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Design and Performance Analysis of a Supersonic Diffuser for Plasma Wind Tunnel

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Abstract**—**Plasma Wind Tunnels (PWT) are extensively used for screening and qualification of re-entry (entry) Thermal Protection System (TPS) materials. Proper design of a supersonic diffuser for plasma wind tunnel is of importance for achieving good pressure recovery (thereby reducing vacuum pumping requirement & run time costs) and isolating downstream stream fluctuations from propagating upstream (where model is tested). This paper presents the details of a rapid design methodology successfully employed for designing supersonic diffuser for high power (several megawatts) plasma wind tunnels and numerical performance analysis of a diffuser configuration designed for one megawatt power rated plasma wind tunnel(enthalpy ~ 30 MJ/kg) using FLUENT 6.3® solver for different diffuser operating sub-atmospheric back-pressures.

Keywords**—**Compressible flow, plasma wind tunnel, re-entry, supersonic diffuser

I. Introduction

SINCE plasma wind tunnels are capable of simulating enthalpies of several mega joules with moderate shear and various ambient conditions for long durations (several minutes), they are extensively used for screening and qualification of Thermal Protection System (TPS) materials, especially those intended for re-entry (entry) applications.

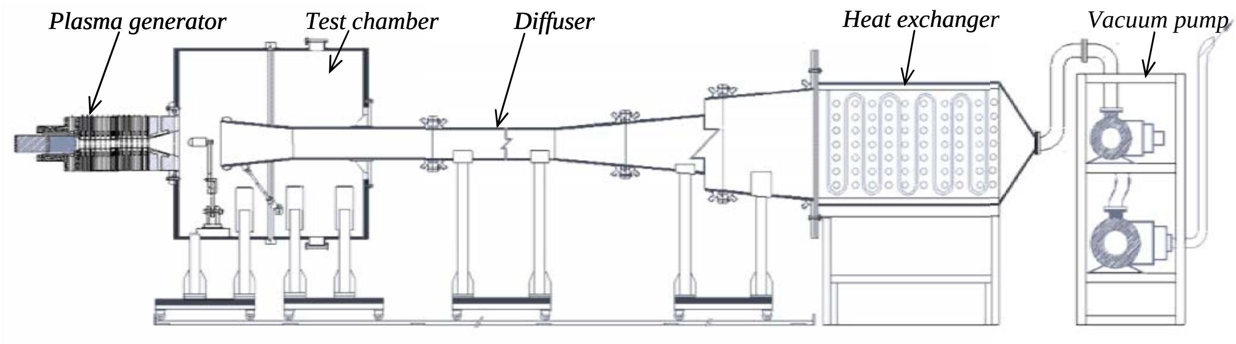

Fig. 1 Schematic of typical plasma wind tunnel

The Plasma Wind Tunnel (PWT) essentially consists of: (1) Plasma generator – where in high enthalpy (high temperature) working fluid is produced by dissociation/ionization of gas(es) by an arc struck between the anode and the cathode. (2) Test chamber – where the required ambient pressure is maintained for testing of the model. (3) Supersonic diffuser – where the transition of supersonic to subsonic flow takes place with a resultant pressure recovery. (4) Heat exchanger – incorporated to reduce the temperature of the working fluid to a level acceptable to the vacuum pumping skid and (5) Vacuum pumping skid – for maintaining the required sub-atmospheric pressure at the exit of the diffuser, which in turn helps in maintaining the required test chamber pressure. The schematic of a typical plasma wind tunnel is shown in Fig.1.

