COMPLETE ANALYTICAL MODEL TO DESCRIBE THE TEST-LEG OF SCIROCCO PWT

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Abstract

In this paper a systematic theoretical description of the foreseen aerothermodynamic behavior of the Italian Scirocco Plasma Wind Tunnel facility has been carried out. To reach this goal, an advanced computational tool has been used. The nozzle non-equilibrium flow, the stagnation pressure and heat flux in Test Chamber and the diffuser efficiencies have been calculated in the all different possible working configurations of the facility. All the available numerical data have been synthetized; as results of this work two very simple analytical formulas, that allow us to foresee the stagnation pressure and stagnation heat flux on the spherical model in hypersonic wind tunnel conditions , have been obtained.

nomenclature

Symbol	Definition
A/A^*	Nozzle area ratio
H_w	Enthalpy at the model wall
H_0	Total enthalpy in arc chamber
P_s	Stagnation pressure on the model
P_0	Total pressure in arc chamber
P_u	Total pressure at the diffuser exit
Q_s	Stagn. heat flux on the model
R	Spherical model radius
R_n	Exit nozzle radius
η	Diffuser Efficiency

Introduction

The Scirocco project is a european program aimed to the realization of a 70 MW arc heated hypersonic facility designated as the Plasma Wind Tunnel (PWT). This facility, whose building is starting in CIRA at Capua (Italy), will be used for experimental measurements regarding the development of the Thermal Protection System (TPS) of reentering space vehicles in earth atmosphere. The main characteristics of this facility will be the very high stagnation conditions, in terms of total enthalpy and total pressure, and the possibility to test large scale models.

The gas in Scirocco will be heated by a 5.5 meter long arc heater, accelerate through a convergent-divergent nozzle, impact on the model in the test chamber and then dissipate the energy in a diffuser and in an heat-exchanger; a functional scheme of the Scirocco PWT, with the main components of the facility, is reported in figure 1.

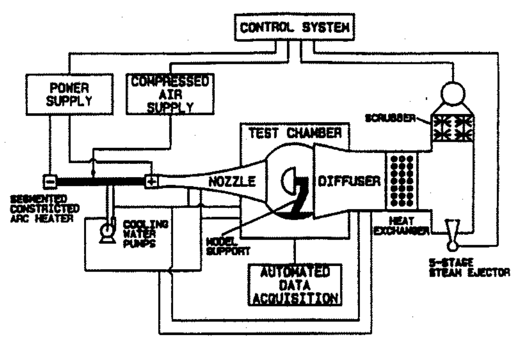

Figure 1 - *Functional scheme of Scirocco PWT*

The complete aerothermodynamic process has been studied in the design phase, that has been completed at the end of the 1995. In this phase Scirocco has been calibrated to meet the requirements requested by ESA (European Space Agency) reported in [1]. The requirements are expressed in terms of stagnation pressure and stagnation heat flux to be reached on a spherical model in test chamber; they mainly impact on the nozzle length and on the modulation of the driving conditions in arc chamber: total pressure and total enthalpy.

Starting from the beginning of 1994, CIRA is developing an internal study and analysis of the Scirocco process, parallel to the design activities and based on advanced computational tools taking into account the more recent modeling for hypersonic phenomena. This analysis has been carried out in a systematic way and required a noticeable cost in terms of CPU hours.

In this paper we will describe the results that have been obtained in the calculation of the pressure and heat flux at stagnation point of the test article in test chamber, and the diffuser efficiency. They came from a simulation of the flow behavior in the convergent-divergent nozzle, and successively of the flow impacting on a spherical body. The calculation of the diffuser performances have been obtained by using a simplifed method that use the CFD nozzle calculations. All the numerical analysis have been made for 25 possible combinations of the values of total enthalpy and total pressure in arc chamber, for the four foreseen exit nozzle diameter and for the two radii of the sphere in test chamber.

Numerical computations description

Scirocco PWT has been designed to operate with four different nozzle exit diameter size of 1.950 meter, 1.350 meter, 1.150 meter and .900 meter. The model in test chamber has a nominal radius of .3 meter and of .24 meter, even if the first radius is not usable at the exit of .900 meter because of blockage problems. In the requirements document [1] seven configurations nozzle-model are foreseen as reported in the following table.

