

Development of Mach 3.6 water cooled Facility Nozzle

By

Jayaprakash C*, Sathiyamoorthy K*, Ashfaque A. Khan*, Venu G*,
Venkat S Iyengar*, Srinivas J**, Pratheesh Kumar P**
and Manjunath P*

* Scientists, ** Technical Officer, National Aerospace Laboratories, Bangalore - 560037
cjpnal@nal.res.in, sathy_cim@nal.res.in

Abstract

This paper describes the design and development of Mach 3.6 water cooled facility nozzle using both analytical and computational approaches and highlights the subsequent experimental tests which showed that the results were in agreement with the design intent. The nozzle has been designed based on method of characteristics to get uniform Mach number at the exit plane. Nozzle operating conditions are 25 bar total pressure, 1700 K total temperature and 30 kg/s total mass flow rate with an exit area of 350 mm x 350 mm.

In addition to the above effort, computational studies were made to predict and validate the flow in the Mach 3.6 nozzle that was designed to produce a uniform supersonic flow. ANSYS-Fluent commercial code was used to compute the flow through a 2-Dimensional convergent divergent nozzle. The geometry and grid were generated using the pre-processor (GAMBIT). In order to capture the boundary layer efficiently, fine grid was generated near the wall. The conservation equations

were discretized with 2nd order upwind scheme. Three different mesh sizes were taken for the grid independence study and five different turbulence models were used for assessing the appropriate model. 2-D steady state RANS (Reynolds Averaged Navier-Stokes) equations were used for computation. Among the models investigated, SST k- ω and RNGk- ϵ turbulence models were found to give better agreement.

Introduction

The Propulsion Division, NAL has established a Mach 3.6 semi-free jet test facility for experimental evaluation of high speed combustors. In semi free-jet test facility, the scramjet combustor can be tested along with intake which is required to understand the combustor intake interaction. An important component of the semi-free jet test facility is the nozzle that has to supply a Mach 3.6 supersonic jet to the test section, where research combustor models are held to study the performance characteristics.

The need for the establishment of ground test facilities for the research and development of high speed combustors has been well documented in Dunn M G., et al.,¹.

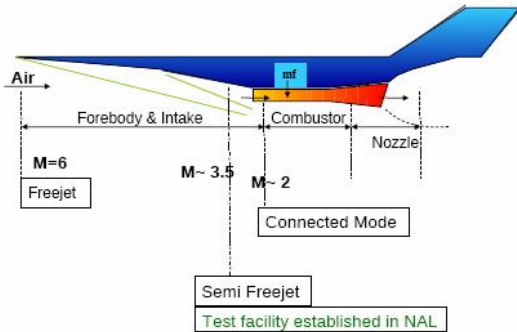


Fig.1 Schematic of the Vehicle Station Mach number

Flight Mach number of 6 and Mach number of 3.6 at the end of fore body of a generic vehicle have been considered and shown in Fig. 1. The simulation parameters of total pressure (P_o), total temperature (T_o) and dynamic pressure (q) have been calculated from the standard Indian atmospheric tables.

Air is stored in the vessels by the air compressor at 200 bar (max) and is admitted into the test rig through control valves for the required test rig pressure of 25 bar (max). The pre-heaters heat the air using kerosene fuel to the required temperature of 1700 K. The instrumentation and control system monitor and control the test rig parameters to the set values. The schematic of the test facility is shown in Fig. 2.

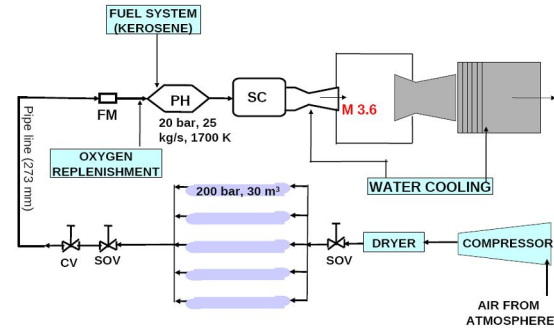


Fig.2 Schematic of the Test Facility

Technical Requirement of the Nozzle

The nozzle has to supply a Mach 3.6 supersonic jet to the test section where scramjet models are held. The nozzle has to be designed based on method of characteristics to get uniform Mach number at the exit plane. The throat section has to be circular arc and the divergent portion has to have contour to turn the flow such that the exit plane Mach number is uniform. The nozzle has to be two dimensional and exit plane needs to be rectangular. Since the flow getting accelerated in the nozzle is at a very high temperature (1700 K), the nozzle needs to be water cooled to withstand the heat.

