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Research Paper

Sensitivity analysis of fluid properties and operating conditions on flow distribution in non-uniformly heated parallel pipes

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HIGHLIGHTS

- The flow distribution of RP-3 is much more sensitive to $d\rho/dT_f$ and c_p.
- The sensitivities of ρ, c_p, λ, μ $d\rho/dT_f$ are much more obvious when $T_{fB} > T_{critical}$.
- The fuel temperature distribution is sensitive to the thermal deviation in the whole temperature scale studied.
- The positive feedback in the mechanism of flow distribution is only obvious when $T_{fB} > T_{critical}$.

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ABSTRACT

Flow rate mal-distribution in parallel pipes has been a common problem in all kinds of heat exchangers, which threatens the performance, even the safety of the applications. Many researches have been focusing on the control methods to achieve a rational flow distribution. However, in order to develop an effective control method, the most sensitive inputs should be located first. In this work, a numerical model of the two-parallel-pipe-system has been developed. The flow and heat transfer are considered. The properties of the hydrocarbon fuel used (RP-3) has been compared and selected. Then the sensitivity analysis on the flow rate and fuel temperature distribution of RP-3 in non-uniformly heated parallel pipes was performed using a local sensitivity analysis method. The target inputs are the thermal properties of RP-3 $(\rho, c_p, \lambda, \mu, d\rho/dT_f)$ and the operating condition: like thermal deviation. The results indicate that the $d\rho/dT_f$ is the most sensitive input and c_p takes the second place. They are much more sensitive when the temperature exceeds pseudo-critical point. The sensitivities of ρ, λ, μ are relatively low. While the thermal deviation is also very sensitive and shows an obvious impact on temperature distribution in the whole temperature scale studied.

1. Introduction

Flow distribution in parallel pipes is a commonly seen problem in many heat exchanging applications, such as boiler, direct steam generator [1,2], nuclear reactor [3], fuel cell [4,5], heat exchangers [6,7], which are closely related to everyday life. Thus the flow distribution problem has drawn a lot of research interests since it is closely coupled with the thermal management [8,9] and the safety of the system. Normally, improper flow distribution of coolant in cooling channels may lead to a waste of coolant capacity or even over-temperature. Unfortunately, it becomes even tough when the available coolant is strictly limited [10]. For example, in high Mach number aero-engines, like Supersonic Combustion Ramjet, the fuel is used as coolant. The combustion heat due to static temperatures as high as 2000 K or even higher has formed a severe thermal environment [11]. The aerodynamic heat due to a Mach number higher than 5 is also tremendous. Thus, to make full use of the fuel heat sink and to maintain the safety and performance of the engine, the limited coolant has to be distributed rationally. Researches related to flow distribution and control are in urgent need.

Much work has been done continuously in recent years regarding the flow distribution problem. The studies in the field are mainly about how to improve the flow distribution uniformity or to achieve the target distribution [12,13]. The main influencing factors being studied are the header design and modification [14,15], the effects of boundary conditions [16,17], the fluid properties [18], the flow regime [19,20], etc. These studies were mostly conducted

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Nomenclature

c_p	specific heat, J/(kg · K)
e	internal energy, J/kg
f	the output function
Gr	Grashof number
m	mass flow rate, kg/s
p	pressure, Pa, in Eqs. (2) and (3) input vector, in Eqs. (10)–(12)
Q	heating power, W
q_s	heat loss, W/m^2
Re	Reynolds number
S	sensitivity coefficient
T	temperature, K
u, v	velocity, m/s
Δm	deviation in mass flow rate, %
ΔQ	thermal deviation, %
ΔT_f	deviation in fuel temperature, %
λ	thermal conductivity, W/m · K
μ	dynamic viscosity, Pa · s
ρ	density of fuel, kg/m^3

Subscripts

A	standard pipe
B	deviation pipe
cal	calculated
critical	pseudo-critical point
ex	experimental
eff	effective value
f	fluid
w	wall

under steady state regime. The transient features and stabilities of the flow distribution were less studied comparatively [2,21,22]. Considering the working fluid, water and some refrigerants are most commonly seen in these studies. However, when it comes to hydrocarbon fuel, the published researches on flow distribution are quite limited. Fu et al. experimentally studied the flow distribution of kerosene in two parallel helical tubes in the non-pyrolysis zone [23]. Chen et al. carried out a numerical study about multi-channel-cooling-plate and analyzed the effects of downstream local block on flow distribution and heat transfer [24]. In our previous works, the flow distribution characteristics in two non-uniformly heated parallel pipes [25,26] and the effects of geometry parameters on flow distribution in a U type parallel system [27] were studied.

