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Engineering Notes

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Improved Fay–Riddell Procedure to Compute the Stagnation Point Heat Flux

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I. Introduction

IT is well known that one of the most remarkable problems in the design of a space vehicle is the evaluation of the heat flux entering the space vehicle during the re-entry path. The knowledge of this quantity influences the correct design of the space vehicle and, more specifically, of the thermal protection system. The pioneering work of Fay and Riddell[1] is, for the soundness of the theoretical basis and the operating simplicity, a milestone in the evaluation of the heat flux at the stagnation point of spherical bodies in a nonequilibrium, dissociating gas. It is a reference point for the scientists working on aerodynamic heating. The Fay–Riddell correlation formulas, obtained by fitting a number of results of computations, are still in use today for the thermal analysis of hypersonic vehicles.

Because of the lack of computer resources at that time (1958), the scarce knowledge of kinetic parameters, like the recombination/dissociation rates and vibrational temperatures, the transport coefficients, and so on, the computing procedure proposed by Fay and Riddell suffers from inaccuracies that reduce the validity of the results and, therefore, the validity of the related correlation formulas. The aim of the present Note is to revive the Fay–Riddell procedure, getting over some of the aforementioned limitations and saving, at the same time, the simplicity of the procedure and therefore the cheapness of the required computer resources.

Currently the heat flux can be evaluated either by correlation formulas, like the ones proposed by Fay and Riddell, or by sophisticated Navier–Stokes solvers, or by formulas fitting experimental data. All of these methods suffer from shortcomings. The first one, besides being not very precise, can even provide wrong results when the independent variables are outside the correlation range. The second one requires large computing resources that may not be available. The results by the third one are strictly dependent on the test conditions and on the catalycity, i.e., the recombination efficiency, of the surface of the test model. The Fay–Riddell computing procedure with the present improvements lies between the first two mentioned methods.

The ultimate purpose of this Note is to provide the hypersonic wind-tunnel experimenter with an easily available tool, providing theoretically reliable results with which to compare the experimental data, and, moreover, to get an insight into the catalycity of the surface of the test model. The computer code developed on the present procedure is, in fact, not time consuming and can also be easily operated on personal computers.

Numerical simulations have been performed with flow total enthalpy ($h_{0\infty}$) up to about 40 MJ/kg. The gas is a mixture of nitrogen and oxygen with a composition very close to air; the mass fractions of oxygen and nitrogen are 0.20 and 0.80, respectively. The results have been obtained by considering all states of the gas (nonequilibrium, equilibrium, frozen) in the boundary layer and the extreme boundary conditions of the fully catalytic wall and the noncatalytic wall. The present procedure has been validated by the comparison of the stagnation point heat flux both with the results of a Navier–Stokes code and with experimental data.

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II. Improvements to the Fay–Riddell Procedure

The present improvements are due to the overcoming of some operating limitations and to the use of updated and more reliable thermodynamic and kinetic parameters.

1) In the present procedure, the gas is a mixture of five chemical species: O_2, N_2, NO, O, and N. The gas is handled as a binary mixture of atoms and molecule. Because the Fay–Riddell equations work on the global atom mass fraction C_A, the current mass fractions of O and N are evaluated, approximately, by scaling the value of C_A by the freestream mass fraction of oxygen and nitrogen. The current mass fractions of O_2, N_2, and NO are then evaluated by the continuity equation of each species.

2) The Fay–Riddell procedure uses constant values of both Prandtl number and Lewis number. The suggested value for the Prandtl number is 0.71, and the values for the Lewis number are 1.0, 1.4, and 2.0. In the present procedure these numbers are computed both as a function of freestream enthalpy and in the boundary layer. As the original Fay–Riddell equations were obtained by assuming these numbers constant, the present procedure suffers from the approximation of integrating the equations by considering Prandtl number and Lewis number variable in the boundary layer. The transport coefficients for each chemical species are computed, as a function of the local gas temperature, by the Chapman–Enskog[2,3] theory. The viscosity and the thermal conductivity of the mixture are evaluated,

