Heat Exchanger Prototype for Alumina Preheating in Aluminium Reduction Cells

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Abstract

The process temperature of an aluminium reduction cell is around 960 °C, thus all supplied raw materials need to achieve this temperature. The most relevant of the materials in terms of mass flow is alumina, which consumes around 0.56 kWh/kg Al in order to achieve the reaction temperature. Recovering some of the energy lost to heat up the alumina is a way to reduce cell specific energy consumption.
In our paper from 2018 a heat exchanger was presented that is designed to preheat the alumina by using the heat of the gases generated by the reduction process. In this article, the results obtained by a prototype built to prove the concept of the proposed heat exchanger are presented. The prototype was constructed in real scale. It uses a natural gas burner as heat source to simulate the off-gas received from the process. As predicted by the models, the alumina was heated up from an ambient temperature to around 500 °C as it passed through the device in a steady flow rate similar to the necessary flow to feed a real electrolysis cell.

Keywords: Aluminium electrolysis cells; energy consumption; alumina preheat; energy recovery, heat exchanger.

1. Introduction

The reduction of the energy consumption in the aluminium electrolysis process has been a subject of many research works in the industry. This occurs because electric energy is a scarce and expensive resource, and its consumption reduction is a decisive factor in the profitability of an aluminium smelter. Some examples of energy recovery in the smelting process studied in the past can be found in the recommended literature [1–10]. Furthermore, heat recovery by external fluids with heat exchangers [1–5] has been employed. The heated fluid recovers energy that is useful in other applications such as decreasing the off-gas temperature before the GTC [2]. In other works, the energy is recovered to preheat raw materials. For example, the preheating of anodes is a desirable use of energy recovery because it potentially improves the process in many aspects [6]. This has been tried in the industry as presented in papers [6] as well as in patents [9].

Alumina preheat could also improve the process, decreasing energy specific consumption while improving the alumina mixing in the bath. Devices for alumina preheat trials can be found in literature. For example, US patent 3,006,825 presents an alumina feeder wherein the alumina is preheated by the burners' off-gas in Soderberg cells whereby the gases pass through an alumina fluidized bed [11]. Further work presents a feeder (US patent 3,371,026) that is claimed to have the ability to preheat the alumina before feeding [12].

In 2017, CAETE Engenharia presented a design of a heat exchanger for alumina preheat [14], using the off gas produced inside the cell cavity. In the referenced work, a novel concept of the heat exchanger was presented and numerical simulations were employed in order to assess the potential energy recovery efficiency and also to estimate the final possible preheat temperature of the alumina feed into the bath. As described with more detail in the paper, preheating the alumina has the potential to improve the electrolysis process thermal efficiency through many aspects, as is summarized below:

a) Reduction in energy consumption to increase the alumina temperature from ambient to process temperature.
b) Dissolution of preheated alumina is easier than cold alumina.
c) When feeding preheated alumina, the cell superheat can be lowered and therefore, heat losses through the sidewalls can be decreased.
d) The heat exchanger device proposed is accompanied with localized pot suction. This potentially reduces the top heat loss because the under-hood space would present lower temperature, thereby reducing both convection and radiation heat losses.

All the above-mentioned combined effects have the potential to reduce the specific energy consumption by 1.2 – 1.5 kWh/kg Al. Hereby the estimation considers that alumina can be fed at 550 °C, the CE can be increased by 1 % and the superheat can be lowered by 5 °C. In this work, a real test prototype of the heat exchanger is presented.

2. Heat Exchanger Design

As presented in the earlier work [14], the heat exchanger design for use in real cells was shown and its most relevant parts and features are explained in Figure 1. The heat exchanger is embedded into the alumina hopper (2) and the alumina feeding is activated by a pneumatic cylinder (3). Alumina passes through the alumina heating chamber (4) reaching the dosing device (6). A crust breaker (5) is necessary to guarantee the crust opening stability. When the pneumatic cylinder acts, the alumina falls into the discharging chute (7). A gas collection cap (8) is placed over the anode cover (9). It presents a vertical sliding degree of freedom allowing for the anode height variation during the anode life. The gas collection cap presents a controllable false air inlet (12) and the hot gases evolving from anodes (10) and bath (11) are collected and directed in counter flow with regard to the alumina flow. The gases leave the heat exchanger at the top where a draft control valve combined with temperature sensor (1) is used to control the off-gas temperature and mass flow.

