COM 2020
CONFERENCE OF METALLURGISTS
MetSoc

PRACTICAL CONSIDERATIONS IN THE DESIGN OF AN EXPERIMENTAL SET-UP FOR LABORATORY-SCALE INVESTIGATION OF SLAG FREEZE-LININGS

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ABSTRACT

In the production of ferrochromium, the conductive lining design philosophy is utilized in furnace containment systems. The philosophy is based on the principle of a process material layer freezing onto the hot face of refractory material. The frozen layer (often referred to as 'freeze-lining') then acts as a buffer between the liquid process materials and the installed components of the containment system. This allows for flexibility in the design of the slag system, focussing on process optimization rather than chemical compatibility with hot face refractory material. Laboratory-scale investigations aid in the optimization of furnace containment designs. The purpose of this paper is to describe the design and commissioning of an experimental set-up based on the immersion of a probe, cooled by a suitable cooling medium, into a crucible containing liquid slag.

KEYWORDS

Cold-probe, Conductive lining, Design, Experimental set-up, Freeze-lining, Furnace containment

INTRODUCTION

Two furnace containment philosophies, insulating and conductive, come to mind when designing a new industrial-scale furnace for ferrochromium (FeCr) production. An insulating lining makes use of convective and conductive heat transfer mechanisms to transfer heat from inside the furnace to the environment (Steenkamp et al., 2017). This is achieved by making use of a refractory layer to conduct heat away from the hot face to the cold face of a furnace. Conductive linings are attained by manipulating the furnace conditions in such a way that a layer of process material "freeze" on the hot face of the refractory lining (Duncanson & Toth, 2004). This frozen process material then acts as a protective layer against refractory wear mechanisms such as alkali attack, thermal stress, and erosion (Duncanson & Toth, 2004). Conductive containment systems, also known as "freeze-lining" refractory systems, have gained popularity due to claims of longer campaign lives and higher operating intensities, allowing for higher reliability and contributions to the profitability of the applied smelting process (Duncanson & Toth, 2004; Kennedy et al., 2015). Duncanson and Toth (2004) stated that in order for a freeze-lining to form, the refractory system should be designed in such a way that heat is efficiently removed to keep refractory temperatures low enough to enable the formation of a freeze-lining. Efficient heat transfer can be achieved by adding external shell cooling or, as in the case of modern high-intensity smelting furnaces, use internally cooled wall panels, plates, or finger coolers (Kennedy et al., 2016; Joubert & Mc Dougall, 2019). Modern furnace containment designs for both arc and resistance furnaces frequently make use of copper coolers to reduce refractory wear and increase productivity (Kennedy et al., 2009; Joubert & Mc Dougall, 2019). These copper coolers normally make use of water as a coolant, which consequently increases the possibility of boiling liquid expanding vapour explosions (BLEVEs) and other high-impact failures.

Freeze-lining technology has proven in recent years to outperform traditional insulating lining technologies (Duncanson & Toth, 2004; Filzwieser et al., 2014; Kennedy et al., 2015, 2016; Joubert & Mc Dougall, 2019), however, limited understanding of the mechanisms at work in the formation of freeze-linings as well as their thermal properties, persists. Various authors (Verscheure et al., 2006; Campforts et al., 2007; Fallah-Mehrjardi et al., 2013; Assis & Pistorius, 2018) have shown that it is possible to investigate freeze-lining formation by making use of "cold-finger" experimental set-ups. This paper describes the design of an experimental set-up that would allow the investigation of ferrochromium freeze-linings, based on a review of the literature available on existing experimental freeze-lining test facilities as well as equipment available.

BACKGROUND

To study the formation of feeze-linings, a fluid-cooled annular flow probe was selected of which the design will be discussed in the design section. In order to describe the heat transfer of this probe system, a set of heat transfer resistance modules can be described as in Figure 1 (Steenkamp et al., 2017). The steady-state heat transfer equations were used to define the expected steady-state conditions, defining the important parameters to be measured during experiments, and allowing for material and equipment selection.

