CFD Analysis of High Temperature and High Velocity System: Plasma Torch

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Abstract- It is a cascaded plasma torch with seven segment including cathode, anode, auxiliary anode and four number of floating rings. Two different designs of segment with two different dimensions are selected for making the segment of seven segmented torch according to the effectiveness of cooling. One is inlet and outlet pipe are on opposite side of water jacket and another one is inlet and outlet pipe are on same side, separated by a separating wall. The numerical model is developed to estimate heat transfer coefficient, compare and analyze the performance of these different types of segment designs of seven segment plasma torch. GAMBIT is used as a pre-processor to create geometry and computational mesh and the CFD Software package FLUENT based on the finite volume method is used to obtain the numerical results. The equations governing the flow and heat transfer are solved numerically by using finite volume techniques and additional transport equations are also solved when the flow is turbulent. The standard k- ϵ model is used for modeling turbulence while the conjugate heat transfer model is used for solving energy equation. The effect of power and mass flow rate on the heat transfer coefficient is studied. The Analysis constraint and mesh size selection criterion is Wall Y Plus value.
Keywords – Heat transfer coefficient, CFD, GAMBIT, FLUENT.

I. INTRODUCTION

Plasma torch are high temperature and high velocity systems. For efficient operation and to prevent failure, thermal and flow analysis of the system is very essential. CFD tools help us to achieve this without doing too many experiments on the actual system, thus saving time and money.

1.1 Plasma Torch Principle & its Application-

Plasma melting of metal involves generation of an electric arc between cathode and anode. When an electric potential difference is set up between cathode and anode, the spark ionizes the gas between the anode and cathode, an arc is formed. Thus a high intensity plasma arc between the electrodes is produced. Plasma torches have been used for producing thermal plasma jet & are used in welding and metallurgical industries for melting of metal in the presence of plasma. In B.A.R.C., Mumbai, it is generally used for coating of metal to prevent corrosion.

1.2 Specifications of Seven Segment Thermal Plasma Torch-

The number of segments is used in the thermal plasma torch to increase the potential difference. Argon gas is passed and cathode is 2% thoriated Tungsten to easily emit the electrons & the high temperature plasma arc coming out of the torch provides more amount of heat. The value of current is fixed about 200-400 Ampere, so we have to increase the value of voltage to get more heat and at the same time, to save the torch material from adverse effect of heat, cooling is done by water in each segment.

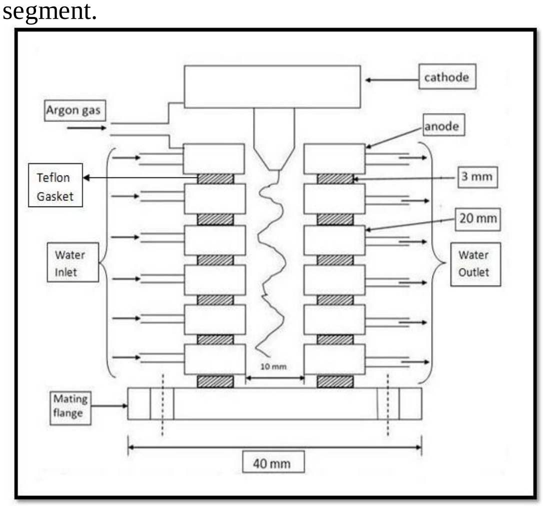

Fig. 1. The Seven Segment Thermal Plasma Torch ; Drawn on the basis of geometry given by B.A.R.C., Mumbai.

The cathode, anode, auxiliary anode and the floating rings are all made of copper. Cooling water flows in each segment, through the gap between the two rings, as the plasma flows through the central hole of the torch. Teflon gaskets of 3 mm thickness are placed in between the segments for achieving insulation & the base pressure less than 10^{-2} mbar in the system. Separate water cooling connection lines are to be provided to each of these segments.

II. PROPOSED WORK

2.1 Cooling Requirement in Each Segment

Plasma torch generally runs at high current, which generates temperature around 2000 – 20000 ° C. It leads to heating of torch body parts and generates very high thermal stress. To withstand a high thermal stress, plasma torch are generally cooled with water circulating in a provided cooling channel. The cooling fluid used is water at atmospheric condition. The fluid flow inside the channel is considered as incompressible and steady flow. Objective of cooling – To prevent the plasma torch from causing excessive temperature of body parts.

