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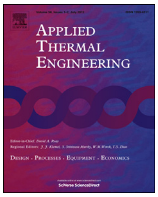

Heat transfer and various convection structures of near-critical CO_2 flow in microchannels

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ABSTRACT

Supercritical/near-critical fluid is very dense and much expandable, and with its preferable flow and heat transfer properties, it has been proposed in various kinds of energy conversion systems. The fluid critical transitions and diverges are very important for both hydrodynamic study and heat transfer applications. The current study deals with the near-critical CO_2 horizontal flow and heat transfer performance in microchannels. Careful numerical procedures are carried out with Navier–Stokes equations, energy and state equations, which are treated with special care for micro-scale investigations. Due to the thermal–mechanical effects of critical fluid, abnormal thermal convection structure and transient micro-scale vortex mixing evolution mode are found in microchannels, which is identified to be governed by basic Kelvin–Helmholtz instability. New sources of near-critical fluid thermal–mechanical perturbations, instead of gravity waves, are found to be responsible for the microscale instabilities for the transient vortex flow development. It is also found that while in closed systems the Piston Effect (PE) is dominant, the thermal–mechanical expansion characteristics yield new convective structures and evolutions in open system (microchannels). At the same time the microchannel heat transfer is greatly enhanced due to the vortex evolutions. Possible model extensions are also discussed, and the near-critical fluid convection problem is then characterized from a more general viewpoint in this study.

1. Introduction

Nowadays, with the development of micro structure devices in micro-electronics, micro-chemical engineering, micro-surgery, micro-pharmaceutics, or MEMS systems, the effective control of micro-scale fluid flow and heat transfer has become more and more important [1]. Microchannel is one of the most frequently seen geometries in micro devices [2]. Besides the generally discussed microchannel flow and heat transfer performances, micro-mixing technologies can also be of great importance when treating with those kinds of micro-processes and critical flow conditions [2,3]. The demand in miniaturization and micro process operation has also triggered new designs for micro-mixing technologies. However, most of those micro-mixing/manipulation methods are very expensive and complex for manufacturing/maintenance as they are too small and delicate when used in real applications. New methods are still in demand and it is in hoped that simple and effective ways be developed from the basic heat transfer and hydraulic laws in microchannels.

Also the current problem of near-critical fluid convection is one topic related to scientific aspect of fluid dynamics and thermophysics. As the gas–liquid critical point is approached in supercritical fluids, strong anomalies can be found in thermal and transport coefficients [4]. The isothermal compressibility and thermal expansion both grow dramatically while the thermal diffusivity tends to zero. For example, the basic property evolutions of supercritical CO_2 fluid are plotted in Fig. 1. It is seen that large deviations or peaks are found for the near-critical states of the fluid. It has been reported that these specific properties induce special coupling processes of thermal equilibrium and mechanical disturbance/instability [4,5]. In closed systems, an additional adiabatic heat transfer mechanism called the Piston Effect (PE) has been identified independently by several teams [5–7]. When heating the boundary of near-critical fluid, a very expandable, thin, diffusive layer is formed, which compresses the bulk fluid and causes the

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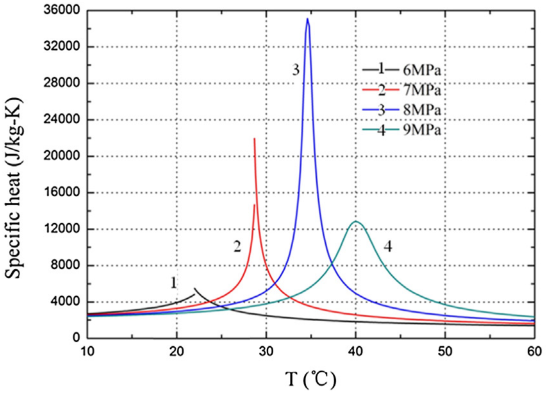
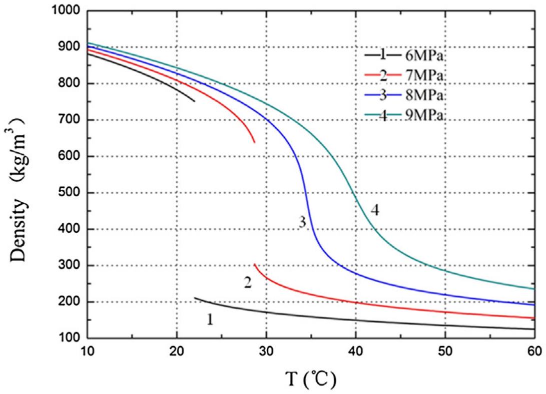
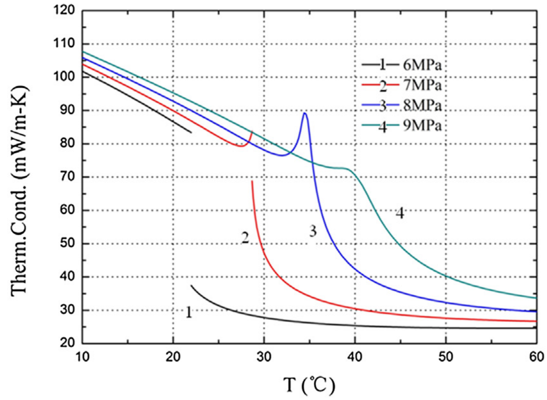