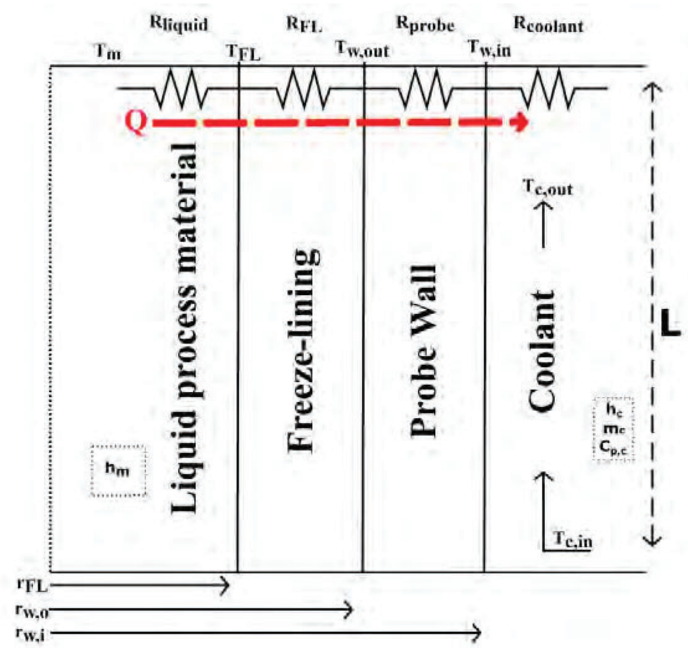


Figure 1. Steady-state heat transfer schematic

The overall rate of energy removal is described by Equation 1. The thermal resistance of the different components in the probe system is defined by the applicable heat transfer mechanism as shown in Equations 2 and 3.

$$Q = \frac{T_{melt} - T_{coolant}}{R_{liquid} + R_{freeze-lining} + R_{probe} + R_{coolant}} \tag{1}$$

$$R_{convection} = \frac{1}{2\pi r h} \tag{2}$$

$$R_{condction} = \frac{ln\left(\frac{r_o}{r_i}\right)}{2\pi k} \tag{3}$$

At steady state, the heat transfer through each component, in series, are equal and therefore governed by the net energy removed by the coolant. By assuming the system is in steady-state, Equation 4–8 can be solved simultaneously using an iterative method. Q (in W) represents the rate of energy removed by the coolant, with $C_{p,c}$ the average heat capacity of the coolant in J/kg.K, and $\dot{m}_c$ the mass flowrate of the coolant in kg/s. $T_{c,in}$ and $T_{c,out}$ represents the inlet and outlet temperatures of the coolant, respectively, in K. The probe dimensions are described by external ($r_{w,0}$) and internal ($r_{w,i}$) radii, and immersion depth (L), all in metres. $T_{w,i}$ and $T_{w,o}$defines the temperatures (in K) at the internal and external surfaces of the outer wall of the probe. T_{FL} represents the melting point of the freeze-lining and T_m the bulk temperature of the molten bath, again in K. The heat transfer coefficient between the bulk coolant flow and the inner surface of the probe wall is defined by h_c in W/m^2.K, while h_m defines the heat transfer coefficient between the freeze-lining outer wall and the molten bath, also in W/m^2.K. The outer radius of the freeze-lining is defined by r_{FL}, in metres.

$$Q = C_{p,c}\dot{m}_c\left(T_{c,out} - T_{c,in}\right) \tag{4}$$

$$Q = 2\pi r_{w,i} L h_c \left(T_{w,i} - \tfrac{1}{2}\left(T_{c,out} + T_{c,in}\right)\right) \tag{5}$$

$$Q = \frac{2\pi k_w L}{\ln r_{w,o}/r_{w,i}}\left(T_{w,o} - T_{w,i}\right) \tag{6}$$

$$Q = \frac{2\pi k_{FL} L}{\ln r_{FL}/r_{w,o}}\left(T_{FL} - T_{w,o}\right) \tag{7}$$

$$Q = 2\pi r_{FL} L h_m (T_m - T_{FL}) \tag{8}$$

In order to solve the steady-state heat transfer equations (Equation 4–8), a few approximations are made. It is assumed that no counter-current heat exchange occurs between the coolant in the inner and outer channels of the probe. Differences in the coolant pressure between the inlet and outlet are neglected, and the influence of the contact resistance between the outer wall of the probe and the freeze-lining is disregarded. Lastly, it is assumed that $L \gg r_w$ and therefore effectively neglecting the heat transfer from the tip of the probe.

LITERATURE REVIEW

The design of an experimental set-up for studying the formation of freeze-lining requires a number of factors to be taken into consideration. The design process is kicked-off by defining the operating temperatures as well as the rate of cooling required to form a freeze-lining, both of which depend on the slag system being investigated. Once the operating and cooling temperatures have been defined, a heating and cooling system can be specified. A literature review was conducted to gather information on existing freeze-lining experimental set-ups which allowed for valuable insight into what equipment selections were made as well as the reasoning behind the selections. From the literature, it could be seen that both induction

(Campforts et al., 2007; Fallah-Mehrjardi et al., 2013) and resistance furnaces (Verscheure et al., 2006; Fallah-Mehrjardi et al., 2014; Assis & Pistorius, 2018) were used as the heating source, reaching bath temperatures up to 1400ºC.

Crucible selection and the need for an inert atmosphere are determined by the slag system under investigation. The crucible and inert atmosphere are designed to limit chemical interactions with the slag and surrounding atmosphere.

