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Thermal Design of Mach 8 Nozzle for Hypersonic wind Tunnel

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Abstract: The wind tunnel forms important aspect of testing of bodies or space vehicle. In the present study Mach 8 nozzle for hypersonic wind tunnel is thermally analysed. The analysis is formed under high temperature conditions as expected in space. The material of nozzle has been tested for high temperature with and without throat cooling conditions. The analysis is performed for alternative cycle of heating and cooling of nozzle. It was found for the conditions of analysis, the temperatures in the material of nozzle are within the acceptable limits.

Keywords: Mach 8, Nozzle, Thermal, Wind tunnel, Space

I. INTRODUCTION

The hypersonic wind tunnel is used to perform wind tunnel simulation studies in the hypersonic range of Mach numbers. Figure 1 shows typical schematic of hypersonic wind tunnel. Such wind tunnels are used for testing by space agencies. The system uses air as working fluid, which is usually heated to high temperatures in a storage air heater before passing through the nozzle. The nozzle used in experimental setup is subjected to high temperatures.

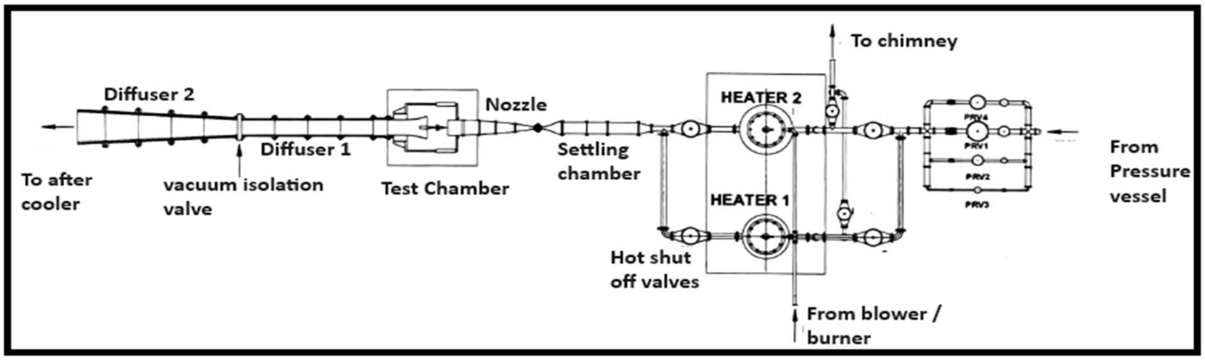


Figure 1: Typical Wind tunnel assembly

II. OBJECTIVE OF THE PRESENT WORK

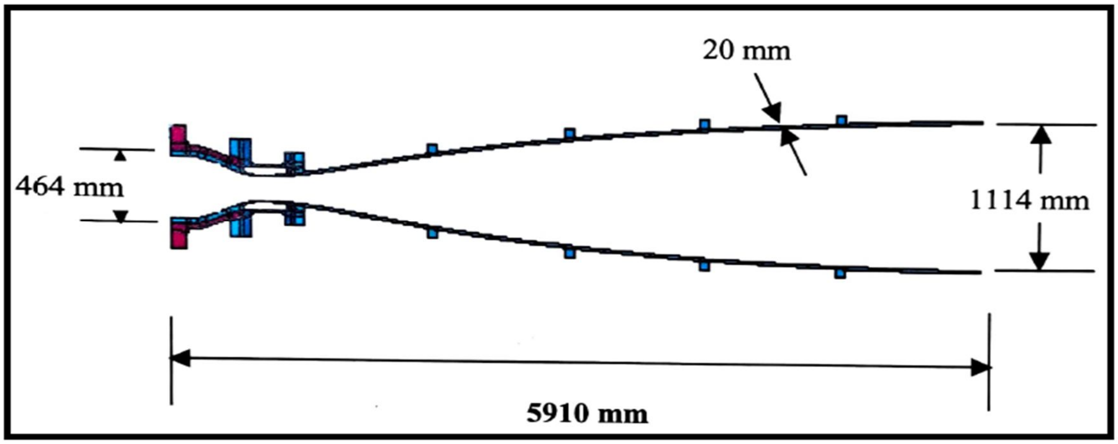


Figure 2: Dimensions of the Nozzle used in thermal analysis

In the present work, the Mach 8-nozzle design for hypersonic wind tunnel is considered for thermal analysis. The design is to be finalized by carrying out exhaustive thermal analyses. It has to be ensured that maximum temperatures in all components of nozzle are within the allowable values satisfying the thermal requirements. The dimensions of nozzle considered for analysis is shown in Figure 2.

III. MACH 8 NOZZLE CONFIGURATION

Schematic of Mach 8 nozzle is shown in Figure 2. SA 516 Gr-70 is selected for subsonic section (convergent portion) with internal ceramic fiber lining. As heat flux increases towards the throat region, ARMCO17-4 PH is used as thermal protection system due to high thermal conductivity. Throat section is cooled by providing water jacket (material SA 516 Gr-70) around it. The divergent portion of nozzle is made in 5 different sections connected at flange. First section after throat is made of ARMCO 17-4 PH material. AISI 304L is used for remaining four divergent sections. The overall dimensions of the nozzle are shown in figure2. The properties of the material used in the thermal analysis are as follows.

