Controlled cooling of aluminium smelting cell sidewalls using heat exchangers supplied with air

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Abstract

Aluminium potshells have increased in temperature and heat flow in recent years. Removal of heat from cell sidewalls for the purposes of temperature control and ledge maintenance in smelters presently takes the form of compressed air impingement directly on the shell, if the need for cooling is detected. These air lances cool in a non-uniform way, are extremely energy inefficient, adversely impact on the workplace environment as a result of the associated noise and dust, and offer no opportunity for energy recovery in the future.

The Light Metals Research Centre (LMRC) has developed a technology with the capability of providing controlled cooling to sidewalls using heat exchangers installed online, which have a much lower air consumption. LMRC has an in-house dedicated testing facility for the development and demonstration of sidewall cooling based on heat exchangers supplied with air. This paper reports the experimental results obtained in the testing facility and analyses the practicality of this technology.

Introduction

Capacity creep in smelting cells

Productivity improvements have prompted aluminium smelters globally to increase the amperage in their potlines. In 1948, typical cell productivity was 385 kg of Al per day. Nowadays it has increased to 2475 kg per day [1]. Productivity is enhanced either by increasing the amperage of existing cells or by introducing new high amperage cell designs, which have lower shell surface area per kilowatt of heat generation.

Sidewall ledge thickness is one of the constraints associated with this capacity creep. Figure 1 depicts the two-dimensional steady state heat transfer through the sidewall and semi-graphitic cathode section of a cell [2]. The heat transferred from liquid electrolyte to frozen ledge is approximately equal to the heat flow through the sidewall lining from frozen ledge to the steel shell. Heat exchange also occurs between side wall and cathode, although this is much lower as shown by the position of the isotherms in Figure 1. The resultant quantity of heat then flows from the exterior of the steel shell to the ambient air. The capacity creep achieved through amperage increase causes higher ohmic heating within the cell. It has been previously reported that ledge thickness has decreased from 15-20 cm to 1-3 cm, when the amperage was increased from 186 kA to 210 kA for a particular cell design [3] . This is due to a much greater heat flow through the cell walls. Additional ohmic heating from increased amperage can be limited by reducing the Anode-Cathode Distance (ACD). However, this is constrained by the minimum achievable ACD without compromising current efficiency, and by ohmic heating increasing with the square of the amperage.

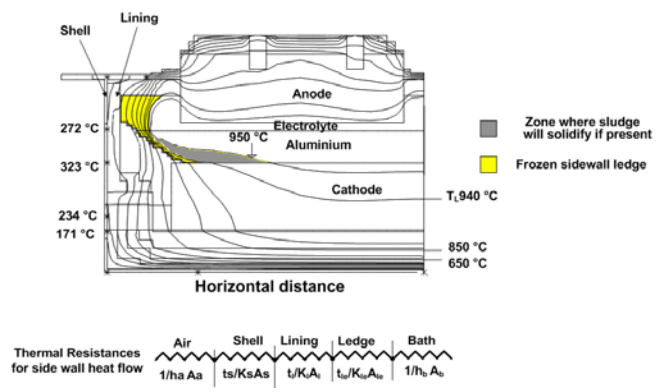

Figure 1: Two dimensional steady state heat transfer through the sidewall section of a cell [2].

The other variables which determine the heat flux through the sidewall are; wall surface area, liquid depth, thermal resistance and thickness of the lining material. Increasing the wall surface area to aid heat transfer again has limited effect, although fins fitted to the shell have partially increased the external surface area for natural convective heat transfer to the ambient air. Changing from carbon-based materials to silicon carbide plus graphite inserts has increased the heat conduction through the sidewall.

Silicon carbide, depending on the binder type is approximately 4-6 times more thermally conductive than rammed carbon [4, 5]. The increases in lining conductivity and reduction in ledge thickness means that approximately 50% of the thermal resistance of the side wall / ledge combination is actually at the shell / air interface [2].

The increased sidewall heat flux due to the process intensification of the smelting cell has resulted in substantial loss of ledge thickness and elevated temperatures of every material in the sidewall. A stable ledge needs to be maintained for adequate life of the sidewall materials. Shell temperatures in excess of 500 ^oC have been measured in the last 3-4 years [6]. In contrast, peak sidewall temperature measurements made by Taylor in the early 1980's recorded temperatures ranging from 255 ^oC to 265 ^oC [7]. The integrity of the steel shell is reduced with higher shell temperatures and corrosive salts are mobilized, potentially leading to shell failure or collector bar connection failure [2]. The best opportunity to increase the sidewall heat flow for a given cell design is to enhance the heat transfer from the sidewall exterior surface. This location has the largest thermal resistance compared to any other element in the sidewall as described above (and also in [8]).

