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Conditions for the occurrence of heat transfer deterioration in light hydrocarbons flows

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ABSTRACT

Heat transfer deterioration could affect heated channel flows of supercritical pressure fluids in a number of technological applications. Aim of the present study is to analyze the phenomenon onset and to investigate its dependence on the pressure, for three light hydrocarbons: methane, ethane and propane. To this goal a parametric numerical analysis is carried out on uniformly heated straight channels varying, for each different species, the inlet reduced pressure and the enforced heat flux. A parabolized Navier–Stokes solver is used to carry out the simulations, together with Helmholtz energy equation of state and accurate models for the transport properties. Results lead to an unambiguous definition of the threshold value for the ratio between heat flux and specific mass flow rate which identifies the boundary for heat transfer deterioration onset. On the basis of this definition, for assigned inlet reduced temperature, a correlation for the threshold parameter in terms of reduced pressure is presented for the considered species.

1. Introduction

The heat transfer deterioration is a thermodynamic phenomenon that could affect supercritical pressure flows which experience a pseudo-phase change; the direct consequence is a loss of cooling capability [1–5]. Therefore, understanding heat transfer deterioration peculiarities is of interest for a number of technological applications dealing with supercritical pressure coolants, among which the regenerative cooling system of liquid propellant rocket engines (LRE). The present study is motivated by the possible use of light hydrocarbons, which have a critical pressure much closer to the typical operating chamber pressure of turbopump-fed engines than the commonly used hydrogen, as rocket fuels. For this reason, when used as coolant in LRE, light hydrocarbons could experience large property variations when crossing the pseudo-critical temperature and possibly heat transfer deterioration (HTD), as it has been demonstrated both experimentally and numerically [1,4]. However, this is not the only application for which HTD phenomenon is of interest, as reported in the wide literature review provided in [6]. It is well understood that the heat transfer deterioration can affect supercritical pressure flows if wall and bulk temperature are respectively greater and smaller than the pseudo-critical temperature, and if the heat flux to specific mass flow rate ratio (q_w/G) is greater than a threshold value $(q_w/G)_{tr}$, which depends on the thermodynamic conditions. Moreover, being the deterioration phenomenon directly connected with the thermodynamic properties of the fluid, a dependence of $(q_w/G)_{tr}$ on the reduced pressure $(\pi = p/p_c)$ and temperature $(\tau = T_c/T)$ could be expected [7].

Aim of the present work is to investigate the $(q_w/G)_{tr}$ dependence on the reduced pressure for three light hydrocarbons: methane, ethane and propane. Being interested to the high Reynolds number (of the order of 10^6) typical of LRE cooling system flows, a parametric analysis is carried out with a fast and suitable numerical solver, which relies on the use of parabolized Reynolds-Averaged Navier–Stokes equations (RANS) [8]. The limits of RANS approaches in quantitatively predicting the effect of heat transfer enhancement and deterioration when buoyancy effects are not negligible, have been critically discussed in [9]. Nevertheless, the present approach is still able to predict, at least qualitatively, the onset of deterioration of forced convection heat transfer in LRE cooling systems, as demonstrated by comparison with experimental data for parahydrogen flow [8]. The selected equation of state and transport property relations are able to correctly predict the fluid behavior in the pseudo-critical region, where all the thermophysical properties experience large variations. More specifically, accurate relations available in the literature, based on Helmholtz energy equation of state, have been adopted in the present study to be able to suitably describe hydrocarbons thermophysical properties both for real and perfect gas conditions.

In the following, attention is given to the criterion used to identify the heat transfer deterioration onset and which permits to individuate the threshold parameter $(q_w/G)_{tr}$ for assigned conditions. Then, the numerical model and the thermophysical property

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models that are used to carry out the simulations are introduced. The large number of results obtained in the parametric study is presented: numerical simulations are carried out for channel flows of methane, ethane and propane, varying the inlet pressure and the heat flux. Finally, the numerical data are reduced to find a correlation for the threshold parameter in terms of the reduced pressure at the channel entrance, for assigned inlet reduced temperature.

2. The heat transfer deterioration onset

Dealing with forced convection heat transfer to supercritical pressure fluids in channels, different heat transfer regimes can be observed. When the temperature of a supercritical pressure fluid crosses the pseudo-critical temperature, that is the temperature at which the isobaric specific heat c_p has a maximum at a specified pressure, the fluid is referred to as supercritical and the heat transfer may differ from the expected *normal* heat transfer [10]. In fact, in a *normal* heat transfer regime, if a constant heat flux is enforced, a monotonic change of the wall temperature is expected along the channel axis. Also, once the thermal boundary layer is formed, the heat transfer coefficient has a monotonic evolution along the channel, eventually growing because of the flow thermal acceleration. On the other hand, heat transfer *enhancement* and *deterioration* can affect heated channel flows of transcritical fluids at low and high heat fluxes, respectively. The heat transfer *enhancement* is caused by the peak of isobaric specific heat in the pseudo-critical region, which brings an increase in the heat transfer coefficient [3,11–13]. Conversely, heat transfer *deterioration* (HTD) is characterized by a thermal spike and a large reduction of the heat transfer coefficient. More precisely, a peak in the wall temperature is observed in the same axial location where the heat transfer coefficient reaches a minimum value.