Various authors (Verscheure et al., 2006; Campforts et al., 2007; Fallah-Mehrjardi et al., 2013) made provision for the sample to be rotated during the experiment. Campforts et al. (2007) found that even though rotation increases the convection rate, no significant change was noticed in the freeze-lining thickness or composition when the rotational speed was varied. The only change in the freeze-lining, as a result of a varied rotational speed, was noticed in the microstructure of the freeze-lining.

Both copper (Verscheure et al., 2006; Assis & Pistorius, 2018) and grade 316 stainless steel (Fallah-Mehrjardi et al., 2013) have been used as probe material. No explicit reason for the use of the selected probe material has been discussed, but it is understood that copper is used as it is the most commonly used material for intensive cooler design, and stainless steel, as it has a higher melting temperature, and would therefore be the safer alternative to copper. The most common probe design was found to be a coaxial tubular system, because a radial system allows for easier fabrication while ensuring uniform heat transfer. The symmetric heat transfer characteristics of a coaxial tubular probe allow for easier model validation and ensure a uniform freeze-lining. The probe dimensions are governed by the size of the crucible containing the process material and the flow requirements of the coolant. The inner and outer tube combination should allow for the required flow rate of the coolant as well as ensure that the specified pressure is met, when a compressible coolant such as air is utilized. The probe length is governed by the depth of immersion into the slag bath and the dimensions of the furnace.

The coolant is selected based on its heat transfer properties and the safety implications associated with a probe malfunction. Water is the most commonly used coolant as it is regularly available and has good heat transfer characteristics, which help reduce the flow requirement of the coolant. Water, however, can lead to catastrophic failures if there is a probe malfunction and water comes in contact with the molten material (Babaitsev & Kuznetsov, 2001). The safer alternative to water would be air, but due to the inefficient heat transfer characteristics of air, high flow rates are required to ensure sufficient heat transfer to enable the formation of a freeze-lining.

The number and types of thermocouples utilized, as well as their positions, are of utmost importance. The readings from the thermocouples are used to define the energy input and output, which is used for validation of the results and predictions, as well as to control the system. When designing the experimental set-up, the correct thermocouples should be selected based on the expected temperature ranges as well as the chemical environment they will be exposed to. The position of the thermocouples outside the probe can be used to validate the growth of a freeze-lining and should, therefore, correspond to the expected freeze-lining thickness as calculated prior to test work.

Once the test is finished and a sufficient freeze-lining sample has formed, the sample can either be retracted and positioned above the molten material interface and allowed to cool down with the furnace, or it can be completely removed and quenched. The freeze-lining sample can be quenched in either water (Fallah-Mehrjardi et al., 2013) or a nitrogen gas atmosphere (Verscheure et al., 2006; Campforts et al., 2007) to limit any further microstructural and phase changes that might occur in the freeze-lining sample. Table 1 lists most of the variables used to draw a comparison among existing experimental set-ups.

Table 1. Data comparison on existing experimental set-ups

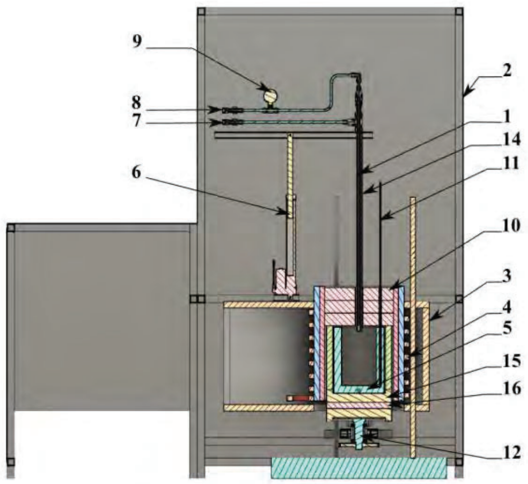
Variable	Unit	#1	#2	#3	#4	#5
Source		(Verscheure et al., 2006)	(Campforts et al., 2007)	(Fallah-Mehrjardi et al., 2013)	(Fallah-Mehrjardi et al., 2014)	(Assis & Pistorius, 2018)
Heating source		SiC resistance furnace	Induction furnace	Induction furnace	Vertical Tube furnace	Vertical resistance furnace
Power specification of heating source		20 kVA	30 kW	25 kW	25 kVA	
Bath temperature	ºC	1350	1375	1200	1300	1400
Slag system		FeO-SiO_2-CaO-Al_2O_3-MgO-CuO-MnO-(ZnO)-(PbO)-S system	Al_2O_3-CaO-FeO_x-MgO-SiO_2-ZnO	Synthetic slags	Cu-Ca-Fe-O system	Mold flux
Crucible diameter	mm			75	100	
Crucible material		Al_2O_3	Al_2O_3	Alumina	MgO	Graphite
Inert atmosphere		Ar, N_2, CO/CO_2 mixture	N_2		N_2	
Inert atmosphere flowrate	L/min		1.667		4	
Sample rotation	Yes [Y]/No [N]	Y	Y	Y	Y	N
Platform rotation speed	rpm	0–30	0–28.5	0–60	10	
Probe material		Copper	Stainless steel	316 Stainless steel	316 L SS	Copper
Probe design		Tubular - Coaxial	Tubular - Coaxial	Tubular - Coaxial	Tubular - Coaxial	Cuboid
Outer tube	mm	20	15	12.7	14	20 x 15 x 6.3
Inner tube	mm	8	7.5	6.35	8	
Probe length	mm	340	600	600		
Thermocouples inside probe		2 (type - S)		4 (type - K)	3 (PT 100)	
Immersion depth	mm		9	80	50	12
Immersion time	min	0.08–180	0.08–60	1–90	5–120	3.33
Coolant medium		Water	Water	Air	Water	Water
Coolant flow rate	L/min		0.066–0.083	150	0.75	
Thermocouple positions from the probe surface	mm	5 (type - K)	10, 20	0, 5, 10, 15, 25 (type - K)	6, 12 (type - S))	
Sample quench medium		Nitrogen gas	Nitrogen gas	Water	Water	

