JOURNAL OF THERMOPHYSICS AND HEAT TRANSFER
Vol. 23, No. 2, April–June 2009

Technical Notes

TECHNICAL NOTES are short manuscripts describing new developments or important results of a preliminary nature. These Notes should not exceed 2500 words (where a figure or table counts as 200 words). Following informal review by the Editors, they may be published within a few months of the date of receipt. Style requirements are the same as for regular contributions (see inside back cover).

Heat Flux Measurement in the Two-Stage Hybrid Electric Thruster TIHTUS

Hannah Böhrk,* Tim Rödiger,† and Monika Auweter-Kurtz‡
Universität Stuttgart, 70569 Stuttgart, Germany

DOI: 10.2514/1.39963

Nomenclature

A	=	area
cal	=	calorimeter
D	=	diameter
dc	=	direct current (first stage)
eff	=	effective
f	=	frequency
fc	=	fully catalytic
h	=	enthalpy
K	=	coefficient
l	=	film length
M_s	=	shock Mach number
$\dot{m}$	=	mass flow rate
P	=	power
p	=	pressure
pl	=	plasma
$\dot{q}$	=	heat flux density
R	=	radius
RF	=	radio frequency (second stage)
S	=	probe
tot	=	total
U	=	voltage
α_c	=	tilt angle of crystal
ΔS	=	difference of Seebeck coefficients
ΔT	=	temperature difference
δ_F	=	film thickness
∞	=	ambient

I. Introduction

A NOVEL two-stage electric thruster TIHTUS is currently under development. The first stage is an arcjet, and the second stage inductively heats the arcjet plume. Because of the unknown power losses to the facility components in the inductively heated stage, a calorimeter is used to determine plasma power and plasma enthalpy.

Moreover, the performance of a new heat flux gauge, an atomic layer thermopile (ALTP), is investigated. The sensor works on the principle of the transverse Seebeck effect and has a fast time response. For the first time, the sensor was exposed to the high-enthalpy partially or fully ionized plasma, measuring the radial distribution of heat flux to the silica sensor surface across the plume.

The present Note is to provide a demonstration of the new ALTP in this harsh regime and to further characterize the two-stage hybrid electric thruster.

II. Plasma Source

The two-stage plasma has been investigated with plasma diagnostics. The present Note presents data of heat flux measurement. The thruster was also investigated by a calorimeter [1] and a gas-dynamic pitot probe [2] to evaluate the thruster's output kinetic energy. The two-stage plasma thruster TIHTUS consists of an arcjet thruster (first stage) and an inductively heating afterburner (second stage) and is described in detail in [2,3].

The first stage is formed by the arcjet thruster HIPARC-W [4]. It has a power draw of up to 100 kW and a converging–diverging nozzle with a throat diameter of 6 mm and an exit diameter of 65 mm. The second stage consists of a cylindrical 270-mm-long discharge tube and a coil of a diameter of 100 mm spun around it as part of a resonance circuit operated at a frequency of $f = 840$ kHz. In induction heating, the power is coupled into the plasma at a near-coil position due to the skin effect [5]. However, for the performance testing of the ALTP, only the first stage is operated.

Central gas flow through the first stage (arc heated or cold) is expanded first into the injection head of the inductive second stage, in which a swirl gas flow can be admixed, and then into the stage's discharge tube, in which it can be further heated. Each operational condition is therefore referred to as $T\ P_{\mathrm{dc}}|P_{\mathrm{RF}} - \dot{m}_{\mathrm{dc}}|\dot{m}_{\mathrm{RF}}$ throughout this Note. As an example, T 20|30–300|0 refers to the operating condition in which 20 kW are coupled into the first stage, 30 kW are coupled into the second stage, a gas flow rate of 300 mg/s is supplied through the arcjet stage, and none is supplied to the second stage.

For a constant sum of powers of 50 kW at a constant mass flow of 300 mg/s, the thruster provides a thrust of up to 2 N at thrust efficiencies between 9 and 14% [3]. Furthermore, a plasma power of up to 25 kW is coupled to the plume with the two-stage thruster [1]. It is continuously operated at an ambient pressure of $p_\infty \approx 35$ Pa. The maximum total pressure is located offaxis with 0.85 ± 0.079 hPa for the operating point of T 20|30–300|0 [2,3]. For the same operating condition, a velocity measured with electric time-of-flight probes of 7389 ± 465 m/s and a temperature of 8689 ± 1308 K derived from the latter measurements are reached in the plume axis [2].