Inlet conditions to the Nozzle

The nozzle has to be designed and manufactured for the following inlet conditions:

- Total pressure : 25 bar
- Total temperature : 1700 K(max)
- Mass flow rate : 30 kg/s
- Inlet Mach number : Subsonic
- Exit Mach number : 3.6

Nozzle Contour Design

The supersonic contour has been designed based on method of characteristics. A C++ program has been written to design the nozzle.

Design of nozzle using method of Characteristics

The nozzle flow path contains three important contours namely:

1. Inlet contour
2. Throat contour
3. Turning contour.

They are shown in the Fig.3

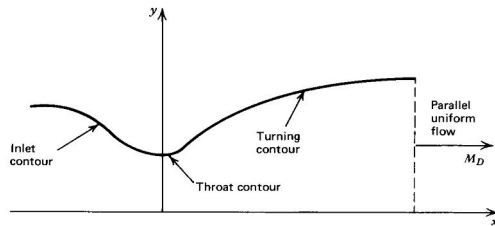


Fig.3 Nozzle flow path Contours

The inlet contour of the nozzle is the portion where the flow is accelerated and guided up to the throat contour. The throat contour is the region where the flow becomes sonic. The trailing portion of the throat contour is called initial expansion contour where flow is accelerated to the required exit Mach number. The turning contour turns the supersonic flow such that the exit Mach number becomes uniform.

There is no specific method to design the inlet contour. Combination of circular arcs is generally used to get the smooth flow in the inlet contour region. The

throat contour is a semi circular arc and the radius of the curvature has been chosen such that the maximum discharge co-efficient is attained. The turning contour is established based on the method of characteristics to get uniform exit Mach number. Since the method of characteristics can only be applied to the supersonic flow, initial value line having supersonic region has been established using Sauer's method. The design methodology given by Zuckrow² has been adapted here.

The designed nozzle has a length 1663 mm with 350 X 360 mm inlet flow area, throat 40 mm X 350 mm and 350 X 350 mm as the exit area.

Test Rig

The Test Rig comprises of Pre-heater-01, Pre-heater-02, Settling chamber ducts, Mach 3.6 facility nozzle and diffuser.

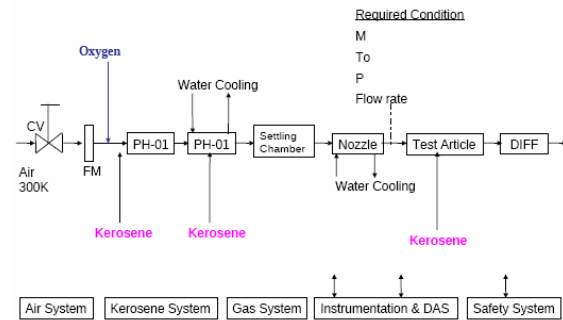


Fig.4 Schematic of the Test Rig

Design of water jacket for the nozzle

The test rig, which supplies air at the mentioned conditions to the test

article, is shown in Fig.4. The Mach 3.6 nozzle is located after the settling chamber duct to get the Mach 3.6 flow for the test article.

Inlet temperature to the Mach 3.6 nozzle is about 1700 K (max), this high temperature flow will create a problem for the material. Heat transfer to the nozzle will be very high and this heat should be removed from the nozzle by passing cooling water at the outer surface to safeguard the material at high temperature. The design of water jacket for the nozzle is very essential to remove heat continuously.

