Skimming of Fluid Slag

by

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ABSTRACT

A 1/12 scale tank was constructed to physically simulate the metallurgical skimming process in order to gain a better insight of the skimming of fluid slag from copper anode furnaces. 1-decanol and water were used to represent the slag and the underlying liquid metal respectively. It was observed that slag skimming was comprised of two steps, a transportation step to carry slag to the skimming lip, and a removal step to move the slag across the lip. The efficiency of the transportation by bath surface circulation was strongly affected by the method of creation of the surface movement. Submerged gas injection failed to carry slag to the lip effectively because of the uncontrollable circulation pattern generated on the bath surface. On the other hand, three impinging gas jets in glancing contact with the bath surface were able to carry slag to the lip effectively. The Re of the jets (I.D. 0.01m) inclined 50° to the horizontal was 6100. The jet configuration was two of the jets were placed close and parallel to the rear wall of the model and faced each other. The third jet was parallel to the model short axis and was directed at the skimming mouth. With the same amount of time, 70% of the slag originally charged to the tank was skimmed with the assistance from the impinging gas jets in comparison to 20% when no jet was used. Detailed analysis of the skimming process revealed that the underlying liquid bath level continuously decreased as the slag was skimmed and resulted in continuous reduction of the skimming rate. In order to compensate the reduction of skimming rate due to bath level reduction, a control strategy was proposed for rotating the furnace continuously to maximize the skimming effectively.

RÉSUMÉ

L'écumage du laitier fluide d'un four de conversion du cuivre blister a été modélisé dans un réservoir construit à l'échelle 1:12. Le 1-décanol et l'eau ont été utilisés afin de simuler respectivement le laitier et le cuivre liquide. Il a été observé que l'écumage pouvait être divisé en 2 étapes distinctes. Dans un premier temps, le laitier est acheminé vers le rebord du four. Ensuite, l'écumage proprement dit s'effectue par déversement du laitier par-dessus le rebord. Les expériences ont démontré que l'efficacité de transport du laitier est grandement affectée par la méthode utilisée pour créer le patron d'écoulement en surface du bain. L'injection d'un gaz sous la surface s'est avérée inefficace due à l'impossibilité de contrôler le patron d'écoulement. D'autre part, l'utilisation de 3 jets de gaz de 1 cm de diamètre formant un angle de 50° avec la surface du bain a permis d'améliorer le transport du laitier. Le nombre de Reynolds associé à chaque jet était de 6 100. La configuration consistait en deux jets placés face à face le long de la paroi arrière du réservoir. Le troisième jet était parallèle aux parois latérales et orienté en direction de l'ouverture. Pour un même temps d'écumage, il a été démontré que 70 % du laitier initialement présent était éliminé en effectuant l'écumage avec le dispositif à 3 jets comparativement à 20 % pour l'écumage sans jet de gaz. De plus, il a été observé que la diminution du niveau du bain liquide au cours de l'écumage provoquait une diminution du taux d'écumage dans le temps. Une stratégie de contrôle consistant à incliner le four durant l'écumage a donc été proposée afin de compenser la diminution du taux d'écumage.

ACKNOWLEDGEMENTS

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Finally but most importantly, I would like to express my heartfelt thanks to my wife, Kim. Her encouragement is my biggest motivation. Without her support, this degree would never have been possible. I would also like to thank her for being the first person in the world to apply my ideas in skimming of molten grease in the kitchen.

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NOMENCLATURE

Symbol	Description	S.I. Unit
g	gravitational constant	m^2/s
D	diameter	m
L	length	m
U	characteristic velocity	m/s
ρ	density	kg/m^3
γ	surface tension	N/m
η	viscosity	Pa s
λ	scaling factor	dimensionless
θ_c	contact angle	degree
θ	angle of rotation	degree

Dimensionless Numbers	
Re	Reynold Number
Fr	Froude Number
We	Weber Number
Bo	Bond Number

Subscripts	
m	model
p	prototype
M	liquid metal
S	slag
SA	slag/atmosphere interface
SW	slag/wall interface
SM	slag/liquid metal interface

1. INTRODUCTION

Preamble

Skimming, as a general term, can be defined as the separation of two stratified immiscible liquids by removing the less dense one. According to this definition, the removal of molten grease from turkey juice in the kitchen and the cleaning up of oil slick in the ocean are examples of skimming even though the methods used in the separation of these immiscible liquids are very different.

As a specific term in metallurgy, skimming refers to the removal of slag or dross from the surface of a pool of liquid metal or matte held in a furnace or ladle. Even though skimming has its own special meaning in metallurgy, the forces governing the behavior of the two liquids in the system are still those of a physical separation of two immiscible fluids, thus solutions to the challenges of effective skimming have wide ranging applications: from kitchens to oceans. Here, the skimming of fluid slag from copper anode furnaces was of concern, but as argued above the results are of general applicability.