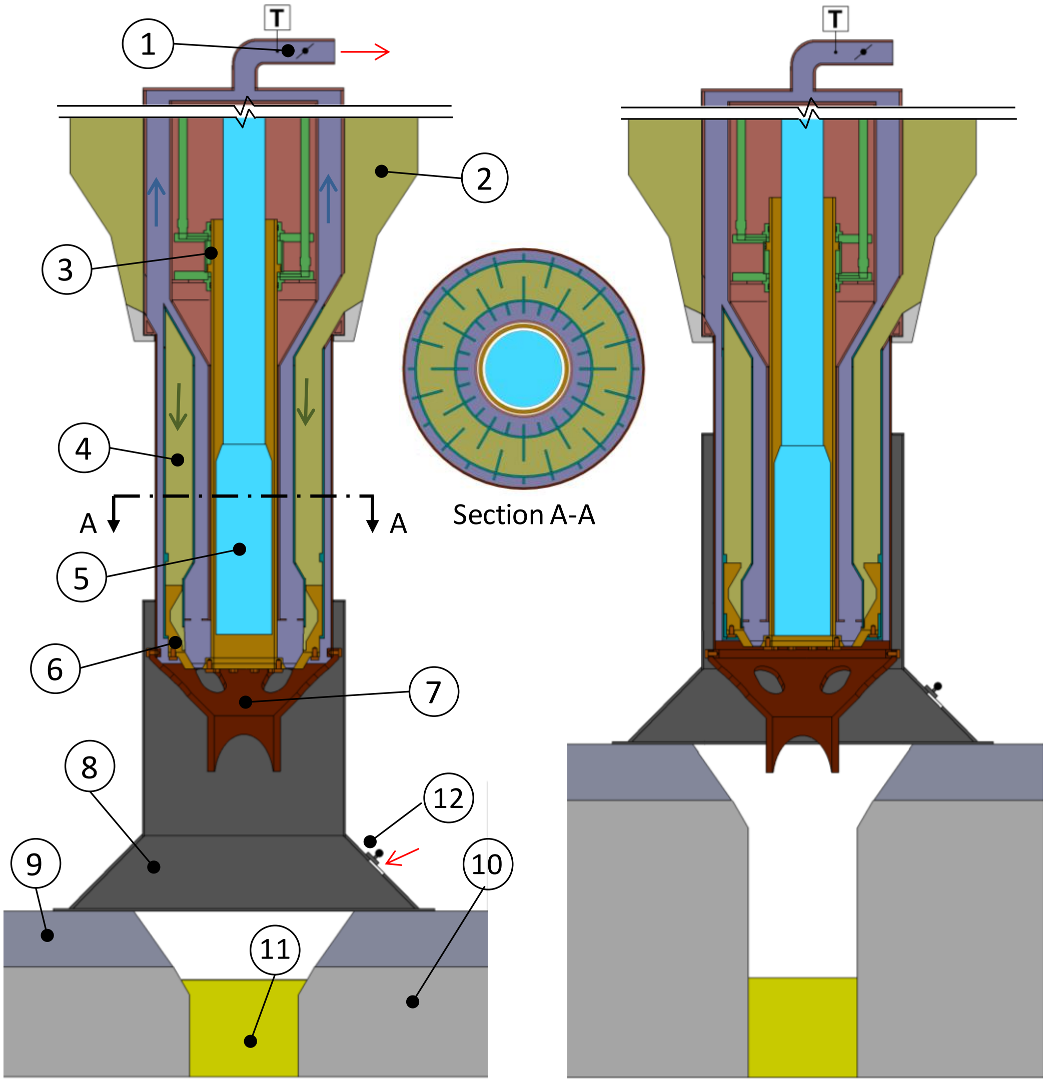

Figure 1. Counter flow heat exchanger with fins, as shown in [14]. Left: exchanger positioned over butt anodes. Right: exchanger positioned over new anodes.

