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Abnormal microchannel convective fluid flow near the gas–liquid critical point

Lin Chen[a], Xin-Rong Zhang[a,b,*], Junnosuke Okajima[c], Shigenao Maruyama[c]

[a] Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing, 100871, China
[b] Beijing Key Laboratory for Solid Waste Utilization and Management, Peking University, Beijing 100871, China
[c] Institute of Fluid Science, Tohoku University, Katahira 2-1-1, Aoba-ku, Sendai 980-8577, Japan

HIGHLIGHTS

- A model for near-critical fluid microchannel flow is established.
- Instabilities and vortex formation are found in microchannel thermal convective flow.
- A boundary thermal–mechanical effect is dominant at the origin of near-critical vortex flow.
- Possible applications and theoretical analysis of the Kelvin–Helmholtz instability are discussed.

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ABSTRACT

This article deals with a CO_2 critical microchannel convective flow with heat applied from two side walls. Fluid near its gas–liquid critical point is very dense and much expandable; meanwhile, the thermal diffusivity tends to zero when it goes near the critical point. In microchannels, the effect of natural convection becomes negligible and the boundary thermal–mechanical effects will dominate the convection and thermal equilibrium processes. We numerically simulate the convection behaviours of near-critical fluids confined in microchannels by solving the Navier–Stokes equations together with conservative equations of mass and energy. Due to the thermal–mechanical effects of critical fluid, abnormal convection-onset structures and transient micro-scale vortex/mixing evolution modes have been found. The thermal–mechanical/acoustic perturbation source identified here contributes to a new type of Kelvin–Helmholtz instability when gravity is suppressed. The thermal–mechanical oscillations in the boundaries serve as the origin of current vortex phenomena from fast boundary expansion and density stratification. The abnormal microchannel vortex evolution and instability mechanisms/threshold are also discussed in detail in this article.

1. Introduction

It is generally known that when a fluid's gas–liquid critical point is approached, strong anomalies can be found in thermophysical properties [1]. Near-critical fluids become very compressible while the thermal diffusivity tends to zero, owing to the divergence of heat capacity. These specific properties induce coupling processes of thermal relaxation and mechanical disturbance/instability. In closed systems, a new mode of adiabatic heat transfer mechanism, called the piston

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[*] Corresponding author at: Department of Energy and Resources Engineering, College of Engineering, Peking University, Beijing, 100871, China. Tel.: +86 10 82529066; fax: +86 10 82529010.

E-mail addresses: xrzhang@coe.pku.edu.cn, chenlinpkucoe@gmail.com, chenlinpku06@163.com (X.-R. Zhang).

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effect (PE), has been identified by several teams [2–4]. In the case of local heating (e.g., through the walls or immersed films or just by spot heating) of a near-critical fluid, a very expandable, thin, diffusive boundary layer is formed, which induces thermal–mechanical waves and compresses the bulk fluid quickly. The acoustic waves travel very rapidly and cause the temperature of the bulk fluid to increase homogeneously or at a speed much faster than ordinary thermal relaxation processes by diffusion.

Due to its thermal–mechanical origin, such 'adiabatic heating' or 'PE' has attracted many research interests, especially in microgravity heat transport and thermal convection anomalies under terrestrial conditions. The physical mechanisms of the fast thermal homogeneity attained by that expansion and compression process in closed cell (like a piston) have been put forward [5–8]. Analytically, Onuki [2] first established the typical timescale of the PE as:

$$t_{PE} = \frac{t_D}{(\gamma - 1)^2} \tag{1}$$

$$t_D = L^2/D_T \tag{2}$$

where γ is the ratio of specific heats ($\gamma = C_p/C_V$), D_T is the fluid thermal diffusivity and t_D is the heat diffusion characteristic time. Adding the effect of compressibility and ensuing thermal acoustic perturbations, respective thermal relaxation processes happen much more quickly than pure thermal diffusion processes, and it may bring new phenomena when coupled with the effect of natural convection under gravity [9].

Such a thermal–mechanical process occurs in near-critical fluids and special focus has consequently been placed on experimental development [10]. Further, the respective thermoacoustic waves were identified and analysed by Miura's high-speed interferometer [11]. Later, analytically the behaviours of thermoacoustic waves were investigated by immersing a film heater in near-critical fluid confined between two solid walls [12]. Good agreement was found for the above series of theoretical/numerical and experimental studies. Besides theoretical developments of equations, those experiments using refined interferometer technology allowed measurement in very small time- and spatial scales, as in the experimental study of Garrabos, et al. [13], where the near-critical CO_2 enclosed in a thermostated sample cell was applied with a thermal pulse under microgravity (in a MIR orbital station mission) and the fluid density/temperature fast relaxation was found. More recently, in an experimental well-designed interferometer study, density changes of the order of 10^{-8} g cm^{-3} on a timescale of 1 μs [11,14] were realised, which brought about more interests in thermal perturbation- and critical thermal equilibrium-related researches. For example, Carles and Dadzie [15] studied the effect of near-critical bulk viscosity divergence on thermal diffusion layers. Gills et al. [16] experimentally examined the characteristics of long wavelength-sound propagation and the related damping effect with respect to the 'distance' from the critical point.

The thermal–mechanical origin of near-critical fluid, as in PE, plays a key role in the fast thermal relaxation-related behaviours of near-critical fluids. Although the PE was first found in a closed system under microgravity and the very strong compression and temperature fluctuations only happen under constrained flow conditions (under global or local heating), the basic boundary thermal compression and vibration process will still happen locally under the near-critical condition and also for open systems with compressible fluids [17]. With this understanding and extension of the thermal–mechanical process in near-critical fluids, more studies have been published both on closed and open systems, discussing its specific contributions to critical convection/relaxation (in more specific geometric situations, indeed with application considerations). For example, the application of such long-distance heat transport in weightlessness has also been experimentally proposed [18]. Although only 10%–30% thermal efficiency was found, an interesting property of fast feedback of thermal input changes (like a thermal link installed) was identified. Further, the thermal oscillations of near-critical ^{3}He at the Rayleigh–Bénard threshold when heating from the bottom wall of a confining shallow cavity [19–21] have been discussed, where interesting behaviours (and discrepancies) and understanding of near-critical fluid thermal convection in cavities and channels were put forward.

Other interests in open systems and in the behaviours when applied under gravity have been suggested. Recent studies into the basic behaviours of near-critical pure fluid have been extended to different geometries as cylinder [13,22] and thin 'disk' shape [23]. Further, the more general kind of two-sided boundaries with heat flux input [24] has been investigated, where timescale analyses across an acoustic timescale and intermediate and diffusion timescales are identified [7] for respective thermal relaxation processes. Instead of 'critical slowing down' (due to low thermal diffusivity in a boundary thermal relaxation process), the expanding thermal boundary greatly affects the convection process and flow structure [25,26]. Later, the effect of the boundary condition on the expanding acoustic thermal equilibrium process was discussed and a cooling effect was suggested as responsible for abnormal temperature behaviours [7]. The local equilibrium process and transient temperature and velocity behave differently during those processes.

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 of near-critical microchannel flows are available in the 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 [15,27]. Until recently, no outstanding publications have been available 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 give rise to new convection behaviours and new physics in channels [28]. Thus, the investigation of near-critical phenomena