	Nozzle exit diameter	Model radius
1	900 mm	240 mm
2	1150 mm	240mm
3	1150 mm	300 mm
4	1350 mm	240 mm
5	1350 mm	300 mm
6	1950 mm	240 mm
7	1950 mm	300 mm

In a first work phase a matrix of 25 cases in different operating conditions has been defined. Practically, 25 pairs of P_0 and H_0 values in arc chamber have been chosen, covering in satisfactory way the Scirocco Arc performance map. In the following figure these points are represented within the Arc Performance map.

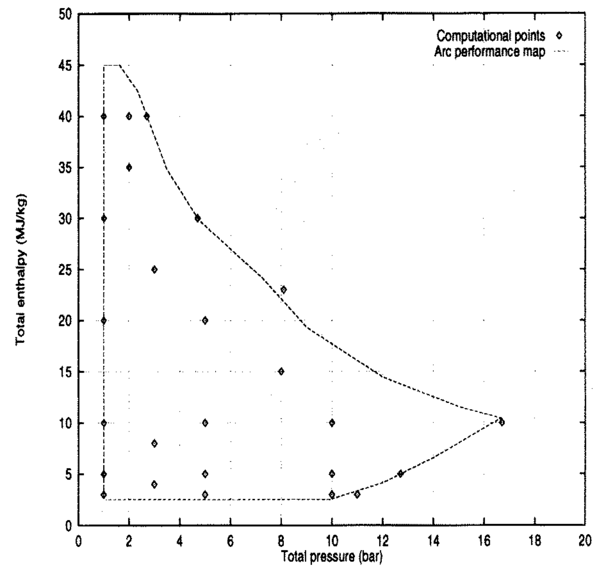

Figure 2 - *Analyzed points within the Scirocco Arc Performance map*

For all these selected cases, a numerical simulation of the flow along the nozzle and over the test article has been carried out using the CIRA hypersonic code H2NS; in this way, the main aerothermodynamic quantities at the nozzle exit point on the centerline have been obtained. Then these quantities were used as input parameter to carry out an axisymmetric CFD simulation of the flow impacting on the sphere model located in the test chamber (supposed close to the nozzle exit). In this way pressure and heat flux on the Scirocco nose configuration in test chamber have been calculated. These results are described in detail in documents [2] and [3].

H2NS is a research hypersonic flow code developed in CIRA. It solves the Full Navier-Stokes equations by means of a finite volume technique, calculating fluxes with a Flux Difference Splitting scheme [4]. It takes also into account chemical and vibrational nonequilibrium, with different chemical thermokinetic models. The transport properties modeling is based on calculated collision integrals ([5] and [6]).

In figure 3 an example of the grid used for computation of the flow over the test article in the test chamber is reported. In order to compute correctly the wall heat flux, a very stretched grid in normal-to-the-wall direction has been used: in particular the minimum normal spacing at the wall stagnation point is $2.210^{-4}m$ with a corresponding aspect ratio of 53.

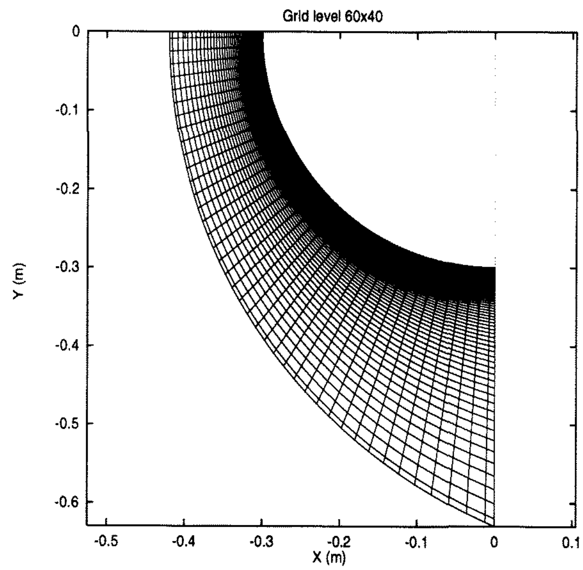

Figure 3 - *Grid used for sphere computation.*

As an example of numerical results over the test article, in figs. 4 and 5 the wall pressure and heat flux diagrams are reported for the case with $P_0 = 10\ bar$ and $H_0 = 3\ MJ/kg$. The model of $0.3\ m$ radius is located at a nozzle exit diameter of $1.95\ m$ with the wall temperature fixed to $1000\ K$. The numerical results are in general in good agreement with the expected experimental results, widely discussed in [7].

