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Research Paper

Diameter effect on the heat transfer of supercritical hydrocarbon fuel in horizontal tubes under turbulent conditions

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HIGHLIGHTS

- Diameter effect on the heated horizontal flow of supercritical hydrocarbon was investigated.
- Buoyancy, flow acceleration and variable properties effects were analyzed systematically.
- Buoyancy effect could lead to the circumferential nonuniformity in the heat transfer.
- Larger diameter tube is likely to induce the impaired heat transfer at the top of the generatrix.
- Low heat flux to mass flux ratio can make the heat transfer enhanced at large diameter tube.

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ABSTRACT

This article presented a numerical investigation of supercritical heat transfer of the hydrocarbon fuel in a series of horizontal tubes with different diameters. The Reynolds averaging equations of mass, momentum and energy with the LS low-Reynolds number turbulence model have been solved using the pressure-based segregated solver based on the finite volume method. For the purpose of comparison, a four-species surrogate model and a ten-species surrogate model of the aviation kerosene RP-3 (Rocket Propellant 3) were tested against the published experimental data. In the current study, the tube diameter varied from 2 mm to 10 mm and the pressure was 3 MPa with heat flux to mass flux ratios ranging from 0.25 to 0.71 kJ/kg. It was found that the buoyancy has significant effect on the wall temperature non-uniformity in the horizontal tube. With the increase of the diameter, the buoyancy effect enhances and the thermal-induced acceleration effect reduces. The buoyancy effect makes wall temperature at the top and bottom generatrices of the horizontal tube increase and decrease, respectively. Due to the coupled effect of the buoyancy and thermal-induced acceleration caused by the significant change of the properties, as the diameter increases, the heat transfer deteriorates dramatically at the top generatrix but remains almost unchanged at the bottom generatrix at high heat flux to mass flux ratio. Heat transfer enhancement is observed at low heat flux to mass flux ratio when the tube diameter is less than 6 mm. Moreover, the safety analysis has been performed in order to optimally design the supercritical cooling system.

1. Introduction

Scramjet engine has been widely accepted as one of the most promising power systems of the hypersonic vehicles due to its high efficiency and high thrust-weight ratio when cruising at March number of 6–10. However, high speed cruise can bring significant friction heat to the Scramjet, leading to the severe thermal management problem. In order to overcome this problem, the regenerative cooling technique is necessary to ensure the engine working reliably [1]. As a potential coolant, hydrocarbon fuel under supercritical pressure absorbs the heat from combustor when the unburned coolant is flowing through the cooling channel. Afterwards, the absorbed heat is returned to the work cycle when the coolant is injected into the combustor. During the cooling process, the hydrocarbon fuel undergoes the transcritical process, that is, its temperature increases from the subcritical temperature to supercritical temperature due to the non-symmetric heating and then it will change into the supercritical fluid. Similar cooling process with symmetric heating occurs in the cool cooling air (CCA) technology in

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Nomenclature

a_n	coefficients in MBWR equation
A	integral area
$Bo*$	Buoyancy parameter
C_P	specific heat at constant pressure ($J\,kg^{-1}\,K^{-1}$)
C_V	specific heat at constant volume ($J\,kg^{-1}\,K^{-1}$)
$C_{\varepsilon 1}$, $C_{\varepsilon 2}$	constants in ε equation
C_μ	constant in eddy viscosity
d	inner diameter of tube (mm)
D	outer diameter of tube (mm)
f_1,f_2	functions in ε equation
f_μ	damping function
Fp^0, FQ^0	correction factor, ≈1
g	gravitational acceleration ($m\,s^{-2}$)
G	mass flux ($kg\,m^{-2}\,s^{-1}$)
G_k	turbulence production by buoyancy ($kg\,m^{-1}\,s^{-3}$)
$Gr*$	Grashof number
h	heat transfer coefficient
H	enthalpy ($J\,kg^{-1}$)
k	turbulent kinetic energy ($m^{-2}\,s^{-2}$)
K_v	flow acceleration parameter
L	total length of tube (mm)
M	molar mass
Nu	Nusselt number
P	pressure (MPa)
Pr	molecular Prandtl number
Pr_t	turbulent Prandtl number
q	wall heat flux ($kW\,m^{-2}$)
R	radius (mm)
Re	Reynolds number
Re_t	turbulent Reynolds number
S_k	source term in k equation
S_ε	source term in ε equation
T	temperature (K)
u	velocity ($m\,s^{-1}$)
x	axial coordinate (mm)
y	radial coordinate (mm)
$y+$	wall non-dimensional distance

