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A robust and accurate numerical method for transcritical turbulent flows at supercritical pressure with an arbitrary equation of state

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ABSTRACT

This paper addresses issues in high-fidelity numerical simulations of transcritical turbulent flows at supercritical pressure. The proposed strategy builds on a tabulated look-up table method based on REFPROP database for an accurate estimation of non-linear behaviors of thermodynamic and fluid transport properties at the transcritical conditions. Based on the look-up table method we propose a numerical method that satisfies high-order spatial accuracy, spurious-oscillation-free property, and capability of capturing the abrupt variation in thermodynamic properties across the transcritical contact surface. The method introduces artificial mass diffusivity to the continuity and momentum equations in a physically-consistent manner in order to capture the steep transcritical thermodynamic variations robustly while maintaining spurious-oscillation-free property in the velocity field. The pressure evolution equation is derived from the full compressible Navier–Stokes equations and solved instead of solving the total energy equation to achieve the spurious pressure oscillation free property with an arbitrary equation of state including the present look-up table method. Flow problems with and without physical diffusion are employed for the numerical tests to validate the robustness, accuracy, and consistency of the proposed approach.

1. Introduction

Understanding the physics of turbulent flows at supercritical pressure is crucial for a wide range of industrial applications. In particular, heat transfer and skin friction characteristics of turbulent boundary layer phenomena at supercritical pressures (i.e., supercritical fluid turbulent boundary layer), are one of the main interests in the regenerative cooling in liquid rocket engines, supercritical steam generators in power plants, refrigerating systems with supercritical CO_2, supercritical fluids for concentrated solar power plants, etc. (more details may be found in the recent review paper by Yoo [1]). In order to understand the turbulent flows at supercritical pressure, it is essential that we need to understand the interactions between the real fluid effects and turbulence, and their resultant turbulence statistics.

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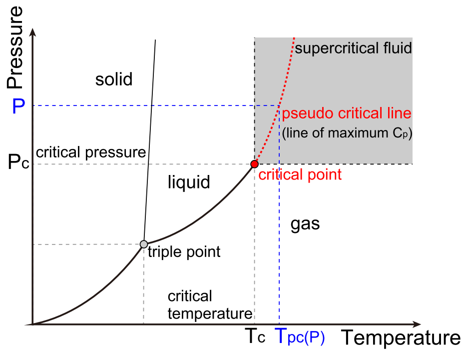
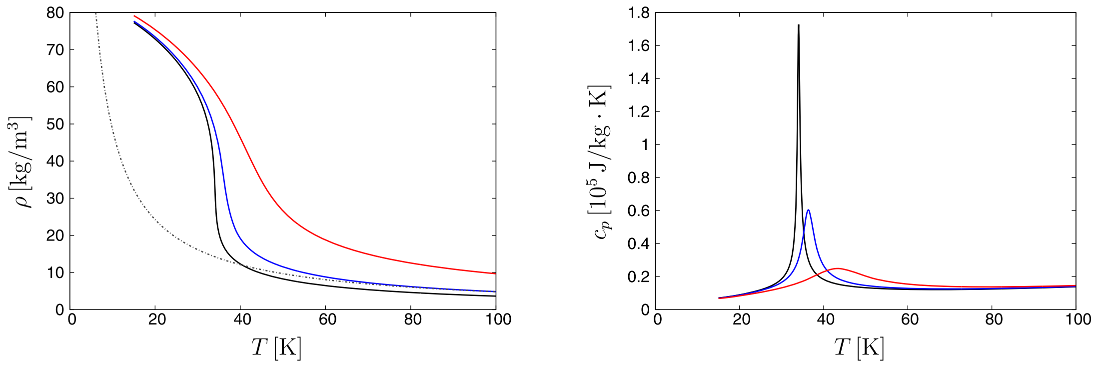


Fig. 1. Supercritical fluids and pseudo-critical temperature at a given pressure in a phase diagram.



(a) Density (b) Specific heat at constant pressure

Fig. 2. Variable thermodynamic properties for parahydrogen using REFPROP (NIST Standard Reference Database 23, Version 9.0). Density and specific heat at constant pressure (black, $p = 1.5$ [MPa]; blue, $p = 2.0$ [MPa]; red, $p = 4.0$ [MPa]; gray dashed line only in (a), ideal gas law at $p = 2.0$ [MPa]). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Peculiar fluid behaviors in supercritical fluids occur within a narrow temperature range through the pseudo-critical temperature $T_{pc}(p)$ (shown in red dotted line in Fig. 1) where the specific heat at constant pressure c_p reaches its maximum value at a given pressure. We note that the pseudo-critical temperature is a function of the pressure p where the pressure is higher than the critical pressure p_c, i.e., $T_{pc}(p)$ changes depending on the pressure as shown in Fig. 1. Through the pseudo-critical temperature at a given pressure, the supercritical fluids behave as a high-density liquid-like fluid when $T < T_{pc}(p)$ and a low-density gas-like fluid when $T > T_{pc}(p)$. However, differently from liquid-gas multiphase flows, the transition of thermodynamic and fluid transport properties from liquid-like fluid to gas-like fluid through $T_{pc}(p)$ occurs continuously at supercritical pressure although the variations are abrupt and severe within a very narrow temperature range (see Fig. 2).

Fig. 3 shows profiles of the density and specific heat at a constant pressure with a smooth sinusoidal temperature distribution in space or time at the constant supercritical pressure of $p = 2.0$ [MPa] for parahydrogen. The temperature ranges from 20 to 100 [K] and thus crosses the pseudo-critical temperature $T_{pc}(p)$ (≈ 36.4 [K]). Although the temperature is given by a smooth function, once the flow temperature varies through the pseudo-critical temperature $T_{pc}(p)$, the fluid thermodynamic properties show the steep variations in space or time within a very narrow temperature range around $T_{pc}(p)$. Through the pseudo-critical temperature $T_{pc}(p)$, the thermodynamic properties show strongly non-linear behaviors and significantly deviate from the ideal fluid due to the real fluid effects. The density varies abruptly and locally through $T_{pc}(p)$, and the specific heat at constant pressure show a peak at $T = T_{pc}(p)$ (around the location x or $t \approx 0.6$ and 0.9 in Fig. 3). In this study, this transitional state is called as "transcritical condition," and the transcritical flow is the flow at supercritical pressure where the transcritical condition exists within the flow. We also call this contact-surface-like abrupt and local variation of thermodynamic properties through $T_{pc}(p)$ as "transcritical contact surface." Note that similar to the multicomponent flows (e.g., Refs. [2–5]), with no physical diffusion $\mu = 0$ and $\kappa = 0$ constant velocity and pressure are physically satisfied across the transcritical contact surface while the other thermodynamic properties, such as the density and temperature, vary abruptly. Interestingly, when the transcritical condition exists within turbulent boundary layers, experimental data show a significant change in turbulent heat transfer (e.g., Yamagata et al. [6], more details may be found in the recent review paper by Yoo [1]), which is one of the main interests in the engineering view point.

In the simulation of transcritical turbulent flows, due to the strongly non-linear real fluid effects, first it is crucial that we need an accurate modeling for the non-linear behaviors of thermodynamic and fluid transport properties at the transcritical