Traditionally compressed air jets have been used, for short periods in emergency situations, to cool sidewall hot spots locally and prevent cell tapouts. Compressed air increases the convective heat transfer coefficient between the ambient air and the shell exterior thus permitting rapid cooling of the shell. A continuous shell cooling system was designed by Alcan (the Forced Cooling Network-FCN), which cools the entire perimeter of the cell [9]. It consists of a series of low pressure air jets located around the cell's perimeter which impinge on the shell surfaces. This is an established cooling system for the AP family of cell technologies [10-13].

However, observation and analysis of the air jet systems reveal the following issues:

- Air jets will increase the dust aeration and dispersion within the potroom due to the unconfined air flow. Air borne dust is a health hazard with potential to cause respiratory diseases and eye injuries [14].
- Air jet cooling is difficult to regulate closely, either in terms of region being cooled or the degree of shell temperature reduction. This is due to the sensitivity of the heat transfer rate to the distance from the impingement point [8].
- Air jet cooling is not amendable to waste heat recovery because the heated air from the cooling process is not captured [8].

The Light Metals Research Centre (LMRC) at the University of Auckland has developed a technology with the capability of providing controlled cooling to sidewalls using heat exchangers, installed on-line, with lower air consumption. Moreover, the hot air from the heat exchangers is collected and removed from the potroom. The heat content of the air (150-200 ^oC) can be potentially recovered. The LMRC Shell Heat Exchanger (SHE) technology has also been implemented without compressed air, using an extraction fan and this application will be demonstrated in a later paper. This paper reports the performance of SHE supplied with compressed air and fitted to sidewall of a full scale cell demonstration model. The expected benefits for smelters from SHE technology are also discussed.

Experimental

Shell Heat Exchangers

Figure 2 shows a typical SHE design developed by LMRC. The shell heat exchanger is comprised of three parts; an exchanger body, an air knife assembly to distribute the motive air and induce more air into the exchanger and an exchanger outlet. The exchanger body incorporates vortex generators (not shown in the Figure) to enhance the heat transfer at low air velocities.

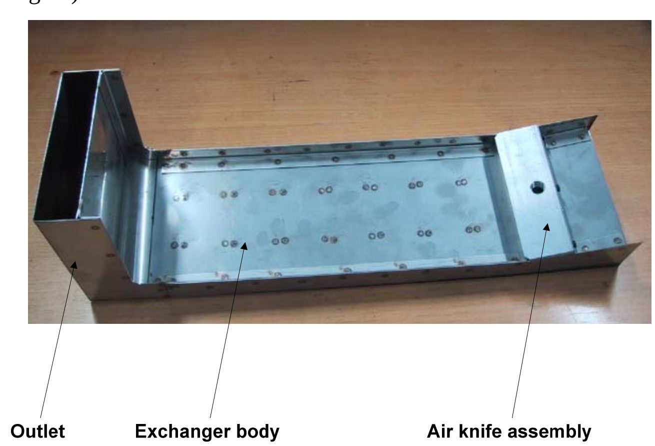

Figure 2: Shell Heat Exchanger (SHE).

Figure 3 illustrates in broad terms the mode of operation of SHEs, in this case for a compressed air source. The air is introduced into the exchanger in such a way that additional ambient air is entrained. The combined stream of motive and induced air flows up the gap between the steel shell and the heat exchanger and then exits via the opening at the top of the exchanger. The cell wall is cooled while the exchanger air is heated. The alternate fan-powered SHE model produces similar heat transfer and has been plant tested earlier. Choice of compressed air vs. fan power should be based on specific smelter design and operating considerations such as compressed air cost.

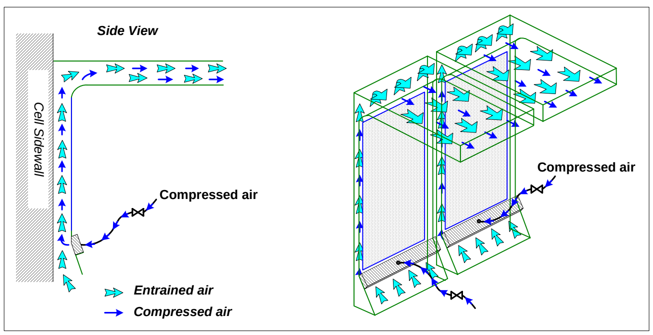

Figure 3: SHE operation using a compressed air source.

