A 3D high order finite volume method for the prediction of near-critical fluid flows

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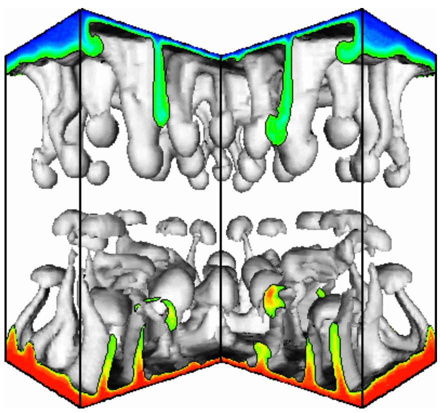
When approaching the gas-liquid critical point (CP) of a pure fluid, the heat diffusivity vanishes while the thermal expansion coefficient and the isothermal compressibility tend to infinity. The mathematical model currently admitted for the near-critical fluid (NCF) behaviour, proposed in [1], is described by the unsteady Navier-Stokes and energy equations in the low Mach number approximation for a dense, Newtonian, viscous, highly heat conducting, calorically perfect, and highly expandable van der Waals' (VDW) fluid.

This study describes a 3D high order numerical tool (compared to its lower order 2D counterparts) for the prediction of NCF flows inside heated enclosures. Due to its very robust description of the numerical fluxes, a fully implicit finite volume method on a staggered mesh with a velocity-pressure coupling algorithm is used to handle the extremely large density gradients encountered in the thermal boundary layers. The method is second order accurate in space and third order in time, the linear systems are solved using Preconditioned CG and Bi-CGSTAB methods, the code is vectorized and optimally operating at 4.2 Gflops on the IDRIS' NEC SX-5 supercomputer. In the CP vicinity, the unavoidable linearization of the VDW cubic equation of state (EOS) leads to a dramatic convergence slow down of the cubic EOS itself and consequently of the whole iterative process. We show how, taking advantage of the mathematical properties of the linearized VDW EOS, one can speed up the global convergence.

The solver is validated for the 3D differentially heated cavity problem: *(i)* the space and the time accuracies are checked by forcing an analytical exact solution, *(ii)* several benchmark tests of natural convection are considered for the Boussinesq approach in cubical enclosures as well as for the perfect gas (PG) in the 2D low Mach number approximation (in the absence of a 3D equivalent). Then, comparisons between the NCF and PG flows in a differentially heated cavity, based on the Rayleigh number, are carried out for both steady and transient states.

The rest of the study is devoted to the unsteady convective flow of a NCF in Rayleigh-Benard configuration. Two-dimensional earlier works [2,3] reported fast and homogeneous temperature equilibrium by thermo-acoustic effects due to the hyper thermal expansion of NCF (piston effect). As the thermal boundary layers thicken in time, the local Rayleigh number exceeds a critical value (1100.6), and a convective instability takes place in both bottom (hot) and top (cold) boundary layers. Inspecting the time-evolution of temperature field patterns, we exhibit corner effects, the three-dimensional behaviour of the flow, and the transition to the turbulence.



Instantaneous temperature patterns exhibiting the 3D Rayleigh-Bénard convective instability and the transition to the turbulent flow in a NCF enclosed in a cubical box.

CP proximity: 1K,
Bottom heating intensity: 2.5mK,
Configuration after 18s of heating.

References

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