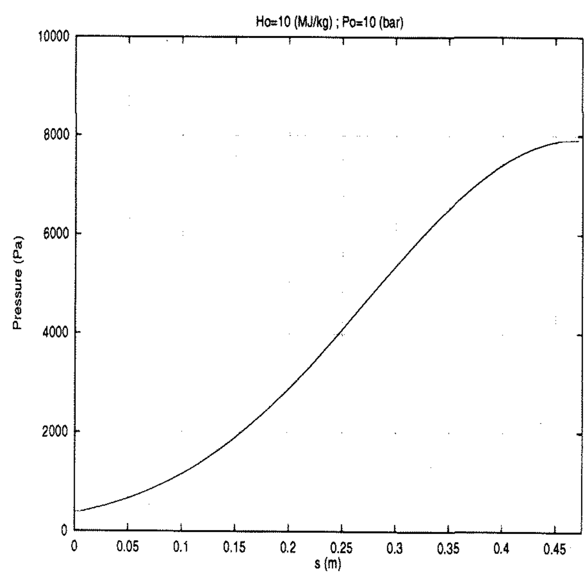

Figure 4 - *Pressure variation on spherical surface.*

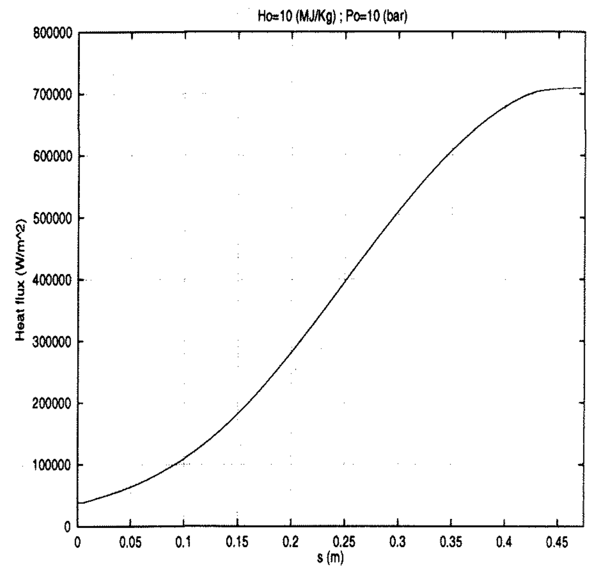

Figure 5 - *Heat flux variation on spherical surface*

All the results of these computations are summarized in [8], where 7 tables are reported, one for each nozzle-model configuration, giving the pressure P_s and heat flux Q_s over the stagnation point of the test article, as a function of the generating conditions H_0 and P_0.

A synthesis work has been made to generate the numerical Scirocco performance map, where Q_s is plotted as a function of P_s for each case (Figure 6). The envelope of this figure represents the ranges of pressure and heat flux that Scirocco is able to produce at the stagnation point of the model in test chamber. In figure 7 the equivalent result is reported, taken from design document [1] and calculated using approximated, conservative and simplified methods. In this figure even the user-requirements of ESA are indicated; it can be noted that both the CIRA numerical results and the designer previsions meet well the ESA requirements.

In particular, the H2NS results present similar previsions for the pressure ranges , but indicate for the heat fluxes possible values higher than the designer previsions up to about $2000\ \frac{kWatt}{m^2}$.