III. Instrumentation

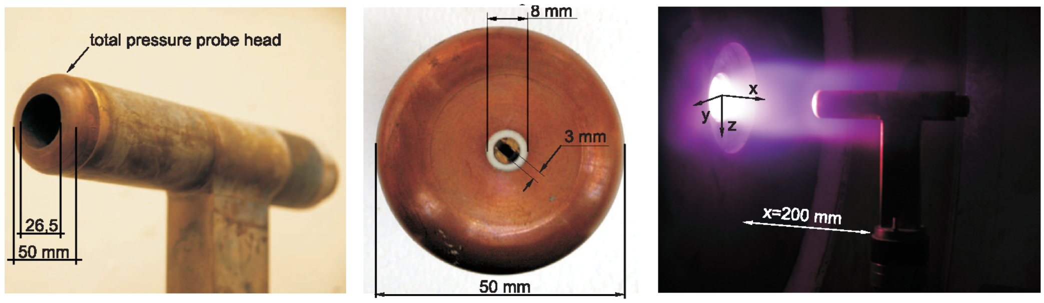
Radial profiles of heat flux density $\dot{q}$ are measured by means of an ALTP mounted on the front surface of a water-cooled blunt-body probe of European standard geometry [flat nose, 50 mm body diameter, rounded edge (see Fig. 1)]. The working principle of the ALTP is based on a thermoelectric field that is created by a temperature gradient inside of an yttrium–barium–copper–oxide

Received 23 July 2008; revision received 29 January 2009; accepted for publication 1 February 2009.

*Research Engineer, Institute of Space Systems (IRS); currently DLR, German Aerospace Center, Institute of Structures and Design, Stuttgart, Germany; hannah.boehrk@dlr.de.

†Research Engineer, Institute of Aerodynamics and Gasdynamics (IAG), Pfaffenwaldring 21.

‡Professor, Institute of Space Systems (IRS); currently President, Universität Hamburg. Fellow AIAA.



a) b) c)

Fig. 1 Instrumentation: a) probe with total pressure probe head, b) heat flux probe head, and c) plasma flow with probe.

($YBa_2Cu_3O_{3\text{-}d} = YBCO$) crystal. This effect was observed by Lengfellner et al. [6] for YBCO crystals in 1992. It is based on the principle of the transverse Seebeck effect, caused by the anisotropy of the YBCO film in combination with the tilt angle α_c of the crystal with respect to the film surface normal. A thermoelectric field, directly proportional to the temperature gradient in the film, is induced in the direction of the film layer. The resulting thermoelectric voltage U produced by a temperature difference over the YBCO film due to the absorption of radiation or convective heat transfer is given by

$$U = \frac{l}{\delta_F} \Delta S \Delta T \frac{\sin 2\alpha_c}{2} \tag{1}$$

where l is the length of the film (normal to the layer orientation), δ_F is the film thickness, ΔT is the temperature difference across the film, and ΔS is the difference in the thermo power values of the untilted crystal. A detailed derivation of Eq. (1) is given by Roediger et al. [7].

The small film thicknesses of the ALTP on the order of 500–700 nm allow for highly-time-resolved heat flux measurements up to the 1 MHz range. The dynamic properties of the gauge are studied by means of exposure to modulated laser radiation (sine [7] and square wave [8] tests), response to a passing shock wave ($M_s = 3.28$, driver gas is helium, and driven gas is nitrogen), and theoretical estimations [8] confirming the dynamic range and allowing quantitative amplitude frequency-response correction. The gauges are calibrated by exposure to laser light radiation and had a typical sensitivity between 50 and 200 $\mu V/(W/cm^2)$. Laser calibration experiments with a pulsed/continuous CO_2 laser operating at a wavelength of 10.6 μm show a linear characteristic of the sensor over more than 11 orders of magnitude. Heat flux rates of a few W/cm^2 up to 2×10^3 W/cm^2 are detectable with the ALTP, which has a damage threshold for a 1 ms pulse. The total uncertainty of the static calibration procedure is estimated as 5.5% [7]. In the present experiments, an ALTP gauge with an active area of 3×3 mm^2 and protective coating is used. A protective coating consisting of SiO/SiO_2 is developed to stabilize the sensitivity of the YBCO film. The sensitivity of ALTP sensors without coating decreases with time, due to the hygroscopic character of the YBCO films. However, the temporal resolution of the sensor with coating is reduced to a certain degree (200–250 kHz) [8].