DESIGN

Experimental set-up

The experimental set-up (Figure 2) was planned around an existing 30 kW electrical induction coil furnace (3). The induction furnace has the capability to heat a graphite susceptor (5), which also acts as the crucible, to temperatures up to 1700ºC. The coil (4) of the induction furnace has an inner diameter, taking into account the required insulation material, of 275 mm. This allowed a graphite crucible (5) with an inner diameter of 140 mm and a height of 230 mm to be inserted in the coil, allowing approximately 3.5 L of process material to be heated. A probe (1) manufactured from grade 316 stainless steel is fitted to an electric actuator (6), allowing the probe to be remotely submerged and retracted from the molten process material during testing. The probe is assembled in a counter flow arrangement, forcing the coolant to flow on the inner surface of the outer tube, optimizing heat transfer between the process material and the air-cooled probe. K-type thermocouples are fitted inside the inlet tube (8) as well as the outlet tube (7) to measure the temperature of the coolant as it passes through the probe. A K-type thermocouple in an alumina sheath (14) is fitted tightly to the probe, measuring the temperature as the freeze-lining forms on the probe surface. A pressure gauge (9) is installed on the inlet, allowing the operator to monitor the pressure in the system and to detect a leak in the probe. The crucible is mounted on a rotating platform (12), made of a layer of refractory material (97% Alumina castable) (15), followed by a layer of insulating material (40P Insulating casting) (16), and a stainless steel framework. This platform is driven by a V-belt pulley system linked to an electric motor (13) fitted to a reduction gearbox which allows for the platform to be rotated at speeds varying from 5 to 60 rpm. In order to limit heat losses, four layers of insulating fibre blanket are fitted to the top of the crucible. This allows the probe to move up and down without too much additional friction while maintaining the heat inside the crucible. The crucible is housed inside a secondary refractory lining (97% Alumina castable) (15) to limit heat losses and to add some thermal mass, permitting better control over the temperature. To prevent an oxidizing atmosphere, the crucible cavity is purged with nitrogen (N_2) at a rate of 6 L/min during a test run. The complete set-up was housed inside a safety enclosure manufactured from mild steel, ensuring the safety of the operator in case of a probe malfunction or crucible burn-through. The set-up was designed in such a manner that the probe could be lowered remotely while the operator maintained a safe distance. This will also allow the operator to cut the power and coolant supply in case of a malfunction.

(a)



(b)

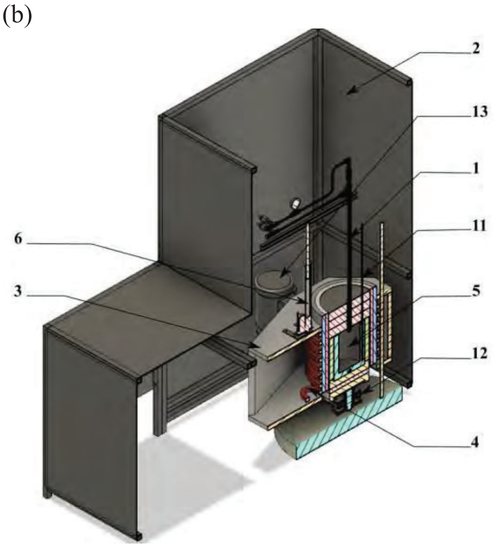


Figure 2. Design of experimental set-up (a) 2-dimensional view and (b) 3-dimensional view

Component selection

The selection of each component in the experimental set-up is discussed in more detail below.