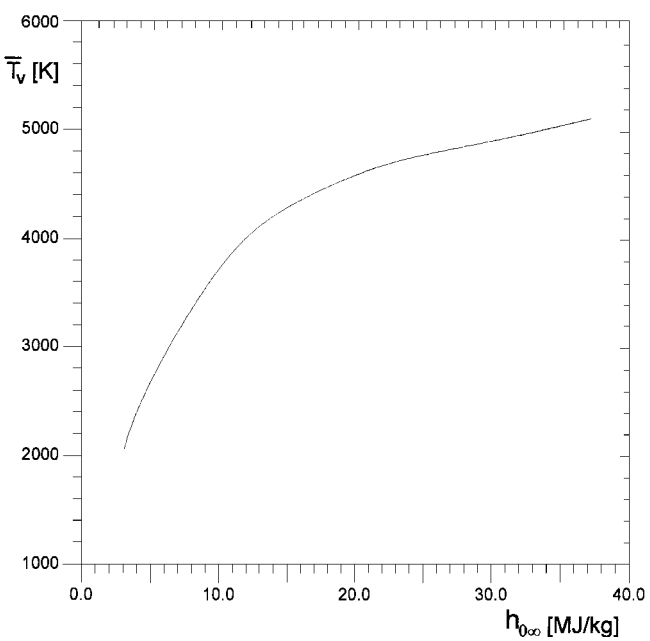

Fig. 1 Freestream average vibrational temperature profile vs flow total enthalpy.

from the coefficients of each species and the local gas composition, by the Wilke rule.

3) In the Fay–Riddell procedure, the vibrational temperature T_v does not change with enthalpy. The constant value of 800 K is suggested for T_v. In the present procedure, T_v is computed as a weighted average of the vibrational temperatures $\bar{T}_v$ of the three diatomic species. The vibrational temperatures are computed as a function of the freestream temperature and therefore of the freestream enthalpy.

4) The Fay–Riddell procedure uses the recombination rate constant K related only to oxygen. In the present procedure, K is a weighted average of the recombination rates of the three diatomic species. For each diatomic species, the temperature dependence laws by Baulch[4] are used.

5) The Fay–Riddell procedure uses unknown, i.e., not referenced, values of both heats of formation and specific heats at constant pressure. In the present procedure, the heats of formation for O, N, and NO by Stull and Prophet[5] are used. Stull and Prophet also provide, for the five chemical species, the specific heats at constant pressure as a function of temperature.

6) The Fay–Riddell procedure evaluates the equilibrium atom mass fraction by interpolating, as a function of temperature, tabulated data for air, reported in an Arnold Engineering Development Center (AEDC) technical note published in 1956. In the present procedure, the equilibrium atom mass fraction is computed by including in the code a routine by Prabhu and Erikson.[6] Because only temperature is required to enter the table, it can be guessed that the AEDC data were obtained at ambient pressure. From the operative point of view, the routine by Prabhu and Erikson looks to be more reliable. In fact, it provides the equilibrium mass fraction of each chemical species as a function of both temperature and density and therefore of pressure.

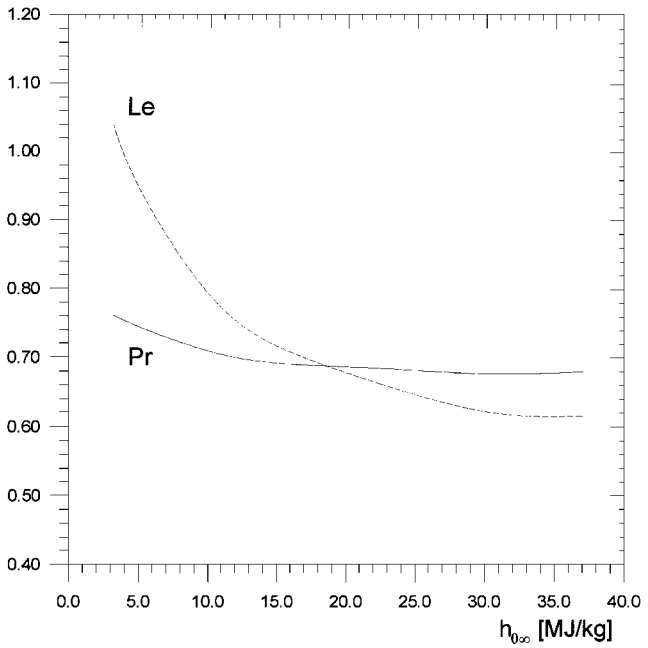

Fig. 2 Freestream Prandtl number and Lewis number profiles vs flow total enthalpy.

