass flow through a nozzle.
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Fluid mechanics; Principles of similarity; Thermophysical properties; Corresponding states; Thermodynamic critical point; Two phase choked flows