Design of water jacket includes the mechanical and thermal design. The working stress for various thickness of the metal is depicted in Table T1 for the maximum pressure condition of 30 bar. Based on the thermal design, the thickness chosen is 16 mm, since $\sigma_{working} = 41$ MPa for the water jacket of size 1.7 x 0.59 m². The factor of safety is 2.2 and it is shown in Table T 1.

T 1. Side plate design for the nozzle

Parameter	Value	Unit
σ_a^*	90	MPa
a	1.663	m
b	0.59	m
F	2.94×10^6	N

FS	σ_w (MPa)	t (mm)
1.5	60	10.9
2	45	14.5
2.2	40.9	15.9
3	30	21.8
3.5	25.7	25.4
4	22.5	29.0

* σ_a - Max. Allowable Stress for Carbon Steel

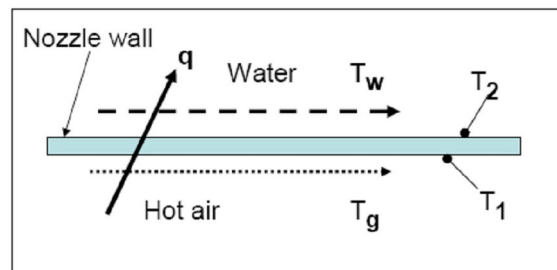
Thermal Design of Nozzle

The thermal design of nozzle is a case of convection and conduction heat transfer from the hot gases inside to the outside water. The heat transfer equations are given below. Steady state heat transfer and forced convection from the hot gases to the nozzle inner surface, conduction in nozzle metal casing and forced convection between nozzle outer surface and water have been considered. The properties of the hot gases have been worked out using NASA-SP-273.

Since the hot gases are at the temperature of the order of 1700 K, the water cooled jacket is provided to protect nozzle metal casing, limiting its outer surface temperature to about 630 K in the steady state heat transfer condition. Heat transfer coefficients on hot side (h_g) and cold water side (h_w) have been calculated.

$$q = \frac{T_g - T_w}{R1 + R2 + R3}$$

where, q- Heat transfer rate (W), T_g -Gas temperature (K), T_w - Water temperature(K) and R1, R2 & R3 are the thermal resistances.



Forced convection from hot gas to the nozzle inner surface

$$q = h_g A_1 (T_g - T_1)$$

Conduction in metal from inner to outer surface

$$q = \frac{k A_2}{L} (T_1 - T_2)$$

Forced convection between outer surface to the water

$$q = h_w A_3 (T_2 - T_w)$$

Heat transfer coefficient h is calculated using following equations:

For forced convection and turbulent flow, the Nusselt number is,

$$Nu_d = 0.023 Re_d^{0.8} Pr^{0.4}$$

Where, Re_d is the Reynolds number and Pr is Prandtl number

The heat transfer coefficient,

$$h \text{ is calculated from, } Nu_d = \frac{h D_h}{k}$$

The water flow rate of 5 kg/s at 4 bar pressure have been selected to limit the metal temperature to 630 K and limit the raise in water temperature to 283 K.

Experimental Tests and Results

The measurement points at the upstream and down stream of the nozzle are shown in Fig.5. The engineering drawing of the nozzle is shown in Fig.6. The Mach 3.6 water cooled nozzle assembly is shown in Fig.7. The Mach 3.6 propulsion test facility was commissioned in Feb-2012 and is shown in Fig.8. The cooling water mass flow rate is about

5 kg/s. The raise in water temperature is about 10° C (max) which is measured during the experimental testing and is in agreement with the designed value. The experimental result for the nozzle is shown in Fig.9, which indicates the stable value of exit Mach number calculated with total pressure and nozzle exit static pressure, for the test duration of 12 seconds. The total temperature measured at the upstream of the nozzle is shown in Fig.10. The total pressure and total mass flow rate of the test rig are shown in Fig.11 and Fig.12.