2.2 Research Objectives

Some of the research objectives that have been outlined and which would benefit the development of energy efficient plasma torch are:

- To compare and analyze the performance of four different designs of segment.
- To determine the heat transfer coefficient of different designs of segment.

So, during the complete analysis of seven segment thermal plasma torch, these already calculated heat transfer coefficient values will be directly used in deleted segments of plasma torch. Hence, the computational time will be saved and complete complex analysis of seven segment thermal plasma torch will be carried out in a simple manner.

2.3 Analysis Criteria

- To study the effect of power on heat transfer coefficient.
- To study the effect of mass flow rate on heat transfer coefficient.

III. EXPERIMENT AND RESULT

3.1. Geometry Description

First Design of Segment

The inlet & outlet pipe are on opposite side of water jacket & height of segment is 20 mm.

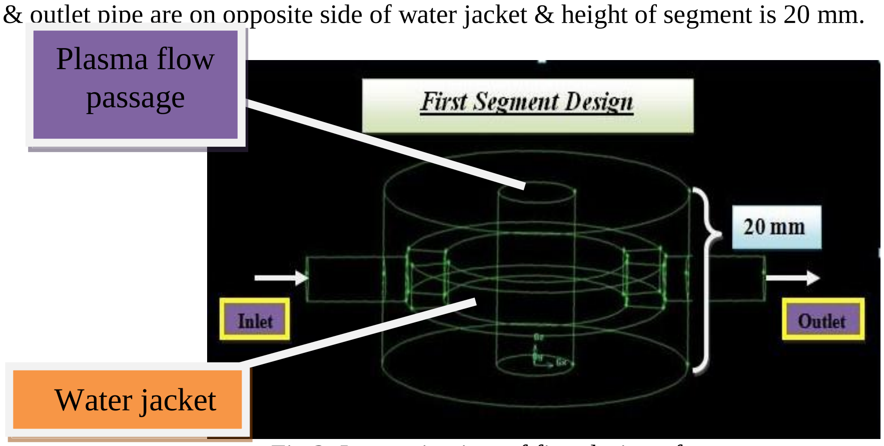

Fig.2. Isometric view of first design of segment

Created in GAMBIT on the basis of dimensions given by B.A.R.C., Mumbai.

Table 1. Dimensions of first design of segment

Plasma flow passage diameter	10 mm
Inner diameter of water jacket	24 mm
Outer diameter of water jacket	34 mm
Segment diameter	40 mm
Inlet pipe diameter	5 mm
Outlet pipe diameter	5 mm
Height of segment	20 mm

3.1.1 Second Design of Segment

The inlet and outlet pipe are on same side of water jacket and are separated by a separating wall of 4 mm thickness.

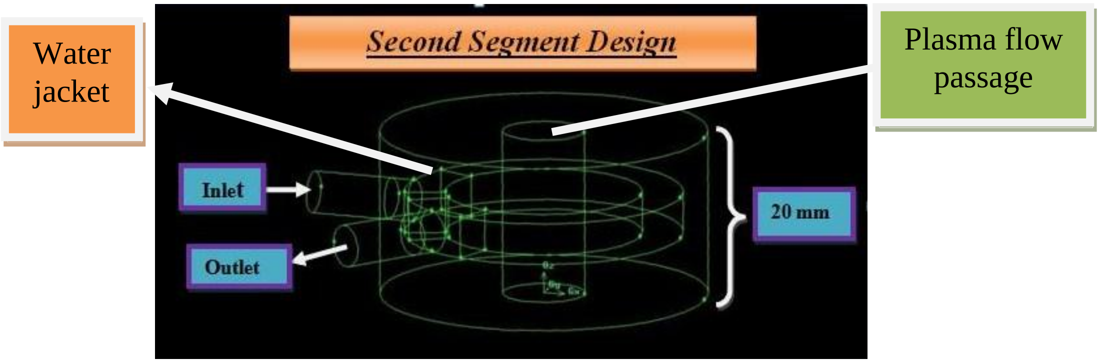

Fig.3. Isometric view of second design of segment

Created in GAMBIT on the basis of dimensions given by B.A.R.C., Mumbai.