III. Analysis of Results

To work in physically congruent conditions, in terms of temperature, density, gas composition, and so on, the code based on the present procedure has been interfaced with a computer code[7] modeling the jet of an arc wind tunnel. The thermo-fluid-dynamic parameters and the gas composition of the jet are considered to be the freestream ones in the present code.

Figures 1 and 2 show the freestream, average vibrational temperature and the profiles of the freestream Lewis number and Prandtl number as a function of $h_{0\infty}$, respectively. These figures show the incorrectness of the Fay–Riddell assumption in keeping vibrational temperature equal to 800 K, Prandtl number equal to 0.71, and Lewis number equal to 1, 1.4, and 2.

The differential Fay–Riddell equations have been integrated by a fourth-order Runge–Kutta algorithm. The wall temperature was 300 K; the wall enthalpy h_w was 0.31 MJ/kg. The present procedure is validated in terms of normalized heat flux $\dot{q}_N$ as a function of the enthalpy potential $(h_{0\infty} - h_w)$: $\dot{q}_N = \dot{q}_w \sqrt{(R_b/p_s)}$, where $\dot{q}_w$ is the wall heat flux (in watts per square centimeter), R_b is the body nose radius (in centimeters), and p_s is the pressure at the stagnation point (in atmospheres).

The numerical results (almost 90) were computed by De Filippis and Serpico[8] and De Filippis et al.[9] by a Navier–Stokes code (H2NS) run by considering a nonequilibrium boundary layer and a fully catalytic wall. The experimental data are both from arc-driven shock

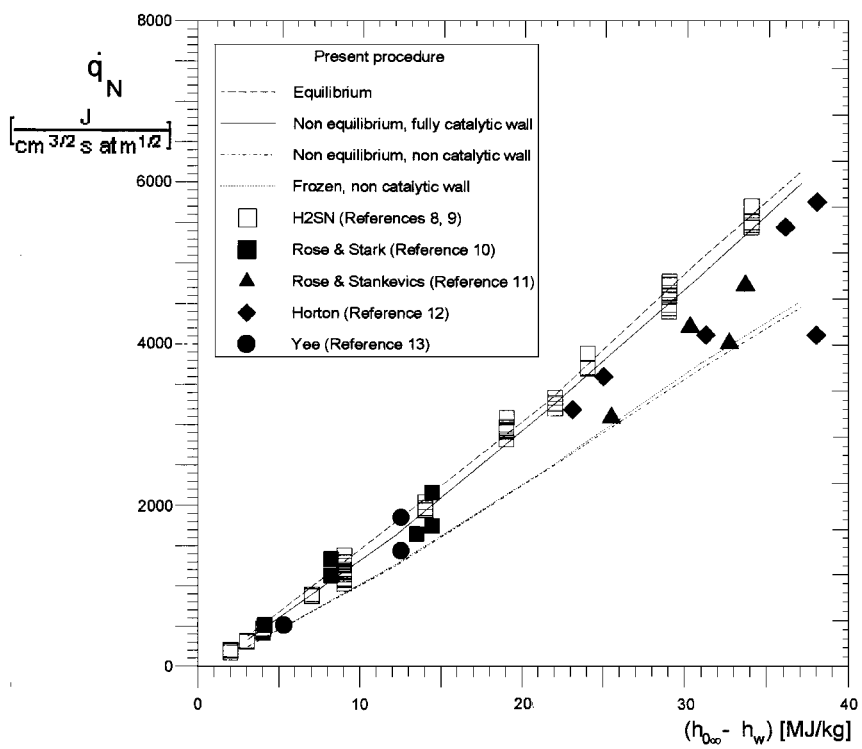

Fig. 3 Normalized heat fluxes vs enthalpy potential.