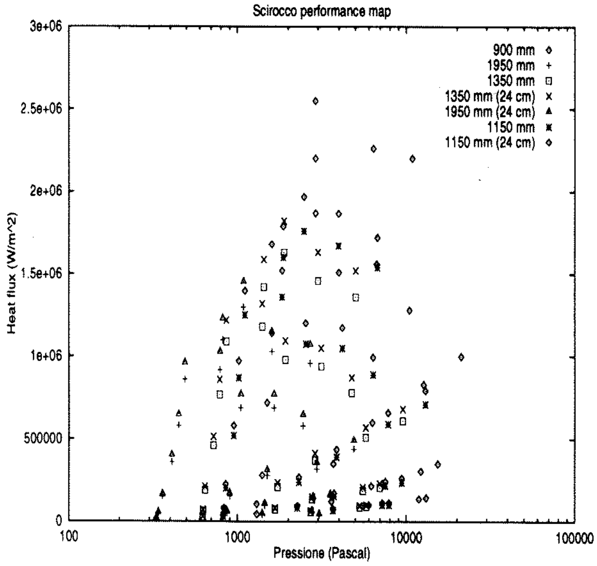

Figure 6 - *Stagnation point performance map calculated by means H2NS code*

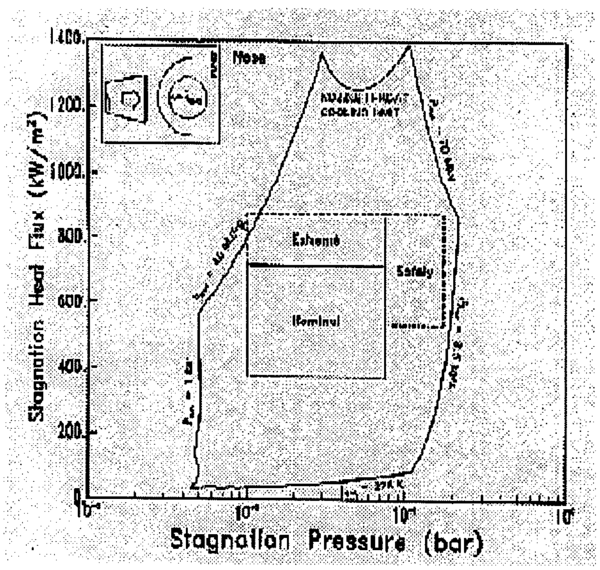

Figure 7 - *Stagnation point performance map calculated in the design phase as reported on the document [1]*

Test Chamber stagnation pressure

Aim of this paragraph is to make an analytical synthesis of the numerical pressure results to have available a relationship linking the driving parameters (H_0,P_0) to the P_s pressure at the sphere stagnation point. This formula can be used in engineering applications to make fast pressure previsions and in future can be validated by the experimental measurements in Scirocco test chamber.

In the figure 8 there is a representation of the P_s variation expressed in Pascal as function of the P_0 total pressure for the cases relative to the nozzle exit diameter of 1.350 meter. Similar plots have been carried out even for the other three Scirocco exits. For all the four cases an almost linear variation and a very small sensible dependency from the the driving total enthalpy H_0 have been obtained. For these reasons we carried out numerous linear and parabolic fits to obtain the following final relationship:

$$P_s = \left(6.148\frac{A}{A^*} - 300.75\sqrt{\frac{A}{A^*}} + 3938\right)\cdot P_o + 202 \quad (1)$$

where P_s is in pascal and P_0 in *atm*. It permits to calculate the stagnation pressure on the spherical model by the knowledge of the total pressure P_0 in arc chamber and the nozzle area ratio.

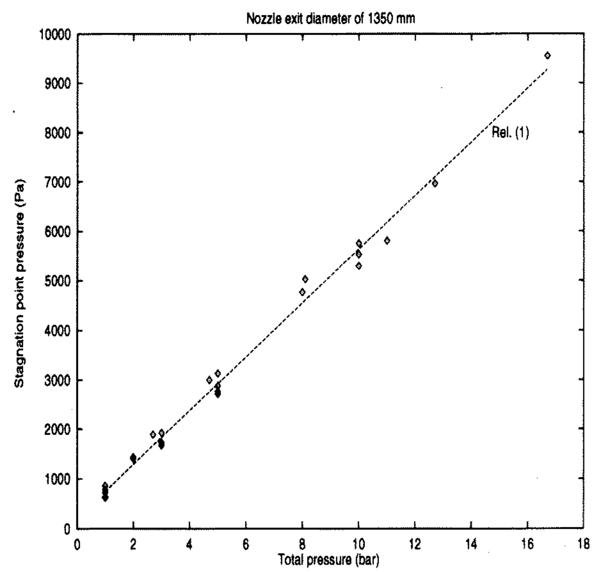

Figure 8 - *Static pressure at stagnation point as function as total pressure. Exit diameter of 1350 mm.*

The previous formula has been compared with the relationship

$$\frac{A}{A^*} = 1.8 \cdot \frac{P_0}{P_s} \quad (2)$$

that is used by engineers and experimentalists for the first coarse calculations and not sensible differencies have been found. In figure 9 there is a plot of the mathematical functions represented by relationships (1) and (2) with fixed total pressure at 5 *atm*. There is even a third curve that has been obtained by theoretical calculations using approximate hypersonic formulas describing the fundamental phenomena of the flow in the wind tunnel: a) expansion in the nozzle,

b) compression across a normal shock wave surface, c) compression downstream the shock wave, along the stagnation line. These last calculations have been carried out considering air mixture not dissociated with γ value constant everywhere and equal to 1.4. The detail of this theoretical analysis are in the references [8] and [9]. The different results between CFD fit and theoretical formula are due to the real gas effects; in fact as the total enthalpy increases the boundary layer thickness in the nozzle grows causing a reduction of the effective area ratio and giving a higher exit pressure (and hence pressure at the stagnation point). In any case the three plots in figure 9 show very similar behaviors indicating that the pressure prevision is not a critical topic.