The heat flux is assumed to be uniform in the stagnation-point region of the blunt-body probe, in which the ALTP sensor is placed. Previous investigations with similar probes in hypersonic flows show the validity of such an approximation (see Roediger et al. [9] and references therein).

The ALTP captures convective heat and incident radiation over a very large wavelength range from far infrared to ultraviolet. Because a rarefied high-velocity flowing plasma is investigated, the major part of the heat flux is due to convection. However, the radiative contribution represents a possible source of error, and a discussion of the optical properties of the ALTP can be found in [8] (and references therein).

A separation of signal contributions caused by convection and absorbed radiation is only possible by knowledge of the prevailing emission conditions in the surrounding gas flow. Therefore, simultaneous spectroscopic measurements could help to identify the radiative component and could be the subject of future work.

To determine local enthalpy, the local heat flux data $\dot{q}$ are combined with the local pitot, or total, pressure measurements [2,3]. The total pressure and heat flux probe heads can be exchanged with each other. The pressure inlet diameter of the pitot tube is 26.5 mm. The probes are mounted in a 310-mm-long probe holder with an outer diameter of $D_S = 2R_S = 50$ mm. The resulting stagnation flow in front of the heat flux and pitot probes are consequently identical. The probes are depicted in Fig. 1.

Total pressure measurements are performed at steady state at each radial measurement position. For the heat flux measurement, however, the probe was radially traversed across the plasma plume at constant speeds between 16 and 330 m/s at an axial distance of $x = 200$ mm from the thruster exit. Because a rarefied high-velocity flowing plasma is investigated, the major part of the heat flux is due to convection. Therefore, it is assumed that the maxima of total pressure and heat flux are located at the same radial position. The traversing velocity can thus be determined by comparison of the heat flux with the total pressure profile.

A cavity calorimeter [1,10] is used to measure plasma power P_{pl}. With an error of approximately 9% [1], plasma enthalpy is thus derived as

$$h_{pl,cal} = \frac{P_{pl}}{\dot{m}} \tag{2}$$

IV. Results with Hydrogen

From total pressure and heat flux measurement, the local mass-specific enthalpy is determined according to an empirical formula by Marvin and Pope [11] (also see Löhle et al. [12]). 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 as in

$$h_{tot}(r) = \frac{\dot{q}_{fc}(r)}{K_{Pope}\sqrt{p_{tot}(r)/R_{eff}}} \tag{3}$$

with the effective probe radius $R_{eff} = 2.3 \times R_S$ [13].

According to Marvin and Pope [11] and their consideration of the boundary-layer equations, it is possible to determine local specific enthalpy from heat flux and total pressure. Their assumptions, however, include a frozen boundary layer and a fully catalytic wall. For hydrogen, it is unknown how the fully catalytic heat flux $\dot{q}_{fc}$ is related to the measured heat flux to the silica sensor. The species-dependent Pope coefficient K_{Pope} of hydrogen is determined from Marvin and Pope as

$$K_{Pope,H_2} = 0,10226\ kW \cdot kg(MJ \cdot m)^{-1}(m \cdot Pa)^{-1/2} \tag{4}$$

The radial measurement data at axial distance $x = 200$ mm of operating condition $T\ 20|0\text{–}300|0$ are displayed in Fig. 2. Because of higher-power coupling in condition $T\ 25|0\text{–}200|100$, both heat flux

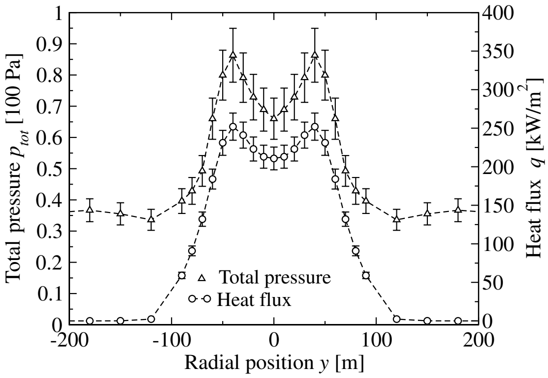


Fig. 2 Heat flux and total pressure at T 20|0–300|0.

