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# Numerical investigation on convective heat transfer to aviation kerosene flowing in vertical tubes at supercritical pressures

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ABSTRACT

Numerical simulations of convective heat transfer to aviation kerosene (China RP-3) flowing in vertical circular tubes at supercritical pressures are reported in this study. Firstly, performance of a variety of Reynolds-Averaged Navier-Stokes turbulence models in predicting the fluid-thermal behaviours under both forced and mixed convection conditions are evaluated. Under forced convection conditions, all models predict a gentler growth of wall temperature along the flow direction than experimental measurements. Under mixed convection conditions, the effect of buoyancy become significant and there are large discrepancies in the predicted wall temperature by different models. Only the low-Reynolds number $k$-$\varepsilon$ models are found to be able to qualitatively predict the flow laminarization and heat transfer deterioration. Profiles of thermal, flow and turbulence fields obtained using various models are studied to explain the differences in predictions. For mixed convection conditions, an examination on the turbulence production due to shear and density fluctuation indicates that the direct effect of buoyancy on the turbulence production is negligible compared with the indirect effect. Furthermore, the effect of turbulent Prandtl number on the predicted heat transfer is studied. It is found that turbulent Prandtl number has a significant influence on the simulation results. Under the conditions considered in the present study, the value of 1.0 for turbulent Prandtl number leads to a closest agreement with the experimental data.

## 1. Introduction

Development of sustained hypersonic air-breathing propulsion (HAP) technologies have received global attentions since the 1960s [1]. At the hypersonic flight regime ($Ma > 6$), the specific impulse $I_{sp}$ of scramjet engine surpasses that of any other type of propulsion options, which makes it the key enabling technology for hypersonic flight applications within atmosphere [2,3]. Due to the drastic aerodynamic heating of vehicle body as well as the extreme high heat load released by the supersonic combustion process, thermal management remains to be a significant technical challenge in the designs of scramjet engines. For operations aimed at long-range flights, regenerative cooling that utilizing onboard fuel as the primary coolant has been considered to be an effective way to prevent the engine wall temperature from exceeding the material limit [4].

The choice of fuel for scramjet engine is another important issue that needs to be carefully considered. Hydrogen could provide the highest energy release and cooling capacity, however it has to face with logistic, cost, and safety problems. In comparison with hydrogen, hydrocarbons have larger densities, which enables a smaller volume and weight of the engine body. The unfavourable safety and operation problems associated with hydrogen could also be avoided [5]. At $Ma < 8$, hydrocarbon fuel is able to provide sufficient heat sink to meet the cooling requirements, which makes it a good fuel candidate for the lower range of hypersonic flight [6–8].

There have been several demonstrations on the viability of regeneratively cooled scramjet engine using hydrocarbon fuels [9–12]. Before entering the combustion chamber, the fuel flows along the cooling channels (in the order of millimetres) which surround the combustion chamber and takes away heat from the wall [13,14]. The typical aircraft fuel system pressure is higher than the critical pressure of most hydrocarbon fuels [15]. For fluids at supercritical pressures, the variation of thermodynamic and transport properties with temperature becomes significant in the heat transfer process. Particularly, the temperature at which the specific heat capacity achieves its peak value at a given pressure is known as the pseudo-critical temperature ($T_{pc}$) [16]. In the vicinity of $T_{pc}$, the rapid decrease of fluid density would bring in the effects of

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## Nomenclature

| | |
|---|---|
| $A$ | cross sectional area of the tube |
| $Bo^*$ | non-dimensional buoyancy parameter, $Bo^* = Gr/(Re^{3.425}Pr^{0.8})$ |
| $c_p$ | isobaric specific heat capacity |
| $C_{\varepsilon 1}$, $C_{\varepsilon 2}$, $C_{\varepsilon 3}$ | constants in the $\varepsilon$-equation |
| $C_\mu$ | constant in the constitutive equation of eddy viscosity model |
| $D$ | inner diameter of the tube; damping function term in the $k$-equation |
| $E$ | damping function term in the $\varepsilon$-equation |
| $f$ | body force; elliptic relation parameter |
| $f_1$, $f_2$ | damping functions in the $\varepsilon$-equation |
| $f_\mu$ | damping function in the constitutive equation of eddy viscosity model |
| $g$ | gravitational acceleration |
| $G$ | mass flux |
| $G_k$ | buoyancy production term of turbulent kinetic energy |
| $Gr$ | Grashof number, $Gr = g\beta D^4 q_w/(\lambda \nu^2)$ |
| $h$ | convective heat transfer coefficient |
| $I_{\mathrm{sp}}$ | specific impulse |
| $k$ | turbulent kinetic energy |
| $K_v$ | non-dimensional thermal acceleration parameter, $K_v = 4\beta q_w/(\rho c_p U_{\mathrm{b}} Re)$ |
| $L$ | turbulent length scale |
| $Ma$ | Mach number |
| $Nu$ | Nusselt number, $Nu = hD/\lambda_{\mathrm{f}}$ |
| $p$ | pressure |
| $p_{\mathrm{c}}$ | critical pressure |
| $P_k$ | shear production term of turbulent kinetic energy |
| $Pr$ | molecular Prandtl number |
| $q_w$ | wall heat flux |
| $r$ | radial coordinate; radius of the tube |
| $Re$ | Reynolds number, $Re = U_{\mathrm{b}}D/\nu$ |
| $Re_t$ | turbulent Reynolds number, $Re_t = k^2/(\nu\varepsilon)$ |
| $S_h$ | energy source term |
| $S_T$ | volumetric heat source |
| $t$ | time |
| $T$ | temperature; turbulent time scale |
| $T_{\mathrm{pc}}$ | pseudo-critical temperature |
| $T_{\mathrm{wi}}$ | inner wall temperature |
| $U$ | velocity |
| $U^+$ | dimensionless velocity |
| $\overline{u_j' t'}$ | turbulent heat flux |
| $\overline{u_i' u_j'}$ | Reynolds stress |
| $\nu$ | kinematic viscosity |
| $\overline{v^2}$ | variance of the normal component of turbulent velocity |
| $x$ | axial coordinate |
| $y$ | normal distance from the wall |
| $y^+$ | dimensionless distance from the wall |

