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Local Enthalpy Measurements in a Supersonic Arcjet Facility

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Results of the application of a mass-injection probe to estimate the local mass-specific enthalpy in a supersonic air plasma flow are presented. Up to now this probe has only been applied to subsonic flows. Numerical calculations to interpret the probe behavior are shown and compared to experimental results. Furthermore, to interpret the measured local mass-specific enthalpies, classical enthalpy estimation methods are used together with analytical calculations of the turbulent free plasma jet and fairly good agreement is found.

Nomenclature

a	=	on the axis
B	=	mass addition factor
c_p	=	specific heat capacity, $\mathrm{J/kg \cdot K}$
h	=	specific enthalpy, $\mathrm{MJ/kg}$
h_{eff}	=	effective enthalpy, $\mathrm{MJ/kg}$
h_{Pope}	=	enthalpy according to Pope's formula $h = q/\sqrt{p_{\mathrm{tot}} + R_{\mathrm{eff}}}$, $\mathrm{MJ/kg}$
I	=	arc current, A
K	=	Pope's constant, $\mathrm{kW/(m^{3/2}\,Pa \cdot MJ)}$
$\bar{M}_c$	=	mean molecular weight of the cooling gas flow
$\bar{M}_\infty$	=	mean molecular weight of the freestream
Ma	=	Mach number
$\dot{m}_{\mathrm{N_2}}$	=	nitrogen gas mass flow, g/s
$\dot{m}_{\mathrm{O_2}}$	=	oxygen gas mass flow, g/s
$\dot{m}_{\mathrm{tot}}$	=	total gas mass flow, g/s
P_{el}	=	electrical power, W
p_a	=	ambient pressure, Pa
p_{tot}	=	total pressure, Pa
Q_{cw}	=	water cooling losses, W
$\dot{q}$	=	heat flux, $\mathrm{kW/m^2}$
$\dot{q}_0$	=	heat flux without mass addition, $\mathrm{kW/m^2}$
$\dot{q}_0$, fc	=	fully catalytic heat flux, $\mathrm{kW/m^2}$
R_{eff}	=	effective probe radius $R_{\mathrm{eff}} = 2.3 \cdot R_p$, m
R_p	=	probe radius, m
R_s	=	radius of the plume, m
r	=	radial coordinate
St_0	=	Stanton number $=()$
T	=	temperature, K
U	=	voltage, V
v	=	velocity, m/s
ξ_i	=	mass fraction of species i
ρ	=	density, $\mathrm{kg/m^3}$

I. Introduction

THERMAL arcjet facilities are used to produce the heat loads for the simulation of high-speed planetary entry flights. Usually, the stagnation point scenario is investigated as a worst case scenario. The most important parameter that has to be simulated is the flow enthalpy. To qualify the ground testing flow, a local specific enthalpy estimation is therefore indispensable.

Meanwhile, several methods to estimate the local mass-specific enthalpy have been investigated [1]. They can be divided largely into two principle methods: 1) probes that are directly used to measure the local mass-specific enthalpy, and 2) methods that use different locally applicable measurement techniques and more or less sophisticated analysis tools of the flow behavior. To give the reader an overview, the main techniques are summarized in the following paragraph.

Enthalpy probes were first proposed by Grey [2]. The principle idea of these probes is to measure the energy of a known amount of the gas flow by heat exchange. These probes have an orifice in the stagnation point to suck gas into the probe. A special cooling water circuit is used to measure the heating capabilities of the portion of the gas which has been sucked in. In additional measurements, the background influences from the heating of the outer surfaces of the probe, for example, are measured. The principle problem of this type of probe measurement is that it is very difficult to know the correct portion to suck, especially in supersonic plasma flows at low densities, where the glowing bow shock makes an optical investigation difficult. Boulos, for instance, intensively studied these probes [3]. New approaches for low-pressure gas flows using this principle have been investigated by Dorier [4].