Sidewall cooling Demonstration Facility

A pictorial view of the potshell sections in the demonstration model is shown in Figure 4. The sections represent two 3 cradle potshells in a 350 kA potline facing each other. The supports for the working floor have been removed from the figure for clarity along with the basement floor. The sidewalls are heated by the electrical elements mounted in the sidewall and are thermally insulated on the inner sidewall face to ensure almost all heat flows through the side wall to the potshell.

Sidewall heating is controlled by PLC, allowing various modes of power input control. Thermocouples are mounted at a number of locations on the potshell in order to measure the vertical temperature profile with and without the shell heat exchangers. The thermocouples are connected to an on-line data acquisition system, which records the temperature data continuously. Peak sidewall temperatures in excess of 480 ^{o}C can be achieved.

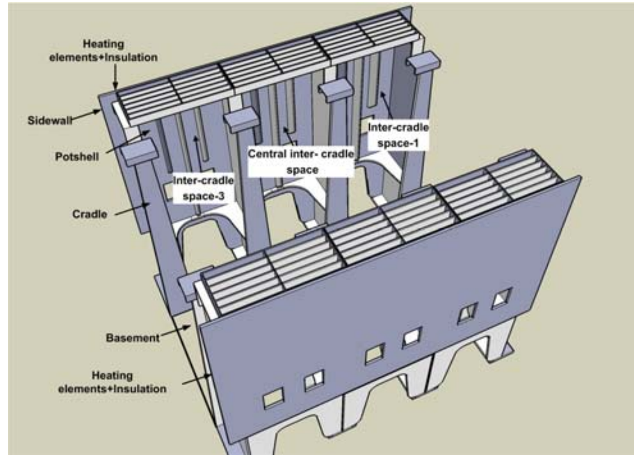

Figure 4: A pictorial view of the LMRC demonstration model.

Procedure

Four shell heat exchangers, (two of 140 mm wide and two of 95 mm wide) were mounted to the central inter-cradle space on one potshell. This has given 77% area coverage of the shell in the inter-cradle space. Tubular ducting was fitted to the exchanger outlets to remove the hot air from the exchangers to the outside of the potshell sections. Compressed air was supplied to the air knife of the SHEs through a pressure regulating valve. Figure 5 shows the actual arrangement of SHEs mounted on the central inter-cradle space of the demonstration model. The potshell was initially heated to a steady state temperature with zero air flow through the SHEs. Once the required temperature was attained on the shell, compressed air was admitted through the SHEs to cool the central inter-cradle space and the same flow rate was maintained until a new steady state value was attained. The following parameters were recorded during the experiments:

- Temperature at various locations on the inter-cradle space with and without SHEs.
- Flow rate, pressure and temperature of the compressed air supplied to the SHEs.
- Velocity and temperature of the hot exit air from the SHEs (measured in the duct, approximately 1 m from the exit of SHEs).
- Temperature of induced air to the SHEs.

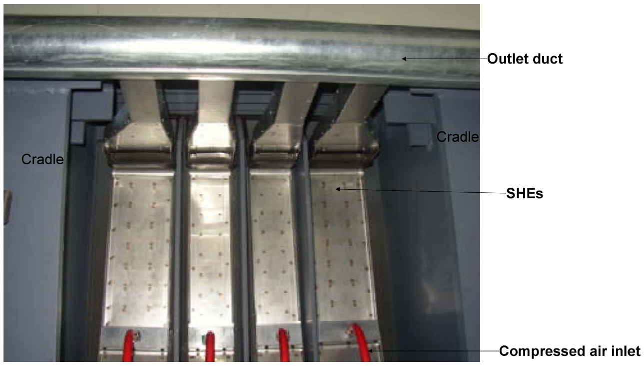

Figure 5: SHEs mounted using a simple one-piece hanger in central inter-cradle space of the demonstration model.

Results

Table 1 shows the sidewall cooling performance of the shell heat exchangers. A peak sidewall temperature reduction of up to 150 °C is obtained in this case. The sidewall cooling was controlled by adjusting the flow of compressed air into the system. The temperature of the air measured at 1 m from the outlet of the SHEs was between 170 to 200 °C. This corresponds to a heat content of 3-5 kW per cradle position. The induced air to compressed air ratio obtained in the experiments was between 1 to 1.6. Redesign of the air knife has now increased this ratio to 2.5-3, reducing compressed air consumption by a further 50 %.

