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Transpiration Cooling Using Liquid Water

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At the German Aerospace Center (DLR), a possible solution for handling extreme aerothermodynamic heat loads has been investigated. The solution involves an innovative new way of transpiration cooling, using liquid water. The concept has been tested at the arc heated wind-tunnel section of DLR. The test campaign will be described and the results will be compared with transpiration cooling using a gas as a coolant.

I. Introduction

ACTIVE cooling options such as transpiration cooling have the potential to reduce heat loads on hypersonic vehicles, allowing thinner leading edges and sharper noses. Aerodynamic performance of such vehicles can thus be greatly improved. An example of such a vehicle is the SpaceLiner, which is currently under investigation at the Space Launcher System Analysis (SART) department of DLR [1–6].

Using fluids as a coolant, the temperatures of the SpaceLiner can be limited. For transpiration cooling a certain coolant mass is required to cool down the vehicle during its flight. Transpiration cooling using a gas (such as nitrogen) has already been studied for different concepts [7]. To reduce overall system mass it is important to use a coolant with a high cooling capacity per unit mass. Such a coolant could be liquid water. Together with the wind-tunnel department at DLR, a test campaign in the arc heated wind-tunnel L2K has been set up to investigate the feasibility of using liquid water as a coolant. To verify the advantage of water compared to gas, additional tests were carried out using nitrogen gas as a coolant.

II. Transpiration Cooling

A cooling fluid can flow through a heated surface made out of a porous material. The fluid absorbs heat by convection and thus cools the material down. Usually, a gas is used as the coolant. A liquid has the advantage that the heat of vaporization can be used as an additional cooling mechanism. Water is an attractive liquid because it has an extremely high heat of vaporization. Liquids will not become hotter than their boiling temperature. In the case of water, this boiling temperature is 100°C at 1 bar and increases proportionally to the pressure. If water remains in its liquid state during the transportation through the porous material, the convective cooling will be very efficient due to the large temperature difference of liquid water and the material when it is not exposed to cooling. When a material with sufficient porosity is used, it will be cooled down to approximately the boiling temperature of the water. To prevent water from evaporating within the porous material, new water has to be supplied at a sufficiently high mass flow rate. The higher the heat required for vaporization, the lower the coolant mass flow can be.

The amount of heat which is necessary to evaporate 1 kg of water depends on the initial temperature of the water, the surrounding pressure, and the heat of vaporization. The heat of vaporization is the additional heat needed for the phase change from liquid to gas.

To vaporize an amount of water, it must first be heated up to the boiling temperature. The energy required for this is defined by the specific heat of water, $C_{\text{water}} = 4186\ \text{J/kg} \cdot \text{K}$. Assuming the water will be supplied at a temperature of 293 K and that the boiling temperature is 373 K (at 1 bar), the temperature difference $\Delta T = 80\ \text{K}$. To heat 1 kg of water up to the boiling temperature the energy supplied must be as follows: $C_{\text{water}} * \Delta T = 334.9\ \text{kJ/kg}$. Then, the phase change occurs. This requires an additional 2260 kJ/kg (at 1 bar). As can be seen the heat of vaporization is much more than the energy that is required to heat up water to a boiling temperature.

Using a liquid as a coolant introduces a capillary pressure in the porous material. This pressure will cause water to flow into regions where no water is present. This capillary action will therefore distribute the liquid over the porous material. A simplified model of capillary action in a porous material can be made by assuming a porous material is made up of a bundle of tubes with a certain radius [8]. As soon as a capillary tube has completely filled with water, there will be no more capillary action. The water level in the material will drop once water evaporates at the surface. The capillary tubes are no longer completely filled with water and capillary action will start again. Consequently new water is automatically supplied to the surface at exactly the required mass flow rate.

The evaporation of the water has an additional cooling effect. The vapor enters the boundary layer, creating a protective layer which blocks the incoming heat flux. This effect is called "blocking" [1]. A schematic representation of this cooling principle is given in Fig. 1.

III. Wind-Tunnel Test Preparations

A. L2K and L3K Arc Heated Wind Tunnels

The cooling concept described above was tested at DLR's arc heated wind-tunnel section. The L2K and L3K arc heated wind tunnels at DLR are especially designed for high enthalpy flows. An arc heater is used to give the flow its high enthalpy. The wind tunnels have a long history in qualifying thermal protection systems. For example, they have been used in the Hermes, ASTRA, X-38, and MSTP programs [9]. The gas species can be varied. Thus it is possible not only to simulate Earth's reentry, but also, for example, a Mars entry. A schematic view of the wind tunnels is given in Fig. 2.

The L3K has a maximal electrical power supply of 6 MW. This generates enthalpies up to 25 MJ/kg at reservoir pressures between

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