A similar approach to the probe technique described in the preceding paragraph has been applied by Herdrich [5]. A calorimeter with an orifice of the size of the plasma plume diameter has been designed to measure the enthalpy in the flow. This system is, on the one hand, limited to moderate enthalpies and, on the other hand, can only give an effective enthalpy value, that is, the mean enthalpy with respect to the plume diameter, which in fact is an additional limiting factor.

The most common approach using the second principle to deduce the local mass-specific enthalpy is the theoretical approach to an empirical formula for the enthalpy by Marvin and Pope [6]. For a wide range of pressures, velocities, and temperatures, the local specific enthalpy can be calculated from a local measurement of the fully catalytic heat flux in the stagnation point and total pressure to a blunt body probe. The local specific enthalpy is then

$$h_{\mathrm{Pope}} = \frac{\dot{q}_{\mathrm{fc}}}{K\sqrt{\frac{p_{\mathrm{tot}}}{R_{\mathrm{eff}}}}} \tag{1}$$

The variable K has been estimated by a linear fit to various experimental data sets and computational heat transfer calculations [7]. Differently constituted plasma flows, for example, CO_2, N_2, H_2, Ar, and air have been investigated. Hence, for these plasma flows the constant K is available and for air it becomes $K = 0.368\ \mathrm{kW \cdot kg/(m^{3/2} \cdot Pa \cdot MJ)}$ [8]. The constant is intended to account for the effect of the thermodynamic and transport properties of the gas at the wall and external to the boundary layer. To account for the catalytic behavior of the surface, often measurements of heat flux on copper

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are performed and correlated to the fully catalytic heat flux (according to Pope [9]) by

$$\dot{q}_{\mathrm{fc}} = 1.2 \cdot \dot{q}_{\mathrm{CuO}} \tag{2}$$

The catalytic efficiency of various materials has been investigated by Stöckle [10]. This work also includes a thorough review of literature data which have been confirmed recently by Park et al. [1].

The local stagnation point velocity gradient in the boundary layer depends on the local mass-specific enthalpy and the geometrical form of the probe. Hence, the probe radius has a significant influence. An effective probe radius R_{eff} is defined which correlates the actual probe radius to an equivalent spherical nose radius with the same shock standoff distance as the cylindrical flat-faced probe which is usually used. For this probe geometry, Marvin and Pope give $R_{\mathrm{eff}} = 2.3 \cdot R_p$ [6]. In principle, radial profiles of heat flux and total pressure can be measured and, consequently, Eq. (1) can be applied to estimate radial profiles of the local mass-specific enthalpy. However, at the edges of the jet a correct measurement is difficult because the probe is not homogeneously affected by the hot plasma.

A relatively new approach first published by Fletcher for nitrogen and argon/nitrogen flows is to use laser-induced fluorescence measurements to measure the enthalpy by summing up the chemical, kinetic, and thermal parts of the enthalpy [11]. The local specific enthalpy of a hot gas flow can be formulated as

$$h = \frac{1}{2}v^2 + \sum_i [\xi_i c_{p_{\mathrm{ges}},i} T + \xi_i (h_i + h_{\mathrm{el},i})] \tag{3}$$

where v is the local freestream velocity, ξ_i the mass fraction of the species i, $c_{p_{\mathrm{ges}}}$ the specific heat capacity, T the local temperature, and h_i and $h_{\mathrm{el},i}$ the enthalpy of formation for the species i and ionization "el,", respectively. This approach has also been applied by one of the authors in a pure oxygen plasma flow, where the constant K is not available, with promising results [12]. However, the application to an air plasma with at least five species to be taken into account is a sophisticated challenge.

From this short overview it becomes clear that a reliable, simple method to measure the local mass-specific enthalpy with the main goals of fewer constraints than the known probes and a less sophisticated setup than the spectroscopic methods has still to be developed.

In this paper, a new probe technique applied for the first time to a supersonic plasma flow is presented. It is based on the effect that the cooling of the boundary layer by injecting a gas flow through the wall leads to a decrease of the measured surface heat flux depending on the freestream enthalpy. The probe technique was first published by Fasoulas and Stöckle in subsonic high enthalpy plasma flows [10,13]. Recently, the application of this probe technique has been extended to supersonic air plasma flows, while the probe design had to be slightly modified. The new results will be presented.