Induction furnace

A 30 kW furnace (by LH Power), with a working inner diameter of 275 mm, was selected for the purpose of this experimental set-up due to availability and because it was shown to be suitable for this type of experiment (Campforts et al., 2007; Fallah-Mehrjardi et al., 2013). This furnace will allow access from both the top and bottom, allowing the crucible to be rotated while being able to manipulate the probe from the top. The induction furnace allowed for freedom in relation to the operating temperature range and would, therefore, permit a range of materials to be investigated. With adequate insulation, the temperature of this furnace can be controlled within 20ºC from the target temperature.

Pressure gauge and flow meter

Initial heat transfer calculations allowed for the pressure gauges and flow meters to be defined. For initial test work, it was decided to use air as a coolant for safety reasons. Tests indicated that the installed system could supply air at a maximum flow rate of 250 L/min at 500 kPa. An analog WIKA air pressure gauge with a positive pressure of 0–10 bar was selected. The analog pressure gauge allows for a visual indication of the pressure in the system as the airflow is adjusted. A 30–300 L/min air flow meter by Key Instruments (FR4500 Series) was selected to control the air flow rate through the probe.

Probe

When it came to the design of the cooling probe, various factors had to be kept in mind. Material selection has proven to be the first hurdle. It needed to be a chemically stable material with a reasonably high melting point and needed to be magnetically neutral - the electromagnetic field produced by the furnace might influence the test results. The material selected had to be regularly available, reducing cost and ensuring that parts could easily be replaced if needed. The probe needed to be fabricated from a material with a large enough surface area to allow for sufficient freeze-lining formation while not freezing up all of the liquid material. Grade 316 stainless steel was identified as the most suitable material compared to the criteria discussed above. As an austenitic stainless steel, it is magnetically neutral and has a maximum operating temperature of 1375–1400ºC (BSSA, 2018). It would also allow for following a modular design methodology based on Swagelok (Swagelok, 2020) standardized fittings when assembling the probe, simplifying replacements and modifications. The probe is assembled from a 16 mm outer tube and an 8 mm inner tube. These dimensions allowed for the required coolant flow rates while not being too large, therefore, avoiding feezing all the process material as it is lowered into the bath.

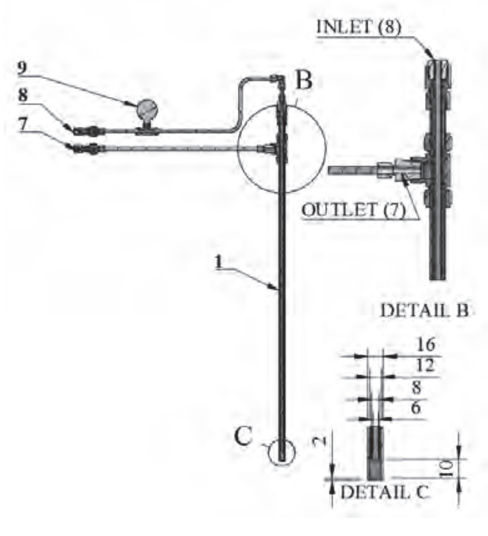


Figure 3. Cooling probe design

Actuator

An SKF Type CAHB-10 electric linear actuator, with a rated load of 500 N, was selected for the initial test work. It possesses over 300 mm stroke length, sufficient to clear the total height of the crucible. It also has built-in upper and lower limit switches, allowing the operator to initiate the stroke remotely knowing the end positions. This allows the probe to be closed off inside the safety enclosure.

Thermocouples

During the proof of concept test work, four thermocouples were utilized. A 1.5 mm diameter K-type thermocouple was fitted inside both the inlet and outlet coolant tubing, approximately 300 mm from the last bend in the direction of the thermocouple, to allow somewhat laminar flow around the thermocouple junction. Another K-type thermocouple, positioned inside a 10 mm diameter alumina sheath, was fitted flush against the outside of the probe, with the junction aligned with the tip of the probe. A B-type thermocouple, also positioned inside a 10 mm diameter alumina sheath, was used to control the temperature and was fitted inside the wall of the graphite crucible to prevent chemical wear of the control thermocouple sheath by liquid slag.