A. Material: Ceramic- liner

Density (kg/m^3) = 4500

Specific Heat Cp and thermal conductivity K

Temp (K)	300	325	350	375	400	425	450	475	500
Cp (J/kg-K)	524.56	529.58	534.83	540.28	545.91	551.67	557.55	563.5	569.5
K (W/m-K)	21.88	21.45	21.07	20.73	20.44	20.19	19.98	19.80	19.65

B. Material: Ceramic fiber

Density, (kg/m^3) = 300
Specific Heat cp (J/kg-K) = 1050

Thermal conductivity K

Temp (K)	300	350	400	450	500	550
K (W/m-K)	0.0793	0.092	0.1032	0.1137	0.124	0.1346

C. Material: SA 516 Gr.-70

Density, (kg/m^3) =7780
Specific Heat Cp (J/kg-K) = 447
Thermal Conductivity (W/m-K) = 32

D. AISI 304L

Density, (kg/m^3) =7900

Specific Heat Cp and thermal conductivity K

Temp (K)	300	350	400	450	500	550
cp (J/kg-K)	477.48	497.49	514.09	527.87	539.34	548.99
K (W/m-K)	14.89	15.77	16.62	17.44	18.23	18.62

E. ARMCO 17-4 PH

Density, (kg/m^3) = 7780
Specific Heat cp (J/kg-K =460.55

Thermal conductivity K

Temp (K)	300	350	400	450	500	550
K (W/m-K)	178.06	175.36	176.92	181.76	188.93	197.46

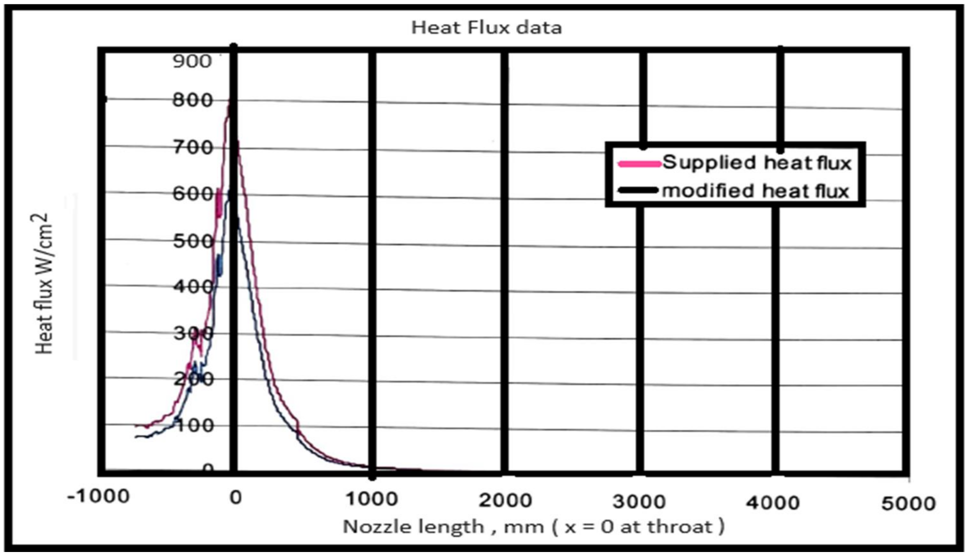


Figure 3: Variation of heat flux along the nozzle length

The internal contour of Mach 8 nozzle is generated using ANSYS. The heat flux data used for nozzle analysis is shown in Figure 3. The data has been taken from literature. A 30 % margin over the heat flux data has been taken for the thermal analysis with air temperature inside nozzle as 750 K. Hence the figure3 shows both heat flux from literature and modified heat flux. The variation of cold wall heat flux along the nozzle axis is seen in the figure 3. Using this data, heat transfer coefficient variation data along the length of nozzle is generated (refer figure 4). This heat transfer coefficient values are applied at the inner surface of nozzle for analysis.