In the following paragraph, the measurement principle is described from a theoretical point of view. Then, the facility and the experimental realization are described, followed by experimental results and comparisons to other enthalpy measurement techniques. Finally, an analytical approach is presented to compare the locally measured value to the mean enthalpy estimated from the plasma generator parameters known as the heat-balancing method [1].

II. Enthalpy Measurement Using a Mass-Injection Probe

The principle of cooling surfaces by injecting a cooling gas flow into the boundary layer is well known in gas turbine technology, where usually the question of the cooling process efficiency is the challenging task [14]. In the present case, the boundary layer around a spherical-shaped probe head is cooled and the question is not about the efficiency of the cooling of the surface but about the enthalpy of the flow, that is, the heating capabilities of the flow.

The heat transfer to a body in a supersonic flow regime can be calculated following the classical approach for solving the boundary layer equations [15]. Mass injection into the flow through the boundary of the probe can therewith be accounted for [6,15]. Usually, to solve these partial differential equations, the Lees–Dorodnitsyn transformation is applied [15]. The boundary layer equations are hence only ordinary differential equations and can be solved numerically. However, the transformation step is only useful if the boundary layer is self-similar, such that the equation becomes independent from one coordinate. Self-similarity is, for example, given for the flat plate but also for a spherical probe head with mass injection in the stagnation point [15]. In contrast, self-similarity is not given for the flat-faced cylinder which is the reason for the current spherical probe design. Theoretical investigations, that is, solving these boundary layer equations, show that similar curves are obtained by plotting the ratio of stagnation point heat transfer without mass injection versus the ratio of the mass-injection rate and Stanton number times the freestream flow rate, that is,

$$\frac{\dot{q}}{\dot{q}_0} = f\left(\frac{(\rho v)_c}{(\rho v)_\infty St_0}\left[\frac{\bar{M}_\infty}{\bar{M}_c}\right]^{0.25}\right) = \mathrm{const} \tag{4}$$

Here, the index c stands for the injection of cooling gas, and $\bar{M}_\infty$, $\bar{M}_c$ are the mean molecular mass of the flow and the cooling gas, respectively. The Stanton number St_0 is defined as the ratio of the effective heat flux to the maximum possible one,

$$St_0 = \frac{\dot{q}_{0,\mathrm{fc}}}{(\rho v)_\infty (h - h_w)} \tag{5}$$

with h and h_w as the enthalpy of the freestream and the one at the wall, respectively. The main assumptions in applying this theory are, as mentioned, the self-similarity of the flow but furthermore a flow in chemical equilibrium. This can, however, be neglected if a fully catalytic wall is used. Therefore the index fc is noted in Eq. (5). In the present case air is injected in the air plasma flow; thus, the molecular ratio equals one. Moreover, the enthalpy at the wall is negligible with respect to the high freestream enthalpy. A so-called mass addition factor can be defined according to

$$B = \frac{(\rho v)_c}{(\rho v)_\infty St_0} = \frac{(\rho v)_c}{\dot{q}_{0,\mathrm{fc}}} h \tag{6}$$

Numerical solution of the boundary layer equations shows that the reduction of heat transfer for an axial symmetric body is a quadratic dependency of the form

$$\frac{\dot{q}}{\dot{q}_0} = 1 - 0.72B + 0.13B^2 \tag{7}$$

Hence, Eqs. (6) and (7) show that by measuring the decrease of heat flux by increasing the mass flow of cooling gas into the boundary layer the local specific enthalpy can be estimated. Despite the assumptions mentioned, the estimation of the enthalpy according to the theoretical approach described here is purely experimental.

The following section will describe how this theoretical approach is realized experimentally.

