Design and Analysis of a Plasma Chamber for Thermal Processing Applications*)

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Thermal Plasma processing has many applications in medical and environmental fields like melting, smelting and waste disposal. Here, the primary vessel known as plasma chamber is preheated to a high temperature of around ~1000°C using plasma arcs. In this design process, CFD (Computational Fluid Dynamics) analysis has played a major role in defining the design of the plasma chamber. The simulation methodology has been benchmarked based on comparison of experiment and CFD simulation carried out for an experimental system available at IPR (Institute for Plasma Research). Transient thermal profile of the chamber has been evaluated using CFD analysis to design a higher capacity plasma chamber for scaled up systems. The analysis helped in identifying the desired material properties, dimensions of chamber and thickness of insulation, refractory materials to be used for the construction of chamber. The design focusses on uniformity of temperatures inside the chamber, identification of hotspot locations and faster ramp up time to desired process temperatures. Temperature at the outer most surface of plasma chamber have also been evaluated using the CFD analysis for human safety. The CFD analysis is computationally expensive and time consuming due to large size, transient behaviour and inclusion of radiation transport.

Keywords: thermal, plasma, plasma processing, CFD analysis, insulation, radiation, arc

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1. Introduction

Thermal plasma processing has wide range of applications which include metallurgical, waste to energy generation and hazardous organic waste disposal in environment friendly manner etc [1–3]. This process utilizes high temperature obtained by plasma arcs to pre-heat the process chamber to high temperature (1000 - 1200°C).Plasma arc is generated by applying electrical power between graphite electrodes which heats the chamber predominantly through radiative heat and further through convection of flowing gas around the arc. The process aims to utilize effective distribution of heat in the chamber using multiple plasma arcs. The chamber is lined with refractories and insulation materials from inside to sustain high temperatures and prevent heat losses. Systematic study of energy and temperature distribution inside the chamber using CFD simulations may assist in preparing appropriate design concept to heat the chamber faster to the desired process temperature with uniform distribution using thermal energy from plasma arcs.

Results of D. Sharma et al. [4] clearly show that CFD analysis predicts the temperature distribution in plasma chamber during preheating to be reasonably close to the experimental values by considering the plasma arc as heat source emitting radiation as well as considering flow of gas around the arc. On the basis of benchmarking and with an objective to upscale and design a higher capacity system, the CFD analysis for different design variants have been performed considering materials as well as functional aspects and a final design variant has been proposed for the process chamber design. CFD model for the size of this chamber include large (~10 - 15 million) number of elements & nodes, inclusion of radiation transport and time dependent transient analysis of the full-scale model which is a computationally expensive and challenging task.

Performing a detailed transient CFD analysis will help in identifying the materials, their thickness and overall dimensions of the chamber. It will also help in estimating outside surface temperatures to be maintained at ambient for human safety.

2. Design Features of Plasma Chamber

The chamber has an approximate height of 2.5 m and 1.5 m clear diameter. It is thermally insulated from inside using lining materials such as refractory/insulation etc. Multiple graphite based nitrogen plasma arc at dif-

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ferent locations along the height of chamber are the heat source. Graphite Electrode assemblies are housed inside the chamber through their respective ports. Each graphite electrode arc assembly has a power output maximum capacity of 100 kW. There are three different layers of thermal insulation inside the plasma chamber. The thermal insulation layer which is directly facing radiation heat flux coming from plasma arc is made of alumina refractory bricks to sustain high temperature. The second layer and third layer act as back-up insulation lining that help in reducing heat losses to the outer wall of the chamber due to their low thermal conductivity. Outer vessel of chamber which act a structural material for the chamber is made of mild steel.

3. CFD Analysis

CFD simulations have been carried using ANSYS CFX software [5]. Plasma arc is simply modelled as a ~75 kW thermal energy heat source sandwiched in the space between the two electrodes shown in Fig. 1 a). Heat generation in arc is varied radially (maximum at inside and linearly varied up-to the circumference) to accurately simulate plasma arc relevant temperatures. Nitrogen gas with desired flow rate is fed into the chamber from each electrode port towards the arc and taken outside from a common outlet at top as shown in Fig. 1 b).

The temperature profile of gas over the heated arc from one of design concept which also shows the flow profile is shown in Fig. 2 a). The temperature profile of plasma arc extracted from one of design concept is also shown in Fig. 2 b) where temperature of around 20000 K can be observed around the core which is close to the measured values in similar arc profile.