The supersonic diffuser is a major aerodynamic component of the plasma wind tunnel and its proper working is of importance for maintaining a well-behaved test section flow in particular and operation of the whole facility in general. In general, the following are the major functions of a supersonic diffuser for the plasma wind tunnel applications: (a) To capture the working fluid i.e. plasma emanating from the nozzle, after striking on the model with minimum spillage. (b) To prevent the downstream fluctuations (at the exit of the diffuser) from propagating to the upstream test chamber (hence the diffuser is sometimes referred to as an isolator) & (c) To present a subsonic flow at its exit with a good resultant pressure recovery. Since plasma wind tunnels are usually intended for continuous operation, the pressure recovery is of significance from the point of vacuum pumping requirement and hence the overall & run time costs. Therefore a good pressure recovery of a supersonic diffuser translates in to having a vacuum pumping system of smaller capacity for a given test chamber pressure.

Given the importance of the diffuser, it is imperative to properly design and analyze its performance before realization. Further, since high enthalpy facilities (PWT) are typically associated with high temperature cum low Reynolds number turbulent flows, their diffuser design and performance are different from those employed in conventional wind tunnels. This paper describes a successful rapid design

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methodology for sizing a typical plasma wind tunnel supersonic diffuser. Followed by performance analysis of diffuser sized for one-megawatt power rated plasma wind tunnel for varying downstream pressures & fixed stagnation conditions, carried out using FLUENT 6.3® solver.

II. Diffuser Design Methodology

The supersonic diffuser consists of a convergent entry section (also known as catch cone) in which appreciable shock compression is achieved at supersonic speeds, followed by a constant area throat of appreciable length for compressing the supersonic flow to near sonic condition and a divergent section which acts as a subsonic diffuser. Fig. 2 shows the schematic of a typical supersonic diffuser. Where L_t and D_{t2} are the length and diameter of the throat respectively, D_{in} and D_{ex} are the inlet and exit diameter of the diffuser respectively, α and β are the semi-cone angle of the convergent and divergent section respectively.

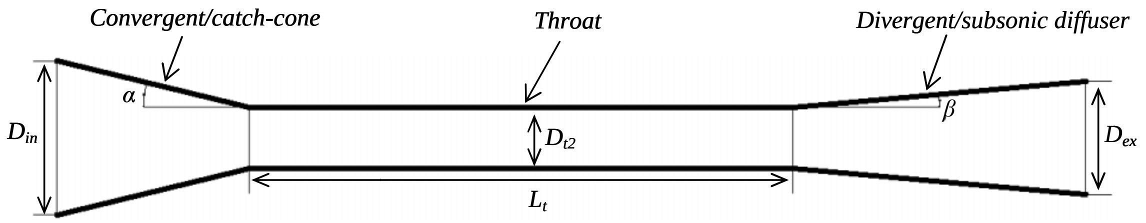

Fig. 2 Schematic of typical supersonic diffuser

Fixing the configuration of a supersonic diffuser calls for sizing of throat diameter & its length, catch cone entrance diameter & its semi-convergent angle and subsonic diffuser. Since diffuser design is carried out for a given nozzle configuration, it is essential to establish the separation distance between the nozzle and the diffuser catch cone in addition to the above mentioned geometrical variables.

A. Sizing of Diffuser Throat

The most fundamental design parameter is the ratio of diffuser throat area to nozzle throat area i.e. A_{t2}/A_{t1}. In contrast to nozzle, the flow inside a supersonic diffuser is against adverse pressure gradient with resultant large boundary layer growth along it. Further, the flow inside the diffuser is complicated by shock – shock interaction, shock - boundary interaction, etc., with resultant loss in stagnation pressure. Therefore for a supersonic nozzle – diffuser system to pass a given nozzle mass flow rate, the area of the diffuser throat needs to be large as compared to a nozzle throat area.

The crux of the design is that the size of the diffuser throat should be sufficiently large to swallow the starting normal shock. However, having more throat area than required will decrease the effectiveness of the diffusion process and hence efficiency of the diffuser. It can be easily shown from first principle that the ratio of diffuser throat area to the nozzle throat area is inversely proportional to the stagnation pressure ratio across the tunnel [1] *i.e.*

(1)

where is the stagnation pressure ratio across the plasma wind tunnel.