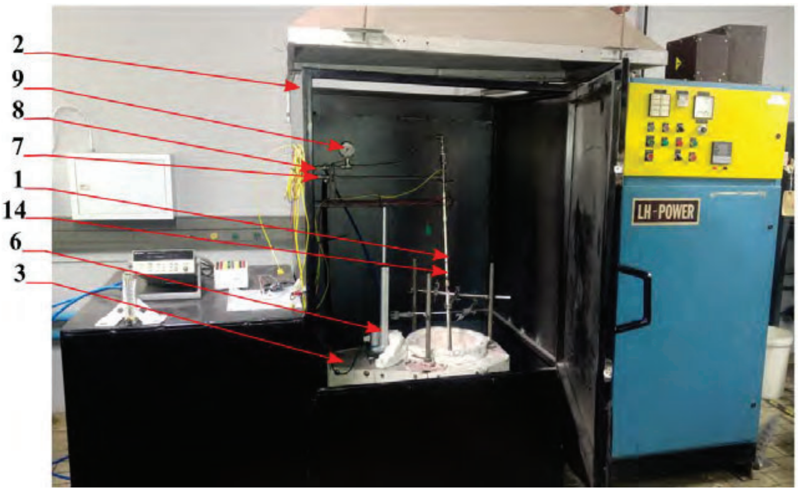
Drive system

To mitigate the risk of the pulley system (used to rotate the crucible) heating as a result of the electromagnetic field around the induction coil, it was fabricated from grade 304 stainless steel. Grade 304 stainless steel is also an austenitic stainless steel, but more cost-effective when compared to grade 316 stainless steel. A V-belt pulley system is utilized to link the electric motor to the rotating platform. A 0.37 kW WEG W22 electric motor is fitted to a 9:1 reduction gearbox. The electric motor is controlled by a Danfoss FC 51 VLT Micro Driver, allowing the rotational speed to be controlled by the operator.

CONSTRUCTION

The actual construction (Figure 4) does not differ much from the 3D models designed during the planning phase (Figure 2). The only difference is that the rotational platform was not installed, as this would result in having to modify the primary refractory lining that surrounded the induction coil. As with all prototypes, one would prefer to fail cheap and fast rather than making various modifications to the existing infrastructure without knowing the outcome of the proposed test work. For proof-of-concept, there was no need to simulate a dynamic environment by rotating the crucible which is why it was decided not to modify the primary refractory lining as of yet.

(a)



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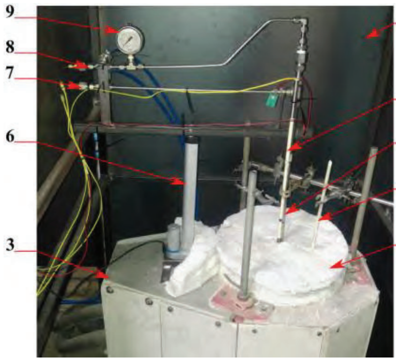
(b)



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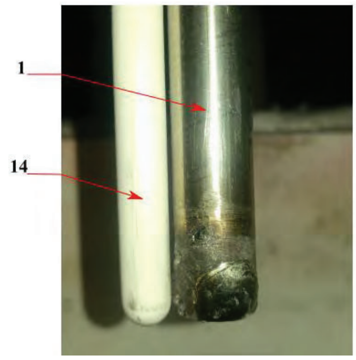

Figure 4. Actual construction (a) with (b) showing the induction furnace and (c) the probe arrangement

HOT COMMISSIONING

Heat transfer calculations

Although the ultimate aim is to prepare freeze-linings from industrial ferrochrome slag, the experimental set-up was hot commissioned using synthetic slag prepared from lime and alumina raw materials, in order to prove the concept. The slag composition was 47% CaO and 53% Al_2O_3 by mass and it was fully liquid at 1413°C (Kowalski et al., 1995).

Assuming a liquid slag temperature of 1413°C and a freeze-lining temperature of 1313°C, the expected probe wall temperatures, as well as the coolant outlet temperature, were calculated using an iterative method as discussed in the background section. The expected temperatures were calculated as a function of a varying coolant flow rate. The maximum supply pressure of 500 kPa, with an initial coolant temperature of 25°C, was used to define the coolant heat transfer properties. Figure 5 illustrates the expected steady-state temperatures at a coolant flow rate of 250 L/min. It shows that the probe surface temperature will be below 500°C, which can be deemed as a safe working temperature for the probe material. It also shows a coolant outlet temperature below the 100°C threshold, which is within the safe operating temperature of the high-pressure air hose utilized.