Nitrogen has very low absorption coefficient values [6] at operating temperatures (up to 2000 K) except for high temperature arc region and thus it is considered to be optically thin media. Monte Carlo Radiation model is recommended in CFX [5, 7] for optically thin media i.e. transparent to radiation at wavelengths (ultra-violet in this case) [8] in which the majority of the heat transfer occurs. Here since both nitrogen and nitrogen plasma arc are modelled as fluids, the fluid- fluid interface formed between these two fluid domains have conservative interface flux for mass, momentum, heat energy and thermal radiation. Radiation energy travels from inside of the arc to the surface (arc- nitrogen interface) and then from this surface to other opaque boundaries. The surface emissivity of refractory and insulation have been provided accordingly.

Temperature dependent properties [6, 9, 10] like specific heat, thermal conductivity, viscosity and mean absorption coefficient of nitrogen have considered for both nitrogen and nitrogen plasma arc. Transient analysis for 1 - 2 hours has been considered to predict the ramp up time. Gas flow rate at inlets, outlets and heat generation profile in arc are the loads and boundary condition inputs for the

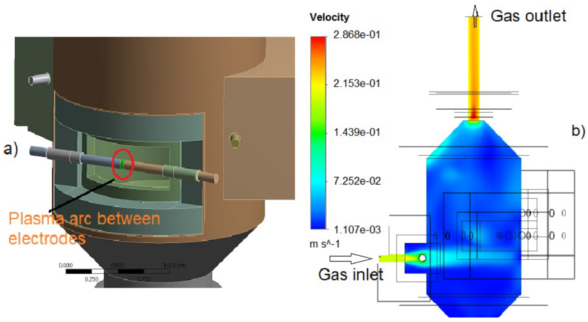

Fig. 1 a) Plasma arc between electrodes, b) Gas Flow profile.

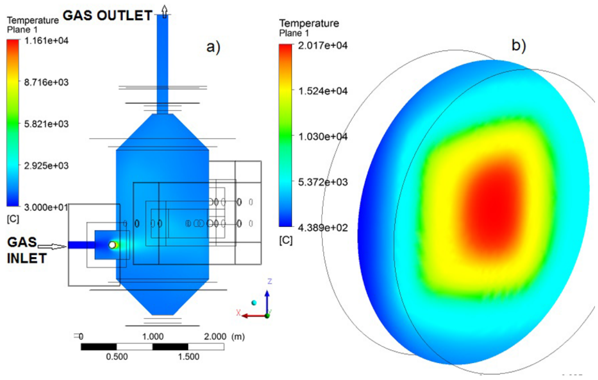

Fig. 2 Temperature profile of a) Nitrogen Gas, b) Plasma arc.

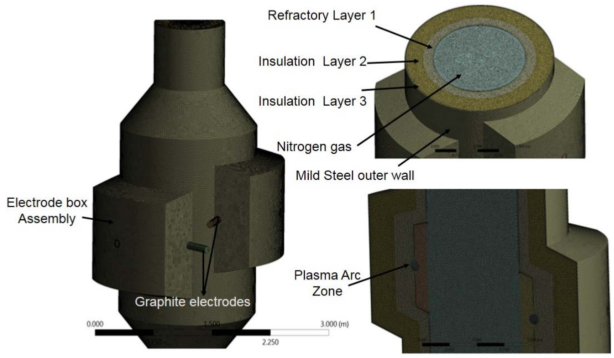

Fig. 3 CFD analysis model of plasma chamber.

CFD analysis.

Analysis has been performed using high performance cluster (HPC) facility. Meshed model for one of the design concept is shown in Fig. 3.

4. Initial Design Concept

To start with, an initial design concept based on feasible inputs has been modelled and analysis performed for 90 minutes. The results in Fig. 4 shows that the average refractory temperature reaches 1000°C in about 30 min. Refractory region above and below the plasma arc at this time experiences a maximum temperature of about ~1630°C as shown in Fig. 5.

The temperature at most of the locations is uniform

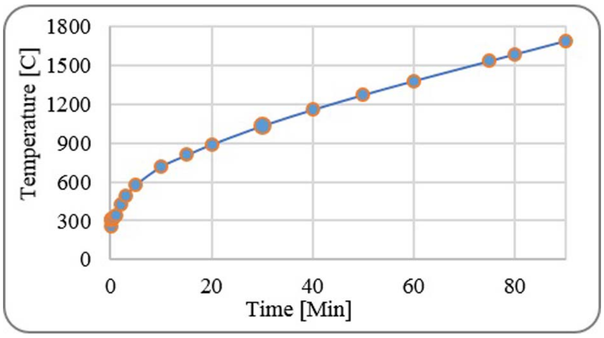

Fig. 4 Average inner refractory surface temperature for initial concept.