III. Enthalpy Probe

To measure the heat flux of an actively cooled surface, both the gas injection and heat flux measurements have to be integrated in the probe head. Figure 1 shows a photograph of the realization of the enthalpy probe head. It has a probe base made of brass and a spherical head of 50 mm in diameter made of copper. The whole probe is water cooled. As seen in Fig. 2, in the stagnation point of the probe, a Gardon gage is mounted to measure the heat flux. Gardon gages are widely used in plasma wind-tunnel applications because of their advantages of small size and fast response. The measurement technique is based on the measurement of the temperature difference between the center of a circular foil and its edge. From a radial heat conduction analysis, the heat flux can be deduced as long as the outer edge of the sensor is at a constant temperature level [16]. Around the sensor are small bore holes through which the cooling gas is fed into

Fig. 1 Photograph of the enthalpy probe head.

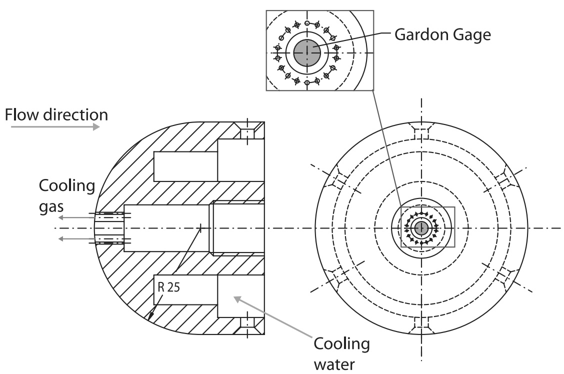

Fig. 2 Enthalpy probe head.

the boundary layer. As mentioned above, the spherical probe head has been chosen to fulfill the theoretical requirement of self-similarity.

From the theoretical approach it becomes clear that the enthalpy can be estimated if the cooling area-specific mass flow rate $\rho \cdot v$ is known [see Eq. (4)]. In the experimental setup, the gas volume flow cannot be measured but the gas mass flow $\dot{m}_a$ can. Thus, an area has to be defined to compute the gas volume flow. The area of interest is the area where the cooling gas flow affects the probe surface, an area which is surely bigger than the sum of the area of bore holes. In the following it will be called effective cooling area A_{eff}. Fasoulas et al. assumed the area to be constant and estimated it from a well-defined measurement condition. This test condition was investigated within a collaborative research center as a critical condition for the leading edge of the Hermes space plane. Besides the classical measurement techniques pitot probes and heat flux sensors, also Langmuir probes, solid electrolyte sensors, and mass spectrometry, were used to characterize the flow (see [17] and references therein). Applying the theoretical approach of Fay and Riddell as well as Goulard, the enthalpy has been determined thoroughly. During the experiments with the enthalpy probe, an area around the bore holes has been observed where the probe head oxidized differently from the rest of the probe [13]. This area agreed very well with the calculated effective area and corresponded furthermore to the measurement data [10]. It is hence believed that this area corresponds to the effective cooling area A_{eff}.

Within the present work, as mentioned previously, the probe head has been modified in order to insert a Gardon gage of a larger diameter. This results in only one ring of bore holes, while the previous design had two rings [10,13].

The new probe design has been investigated using a numerical code developed at the Institut für Raumfahrtsysteme by Grau called SINA (sequential iterative nonequilibrium algorithm) [18]. The idea is to compute a condition which is close to the current measurement condition to interpret the experimental results. Moreover, from the numerical results all flow parameters can be read out at any point

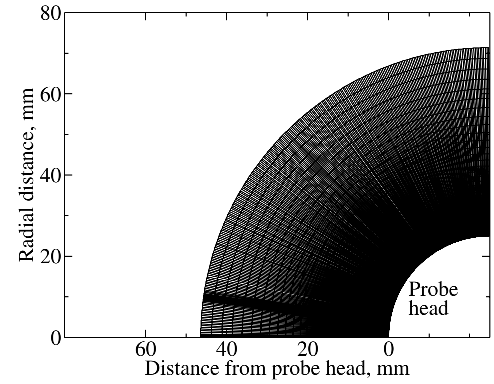

Fig. 3 Newly developed mesh for numerical calculation using SINA.

