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Engineering Notes

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Numerical Correlations Between Flight and Plasma Wind-Tunnel Tests

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Nomenclature

H_0 = reservoir enthalpy, MJ/kg
L_{ref} = reference length
N = atomic nitrogen concentration
O = atomic oxygen concentration
P = static pressure, bar
P_0 = reservoir pressure, bar
Re = Reynolds number
T = static temperature, K
Z = altitude, km

Introduction

IT is well known that in the hypersonic regime a complete ground-facility simulation of the flowfield is not possible, mainly because of the nonequilibrium phenomena related to the dissociation due to the very high temperatures. It is not possible, for example, to simulate Mach and Reynolds numbers and wall heat fluxes at the same time. Nonequilibrium phenomena require a full-scale simulation because the reference length plays an important role in such flows, rendering the investigation unscalable. However, in general, such a simulation is not possible because of the excessive cost of the very high levels of energy required. For these reasons only a part of the entire geometry (nose or leading edge, for example) is usually tested in such facilities; the testing of the whole configuration is not possible.

To obtain the required high values of total enthalpy, the gas is heated in the reservoir (with an arc heater, for example), and then it is accelerated in a convergent–divergent nozzle; the flow, initially in chemical equilibrium at high temperature, tends to recombine during the expansion, up to Mach 3–4, when freezing occurs. The result is that the flow reaches the test chamber in dissociated nonequilibrium conditions, leading to a significant difference of the flowfield over the model with respect to flight conditions, especially in terms of energy distribution and species concentrations.

The arc-heated wind tunnels are more promising for the study of the thermal protection system (TPS) of a hypersonic vehicle; such facilities are generally used to duplicate only heat and pressure loads and not for aerodynamic simulations. It is necessary to know a priori how the tunnel regulation parameters have to be set to duplicate the desired effect in the facility; this step can be performed using computational fluid dynamics (CFD) complex tools.

In the present Note, the numerical tests have been performed inside the plasma wind tunnel (PWT) Scirocco, currently under construction at the Italian Aerospace Research Center (CIRA). This facility is designed essentially for testing the TPS of a re-entering space vehicle. Attention is focused on the problem of the reproduction of the heat flux on the surface of the body. A number of calculations have been made to cover the operating envelope of Scirocco.

Computational Tool

The code used for this study is a two-dimensional axisymmetric Navier–Stokes flow solver, able to solve both external and internal flows in chemical and vibrational nonequilibrium. The solver is based on a flux-difference-splitting upwind formulation[1] with a second-order essentially-not-oscillatory scheme approximation and has been widely tested by using several numerical and experimental data in a number of workshops.[2–5] The discretization is based on a standard finite volume approach using a multiblock structured grid. The integration scheme is a forward Euler scheme with a semi-implicit treatment of source chemical terms.

From the modelization point of view, several chemical models are available, all taking into account the species O, N, NO, O_2, and N_2. The influence of the chemical model has been stressed in Refs. 2 and 6. The vibrational nonequilibrium is modeled through the Landau–Teller rule using the Millikan–White coefficients. Also, different transport models have been implemented.[7] In Ref. 6 the importance of accurately modeling these terms has been discussed in nozzle and flight cases.

Scirocco PWT

The need of developing a TPS system came first from the Hermes spaceplane program and then from the Manned Space Transportation Program; therefore, the European Space Agency entrusted CIRA with designing, building, maintaining, and operating a 70-MW arc-heated hypersonic facility designated the PWT Scirocco.[8,9] The performance characteristics of the PWT are described in terms of 1) the operating envelope, which establishes the stagnation enthalpy (5–40 MJ/kg) and reservoir pressure level (1–17 bars) for plasma flow; and 2) the capability of the nozzles to reproduce the required stagnation and boundary layer flows. The circular nozzle is designed to have a divergent part 5.317 m long, a throat diameter of 75 mm, and an exit diameter of 1.967 m. After these preliminary computations, the operating envelope was slightly extended ($3 < H_0 < 45$).