Equation (1) may appear simple, but it is not possible to know the actual stagnation pressure across the nozzle – diffuser before its realization and operation. However, for preliminary design, the stagnation pressure ratio across the tunnel is assumed to be that of the stagnation pressure ratio across a normal shock for a given diffuser inlet Mach number and sonic flow in the diffuser throat [2]. The stagnation pressure ratio across a normal shock is given by:

(2)

where M_{di} is the diffuser entry Mach number and γ_{eff} is the effective specific heat ratio.

The question of whether the pressure ratio across the tunnel is greater or less than that of the stagnation pressure ratio across a normal shock at a given diffuser inlet Mach number is subject to discussion. However, it may be said with some degree of certainty that the deceleration of high supersonic flow to a subsonic flow inside a diffuser due to alternating compression – expansion wave against an adverse pressure gradient may incur somewhat higher stagnation pressure loss as compared to a single normal shock. Hence, the throat area derived based on normal shock criteria (isentropic relationship) may actually under estimate the diffuser throat area (This is from the viewpoint of starting the tunnel). Further, low Reynolds number flow is a characteristic of an arc plasma wind tunnel and hence one can anticipate strongly boundary growth along the throat, thereby reducing the effective throat area. Similar inferences were also drawn based on numerical analysis of low Reynolds number flow inside diffuser using RANS solver. The above discussions were with respect to a clear tunnel and for a tunnel with model installed, the size of the diffuser throat should be larger than a clear tunnel in order to account for flow blockage and additional stagnation pressure loss incurred, when a model is injected in to the test section flow stream [3].

B. Sizing of Length-to-Diameter ratio of Diffuser Throat

The performance of supersonic diffuser in high enthalpy, low Reynolds number facilities (PWT) are known to be sensitive to the diffuser throat length-to-diameter ratio [4] and the diffuser throat length required to contain the entire shock train in a low Reynolds flow is known to be greater than required for higher Reynolds number flows. Hence, care should be exercised when sizing the length to diameter ratio of the throat (L_t / D_{2t}) in order to have an efficient compression in the throat.

Predicting the length of the shock train for a given throat entry Mach number and hence the length of the constant area duct is not an easy task because of the complexity of the flow physics involved. However, P.J.Watrup and F.S.Billig [5] have suggested a shock length correlation (in quadratic form) based on their parametric experiments conducted in cylindrical ducts. This correlation is a function of the throat inlet Mach number, the ratio of the static pressure at the inlet and exit of the diffuser throat, the throat inlet boundary-layer momentum thickness and the throat inlet Reynolds number (based on the inlet momentum thickness). The main conclusion to be drawn from the correlation is, the ratio of shock train axial length to duct height (L_t / D_{2t}) can be large compared to 1, when throat inlet Mach number is small and backpressure ratio is large [6]. However, calculation of L_t / D_{2t} ratio requires value for momentum thickness for a given set of conditions; any ambiguity in estimation of momentum thickness will result in grossly wrong prediction of L_t / D_{2t} ratio.

Plasma wind tunnel supersonic diffuser design mostly rely on subscale diffuser tests for estimating the approximate diffuser performance and hence the diffuser length. References [4], [7] and [8] pertaining to high enthalpy facilities have reported a L_t / D_{2t} ratio up to 15 for diffuser throat. Further, our CFD studies & experience in operation of plasma wind tunnels have shown that L_t / D_{2t} ratio in the range of 12 – 15 is required for low Reynolds number, high supersonic flows.

C. Sizing of Diffuser Catch-cone (Convergent Section)

The foremost task of the catch-cone is to capture the flow emanating from the nozzle, including the flow deflected by the model and to effect compression with minimum stagnation pressure loss. Spillage may occur during model injection & testing and should be kept to a minimum in order to ensure that the test chamber pressure does not increase, which in turn may tamper the nozzle flow physics. Fig. 3 shows the schematic of diffuser – nozzle system. Where L_{sep} is the separation distance between diffuser and nozzle.