The simulations presented in the referred article [14] have shown the potential of energy recovery in the heat exchanger in. The CFD models have also shown that alumina can be preheated to a temperature of 500 – 600 °C as visually described, for example, in the simulation results of Figure 2. In the picture below, the simulated gas flow vectors and the alumina temperature field during the process are presented for two different vertical planes slicing the heat exchanger.

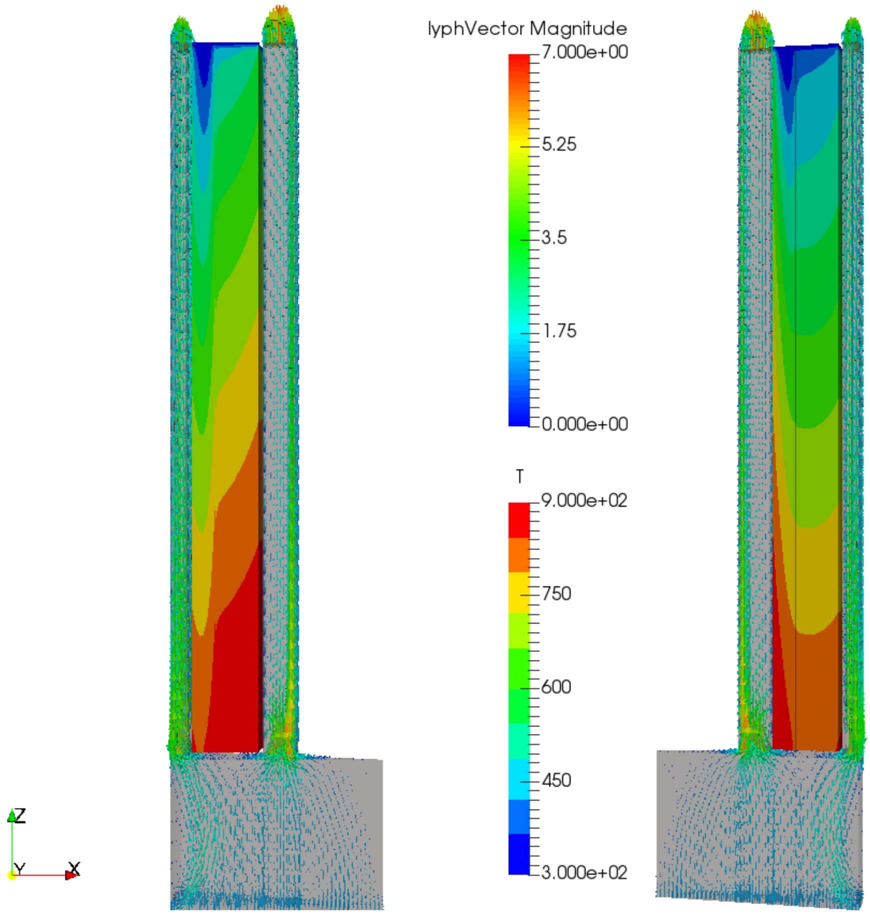

Figure 2. Gas velocity vectors [m/s] and alumina temperature in [K] inside the heat exchanger, according to numerical simulations [14]. Left: plane cutting the inner side fin. Right: plane cutting the outer side fin.

3. Heat Exchanger Prototype Test

A first, industry size prototype for testing the concept was designed and constructed by CAETE Engenharia. The prototype is installed in a laboratory room where a controlled process of alumina feed can be studied. The main body of the exchanger is equal to the design to be applied in real cells. Alumina is fed manually at an open top funnel, while the hot gases are produced by combustion of natural gas in a bottom chamber. Instead of an alumina chute present in the original project, here the alumina passes through controllable nozzles in continuous flow at the exchanger outlet placed in radial distribution. The amount of energy from the flame is calculated to match the energy emitted by the hole at the cell crust in an actual cell. In the same manner, the total gas flow is adjusted by introducing false air making both the flux of energy and gas velocities similar to the values produced by the electrolysis process. Figure 3 presents the prototype design explaining the counter flow of gas and alumina (left), as well as a photo of the actual prototype installed in the laboratory (right).