which is advantageous for investigating the effective cooling area. Because results using the mesh of Grau showed unphysical phenomena, a new mesh explicitly adapted to the spherical probe head has been generated (see Fig. 3) [19]. The enthalpy varies linearly with the effective cooling area inserted into the formulas. This can be seen when inserting Eq. (6) into Eq. (7) and solving for the freestream enthalpy h, which gives approximately

$$h \approx \frac{A_{\text{eff}}}{\dot{m}_a} \cdot 2.77(\dot{q} + \sqrt{\dot{q} \cdot \dot{q}_0}) \tag{8}$$

Extrapolating the cooling area estimated by Fasoulas to the present measurement condition leads to an effective cooling area of $A_{\text{eff}} = 3.37 \times 10^{-4}\ \text{m}^2$.

As will be shown in the section Results, this calculation corresponds well to the calculation according to Pope's formula as well as the heat-balance method when additional analytical relations from the turbulent freejet theory are used.

IV. Facility and Operating Conditions

At the Institut für Raumfahrtsysteme, a plasma wind-tunnel facility equipped with a thermal arcjet named PWK4 is in operation to simulate the chemical and thermal loads in the lower altitudes of a reentry trajectory [20]. The facility is also used for the thermal protection material qualification of ballistic capsules [21]. The plasma wind-tunnel PWK4 consists of three major parts: a vacuum vessel with a length of about 6 m and a diameter of 2 m, which is connected to a vacuum system, and a plasma generator which is integrated in the conical part of a movable front lid. The entire plasma flow can be investigated with optical methods using windows on both sides of the vacuum chamber. The vacuum system is a roots-type pump system with four stages. In the vessel, the ambient pressure can be set between 50 Pa and 1000 hPa. Figure 4 shows a sectional view of the generator. In principle, an arcjet plasma torch is operated with a central cathode and an annular anode. The propellant is injected into the ring-shaped gap between the two electrodes. A converging–diverging nozzle transfers the flow continuously to supersonic speed. Electric power is transferred to the propellant by means of Ohmic heating within the electric arc between the anode and cathode. The thermal arcjet of type RB3 used in the present investigation has been optimized for Earth reentry simulation, which means the combustion chamber serves as an anode and the oxygen part of the air flow is injected directly before the nozzle (see Fig. 4) [20]. Mainly the nitrogen part that flows alongside the cathode is heated by the electric arc, but the oxygen injection has been designed close to the nozzle throat for good mixing purposes.

For the present investigation the facility has been operated at a constant power level of 56.4 kW and at a constant total mass flow of $\dot{m} = 6.52\ \text{g/s}$. The mass flow is adjusted using two flow meters, one for oxygen and one for nitrogen, with an accuracy of 0.5%. The power is controlled by the arc current with a standard deviation of less than 5%. The heat losses into the cooling water are estimated using a water flow meter with an accuracy of $<5\%$ and two resistance

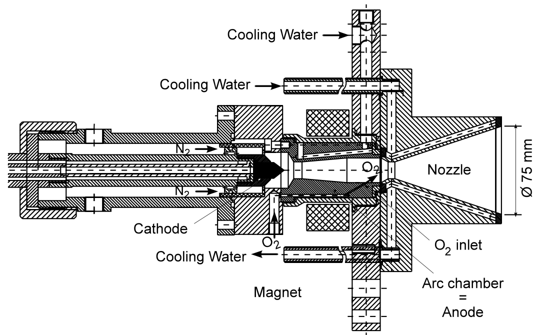

Fig. 4 Plasma wind-tunnel PWK4.