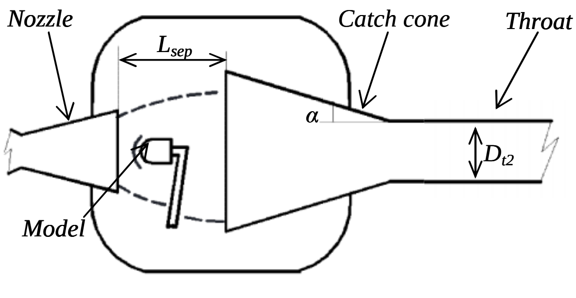

Fig. 3 Schematic of nozzle-diffuser system

Since plasma wind tunnels are extensively used for aero-thermal studies, it is necessary to incorporate axial movement of the model in order to simulate real time varying heat flux on the model, such as those encountered during re-entry. This calls for adequate separation between nozzle and the diffuser entrance. However, for near shock free aerodynamic flow reproducibility perspective, it is desirable to have model placed and tested near to the nozzle exit; this demands having model and diffuser entrance close to nozzle exit. It is inferred from experimental & CFD studies on high supersonic enclosed free-jet plasma wind tunnels that a nozzle – diffuser separation distance (L_{sep}) of 1.5 – 2.5 times the nozzle exit diameter may be adequate from the point of view of model testing and aerodynamic constraints. Too large a separation may cause considerable spillage & poor diffuser performance.

Since plasma wind tunnels are usually of enclosed free-jet type, the catch entrance diameter (D_{in}) needs to be larger than the exit nozzle diameter. The entrance diameter of the catch cone should be sized considering nozzle-diffuser separation distance, blockage area & flow deflection due to the presence of model and nozzle flow divergence angle. Usually catch cone entrance diameter in the range of 2- 3 times the nozzle diameter exit may be sufficient.

The performance of catch cone & hence diffuser strongly depend on catch-cone semi-convergent angle (α). As the supersonic flow is turned on to itself in the catch cone, it inevitably generates shocks with resultant stagnation pressure loss. Therefore, in order to keep these losses to a minimum & to obtain a good pressure recovery, a small semi-convergent angle is desired. However, length constraint calls for having high semi-convergent angle, which may generate strong oblique shock with resultant high heat transfer to the hardware at the flow impingement point. The primary variables that dictate the semi-convergent angle are nozzle exit Mach number and its semi-divergent angle. It is worth noting that the effective angle seen by the flow (in the diffuser catch cone) is the vector sum of catch cone and nozzle semi-angles and the strength of the oblique shock the flow generates depends on the flow effective angle & Mach number. For tunnels having conical nozzle with semi-divergent angle up to 10 degrees and nozzle exit Mach number up to 4.5, semi-convergent angle in the range of 4 - 6 degree is preferred.

D. Sizing of Divergent Section (Subsonic Diffuser)

All supersonic diffusers employ a subsonic diffuser at the exit of the constant area throat for obtaining low subsonic flow with a good pressure recovery. The subsonic diffuser is a divergent conical duct with one end connected to the throat and the other end to the heat exchanger – vacuum pump set up. The inlet diameter of the subsonic diffuser is same as that of the throat diameter. The area ratio & hence the exit diameter of the subsonic duct is dictated by the conditions required at the exit of the diffuser i.e., the Mach number, pressure, etc. Sometimes the inlet dimension of the heat exchanger may dictate the exit dimension of the subsonic diffuser. The semi-divergent angle (β) is dictated by considerations such as flow separation (due to adverse pressure gradient in the divergent) and length constraint. Small angle for the divergent ensures smooth subsonic flow without separation but at the expense of increase in the duct length. Semi-divergent angle in the range of 3 –5 degree is preferred.

In addition to the design presented above, the question of diffuser starting needs to be addressed. The transient starting phenomenon of the diffuser is major concern in the design of convectional wind tunnels and it strongly depends on the pressure ratio across the tunnel and the ability of throat to swallow the starting normal shock. However, for high enthalpy facilities that simulate high altitude ambient conditions, the pressure ratio available across the tunnel is large and the question of diffuser starting hardly arises, provided the throat is sized properly.