In metallurgical practice, skimming has remained an issue that has not received much attention, perhaps because it is seemingly trivial, perhaps because attempts to improve it have not been fruitful, or perhaps because it has always been good enough to satisfy demands. However, things are changing. Metallurgists are using slag for increasingly complex purposes and there is now a need for greater control over slag composition, e.g. it is necessary to avoid contamination of subsequent slag by slag carry forward. The conventional process of gravity driven skimming may no longer be adequate, hence the idea here to revisit this ancient process.

Since the lexicon associated with skimming is loose, it was thought useful to start with definitions of some terms that are used in this thesis:

- Skimming - the transfer of slag from the interior of a furnace to the exterior of the furnace without separation of the slag from the underlying metal or matte until the slag reaches the skimming mouth (in contrast to the bailing of dross out of a lead kettle).
- Skimming Enhancement – apparatus, methods and procedures to improve of skimming efficiency and extent.
- Skimming Efficiency – the rate at which slag is removed with enhancement as compared to unenhanced skimming.
- Skimming Extent – the fraction of slag that had exited the vessel at the time when the overflow rate of the slag had fallen to a negligible value or stopped.

1.1 Introduction

In this research, skimming of a **fluid** slag from a horizontal, cylindrical, rotary furnace and two methods to enhance skimming were studied. The two methods of enhancement studied were:

- The use of impinging gas jets in glancing contact with the slag layer to carry the slag towards the skimming mouth and
- The continuous rotation of the furnace to maintain maximum pressure head to drive the overflow of slag.

Skimming assisted by mechanical rakes was not considered.

In practice, un-assisted, conventional skimming requires the movement of slag from inside the vessel to outside the vessel via the skimming mouth driven by gravity. Rotary furnaces allow for the adjustment of the position of the skimming mouth lip, hereafter simply referred to as the lip, relative to the interface between the stratified liquids in the vicinity of the lip. Skimming is started and stopped by adjusting this relative position.

In order for slag to start and continue flowing across the lip, the fundamental requirement is that slag is next to the lip on the inside of the vessel. To illustrate this concept, consider an extreme example: if all the slag in a vessel is resting as an isolated pool located at the center of the melt surface, flow of slag across the lip is not possible until some slag is moved to the interior edge of the lip.

Thus the skimming process is actually comprised of two steps, namely, a *transportation process* whereby slag moves to the lip and a *removal process*, whereby slag that is at the lip, flows over the lip. There are two types of transportation, one due to the tendency of slag to wet on the wall of the vessel and spread towards the lip and the other due to assistance from an external agent or agents. Both types of transportation are considered here.

Closer examination of the removal process also reveals that there are two types of flow across the skimming lip. One is simply the flow that results from the pressure head that exists when the upper surface of the slag next to the lip is above the level of the lip and the other is the creeping flow that occurs due to wetting of the slag that is in contact with the interior walls of the vessel on the vertical sides of the skimming mouth at the corners of the lip. Both types of removal are considered here.

1.2 Problem Statement

The objective of the present research was to measure and identify methods to maximize skimming effectiveness using unassisted natural skimming as a point of reference. Two means of enhancement were considered, namely the use of impinging gas jets in glancing contact with the slag layer to carry the slag towards the skimming mouth and continuous rotation of the furnace to maintain maximum pressure head to drive the overflow of slag

The method chosen was to construct a low temperature physical model of skimming and to measure the rate and extent of slag skimming with and without enhancement from the glancing gas jets. The present work was not a rigorous modeling of a particular prototype, but rather a proof of principal exercise to evaluate possible means to improve the skimming process. Since there was no real cessation of slag overflow, it was decided that extent of skimming was to be quantified and reported as the fraction of the initial slag that was removed rather than the amount of slag skimmed up to an arbitrarily choosing a cut-off value. For practical and illustrative purposes, the fraction of slag skimmed up to the point when the skimming rates with or without enhancement are similar was reported and compared.

1.3 Structure of the Thesis

The thesis begins with ***Chapter 2***, which presents the background of pyrometallurgical production of copper from sulphide concentrate. The industrial skimming practice and entrainment phenomena during skimming are described.

Chapter 3 discusses the movement of slag during skimming. The discussion is separated into two parts, movement of slag in removal step, and movement of slag in transportation step. Generation of bath surface circulation to carry slag to the skimming lip by two methods is explored and the behavior of the system is compared.

Chapter 4 presents the similarity consideration in physical modeling of the skimming process. Criteria to establish similarity between the model and the prototype are presented.

Chapter 5 describes the selection of materials used in the experiment, the experimental apparatus and the experimental procedure.

Chapter 6 presents the results of experiments.

Chapter 7 presents a discussion of the experimental results. The efficiency of carrying slag to the skimming lip by bath surface circulation generated by submerged gas injection and impinging gas jets is compared and contrasted. The limitation on detaching the slag from the wall by bath surface circulation is presented. Finally, a control strategy is proposed to maintain the relative position of the skimming lip and the slag/metal interface to maximize the skimming effectiveness.

