International Journal of Heat and Mass Transfer 109 (2017) 326–335

Contents lists available at ScienceDirect

International Journal of Heat and Mass Transfer

journal homepage: www.elsevier.com/locate/ijhmt

Transient responses of turbulent heat transfer of cryogenic methane at supercritical pressures

Bo Ruan [a], Shizhang Huang [a], Hua Meng [b,*], Xiaowei Gao [a]

[a] School of Aeronautics and Astronautics, Dalian University of Technology, Dalian, Liaoning 116024, China
[b] School of Aeronautics and Astronautics, Zhejiang University, Hangzhou, Zhejiang 310027, China

ARTICLE INFO

Article history:
Received 27 October 2016
Received in revised form 3 January 2017
Accepted 4 February 2017

Keywords:
Transient process
Thermal expansion
Flow oscillation
Thermophysical property
Regenerative cooling

ABSTRACT

A numerical study has been conducted to analyze transient responding behaviors of fluid flow and heat transfer of the cryogenic methane at supercritical pressures, the physical phenomena closely related to the regenerative rocket engine cooling application. A steady-state cold flow is instantly enforced with a constant surface heat flux to activate the transient heat transfer process. The effects of surface heat flux, inlet flow velocity, and pressure on transient responses are studied in detail to obtain fundamental understanding of the underlying physical mechanisms. Results indicate that the increased fluid temperature during the heat transfer process leads to the significantly decreased fluid density at a supercritical pressure and consequently causes strong fluid thermal expansion, which results in flow oscillations. The strong pressure effect on thermophysical property variations in the supercritical-pressure heat transfer process, particularly in the trans-critical region, can lead to further extension of the transient responding process at a low inlet flow velocity and/or under a high surface heat flux. Flow oscillations become stronger and last longer under a higher surface heat flux and/or at a lower inlet flow velocity. An increased operating pressure slightly decreases the transient responding time. Under the tested conditions in the present work, the maximum transient response time is around 20 ms.

1. Introduction

Regenerative cooling using a propellant as the cooling agent is an effective approach for thermal protection of aerospace propulsion and power-generation systems, such as rocket and supersonic combustion ramjet (scramjet) engines [1,2]. In the development of future green and reusable rocket engines based on the bipropellant combination of liquid oxygen (LOx) and methane [3,4], in order to ensure engine reliability and durability, the cryogenic methane is used to actively cool the rocket thruster before it is injected into the combustor for power generation. The regenerative engine cooling process of methane generally occurs at a high pressure above the critical point of the propellant, thus leading to convective heat transfer at supercritical pressures.

Fundamental studies have been conducted to obtain a comprehensive understanding of the heat transfer phenomena of cryogenic methane at supercritical pressures. A number of experimental studies have been carried out. Neill et al. [5] practically tested the cooling performance of liquid methane in rocket engine cooling channels and demonstrated the effectiveness of the cooling process. Gu et al. [6] experimentally investigated the heat transfer phenomena of methane in a horizontal cooling tube under different pressures and surface heat fluxes. They observed the heat transfer deterioration (HTD) phenomenon. Trejo et al. [7] studied heat transfer of methane in rocket cooling channels and analyzed the effects of different channel geometries and surface roughness on the heat transfer process. Votta et al. [8] designed a test article, which is composed of a single rocket engine cooling channel and a copper-alloy block warmed up by cartridge heaters, and conducted experimental investigation on heat transfer of trans-critical methane. The channel inlet and outlet temperature and pressure, mass flow rate, and wall temperature were measured.

Significant efforts have also been made to numerically investigate turbulent heat transfer of methane at supercritical pressures. Pizzarelli et al. [9] and Wang et al. [10] carried out systematic studies on convective heat transfer of methane in a circular cooling tube at supercritical pressures. Heat transfer deterioration (HTD) phenomenon was observed under a sufficiently high surface heat flux and/or at a relatively low inlet flow velocity in trans-critical region, as the fluid temperature increases from the subcritical to supercritical state. Results indicate that the HTD phenomenon is closely related to the strong variations of thermophysical proper-

---

* Corresponding author.
E-mail address: menghua@zju.edu.cn (H. Meng).

http://dx.doi.org/10.1016/j.ijheatmasstransfer.2017.02.006
0017-9310/

Nomenclature

C	constants in turbulent model
D	inner diameter of a cooling tube, mm
e_t	total energy, J kg^{-1}
G_k	turbulence generation term
h	enthalpy, J kg^{-1}
k	turbulent kinetic energy, J kg^{-1}
p	pressure, Pa
q_w	surface heat flux, wm^{-2}
r	radial coordinate, mm
t	time, s
T	temperature, K
$\vec{u}$	velocity vector, ms^{-1}
V	volume, mm^3
x	axial coordinate, mm

Greeks

ε	turbulent dissipation rate, m^2 s^{-3}
λ	thermal conductivity, W m^{-1} K^{-1}
ρ	density, kg m^{-3}
σ	turbulent Prandtl number
$\boldsymbol{\tau}$	viscous stress tensor, Nm^{-2}
μ	viscosity, kg m^{-1} s^{-1}

