



Experimental investigation of the flow and heat transfer instabilities in *n*-decane at supercritical pressures in a vertical tube

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ARTICLE INFO

Article history:

Received 9 August 2017

Received in revised form 16 November 2017

Accepted 12 December 2017

Keywords:

Supercritical pressure fluids

Hydrocarbon fuels

Convection heat transfer

Flow instabilities

ABSTRACT

The fuel may be used in hypersonic vehicles to cool various surfaces; however, supercritical pressure fuels have been found to have deteriorated heat transfer rates and instabilities for some flow conditions. The flow and heat transfer instabilities in supercritical pressure *n*-decane were investigated experimentally in this work, with pressure of 2.5 and 3.0 MPa and inlet temperature of 16–225 °C. The heat flux was slowly increased to observe the flow in different stages as well as to obtain the boundary lines for a stability map. Seven stages were observed with different stability features. The transition to turbulence was found to be the main reason for the instability for stage b with slightly irregular oscillations, while dramatic variations of the thermal properties caused Helmholtz oscillations with regular frequencies and large amplitudes. The heat transfer deterioration in conjunction with an instability with buoyancy due to the density variation was found to be the reason. Higher pressures, inlet mass flow rates or fluid temperatures or downward flow weakened the instabilities, so these should be used in engineering designs to reduce the heat transfer deterioration and instability. The stability map provides further support for the nonlinear dynamic theory explaining the oscillations.

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1. Introduction

Regenerative cooling systems in hypersonic vehicles will use the fuel as a coolant. The fuel coolant flows through small channels in the combustor and vehicle walls to protect the material from melting and even being destroyed [1–6]. The fuel is heated before flowing into the combustor which then also improves the combustion. The use of the fuel as coolant also avoids carrying additional coolant so that the vehicle is able to work at higher velocities.

Several issues must be studied to ensure high heat transfer rates and the safety of the regenerative cooling system. Besides the chemical reactions at high temperatures such as cracking and deposition [5,7,8], the unique heat transfer characteristics of supercritical pressure fuels must be investigated since supercritical operating pressures will be used to avoid phase change. The dramatic thermal properties variations at supercritical pressures cause significant buoyancy and/or acceleration in vertical and horizontal tubes and rectangular channels [9–12], which leads to either heat transfer enhancement or deterioration for various flow conditions. Numerical investigations on heat transfer for supercritical pressure fuels were also performed to study the details [13],

but developing an accurate turbulence model still remains to be a challenge due to the complicated thermal property variations [14,15]. Heat transfer of supercritical pressure fluids was also widely studied for the application in enhanced geothermal system (EGS) with CO₂ [16,17] and refrigerants such as R134a and R22 [18,19].

The dramatic thermal property variations can cause the fuel flow in the heated tube to oscillate in many cases. Hines [20] observed an audible oscillation in heat transfer experiments with RP-1 and diethyl cyclohexane at supercritical pressures with frequencies of more than 1000 Hz. Other experiments with supercritical pressure water [21] and *n*-heptane [22] have produced high frequency, audible oscillations. Other oscillations have been observed with much smaller frequencies on the order of 10 Hz [23,24]. Hitch and Karpuk [25] found both Helmholtz oscillations (with low frequencies) and acoustic oscillations (with much higher frequencies) in their experiments and developed a mixer to enhance the heat transfer as well as to stabilize the flow [26]. Fluid temperature, wall temperature and pressure oscillations cause thermal stresses and pulsations that can weaken the tube structure and even lead to failure [27,28]. Other kinds of oscillations such as in parallel tubes have also been reported [29].

Several theories have been developed for the oscillation mechanisms. Acoustic oscillation frequencies are on the order of a/L so

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Nomenclature

A	amplitude [K or °C]
Bo^*	Buoyancy number
c_p	specific heat capacity [J/K]
d	tube diameter [m]
f	frequency [Hz]
Fr	Froude number
g	gravity, 9.8 [m/s ²]
G	mass flow rate [kg/s]
Gr^*	Grashof number
h_f	fluid bulk specific enthalpy [J/kg]
h_x	local heat transfer coefficient [W/(m ² ·K)]
I	current [A]
k	stiffness of the fuel column [N/m]
L	tube length [m]
m	mass of the fuel column [kg]
N_{SUB}	sub-pseudo-critical number
N_{TPC}	trans-pseudo-critical number
Nu	Nusselt number
p	pressure [MPa]
Pr	Prandtl number
q_w	heat flux [W/m ²]
q_v	volumetric heat source [W/m ³]
Q	heat loss [W]
R	resistance [Ω]
Re	Reynolds number
S	cross-sectional area [m ²]

t	time [s]
T	temperature [K or °C]
u	bulk velocity [m/s]
U	voltage [V]
x	axial coordinate [m]