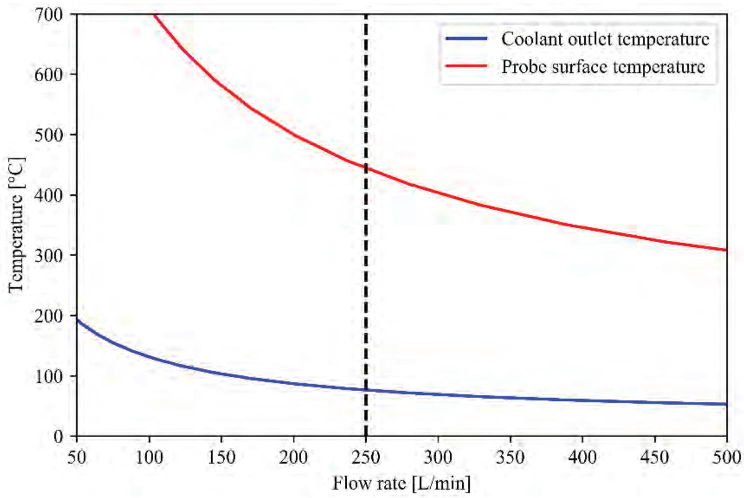

Figure 5. Coolant and probe temperatures as a function of air flow rate

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The maximum steady-state freeze-lining thickness is expected to be in the range of 26 mm, as seen in Figure 6. The steady-state freeze-lining thickness at 250 L/min is calculated to be in the range of 20 to 21 mm, which takes into account the diameter of the probe, result in a final probe diameter of 58 mm. This final probe diameter indicates that the crucible cavity diameter of 140 mm would be sufficiently large enough to prevent the entire bath from freezing up.

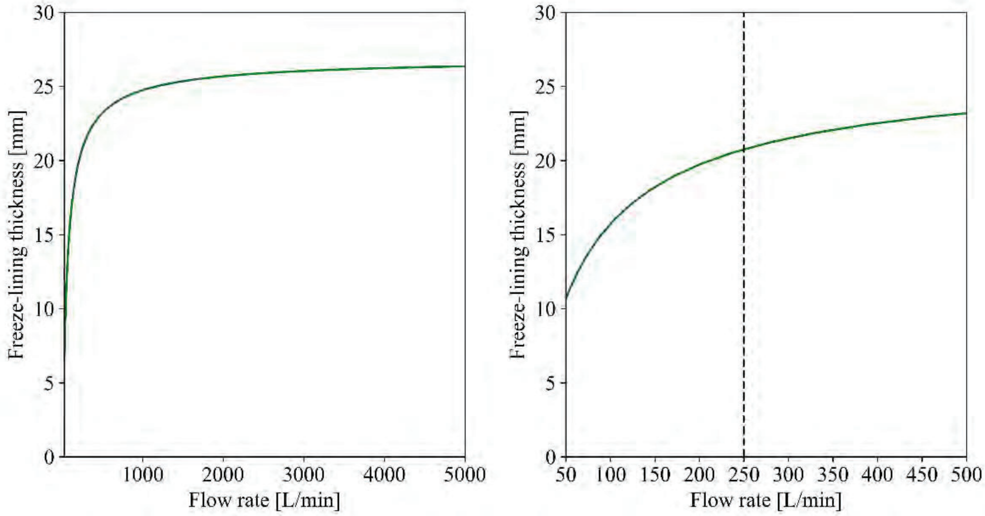

Figure 6. Freeze-lining thickness as a function of air flow rate

Experimental procedure

The 2.78 kg of raw materials were in powder form and blended well, through manual mixing, prior to the experiment. When utilizing industrial slag, the material should be crushed to <1 mm, to enhance the melting rate and ensure homogeneity of the sample when conducting the freeze-lining experiment. The volume reduction of the slag should be considered and if a filled crucible (in the cold state) will not allow for at least 80 mm molten slag, the batch can be topped up with additional slag once molten. The mass of the crucible, as well as the feed material, should be recorded to allow mass balances to be conducted after the completion of the test.

Once the feed material was placed inside the graphite crucible, the probe was lowered to approximately 50 mm below the brim of the graphite crucible. This allows for the probe tip to be heated gradually, as thermal shock can result in cracks in the weld joint at the bottom of the tip, resulting in failure.

When the probe and feed material were in place, the insulating fibre blanket layers were put in position, ensuring openings with adequate tolerances to allow the probe to move up and down freely and to position the control thermocouple in the crucible wall.

The furnace was then switched on and programmed to achieve a heating rate of approximately 4.5ºC/min to limit the risk of thermal shock. The coolant was also introduced but at a low flow rate (about 10% of the final flowrate). The coolant flow rate was adjusted throughout the test, governed by the coolant outlet temperature and the operating temperature of tubing utilized. The purge gas was also switched on to prevent unwanted chemical reactions (at 6 L/min).

Once the slag temperature, measured by the B-type thermocouple in the crucible wall, reached the calculated liquidus temperature, the coolant flow rate was increased to the predetermined test flow rate. The probe was then lowered into the melt using the electric actuator. Temperatures were monitored continuously to ensure that the probe surface temperature, as well as the coolant temperatures, decrease after the initial temperature spike. This will confirm the formation of a freeze-lining. If the temperature decrease is not observed after about 2 minutes, the coolant flow rate should be increased as a freeze-lining is most likely not forming.

After the probe was submerged for the required time, the electric actuator was activated again to retract the probe with the freeze-lining sample attached. Once the sample was removed from the molten bath, the power input was switched off while the cooling was maintained. Some of the fibre blanket layers were removed to increase the cooling rate. Once the set-up was cooled down sufficiently, the probe was removed and the freeze-lining sample extracted.