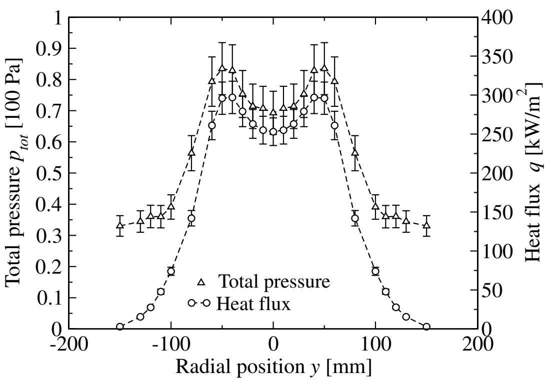


Fig. 3 Heat flux and total pressure at T 25|0–200|100.

and total pressure are higher than in the former operating condition (see Fig. 3). The error of the heat flux measurement was noted previously as 5.5%, and the total pressure underlies a measurement error of 10%. Thus, a reproduced uncertainty yields 10.5% in the method according to Marvin and Pope [11]. Additionally, they give an error of their semi-empirical method to up to 30–40%.

The value of the plasma enthalpy, derived from calorimetric measurements with the cavity calorimeter and according to Eq. (2), is determined for the considered operating condition T 20|0–300|0 to 36.67 MJ/kg. The value corresponding to the result of Eq. (3) and integrated according to

$$h_{\mathrm{pl}} = \int_A h \mathrm{d}A = \frac{1}{A}\sum_i h_i A_i \tag{5}$$

yields 31.44 MJ/kg and differs by about 14% from the calorimetrically determined enthalpy at the plasma source exit.

It must be kept in mind that due to the uncertainty in the traversing system, the heat flux profile was assumed to have its maxima concurring with total pressure maxima. Although this seems to be a valid assumption, especially because the plasma is flowing at high velocity (greater than 6000 m/s [2]), Eq. (5) is sensitive to an uncertainty of the plume cross section A.

At the operating condition of T 25|0–200|100, the calorimetric measurement yields 36.5 MJ/kg, and the integral of the local measurement results in 30.0 MJ/kg. The values differ by about 18% from each other. The values are recalled in Table 1. The table shows that in both cases, the results obtained after integration of the local specific enthalpy derived according to Marvin and Pope [11] indicate lower enthalpy than the calorimetrically measured results. This deviation can be explained by the unknown relation of the fully catalytic heat flux to the heat flux onto the lowly catalytic active silica-coated surface of the ALTP.

Table 1 Comparison of enthalpy values

	$h_{\mathrm{pl,cal}}$, MJ/kg	$h_{\mathrm{pl,Pope}}$, MJ/kg	Deviation, %
T 20|0–300|0	36.7	31.4	14.4
T 25|0–200|100	36.5	30.0	17.8

The hydrogen atoms do not fully recombine at the silica surface, as assumed in the theory of Marvin and Pope [11]. For air and copper sensors, this relation is known as $\dot{q}_{\mathrm{fc}} = 1.2\dot{q}_{\mathrm{Cu}}$ [13]. In the present case of hydrogen and the silica-coated ALTP, no values are accessible for the behavior relation of the fully catalytic and the lowly catalytic surface. From the few results of the present investigation, taking into account the uncertainties in total pressure, heat flux, the calorimeter measurement, and a conservative 40% that Marvin and Pope [11] give for their empiric formulation, the ratio is determined in a first approach to

$$\dot{q}_{\mathrm{fc}} = (1.16 \pm 0.7)\dot{q}_{\mathrm{SiO/SiO_2}} \tag{6}$$

For accurate enthalpy measurement, however, reliable data of reaction coefficients and energy accommodation coefficients are necessary.

V. Conclusions

The investigation in the present Note addresses the use of a newly developed atomic layer thermopile in the high-enthalpy environment of an electric arcjet thruster plume. It is shown that long-term measurements in the range of a few seconds could be taken, providing a radial heat flux distribution in the plume to the silica surface of the sensor.

To verify the measurement, data were combined with pitot pressure data so that the locally resolved enthalpy could be derived. The enthalpy integrated across the plume cross section was then compared with calorimetrically measured plasma enthalpy. The results are good, with a deviation of less than 18%. The deviation is a result of, among other factors, missing data for the lowly catalytic sensor surface behavior in hydrogen.

