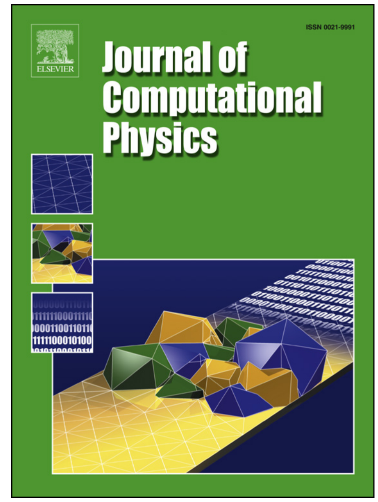
Accepted Manuscript



An entropy-stable hybrid scheme for simulations of transcritical real-fluid flows

Peter C. Ma, Yu Lv, Matthias Ihme

PII: S0021-9991(17)30217-6
DOI: http://dx.doi.org/10.1016/j.jcp.2017.03.022
Reference: YJCPH 7226

To appear in: *Journal of Computational Physics*

Received date: 30 August 2016
Revised date: 9 March 2017
Accepted date: 12 March 2017

Please cite this article in press as: P.C. Ma et al., An entropy-stable hybrid scheme for simulations of transcritical real-fluid flows, *J. Comput. Phys.* (2017), http://dx.doi.org/10.1016/j.jcp.2017.03.022

An entropy-stable hybrid scheme for simulations of transcritical real-fluid flows

Peter C. Ma[a], Yu Lv[*,a], Matthias Ihme[a]

[a]*Department of Mechanical Engineering, Stanford University, Stanford, CA 94305, USA*

Abstract

A finite-volume method is developed for simulating the mixing of turbulent flows at transcritical conditions. Spurious pressure oscillations associated with fully conservative formulations are addressed by extending a double-flux model to real-fluid equations of state. An entropy-stable scheme that combines high-order non-dissipative and low-order dissipative finite-volume schemes is proposed to preserve the physical realizability of numerical solutions across large density gradients. Convexity conditions and constraints on the application of the cubic state equation to transcritical flows are investigated, and conservation properties relevant to the double-flux model are examined. The resulting method is applied to a series of test cases to demonstrate the capability in simulations of problems that are relevant for multi-species transcritical real-fluid flows.

Key words: Real fluid; spurious pressure oscillations; double-flux model; entropy stable; hybrid scheme

1. Introduction

The accurate and robust simulation of transcritical real-fluid effects is crucial for many engineering applications, such as fuel injection in internal-combustion engines, rocket motors and gas turbines. For example, in diesel engines, the liquid fuel is injected into the ambient gas at a pressure that exceeds its critical value, and the fuel jet will be heated to a supercritical temperature before combustion takes place. This process is often referred to as a transcritical injection (see Fig. 1). The largest thermodynamic gradient in the transcritical regime occurs as the fluid undergoes a liquid-like to a gas-like transition when crossing the pseudo-boiling line [1], which is shown by the black dashed line in Fig. 1. At elevated pressures, the mixture properties exhibit liquid-like densities and gas-like diffusivities, and the surface tension and enthalpy of vaporization approach zero [2]. This phenomenon was shown by recent experimental studies [1, 3, 4]. However, these complex processes are still not well understood experimentally and numerically. Therefore, to provide insights into high-pressure combustion systems, reliable numerical simulation tools are required for the characterization of supercritical and transcritical flows.

Due to the unique thermodynamic behavior and large gradients of thermodynamic quantities in the transcritical regime, several challenges must be overcome to enable the numerical prediction of transcritical flows. One challenge is the accurate description of thermodynamic and transport properties across the transcritical regime. Cubic equations of state (EoSs), such as Peng-Robinson (PR) EoS [5] and Soave-Redlich-Kwong (SRK) EoS [6], have been used extensively in transcritical and supercritical simulations for their acceptable accuracy and computational efficiency. Volume-translation methods for cubic EoS were applied to supercritical simulations to further improve the accuracy of thermodynamic descriptions [7]. More complex state equations are also available, such as the Benedict-Webb-Rubin (BWR) EoS [8], and state relations that are explicit in Helmholtz energy [9], but they often involve complicated implementation and high computational

*Corresponding author

Email addresses: peterma@stanford.edu (Peter C. Ma), ylv@stanford.edu (Yu Lv), mihme@stanford.edu (Matthias Ihme)