Greek symbols

β	thermal expansion coefficient (K^{-1})
γ	$1/(\rho_{c0})^2$
ε	dissipation rate of k ($m^{-2}\,s^{-3}$)
λ	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
μ	molecular viscosity (μPa s)
μ_t	turbulent viscosity (μPa s)
ρ	density ($kg\,m^{-3}$)
σ_k,σ_ε	turbulent Prandtl number
τ	shear stress ($kg\,m^{-1}\,s^{-2}$)
υ	kinematic viscosity, $\upsilon = \mu/\rho$

Subscripts/Superscripts

0	reference substance
b	bulk
c	critical
in	inlet
r	relative
w	wall
l	superscript for low pressure

the modern advanced gas turbine engines [2]. The fascinating feature of the fluid under supercritical pressure is that the thermophysical property varies significantly with temperature in the vicinity of the pseudo-critical point. Therefore, to investigate the characteristics of the supercritical heat transfer is becoming one of the most challenging issues and an important subject [3].

Cagniard de la Tour in 1822 [4] was perhaps the first one to study the supercritical phenomenon and then the research on flow and heat transfer under supercritical pressure has never been stopped [5,6]. With the development of the current study, some detailed reviews of the heat transfer at supercritical pressure have been implemented [7–9]. It is believed that at low heat flux to mass flux ratio, the heat transfer enhancement characterized by the gently changing temperature and high heat transfer coefficient near the pseudo-critical point occurs. While the heat transfer deterioration featured by the suddenly raised temperature occurs at high heat flux [10]. Generally, due to high heat sink capacity, heat transfer enhancement is preferred in the practical applications, and to avoid the material failure caused by sufficient high wall temperature, more attention is paid to reduce the heat transfer deterioration [11].

In both heat transfer enhancement and heat transfer deterioration modes, supercritical heat transfer is influenced by the variable property effect, coupled with the buoyancy effect and thermal-induced acceleration effect. The effect of the buoyancy and thermal-induced acceleration on the supercritical heat transfer may vary when the flow direction changes from the vertical flow to the horizontal flow. Li et al. [12] experimentally studied the distinctions of the heat transfer characteristics between the horizontal and vertical upward flows of the supercritical pressure water. It was found that at high heat flux to mass flux ratio, the thermal-induced acceleration is the key factor leading to the heat transfer deterioration in the vertical flow. Whereas in the horizontal flow, the buoyancy effect played a larger effect than that in the vertical flow. From the numerical simulation of Li et al. [13], it was stated that when the heat transfer deterioration happened in the horizontal tube, the buoyancy effect resulted in the vertical stratification and the accumulation of the light supercritical pressure fluid. More deeply, the buoyancy effect was proved to be responsible for the occurrence of the secondary flows and the circumferential nonuniformity on heat transfer in the horizontal flow of the supercritical water [14].

Except for the flow direction, there are other factors, such as diameter, which may have significant effect on the supercritical heat transfer. Shang et al. [15] numerically investigated the diameter effect to the heat transfer of the supercritical water. It has been found to be easier to induce the heat transfer deterioration in the large diameter tube (10 mm), and the heat transfer deterioration gradually weakens with the mass flux increasing. Afterwards, the experiment of the water flowing in the horizontal tubes at supercritical pressure has been carried out by Yu et al. [16]. It has been concluded that the diameter has very little effect on the heat transfer at low heat flux to mass flux ratio (0.16 kJ/kg), but can result in the obvious buoyancy effect at high heat flux to mass flux ratio (0.4 kJ/kg). Yildiz [17] provided a detailed survey about the tube diameter effect on the heat transfer at supercritical pressures and found that the large diameter might contribute to the reduced heat transfer coefficient in the heat transfer deterioration mode. The latest study on the hydraulic characteristics of the supercritical hydrocarbon fuel in tubes with different diameters was experimentally investigated by Guo et al. [18], and the magnitude of the pressure drop along the tube was found to be much larger in the larger diameter tube.

All the studies mentioned above presented significant results concerning the diameter effect and flow direction effect on a supercritical flow, but the comprehensive study combining the diameter effect with the horizontal flow is rare and the existed research is mainly focused on the water and carbon dioxide [19–22]. It has been concluded that the