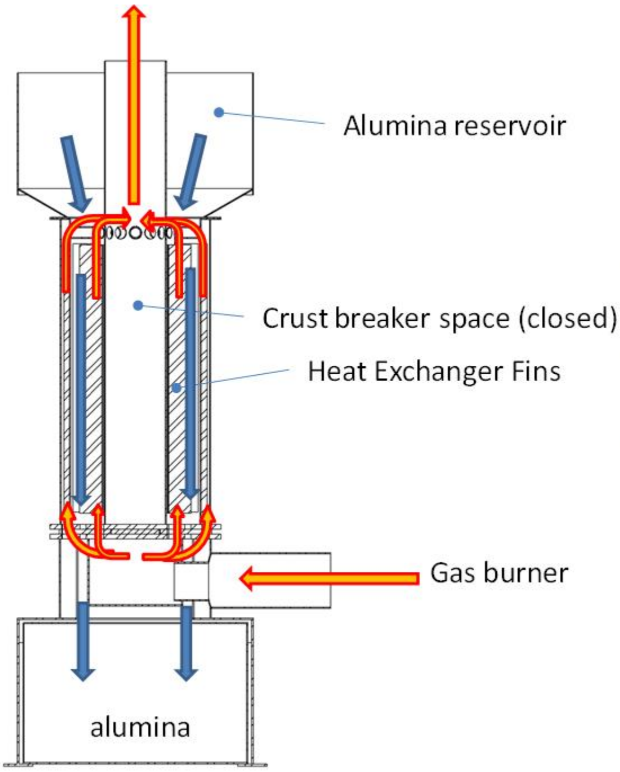

Figure 3. Left: experiment concept for the alumina exchanger prototype. Right: actual prototype installed in the laboratory.

The welded fins placed in the core of the heat exchanger are a very important feature. They have the task of enhancing the exchange of heat between the hot gases and the alumina, thereby increasing the exchanger efficiency up to a desirable level. The size, quantity and shape of the fins were studied in-depth and optimized by numerical modelling. The final construction of the fins is shown in Figure 4.

Figure 4. Prototype construction process. All fins are welded in both gas ducts and alumina duct.

Instead of the heat exchanger being attached to the alumina hopper, in the prototype an alumina reservoir possessing a funnelled shape is attached at the top of the heat exchanger, as shown in Figure 5. In this setup the alumina must be fed manually, filling the reservoir that must be replenished when necessary.

Figure 5. Left: prototype top view. Right: prototype with the alumina feeding reservoir.

4. Experiment Data Acquisition and Analysis

The objective of testing the prototype is to verify if the alumina temperature can reach the desired level at the exchanger discharge. Additionally, the internal gas and alumina temperatures inside the exchanger ducts during the process are also monitored. A set of eleven thermocouples is placed inside the heat exchanger, mounted in the positions as described in Figure 6. Five of the thermocouples (TG1, TG2, TG3, TG4 and TG5) are placed inside the gas ducts to monitor the gas temperatures. The remaining six thermocouples are placed inside the alumina duct at different radial and longitudinal positions to monitor the alumina temperature during the experiment (TA1, TA2, TA3, TA4, TA5 and TA6). After the experiment, the bulk temperature of the heated alumina that is collected is also measured, inspecting many points inside the deposit.