The reasons that lead to HTD have been made clear in several studies available in the literature [6,14–16]. For natural and mixed convection, buoyancy and laminarization effects due to local acceleration of the flow are the main reasons that lead to HTD. Nevertheless, according to [17,18], the forced convection flow conditions considered in the present study, typical of LRE, are such that buoyancy and laminarization effects can be neglected. In fact, Jackson buoyancy parameter[1] ($Bo^* = GrRe^{-3.425}Pr^{-0.8}$) is lower than 10^{-11} compared to the threshold value for buoyancy effect to become important of $6 \cdot 10^{-7}$. Similarly, for the present cases the condition for acceleration effect to become important[2] $4q^+Re^{-0.625}Pr^{-0.4} > 2.9 \cdot 10^{-5}$ is not satisfied, being the left hand side of the inequation of the order of 10^{-7}. Thus for the present forced convection cases, HTD is a phenomenon which occurs when a subcritical temperature channel flow is sharply heated up: the high temperature gradients in the channel section lead to the formation of a layer of low density fluid near the wall, where the temperature is supercritical, which has low heat transfer capabilities, whereas the core of the flow is still cold and slow. As a consequence, the velocity profile assumes a *M*-shape. If the flow is further heated up, the bulk temperature finally exceeds the pseudo-critical temperature T_{pc}. The pseudo-phase passage occurs, leading to a decrease of the density and, accordingly, to a growth of velocity. The velocity growth causes a recovery of the coolant capability and, as a consequence, once T_{pc} is exceeded, the wall temperature decreases.

Even though the phenomenon is known and understood from a phenomenological point of view, conditions for the HTD onset are not clearly defined in the literature [3]. The reason is that the phenomenon is not discontinuous but takes place over a finite length of the channel, or in other words in a finite range of bulk temperature values. However, on the basis of the aforementioned definitions of heat transfer regimes, the heat transfer is considered as deteriorated if, for a constant heat flux, the wall temperature exhibits a peak. Based on this definition, a criterion to identify the HTD onset for a given pressure level has been established in a previous work by the authors [16]. The main details are reported here for the sake of clarity. A flow of methane in a straight channel with a circular cross section is considered. The inlet conditions are those of a compressed fluid: the pressure is supercritical and the temperature is subcritical. Different heat fluxes are considered for an assigned methane mass flow rate. The resulting wall temperature and heat transfer coefficient evolutions with the bulk temperature, for each heat flux, are reported in Fig. 1.

Two distinct behaviors can be observed when varying (q_w/G): for the lower values the heat transfer is normal, possibly with a local enhancement, and the wall temperature increases all along the channel; for the higher values of (q_w/G) the heat transfer is deteriorated and the wall temperature exhibits a peak. Therefore, there is a threshold value of $(q_w/G)_{tr}$ which defines the boundary between the two behaviors and hence identifies the minimum value of the heat to mass flux ratio for the heat transfer deterioration to occur. It follows that, in the case of HTD, the wall temperature derivative with respect to x has also negative values and thus a negative minimum value. Differently, for non-deteriorated cases dT_w/dx is always positive. Therefore, the value of q_w/G for which the minimum dT_w/dx is zero can be considered as the threshold value, as shown in Fig. 2, where the minimum of dT_w/dx reached along the channel is reported against the q_w/G for each test case.

Besides the main dependence on the value of (q_w/G), the HTD has been found to be strongly affected by the pressure and temperature at the channel inlet [14,19,20]. In particular, in a previous study on methane channel flows [6], it has been highlighted that decreasing the pressure, the deterioration occurs at lower values of (q_w/G), because of the higher variations in all the thermophysical properties experienced by the fluid when it passes from a liquid-like to a gas-like state. In fact, as pressure diminishes, it approaches its critical value, and the lower the supercritical pressure the larger the variation of thermophysical properties when temperature crosses the pseudo-critical temperature is. On the other hand, decreasing the inlet temperature at assigned inlet pressure and $(q_w/G) > (q_w/G)_{tr}$ moves the wall temperature peak downstream and increases the peak value.

Looking for a prediction of the flow and heating conditions leading to heat transfer deterioration, a recent parametric study on heated channel flows has permitted to find a correlation which expresses the threshold parameter as a function of pressure for methane [16]. In the present study the attention is focused on the pressure influence over $(q_w/G)_{tr}$, for several light hydrocarbons, including results obtained for methane in [16]. In particular, being the HTD strongly related to the thermophysical properties, a similar dependence over the reduced pressure $\pi = p/p_c$ is expected for the different species. Starting from this assumption, the criterion defined above for HTD onset is used in the following to determine and compare the $(q_w/G)_{tr}$ for methane, ethane and propane for different reduced pressure levels. All the simulations are carried out for the same inlet reduced temperature $\tau = T_c/T$. The temperature influence on the phenomenon is not taken into account in the present study.

[1] In the Jackson buoyancy parameter the Grashof number is expressed as $Gr = g\beta q_w D^4/(k^2)$ where g is the standard gravity constant, β is the bulk thermal expansion coefficient, q_w the wall heat flux, D the channel diameter, k the bulk thermal conductivity and ν the bulk kinematic viscosity. Reynolds and Prandtl numbers are also evaluated with bulk quantities.

[2] The reduced heat flux is defined as $q^+ = (q_w/G)/(c_p/\beta)$.