Table 2. Dimensions of second design of segment

Plasma flow passage diameter	10 mm
Inner diameter of water jacket	24 mm
Outer diameter of water jacket	34 mm
Segment diameter	40 mm
Separating wall thickness	4 mm
Inlet pipe diameter	5 mm
Outlet pipe diameter	5 mm
Height of segment	20 m

3.1.2 Third Design of Segment

This design of segment is having same design & dimensions as that of the first design of segment. The only difference is that the height of segment in this case is 13 mm instead of 20 mm.

3.1.3 Fourth Design of Segment

This design of segment is having same design & dimensions as that of the second design of segment. The only difference is that the height of segment in this case is 13 mm instead of 20 mm.

3.2 Operating Conditions-

Analysis is performed for the following three cases.
i. Uniform distribution of heat transfer value (Q) on hfw1 and hfw2.
ii. When heat transfer value (Q) on hfw2 > heat transfer value (Q) on hfw1.
iii. When heat transfer value (Q) on hfw2 < heat transfer value (Q) on hfw1.
But suitable & accurate results are coming for above i. and ii. cases & the results and discussions are presented for the i. case.

Table 3. Operating conditions

Uniform distribution of heat transfer value (Q) on hfw1 & hfw2	
Mass flow rate (lpm)	1 lpm, 2 lpm, 3 lpm, 4 lpm
Net heat transfer value (KW)	0.2 KW, 0.5 KW, 1 KW, 2 KW, 5 KW, 10 KW

3.2.1 Nomenclature -

h – Heat transfer coefficient (W/m^2K), hfw1- Heat flux wall 1 i.e, upper & lower surface of segment
hfw2 – Heat flux wall 2 i.e, plasma flow passage wall, Δt - Change in temperature in K.

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3.2.2 Governing Equations-

The fundamental equations governing the physical process of Newtonian viscous fluid flow are the continuity and momentum equations. For the convenience of utilizing a tensor notation the x, y, z, coordinates will be denoted as x_1, x_2, x_3 and the u, v, w components of velocity as u_1, u_2, u_3. Neglecting body forces, the continuity and momentum equations can be written in Cartesian tensor form as follows:

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho u_i) = 0 \quad (1)$$

$$\frac{\partial}{\partial t}(\rho u_i) + \frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial}{\partial x_j}\left[\mu\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_i}{\partial x_i}\right)\right] + \rho g_i \quad (2)$$

Where i,j = 1,2,3…

The momentum equation written in the above form is known as the Navier-Stokes equation. This set of equations is a general set of equations that, along with some additional model equations can be used for calculations of any Newtonian viscous fluid flow in Cartesian coordinates. While the governing equation for solving the temperature field is provided by

$$\frac{\partial}{\partial t}(\rho E) + \frac{\partial}{\partial x_i}\big(u_i(\rho E + p)\big) = \frac{\partial}{\partial x_i}\left(k\frac{\partial T}{\partial x_i}\right) \quad (3)$$

Where, E is the total energy.

The transport equations of the k- ε turbulence model are as follows:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + G_k + G_b - \rho\epsilon - Y_M + S_k \quad (4)$$

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}(G_k + C_{3\epsilon}G_b) - C_{2\epsilon}\rho\frac{\epsilon^2}{k} + S_\epsilon \quad (5)$$

Equation 1, 2, 3, 4 & 5 from FLUENT Inc., FLUENT 6.3 User's Guide, 2006.

3.2.3 Solution Criteria-

The governing equations are solved at all grid points and residual values are plotted for each iteration till the Root Mean Square (RMS) values of residuals for energy & other lies below 0.000001. Fluent is used as a postprocessor for visualization of property variations such as temperature, velocity and pressure.

FLUENT – Based on finite volume method – used to obtain the numerical results. The equations governing the flow and heat transfer are solved numerically using finite volume technique. Standard k-ε model is used for modeling turbulence and conjugate heat transfer model is used for solving energy equation.

