



Flow dynamics in transient heat transfer of *n*-decane at supercritical pressure



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ABSTRACT

Turbulent heat transfer of hydrocarbon fuel at supercritical pressure plays a crucial role in regenerative cooling of aerospace propulsion systems. In this paper, flow dynamics in transient heat transfer of *n*-decane at a supercritical pressure of 5 MPa has been numerically investigated, focusing on the effects of a number of key influential parameters, including the surface heat flux, surface heating rate, cooling tube length, and inlet flow velocity, on the transient responding behaviors. Results indicate that the transient responding process is dictated by two fundamental mechanisms: the initial thermoacoustic oscillation, which is caused by strong fluid thermal expansion, and the subsequent transient convection. The thermoacoustic oscillating magnitude increases as the surface heat flux, surface heating rate, and cooling tube length are increased, but it decreases as the inlet flow velocity is increased. The surface heating rate and cooling tube length also exert strong impacts on the oscillating frequency of the thermoacoustic wave. Moreover, the cooling tube length and inlet flow velocity significantly affect the second-stage transient convective process and thus the total transient responding time, which both increase as the cooling tube length is increased and/or the inlet flow velocity is decreased. Results obtained herein are helpful for fundamental understanding of the transient heat transfer mechanisms relevant to regenerative engine cooling processes.

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1. Introduction

Supercritical-pressure heat transfer of hydrocarbon fuels occurs in the regenerative engine cooling process in many aerospace propulsion systems, including the rocket, advanced gas turbine, and supersonic combustion ramjet (scramjet) engines [1,2]. At supercritical pressures, strong variations of thermophysical properties exert significant impacts on fluid flows and heat transfer, which exhibit physical and transport features distinct from low-pressure counterparts.

Many experimental and numerical studies have been conducted to obtain fundamental understanding of heat transfer characteristics of hydrocarbon fuels at supercritical pressures. Gu et al. [3], Trejo et al. [4], and Votta et al. [5] carried out experimental investigations on heat transfer of the cryogenic methane at supercritical pressures, intended for regenerative cooling applications in the future reusable liquid oxygen (LOx) and methane rocket engine. Pizzarelli et al. [6,7], Wang et al. [8], Urbano and Nasuti [9], Wang et al. [10], and Xu et al. [11] conducted numerical studies of

supercritical-pressure heat transfer of methane, mainly analyzed the effect of thermophysical property variations on fluid dynamics and heat transfer. Zhong et al. [12], Zhang et al. [13], Yang et al. [14], and Liu et al. [15] carried out experiments of supercritical-pressure heat transfer of the heavy hydrocarbon fuels, such as *n*-decane and aviation kerosene, intended for practical engine cooling applications in the advanced gas turbine and scramjet engines. Numerical studies of heat transfer of *n*-decane and aviation kerosene at supercritical pressures were further made by Ward et al. [16], Ruan et al. [17], Xu and Meng [18,19], Feng et al. [20], and Zhang et al. [21]. These works particularly examined the physico-chemical phenomenon of endothermic fuel pyrolysis and its significant influences on heat transfer. All these studies were, however, focused exclusively on the steady-state fluid flow and heat transfer process.

Many experimental, analytical, and numerical studies revealed flow oscillations of various fluids at supercritical pressures during transient heat transfer processes [22–25]. Thermoacoustic transport was found to be a main factor dictating the oscillating transport phenomena during a rapid heating process. The thermally induced pressure wave, or thermoacoustic wave, which was generated by the rapid temperature rise and strong property variations,

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Nomenclature

C	constants in turbulent model
C_p	constant-pressure heat capacity, J kg ⁻¹ K ⁻¹
e_t	total energy, J kg ⁻¹
G_k	turbulence generation term
k	turbulent kinetic energy, J kg ⁻¹
L	heated section length, mm
p	pressure, Pa
Pr	Prandtl number
q_w	surface heat flux, W m ⁻²
r	radial coordinate, mm
Re	Reynolds number
t	time, s
T	temperature, K
$\vec{u}$	velocity vector, m s ⁻¹
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
τ	viscous stress tensor, N m ⁻²
μ	viscosity, kg m ⁻¹ s ⁻¹

Subscripts

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

propagates at the speed of sound and bounces back and forth between different walls until it is viscously dissipated [24–27].