In fact, the flow distribution problem of hydrocarbon fuel in the SCRamjet is quite different from other applications. Firstly, the pressure is usually supercritical. Then, the heating is normally far from uniform and local hot zones may exist. The temperature distribution could be very uneven. What's worse, the heat flux can be as high as 3 MW/m^2. The fuel will experience a great temperature rise, going through the pseudo-critical zone and even pyrolysis zone. Greatly property variation happens as a result. However, the property variations in different channels will be very different, which makes the flow distribution even worse. A positive feedback may occur under the interactions between non-uniform heating and flow distribution [25]. The flow mal-distribution is more severe. As we can see, the mechanism of flow distribution of hydrocarbon fuel is complex and closely connected to the fuel properties and operational conditions. Clearly, in order to develop an effective control method, it is necessary to penetrate all the complex relationships and find the most sensitive inputs. This is right the scope of sensitivity analysis.

As we know, sensitivity analysis has been applied in many fields to locate the most important inputs and to simplify problems [28–31]. The simplification of chemical kinetics mechanism is a commonly seen example [32,33]. Just like the applications in other fields, the sensitivity analysis is also a good method to help solve the flow distribution problem.

In this work, a numerical model was developed and validated by experimental data. A sensitivity analysis on the flow rate and fuel temperature distribution of hydrocarbon fuel (RP-3) in parallel pipes was performed using a local sensitivity analysis method and this model. The aim is to identify the most sensitive factors in the thermal properties $(\rho, c_p, \lambda, \mu, d\rho/dT_f)$ and an operating condition parameter: thermal deviation. So that the control methods of flow mal-distribution can be designed accordingly.

2. Model description

2.1. Geometry descriptions

The 2-parallel-pipe system presented experimentally in previous work [25] is adopted in this work as the computing geometry. The heated section is different in length. When imposing the same voltage on the two heated sections, the heating power is inversely proportional to the heated length. The thermal deviation is obtained by adjusting the heated length of deviation pipe. The 2D numerical model assumption is justified by the fact that the flow distribution is investigated and no 3D effects, multiphase or multispecies flow are to be expected. Therefore, all the pipes used in the experiments were converted into rectangular channels as shown in Fig. 1. As shown in Fig. 2, in the conversion, the flow cross-section area and the volume of the channels are kept as the same as the experimental values. In addition, direct current was used to heat the pipe in the experiments, making the whole outer surface of the pipe to be heated surface. To keep the same heat flux and heating power, the area of the heated surface in numerical simulations should be the same as experiments. Hence, the height of all the channels in the z-direction is set to be 3.141592 mm (π number value in mm) to ensure numerically the same heated surface area and the same heat flux. The diameters of the original pipes and headers used in experiments are also shown in Fig. 1.

The turbine flow meter used in the experiments were simplified into a U type channel base on the geometry parameters from the manufacturer (for reproducing the pressure drop as a function of mass flow rate). This enables taking the local flow resistance at the entrance of the flow meter into consideration. More detailed information is presented in Fig. 1.

2.2. Governing equations

The flow in the pipes is assumed to follow the 2-dimensional steady-state continuity, momentum and energy equations. Eq. (1) is the continuity equation:

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

$$\frac{\partial(\rho uu)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} = -\frac{\partial p}{\partial x} + \frac{\partial}{\partial x}\left[\mu_{eff}\left(2\frac{\partial u}{\partial x} - \frac{2}{3}\left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}\right)\right)\right] + \frac{\partial}{\partial y}\left[\mu_{eff}\left(\frac{\partial u}{\partial y} + \frac{\partial v}{\partial x}\right)\right] \tag{2}$$