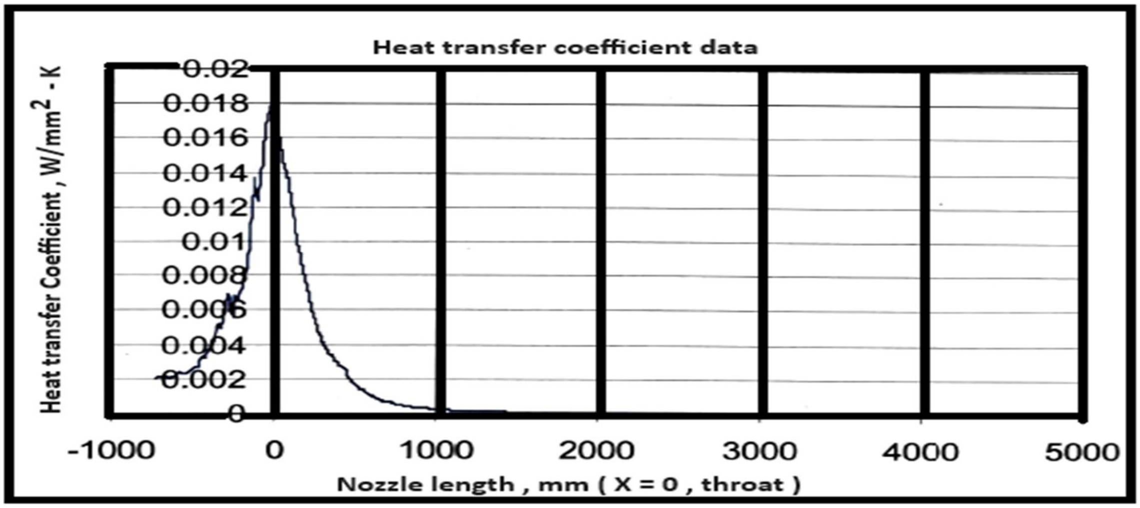


Figure 4: Heat transfer coefficient variation along the nozzle length.

IV. FE MODEL

2D model is generated using ANSYS software. The Nozzle cross-section is meshed using PLANE55 elements [l]. PLANE55 element is 4-noded plane element with one degree of freedom (Temperature) per node, with 2-D steady state and transient analyses capability. The FE model of the Mach 8 nozzle is shown in Fig 5. The model has 15090 nodes and 13708 elements. Radiation boundary conditions are applied using MATRIX50 super-elements. LINK32 elements [1] are used for generating the MATRIX50 super-elements [1].

V. BOUNDARY CONDITIONS

The boundary conditions applied on the structure are schematically shown in Fig 6. As can be seen the outer surfaces are subjected to natural convective boundary conditions with 303K as ambient temperature. Churchill and Chu Correlation used for average Nusselt number (Nu) calculation are as below [2].

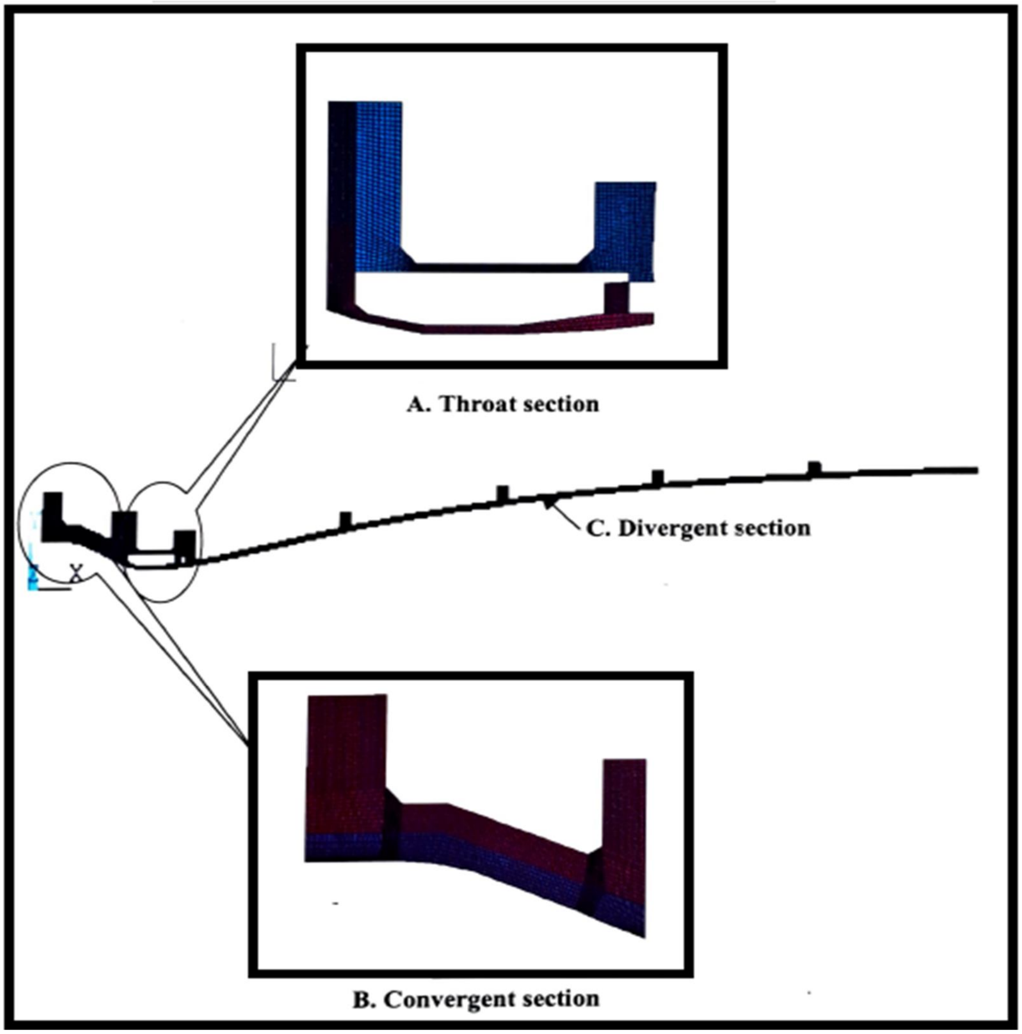


Figure 5: FE model of a Nozzle

$$Nu = \left\{ 0.6 + \frac{0.387\, Ra^{1/6}}{\left[1 + \left(\frac{0.559}{Pr}\right)^{9/16}\right]^{8/27}} \right\}^{2}$$

