

THERMAL QUALIFICATION OF TRANSPIRATION COOLING FOR ATMOSPHERIC ENTRY

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OVERVIEW

In the arc heated facility LBK a transpiration cooling concept based on porous CMC material was qualified for application in external hypersonic flow, in particular for atmospheric entry. The experimental setup allowed a direct comparison of the thermal behaviour of transpiration cooling to a well-qualified passive thermal protection technology. Tests were performed for different coolants at various flow rates in order to identify the influence on cooling efficiency. Nitrogen, argon and helium were used as coolants. It was found that for a given configuration there is an optimal coolant flow rate for each coolant. These optimal coolant flow rates could be identified and compared for all coolants used.

1. INTRODUCTION

During atmospheric entry some components of a space vehicle, as e.g. nose cap, leading edges and flaps, are exposed to extreme thermal loads. These components need a sophisticated thermal protection which is commonly based on ceramic surface materials for Earth re-entry of a reusable vehicle. Ceramic materials are capable of sustaining very high temperatures. This property is used to protect the vehicle's interior from being heated, since at high surface temperature most of the huge convective heat that is generated by the hypersonic flow is radiated back to space leaving only a small fraction penetrating the surface. This passive protection philosophy, however, is limited by the surface materials' operational limit temperature. In general, these limits are exceeded for planetary entries and Earth return, but also if vehicles are designed with smaller nose radii in order to improve their flight performance. These scenarios can be met either by switching to single-serving ablative systems or by extending the capabilities of reusable systems using active cooling.

Transpiration cooling is a very promising active cooling concept. The coolant is a gas that effuses through a porous surface material to the outside without disturbing the external flow field considerably. The fundamentals of transpiration cooling were investigated since the 1950s [1, 2, 3], but applications focussed on turbine blades and combustion chambers at that time. The capabilities could significantly be extended with porous ceramic composite materials (CMC). At DLR, a transpiration cooling concept based on porous carbon reinforced carbon (C/C) was developed and successfully applied to combustion chamber cooling in rocket engines [4, 5, 6]. This concept was now adapted to atmospheric entry conditions. Its applicability as part of a thermal protection system was checked during several test campaigns in the arc heated facilities LBK.

2. TEST FACILITY

LBK is one of the European key facilities for qualification of thermal protection systems. Tests can be performed at realistic combinations of convective and radiative heat loads and components can be tested in an atmosphere with a realistic gas composition for time periods that are characteristic for atmospheric entry, i.e. for several minutes. A sketch of the facility with its two test legs L2K and L3K is given in Fig. 1, more details are described by Gülhan and Esser [7, 8].

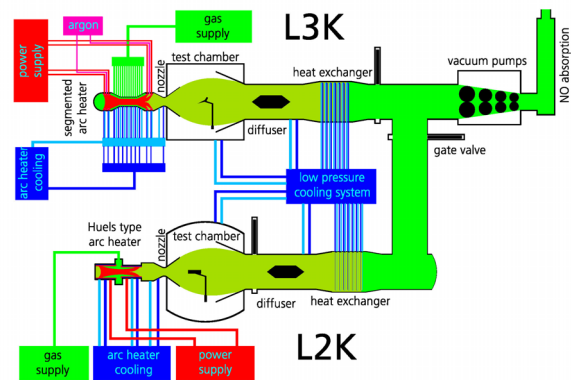


FIG 1. Sketch of the LBK facility.

Each test leg provides a hypersonic high-enthalpy flow field in the test chamber. The required energy is transferred to the working gas by an arc heater which is located upstream. At L2K, there is a Huels-type heater with an electrical power of 1 MW and at L3K a 6 MW segmented arc heater. The working gas is accelerated to hypersonic velocities by conical nozzles with a half angle of 12°. Depending on the nozzle's exit diameter Mach numbers in the range from 4 to 10 can be achieved at stagnation pressures up to 400 hPa.

Both tests legs were used for tests with transpiration cooling. First screening tests were run in the L2K facility in order to check the applicability of transpiration cooling and identify operational parameters for coolant supply [9]. For thermal qualification testing was switched to the L3K facility, where higher enthalpy levels, surface temperatures and surface pressures can be achieved.

3. MODEL AND INSTRUMENTATION

Thermal testing of transpiration cooled structures in a hypersonic high enthalpy flow field requires an experimental setup that allows for continuous coolant supply at

adjustable mass flow rates through a porous sample in the surface of windtunnel model. The setup that was used for the test campaign in the L3K facility is shown in Fig. 2. The complete setup is installed on top of a water-cooled model holder with a blunt nose, which is water-cooled as well. The model has an overall width of 194 mm and a length of 286 mm.

The cubic coolant reservoir which is made of C/C-SiC is mounted just on top of the model holder's base. There are three connections to the reservoir's side wall (see Fig. 2a). The left one corresponds to the coolant supply line, the other two are connectors for measuring pressure and temperature inside the reservoir. The coolant itself was supplied from K-bottles outside the test chamber with a controller installed in the supply line that allows for constant feeding at specified levels between 0.2-10 g/s. This concept had principally been approved during the screening tests. Nitrogen, helium and argon were used as coolant gases.