III. Numerical flow analysis of supersonic diffuser

It is imperative that the performance of diffuser configuration in terms of pressure recovering ability, ability to maintain well behaved test section flow, etc., be known for its consideration and possible use in the plasma wind tunnel. In absence of subscale tests, numerical flow simulation is the only option available for predicting the diffuser performance. Here, details of flow simulation carried out for a nozzle-diffuser system (sized for a typical one megawatt power rated plasma wind tunnel based on diffuser design methodology presented in this paper) for evaluating the performance of the diffuser is presented. Geometrical details of the nozzle & supersonic diffuser sized for one megawatt PWT given in Table I and is considered for numerical performance analysis. The effective stagnation pressure and temperature considered for the nozzle-diffuser system is 4 bar and 5000 ^{o}K respectively.

TABLE I
Geometrical Details of Nozzle-Diffuser System Considered for Numerical Performance Analysis

Geometrical Parameter	Value
Nozzle area ratio	36.0
Nozzle throat diameter	18.0 mm
Nozzle semi-conical angle	9 degree
Separation distance between nozzle and diffuser, L_{sep}	~ 300 mm
Inlet diameter of diffuser, D_{in}	350 mm
Semi-cone angle of diffuser convergent section, α	~ 6 degree
Diffuser throat length-to-diameter ratio, L_t / D_{2t}	~ 15
Semi-cone angle of diffuser divergent section, β	~ 5 degree
Inlet diameter of diffuser, D_{in}	500 mm

A. Numerical flow simulation

The equations governing the flow physics are the Navier-Stokes equations for axi-symmetric, compressible, turbulent flow. In CFD lexicon, Navier-Stokes equations include equations for conservation mass, energy and momentum (axial & radial direction) for this problem. The Favre-averaged Navier-Stokes equations, obtained by density-weighted time averaging of Navier-Stokes equations are solved using FLUENT 6.3®.An appropriate k-ε model applicable for low Reynolds flow is used as the turbulence model. Since the working fluid being a high temperature air, the variation of thermodynamic (specific heat, etc) and transport (viscosity, conductivity, etc) properties with respect to temperature are acknowledged in the simulation. The appropriate values of transport and thermodynamics properties for high temperature air sourced from [9], [10].

No-slip and adiabatic conditions imposed on the axi-symmetric walls of the nozzle-diffuser system. Pressure boundary conditions imposed at the inlet (nozzle throat) and outlet (diffuser exit). The solver uses the imposed outlet pressure only if the exit flow is subsonic. The computational domain is discretized using quadrilateral elements and the mesh/elements near the walls are fine compared to other regions, in order to capture the boundary layer physics (velocity gradient, etc.) adequately. Further, dynamic mesh adaption/refinement technique employed for properly resolving flow field where pressure gradients are large.

Regarding convergence, the iterations were carried out till the mass flow imbalance between the inlet and exit of the nozzle-diffuser system is less than at least 0.2 % and in the process, the residual convergence of at least 10^{-5} is obtained for continuity, momentum, energy and scalar transport equations.

B. Results and discussion

The performance of the diffuser assessed by evaluating its ability to maintain the required test-section flow, ability to compress supersonic flow to low subsonic flow, ability to recover pressure, etc. This invariably calls for performance analysis of diffuser for various diffuser back-pressures. Therefore, diffuser flow simulation was carried for various sub-atmospheric back-pressures ranging from 200 pa to 7500 Pa for given stagnation conditions. The diffuser centre-line (axis) Mach number distribution for different back pressures is shown in Fig. 5 (back pressures: 200, 1200, 2800, 3700 Pa) and Fig. 6 (back pressures: 4000, 5000, 6000, 7500 Pa) and the diffuser wall static pressure distribution is shown in Fig. 7 (back pressures: 200, 1200, 2800, 3700 Pa) and Fig. 8 (back pressures: 4000, 5000, 6000, 7500 Pa).