Chapter 8 provides the conclusion of the research and recommendation of future work.

2. SKIMMING IN COPPER PRODUCTION

2.1 Pyrometallurgical Copper Production

The flowsheet of a general pyrometallurgical copper production from sulfide concentrate can be classified into three steps, matte smelting, converting and fire refining, as shown in Figure 2.1.

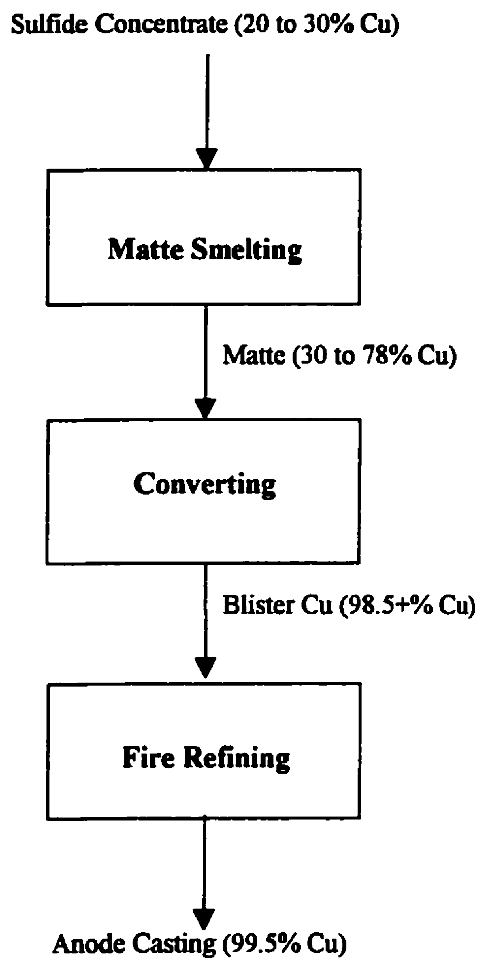


Figure 2.1 General Flowsheet of Copper Production [1]

2.1.1 Matte Smelting

The first step in production of copper is matte smelting. The designs of matte smelting furnaces have changed significantly in the past generation but the function of these furnaces has not changed. The purpose of matte smelting is to melt and partially oxidize the concentrate to generate a molten matte primarily composed of copper and iron sulfides and a silicate slag. The products of matte smelting report to four different streams:

1. Matte - the matte stream consists primarily a molten solution of Cu_2S and FeS along with some minor elements. The grade of matte produced ranges between 30% to 78% Cu depending on the plant practice
2. Slag - the slag stream is roughly comprised of molten fayalite formed by the reaction of silica flux with FeO produced from the oxidation of iron sulfides.
3. Offgas - the gas stream contains mainly SO_2 from the oxidation of the sulfide concentrate and N_2 from the air used for oxidation along with some waste gas from the burning of carbonaceous fuel used to provide energy to the furnace.
4. Dusts- the dust stream contains the solid particles entrained in the offgas and contains substantial levels of minor elements.

2.1.2 Converting

The matte produced from smelting is transformed into slag and blister copper in the converting step. Most of the primary copper produced is treated in the Pierce-Smith converter. A Pierce-Smith converter is essentially a horizontal, cylindrical, rotary furnace with tuyeres, which allow air to be blown into the molten bath, on one side of the vessel. Converting is carried out in two sequential steps. The first step of converting is to oxidize the iron sulfide in the matte to produce iron oxides that react with silica flux added to generate a fayalite slag. This step is referred to as the "Slag Blow". The fayalite slag is skimmed and then the converting operation proceeds to the next step. The second step is called the "Copper Blow". In this step, the remaining Cu_2S is oxidized by the air to produce blister copper with about 0.3% sulfur. The blister copper produced is transferred to fire-refining.

2.1.3 Fire-refining

Fire-refining is carried out in an anode furnace. The first step of fire-refining is to further oxidize the sulfur dissolved in the blister to SO_2 by blowing air into the molten metal bath. Then follows deoxidation to decrease the concentration of dissolved oxygen in the molten metal. This reduction is performed by hydrocarbon gases or occasionally wooden poles. On top of desulfurization and deoxidation, some minor elements removal is also handled in the fire-refining step. One common approach to remove impurities is by preferential oxidation. Sometimes, basic fluxes are used to maximize impurity removal in fire-refining. The slag produced in the process in both steps is skimmed and the molten metal is tapped and transferred to anode casting.

2.2 Necessity of Skimming

As revealed in the copper production process, the intermediate products are skimmed before the production process can proceed to the subsequent operation. As an example, the slag produced in both converting step and fire-refining step must be skimmed before the process can be continued.