Here,
$h_{air} = 6$ W / m2 – K

Ra_D = Rayleigh number
Pr = Prandtl number
h_{air} = Average heat transfer coefficient for natural convection

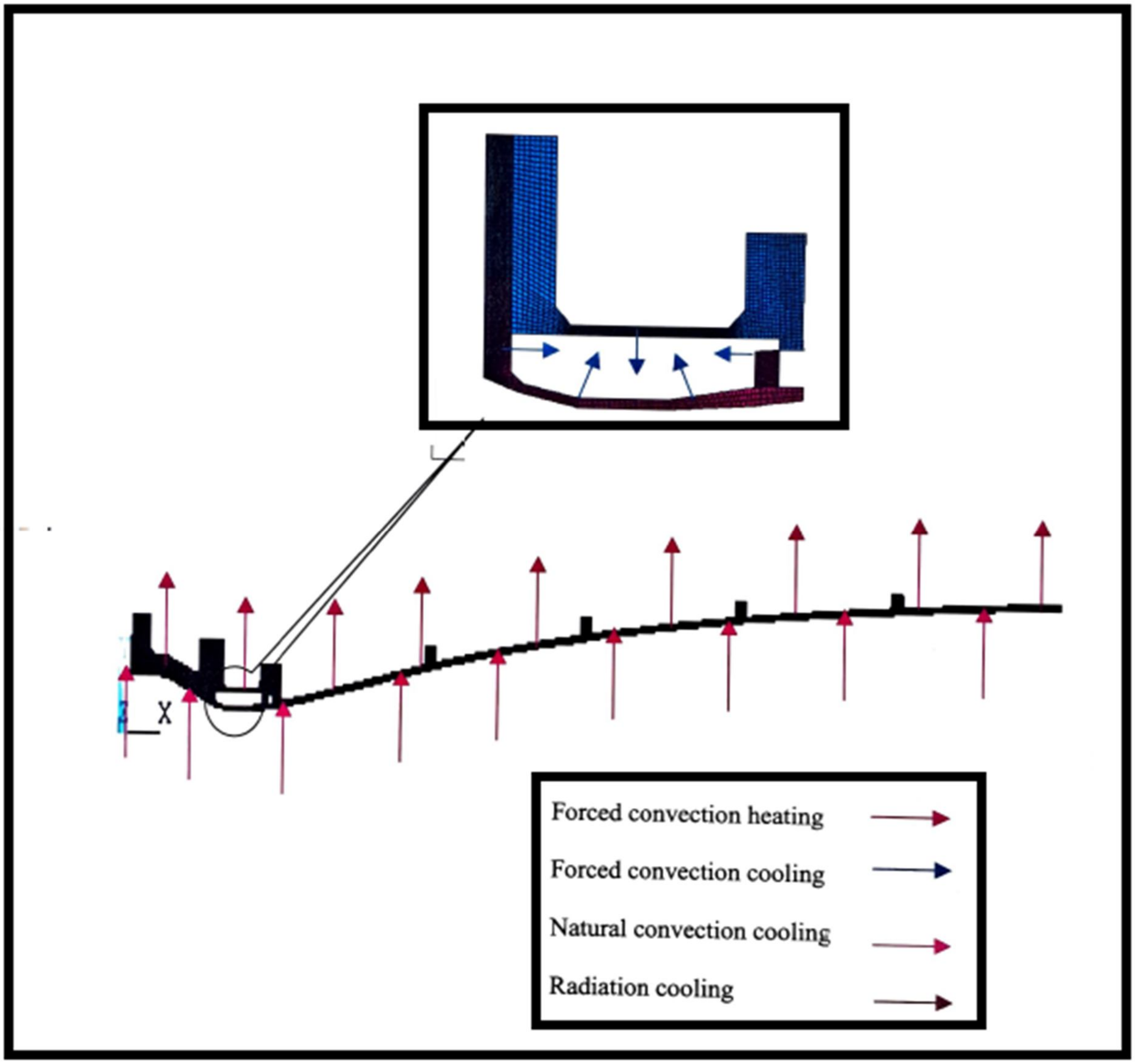


Figure 6: Various boundary conditions on nozzle

The heat transfer coefficients for throat cooling are calculated using following correlation for forced convection [2] with bulk temperature of water as 303 K.

$Nu = 0.023\, Re^{4/5}\, Pr^{0.4}$ for $Re > 10000$
Mass flow rate of water in jacket is taken as 10 kg/s
Average heat transfer coefficient calculated is = 2392 $W/m^2 - K$

Radiation boundary condition is applied on the outer surfaces of the nozzle as shown in figure 6. The emissivity value is considered as 0.8 as it is proposed to use coating on outer surface to enhance radiation. Above boundary conditions are used for analysis during nozzle cooling operation of 5400 sec. During blow down operation in convective boundary condition is also applied on inner surface of nozzle with gas temperature of 750 K.

VI. SOLUTION METHOD

Analysis for nozzle is done for two different cases

1) Without active throat cooling.
2) With throat cooling.

