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Mean statistics of a heated turbulent pipe flow at supercritical pressure

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ABSTRACT

Direct numerical simulations (DNS) of a heated turbulent pipe flow with a fluid at supercritical pressure are performed at a Reynolds number of $Re_\tau = 360$, based on pipe diameter and friction velocity at the inlet. A constant wall heat flux is applied and the temperature range within the flow domain incorporates the thermodynamic region where large variations in thermophysical properties occur. The contribution of these property variations on the mean flow is studied. As compared to ideal gas heat transfer, additional terms appear in the mean flow governing equations. These terms can significantly affect the energy balance, because they modify the averaged wall heat flux and the enthalpy diffusion close to the pipe wall. Furthermore, the averaged thermophysical properties, especially the isobaric heat capacity c_p, deviate significantly from those evaluated using the mean temperature or enthalpy. This is due to an averaging artifact called the Jensen inequality, caused by the enthalpy fluctuations and the non-linear dependence of thermophysical properties with respect to enthalpy. Turbulent statistics for one forced convection and two mixed convection cases in an upward flow are discussed. A decrease in turbulent kinetic energy is observed for the forced convection and the low buoyancy case, which cause heat transfer deterioration indicated by high wall temperatures. For the high buoyancy case the turbulence activity first reduces (heat transfer deterioration) and then increases due to turbulence recovery.

1. Introduction

Fluids at supercritical pressure, i.e., at pressures above their vapor–liquid critical point, do not undergo distinct liquid to gas phase transitions. These fluids exhibit significant deviations from ideal gas behavior and their peculiar properties can be exploited in many industrial applications. In chemical industry fluids at supercritical pressure are used in extraction processes, such as desorption, drying, cleaning; formation of micro and nano particles using rapid expansion of supercritical solutions in pharmaceutical industry. A thorough review of these processes is given in [1]. Applications in the energy industry involve biodiesel production [2], working fluids in power cycles [3,4], refrigerants [5], enhanced oil recovery [6], and fuel injection systems [7]. In most of the aforementioned applications heat transfer under turbulent conditions plays a crucial role, whereby the physical mechanism and modeling requirements are currently not well understood.

During the continuous transition of fluids slightly above the critical pressure the thermophysical properties of the fluid vary significantly within a narrow temperature range across the pseudo-critical temperature (T_{pc}). The pseudo-critical temperature is defined as the temperature at which the specific heat at constant pressure (c_p) attains its peak value. Fig. 1 shows the variation of thermophysical properties of CO_2 at a thermodynamic supercritical pressure $P_0 = 80$ bar ($P_{critical} = 73.773$ bar) as a function of enthalpy. The large thermophysical property variations alter the conventional behavior and statistical properties of turbulent flows and the corresponding turbulent heat transfer. Experimental and previous numerical studies of heat transfer characteristics to flows at supercritical pressure have been reviewed by [8] and detailed turbulent statistics containing second order moments for Reynolds stresses and turbulent heat flux obtained from DNS using the low Mach number approximation of the Navier–Stokes equations are given in [9,10]. Fully compressible DNS of turbulent mixing layers with supercritical fluids are given in Refs. [11].

The objective of the current study is to further investigate the turbulent heat transfer mechanisms to supercritical fluids in pipe flows using detailed turbulent flow statistics. The simulation conditions correspond to one forced and two mixed convection cases in upward pipe flows, with similar conditions as reported in Bae et al. [9] for their cases A, B and D. We discuss turbulent statistics, not discussed previously, such as turbulent shear stress, radial turbulent heat flux, turbulent kinetic energy and its production rates (shear and buoyant production). Additionally, we show the interaction of highly non-linear thermophysical property variations (viscosity μ, thermal conductivity λ, isobaric heat capacity

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c_p, and density ρ) with turbulent fluctuations in the flow field. These interactions generate additional second order moments related to the viscosity–velocity-gradients and thermal conductivity–temperature-gradients in the mean flow governing equations. We show that these correlations significantly alter the mean enthalpy distribution (and the related temperature) within the flow field and the resulting mean enthalpy at the wall. We further show that the properties evaluated at the mean enthalpy strongly deviate from their corresponding Reynolds or Favre averaged mean value. This can be explained using the Jensen inequality. These findings can help to improve present turbulence models, which currently fail to predict turbulent heat transfer to fluids at supercritical pressures [13].

2. Overview of heat transfer mechanisms in variable property flows

We start by summarizing the heat transfer mechanisms observed for flows with variable properties. In a heated flow the fluid density decreases, whereby the decrease depends on the thermodynamic state of the fluid. For instance, at subcritical states the density changes are small and gradual, whereas at supercritical states (close to the pseudo-critical temperature T_{pc}) the changes in density are sharp and large. The decrease in density causes two effects: (i) buoyancy and (ii) flow acceleration due to thermal expansion. Additionally, the variations of thermophysical properties, such as specific heat c_p, thermal conductivity λ and viscosity μ also affect the heat transfer mechanism. These three effects are discussed in more detail below.