2.2.1 In Converting

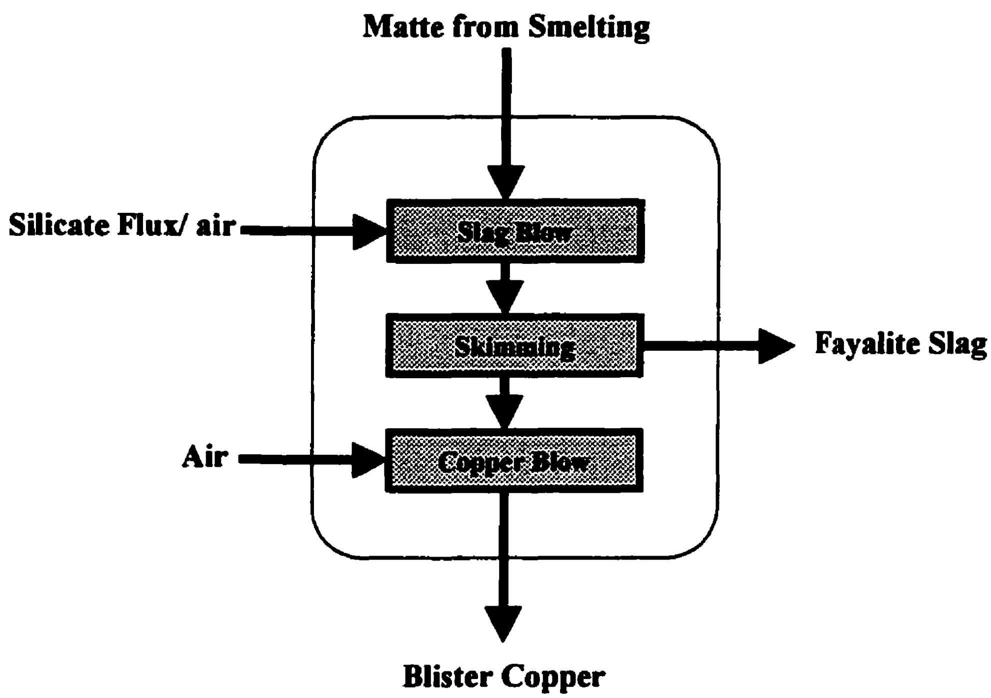


Figure 2.2 Schematic Flowsheet of Converting Step

As mentioned before, converting is carried out in two sequential steps, the slag blowing and the copper blowing step. In industrial operation, the matte is added to the converter in several steps until there is sufficient copper in the converter for Copper Blow. The slag generated from each load of matte is skimmed before the addition of next load of matte. Therefore, in production of one batch of blister copper, the molten metal bath in a converter must be skimmed several times.

