Fuel 161 (2015) 105–112

Contents lists available at ScienceDirect

Fuel

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

Flow rate distribution of cracked hydrocarbon fuel in parallel pipes

Jiang Qin [a], Yuguang Jiang [a], Yu Feng [a], Xiaojie Li [a], Haowei Li [a], Yaxing Xu [a], Wen Bao [a,*], Silong Zhang [a], Jiecai Han [b]

[a] School of Energy Science and Engineering, Harbin Institute of Technology, Harbin 150001, PR China
[b] School of Astronautics, Harbin Institute of Technology, Harbin 150001, PR China

HIGHLIGHTS

- Mal-distribution of coolant causes a waste of heat sink and even over-temperature.
- Distribution of cracked hydrocarbon fuel in parallel pipes are studied.
- Two flow rate deviation amplification mechanisms are found.
- The mal-distribution mode varies with thermal deviation.
- Higher pressure suppresses the mal-distribution.

ARTICLE INFO

Article history:
Received 8 April 2015
Received in revised form 2 August 2015
Accepted 10 August 2015
Available online 17 August 2015

Keywords:
Flow distribution
Parallel pipes
Hydrocarbon fuel
Supercritical pressure

ABSTRACT

A model consisting of two parallel pipes with common inlet and outlet manifolds was established and used to run simulation and experimental study on the flow rate distribution of cracked hydrocarbon fuel in parallel pipes under supercritical pressure. Both simulation and experimental results indicated that mass flow rate and fuel temperature distribution of cracked hydrocarbon fuel in parallel pipes was closely related to the difference in fuel density in pipes. Two deviation amplification mechanisms were found. In addition, the mode of mal-distribution varies with thermal deviation and the distribution was effectively improved by the increase of pressure. And the total mass flow rate could hardly have any effects on the flow rate distribution. All these results could be used to help the full utilization of fuel heat sink and avoid over-temperature.

1. Introduction

Scramjet is a promising propulsion system for hypersonic missile and reusable air-space integrated fight vehicle [1,2]. Due to high flight Mach number, the combustion temperature and heat transfer rate of a scramjet are very high. Thus, cooling becomes a major concern. Regenerative cooling is generally accepted as the most promising method [3]. Considering limited quantity of fuel on board, endothermic hydrocarbon fuel with extra chemical heat sink is used to further increase the cooling capacity [4–6]. Fuel flows through the parallel cooling channels as coolant to cool the wall before it's injected into the combustor [7,8] while a supercritical pressure is kept in the channels to avoid boiling crisis.

However, heat flux is not uniform or constant in the wall of a scramjet, which may lead to the mal-distribution of mass flow rate and fuel temperature in different channels. As a result, fuel heat sink is not fully utilized in the low temperature channels. Over-temperature may occur in the high temperature channels to cause thermal protection failure and damage to engine structure. Therefore, it's of great significance to study the flow rate distribution of cracked hydrocarbon fuel in parallel channels under supercritical pressure so that the fuel heat sink could be fully utilized to avoid over-temperature.

Much work has been done in recent years on boiler, solar power generator [9,10] and fuel cell [11,12] continuously, since the distribution characteristics are important to the safety and efficiency of above mentioned applications. Structure of inlet and outlet manifold has been another focus for the study on the flow rate distribution characteristics [13,14] of fluids including water, carbon dioxide and other refrigerants. Due to pyrolysis, the flow and heat transfer of hydrocarbon fuel is quite different from other fluids [15,16]. A lot of work has been done on the pyrolysis of hydrocarbon fuel through single heated channel experiments [17–20] to improve its chemical heat sink [21,22] and to avoid thermal oxidation coking [23,24].

* Corresponding author at: No. 92, West Da-Zhi Street, Harbin, Heilongjiang 150001, PR China.
E-mail address: baowen@hit.edu.cn (W. Bao).

