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Research Paper

Experimental investigation on thermal-hydraulic characteristics of endothermic hydrocarbon fuel in 1 mm and 2 mm diameter mini-channels

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HIGHLIGHTS

- We found thermal-hydraulic characteristic of endothermic fuel was a quintic curve.
- Boiling and pyrolysis caused the transition of the pressure drop profile.
- Transition point of the curve related to fuel temperature regardless of heat flux.
- Multi-valued characteristic also existed at supercritical pressure conditions.
- Bigger magnitude of pressure drop variation in bigger diameter channel.

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ABSTRACT

The thermal-hydraulic characteristics of endothermic hydrocarbon fuel were experimentally investigated in circular mini-channels with inner diameters of 1.0 and 2.0 mm and heated length of 800.0 mm. The effects of heat flux ranging from (400 to 1750) $kW \cdot m^{-2}$, pressure from (1.0 to 6.0) MPa, and inner diameter were studied. We found that the thermal-hydraulic characteristics of endothermic fuel could be described by a quintic curve. Two positive slope regions and two negative slope regions were experimentally obtained. The boiling or pseudo-boiling, and fuel pyrolysis which led to the rapid density reduction caused two negative slope regions in the curve. The negative slope region at fuel pyrolysis conditions always existed at the tested subcritical and supercritical pressures. The effect of heat flux on the thermal-hydraulic characteristics was not significant. The transition points were fixed and connected to the zeotropic process or pseudo-boiling temperature and pyrolysis reactions regardless of heat fluxes. The multi-valued characteristics can be reduced in small channels, as the magnitude of pressure drop variation was much larger in big channels. The study on thermal-hydraulic characteristics of endothermic fuel starts a new direction in fluid dynamics considering the chemical reaction.

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1. Introduction

Flow instability [1] as a critical problem has been investigated by many researchers in power plant boiler using water as a coolant, which could lead to water-cooled wall tubes explosion when a boiler was running under an inappropriate operation condition. Unstable flow conditions of working medium in a heated channel may lead to damage when vibration and thermo-fatigue stress due to variation of temperature of the channel wall occurred, and may also cause local high temperature even burnout along the flow path of the channel on account of existence of the liquid deficiency region. Hydrocarbon fuel has received increasing interests from various fields, especially in aeronautic and aerospace technology, such as the scramjet, a promising candidate for hypersonic air-breathing propulsion system [2–4]. As a high energy density fuel, hydrocarbon can be used to booster engines of air-breathing vehicles such as aircraft and rocket, while as a potential coolant, it can also be utilized to lower the structural temperature of critical components of a vehicle. Regenerative active cooling technology is a promising technology adopted in the next generation novel high-speed vehicle which will exactly use the idea aforementioned.

Boure et al. [5], Kakac and Bon [6] reviewed the flow instabilities in two-phase flow system. Wang [7] had experimentally investigated the effects of inlet/outlet configuration on flow boiling instabilities in parallel microchannels, and they found that outlet

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Nomenclature

d	inner diameter, m
f	frictional factor, –
l	length of section, m
$\dot{m}$	mass flow rate, kg·s^{-1}
p	pressure at outlet of test sections, MPa
q	heat flux, kW·m^{-2}
A	area, m^2
G	mass velocity, kg·m^{-2}·s^{-1}
I	current, A
L	length or thickness, m
Q	heating power, W
R	Impedance, Ω
t	temperature, °C
Δp	pressure drop, kPa

Greek

ρ	density, kg·m^{-3}
v	velocity, m·s^{-1}

Subscripts

amb	ambient condition
cross	cross-section
e	electrically heated
f	bulk fluid
loss	heat loss
wetted	wetted surface

