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Experimental investigation of self-pumping internal transpiration cooling

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ABSTRACT

In this study, a self-pumping internal transpiration cooling method was experimentally investigated for cooling a high heat flux surface with a maximum heat flux of 1.1 MW/m^2. The heat was conducted from the outer surface to the internal porous plate surface by a copper plate with fins. Transpiration cooling occurred on the porous plate surface with the vapor exhausted through the space between the copper fins. The experiment results indicated that the water coolant automatically flowed from the water tank to the porous surface without any pumps. The outer surface was effectively cooled to approximately 435 K by the internal transpiration cooling when the heat flux was 1.1 MW/m^2. The coolant mass flow rate self-adaptively increased with increase in the heat flux. The coolant mass flow rate exhibited a rapid automatic response to changes in the heat flux while the internal porous surface temperature remained at approximately 373 K. The coolant for the self-pumping internal transpiration cooling was more efficiently utilized than that of traditional transpiration cooling. The self-pumping internal transpiration cooling system exhibited less interaction with the external environment and did not include a complex pump system such as that used in traditional transpiration cooling systems.

1. Introduction

Transpiration cooling is an effective method for cooling high heat flux surfaces, and it is widely investigated to protect key components of hypersonic vehicles from overheating and damage [1–5]. Fig. 1 shows a schematic of the transpiration cooling of a nose cone. The hypersonic mainstream creates an extremely high aerodynamic heat flux on the nose cone. The coolant flows through the porous media to provide intense convective cooling and subsequently forms a thin film on the surface to protect the surface from the aerodynamic heating [6]. The outside flow conditions significantly affect the transpiration cooling because the porous wall is in direct contact with the outside flow. The pressure near the stagnation point is significantly higher than those along sections of the nose cone, and this leads to additional coolant flow through other parts of the nose cone although not through the stagnation point. Additionally, the aerodynamic heat flux near the stagnation point significantly exceeds those along other parts of the nose cone [7]. Thus, the temperature at the stagnation point is the highest on the nose cone with transpiration cooling [8,9]. Wang et al. [10] designed a wedge-shaped nose cone with a non-uniform thickness porous wall. The wall near the stagnation point was thinner than at other locations such that additional coolant could flow through the stagnation part than through other points on the nose cone. Xiong et al. [11] investigated transpiration cooling of a wedge-shaped strut with two internal cavities. Non-uniform coolant injection was used to inject additional coolant into the leading-edge part. Jiang et al. [12] investigated combined transpiration and film cooling to protect a porous wedge shaped strut. A row of micro film holes was drilled into the leading edge such that additional coolant could cool the stagnation region.

The coolant flow for the transpiration cooling also influences the boundary layer along the porous surface. Huang et al. [13] measured the boundary layer development and the interactions between the mainstream and the coolant flow via a particle image velocimetry (PIV) measurement system. The PIV measurements indicated that the coolant changes the boundary layer structure. Foreest et al. [14] and Zhao et al. [15] found that an ice layer formed on the surface of a nose cone when water is used for the transpiration cooling. The equivalent aerodynamic shape of the nose cone subsequently changed due to the influence of the coolant on the boundary layer. Thus, the external transpiration cooling and the aerodynamics interacted with each other.

Transpiration cooling efficiency when liquid water was used as the coolant significantly exceeded that of a gas coolant due to the

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Nomenclature

P	pressure [Pa]
T	temperature [K]
$\dot{m}$	mass flow rate [g/s]
H	height difference [mm]
g	gravitational acceleration [m/s^2]
c	specific heat capacity [J/(g·K)]
d_p	particle diameter [μm]
R	copper plate diameter [mm]
L	thickness [mm]
K	porous media permeability [m^2]
F	force [N]
q	heat flux [W/m^2]
V	Darcy velocity [m/s]

Greek symbols

ε	porosity
λ	latent heat of evaporation [J/g]
α	percentage of heat flux conduction
ρ	density [kg/m^3]

