Admissibility of nonclassical shock waves in near-critical singl-component fluids - new findings

NR Nannan, A Lucchini, P Colonna (PI) (TUD/P&E/ET)

Introduction

Disturbances propagating at supersonic velocity can eventually coalesce into shock waves, viz. surfaces through which there is a flow of matter which experiences an abrupt - from a macroscopic viewpoint seemingly discontinuous - change of properties. For example, through a shock wave there is a sudden increase of pressure or change of flow velocity. Mathematically, shock waves are discontinuous solutions of the Euler equations and feature a (super)sonic to (sub)sonic speed transition and an increase of the entropy of the substance[1]. Their nature, i.e., whether the pressure-change experienced by the substance is compressive or expansive, is governed by the peculiarities of the fluid or the physics that determines the thermodynamic behavior under imposed conditions. Among other things, the so-called fundamental derivative of gas dynamics, Γ, is key in the analysis and understanding of the compressible flows in general, and shock-wave admissibility in particular. Γ is a caloric property defined as

$$\Gamma = 1 + \frac{\rho}{c}\left(\frac{\partial c}{\partial \rho}\right)_s , \qquad (1)$$

where ρ is the density, s denotes the entropy and c represents the zero-frequency speed of sound. One can show, making appropriate assumptions and hypotheses, that $\Gamma > 0$ permits compressive shock waves only, whereas $\Gamma < 0$ permits only expansive shock waves[2].

Recently, a detailed study was conducted with the specific aim of investigating the behavior of Γ in the vapor-liquid critical region of a single-component fluid, i.e., a thermodynamic regime where critical anomalies manifest, e.g., divergence of for example the isothermal compressibility and the isochoric heat capacity, or the fact that the zero-frequency speed of sound approaches zero[3].

Results

The vapor-liquid critical region of a single-component fluid is described by so-called scaling laws and falls in the universality-class of 3D-Ising like systems, i.e., systems governed by short-range interaction forces. Such a scaling law formulated in terms of pressure P, temperature T and is chemical potential is μ, is[4]

$$\underbrace{\tilde{P}}_{\frac{P-P_c}{P_c}}\left(\overbrace{r,\theta}^{\text{[illegible]}}\right) = 1 + \sum_{i=1}^{3} \tilde{P}_i\left(\Delta\underbrace{\tilde{T}}_{\frac{T-T_c}{T_c}}\right)^i + \Delta\tilde{\mu}\left(1 + \tilde{P}_1\Delta\tilde{T}\right) + \underbrace{\Delta\tilde{P}}_{\text{[illegible]}} \qquad (2)$$

Here, r and θ are parametric variables; their meaning is shown in Fig. 1 for fluid methane. Calculations for methane illustrated in Figs. 2 and 3, and confirmed for other fluids such as water and carbon dioxide, show that, due to the critical anomalies, Γ diverges as the critical point is approached, independent of the direction. Even more interesting is the finding that $\Gamma \to -\infty$ as the critical point is approached from the vapor-liquid equilibrium (VLE) region, see Fig. 4.

This implies the admissibility of nonclassical expansion shock waves which can feature condensation.

The nonclassical gasdynamic behavior is therefore governed by the physical behavior of fluids in the critical region, and not per se by the fluid's features, that is, its molecular complexity. To the knowledge of the authors, this is a new finding.

Experimental validation?

The obtained results for Γ are based upon the assumptions of thermodynamic equilibrium and homogeneously dispersed phases (stratification is therefore excluded). Assessment of the validity of these assumptions mandates experimental verification. For this purpose, the Flexible Asymmetric Shock Tube at the P&E lab can be used, although specific modifications must be made. Furthermore, the structure of these nonclassical shock waves must be investigated since also transport properties display critical anomalies. These theoretical results can also be employed to explain the experimental results published in the early 80s by Borisov et.al.[5] on the possible observation of the mentioned critical nonclassical expansion shock waves.

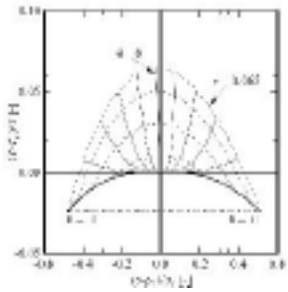

Figure 1 The parametric distance, *r*, and the contour variable β in the scaled T-ρ plane of methane.

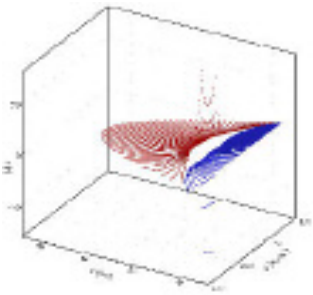

Figure 2 The fundamental derivative of gas dynamic in the critical region of methane.

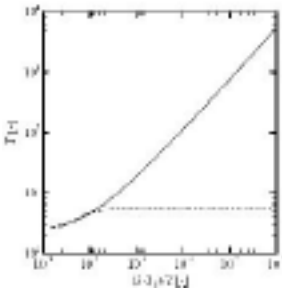

Figure 3 Divergence of $\Gamma \rightarrow -\infty$ The exponent of the power law is 0.89 and is universal.

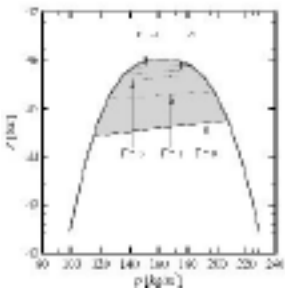

Figure 4 Iso Γ - lines in the VLE region of methane computed with the scaled fundamental equation.

References

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