From the centerline Mach number distribution and test section contour plots (not shown here) for various back pressures ranging from 200 – 7500 pa, the flow expands as it leaves the nozzle exit (since the nozzle is under expanded) to Mach number of about 5.2 until it hits the catch cone (not necessarily at the entrance of the catch cone). Once the flow hits the catch cone, it inevitably generates compression/shock wave, which in turn compresses the high supersonic to low supersonic Mach number (~ 1.4). This is followed by flow expansion through expansion wave and this phenomenon of alternating compression and expansion of decreasing magnitude happens throughout the catch cone and to a large extent in the throat. However, in the aft end of the diffuser throat and divergent, the flow picture may be different for different back- pressures. For example, for low back pressures (< 1500 Pa), the flow may actually accelerate in the divergent and for back pressures greater than 3500 Pa, there is hardly any scope for expansion and the flow decelerates (through compression – expansion wave or through a terminal shock) till the diffuser exit. For back pressures greater than 7200 Pa, a normal shock appears in the aft end of the catch cone with resultant subsonic flow in the rest of diffuser and for very high back pressures (> 10000 Pa), the normal shock appears in the test section with resultant subsonic flow throughout the diffuser.

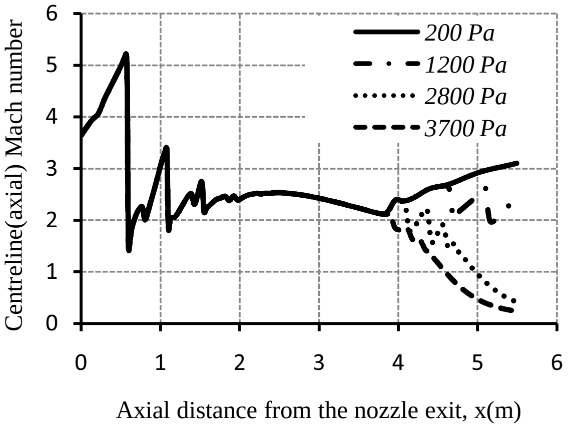

Fig. 5 Centerline Mach number distribution for back-pressures 200, 1200, 2800 and 3700 Pa

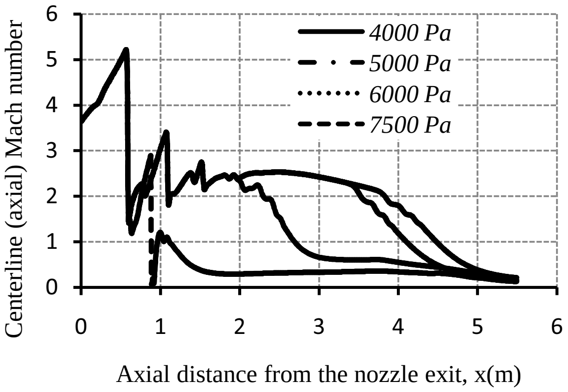

Fig. 6 Centerline Mach number distribution for back-pressures 4000, 5000, 6000 and 7500 Pa

From the diffuser wall static pressure distribution plots for back pressures less than 3500 Pa, the flow expands in the divergent (to varying degree, depending on the back pressure) until it equalizes the respective imposed back pressure. However, for back pressure greater than 3500 Pa, the wall static pressure increases monotonically in the divergent of the diffuser. For back pressures in the range of 4000 – 6000 Pa the terminal shock moves upstream of the diffuser with monotonic increase in pressure until the exit of the diffuser and for back pressures in excess of 6000 Pa, the flow traverses through severe terminal shock in the throat/catch cone with resultant pressure rise equal to the respective diffuser back pressure; thus rendering the rest of the diffuser useless.