PWT Analysis

The PWT calculations have been performed assuming chemical equilibrium until the throat, whereas in the divergent section nonequilibrium conditions are used. The model considered in the test chamber is a biconic capsule of the kind under study at the European Space Agency and has a length of 0.6 m. The input conditions for the test chamber are the ones on the symmetry axis of the nozzle at the exit section.

To make a parametric study of its characteristics, a matrix of points in the space of reservoir pressure and enthalpy has been calculated, extending over the operating envelope of Scirocco. The calculations have been performed also out of the defined operating

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envelope, in order to show possible extensions of the use of the facility.

In Table 1, a number of values of interest are reported for all of the computed cases. The Reynolds numbers are generally very small, and this causes some difficulties in solving for the flowfield in the test chamber. Also, the pressures and the densities are very low; this fact must be taken into account because the system may be in the rarefaction regime and therefore near the limit of validity of the Navier–Stokes equations. With regard to the concentrations, the oxygen is completely dissociated in all the 20-MJ cases, whereas diatomic nitrogen is present even at higher enthalpies. Furthermore, the temperature reaches a maximum near $H_0 = 20$ MJ; the reason is that there are two opposite effects of an increase in the enthalpy: on one hand, the temperature rises in the throat, but on the other hand, the gas is more dissociated, which means that there is a stronger expansion in the divergent section. So it is reasonable to expect an inversion of the trend of exit temperature.

In all of the cases, the exit conditions from the nozzle are taken as input for a model put in the test chamber; the geometry chosen is a biconic capsule of 0.6-m length ($\frac{1}{10}$ scale).

Note that in the wind-tunnel conditions, especially for low-pressure tests, the bow shock gets far from the body as the test Mach number increases, with the total enthalpy increasing. This effect is due to the strong dissociation obtained in the test chamber in these conditions; in fact, at low pressure and high enthalpy, to distinguish the bow shock region from the boundary layer is no longer possible, and the flowfield becomes a viscous shock layer. This results in a large standoff distance in the wind tunnel with respect to the flight conditions.

Table 1 Exit conditions from the nozzle on the symmetry axis

P_0	H_0	M_{fr}	Re	T, K	P, Pa	O	N
1	5	9.74	1,132	183	2.81	0.04	0
1	10	10.67	861	206	2.41	0.21	$5 \times e{-7}$
1	20	11.8	763	216	2.20	0.23	0.19
1	40	14.55	1,074	150	1.7	0.23	0.65
5	5	9.8	4,385	197	11.9	0.02	0
5	10	10.26	2,805	261	11	0.17	0
5	20	11.04	2,034	320	10.2	0.23	0.12
5	40	13.45	2,239	241	7.1	0.23	0.53
10	5	9.69	7,871	211	23.5	0.02	0
10	10	9.75	4,505	321	24.1	0.13	0
10	20	10.26	2,984	430	22.9	0.23	0.08
10	40	12.23	2,928	350	16.2	0.23	0.46
18	5	9.53	13,226	226	44.1	0.01	0
18	10	9.3	6,870	383	47.4	0.10	0
18	20	9.52	4,257	553	47	0.23	0.051
18	40	10.97	3,976	504	37.6	0.23	0.410

Flight Cases

In flight conditions, two geometries have been considered: a full-scale model of 6-m length and a scaled-down model of 0.6-m length. A number of points of the assured crew return vehicle (ACRV) flight corridor have been computed, and the results have been compared with the ones obtained in the test chamber. The flight corridor of the ACRV was used because it is the available vehicle most similar to the considered capsule. The calculations have been made for the full-scale model and for the $\frac{1}{10}$-scale one, to emphasize the influence of the dimensions on the solution.

For the free flight conditions, the flowfield experienced by the full-scale model ($L_{ref} = 6.0$ m) is nearer to the equilibrium conditions than with the $\frac{1}{10}$-scale model. The nonequilibrium effects lead to strong differences between the two flowfields, besides the usual differentiations due to Re. These effects, which characterize and differentiate the high-enthalpy aerodynamics with respect to the classical one, call for full-scale simulation.