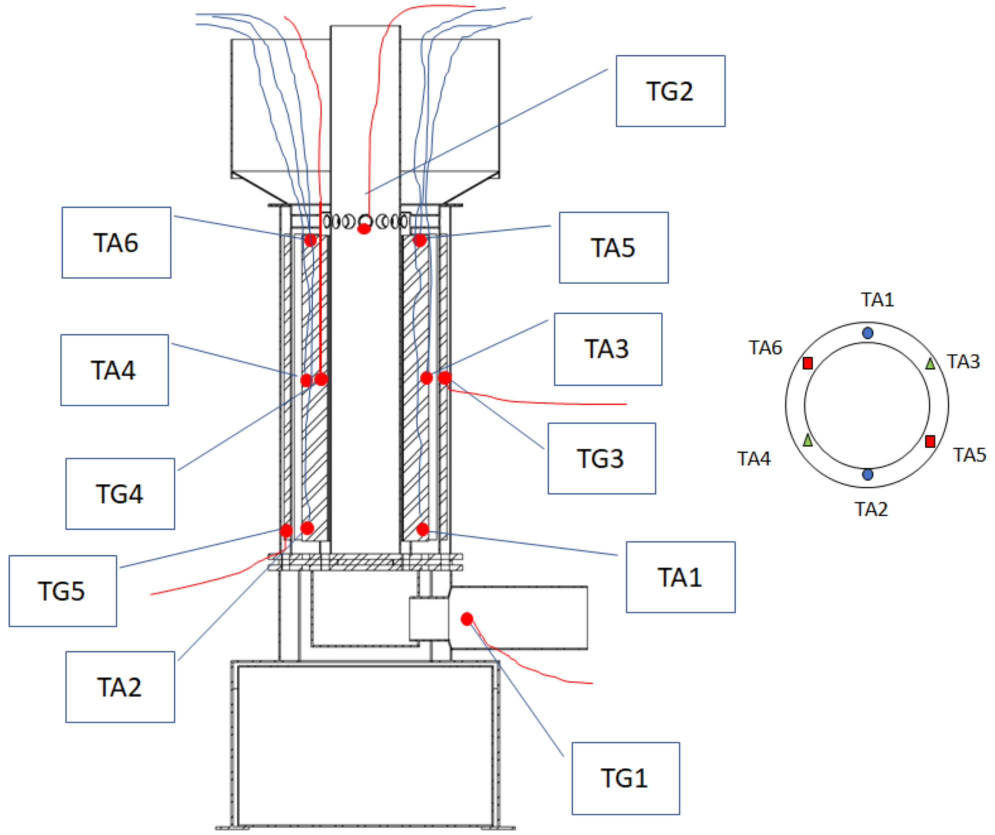

Figure 6. Schematic view of the thermocouples placed inside the prototype for temperature acquisition. TGs are thermocouples placed inside the gas flow ducts. TAs are thermocouples placed inside the alumina flow ducts.

Figure 7 shows the final prototype setup with all thermocouples installed, including exhaust duct and burner, ready for the experiment.

Figure 7. Prototype ready for the experiment.

Smelter grade alumina was used during the experiment. There was only 50 kg of alumina available, sufficient for 15 min of continuous flow inside the heat exchanger. First (Phase 1), the exchanger is preheated by running the combusted gas flow without alumina (void alumina duct). Then the alumina starts to be fed and the heat exchanger begins to work thereby emulating the real cell feeding rate, which is the zone of interest of the experiment (Phase 2). After the completing feeding the alumina, the last part of the data acquisition refers to the phase when the remaining alumina inside the exchanger is discharged without the introduction of new (cold) alumina until 100 % of the alumina leaves the unit and the equipment is empty (Phase 3). The Figure 8 presents the temperatures acquired during the experiment, for the most relevant selected points (TG1, TA1, TA2, TA3 and TA4). All three phases are shown in the graph.