Greek symbols

β	thermal expansion coefficient [1/K]
λ	thermal conductivity [W/(m·K)]
μ	viscosity [Pa·s]
ν	kinetic viscosity [m ² /s]
Π	inner perimeter [m]
ρ	density [kg/m ³] or resistivity [Ω ·m]

Subscripts

b	bulk value
c	critical
f	fluid
i	inner
in	inlet
o	outer
out	outlet
pc	pseudo critical
w	wall

they are related to sound wave resonance [16,20,30]. The Helmholtz oscillation mechanism is similar to the classic mass-spring-damper model which has also been used to explain two-phase flow oscillations [31,32]. DiMarco et al. [33,34] derived a lumped parameter heater dynamics model to simplify a boiling tube model to a six degree-of-freedom dynamic system and applied classic linear and nonlinear stability analyses to obtain the stability boundaries. Their method was further developed by Ambrosini et al. [35,36] and applied to explain oscillations in supercritical fluids [37]. Sharabi et al. [38] and Paruya et al. [39] also modeled the oscillations as a classic bifurcation in a nonlinear dynamic system. The most important objective of their works was to find the stability boundary on a stability map with N_{TPC} as the abscissa and N_{SUBPC} as the ordinate, with these definitions given later.

Recent works [9,21,40] have presented more oscillation and heat transfer information, but few [41] have studied oscillations and flow stabilities with a continuously varying heat flux or investigated the mechanisms for the different stability stages, which is very important for getting detailed knowledge of how the system stability response with heat fluxes and building the criteria. This work describes an experimental investigation of flow and heat transfer instabilities of supercritical pressure *n*-decane for flow in a vertical tube to analyze the characteristics of the different stability stages with small steps in the heat fluxes. The results are used to develop a stability map for *n*-decane.

2. Experimental system and data reduction

2.1. Experimental system and data collection

Fig. 1 shows a schematic of the experimental system. The fuel was pumped from tank 1 through the system and into tank 2. The decompression valve was used to adjust the working pressure in the tube. The main test section and pre-heater were vertical

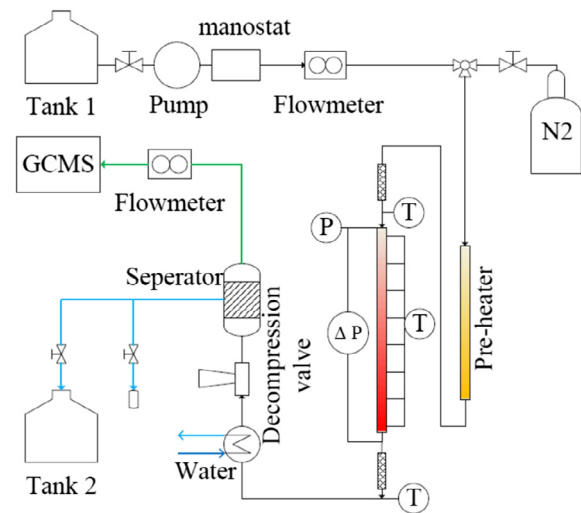


Fig. 1. Experimental system.

stainless steel tubes which were heated by alternating current and thermally insulated by a layer of aluminum silicate fiber, with corrections for the heat losses. Two voltage stabilizer were used to provide constant input currents for pre-heater and test section. The cooler was a water-cooled pipe heat exchanger. The flow direction could be reversed by four valves as shown in Fig. 2. Detailed information about the experimental system was also reported by Liu et al. [10].

The test sections were 950 mm long with inner and outer diameters of 2 mm and 3 mm. Thirty-one K-type thermocouples were spot welded onto the tube wall to measure the local wall temperature with two 2 mm sheathed thermocouples used to measure the

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