Table 1: Performance summary of Shell Heat Exchangers(+)

Total air flow (kg/h)	No SHEs	58	95	111
Compressed air flow (kg/h)	No SHEs	24	34	50
Peak potshell temperature (°C)	470	460	410	370
Maximum potshell temperature reduction (°C)	-	60	120	150
Average potshell temperature reduction (°C)	-	21	72	95
Temperature of heated air (°C)	-	189	176	160
Heat energy transferred to air (kW)	-	2.8	4.2	4.4

(+)*All data quoted per cradle position (4 SHEs in this case)*

Figures 6 to 8 compare the vertical temperature profile at various air flow rates with and without SHEs installed. When no air is supplied to the installed SHEs, they can act as insulators. So SHE relaxation from the shell is provided for, when not in operation.

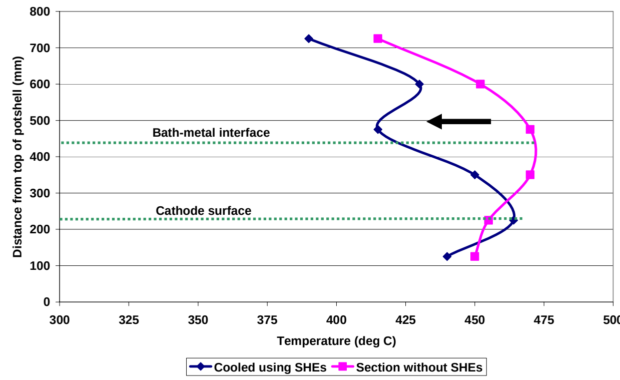

Figure 6: Shell sidewall temperature profile with and without SHEs installed with 24 kg/h compressed air per cradle position.

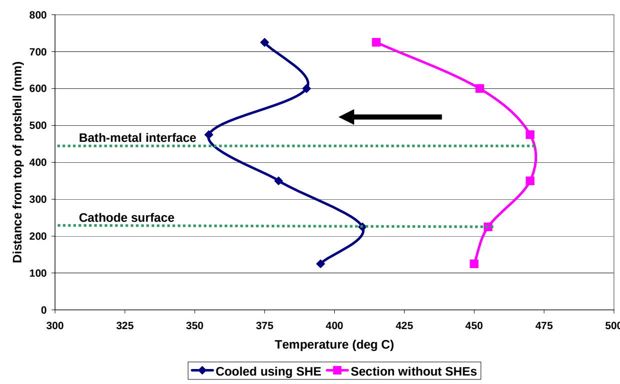

Figure 7: Shell sidewall temperature profile with and without SHEs installed with 34 kg/h compressed air per cradle position.

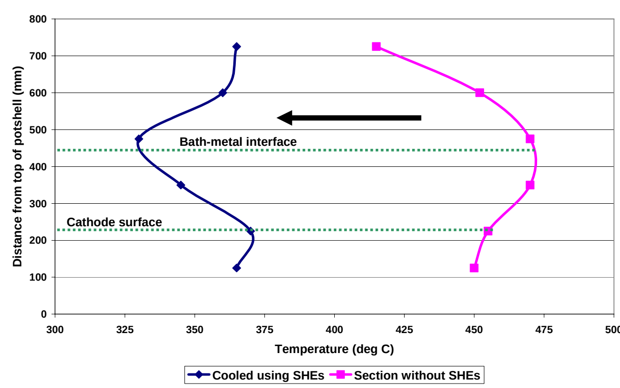

Figure 8: Shell sidewall temperature profile with and without SHEs installed with 50 kg/h compressed air per cradle position.

An analysis of the experimental data reveals that the SHEs have increased the heat flux through the sidewall of the demonstration model. For example, at 72 ^oC average cooling, the total heat extracted by the supplied air from the central inter-cradle position was 4.2 kW (Refer to Table 1). With a SHE coverage of 0.235 m^2, the heat transferred to the air per unit area of the exchanger covered on the shell (Q) was 17.74 kW /m^2. Because there was no significant heat loss in the 1m section of duct from the SHEs outlet to the measuring point, the effective shell to air heat transfer coefficient for this particular case can also be computed and equals 54 W/m^2 ^oC, as shown by Equation (1).

$$h_f = Q/(T_{cs}-T_{air}) \qquad (1)$$

Where, h_f is the effective heat transfer coefficient, W/m^2 ^oC.

