International Journal of Thermal Sciences 102 (2016) 274–284

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

journal homepage: www.elsevier.com/locate/ijts

Modeling heat transfer of the electrothermal reactor for magnesium production

Sourav Mondal [a, b], Madan Mohanasundaram [c], D.C. Sau [c], Rajneesh Kumar Gupta [c], Manoj Kumar [c], K.K. Paul [c], Sirshendu De [a, *]

[a] Department of Chemical Engineering, Indian Institute of Technology Kharagpur, Kharagpur 721302, India
[b] Mathematical Institute, Oxford University, Oxford OX2 6GG, United Kingdom
[c] CSIR-National Metallurgical Laboratory, Jamshedpur 831007, India

ARTICLE INFO

Article history:
Received 4 July 2015
Received in revised form
21 November 2015
Accepted 23 November 2015
Available online 7 January 2016

Keywords:
Computation fluid dynamics (CFD)
Radiation
Conduction
Convection
Electrothermal reactor
Magnesium production

ABSTRACT

Thermal analysis of high temperature electrothermal reactor for magnesium production was carried out in full 3D configuration using computational fluid dynamics (CFD). As the temperature inside the reactor reaches to 1200–1500 K, it becomes difficult to understand and control the heat transfer inside the reactor as the thermocouples were embedded in the insulating layers, much away from the core. The present analysis provides a useful tool to correlate the core temperature with experimental thermocouple readings. The transient state CFD simulation is carried out for the actual pilot scale design of the reactor, considering all the modes of heat transfer-conduction, convection and radiation and actual temperature dependent physical properties of the insulating materials. The heat flux and the spatial temperature profile of the various interfaces of insulation layers were also quantified.

1. Introduction

Melting of magnesium ore and subsequent reduction requires a temperature of around 1000–1700 °C, depending upon the partial pressure of the reactor atmosphere. The production of magnesium from its ore by reduction in the form of briquettes by external heating at high temperature has been already known and utilized at industrial scale with the development of the Pidgeon process [1]. The energy efficiency of such process is low, labor intensive, and has low space-time yield for large scale production with increasing market demand. As a result, there have been efforts for the design of high temperature furnaces with improved thermal efficiency [2–4]. Many researchers in the past have proposed electrically heated furnaces which can raise temperature upto 1600 °C. There can be various means of heating the ore and the reductant, such as by radiation to the surface of reaction mixture [5], submerged arc electric mode [6,7], resistance heating of the molten magnesium reflux [8], etc. The complexity of these thermal and electrothermal process furnaces lies in uniform heating of the reaction mixture, prevention of premature melting of the ore, effective utilization of the developed heat, knowledge of the heat flux across the insulation layers to optimize the thickness and control of the heating process to optimize the transmission of energy to the reaction bath (both inductive and Joule heating) [9,10].

The efficient operation of the magnesium electrothermal reduction reactor requires a good understanding of heat transfer mechanisms, the associated heat of absorption and temperature evolution of the system. Computational fluid dynamics (CFD) provides a realistic and appropriate mean to study and analyze the heat transfer phenomenon during the complex physical process. One of the major advantages of using CFD as a modeling tool is actual representation of the problem including the environment with multiple physical phenomena simulated simultaneously. During the past decade, there were reports of implementing CFD to study the heat transfer effects in real life problems, like, pilot scale bakery oven [11], gas turbine combustor [12], industrial continuous bread baking oven [13], domestic refrigerators [14], hearth of a blast furnace [15], solar collector [16] and plate type heat exchanger [17]. In case of

* Corresponding author. Tel.: +91 3222 283926; fax: +91 3222 255303.
E-mail address: sde@che.iitkgp.ernet.in (S. De).

http://dx.doi.org/10.1016/j.ijthermalsci.2015.11.018
1290-0729/

electrothermal process of magnesium reduction all three modes of heat transfer mechanism are dominant and because of complex system design, a three dimensional model is warranted to understand the complete process. Since, the heat input to the system is transient in nature, the system never attains equilibrium, and therefore, the unsteady state analysis is necessary.

A robust theoretical model was developed and validated [18] to evaluate the influence of various operating parameters on the electrical characteristics of a system where molten oxide slag was heated by passing electrical current through the slag. A new model was formulated for magnesium production in horizontal retort based on chemical reaction kinetics [19]. It showed that temperature had profound effect on magnesium reduction and heat absorption power. A comprehensive unsteady state model was developed [20] and investigated the effect of thermal-flow field on the performance of magnesium reduction in Pidgeon process. However, there is no such reported study on the electrothermal reactor.

