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Experimental study on the transient thermal characteristics of an integrated deflector under the periodic impingement of a supersonic flame jet

J.J. Zhang, Z.G. Qu *, R.P. Fu, Y.L. He

Key Laboratory of Thermal Fluid Science and Engineering of Ministry of Education, School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

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ABSTRACT

The flow deflector effectively facilitates thermal spreading and the split of high-temperature gas flow from jet impingement. In this study, we developed two samples of integrated deflectors with four layers. The first sample consisted of a composite of silicon carbide reinforced with carbon fiber (C/SiC), carbon aerogel, silica aerogel, and a sandwich corrugated plate. The second sample replaced carbon aerogel with lithium fluoride (LiF), a high-temperature composite material of phase change. Under the periodic impingement of a supersonic flame jet, the transient thermal response of the two deflectors was investigated experimentally. The thermal image of the impinged surface was obtained by an infrared camera. After four periods, the periodic temperature variation in this surface stabilized. The thermal disturbance propagated and attenuated gradually from the impinged surface to the corrugated plate back surface. The back surface temperature of corrugated plate increased monotonically with impingement period without any fluctuation. The entire temperature of the deflector was effectively controlled in the range from 3400 K (the total gas temperature) to 480 K at the centerpoint of the back surface of the sandwich corrugated plate without incurring thermal damage. The deflector temperature level and the ablation rate of the impingement surface were lowered further using LiF as a thermal shield layer because of its high storage of latent energy.

1. Introduction

In the field of propulsion research, the eruption of high-velocity and high-temperature exhaust gas from propulsion systems can threaten the security of devices and their surroundings. Therefore, the gas should be deflected in the appropriate direction using a flow guide device called the deflector [1]. In deflector system design, the characteristics of gas flow and heat transfer are vital. The impingement of exhaust gas upon the deflector can be considered a problem of supersonic impingement of extreme flame jet. In relation to this issue, previous related investigations mainly concentrate on either supersonic air impingement with low temperature (ambient temperature) or flame impingement with low velocity (subsonic).

With respect to supersonic air impingement, some studies have focused on the flow and aerodynamics of jet/surface interaction [2–5]. Other works have examined the cooling performance of a heated surface impinged with a supersonic air jet. Donaldson and Snedecker [6,7] conducted an extensive experimental study on flow features and heat transfer rate of the jet impingement. Results found that the heat transfer near the stagnation point of turbulent jet can be modified based on heat transfer relation of the laminar jet with same pressure distribution by introducing a turbulent correction factor. Rahimi et al. [8,9] experimentally investigated an under-expanded air jet with ambient temperature by impinging it onto a heated flat and cylindrical surface, respectively. Their study results revealed that heat transfer in the impingement zone was extremely high and that the conventional method that represented Nusselt number as a function of Reynolds number was inadequate in supersonic flows wherein the pressure ratio or Mach number should also be considered. Fox and Kurosaka [10] analyzed the cooling effect of supersonic jet from a convergent-divergent nozzle. They proposed a mechanism of shock-induced cooling for supersonic jet and this mechanism was verified by the test data. The shock-induced cooling, which was caused by the interaction of shock and vortical vertical structures, was significantly larger than the subsonic cooling. Yu et al. [11] also analyzed heat transfer on a heated flat surface impinged by a supersonic cool air jet and determined that a second Nusselt number peak appeared at

* Corresponding author. Tel./fax: +86 29 82668036.
E-mail address: zgqu@mail.xjtu.edu.cn (Z.G. Qu).

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Nomenclature

A	area of the C/SiC plate [mm^2]
a	thermal diffusivity, $\lambda/\rho c$ [m^2/s]
ρ	density [kg/m^3]
c	specific heat capacity [J/(kg K)]
λ	thermal conductivity [W/(m K)]
m_a	mass of the C/SiC plate after the test [g]
m_b	mass of the C/SiC plate before the test [g]
N	number of impingement periods
T_i	temperature of the impinged surface [K]
T_b	temperature of the back surface [K]
δ_a	thickness of the C/SiC plate after the test [mm]
δ_b	thickness of the C/SiC plate before the test [mm]
ε_l	line ablation rate [mm/s]
ε_m	mass ablation rate [$g/(s \cdot cm^2)$]
t	time [s]
U	uncertainty
x	horizontal coordinate on the impinged surface [m]
y	vertical coordinate on the impinged surface [m]

$R/D \approx \pm 2.0$ as a result of the transition of wall jet flow to turbulent flow or to flow separation by the movement of the secondary vortex. Recently, Paker et al. [12] experimentally studied the heat transfer for a nichrome heater under the impinging of a supersonic air jet with dispersed water droplets. Their study results showed that the addition of water droplets both increased the jet cooling capacity and smoothed the spatial temperature distribution of the heated surface. In the aforementioned mentioned cases where heated surfaces were cooled by supersonic air impinging, the convection was dominant in heat transfer, and the radiation heat transfer was not considered.