2.2.2 In Fire-refining

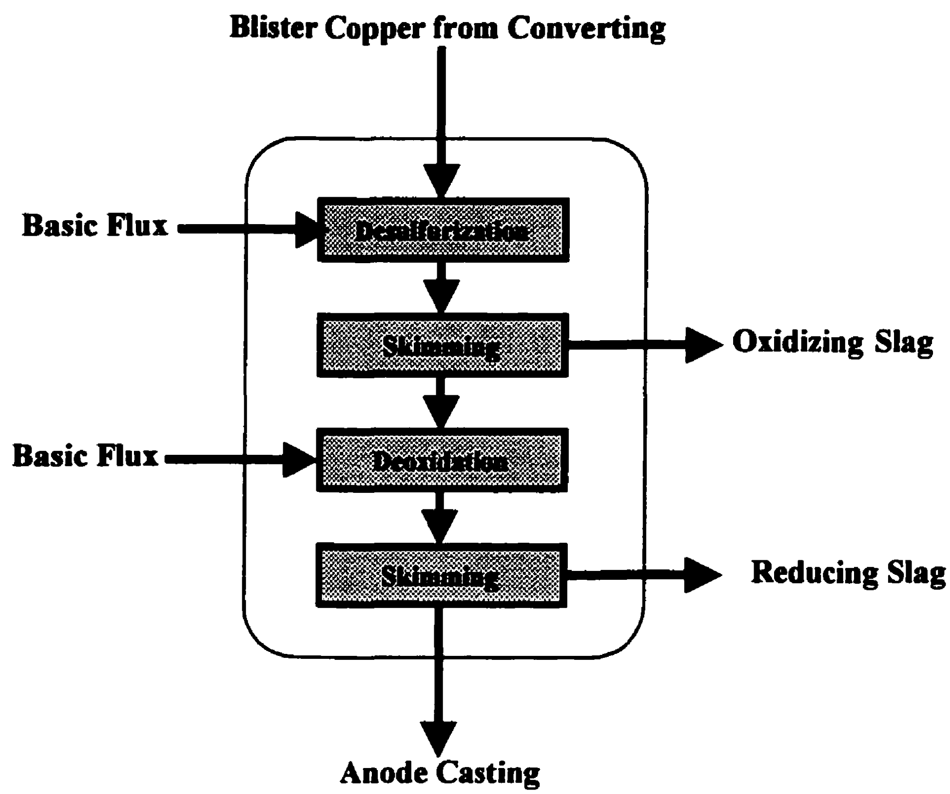


Figure 2.3 Schematic Flowsheet of Fire-refining Step

When basic flux is added to the anode furnace to control the minor elements level in the production of anode copper, completeness of skimming of slag is a crucial factor determining the successfulness of the operation. The distributions of minor elements strongly depend on the oxygen potential in the system. During desulfurization, the oxygen potential is high. Under this circumstance, certain minor elements distribute themselves into the produced oxidizing slag. However, if this slag remains in the furnace and is carried forward to the deoxidation step, the removed minor elements re-distribute themselves back into the liquid metal phase due to the decrease of oxygen potential. Therefore the oxidizing slag produced in desulfurization must be skimmed before the process proceed. After the slag produced in desulfurization is skimmed, another load of basic flux is added to the furnace to remove the remaining minor elements during reduction. The reducing slag produced in the deoxidization step must also be skimmed before the furnace is tapped, during tapping, vortexes form and the vortex trends to drag the slag floating on the surface of the molten metal bath through the tap hole and contaminates the anode during casting. Therefore, skimming of the reducing slag produced in the deoxidation step is also necessary.

2.3 Conventional Skimming Practice

In the copper industry, skimming of slag from a rotary furnace is usually done by rotation of the horizontal cylindrical vessel until the level of the skimming mouth is at about the same level of the slag/liquid metal interface. Then the slag overflows across the skimming lip and is collected by a ladle placed directly below the skimming mouth.

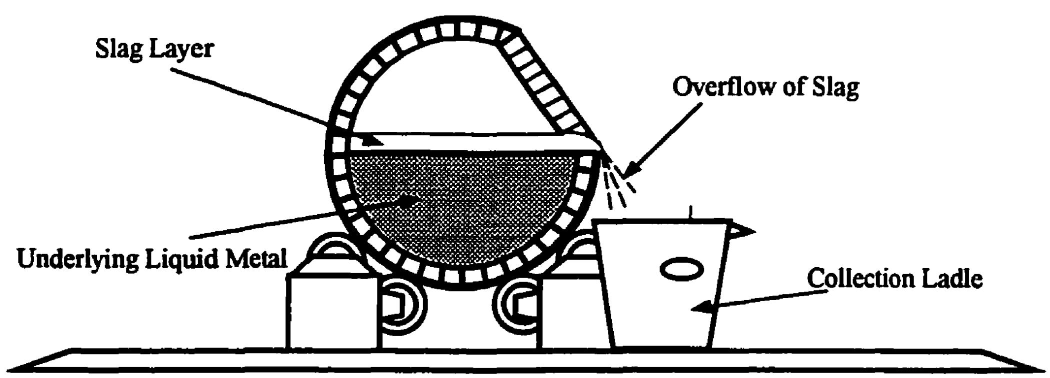


Figure 2.4 Illustration of Conventional Skimming Practice [1]

The effectiveness of the skimming process is measured by the efficiency and the extent of the process. The efficiency of skimming is the rate of the slag being removed from the furnace. The extent of skimming refers to the completeness of the removal at the end of the process.

A closer examination of the skimming process reveals that the skimming process is comprised of two steps: namely, the transportation step and the removal step. To illustrate this concept, consider skimming a piece of slag initially located at the end of the furnace. In order to remove this piece of slag from the furnace, it must be moved from its original position to the skimming lip. This movement is referred as the transportation step. Once the slag is at the skimming lip, force(s) must be applied to drive the slag to flow across the skimming lip and eventually exit the furnace. The movement of slag across the skimming lip is called the removal step.

To improve the effectiveness of the skimming process means to improve the performance of both the transportation step and the removal step. If either of these two steps fail, the skimming process cannot be continued due to either no slag is available at the mouth to be skimmed or the slag accumulated at the mouth cannot move across the lip.

One of the important factors that determine the movement of slag in both transportation and removal steps is the interfacial interaction between the slag and the refractory lining. Schlesinger [2] stated that refractory material currently use in copper smelting, converting and refining furnaces comes from one particular composition group, the magnesia-chromite (mag-chrome) based refractories. The base of mag-chrome refractories is chromite ores. In addition to Cr_2O_3 and MgO, mag-chrome refractories also contain sizable percentages of Al_2O_3, Fe_2O_3 and SiO_2. The alumnia content in conventional mag-chrome refractories ranges from 8-21 mass percent. Donald et al [3] measured the contact angle between fayalite-type slags and alumina using sessile drop technique. The contact angle was determined to be relatively low, approximately 18°. The wettability of FeO-SiO_2 slag was studied for Al_2O_3-SiO_2 brick by Yokoyama et al [4]. In their study, the evolution of contact angle of FeO-SiO_2 slag on a total of seven brick samples with different Al_2O_3 to SiO_2 ratio were determined. In all cases, the contact angles decreased to about 15° within one minute. Donald et al [5] studied the contact angles between fayalite-type slag and some potential materials that may be used as refractory lining in non-ferrous metallurgy vessels. The materials included graphite, boron nitride, titanium nitride and titanium boride. The contact angles between the slag and all tested materials were less than 90°. As can be seen in the literature data, the slag produced in copper industry usually wets on the refractory lining of the furnaces

2.3.1 Entrainment of Underlying Liquid Metal during Skimming

An important factor that limits the effectiveness of skimming is the entrainment of underlying metal during skimming. In order to investigate the relationship between the skimming effectiveness and the entrainment of the metal, it is necessary to understand the causes of the entrainment phenomena.