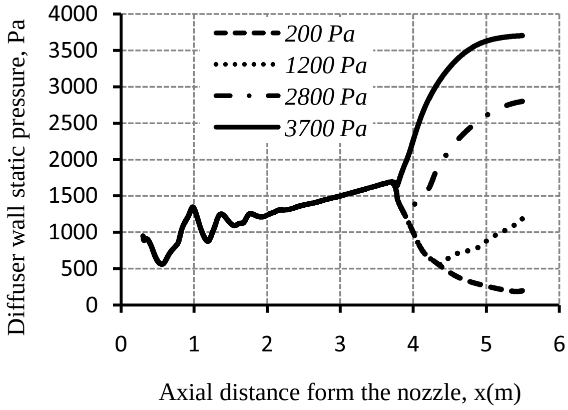

Fig. 7 Static pressure distribution along diffuser wall for back-pressures 200, 1200, 2800 and 3700 Pa

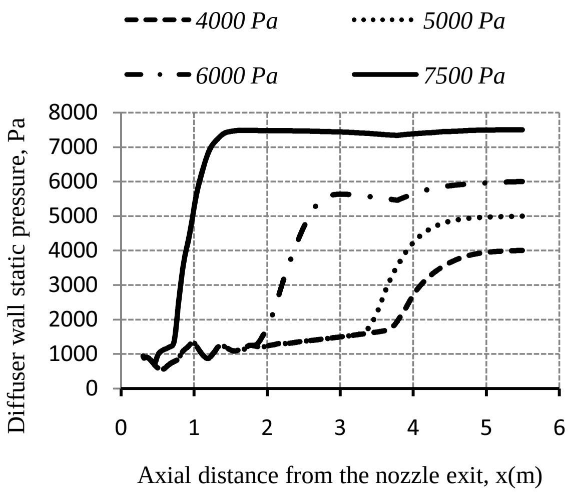

Fig. 8 Static pressure distribution along diffuser wall for back-pressures 4000, 5000, 6000 and 7500 Pa

To sum up, the designed diffuser is capable of maintaining an undistributed flow in the test section for back pressures in the range of 200 – 7000 Pa. In order to obtain definite subsonic flow at the exit of the diffuser (as demanded by the diffuser downstream components), it is required to operate the diffuser at a back pressure exceeding 2500 Pa. However, appearance of normal shock in the catch-cone/throat intersection around 7500 Pa limits the upper operating back pressure to 7000 Pa. Thus, taking into account the two main diffuser requirements, namely the ability to maintain undistributed test section flow and ability to compress the high supersonic to low subsonic flow, it is recommended to operate the diffuser in the back pressure range of 4000 – 4500 Pa. Introduction of a specimen/model in the test section may result in reduced diffuser performance, which in turn reality lowers the desired operating sub-atmospheric back pressure to 60% of the above stated value.

IV. Conclusion

The supersonic diffuser is an important aerodynamic component of the plasma wind tunnel, and its proper working is essential for meeting various objectives, such as the ability to maintain the required test-section flow, to recover pressure and to decelerate high supersonic flow to low subsonic flow. This inevitably calls for a design methodology that can be employed for designing low Reynolds number supersonic diffusers. Towards this objective, a detailed design methodology for sizing a supersonic diffuser operating presented in this paper. The design takes into account the high viscous nature of the flow in the diffuser and model blockage. However, the design methodology presented here is mainly meant for arriving at a preliminary configuration for the diffuser, which may be improved upon or optimized by undertaking a detailed performance evaluation using numerical flow simulation.

The performance analysis of the diffuser sized for a one megawatt power rated plasma facility (using the design methodology presented above) was carried out for different back pressures and it is found that the diffuser is capable of maintaining the required test-section flow for wide range of back pressures (200 – 7500 Pa). But requirements such as subsonic flow at the exit of the diffuser and avoidance of a terminal (normal) shock in the catch-cone or first half of the diffuser throat, requires operating back pressure in the range of 2400 – 2700 Pa.

In general, the performance of the diffuser is sensitive to its throat diameter cum length, the nozzle to which it is attached to and the operating back-pressure.

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