thermometers of type PT100 to measure the temperature at the inlet and outlet of the generator water cooling circuit. The accuracy of PT100 is given as $\Delta T = (0.3 + 0.005 \cdot T)$ in Kelvin. The generator settings are held constant throughout the experiments. The values are as follows: $I/\mathrm{A} = 600$, $p_a/\mathrm{Pa} = 60$, $U/\mathrm{V} = 94$, $\dot{m}_{\mathrm{N}_2}/\mathrm{g/s} = 5$, $\dot{m}_{\mathrm{O}_2}/\mathrm{g/s} = 1.52$, $P_{\mathrm{el}}/\mathrm{kW} = 56.4$, $Ma = 4$, and $p_{\mathrm{tot}}/\mathrm{Pa} = 1250$. The experiments are performed at an axial distance to the generator's nozzle exit of 90 mm. The local Mach number has been estimated from local total pressure measurements. Together with the simultaneously measured ambient pressure, the Mach number can be estimated applying the Rayleigh supersonic pitot relation [22].

A first, well-known method to estimate the enthalpy of the plasma flow is the so-called heat-balance method [8]. The electric input power minus the measured cooling losses per mass flow gives an effective value of the enthalpy at the nozzle exit. However, this enthalpy value means the overall enthalpy in the plasma flow at the nozzle exit, which we call effective enthalpy, that is,

$$h_{\mathrm{eff}} = \frac{P_{\mathrm{el}} - Q_{\mathrm{cw}}}{\dot{m}_{\mathrm{tot}}} \tag{9}$$

For the measurement condition described previously and the accuracy for the measurement equipment described above, the effective enthalpy leads to $h_{\mathrm{eff}} = 6.2 \pm 1.1$ MJ/kg. The measurement accuracy strongly depends on the temperature measurement of the cooling water, while the gas flow measurement error is almost negligible.

The effective enthalpy value related to the local plasma flow diameter should be measurable alongside the axial plasma flow axis as long as no radial gas inflow occurs [23]. An indicator for this behavior can be seen from radial total pressure and heat flux profiles. Figure 5 shows these measurements at 90 mm downstream from the generator exit, the distance chosen for the experimental investigation of the present work. In a turbulent freejet, a boundary layer between the flow and the resting air in the vacuum chamber builds up. With increasing distance, this layer increases and measurable pressure and heat flux gradients occur at the edges of the radial profile. As can bee seen from Fig. 5, the expected decrease at the radial edges of the freestream are measured and no interaction with the outer region can be identified, that is, the profiles tend continuously toward the ambient values. This strongly indicates that the theory of turbulent freejet is applicable and radial inflow does not have to be taken into account [23].

Evidently, the enthalpy value calculated this way gives no information about the radial distribution. Especially in thermal arcjet generators, the assumption of a settling chamber enthalpy often called h_0 is not allowed. Thus, the nozzle flow calculation often performed in constricted arcjet generators cannot be applied to the particular type of generator used for the present investigation [1,20].

V. Results

Figure 6 shows the result of an experiment at the conditions described in Sec. , together with the theoretical quadratic dependency according to Eq. (7). As can be seen, the measurements follow the theoretically expected characteristic up to a certain mass addition

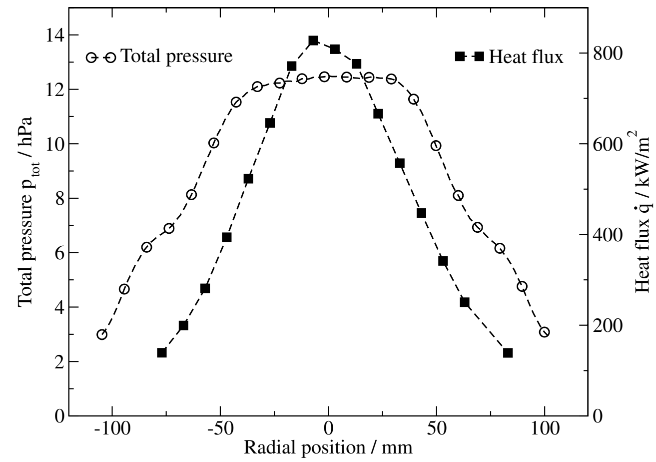

Fig. 5 Radial profiles of total pressure and heat flux on oxidized copper.