2.1. Influence of variation in specific heat c_p, thermal conductivity λ and viscosity μ

Yamagata et al. [14] experimentally investigated the effect of thermophysical property variations on heat transfer to supercritical water in heated tube geometries. For low heat to mass flux ratios, where buoyancy and thermal expansion effects are small, they observed an enhancement in heat transfer, which can be explained using the empirically obtained Dittus–Boelter correlation [15]. The heat transfer coefficient H can then be expressed as a function of thermophysical properties

$$H \propto \lambda_b^{0.6}\mu_b^{-0.4}c_{p,b}^{0.4}. \quad (1)$$

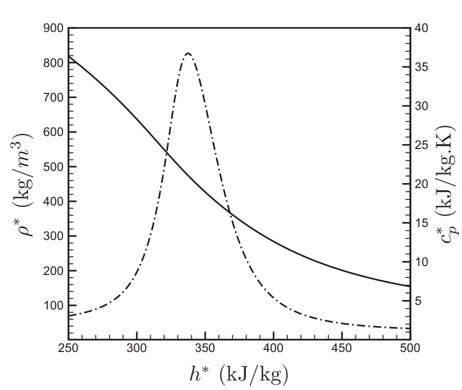
The subscript $_b$ represents the bulk quantities. Given the thermophysical property variations for CO_2 at $P_0 = 80$ bar (Fig. 1) it can be seen that the increase in c_p and the decrease in μ are dominant as compared to the decrease in λ. This is causing the heat transfer coefficient to increase. A physical sound explanation is given by Licht et al. [16] to explain the results obtained by Yamagata et al. [14]. They state that at low heat flux values the energy input is not large enough to overcome the large values of specific heat close to the wall and thus a low wall to bulk temperature gradient is obtained. By increasing the wall heat flux, the energy input will be large enough to overcome the large specific heat values at the wall, causing an increased temperature gradient at the wall and a localized region of large c_p away from the wall. This results in a higher wall to bulk temperature gradient and hence impairs the heat transfer [16].

2.2. Influence of flow acceleration

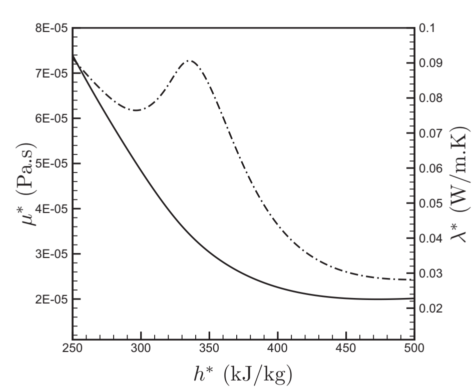
Flow acceleration is caused due to thermal expansion, and in upward flows also due to buoyancy. However, the net acceleration of buoyancy on the total cross-section is zero, whereas thermal expansion causes net acceleration because the bulk velocity increases. In laminar flows the thermal expansion, and in upward flows also buoyancy, increases convective heat transfer because of flow acceleration. In downward flows, the heat transfer is deteriorated when deceleration due to buoyancy is larger than acceleration due to thermal expansion. In turbulent convection the effects are opposite [17]. Although, flow acceleration increases the velocity close to the wall, it reduces turbulence production. The wall normal velocity gradient in the viscous dominant region increases, where it has a small influence on the turbulence production. On the other hand, the velocity gradient further away from the wall decreases, thus decreasing the turbulence production. Similar observations were made by [18], where for accelerating turbulent boundary layers, they observed a reduction in bursting frequency which is the primary mechanism for turbulence production. Since, mixing dominates the heat transfer mechanism in turbulent flows, the heat transfer effectiveness decreases. In downward flows with buoyancy, turbulence production increases, when deceleration due to buoyancy is larger than acceleration due to thermal expansion, thereby enhancing heat transfer.

2.3. Influence of buoyancy

The effect of buoyancy plays an interesting role in terms of heat transfer recovery (after deterioration) for turbulent flows and usually dominates the flow behavior. Buoyancy, causing local flow acceleration or deceleration depending on flow direction, is sometimes referred to as external or indirect effect. However, it also has



(a) Density ρ (——) and isobaric heat capacity c_p (—·—)



(b) Dynamic viscosity μ (——) and thermal conductivity λ (—·—)

Fig. 1. Variation of thermophysical properties based on Ref. [12] of carbon-dioxide CO_2 vs. enthalpy h^* at a pressure of P_0 = 80 bar. The peak of the heat capacity at constant pressure indicates the location of the pseudo-critical temperature T_{pc}.