However, thermal radiation should be studied because it is important in the impingement of high-temperature flame jets. The literature on the steady heat transfer of flame impingement has been reviewed in detail by Viskanta [13] and Chander et al. [14]. However, these studies mostly involved low-velocity flame, which is determined by the limited chamber pressure. This limited pressure is generated by the use of gas as fuel. Malikov et al. [15] experimentally and theoretically investigated the heat transfer of flame impinging normally on load surfaces using natural gas as fuel. In the experiment, jet velocity reached 230 m/s and the temperature of the combustion gases ranged between 1200–1800 K. These studies results demonstrated that convection accounted for 60–70% of the total heat transfer between the flame and the impinged surface. The remaining heat transfer was primarily controlled by radiation. Dong et al. [16] experimentally studied the impingement of low-velocity (Re = 2,500) butane flame on an inclined copper plate cooled by water and found that the location of maximum heat flux point shifted away from the impingement position by reducing the inclination angle. To experimentally and numerically study the thermal management characteristics and the transient thermal response of a sandwich panel under propane flame impingement (exit temperature of 1400 K), Carbajal et al. [17,18] and Queheillalt et al. [19] designed a multifunctional sandwich panel that combined a flat heat pipe with structural load support. The study results showed that the heat pipe panel had a lower maximum temperature than a solid aluminum plate because the phase change in the working medium of heat pipe effectively transferred the heat. However, this designed heat pipe can be disabled if either the flame temperature or impingement time increased. In addition, Dong et al. [20,21] optimized heat transfer in the impingement of a port-array inverse diffusion flame upon a water-cooled plate and discussed the effects of nozzle-to-plate distance, equivalence ratio, and the Reynolds number of an air jet.

As indicated above, existing investigations of jet impingement primarily concentrated on either the flow and cooling capacities of supersonic air jet impingement with ambient temperature or the heat transfer in the impingement of subsonic steady flame. When flame velocity exceeds that of sound speed, the heat transfer between the flame and the impinged surface is intensively affected by the complex flow patterns of supersonic exhaust gas. Also, the very high temperature of ambient causes some difficulties in quantitative measurement of thermal feature. These factors make the study about the supersonic flame impingement to be challenging. To the best of authors' knowledge, the similar researches were rarely reported in the open literature. In the present study, two integrated deflectors with multiple layers were designed. The transient thermal characteristics of the two deflectors were experimentally examined under the periodic impingement of a supersonic flame jet.

2. Experimental rig

Fig. 1 shows the experimental schematic diagram of supersonic flame impingement on the integrated deflector. The integrated deflector, which contained four layers of different materials, was periodically impinged by the supersonic high-temperature gas from the flame jet. In practice, to deflect the gas toward the given direction, the deflector is generally obliquely impinged by gas with an inclination angle of 30–60° [4,22]. Therefore in present study, an inclination angle of $\theta = 45°$ as a typical example was selected for the sample. The entire experimental rig consisted of four sections, namely, the integrated deflector samples, flame jet, sample installation structure with data acquisition, and infrared camera.

2.1. Integrated deflector samples

The designed deflector sample consisted of the following four layers (as shown in Fig. 1): the ablation-resistant layer (layer 1), high-temperature heat insulation layer (layer 2), low-temperature heat insulation layer (layer 3), and auxiliary function layer (layer 4). Two samples of integrated deflector (#1 and #2) were prepared in present study, as illustrated in Fig. 2(a) and (b).

In sample #1, four layers of materials (layers 1, 2, 3, and 4) were stacked from top to bottom with uniform size at 100 mm (length) $\times$ 100 mm (width). The material of layer 1 was the silicon carbide plate reinforced with carbon fiber (C/SiC) and the thickness was 5.2 mm, this material behaved an excellent ablation resistance under aerodynamic heating (applicable temperature of more than 2300 K as received from the manufacturer). The layer 2 was a carbon aerogel with 4.2 mm thickness, which could offered a good insulation performance under the high temperature (applicable temperature of less than 2000 K). The layer 3 was a silica aerogel with 10.0 mm thickness, it owned better insulation performance but lower applicable temperature (less than 1300 K) compared to carbon aerogel. The layer 4 was a sandwich corrugated plate made of 304 type stainless steel with the total thickness of 17.5 mm. The thickness of substrate plate was 1 mm and the inclination angle of the wave sheet was 45°. The selection of sandwich corrugated plate was based on the reason that it could activate the auxiliary functions of the deflector, such as the noise reduction and load bearing.