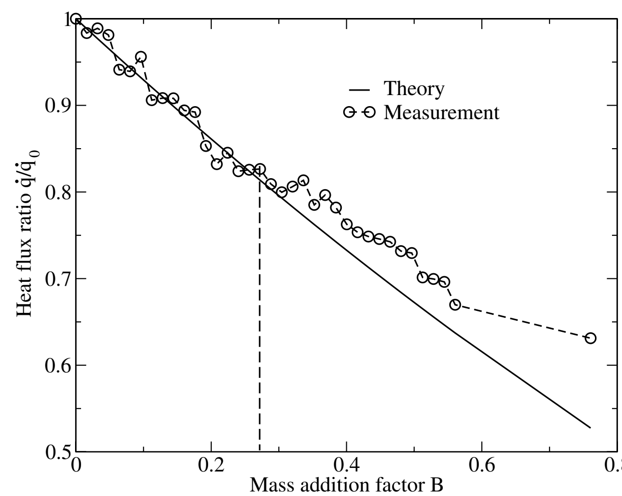

Fig. 6 Experimentally measured heat flux ratio and theoretically expected dependency.

factor. Figure 7 shows the same range of mass addition factors together with a flow visualization of the region right in front of the bore holes. As can be seen, at the same mass addition factor of $B = 0.28$ the values obtained from the experiment and the calculated values start to deviate from the quadratic curve. Furthermore, from the flow visualization a vortex forms in front of the stagnation point, beginning at this mass addition factor. Park shows similar results [24]. The measurements performed by Yakushin et al. were conducted with a flat-faced probe head [25]. Although their measured heat flux reduction follows the theory, this probe design violates the theoretical assumption for self-similarity of the boundary layer which is given for a spherical probe head.

From this investigation, it can be concluded that the measurements always have to be performed at very low mass addition gas flows to avoid vortex building and hence to follow the theoretical approach.

Using the measured data (Fig. 6) to deduce the local mass-specific enthalpy leads to a measured centerline value of $h = 15 \pm 2$ MJ/kg. Figure 8 shows the results of all different possibilities to estimate the local mass-specific enthalpy applied within this paper. It can be seen that the enthalpy probe measurement and the application of Eq. (1) are in good agreement. The error bars indicate the accuracy of Pope's formula.

However, the centerline value is roughly a factor of 2 higher than the effective enthalpy value calculated using the energy-balancing method. To relate the two quantities, effective enthalpy and local radial enthalpy profile, the following analytical approach is proposed. The radial profile of total pressure and heat flux can be

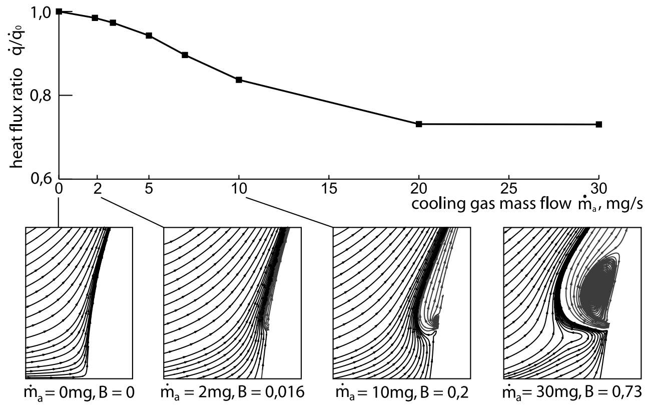

Fig. 7 Numerically calculated heat flux ratio for different cooling gas flows and flow visualization in front of the bore holes.