Referring to Figure 2.5, point A representing a point at the edge of the skimming lip and point B is the slag/liquid metal interface at the wall. Assuming both the slag and the underlying liquid metal are static, pressure at point B, P_B, is at higher pressure than that at point A, P_A. The pressure differential, $P_B - P_A$, equals to hydrostatic head of the liquid layer between point A and point B, $\rho g \Delta h_w$ where ρ is the density of the liquid, g is the gravitation constant and Δh_w is the distance between the edge of the skimming lip and the slag/liquid metal interface.

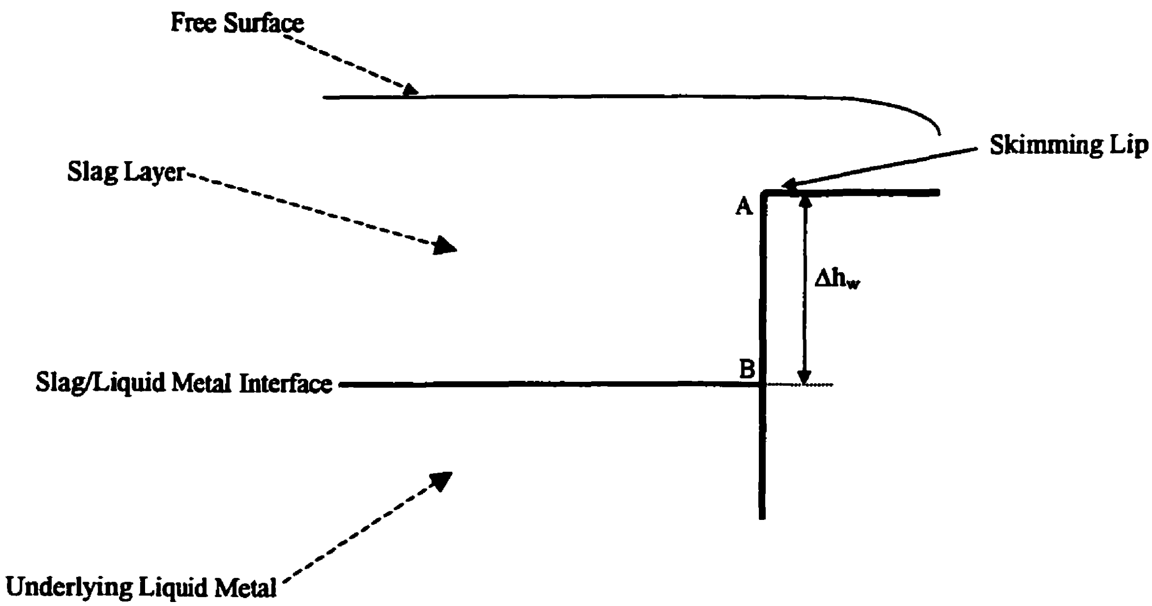


Figure 2.5 Illustration of the Cause of Entrainment

During skimming, slag at point A moves across the skimming lip at a certain velocity, V_A. Part of the pressure head at A is converted into velocity head. As a result, pressure at point A reduces to P'_A. In comparison to the pressure difference when the liquid is static, the pressure differential between point A and point B increases as the slag flows across the skimming lip. Therefore, the underlying liquid metal experiences an upward pressure and the slag/liquid metal interface moves upward to counter balance the change in pressure differential. An increase in skimming rate results in an increase in velocity head at point A. As a consequence, pressure head at point A is further decreased. If V_A is further increase, eventually it leads to the pressure head at point A being decreased by $\rho g \Delta h_w$. Therefore, the pressure differential experienced by the slag/liquid metal interface is large enough to overcome the opposing gravity pressure differential and the underlying liquid metal is entrained in the stream of slag flow as shown in Figure 2.6.