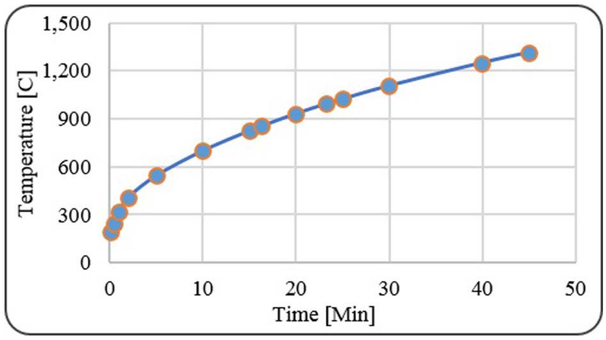

Fig. 6 Average inner refractory surface temperature for second design concept.

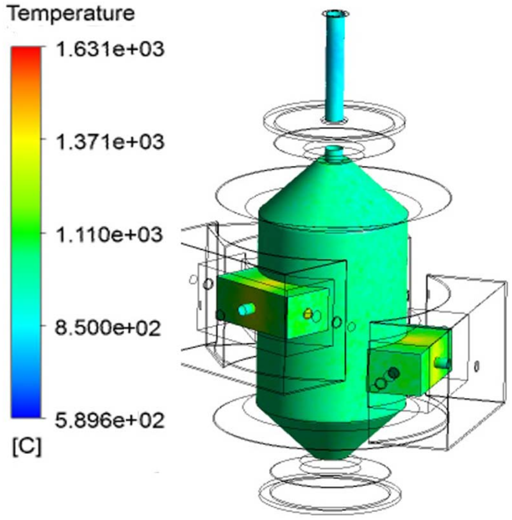

Fig. 5 Refractory inner surface temperature initial concept at 30 minute time.

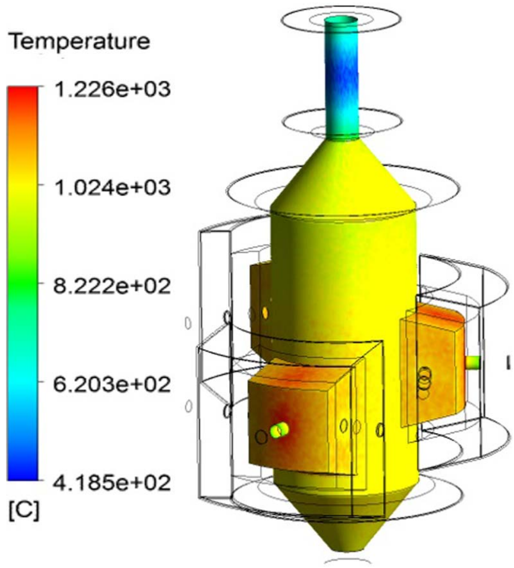

Fig. 7 Refractory inner surface temperature at 25 minute time for second design concept.

and is above 1000°C but at the region above and below the arc it is above 1300°C which is not desirable. To reduce high temperature at the region directly above and below the plasma arc, a tapered profile of electrode ports is proposed.

5. Second Design Concept

In the second design concept, with inclusion of tapered profile for electrode ports, the height of the chamber is increased to accommodate electrode boxes which are placed at different heights. The inside diameter of the chamber is reduced to compensate the volume increase due to increase in height of the chamber. Figure 6 shows that the average refractory surface temperature crosses 1000°C at 25 min compared to 30 min in the initial concept. The maximum temperature at 25 min is about 1226°C as shown in Fig. 7 which highlights the effect of tapered profile of electrode ports on the hotspot temperature. Also the temperature is seen to be uniformly distributed and is above 1000°C at most locations.

6. Third Design Concept

The third conceptual design involved major changes in the design concept of the chamber with further increase in height to introduce a connection window in the design for purpose of application or process where this chamber will be utilized.

Figure 8 shows the temperature profile of the inner surface of the chamber at 30 minute time. The results in Fig. 9 show that the top of chamber will not be as hot as lower part. This is due to larger gap between electrode positions inside the chamber from upper region of the chamber. The radiation from plasma arc is not directly heating the upper region of the chamber and thus there is temperature difference in the bottom region (covered by plasma arc) and upper region of the chamber which is not desirable for efficient processing.

It is therefore observed that having connection port at the side will lead to increase in height and introduce cold zones in the chamber. Thus, it is proposed to have connection window at the top and gases outlet at sides.

