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Research paper

Experimental investigation of full-coverage effusion cooling through perforated flat plates☆

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HIGHLIGHTS

- Effusion cooling using perforated plate was investigated experimentally.
- The effect of cooling hole diameter was investigated.
- The cooling efficiency results were close to that of transpiration cooling.

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ABSTRACT

The flow and heat transfer mechanisms of perforated plate effusion cooling with hole diameters of $d = 1$ mm and 0.5 mm were investigated experimentally. The effects of injection rate and hole diameter on the exterior surface temperature distribution were studied using an IR imaging system. A particle image velocimetry (PIV) measurement system was also used to qualitatively study the turbulent boundary layer development and the interactions between the mainstream and the coolant flow. The surface temperature contours showed that for all the injection rates in the present study, the coolant generated a uniform protective film on the wall. When the blowing ration was high ($F = 2\%$~2.5%), the cooling efficiency of perforated plate with $d = 1$ mm holes was much lower than that of $d = 0.5$ mm case because of the strong mixing and impulse in the boundary layer. And the cooling effectiveness of the full coverage effusion cooling with densely arranged $d = 0.5$ mm cooling holes ($\varepsilon = 19.6\%$) could be nearly the same with transpiration cooling with sintered porous flat plate ($\varepsilon = 36\%$).

1. Introduction

Thermal protection system is an essential part in supersonic vehicles and gas turbines. The heat flux at the stagnation point of a hypersonic vehicle nose cap is estimated to be 1.4×10^7 W/m^2, while in the scramjet combustion chamber the heat flux varies from 1.2×10^6 to 2.34×10^7 W/m^2 [1]. The inlet temperature for the next generation turbine already exceeds 2000 K, which is in excess of the softening temperature of the metallic material [2]. Therefore, different heat dissipation methods are normally applied, including regenerative cooling, spray cooling, film cooling, transpiration cooling and heat pipe cooling. Compared with the film cooling which is widely applied in modern gas turbine blades, effusion cooling uses many rows of cooling holes. While the diameters of these cooling holes could be down to 0.2 mm, the excess use of coolant and strong impulse of coolant jet to the main flow could be considerably avoided. Furthermore, densely-spaced effusion holes could utilize the convection cooling inside the structure better and decrease the area which is not shielded the surface from the hot main flow. Thus, the effusion cooling is believed as the next logical step in gas turbine blade cooling [3].

Previously, literature concerning effusion cooling mainly is devoted to the geometric parameters effects and coolant-hot-gas interaction. Similarly with studies of film cooling, hole shape and angle are considered as the dominant factors of the cooling efficiency. Decreasing the hole's diameter and simultaneously increasing the number of holes can lead to an improvement of

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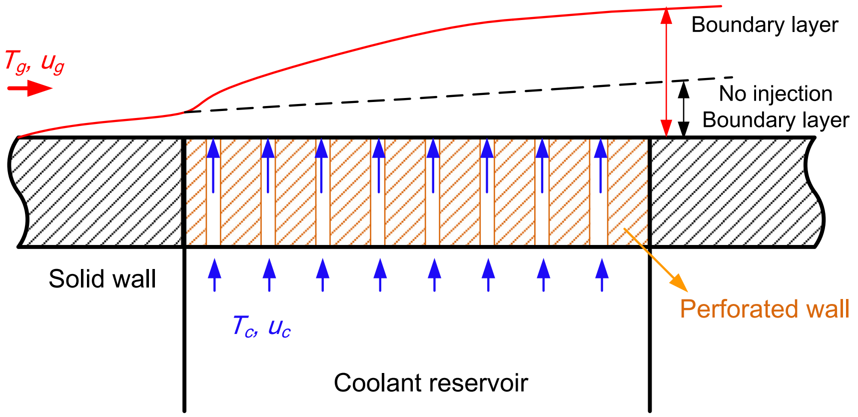
cooling efficiency because of the decrease of the induced mixing in the boundary layer [4,5]. Decreasing the hole angle and a diffuser shaped cooling hole are believed beneficial to decrease the lift-off of the coolant jet and increase the lateral spread according to the experiences of film cooling studies [6,7]. But no obvious increase of cooling efficiency was observed when the injection angle was lower than 30°. Furthermore, steep injection angles would perform better for high blowing ratios because of the increased vortex interactions and manufacture difficulties [8].