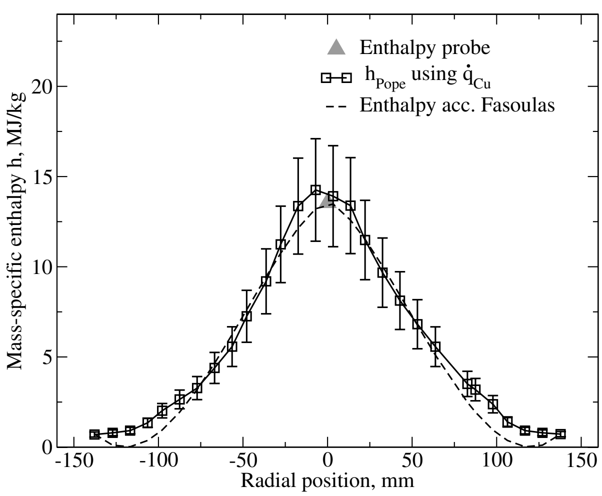

Fig. 8 Comparison of the radial enthalpy profile using Pope's formula with two different heat flux measurements and local enthalpy probe measurements together with the turbulent freejet theory.

calculated using the above-mentioned turbulent freejet theory. Abramovich [23] proposes universal equations for the velocity

$$v(r) = v_a\left[1 - \left(\frac{r}{R_s}\right)^{3/2}\right]^2 \tag{10}$$

where the index a indicates the maximum value on the centerline. The temperature profile under the assumption of chemical and thermal equilibrium is defined as

$$\frac{T^*(r) - T^*_\infty}{T^*_a - T^*_\infty} = 1 - \left(\frac{r}{R_s}\right)^{3/2} \quad \text{with} \quad T^* = T + \frac{v^2}{2 \cdot c_p} \tag{11}$$

Here, T^* denotes the stagnation temperature. Fasoulas enlarged these formulas by a universal equation of the mass-specific enthalpy of the form

$$h(r) = h_a\left[1 - \left(\frac{r}{R_s}\right)^{3/2}\right]^3 \tag{12}$$

where h_a again denotes the local centerline mass-specific enthalpy [26]. As can be seen in Fig. 8 using the measured centerline enthalpy and this equation leads to good agreement of the measured radial enthalpy profiles estimated from the total pressure and heat flux profiles together with Eq. (1).

Assuming chemical and thermal equilibrium and with the help of the ideal gas law, the effective enthalpy can be calculated using the turbulent freejet theory [23]. As defined above, the effective enthalpy is the mean value related to the local flow diameter R_s and the local mass flow $\dot{m}$. Taking Eqs. (11) and (12) and relating the integrated enthalpy to the local flow diameter leads to

$$h_{\mathrm{eff}} = \frac{2\pi}{\dot{m}} h_a v_a \frac{p}{R} \int_0^{R_s} \left[1 - \left(\frac{r}{R_s}\right)^{3/2}\right]^5 \cdot T(r)^{-1} r \, \mathrm{d}r \tag{13}$$

Equation (13) is valid at any distance from the generator exit and under the assumption of chemical and thermal equilibrium as well as under the assumption that no radial gas inflow occurs. Assuming a mean temperature of $T = 1500$ K and a velocity of $v_a = 4000$ m/s, values which have been taken from the numerical calculation, and with the locally measured enthalpy value using the mass-injection probe, the effective enthalpy becomes $h_{\mathrm{eff}} = 7.26$ MJ/kg. This value lies slightly above the effective enthalpy calculated—though still within the measurement error—at the generator nozzle exit ($h_{\mathrm{eff}} = 6.2$ MJ/kg), but it shows that a local centerline enthalpy of $h = 15$ MJ/kg is reasonable.

VI. Conclusions

Within this paper, results of a new enthalpy probe applied to supersonic air plasma flows are described. The probe behavior has been investigated theoretically using numerical calculation methods. Moreover, the flow has been investigated using local heat flux and total pressure measurements to apply the well-known enthalpy estimation approach of Pope as well as the heat-balance method has been applied.

The results obtained with the new probe agree well with the theoretical approach and the numerical results. As a major conclusion, the gas injection into the boundary layer has to be very small to keep the perturbations of the flow small, which has been underlined by the numerical calculations.

Finally, all measured enthalpy values have been compared and using the analytical theory of turbulent freejets, even the heat-balance method shows fairly good agreement to the local measurements.

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