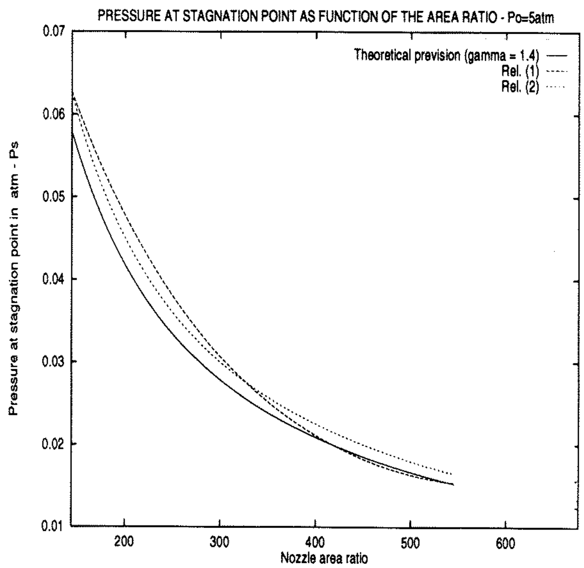

Figure 9 - *Relationship for $P_s = P_s(P_0, A/A^*)$ obtained with three alternative methods.*

Test Chamber stagnation heat flux

The heat flux at the stagnation point of a blunt body in hypersonic conditions can be obtained by using the classical Fay-Riddel formulas. To use these formulas it is necessary know some aerothermodynamics quantities at the boundary layer edge. For this reason it is widely used in engineering applications a simplified relation that calculates the stagnation heat flux by using only the total and the wall enthalpy, the stagnation pressure and the body nose radius. This formula has the following expression (fully catalytic condition) :

$$Q_s = K \cdot \sqrt{\frac{P_s}{R}} \cdot (H_0 - H_w) \qquad (3)$$

where K is called the heat transfer factor. The more used value for K in literature is 112.4, expressing the enthalpies in MJ/kg, the pressure in atm, the heat flux in W/cm^2 and the sphere radius in cm.

In figure 10 we reported all the CFD heat flux results compared with the ones obtained using the complete and simplified Fay-Riddel formulas. To use the complete Fay-Riddel formula a preliminary Euler computation has been necessary.

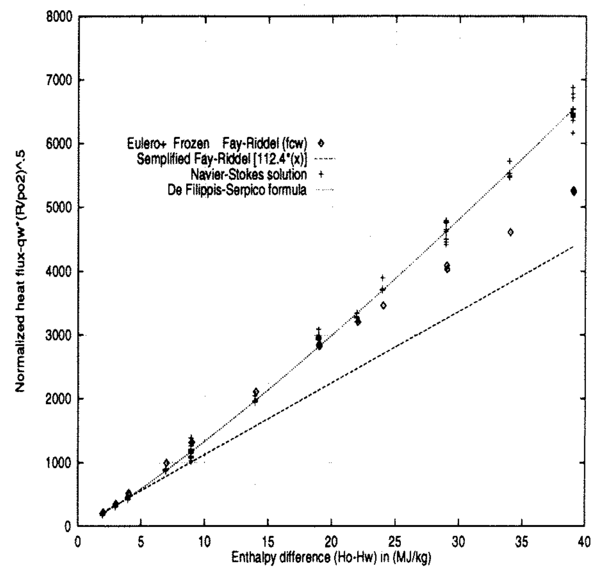

Figure 10 - *Fay-Riddel formula verification.*

In this graph also the De Filippis-Serpico formula has been shown; this last formula has the following expression:

$$Q_s = 90 \cdot \sqrt{(\frac{P_s}{R})} \cdot (H_0 - H_w)^{1.17} \qquad (4)$$

where the enthalpy difference is expressed in MJ/kg, the radius R in cm, the pressure in *bar* and the heat flux in $Watt/cm^2$.