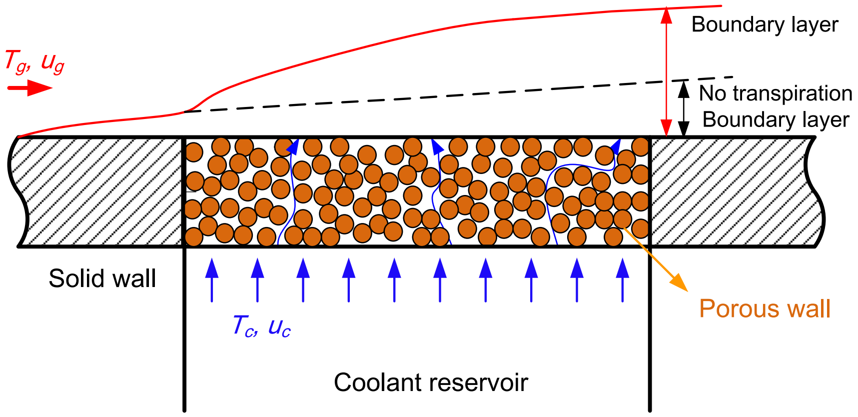
Simultaneously, transpiration cooling has been identified as one of the most efficient cooling techniques for protecting vehicle surfaces from very hot gas streams and has been proposed as a possible means for cooling rocket nozzles, reentry vehicle chambers and gas turbine blades. In general, the differences between the effusion and transpiration cooling are always not clear. The transpiration cooling structure often uses a porous media like sintered material or ceramic foams aiming to reach a thermal equilibrium when the coolant moves through the solid. So the mechanism includes strong convection within the solid matrix and a continuously developing gas film on the hot gas side of the porous structural surface that blocks the hot stream from touching the surface. The schematics of full coverage effusion cooling and transpiration cooling were shown in Fig. 1. On the other hand, the effusion cooling often utilizes a perforated plate with discrete cooling holes. But these theoretical differences are not always regarded in practice [3].

Transpiration cooling cases which use excellent thermally stabilized materials, such as ceramic matrix composites (CMC), can withstand high temperatures exceeding 2500 K [9–11] and heat loads up to 6×10^7–1.4×10^9 W/m^2 [12]. Relatively simple geometries, such as flat plates, have been investigated theoretically, experimentally and numerically in former transpiration cooling studies [13–16]. Recently, transpiration cooling is applied into the thermal protection of some re-entry vehicles and scramjet cases. These studies were usually conducted in high enthalpy wind tunnels which can produce extremely high pressures and temperatures to simulate high heat load with complex structures. Otsu et al. [18] experimentally investigated transpiration cooling of porous ceramics head made of sintered alumina particles in a 750 kW arc-heater facility. And the heat flux at the stagnation point was as high as 1.2×10^7 W/m^2. No visible damage was observed on the ceramic surface and no change in density and gas permeability was found after the experiment, which proved a brilliant cooling performance. Serbest et al. [19] experimentally investigated transpiration cooling of a porous cylinder using carbon fibers reinforced carbon matrix material to demonstrate the applicability to the rocket engine throat. Huang et al. [20,21] developed a porous fuel strut injector for scramjet engine using metal injection molding method and the experimental and numerical results showed excellent cooling performance.

Andrew et al. [4] conducted an experimental comparison of cooling performance between effusion and transpiration cooling



(a) Effusion cooling using perforated plate



(b) Transpiration cooling using porous media

Fig. 1. Schematics of full coverage effusion cooling and transpiration cooling.