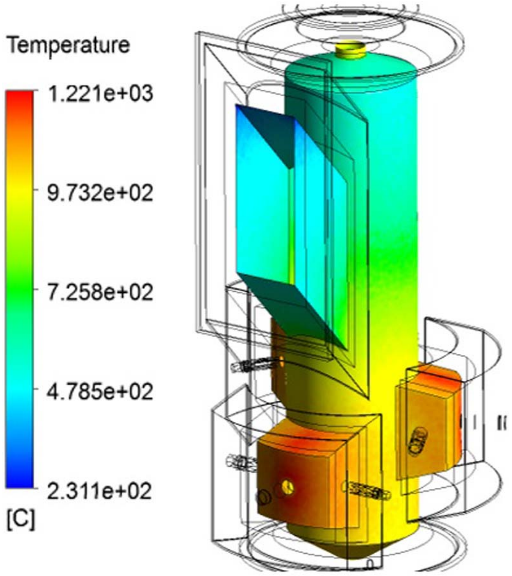

Fig. 8 Refractory inner surface temperature for third concept at 30 minute time.

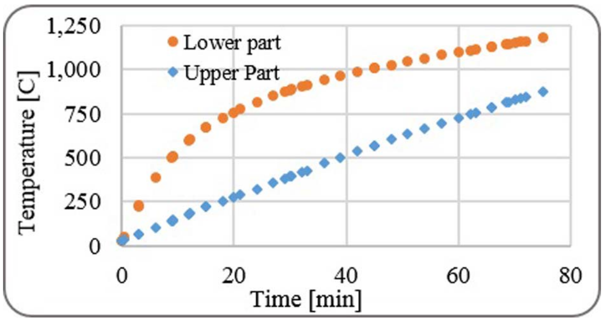

Fig. 9 Average refractory temperature for third concept.

7. Final Proposed Design Concept of Plasma Chamber

Final conceptual design of plasma chamber has been proposed keeping in mind the functional aspects of preceding variants and incorporating feasible inputs into the design. In this design concept, connection window is proposed to be connected from the top of the chamber thereby again reducing chamber's height. An ignited coke bed at the bottom of the chamber has also been proposed in this design concept to further increase the heat content of the system and is included using porous media approach [5] in the CFD model using suitable inputs [11, 12]. Meshed model of the final design concept and refractory temperature at 45 min is shown in Figs. 10 and 11 respectively.

Average refractory temperature reaches 1000°C at around 38 minutes as shown in Fig. 12. Here the maximum temperature at 38 min is less than 1300°C which is below the refractory limit. The temperature distribution also seems to be uniform with most of refractory surface above 1000°C at 45 min as shown in Fig. 11.

Figure 13 shows the mid plane temperature of plasma arc, nitrogen and refractory at t = 45 min. Plasma arc is having maximum temperature of 5400°C which is lower than earlier design concepts. The reason for plasma arc having lower temperature as compared to earlier simulations is due to a different nitrogen feeding mechanism. The nitrogen is being fed onto the arc from three sides fed through a narrow hole in the electrode rod which is causing the centre of the arc to dissipate the temperature to the surrounding nitrogen. The effect of buoyancy model considered in this analysis can be visualized with hot gas near

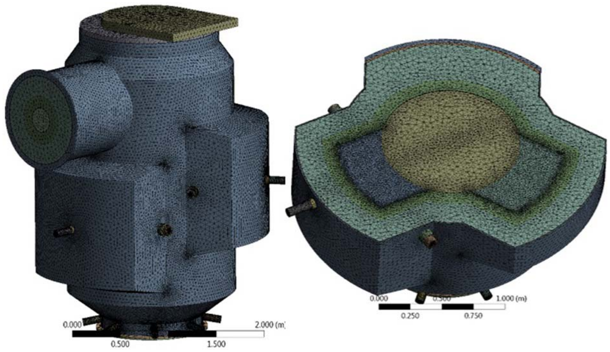

Fig. 10 Model for final design concept.

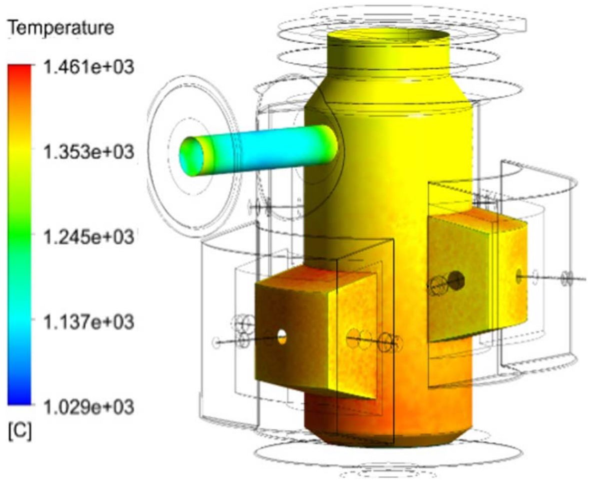

Fig. 11 Refractory inner surface temperature at 45 minute time for final design concept.

