Shock-refraction properties in dense vapours

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Long Abstract

Introduction

Dense vapours are single-phase gases featuring large heat capacities relative to their molecular weights. Examples are hydrocarbons, perfluorocarbons or siloxanes. They are of practical interest in energy-conversion cycles operating on low-temperature heat sources such as Organic Rankine Cycles (ORCs) where the expansion process may be performed in just one stage. Part of the expansion occurs close to the thermodynamic critical point (TCP) where the sound speed substantially decreases, making the expander flow highly supersonic (up to Mach 3) and causing shockwaves to form in the expander [1].

Based on linear theory, shocks in ideal gases have been known to generate thermo-acoustic modes. Ribner [2] has for example demonstrated how turbulence intensities as low as 0.1% could turn into a 120 dB noise level downstream of the shock. More recently, the ability of linear theory to predict the post-shock turbulence kinetic energy was found to be remarkable when compared against state-of-the-art three-dimensional Navier–Stokes simulations [3].

To date, no theory exists on both the turbulence and shock-refraction properties in dense vapours near the TCP. The present work constitutes a first step in that direction, highlighting some unique features of the dense-gas shock-refraction properties.

Method and results

Shock-refraction properties are studied from the point of view of both the linear theory and direct numerical simulations (DNS) of the compressible Navier–Stokes/Euler equations of a gas featuring an arbitrary equation of state (EoS). Quantitative results are obtained for the van der Waals EoS. A new solver using high-order dispersion-relation-preserving (DRP) centred difference schemes was developed. A shock-capturing technique based on analytical solutions of the viscous-shock structure was invented, allowing for the precise control of the numerical-shock thickness and delivering virtually wiggle-free solutions. This is particularly important when portions of the Hugoniot lines become non-convex (in the pressure–specific volume phase).

Exceptionally-strong entropy modes are found to be produced by dense-gas shocks (up to two orders of magnitude greater than in ideal gases). In particular, some shocks are shown to potentially become very selective in their refraction properties. This is due to the combined effect of significant van der Waals forces with a large number of active degrees of freedom in the molecule, making some portions of the Hugoniot line non-admissible, in turn producing discontinuous eigen-mode amplification factors (see Fig. 1). This allows one to direct the energy of an incoming perturbation more into the acoustic, or the entropic, or the vortical mode (see Fig. 2) – something which is not feasible in ideal gases.

The selectivity of the shock can modify the turbulence properties in a unique manner, ultimately prompting a need to re-think turbulence models in such flows. The final presentation will share some early results in the context of wall-bounded turbulence.

References

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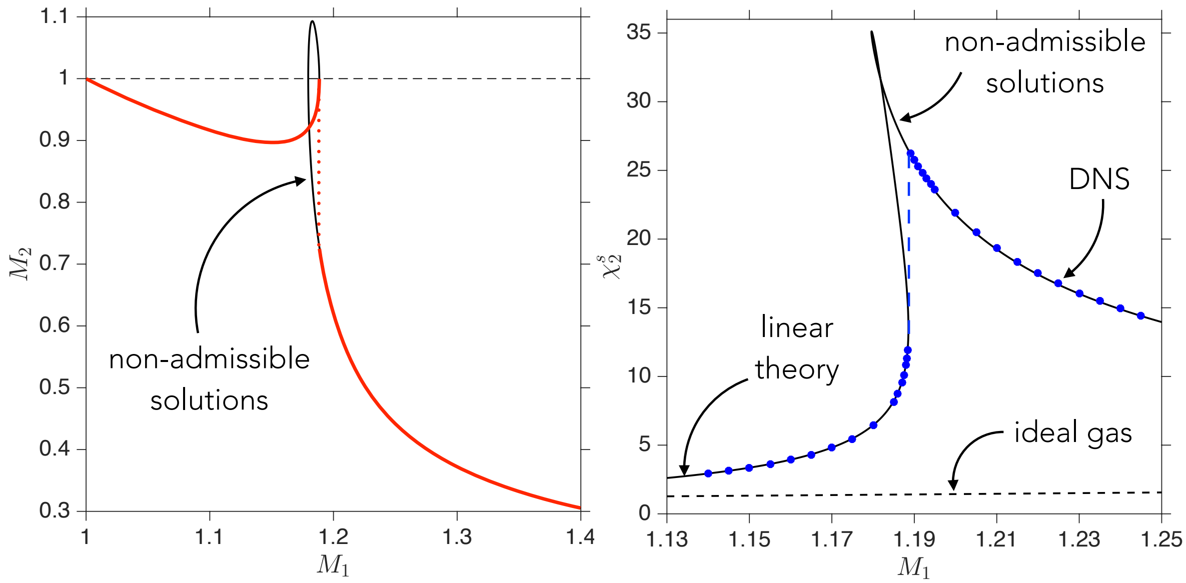

Figure 1. Left: post-shock Mach number as a function of the pre-shock Mach number. Right: amplification factor of an entropy mode across the shock. Both plots are for $T_1/T_c = 1.00$, $p_1/p_c = 0.63$ for PP10 modelled as a van der Waals gas ($C_v/R = 156.2$).

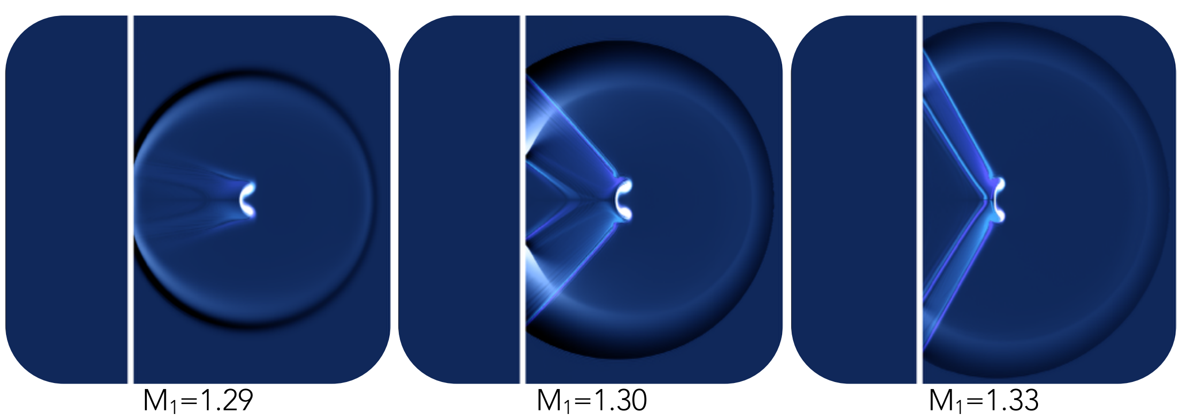

Figure 2. Refraction of a low-density pulse (in white) on a shock at $T_1/T_c = 1.00$ and $p_1/p_c = 0.55$ for PP10 modelled as a van der Waals gas ($C_v/R = 156.2$) and very small variations in the incoming Mach numbers. The colouring is such that both the dilatation rates and the vorticity field are made visible. More energy goes into the acoustic modes (left) and the vortical modes (right).