Problems addressed during the hot commission

Hot commissioning allowed for valuable insights into how the initial design could be improved:

- The first problem observed during commissioning was misalignment. Due to the probe assembly being top-heavy when the actuator was fully extended, it was pulled out of alignment and caused problems when the actuator was lowered again. The problem was mitigated by making use of two laboratory clamps to align the probe as it was lowered into the bath.
- The actuator used did not provide positional feedback, making it difficult to know the exact position of the probe tip. This was a known limitation of the actuator used for this design, which was a repurposed component from another project, and will be addressed as part of future improvements.
- High-pressure air hoses were used for both the coolant inlet and outlet but the initial temperature spike, as a result of submerging the probe in slag, softened the tubing to a large degree. The combination of a softened tube and high supply pressure resulted in the tubing dislodging from the metal hose connector. After the first “hot” test the outlet hose was replaced with a reinforced steam hose, circumventing the problem of coolant hoses dislodging during testing.

Freeze-lining

Figure 7 illustrates the first freeze-lining sample produced by the experimental set-up, using the $CaO\text{-}Al_2O_3$ synthetic slag. The freeze-lining only reached a thickness in the range of 11 mm as the probe was only in the molten material for about 60 seconds before it had to be retracted as a result of a dislodged outlet tube. Even though the expected steady-state thickness has not yet been reached, at that time interval, the results indicate that it is indeed possible to generate a freeze-lining sample using the experimental set-up.

The experimental results illustrate that even though steady-state calculations are important to specify the equipment, transient heat transfer models are necessary to help predict the initial temperature spikes as the probe is submerged into the molten material. The temperature is expected to come down to the steady-state temperatures as the freeze-lining starts to form, but the experimental equipment should be designed with the initial temperature spike in mind.

(a) (b)

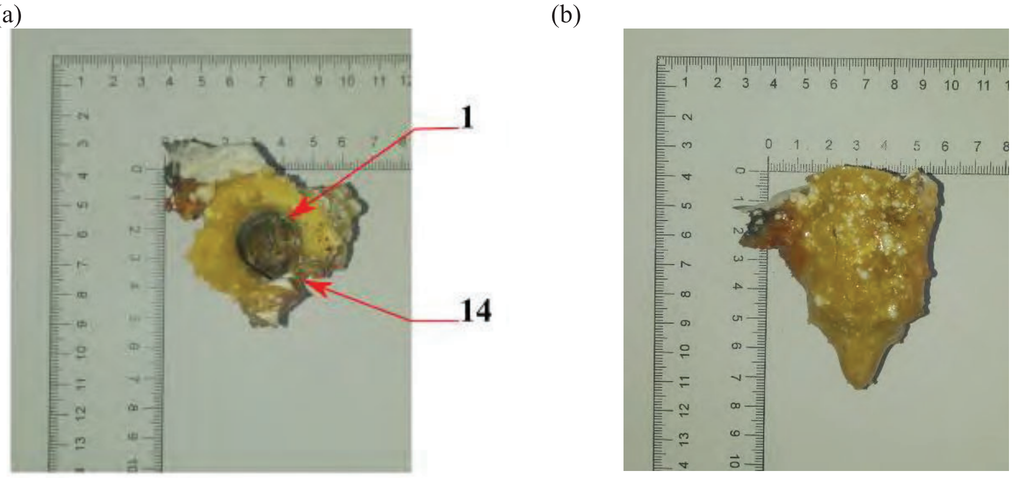

Figure 7. First freeze-lining sample from CaO-Al_2O_3 synthetic slag: (a) top view and (b) side view

CONCLUSION

An experimental set-up was designed and commissioned that enables the simulation of freeze-linings. This experimental set-up was designed from existing equipment and regularly available material to ensure ease of construction and to reduce the overall cost. Results from this project serve as proof of concept and show that it is possible to generate a freeze-lining with the use of this design and therefore motivate future investment in this project. The commissioning phase illuminated various areas of improvement, showing that more work is required before this experimental set-up will produce reliable results.

The most important upgrade to the existing system will be to improve the linear actuating system. A new and improved linear movement system has to ensure better positional control and should be able to carry a larger load. This will allow the weight of an upgraded probe design with the capacity to house more thermocouples which can then be used to formulate a more accurate temperature profile of the forming freeze-lining. The upgraded linear movement system will also allow an external cooling circuit to be fitted to the air outlet, circumventing the need for specialized high-temperature hosing.

Once the improvements on the experimental set-up have been implemented, complex slag systems can be investigated to aid in furnace containment designs as well as to generate data for desktop study validation. The experimental set-up will allow the crystal structure and chemical composition of freeze-linings to be investigated, contributing to the understanding of freeze-lining formation and the mechanisms at work. The experimental results can then also be used to refine the computational models, improving future design calculations and predictions.

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