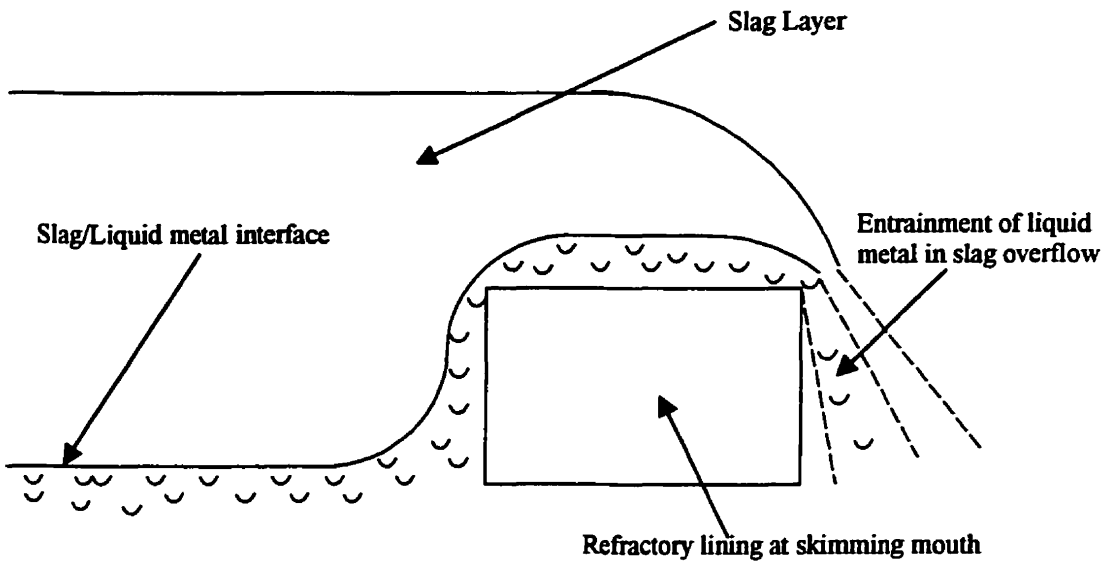


Figure 2.6 Entrainment Liquid Metal during Skimming

As revealed in the above analysis, the major factors that determine whether entrainment of underlying liquid metal occur during skimming are the velocity of slag flow across the skimming lip and the distance between the edge of skimming lip and the slag/liquid metal interface.

2.3.1.1 Effect Interfacial Properties on Entrainment

In order to determine the limitation on the relatively position between the edge of the skimming lip and the slag/liquid metal interface and the flow rate of slag across the lip, it is important to know the interfacial properties between the slag, the underlying liquid metal and the refractory lining.