A dedicated DAS with 16 bit ADC modules and an accuracy of $\pm 35 \mu V$ has been used to acquire all the measured parameters viz., pressure, temperature and mass flow rate. The accuracy of pressure transducers is $\pm 0.2\%$ of full scale. B-type thermocouples were used to measure the temperature of the order of 1700 K with an accuracy of $\pm 1.7^\circ C$. The fuel mass flow rates were measured with an accuracy of $\pm 0.5\%$ of full scale. Orifice plate is used to measure the air mass flow rate with an accuracy of $\pm 0.5\%$.

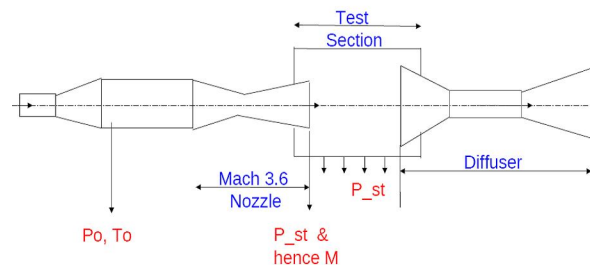


Fig.5 Schematic of the measurement plan

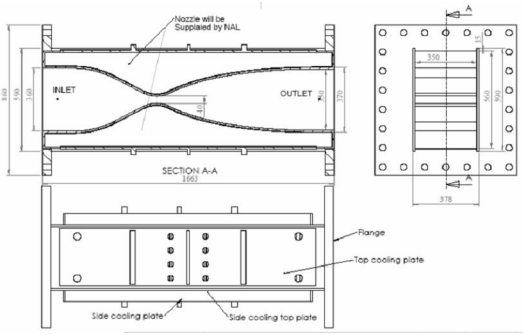


Fig.6 Engineering drawing of nozzle



Fig.7 Mach 3.6 water cooled nozzle



Fig.8 Semi free-jet test rig

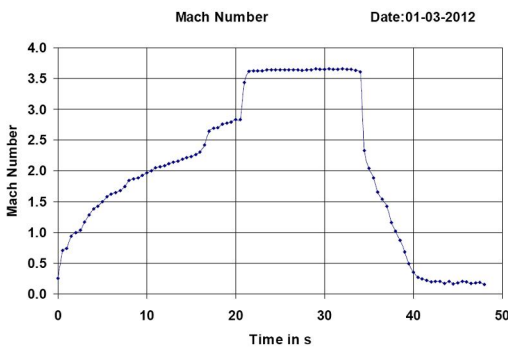


Fig.9 Mach number

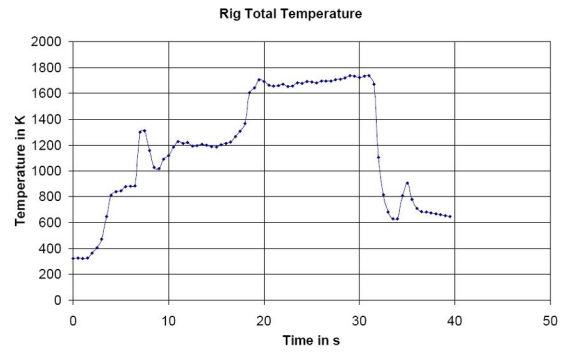


Fig.10 Rig Total Temperature

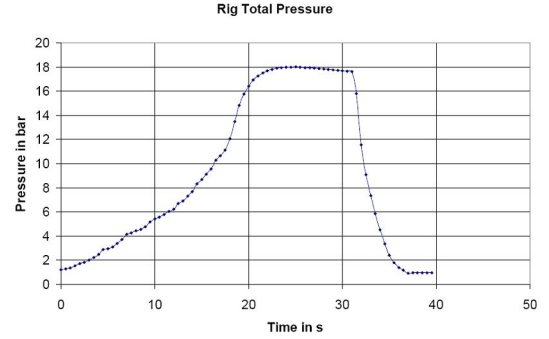


Fig.11 Rig total pressure

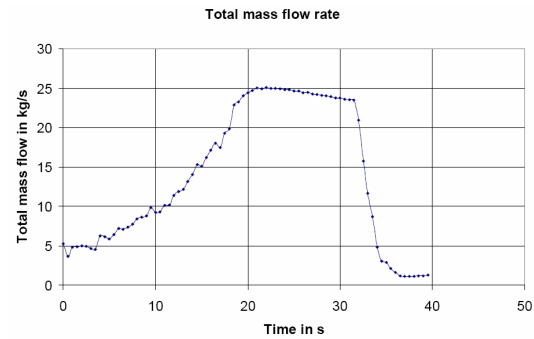


Fig.12 Rig total mass flow rate

Computational Details

The geometry and structured grid for the nozzle have been generated using the pre-processor (GAMBIT). Since the nozzle is symmetric about the centerline, only half part of the nozzle was taken for computation. In order to capture the boundary layer efficiently, boundary layer grid was generated near the

wall by considering the y^+ value. The conservation equations were discretized with 2nd order upwind scheme. Three different mesh sizes containing 38710, 74700 and 215800 number of cells were taken for the grid independence study. Different turbulence models (Sk- ϵ , RNGk- ϵ , Rk- ϵ , Sk- ω and SSTk- ω) were used for assessing the appropriate model. 2-D steady state RANS (Reynolds Averaged Navier-Stokes) equations were used for computation. Pressure based solver was successfully used for such a high Mach number flow.