Transient responding behaviors of supercritical-pressure turbulent heat transfer of the hydrocarbon fuel, methane, were recently numerically investigated by Ruan et al. [28]. A constant wall heat flux was instantly enforced on a steady-state cold flow in a circular mini cooling tube. Numerical results indicate that significantly decreased fluid density during a transient heat transfer process at a supercritical pressure induces strong thermal expansion. Flow oscillation becomes stronger and lasts longer under a higher surface heat flux and/or at a lower inlet flow velocity. Detailed numerical studies on transient supercritical-pressure fluid flows and heat transfer of a heavy hydrocarbon fuel, e.g., *n*-decane or aviation kerosene, have not been conducted in the open literature.

In this paper, based on our previously developed numerical models for simulating both steady-state and transient turbulent heat transfer of hydrocarbon fuels at supercritical pressures [8,11,17–19,28], the transient fluid flows and heat transfer of *n*-decane, a pure hydrocarbon fuel and a simple surrogate of the aviation kerosene, during rapid heating processes at a supercritical pressure are numerically investigated in detail. The present study focuses on flow dynamics during transient supercritical-pressure heat transfer of *n*-decane, and the key influential parameters, including the surface heat flux, transient heating rate, cooling tube length, and inlet flow velocity, on transient responding behaviors are comprehensively examined. Two dictating mechanisms, the thermoacoustic oscillation and transient convective transport, are reported and discussed.

2. Theoretical formulation

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

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

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

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

The standard k – ε turbulence model, along with an enhanced wall treatment, is used to handle turbulent fluid flows. The two

conservation equations of turbulent kinetic energy and turbulent dissipation rate are as follows.

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

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

In the enhanced wall treatment, a low-Reynolds-number one-equation Wolfstein model, which retains the turbulent kinetic energy equation but calculates the turbulent dissipation rate using an analytical formulation, is solved to obtain accurate numerical results in the near-wall region. In this treatment, wall function is not needed. More details concerning the turbulence model can be found in [29].

All the variables in Eqs. (1)–(5) are defined in the nomenclature.

Drastic variations of thermophysical properties, particularly in the transcritical (when the fluid temperature rises from subcritical to supercritical state at a supercritical pressure) region, make significant impact on fluid flows and heat transfer at supercritical pressures. It is thus a prerequisite to accurately calculate these properties in numerical studies of the supercritical-pressure heat transfer. Based on previous research works [30–34], the extended corresponding-state (ECS) method is used in the present study to calculate the thermophysical properties of *n*-decane, including its density, viscosity, heat capacity, and thermal conductivity. As shown in Fig. 1, the thermophysical properties of *n*-decane calculated using the ECS method are compared with the NIST data at a supercritical pressure of 5 MPa. Very good agreement between the two sets of results clearly demonstrate the accuracy and reliability of the property-evaluation method. More detailed validations of the calculated thermophysical properties of *n*-decane and other hydrocarbon fuels can also be found in our previous numerical studies [8,17,18,33].

The property calculation method described in the preceding section is implemented into a CFD package, Fluent, using user defined functions, and applied in the following transient numerical simulations of supercritical-pressure heat transfer of *n*-decane. The pressure-based solver and the PISO numerical algorithm are used in the transient calculations. The second-order upwind and second-order central differencing schemes are used to discretize the convective and diffusive terms in the conservation equations, respectively [29].

It should be noted that the numerical model is the same as that described in our previous publication [28], but it is used herein to

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