T_{cs} is the average temperature of the sidewall with SHEs installed, ^oC.

T_{air} is the temperature of air at the basement, ^oC.

The heat flux through the cradle position without the SHE installed is estimated to be 12000 W/m^2, as shown by Equation (2).

$$Q_{noSHE} = h_n (T_s-T_{air}) \qquad (2)$$

Where, Q_{noSHE} is the heat flux through the cradle position without SHE installed, W/m^2.

h_n is the effective heat transfer coefficient of air in natural convection + radiation, W/m^2 ^0C (taken as 30 W/m^2 ^0C [2] at 400-450 ^oC).

T_s is the average temperature of the sidewall without SHEs installed, ^oC.

Hence, approximate additional heat flux removed by the SHEs equals 5740 W / m^2.

Application of the SHE Technology

By installing SHEs on the potshell of smelting cells, additional heat can be extracted, thus maintaining the sidewall at a safe service temperature. In situations where the amperage increase is limited by the heat balance at the sidewalls, the implementation of the SHEs is an economic and immediate option to enable higher line current. Typically, depending on the pot design and the perimeter of the shell to be cooled, 16 to 60 heat exchangers are installed at locations of highest shell temperature, increasing the sidewall protection where the ledge is the thinnest. Installing more exchangers (30-60) allows control over the temperature distribution around the whole cell and enables higher amperage increase through more heat extraction. A simple illustration of the economic benefit of the technology is given in Table 2 and a chart showing the estimated cost and annual revenue increase vs. number of exchangers is shown in Figure 9. This analysis is cell technology and site dependant, but clearly indicates the value of the technology for smelters.

Table 2: Example of economic benefits of SHEs (per cell basis)

Estimated number of heat exchangers fitted per cell	50
Price for heat exchangers, inlet & outlet ducting, instrumentation and installation ($US, 000)	24
Annual operating cost for requisite compressed air ($US, 000)	13
Annual increase in metal production (tonnes)	27.6
Annual increase in revenue ($US, 000)	27.6
Payback period (years)	**1.33**

(Assumes amperage increase of 10 kA at 94% CE and $1000/t incremental profit)

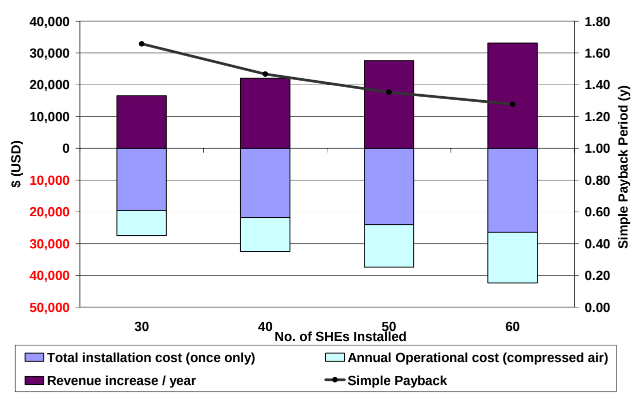

Figure 9: Estimated cost and revenue increase (annual) vs. number of SHEs for one cell technology.

While no account is taken in this analysis, significant financial benefit can also be realised from SHE installation due to the ability to control superheat of the bath independently of anode-cathode distance. It can be shown that by smelter cost / waste analysis that avoidance of extreme superheat could add a further 5 Million USD per annum profit to an average smelter because of the improved anode performance and lower sidewall damage.

Another unaccounted benefit of the technology is recovery of the hot air exhausting from the exchangers. The exhaust temperature is typically between 150 and 200 ^{0}C, depending on the ambient temperature and the heat flux at the potshell. Capture of this benefit through heat exchange with other smaller material streams is currently being researched by LMRC.

Requirements in plant

The operating requirements of the SHEs are broadly given in bullet points below.

- Motive air source: Compressed air or Extraction fan (external to the potline).
- Ducting for air, and valving for air flow through SHEs.
- Alarm to alert the failure of the system (air flow).
- Low maintenance requirements.

SHEs can be installed either from the catwalk or from the basement of the potline and the installation procedure varies with the cell design and access to the shell. The hot air from the SHEs needs to be ducted out appropriately from the potrooms, providing cooler temperatures on the operating floor while enabling heat recovery (for example pre-heating of the anodes and alumina).

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