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Transient heat transfer computational model for the stopped aluminium reduction pot – Cooling techniques evaluation

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HIGHLIGHTS

- We examined the cooling trend of an aluminium reduction pot.
- We developed a transient finite element model for the pot.
- The impinging jet cooling technique was investigated as a viable cooling option.
- The pot-shell forced cooling technique was also investigated as a viable cooling option.

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ABSTRACT

In aluminium smelters, cooling of a stopped reduction pot takes about seven days in a free convection environment before the relining process can commence. As the pot's steel component (potshell) is saved for the subsequent generation of pots, reducing the cooling time is desirable to ensure consistent smelter production. In this work, a 3-D Finite Element Heat Transfer (FEHT) model is developed, validated with experimental data and used to evaluate the effectiveness of forced convection cooling techniques for the pot. Two separate forced cooling techniques; parallel forced air flow and impinging jet air cooling are applied on the potshell and metal pad surfaces respectively. Air velocities ranging from 5 to 20 m/s are considered for both setups. Results showed that the metal pad forced cooling technique reduces the pot's cooling time significantly. The potshell cooling technique is limited by the high heat capacity of the back insulation layer and the thermal back diffusion from the pot's high temperature contents. The knowledge developed in this article is useful in designing and analysing suitable heat transfer tools for the stopped aluminium reduction pot.

1. Introduction

In the aluminium industry, primary aluminium is extracted from its ore (alumina) by feeding direct current (DC) into a line of electrolytic cells connected in series. The fundamental process with which these cells operate is named the Hall–Héroult process after its inventors [1,2]. Each reduction cell consists of a large lined metal container commonly referred to as the reduction pot, carbon cathode, carbon anodes and a superstructure. During operation, the pot houses an electrolytic bath of molten cryolite which functions as the electrolyte and a solvent for alumina. Aluminium metal produced by the electrolytic process sinks to the bottom of the reduction pot, while the gaseous by-products form at the top of the pot. Subsequently, aluminium is sucked from the bottom and transported to the furnace in the cast house where it is alloyed then cast into several forms of aluminium products.

The aluminium reduction pot constitutes a steel shell (potshell) with layers of lining materials assembled inside to regulate the pot's heat transfer mechanism. The potshell usually consists of a steel cradle partly or fully welded to a steel container [3]. It typically consists of a stiffening I-beam at the vertical side of the pot and a similar beam beneath the pot to counteract the outward bending of the side linings and upward bending of the carbon cathode respectively. The lining materials at the bottom of the pot are layers of insulating bricks installed to prevent substantial heat loss through this section of the pot. On top of the bottom lining materials are carbon blocks which are negatively charged and act as the cathode of the cell. These blocks are selected as they provide high operating strength, high density, and lower electrical resistivity

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than that of the continuously rammed paste type of linings [4]. However, to form a liquid tight container and minimize thermal shock, carbon paste is rammed within the evenly spaced cathode block. The efficiency of sealing with the paste is an important factor in determining the life and energy efficiency of a reduction pot, which depends to a great degree on the extent and rate of electrolytic penetration into the pot's bottom lining [4]. Lining materials are also used to separate the electrolyte/aluminium inside the pot from reaching the potshell. Materials used for the pot's side lining are strategically selected to maintain the required heat balance in the cell. The structure (transverse section) of our modelled aluminium reduction cell with its material configuration is shown in Fig. 1. This cell and its materials are a modification of the prototype presented in the reference [5].

In aluminium smelters, it is common knowledge that the reduction cell cannot easily be stopped and restarted. However, various occurrences which include power outages, cell failure, wear, high cathode voltage drop may cause interruption of the cell's operation. Based on Zhao et al.'s [6] experience, non-planned cell power outage of more than 4 h can result in complete freezing of the bath. As the cells are connected in series, this could force a shutdown of all cells in a potline. On the other hand, if no interruption occurs, the continuous operation of the cell causes its inner lining to wear off eventually forcing its shutdown for rebuilding. Irrespective of the nature of shutdown, the costly potshell is usually retained for subsequent reconstruction of the pot as such; the rebuilding process would have to be delayed till the pot is cooled down to temperatures at which it is safe to strip off the potshell. The typical free convection cooling technique has proven to be a very slow process; taking about 7 days, depending on the ambient temperature. As the expected cell lifetime is now about 2000 days [5], this downtime might seem negligible. However, considering a modern smelter of 500pots producing 2.5 tonnes of aluminium per pot per day; the accumulated downtime could reduce the smelter's production capacity by 8750 tonnes (14 million USD worth of aluminium).