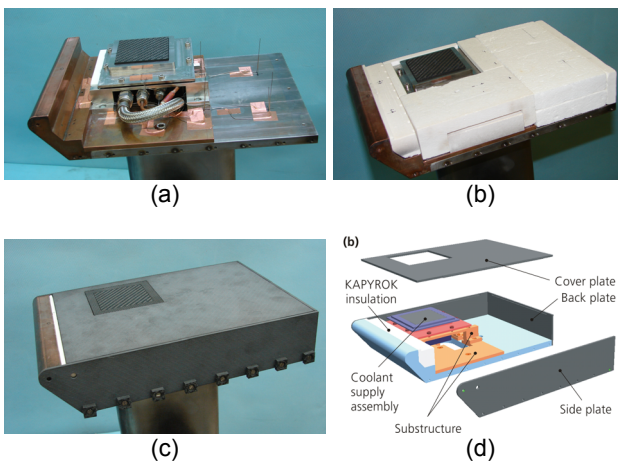


FIG 2. Setup of the test model.

For reliable operation the porous sample was installed on top of the reservoir. 61 mm wide square samples made of carbon reinforced carbon with a volumetric porosity of 17% and a thickness of 6 mm were used. A tight connection to the reservoir was obtained by a carbon seal which was compressed by a jacket frame made of high-temperature alloy PM2000.

The remaining space between the cover plate on top and the base plate was filled with insulating material as shown in Fig. 2b. The insulation prevents the aerothermal heating on the top surface from being influenced by the cooled parts of the model holder. Furthermore, the insulation material avoids internal radiation, which might lead to a substantial heating to the model's interior due to the expected high surface temperatures.

The samples are embedded in a cover plate made of carbon reinforced silicon carbide (C/C-SiC) which is a well qualified reusable high-temperature thermal protection material. Detailed information on the C/C-SiC material is given in [10, 11].

The model was primarily instrumented for temperature measurements. In total 17 thermocouples were installed inside, 8 of them were located just below the C/C-SiC

cover plate and 4 inside the insulation material. The coolant's state in the reservoir was monitored by a thermocouple and a pressure gauge. The remaining thermocouples were used to monitor the temperatures of reservoir walls, the sample's rear side and the base plate of the model holder. The locations of the thermocouples projected to the top surface are plotted in Fig. 3.

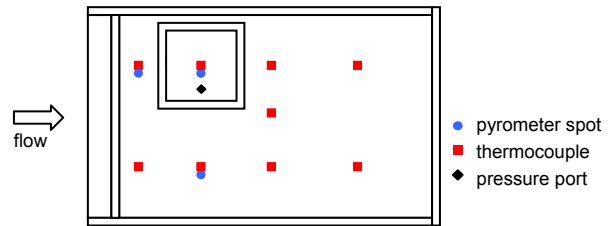


FIG 3. Locations of measurement spots.

In addition to the thermocouple measurements inside the model the surface temperature distribution was recorded by infrared cameras. During all tests a camera with a high temperature measuring range between 350°C and 2000°C was used. The temperature range was well suited for the non-cooled parts of the surface as shown in Fig. 4a. For the porous sample, however, the camera was working near to or even below the low temperature limit of its range. In order to obtain a better temperature of this particular area a second infrared camera was added which was set for measurements in the range of 0 - 500°C. The image in Fig. 4b demonstrates that the cooled parts of the surface are resolved well, while the hot parts are overexposed.

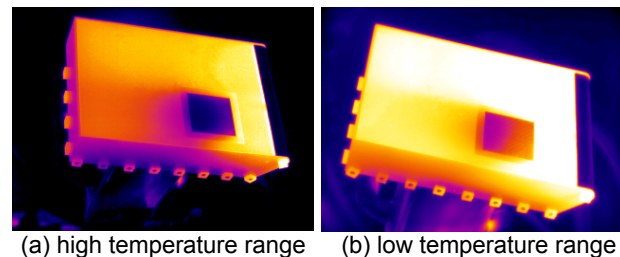


FIG 4. Typical images of the two infrared cameras (flow from right to left).

The camera measurements were supported by pyrometer measurements at specific spots on the surface, i.e. the centre of the porous sample, at the reference spot on the non-cooled side, and at a location upstream of the sample (see Fig. 3). Since the pyrometers work in the near infrared regime at about 1 μm , their measurements are almost not affected by uncertainties in the surface material's emissivity. Therefore, they can be used to correct the results of the infrared cameras which work in the far infrared regime between 8 μm and 13 μm and are sensitive to emissivity. The correction procedure is described in detail by Esser et al. [12].

Due to the symmetry of the model the non-cooled side provides a kind of technological reference with regard to results of transpiration cooling, since the non-cooled surface is completely made of a reusable TPS material that is able to withstand the test conditions without being actively cooled. Therefore, the spot on the non-cooled side which