Subscripts

C	coolant
∞	flame
W	copper plate surface wall
P	sintered porous slice surface
fib	packed fibers
fins	fins on the copper plate

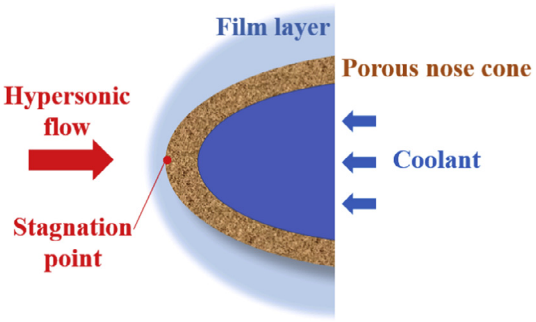
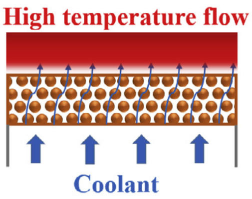


Fig. 1. Schematic of transpiration cooling of a nose cone.

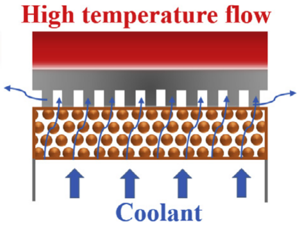
high latent heat of water [14–17]. Accurate pumps were needed to inject the water into the hot surface [10,15,17] although these could fail in extreme flight environments. The water coolant mass flow control is also extremely complex given changes in the aerodynamic heating with respect to the flight Mach number with flow rates that are either too high or too low [17], and a fixed coolant injection pressure leads to variable coolant mass flow rates [10]. Thus, the coolant injection and control system should be further investigated to improve the transpiration cooling when liquid water is used as the coolant.

In nature, creatures always display specific characteristics that adapt to the environment after extremely long evolutionary processes. Bionics is widely used in several fields. Trees transport water from the moist soil to leaves without any pumps. Redwood trees are as high as 112.7 m [18], and thus, the suction force in these trees is sufficiently high to successfully pull water to the aforementioned heights. Transpiration, capillary forces, and cohesion provide power to drive the water based on cohesion–tension theory [19]. Xylem is a porous media with micro conduits, and this is required to reduce the risk of cavitation [20]. The tree transpiration rate increases with increase in the ambient temperature and sunlight [21]. Jiang et al. [22] investigated a biomimetic, self-pumping, and self-adaptive transpiration cooling system without any pump, inspired by the tree transpiration process. The porous plate was heated by a high temperature flame. Their results indicated that the system effectively cooled the hot surface heated by a butane flame with a temperature of 1639 K and a maximum heat flux of 0.42 MW/m^2. The experiments also indicated that the coolant mass flow automatically increased with increase in the heat flux with a maximum cooling efficiency of 94.5%. However, the porous material was exposed to the external environment, and this could lead to undesirable interactions between the transpiration and external environment.

This study investigated a self-pumping and self-adaptive internal transpiration cooling method. Traditional transpiration cooling in previous studies is directly exposed to the external environment as shown in Fig. 2(a) and easily affected by the environmental factors including dust blockage and local high pressure blockage, which are problems that should be solved in practical applications. The internal transpiration cooling proposed in the study isolates transpiration cooling with the outside environment as shown in Fig. 2(b), and this decreases the effect of the environment on transpiration cooling. The self-pumping and self-adaptive internal transpiration cooling in this study maintains the advantages of self-pumping and self-adaptive effects and improves the disadvantages of external transpiration cooling as denoted in the study by Jiang et al [22]. With respect to internal transpiration cooling in this study, transpiration occurs inside a finned plate on top of the porous wall. The finned plate is an impermeable metal plate with fins that separate the porous plate from the mainstream. The coolant flows through the porous plate to provide intense convective cooling and subsequently flows through the micro fins to provide additional convective cooling. The efficiency and reliability of the self-pumping internal transpiration cooling system were



(a) Traditional transpiration cooling



(b) Internal transpiration cooling

Fig. 2. Schematics of transpiration cooling and internal transpiration cooling.