Axisymmetric analysis is done for nozzle. For all the cases CFD data was used as input to generate, the temperature contours in the nozzle for 5 blow down cycle operation. Each blow down was considered to be of 30 sec durations (heating) followed by a 1.5-hour gap where the nozzle cools back by natural convection and radiation. Heating and cooling constitute one cycle of analysis. Thermal and mechanical properties of different materials used for analysis is given in Appendix.

VII. RESULTS AND DISCUSSIONS

2-D Axisymmetric transient thermal analyses are carried out for both the cases. Analysis was done for 30 sec for blow down operation followed by cooling for 5400 sec. The temperature distribution in the nozzle is obtained. The temperature contours at 30 sec without throat cooling and with throat cooling is shown in Fig 7 and 8 respectively. It is observed that maximum temperature at throat reduces from 749.8 K to 746 K due to cooling. Table 1 shows the maximum temperature attained by different material of nozzle without throat cooling. Fig.9 and fig.10 shows temperature contours for first and fifth cycle of analysis. Maximum temperature attained by each material during five cycle (blow down and cooling) is recorded in table 2. Maximum rise is found in case of ceramic liner, i.e from 348 K to 379 K. Temperature variations at flange joint is important consideration for design as material changes generate considerable temperature gradient which is the cause of thermal stress. Point A and B at flange joint is considered (figure 11) and temperature variation for five cycles is plotted (figure 12 and figure 13). At point A temperature fluctuates from 303 K to 580 K while for point B it is 303 K to 315 K.

Table 1: Maximum temperature attained by different metals of Nozzle

Section	Material	Max. Temperature (K)
Convergent	Ceramic Liner	749.8
	Ceramic Fiber Insulator)	749.7
	SA 516 Gr-70	306
Throat	ARMCO 17-4 PH	749.6
	SA 516 Gr -70	305
Divergent	AISI 304L + ARMCO 17-4 PH	680

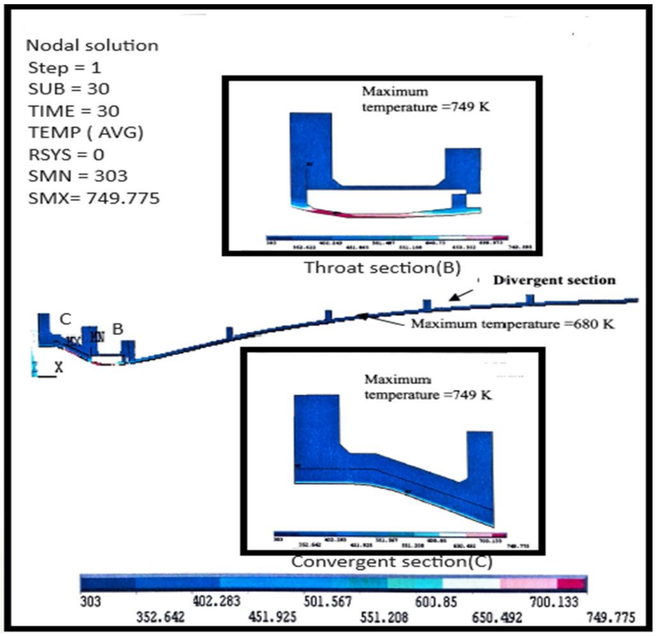


Figure 7: Temperature Contours at 30 second (without throat cooling)

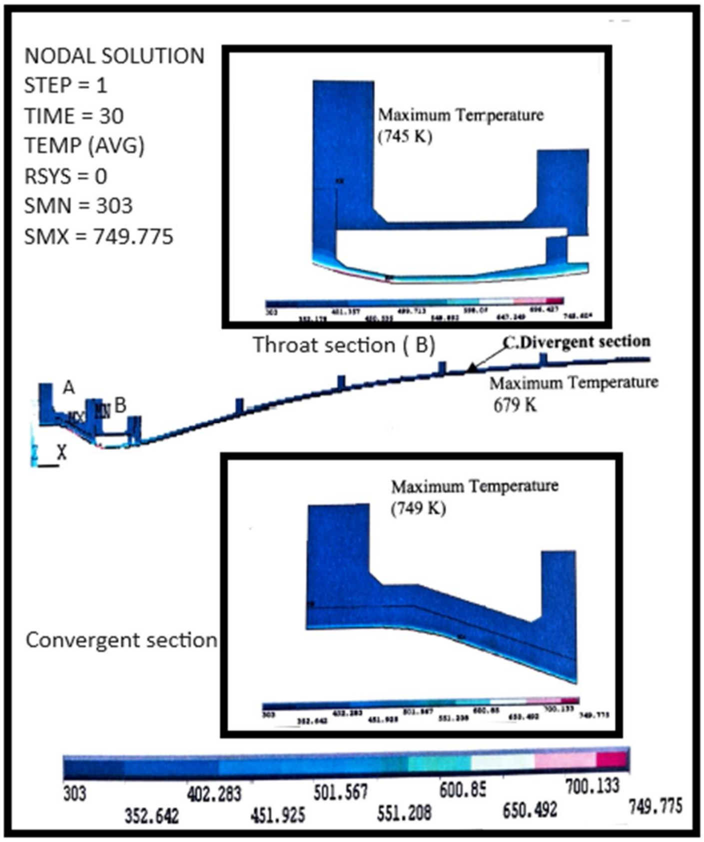


Figure 8: Temperature contours at 30 second (with throat cooling)