restriction of heated channels had much larger oscillation amplitudes of temperature and pressure, while inlet restriction of heated channel could sustain nearly steady flow boiling. Kandlikar et al. [8] experimentally investigated the stabilization effects of pressure drop elements and fabricated nucleation sites to inhibit the flow boiling instability in microchannels, and they concluded that, solely introducing inlet restriction lead to partially reduction in flow instability, and solely implementing nucleation sites destabilized the flow boiling, however, combination of both measures could eliminate the flow boiling instability and flow reversal phenomena. Xiong et al. [9,10] experimentally and numerically investigated the flow instability in parallel channels with supercritical pressure water, and they found that increasing pressure and decreasing inlet temperature could make system more stable, developed a time-domain analysis based in-house code that predicted the stability boundaries. Hitch and Karpuk [11] experimentally investigated the heat transfer and flow instabilities of supercritical fuel, and found that flow oscillations generally occurred with relatively low supercritical pressure and tube wall temperature above the pseudo-critical temperature. Zhou et al. [12] experimentally investigated the flow instability mechanism of supercritical endothermic hydrocarbon fuel, and concluded that the acute decrease of fuel density near the pseudo-critical temperature and pyrolysis cracking temperature region is the primary cause for flow instability. But Zhou et al. [12] focused their attention on the dynamic instabilities, such as density-wave oscillations and pressure drop oscillations with accumulator, while present work paid main attention to the static instabilities, such as Ledinegg instabilities or flow excursion.

As for the scramjet, the regeneratively cooling structure consist of a lot of parallel cooling passages distributed in the hot wall of a hypersonic vehicle, and fuel is pumped through these passages to absorb the aerodynamic heating and combustion heat as to protect the body structures and facilitate the combustion of fuel under extreme conditions [13,14]. As parallel channel system introduces other factors affecting the flow instability, and there were rare references about the Ledinegg instability in supercritical fuel utilized in hypersonic vehicles, hence we use a single mini-channel to simulate one of the cooling passage in scramjet to reveal the inherent characteristics of hydrocarbon fuel in a heated channel.

In this paper, experimental investigations of kerosene based hydrocarbon fuel in circular mini-channels were presented to reveal the thermal-hydraulic characteristics of the coolant in thermal protection system.

This study can also provide a reliable thermal-hydraulic database for the regenerative active cooling technology, which is promising in the engineering applications of the thermal protection system (TPS) developed for a novel hypersonic vehicle. However, to our knowledge the researches on Ledinegg instabilities of supercritical hydrocarbon fuels in heated mini-channel had not been reported in open literatures.

The mechanism of flow instabilities for supercritical hydrocarbon fuel is another object in this work. Compared to normal medium such as water, hydrocarbon fuel composed of many chemicals would undergo different chemical reactions under high temperature, and this makes the flow and heat transfer processes of hydrocarbon fuel particularly complicated. Moreover, compared with two-phase flow instabilities, supercritical flow instabilities have been less researched and some unique features for supercritical hydrocarbon fuel need further exploitation. This work here tries to make some attempts on these topics and reveal some characteristics of this kind of processes.

2. Experimental setup

2.1. Test apparatus

A single circular tube was used to simulate the flow passage of the regeneratively cooled structure. All the experiments were carried out on the Fuel's Performance Evaluation Test Rig in Xi'an Jiaotong University with pressure of (0.1–10.0) MPa and mass flow rate of (0–6.5) g·s^{-1}. Schematic diagram of the test rig is shown in Fig. 1.

The test loop mainly consisted of a triple plunger pump with maximum liquid supply capacity of 55.6 kg·s^{-1} and maximum pressure of 40.0 MPa, valve bank to regulate the flow rate and the pressure, a test section, a heat exchanger and a gas-liquid separator and collector. A kerosene based hydrocarbon fuel was used as the working fluid. Part of the test fuel goes back to the kerosene storage tank through a bypass loop with a control valve, and the rest part passed through low temperature filter, control valves and mass flow meter, and then flowed into the horizontal test section. The mass flow rate of the test fuel was measured by a Coriolis-force flow meter. The test fuel was electrically heated through the test section by a low voltage and high alternative current Silicon Controlled Regulator (SCR) power supply (80 V, 250 A and 20 kW), which could supply a uniform heat flux. Joule heating of the test section creates a circumstance similar to the heat environment in the scramjet combustor. After the test section, hot fuel fluid was cooled by a counter-flow type heat exchanger made of galvanized carbon steel tubes and stainless steel tubes. A backpressure valve was utilized to control the fuel pressure. Then a gas-

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