*Greek symbols*

| | |
|---|---|
| $\beta$ | isobaric thermal expansivity |
| $\delta$ | Kronecker delta |
| $\varepsilon$ | dissipation rate of turbulent kinetic energy |
| $\lambda$ | thermal conductivity |
| $\mu$ | dynamic viscosity |
| $\mu_t$ | turbulent viscosity |
| $\rho$ | density |
| $\sigma_k$ | turbulent Prandtl number for $k$ |
| $\sigma_\varepsilon$ | turbulent Prandtl number for $\varepsilon$ |
| $\sigma_t$ | turbulent Prandtl number |
| $\tau$ | viscous stress |
| $\omega$ | dissipation per unit turbulent kinetic energy |

*Subscripts*

| | |
|---|---|
| b | bulk |
| f | fluid; forced convection |
| in | inlet of the tube |
| $i, j$ | spatial indices |
| out | outlet of the tube |
| ref | reference |
| w | wall |
| s | solid |

buoyancy and thermal acceleration, which would induce modifications of mean flow and turbulence fields. These effects, combined with the non-uniform distribution of fluid properties across the boundary layer would have a significant influence on the heat transfer process.

In order to investigate the convective heat transfer characteristics of hydrocarbon fuel at supercritical pressures, a lot of experimental efforts have been carried out. Hitch and Karpuk [17] conducted experiments of heat transfer to supercritical JP-7 in vertical circular tubes. Heat transfer deterioration (HTD) along with large temperature and pressure oscillations were observed when the reduced pressure ($p/p_{\mathrm{c}}$) was below 1.5 and the wall temperature was higher than $T_{\mathrm{pc}}$. Hu et al. [18], Zhong et al. [13], Zhang et al. [19], Liu et al. [20], and Li et al. [21] experimentally studied convective heat transfer of China RP-3 aviation kerosene flowing in circular tubes at supercritical pressures. In these studies, the effects of operating parameters (mass flux, wall heat flux, pressure, inlet temperature, and flow direction) on the heat transfer process were carefully investigated. Under large mass flux conditions, heat transfer enhancement (HTE) was observed when the wall temperature exceeded $T_{\mathrm{pc}}$; under small mass flux conditions, dramatic increase of wall temperature was observed at the entrance region for both downward and upward flows. This kind of HTD was attributed to the slow development of thermal boundary layer and the buoyancy effect, respectively. Furthermore, a number of semi-empirical correlations for predicting heat transfer to RP-3 at supercritical pressures have been proposed based on the experimental data, as shown in the technical note by Chen and Fang [22].

It should be noted that the data obtained in most of the experimental studies are limited to wall temperature, inlet/outlet fluid temperature, and pressure drop along the test tube. As an alternative approach, computational fluid dynamics (CFD) method could offer more detailed information of thermal, flow, and turbulence fields, which is necessary to gain deeper understanding of the underlying physics of the heat transfer process. Therefore, growing attentions have been paid on numerical simulations on flow and heat transfer of hydrocarbon fuel at supercritical pressures. In turbulent heat transfer simulations, the predicted flow field and heat transfer rate is highly dependent on the turbulence modelling method. Different types of Reynolds-Averaged Navier-Stokes (RANS) turbulence models were employed in the existing simulations: the shear stress transport (SST) $k$-$\omega$ model (Meng et al. [23]), the standard $k$-$\omega$ model (Zhu et al. [24]), and the renormalization group (RNG) $k$-$\varepsilon$ model with the enhanced wall functions (Zhong et al. [25], Liu et al. [26]). However, it is acknowledged that most of the turbulence models are developed for constant property fluids. Therefore, the applicability of these models in predicting heat transfer to fluids at supercritical pressures (associated with