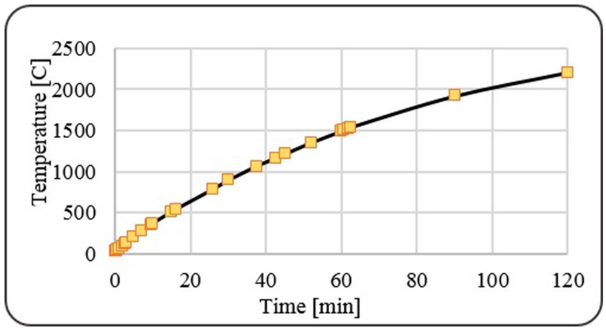

Fig. 12 Average refractory temperature for final design concept.

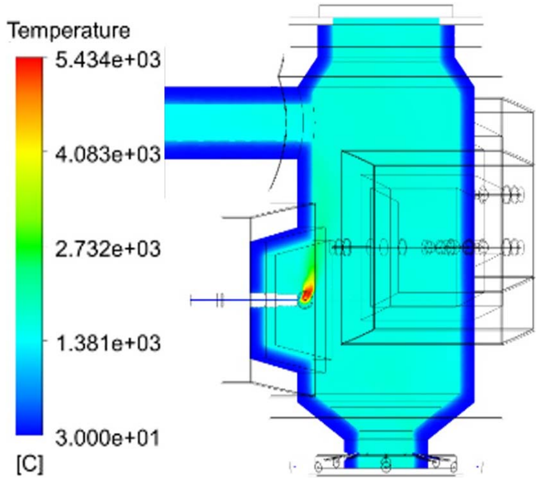

Fig. 13 Temperature profile nitrogen, arc and refractory at 45 min for final concept.

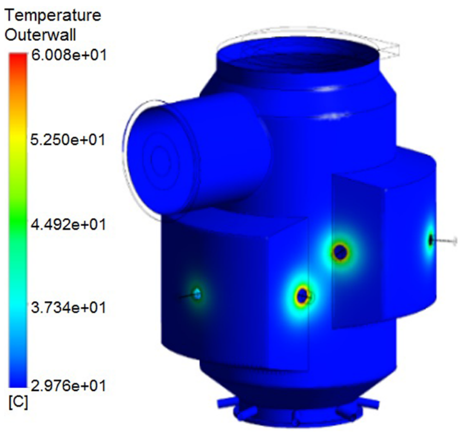

Fig. 14 Outer surface temperature at 45 min for final design concept.

the arc rising upwards.

The outer surface temperature is less than 60°C as shown in Fig. 14 which is nearly safe for accidental human contact. The insulation on graphite rod is effective in shielding outer steel surface from hot graphite rods as shown by the temperature on outer steel surface near the electrode.

The maximum temperature of graphite electrode near the plasma arc at 45 min time is around 2000°C as shown in Fig. 15.

The energy balance performed at t = 45 min shows that most of the thermal energy input (~90%) is absorbed and stored in refractory and coke bed.

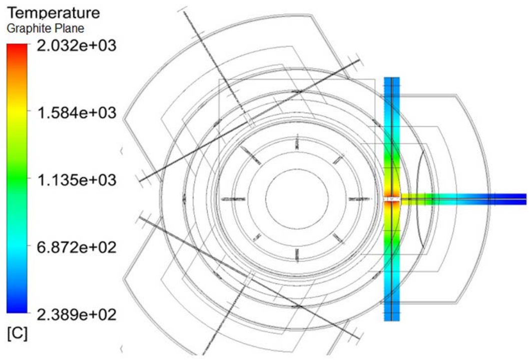

Fig. 15 Graphite electrode temperature at 45 min for final design concept.

8. Conclusion and Future Work

The proposed final concept is acceptable for the design of plasma chamber. It satisfies desired functional requirements like fast temperature rise, appropriate lining and insulation materials, heat content confined to refractory & coke bed and low heat losses through outer wall. This CFD analysis has helped in selecting appropriate refractory/insulation materials, required thickness, estimating pre-heating time and hot-spots locations. Further, analysis and design optimization according to our present applications will be performed.

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