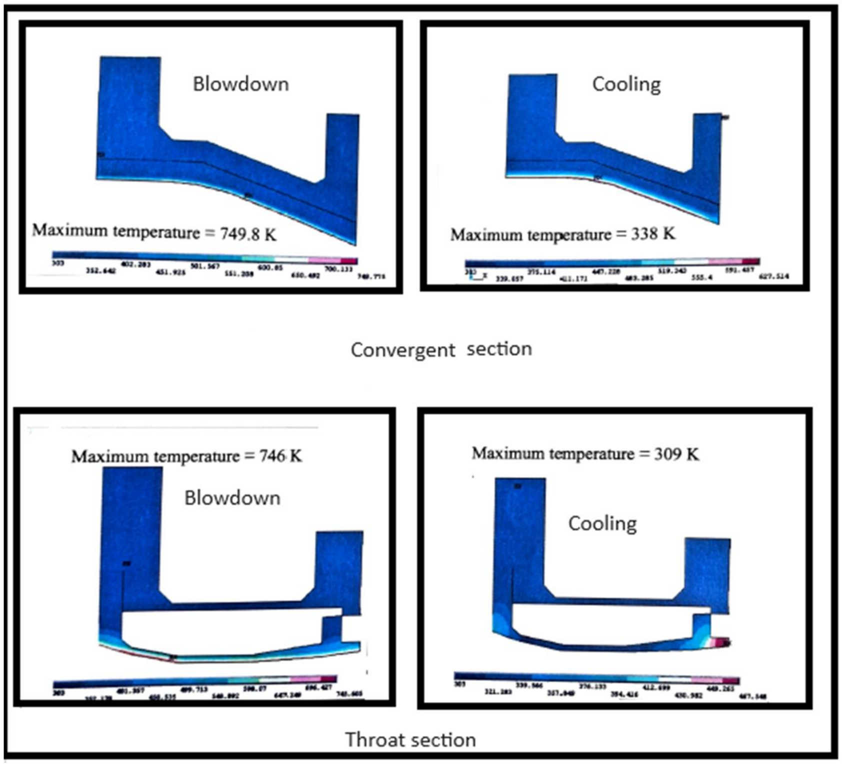
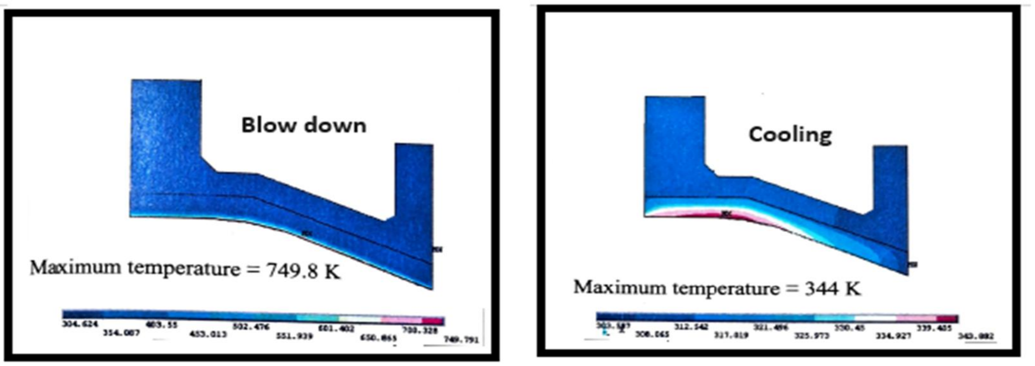
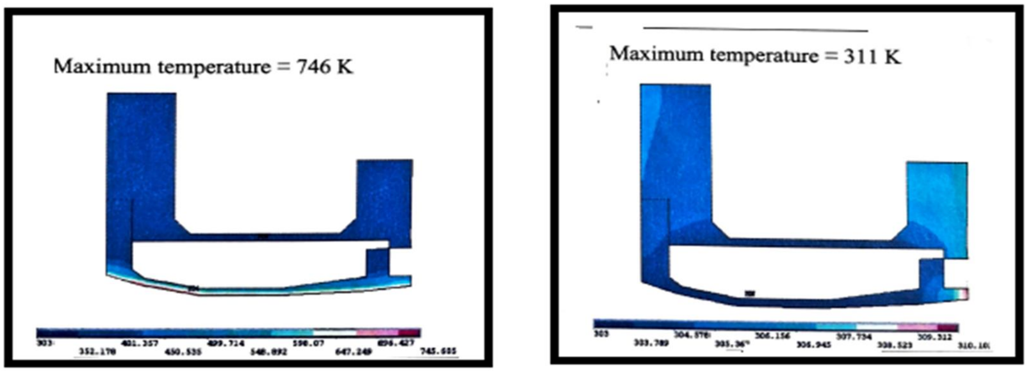


Figure 9. Temperature contour in convergent and throat section of Nozzle during first cycle



Convergent section



Throat section

Figure 10. Temperature contour in convergent and throat section of Nozzle during fifth cycle.