tubes and from a ballistic range. All measurements were made by calorimetric gauges mounted at the stagnation point of hemisphere cylinders. The test gas was air. The shock tube data are by Rose and Stark,[10] Rose and Stankevics,[11] and Horton and Babineaux.[12] Rose and Stankevics carried out a specific analysis to determine both the thermochemical state of air and the effects of catalycity of the surface of the calorimeter. Their conclusion was that air was frozen in the boundary layer and the wall catalytic effect was negligible. The analysis by Rose and Stark relied on the comparison with the results by the Fay–Riddell correlation formulas. Their conclusion was that air was in equilibrium. Horton and Babineaux did not perform such an analysis. The ballistic range data are by Yee et al.[13] The heat flux was measured by launching from a light gas gun small models flying through air. The measurements were made at an ambient temperature of 300 K and at an ambient pressure of 0.1 atm. According to the opinion of Yee et al., for these conditions the stagnation density is so high (approximately atmospheric) that air in the shock layer is in equilibrium.

The comparison of the normalized heat fluxes is shown in Fig. 3. The match of the present results with the ones by H2NS is excellent in the whole range of enthalpy potential. The match with the experimental data is pretty good up to the enthalpy difference of 14 MJ/kg for each state of the gas. At low enthalpy levels, in fact, the dissociation is not remarkable, and thus it is not really necessary to specify the state of the gas. The present results show a reasonable good agreement with the data by Rose and Stankevics. The agreement with the data by Horton and Babineaux is also good. This agreement indicates that the test gas considered by Horton and Babineaux should be in nonequilibrium and the wall of the calorimeter should be fully catalytic.

IV. Conclusions

Fay and Riddell's classical solution concerning the stagnation point heat transfer in high-speed flow was reexamined. The approximations used in the Fay–Riddell work were identified, and some of them are removed in the present procedure.

Numerical results by the present procedure were validated with existing ground test data and Navier–Stokes results. Good agreement between the present results and experimental data is noted. Therefore, the improved Fay–Riddell procedure can be a ready-to-use tool for researchers in hypersonic wind-tunnel experiments. It is particularly useful to assess the wall catalycity effects of the test models.

More general models for the transport coefficients, e.g., the Yun–Mason model, and the variability of the vibrational temperature in the boundary layer can be easily included in the present procedure.

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Flow Visualization on Lower Surfaces of Wave Rider Configurations at Mach 5.5

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Nomenclature

L/D = lift-to-drag ratio
M_∞ = freestream Mach number
β_s = conical shock-wave angle
δ = one semivertex angle
ε = emissivity

Introduction

SINCE the pioneering work of Nonweiler[1] and Jones,[2] wave riders did not attract researchers' attention for a long time until, in 1980, Rasmussen[3] proposed a cone-derived wave rider. Later, Rasmussen and his co-workers designed an optimized configuration[4] of the cone-derived wave rider. Since then, experimental[5–7] and theoretical[8–13] studies, including design and evaluation based on computational fluid dynamics, have been performed extensively on this configuration. In these configurations, a high-pressure layer below the body is created with a shock wave attached to the leading edge. Hence, the flowfield on the lower surface is of particular importance. Little experimental work has been performed on the nature of the lower-surface flowfield, especially on the surface heat transfer effect. The purpose of the present study is to investigate experimentally the characteristics of the flowfield around such configurations. We observe the flowfields on the lower surfaces of two general cone-derived wave riders, a general cone-derived wave rider (GCWR), and an optimized GCWR using oil-flow, wall-tracing, and infrared thermographic methods. The oil-flow method makes it possible to observe the detailed flow pattern on the lower surfaces whether or not the compressed flow has leaked from the lower compression region through the leading edge. The thermographic measurement is performed to observe the surface temperature fields due to the aerodynamic heating.

GCWR

The GCWR was originally proposed by Rasmussen[3] in 1980 based on the hypersonic small disturbance theory (HSDT). Later such a configuration was numerically tested[9] with the solution of the Euler equation. Stecklein and Hasen[9] designed their configurations based on the Taylor–Maccoll equation "cast in hypersonic small disturbance form." We design the GCWR based on the exact

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