This formula, widely discussed in ref. [11], ,has been recently used to make a prevision on the Electre model in wind tunnel conditions, giving a good agreement with numerical and experimental values, ref. [12]. Looking at the figure a good agreement between the heat flux values computed by means of the complete Fay-Riddel formula and the CFD Navier-Stokes computations is realized only up to 23 MJ/kg. This behaviour is due to the arbitrary extrapolation of Fay-Riddel results up to 40 MJ/kg. The simplified Fay-Riddel formula give s a very low heat flux values with respect the CFD computation and the complete Fay-Riddel formula; the differencies are probably due to the real gas effects that the simplified Fay-Riddel relation does not take into account (assume constant characteristic number as

Lewis number and Prandtl number). In this case a more suitable value for the heat transfer factor K seems to be 171. At this point the formulas (1) and (3) (or (4)) constitue an algebraic equation system to calculate the Ps and Qs stagnation values as function of Po and Ho values. They are two very 'user-friendly' formulas to have a quantitative description of the Scirocco PWT performances.

Diffuser description

To complete the numerical-analytical study of the test leg of Scirocco PWT, an evaluation of the diffuser performances, in terms of pressure recovery, has been carried out. The main geometric characteristics of the Scirocco PWT diffuser are: a total lenght of about 42 [m] with a constant throath diameter of 2.12 [m]. The rule of the diffuser is to give a subsonic flow (at the vacuum system inlet) starting from a supersonic very low pressure flow (at the nozzle outlet); the obtained final pressure level is a very important parameter for the vacuum system and for the pressure level in test chamber.

The main physical aspects of the flow in the diffuser are the following:
- initial supersonic compression
- shock wave-boundary layer interaction
- final subsonic compression

These phenomenologies produce a pressure loss because of the viscous effects. Two different effects can be individuated, on the basis of the available eperimental results([15],[16],[17]), that make very important a correct design of the diffuser, in particular reagarding its length. On the one hand, the classical wall viscous effects that increase the losses at the increasing of the diffuser length. On the other hand, if the diffuser throath is not sufficiently long, the shock waves system that must lead to subsonic Mach number can be not completely contained in the throath, and this causes a strong decrease of the efficiency. The last phenomenon becomes significant when the Reynolds number is very low, and this is the reason why the diffuser throath, for low Reynolds facilities such Scirocco, must be very long. However, at the moment, to find an optimum length that balances the two previously described effects is very difficult, and therefore it is convenient to design the diffuser on the basis of experimental data of other similar facility.

To evaluate the pressure "performances" of the Scirocco PWT diffuser, the simplified formula of Monnerie has been used, [14]. With this formula the diffuser efficiency, defined as the ratio of the exit diffuser pressure with respect to the supersonic stagnation pressure, can be calculated by using the geometric exit nozzle radius and the displacement thickness at the supersonic nozzle exit:

$$\eta = (1 - \frac{\delta_1}{R_n})^2$$

This formula has been obtained with the following assumptions:

- At the nozzle exit the flow is uniform out the boundary layer thickness
- The wall diffuser is adiabatic
- $Mach >> 1$
- Subsonic and uniform flow at the exit constant area channel

For the Scirocco conditions these assumptions are quite well verified, except for the adiabatic wall condition. About the last hypothesis, it is verified if the length of the throath diffuser is sufficent to contain all the shock waves system, as discussed before.

To verify the goodness of this formula, the available experimental efficiencies have been compared with the ones obtained by using the Monnerie formula. The results are shown in figure 11, where the Reynolds number is referred to the nozzle exit diameter.