The cost, size and operating conditions of the pot limits design studies via onsite measurements. However, several mathematical models developed for the aluminium reduction cell have proven useful in design and development procedures [7–12]. Most studies in this field have focused on modelling the start-up and actual smelting operations of the pot. The few studies focused on reducing the pot's shutdown induced downtime are references [13–16] but none of these authors have identified an efficient cooling technique for the stopped pot. The most beneficial literature to the present study includes studies which have identified possible areas of the pot's surface where the cooling of the pot might be effective. One of this is the patented work of Bos et al. [17] which described a cooling system with a fundamental cooling strategy of increasing the heat transfer from the potshell surface. Their piece acknowledged the possibility of using a plurality of the original online cooling device for offline cooling purposes however, the performance of such system was not examined. Another study which signals an effective surface area to cool the pot is that of Solheim et al. [18]. The study portrayed the pot's top section as the location responsible for the greatest heat loss during pot operation depicting a location with the lowest resistance to heat flow however, no attempt to force cool the pot from this location has been encountered.

In the present study, validated finite element models of the pot developed on ANSYS's commercial Computational Fluid Dynamics (CFD) and FEHT modules are used to calculate the cooling trend of the pot under various cooling scenarios, in an attempt to identify an efficient cooling procedure. In this regard, two potentially effective cooling processes were considered: potshell and metal pad forced cooling procedures. Due to the potshell and metal pad's location in the pot, different cooling schemes were adapted for effective cooling at these sections: ducts situated beneath the pot are used to force the flow of air over the potshell's surface while impinging jet systems are used to do same at the metal pad's surface.

2. Methodology

The modelling approach adopted in this study has been validated in our previous studies [14,19]. In the present study, our previous models of the pot are extended to predict the effect of forced cooling parameters on the pot's cooling trends. Using the ANSYS platform with specialized CFD (FLUENT) and heat transfer (Mechanical APDL) modules, our approach to the multi-physics problem involved developing models on both modules and transferring solutions between them. The advantage of this approach lies in the ease and effectiveness with which the accuracy of each model is ensured as adequate resolution of grid sizes can be adapted for the respective models, depending on the physics

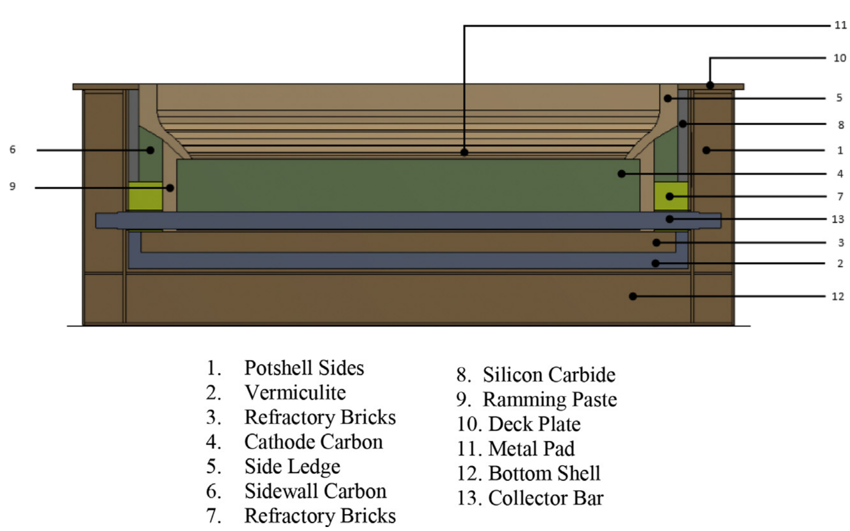

Fig. 1. Structure and materials of a prototype aluminium reduction pot. 1. Potshell sides. 2. Vermiculite. 3. Refractory bricks. 4. Cathode carbon. 5. Side ledge. 6. Sidewall carbon. 7. Refractory bricks. 8. Silicon carbide. 9. Ramming paste. 10. Deck plate. 11. Metal pad. 12. Bottom shell. 13. Collector bar.