3.3 Meshing Description-

Table 4. Meshing details of first design of segment

Grid Size(mm)	Cells	Faces	Nodes
0.2	1364802	3186196	599615
0.5	161722	362682	58467
1	40971	89738	12716
2	12498	27419	3760

Table 5. Meshing details of second design of segment

Grid Size(mm)	Cells	Faces	Nodes
0.2	1076013	2566865	519498
0.5	135868	298644	43208
1	39157	85845	12097
2	11852	26049	3539

3.4 Project Methodology-

An analysis constraint or mesh size selection criterion is wall y plus value. Recommended range of wall y plus value in this case is 20 to 60. So, 0.5 mm & 1 mm grid sizes are found suitable. Grid independence test is also carried out.

3.5 First Design of Segment-

I. Effect of power on heat transfer coefficient

Mass flow rate = 2 lpm for all the cases

Table 6. Results for net heat transfer = 0.2 KW

Sr.No	Grid size/Meshing (mm)	h(W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4354.48	15.42	16.63
2.	0.5	3635.54	18.47	40.42
3.	1	3419.91	19.64	52.51
4.	2	3128.51	21.47	126.7

Table 7. Results for net heat transfer = 0.5 KW

Sr. No	Grid size/Meshing (mm)	h (W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4250.27	39.5	16.64
2.	0.5	3635.54	46.19	40.42
3.	1	3419.89	49.1	52.51
4.	2	3128.35	53.67	126.7

Table 8. Results for net heat transfer = 1 KW

Sr. No	Grid size/Meshing (mm)	h (W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4349.84	77.2	16.56
2.	0.5	3635.54	92.37	40.42
3.	1	3419.9	98.2	52.51
4.	2	3128.51	107.3	126.7

Table 9. Results for net heat transfer = 2 KW

Sr. No	Grid size/Meshing (mm)	h(W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4212.32	159.45	19.4
2.	0.5	3635.55	184.74	40.42
3.	1	3419.91	196.39	52.51
4.	2	3128.51	214.68	126.7

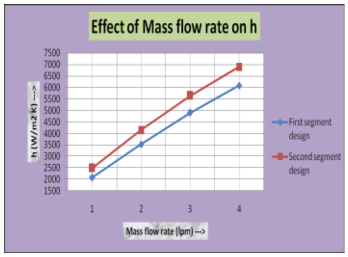
Table 10. Results for net heat transfer = = 5 KW

Sr. No	Grid size/Meshing (mm)	h(W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4225.24	397.4	19.45
2.	0.5	3635.55	461.85	40.42
3.	1	3419.91	490.98	52.51
4.	2	3128.51	536.71	126.7

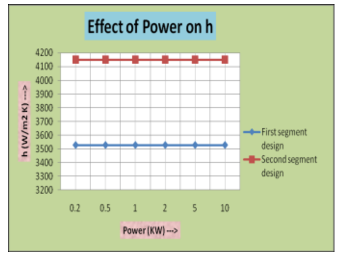
Table 11. Results for net heat transfer = = 10 KW

Sr. No	Grid size/Meshing (mm)	h(W/m^2 K)	Δt	Wall Y Plus
1.	0.2	4216.73	796.39	16.11
2.	0.5	3635.55	923.71	40.42
3.	1	3419.91	981.95	52.51
4.	2	3128.51	1073.4	126.7

3.6 Results & Comparison-



Graph1



Graph2

Graph 1. shows - Heat transfer coefficient for first & second design of segment are estimated as 3527.73 W/m^2 K & 4150.82 W/m^2 K respectively.

Graph 2. shows - Heat transfer coefficient for first design of segment increases from 2070.17 W/m^2 K to 6086.51 W/m^2 K. Heat transfer coefficient for second design of segment increases from 2479.35 W/m^2 K to 6906.95 W/m^2 K.

Graph 1 & 2 – Designed for the better visualization and comparison of analyzed results.

IV. CONCLUSION

i. As power increases, heat transfer coefficient (h) remains constant.

ii. As mass flow rate increases, heat transfer coefficient also increases for all the design of segment.

iii. The second design of segment is having higher value of heat transfer coefficient than the first design of segment.

iv. Not significant effect of height of segment - The results of third & fourth design of segment are nearly same as first & second design of segment respectively.

v. For complete seven segment thermal plasma torch - To save computational time & to carry out complete complex analysis in a simple manner, calculated heat transfer coefficient values will be directly used in deleted segments & water cooling will be carried out in top segment only.