A damage threshold of 20 MW/m^2 for a 1 ms pulse is assumed to be the maximum heat flux supported by the gauge. For the use in continuously operated plasmas, further testing is foreseen in the two-stage hybrid thruster at higher plume enthalpy.

References

[1] Böhrk, H., and Auweter-Kurtz, M., "Efficiency Analysis of a Two-Stage Hybrid Electric Thruster," *Journal of Thermophysics and Heat Transfer*, Vol. 22, No. 2, 2008, pp. 309–312.
doi:10.2514/1.34283

[2] Böhrk, H., and Auweter-Kurtz, M., "Velocity and Total Pressure Measurement in the Two-Stage Hybrid Thruster TIHTUS," *EUCASS Advances in Aerospace Sciences*, Vol. 1, edited by L. deLuca, C. Bonnal, O. Haidn, and S. M. Frolov, 2009, pp. 381–398.

[3] Böhrk, H., and Auweter-Kurtz, M., "Thrust Measurement of the Hybrid Electric Thruster TIHTUS by a Baffle Plate,"*Journal of Propulsion and Power* (to be published); also AIAA Paper 2007-5297, 2007.

[4] Auweter-Kurtz, M., Gölz, T., Habiger, H., Hammer, F., Kurtz, H., Riehle, M., and Sleziona, C., "High-Power Hydrogen Arcjet Thrusters," *Journal of Propulsion and Power*, Vol. 14, No. 5, Sept.–Oct. 1998, pp. 764–773.
doi:10.2514/2.5339

[5] Eckert, H. U., "The Induction Arc: A State-of-the-Art Review," *High Temperature Science*, Vol. 6, 1974, pp. 99–134.

[6] Lengfellner, H., Kremb, G., Schnellbögl, A., Betz, J., Renk, K. F., and Prettl, W., "Giant Voltages Upon Surface Heating in Normal YBCO Films Suggesting an Atomic Layer Thermopile," *Applied Physics Letters*, Vol. 60, No. 4, 1992, pp. 501–550.
doi:10.1063/1.106613

[7] Roediger, T., Jenkins, S., Knauss, H., v. Wolfersdorf, J., Gaisbauer, U., and Kraemer, E., "Time-Resolved Heat Transfer Measurements on the Tip Wall of a Ribbed Channel Using a Novel Heat Flux Sensor Part 1: Sensor and Benchmarks," *Journal of Turbomachinery*, Vol. 130, No. 1, 2008, Paper 011018.
doi:10.1115/1.2751141

[8] Knauss, H., Roediger, T., Smorodsky, B. V., Scrulijes, J., Bountin, D. A., Gaisbauer, U., Kraemer, E., Maslov, A. A., and Seiler, F., "A Novel Sensor for Fast Heat Flux Measurements," *Journal of*

Spacecraft and Rockets (to be published); also AIAA Paper 2006-3637, 2006.

[9] Roediger, T., Knauss, H., Wagner, S., Kraemer, E., Bountin, D. A., Smorodsky, B. V., Chirashenko, V. F., Zvegintsev, V. I., and Maslov, A. A., "The Atomic Layer Thermopile—A Fast Heat Flux Sensor for Measuring High Heat Loads in Short Duration Hypersonic Ground Testing Facilities," *ICMAR 2008*, 2007.

[10] Herdrich, G., "Aufbau, Qualifikation und Charakterisierung Einer Induktiv Beheizten Plasmawindkanalanlage zur Simulation atmosphärischer Eintrittsmanöver," Ph.D. Thesis, Univ. Stuttgart, Stuttgart, Germany, 2004 (in German).

[11] Marvin, J. G., and Pope, R. B., "Laminar Convective Heating and Ablation in the Mars Atmosphere," *AIAA Journal*, Vol. 5, No. 2, 1967, pp. 240–248.
doi:10.2514/3.3948

[12] Löhle, S., Auweter-Kurtz, M., and Eberhart, M., "Local Enthalpy Measurements in a Supersonic Arcjet Facility,"*Journal of Thermophysics and Heat Transfer*, Vol. 21, No. 4, 2007, pp. 790–795.
doi:10.2514/1.30543

[13] Löhle, S., "Untersuchung von Wiedereintrittsplasmen mit Hilfe Laserinduzierter Fluoreszenzmessungen," Ph.D. Thesis, Univ. Stuttgart, Stuttgart, Germany, 2006 (in German).