Comparison Between Flight and Wind-Tunnel Results

The main goal of this study was to determine which are the generating conditions that lead to the value of a certain quantity foreseen to be in flight. The comparison between flight CFD reconstruction and wind-tunnel results has been done using a parametric study of wind-tunnel capabilities. All of the presented charts report the phenomena under investigation as a parametric function of total enthalpy and total pressure (H_0, p_0). The flight results are reported by plotting in the abscissa the enthalpy value corresponding to the point of the flight corridor, so as to compare the cases with the same total enthalpy. A strong hypothesis has been made in the assumption of a fully catalytic wall—a condition that depends, as is well known, on the characteristics of the material.

In Fig. 1, the total wall heat flux as a function of total enthalpy and pressure is plotted; also, the limits of the Scirocco operating envelope are shown approximately. It appears evident that it is possible

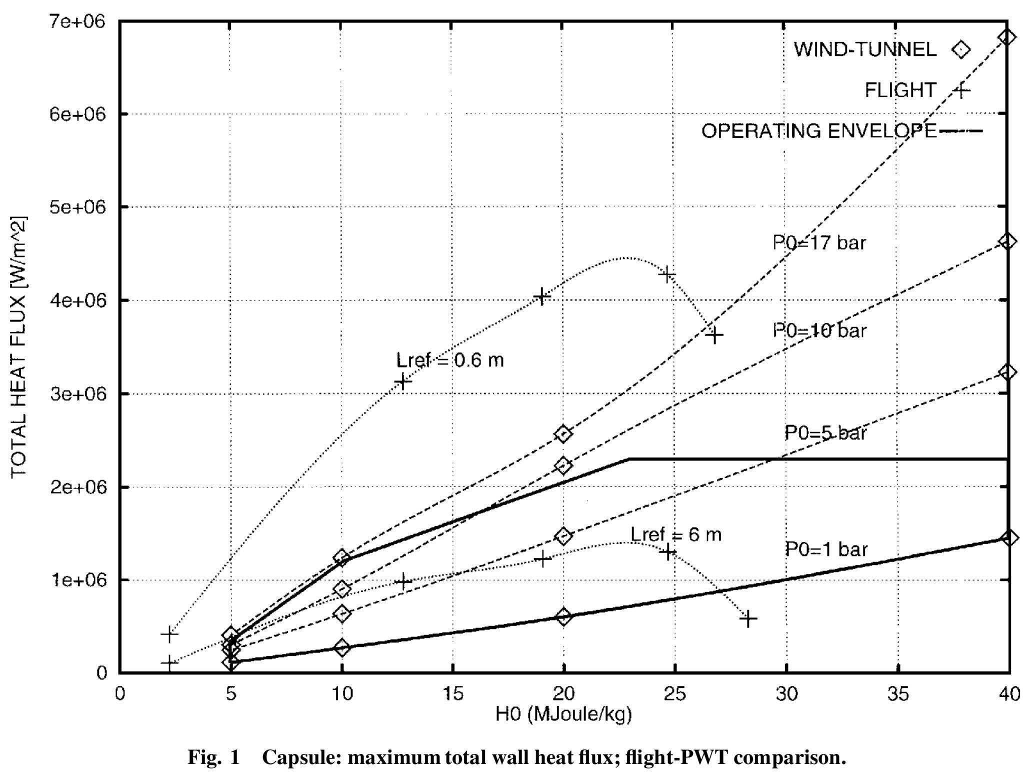

Fig. 1 Capsule: maximum total wall heat flux; flight-PWT comparison.