In this work, a CFD based model has been developed to simulate the preheating stage of the electrothermal reactor of magnesium production. The transient mode calculation provides the temperature history of the problem space. Due to non-linearity in the electrical energy input to the system, the heating rate was not uniform. The energy input to the system was controlled by the precise movement of the electrode which induces the arcing using the AC current to melt the solid ore particles. Since, the insulating layers are composed of different materials, the temperature dependent thermal properties are invoked into the model to make it more realistic. The inert environment to the reduction is maintained by introducing argon at high vacuum conditions. In order to validate the CFD simulated results, two sets of experimental results of the temperature profiles at discrete points (measured by thermocouples) are compared. Since, the system is maintained at high temperature, the dynamics of the heat flux across various insulating layers, level of radiant heat flux to the internal lining and the evolution of the bath temperature are difficult to measure by experimental techniques (for large scale systems) and remains dark. The CFD based simulation in this work can provide deep insight to such critical details.

2. Experimental details

The design of the pilot scale electrothermal reactor used for smelting of the magnesium ore and reduction is shown in Fig. 1. The reactor is fabricated according to the dimensions mentioned in Fig. 2. Argon gas was fed to the main reactor chamber (1) through the antechamber (2). The calcined dolomite and bauxite were charged though the bin (3), followed by ferro-silicon through another bin (4). The electrode (5) was brought down to melt the slag and to attain the necessary temperature for reduction reaction. In operation, reduced magnesium was transported along with argon to the connector-condenser (6) where the temperature was maintained at 750–900 °C by the embedded heater to condense the magnesium in liquid form. The capacity of AC transformer was upto 3500 A current and upto 85 V which was used for heating the reactor. During the process of heating by arcing, around 10 kg of coke, 25 kg of iron turnings and 40 kg of synthetic slag were introduced into the system. This synthetic slag consisted of 5.904 kg calcined dolomite, 8.624 kg calcined bauxite, 17.76 kg lime and 8.944 kg quartzite. This resulted in a pool height of around 115 mm. After 10 h of initial melting of iron turnings, synthetic slag was charged into the system in batches of 2.06 kg, every 15 min. Twenty such batches of synthetic slag were fed into the system so that the molten pool became stable and uniform, leading to increment in the pool height by 40 mm. The slag melting was done at atmospheric pressure using single phase single electrode furnace which was followed by the charging of magnesium reduction material under low pressure of 10–50 mbar. The argon was bled into the system at the rate of 0.5–1 l/min at room temperature.

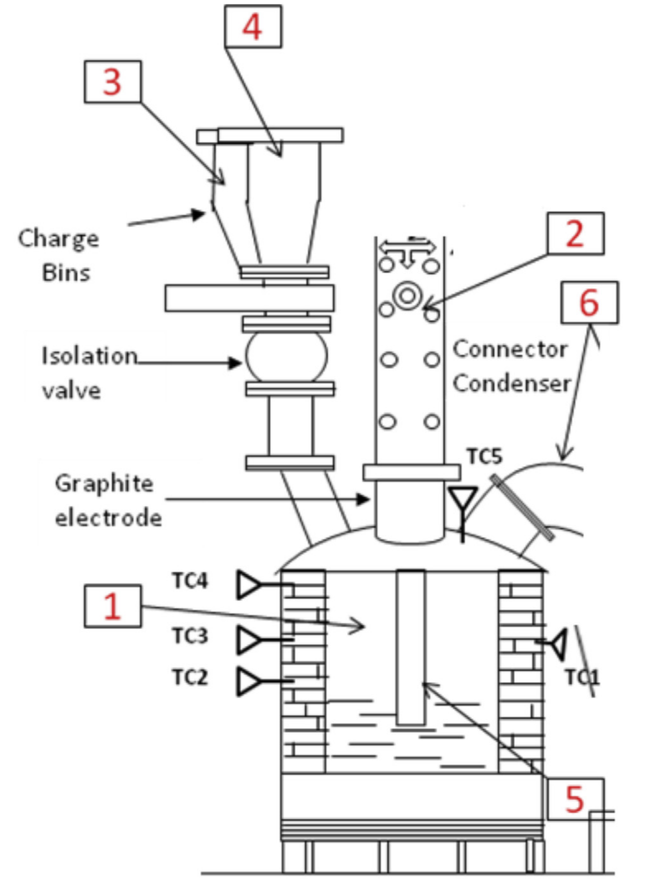

Fig. 1. Schematic diagram of electrothermal reactor for melting of oxide slag and magnesium ore.

3. CFD modeling

A three dimensional model of the reactor according to scale was developed using geometry and model building CAD software [21] as shown in Fig. 3. All the lining thicknesses were incorporated in the model comprising of different materials specified in different zones. Unstructured volume meshes were generated using Tetrahedron volume element with 4 nodes per element. A mesh independence study was performed considering the uniform interval size of 2, 5, 10 and 20 units. The maximum change in the temperature obtained around 0.32 K, while the mean variation (averaged for all the nodes) is less than 0.11 K, when the mesh size is increased from 10 to 20 units. Thus, interval size specified was 20 units for meshing the entire solution space. TGrid mesh mapping scheme was applied [22]. The total number of tetrahedral mesh generated was 4,128,696. Analyzing the 3D mesh generation report, it was found that less than 0.1% of the total meshed elements had skewness greater than 0.93. The slag-fluid interface was meshed carefully with non-uniform grid spacing using a sizing