Boundary conditions

The inlet boundary has been specified as given below:
 $P_0 = 20$ bar, $T_0 = 1700$ K.
 The flow direction is specified as normal to the inlet.

Results and Discussion

The converged solutions captured the overall features of the flow. Mach number contour using medium grid with SSTk- ω model is shown in Fig 13, which indicates that the overall flow features are captured correctly. It also indicates that the peak value of Mach number at the exit of the nozzle is 3.56. There is no significant difference in the exit Mach number plot with different mesh sizes as shown in Fig.14. This indicates that the solutions are grid independent. In addition, it also indicates a uniform value of Mach number (3.56) at the exit of the nozzle except in

the boundary layer region. The uniform value of exit Mach number (3.56) agrees with the experimental results as shown in Fig.9. The velocity profiles at the exit of the nozzle with medium grid for five different turbulence models, shown in Fig.15, also does not show any significant variation. However, SSTk- ω and RNGk- ϵ results were found to be comparatively better than the other models.

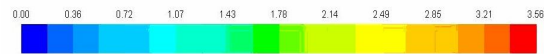
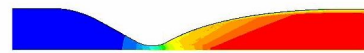


Fig.13 Mach number contour (Medium Mesh, SSTk- ω)

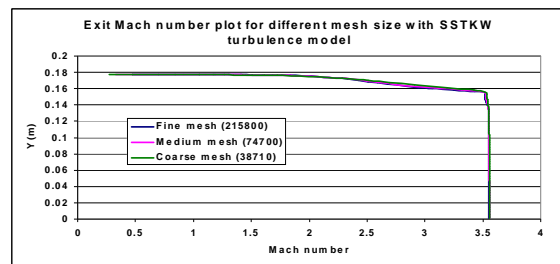


Fig.14 Mach number plot at the exit of the Nozzle for different grid size with SSTKW turbulence model.

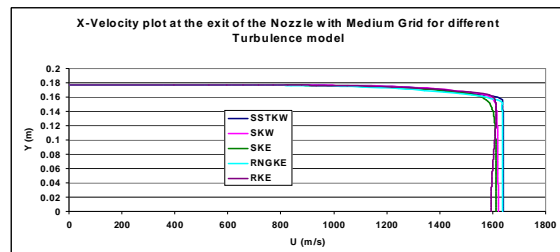


Fig.15 X - Velocity plot at the exit of the Nozzle for different Turbulence model (Medium Grid)

Conclusions

Mach 3.6 water cooled nozzle has been designed and developed. It was successfully commissioned and is operating under the required conditions. The experimentally measured exit Mach number matches with the design value as well as CFD predicted Mach number.

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