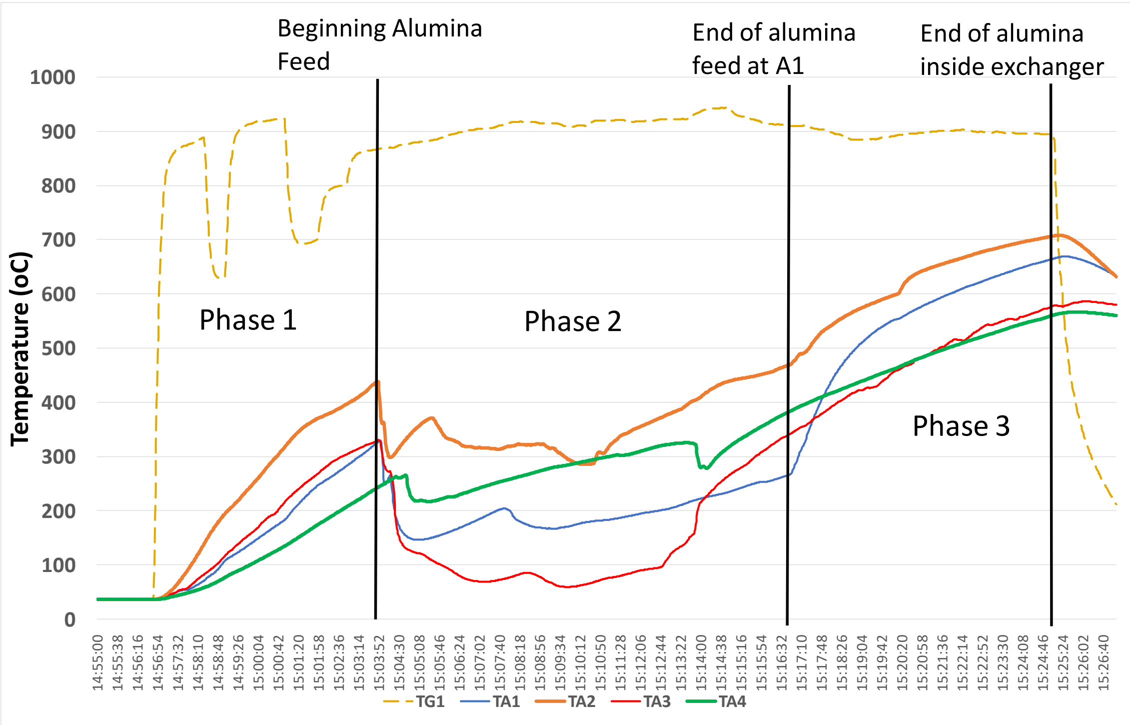

Figure 8. Temperature [°C] profiles during the prototype test for selected positions inside gas (TG1) and alumina (TA1, TA2, TA3 and TA4) ducts.

From the obtained temperature profiles the following observations are made:

- There is an uneven distribution of temperatures around the exchanger. This is observed in all three phases. The asymmetry present in gas flow is likely the reason for this unevenness and this is caused by the combustion gases that are fed to the prototype by a lateral tube. This effect is expected to be minimized in the real cell operation.
- In Phase 1 the equipment is heated up to 450 °C inside the alumina duct; this is achieved in approximately 7 minutes.
- In Phase 2 the flow of alumina is established. The alumina is a granular material and a flow of granular material is not always perfect when continuous. Instead, the internal alumina flow seems to present an intermittent sliding, which is a characteristic of a granular flow. This makes alumina temperature to bounce from time to time but it is realistic as those characteristics cannot be changed.
- In the Phase 3 the alumina discharge temperature increases because the feed of fresh alumina stopped.

The final bulk temperature is measured inside the alumina deposit at the end of the alumina feeding experiment. This temperature represents the time and volume averaged alumina temperatures that leave the heat exchanger during the experiment. It reached around 500 °C on average. In the experiment, the system was still transient at the end of feeding, due to the insufficient alumina available to continue the experiment up to a stationary condition. It is estimated by modelling, that around 45 min of continuous experiment would be required to achieve steady state, instead of the 15 min continuous feeding available.

Figure 9. Bulk temperature inspection in the alumina deposit, after the alumina flow ended in the experiment.

5. Conclusions

The experiment using the prototype has confirmed the heat recovery potential of the heat exchanger and the results are in good agreement with the predicted values from previous numerical models. Alumina discharge temperature reached the predicted temperature level of 500 °C.

The experiment has also shown that the pseudo steady state of alumina flow is in reality a sequence of intermittent slidings of alumina particle packs, which is very characteristic of a granular flow. The thermal steady state condition of the heat exchanger was not achieved during the 15 minutes of process. The model shows that it takes 45 minutes but the current setup is not providing sufficient process time allowed the achievement of thermal steady state. However, if this can be achieved in future experiments then the alumina discharge temperature could be even higher.

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