http://dx.doi.org/10.1016/j.fuel.2015.08.015
0016-2361/

Nomenclature

m_t	total mass flow rate (kg/s)
m_A	mass flow rate of pipe A (kg/s)
m_B	mass flow rate of pipe B (kg/s)
ρ	density of fuel (kg/m^3)
u	velocity of fuel (m/s)
h	enthalpy (J/kg)
C_P	constant-pressure specific heat (J/(kg K))
μ	dynamic viscosity (Pa s)
f	friction coefficient
q_f	heat flux (W/m^2)
ΔP	pressure drop (Pa)
Re	Reynolds number
δ	surface roughness
H_c	chemical heat sink (J/kg)
k	chemical reaction rate constant (s^{-1})
A	pre-exponential constant (s^{-1})
E_a	activation energy (J/mol)
A_c	flow area of throttle in cold end (m^2)
A_h	flow area of throttle in hot end (m^2)
A_{inner}	flow area of pipe (m^2)
K_c	throttle coefficient for cold end
K_h	throttle coefficient for hot end
ΔQ	thermal deviation
Δm	deviation in mass flow rate
ΔT_f	deviation in fuel temperature
$\Delta \rho$	deviation in density
Y	mass conversion of reactant
R	universal gas constant (J/(mol K))

Subscripts

lc	local resistance at cold end
lh	local resistance at hot end
f	frictional resistance
1	heating power Q_1
2	heating power Q_2

So far, the research on flow rate distribution of cracked hydrocarbon fuel in parallel channels is hardly found. Only Ran et al. (2012) studied the flow distribution of kerosene in parallel pipes before pyrolysis occurs [25].

A model consisting of two parallel pipes was established and used to run simulation and experimental study on the flow rate distribution of cracked hydrocarbon fuel in parallel pipes under supercritical pressure and the influences of thermal mal-distribution, pressure and total mass flow rate as well.

2. Modeling with parallel pipes

2.1. Geometry model and hypotheses

In the scramjet, there're usually hundreds of parallel cooling channels through which fuel flows to cool the thermal structure at a temperature of 300–1000 K. Two parallel pipes are used in the model as simplified cooling channels of scramjet, since the close-coupled characteristics of mass flow rate and fuel temperature is clearly presented in this configuration. Similar simplifications are common in studies about parallel systems [9,10].

The following are the hypotheses used by the modeling:

(1) The radial difference in all parameters is ignored.
(2) The kinetic energy and heat generated by the viscous effect of hydrocarbon fuel is ignored.
(3) Channels are horizontal and gravitational potential energy of hydrocarbon fuel is constant.
(4) Axial heat conduction of hydrocarbon fuel is ignored.
(5) The effect of coke is ignored since the high flow velocity set in this work.

2.2. Mathematical model

A homogeneous one dimensional model was developed to demonstrate the steady state solution of mass flow rate and temperature distribution. The common inlet and outlet ensures the two parallel pipes an equal pressure drop and the total mass flow rate is set to be constant.

Mass conservation equation can be expressed as:

$$\frac{\partial(\rho u)}{\partial x} = 0 \tag{1}$$

Momentum conservation equation can be written as:

$$\frac{\partial(\rho u^2)}{\partial x} = -\frac{1}{2}\frac{f}{d}\cdot(\rho u^2) - \frac{\partial P}{\partial x} \tag{2}$$

where d is the equivalent diameter of a pipe and f is the friction coefficient.

$$\frac{\partial(\rho u h)}{\partial x} = \frac{4}{d}\cdot q_f - \rho\cdot(1-Y)\cdot k\cdot H_c \tag{3}$$

where Y is the mass conversion of reactant. H_c is the chemical heat sink of fuel.

Hydrocarbon fuel is a complex mixture with most of its components following the complicated mechanism of pyrolysis including hundreds of species and reactions with possible interactions. In order to highlight the characteristics of mass flow rate distribution instead of the detailed chemical kinetic processes, the model is simplified using n-dodecane, one of the main components of hydrocarbon fuel and used in many related researches [26–28]. In addition, pyrolysis is considered as the first order reaction and global chemical mechanism is adopted. PPD assumption is used to describe the products of pyrolysis [29].

So the conservation equation of cracking products for n-dodecane can be expressed as:

$$\frac{\partial(\rho u Y)}{\partial x} = \rho\cdot(1-Y)\cdot k \tag{4}$$

where k is the chemical reaction rate.

Additional equations of physical properties based on NIST database are required to form a complete system. The density and constant-pressure specific heat of the mixture can be calculated from the mole percentage.

$$\begin{cases}\rho = \sum x_i\cdot\rho_i \\ C_p = \sum x_i\cdot C_{p_i}\end{cases} \tag{5}$$

This model is mainly used to qualitatively analyze the characteristics of the mass flow rate distribution of hydrocarbon fuel by using n-dodecane.

3. Experimental set-up

As shown in Fig. 1, two high temperature alloy pipes with an inner diameter of 2 mm were used to simulate the parallel cooling channels. China No. 3 kerosene (RP-3) was used as the fuel and