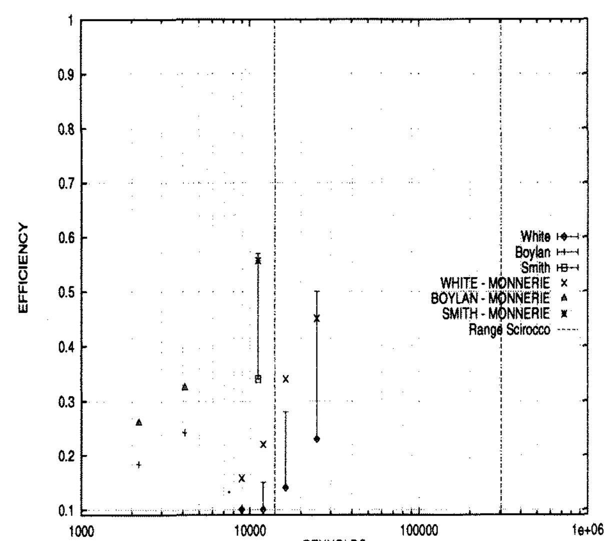

Figure 11 - *Experimental-Monnerie comparison*

It is possible to note that the simplified formula generally slightly overestimates the experimental results; however it must be underlined that the range of values of efficiency from experiments is quite wide, depending on the phase of the measurement (startup or breakdown phase). It is clear that a very simplified formula, like the one given by Monnerie, can give only the order of magnitude of the efficiency; in order to have more precise informations, a complete CFD calculation of the diffuser would be necessary. The complete experimental data are available in [16], [17], [18].

The efficiency prevision for the Scirocco PWT diffuser has been obtained by using this formula, with the boundary layer thickness at the exit of the nozzle computed with H2NS; the results are shown in figure 12.

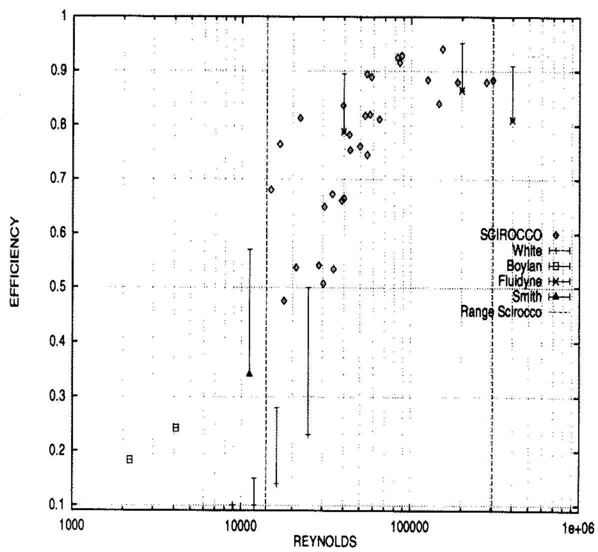

Figure 12 - *Monnerie prevision for Scirocco PWT diffuser*

Also available experimental data of the other diffusers have been superimposed on this diagram, so to emphasize how the general trend of the efficiency as function of the Reynolds number, calculated for Scirocco by means of the Monnerie formula, follows the trend of experimental data. In fact it is possible to note the rapid decrease of the diffuser efficiency with decreasing of the reynolds number.

Finally, it must be said that a complete numerical simulation would be necessary also for the diffuser, both for better understanding the phenomena that occur inside it, and for having a more precise estimate of the real performances of the diffuser. Therefore, the final goal of all the numerical activity on the Scirocco facility, remains to have a complete simulation of the process by means of advanced CFD codes.

<u>Conclusions</u>

In this work a prevision of the performances of the hypersonic wind tunnel SCIROCCO has been carried out. These calculations covered the whole arc heater performance map designed for the facility and they have been carried out using an advanced hypersonic computational code.

The possibility to massively use the computational tools for plasma wind tunnel flow previsions has been demonstrated. In particular the aerothermodynamic behavior of the air in the nozzle and in test chamber have been simulated varying the total pressure and the total enthalpy in arc chamber and the data relative to the heat-flux and the pressure at stagnation point on the model in test chamber have been extracted.

In this work two 'user-friendly' correlation formulas have been found. The first links the stagnation pressure on the model in test chamber to the total pressure in arc chamber at different nozzle area ratios. The second calculates the stagnation heat flux as function as the total enthalpy in test chamber, the enthalpy at model wall and the stagnation pressure calculated by the previous formula. Both the relationships are a simple algebraic equation system, whose solution is the complete Scirocco performance prevision.

The obtained results have been compared with the semiempirical formulas used by engineers and experimentalists. No substantial differences have been found for the pressure, but there are discrepancies for the heat flux previsions above 5 MJ/kg of enthalpy, even with respect to the theoretical Fay-Riddel previsions. The reasons of the discrepance are in a phase of analysis.

Finally, a first analisys has been done about the diffuser, by means of the semiempirical Monnerie formula, in order to verify the performances in terms of efficiency; this formula has been found quite good for estimating the order of magnitude of efficiency, but a complete CFD simulation would be surely useful for a better understanding of all the phenomena that occur inside the diffuser.

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