V. REFERENCES

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VI. APPENDICES

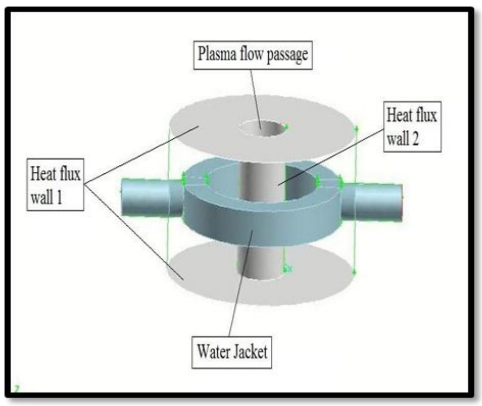

Fig.4. Showing internal structure of first design of segment Created in GAMBIT in shaded rendering form

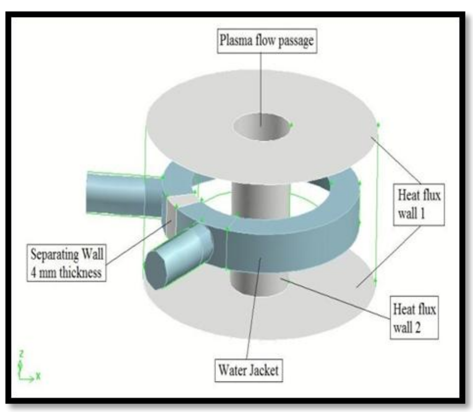

Fig.5. Showing internal structure of second design of segment Created in GAMBIT in shaded rendering form

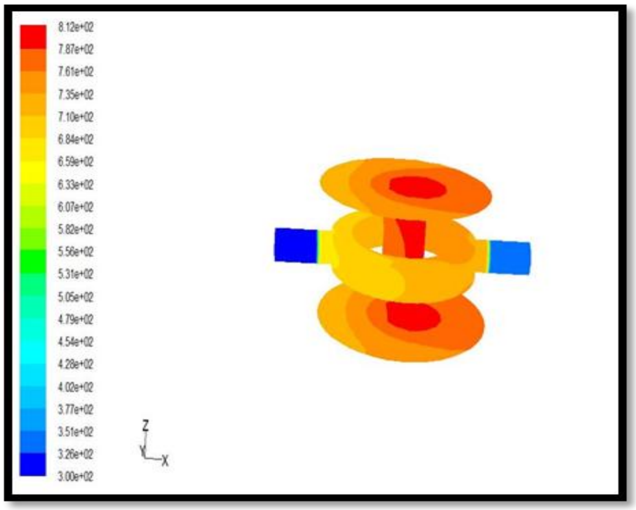

Fig.6. Temperature contour of first design of segment Figure obtained after the analysis in FLUENT

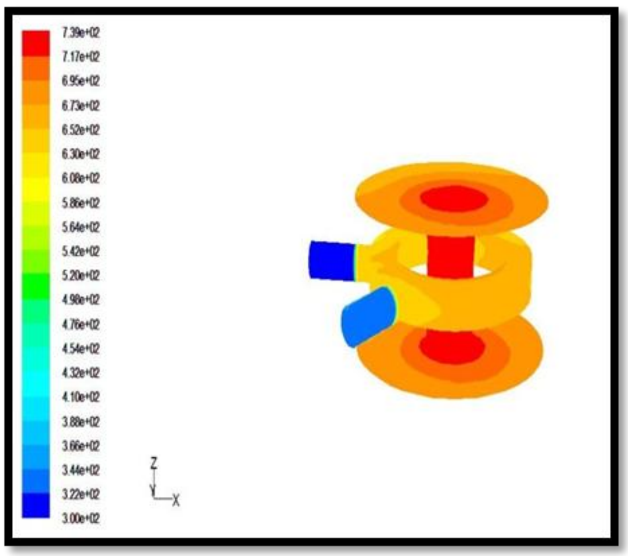

Fig.7. Temperature contour of second design of segment Figure obtained after the analysis in FLUENT