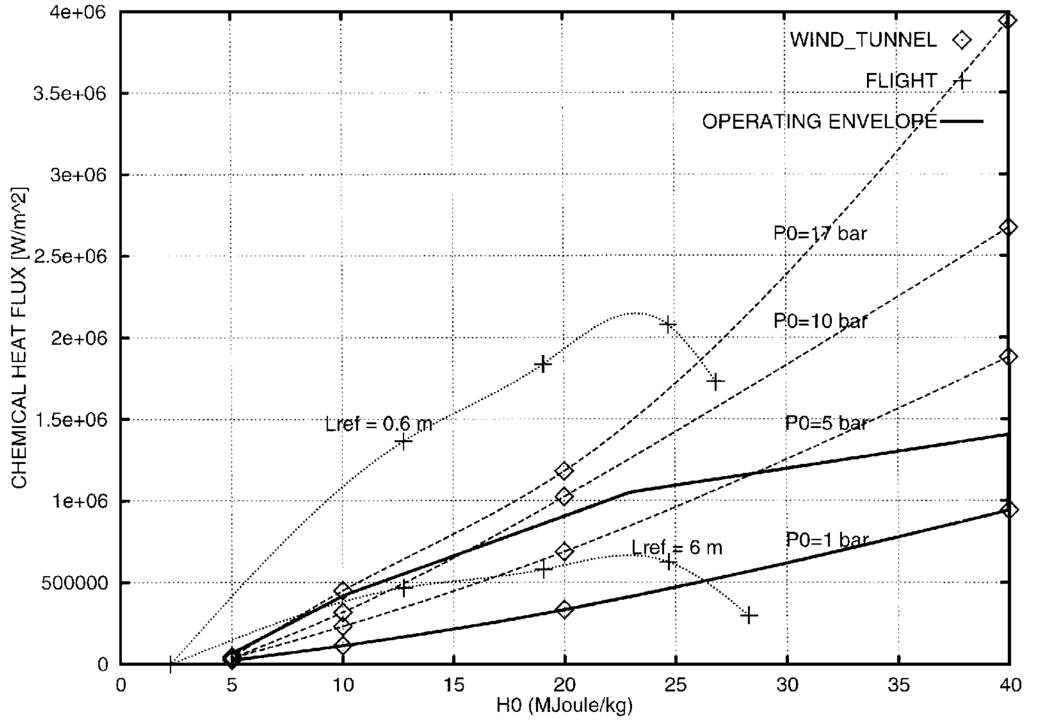

Fig. 2 Capsule: maximum chemical wall heat flux; flight-PWT comparison.

to set the facility regulation parameters (H_0, p_0) to duplicate the stagnation-pointheat flux. Moreover, as is seen in Fig. 2, the chemical component is also well reproduced, except at the low enthalpies (and therefore the low altitudes), where simulation is not possible at the same level of total enthalpy.

However, at a deeper level of analysis, it has been noted that for this kind of vehicle it is necessary to resort to a different geometry to be able to reproduce the same heat load. In previous papers we concluded that for a Hermes re-entry trajectory, Scirocco is able to simulate the total heat flux at the stagnation point only if the same dimension is used.[10,11] In other words, we concluded that the real scale must be used to duplicate the thermal load. In the Hermes conditions, even if it is not possible to duplicate the conductive and the chemical contribution, the pressure level is well reproduced. The reason is that the facility was designed for a Hermes spacecraft re-entry trajectory, but the present calculations instead use a different re-entry trajectory. For capsule re-entry, the pressure level experienced during the flight is much higher at the same freestream Mach number.

Finally, the pressure in the test chamber can be regulated through chemical effects, whereas for nonreactive nozzles the pressure is regulated only by the area ratio. In nonequilibrium nozzle flow, the chemical process changes the pressure in the test chamber. This effect, if well controlled, could be used to vary that pressure.

Conclusions

A methodology to investigate the simulation capabilities of the planned PWT Scirocco has been made. For such facilities, generally used for testing TPS materials, one needs to know a priori how to set the tunnel regulation parameters. In this Note, a CFD tool has been used to perform this step. The same methodology can be used to extend the possible utilization of actual facilities.

Based on the computations, it can be said that the full-scale simulation does not lead to correct heat loads, at least at the same level of total enthalpy. For scaled-down simulation, on the contrary, it is possible to find the desired regulation.

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