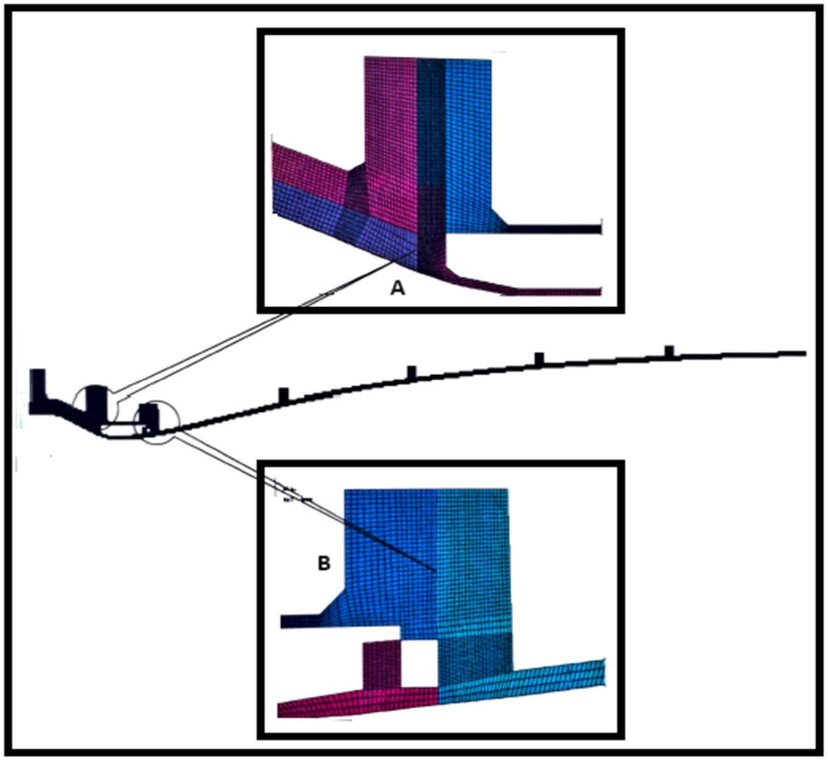


Figure 11: Location of points at flange joint

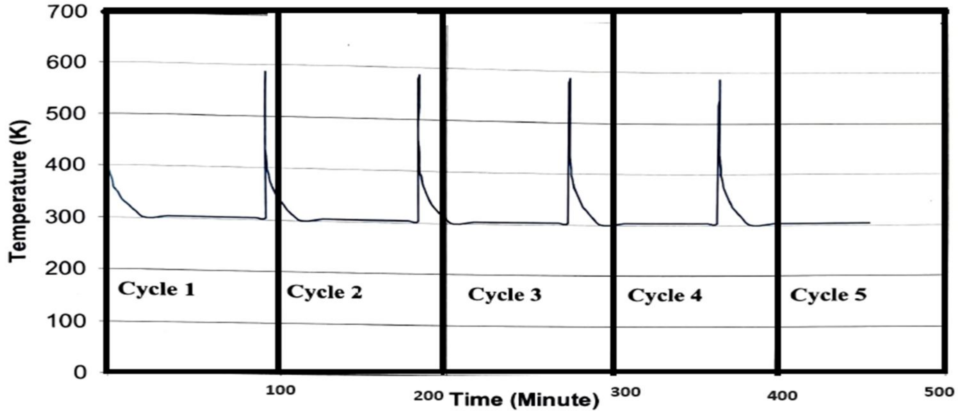


Figure 12: Temperature variation at Point A

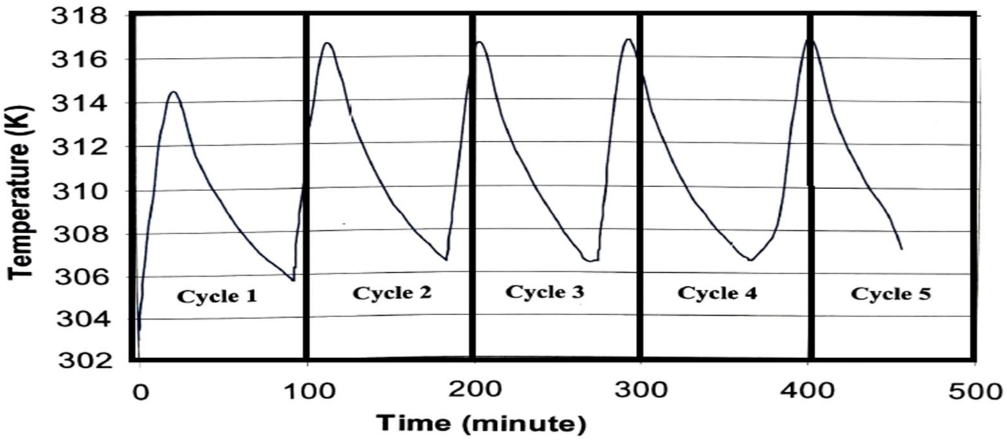


Figure 13: Temperature variation at Point B

Table 2: Maximum Temperature attained with throat cooling during five cycles

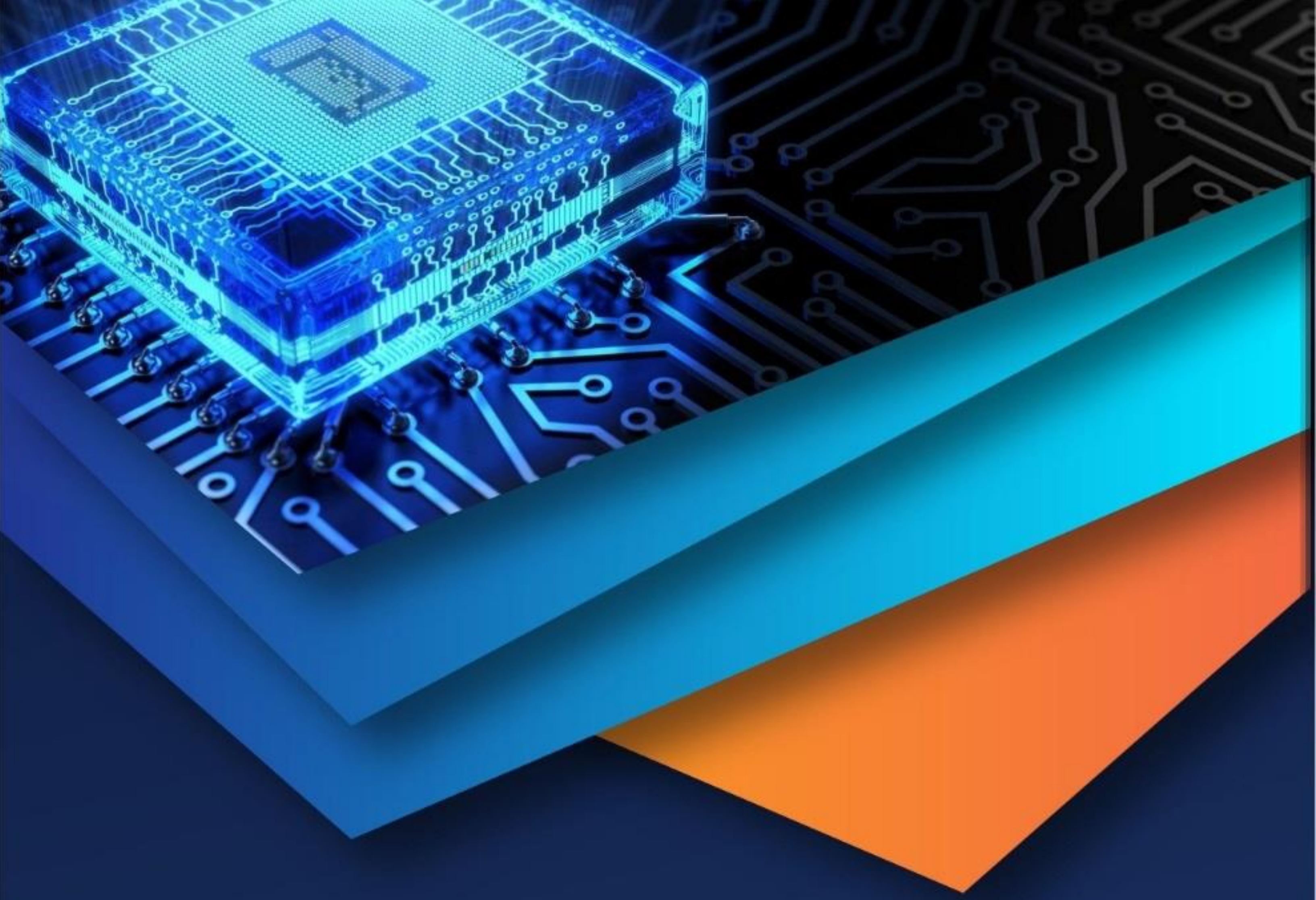
Section	**Material**	**Max. Temperature (K)**									
		Heating 1	**Cooling1**	**Heating 2**	**Cooling 2**	**Heating 3**	**Cooling 3**	**Heating 4**	**Cooling 4**	**Heating 5**	**Cooling5**
Convergent	Ceramic Liner	749.8	338	749.8	343	749.8	343	749.8	344	749.8	344
	Ceramic Fiber (Insulator)	749.7	338	749.7	343	749.7	343	749.7	344	749.7	344
	SA 516 Gr-70	305	307	309	310	310	311	310	312	312	312
Throat	ARMCO 17-4 PH	746	309	746	310	746	310	746	311	746	311
	SA 516 Gr -70	304	307	308	308	308	308	308	308	308	308
Divergent	AISI 304L + ARMCO 17-4 PH	680	348	681	373	681	373	681	377	681	379

VIII. CONCLUSION

The Mach 8 Nozzle thermal analysis has been performed. It is found that maximum temperatures attained by all the components during the blow down operation and cooling operation are well within the material safe limits.

REFERENCES

[1] ANSYS reference material
[2] Fundamentals of Heat and Mass Transfer, Frank P. Incorpera, David P. Dewitt, Fourth Edition.
[3] Thermal Properties of Metals, ASM International, First Edition, 2002



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