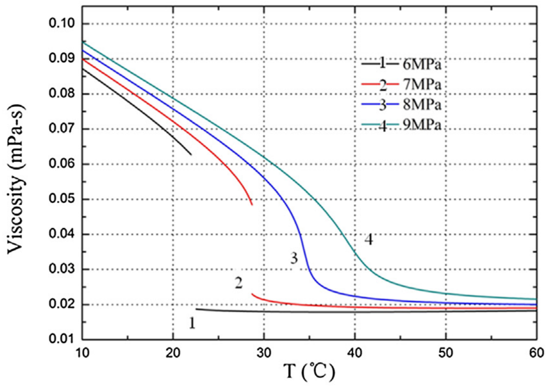
(a) specific heat



(b) density



(c) thermal conductivity



(d) viscosity

Fig. 1. Variation of thermoproperties with temperature and pressure in the critical region.

temperature of the bulk fluid to increase at acoustic time scale. Therefore heat is transported much faster than simple diffusion in such systems by the thermal–mechanical expansion and compression process - like a thermal piston [5–7].

Indeed, as one kind of near-critical thermal–mechanical processes, this specific behaviors contribute to normal heat convection/relaxation both in closed system or open systems. Though Piston Effect was first found in a closed system under microgravity and the very strong compression and temperature fluctuations only happen in constrained flow condition (under global or local heating), the basic boundary thermal compression and vibration process will still happen locally in near-critical condition and also for open systems with compressible fluids. For example, the thermal oscillations of near-critical ^{3}He at Rayleigh–Bernard threshold when heating the fluid from the bottom wall of a shallow cavity [8,9]. Recent studies into the basic behaviors of near-critical pure fluid have extended to two sided boundary heat flux input [10] and the respective time scale analysis will cover from acoustic time scale, intermediate to diffusion time scales [7]. The first studies were of small size channel thermal effects in cylindrical cells (with fluid thickness $L = 10$ mm) [11] or thermal plumes [12]. Instead of 'critical slowing down' (due to small thermal diffusivity in boundary thermal relaxation process), the expanding thermal boundary greatly affects the convection process and flow structure [13]. The local equilibrium process and transient temperature and velocity behave differently during those processes.

With the above understanding and extension of thermal–mechanical process in near-critical fluids, more studies come out both on closed and open systems, discussing its specific contributions to critical convection/relaxation (in more specific geometric situations, indeed with application considerations). In order to further explore the thermal–mechanical effects of near-critical fluids in open systems, the current study puts the focus on a thin microchannel configuration. Up to now, very few studies on the overall hydrodynamic and heat transfer studies of near-critical microchannel flows are available in open literature. Also only several studies have discussed the thermal–mechanical characteristics and the convection onset/thermal instability problem of near-critical fluid in normal or mini-scale channels [14,15].

Till recently, very few outstanding publications are found for such critical thermal–mechanical and thermal relaxation process, due to both the complexities of near-critical fluid properties and the micro-scaling effects. For example, the coupled effect of expansion boundary and thermal plumes (under gravity) will bring new convection behaviors and new physics in channels [16]. Thus the investigation of near-critical phenomena in microchannel can be very promising, but with many difficulties still exist for near critical fluid convection. Besides the general microscale difficulties, the major challenges for microchannel flow with near critical CO_2 fluid may include: sensitive critical fluid properties [4,9], possible gravity dominated complex flow convection [8,17], and near-critical thermal–mechanical effect as discussed [7]. More recently, Chen et al. [18,19] have conducted a series of studies into the basic convective stability evolution of near-critical fluid flow inside microscale channels and reported the thermal–mechanical development for that confined near-critical model. Much different from conventional closed systems, new kind of instability trend are found for open channels (with the same thermal–mechanical origin of near-critical dynamics). However, the physical mechanisms and detailed heat transfer performance still need more systematic investigations in this field.

The current study is one extended analysis [18,19] of the general response of a developed isothermal near-critical fluid flow when subjected to boundary heating. We present interesting findings focused on the near-critical hot boundary layer (HBL)