Subscripts

in	inlet parameters
k	parameter related to turbulent kinetic energy
out	outlet parameters
t	turbulent value
ε	parameter related to turbulent dissipation rate

ties in the trans-critical region. Urbano and Nasuti numerically examined the effects of property variations on supercritical-pressure heat transfer of methane [11] and analyzed the onset conditions for heat transfer deterioration [12]. Pizzarelli [13] further proposed a correlation, based on numerical results, to determine heat transfer deterioration of methane at supercritical pressures. The effect of ribbed cooling tube on supercritical-pressure heat transfer of methane was studied by Xu et al. [14]. Results indicate that a ribbed tube surface can significantly improve heat transfer performance and in particular can drastically weakens heat transfer deterioration under a high surface heat flux at a supercritical pressure.

Ruan and Meng [15], Wang et al. [16], and Pizzarelli et al. [17,18] numerically investigated supercritical-pressure heat transfer of methane in rectangular cooling channels with asymmetric heating enforced on one of the channel surfaces. The channel geometry and heating method are more relevant to rocket engine applications. Effects of the cooling channel aspect ratio and thermal conduction in the solid channel wall on the heat transfer process were examined in detail [16,17].

It should be mentioned that in the open literature, many experimental and numerical studies on supercritical-pressure heat transfer of other hydrocarbon fuels, including n-decane and aviation kerosene, have also been extensively conducted [19–25], intended for applications in regenerative cooling of scramjet engines, the power plant for future hypersonic flight vehicles.

All these aforementioned studies, however, focus on the steady-state heat transfer process at supercritical pressures. A number of experiments [26–29] revealed that flow oscillations could occur in convective heat transfer of various fluids, including helium, Jet-A, and JP7 etc., at supercritical pressures. Different oscillation modes, such as thermoacoustic and thermally-induced flow oscillations, have been clearly observed. The flow oscillations could cause damage to the test section and heat exchanger components [26–29]. The underlying mechanisms that induce flow oscillations are, however, still not fully understood. Moreover, since the transient variation in engine cooling channels can certainly affect the stability of fuel injection and subsequently might influence the combustion process (it should be emphasized that whether and how the flow oscillations in a cooling channel influence combustion instability is unclear and needs significant studies that are far beyond the scope of this paper), detailed numerical studies on transient heat transfer processes at supercritical pressures are, therefore, needed to obtain a fundamental understanding of the thermophysical and transport phenomena.

In this paper, the transient behaviors of turbulent heat transfer of cryogenic methane in a circular cooling tube at supercritical pressures are numerically investigated. The fluid flow process is first allowed to reach a steady state before heat transfer starts. A constant surface heat flux is then instantly enforced on the cooling tube wall to activate a transient fluid flow and heat transfer process. Thermally-induced flow oscillations occur during the process and are analyzed in the present work. The effects of different surface heat fluxes, inlet flow velocities, and operating pressures on the transient heat transfer processes of methane at supercritical pressures are fundamentally examined.

2. Theoretical formulation

The transient conservation equations of mass, momentum, energy are numerically solved in the present work:

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{u}) = 0 \tag{1}$$

$$\frac{\partial (\rho \vec{u})}{\partial t} + \nabla \cdot (\rho \vec{u}\,\vec{u}) = -\nabla p + \nabla \cdot \boldsymbol{\tau} \tag{2}$$

$$\frac{\partial (\rho e_t)}{\partial t} + \nabla \cdot (\rho \vec{u}\, e_t) = \nabla \cdot (\lambda \nabla T) - \nabla \cdot (p \vec{u}) \tag{3}$$

The standard $k{-}\varepsilon$ turbulence model is applied to treat turbulent fluid flows. The two equations are in the following forms:

$$\frac{\partial (\rho k)}{\partial t} + \nabla \cdot (\rho \vec{u}\, k) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\nabla k\right] - \rho\varepsilon + G_k \tag{4}$$

$$\frac{\partial (\rho \varepsilon)}{\partial t} + \nabla \cdot (\rho \vec{u}\, \varepsilon) = \nabla \cdot \left[\left(\mu + \frac{\mu_t}{\sigma_\varepsilon}\right)\nabla \varepsilon\right] + C_1 \frac{\varepsilon}{k} G_k - C_2 \rho \frac{\varepsilon^2}{k} \tag{5}$$

In the near-wall region, in order to capture the sharp temperature gradient, the enhanced wall treatment, which solves a one-equation Wolfstein model, is employed for numerical calculations. More details can be found in [30].

In Eqs. (1)–(5), the standard variables in fluid mechanics are used and defined in the nomenclature.

In a supercritical-pressure heat transfer process, drastic variations of thermophysical properties occur and make significant impact on fluid flows and heat transfer, particularly in the trans-critical region. It is thus a crucial issue to accurately evaluate these properties in numerical simulations of transport processes at