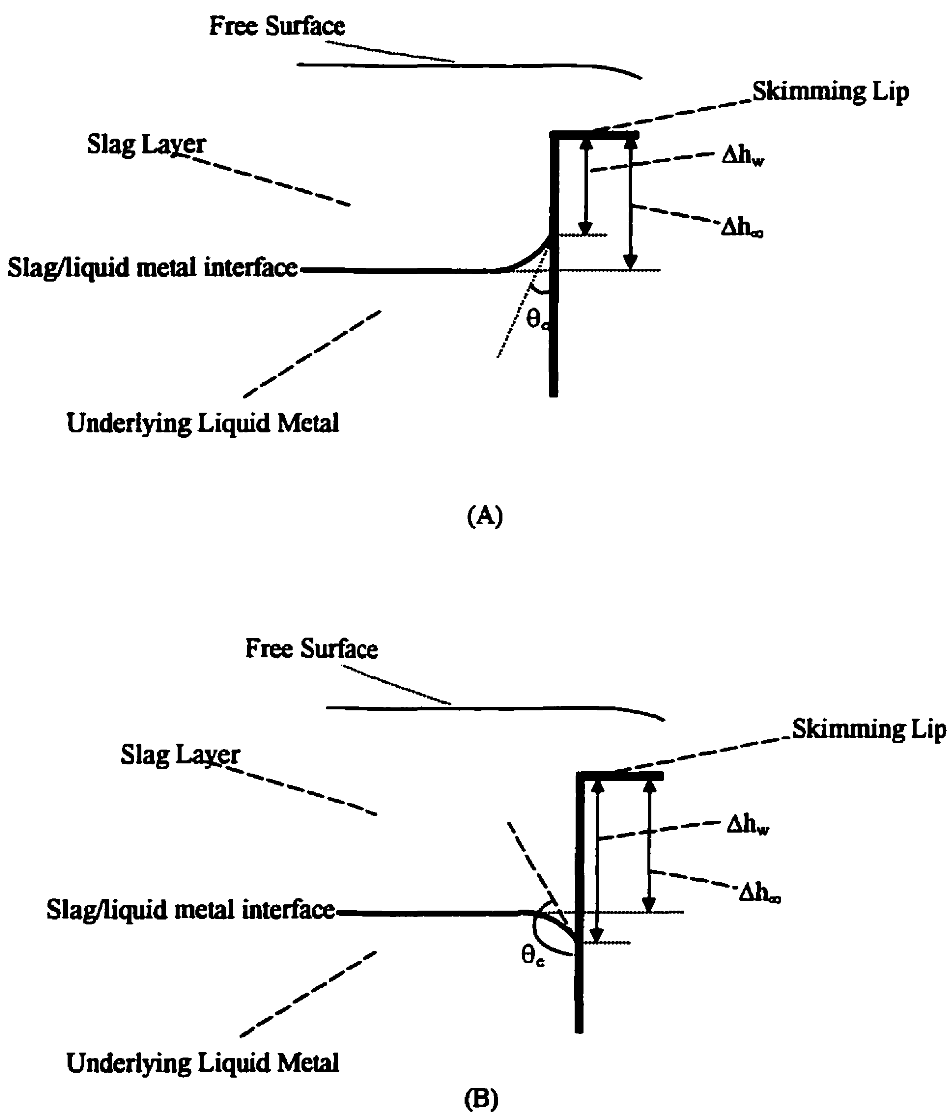


Figure 2.7 Profiles of Slag/Liquid Metal Interface at the Wall

If the underlying liquid metal wets on the refractory better than the slag, the contact angle (θ_c) at the slag/liquid metal/refractory triple point is less than 90° as shown in Figure 2.7 (A). In this situation, the distance between the slag/liquid metal interface and the skimming lip at the wall (Δh_w) is less than that distant from the wall (Δh_∞). On the other hand, if the slag wets the refractory better than the underlying liquid metal, θ_c will be greater than 90°. Then, Δh_w will be greater than Δh_∞ as shown in Figure 2.7 (B). When comparing the tendency of entrainment of underlying liquid metal during skimming in both cases, it can be seen that the underlying liquid metal is more easily entrained in the stream of slag flow in the former case than the latter one. Therefore, it is advantageous that the underlying liquid metal does not wet on the refractory in order to reduce the chance of entrainment of liquid metal during skimming. On the other hand, wetting of slag on the refractory at the skimming mouth is advantageous in terms of skimming and the better the slag wets on the refractory, the higher it will climb above the slag/liquid metal interface at the wall. As a result, more space is available to operate without distributing the underlying liquid metal. Moreover, the wettability of slag on refractory also determines the contact angle of the slag/liquid metal interface at the wall; the better the slag wets on the refractory, the greater the contact angle at the triple point.

From Section 2.3, it is known that the slag in copper industry usually wets on the refractory lining. In order to predict the wetting profile at the slag/molten copper/refractory interface, it is important to know the interfacial properties between molten copper and the refractory lining. Wettability of refractory oxides to molten metals were investigated by Frossberg [6]. Results of his work indicted that molten copper does not wet conventional refractory. The contact angles between molten copper/Al_2O_3 and copper/ MgO were determined to be 120° and 128° respectively. Ueki et al [7] studied the wettability of liquid copper to zirconia. The contact angle between liquid copper and ziconia was found to be 126°. Also, Labbe and Brandy [8] found that the wetting of liquid copper on aluminum nitride is poor. The contact angle was about 135°.

According to the literature, one may conclude that molten copper does not wet on refractory while the slag does. At the lip during skimming, the molten copper bath is covered by a layer of slag. Therefore, it is important to know the contact angle of the slag/liquid copper interface and the refractory lining. Unfortunately, there is no available information about this issue but the contact angle can be roughly estimated using the available literature data. At the wall of a furnace containing a bath of molten copper, the Young's equation can be written as:

$$\gamma_{AR} = \gamma_{CA} \cos\theta_{ACR} + \gamma_{CR} \quad (2.1)$$

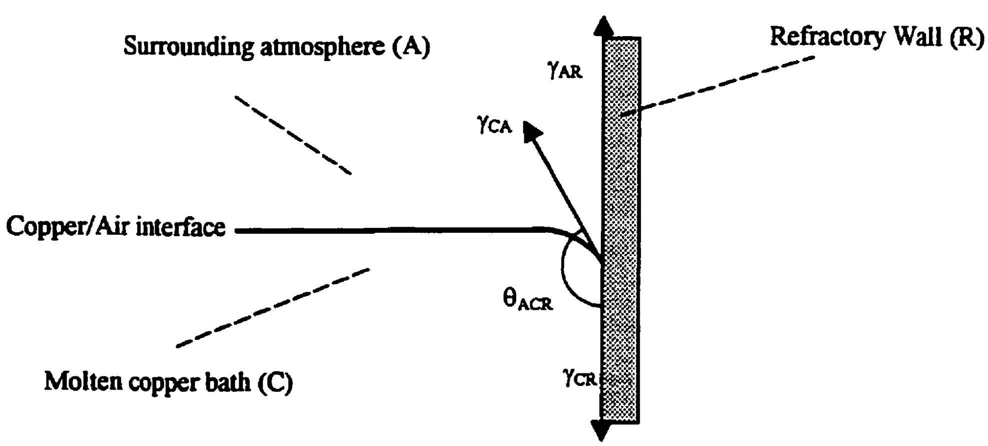


Figure 2.8 Wetting Profile of Molten Copper on Refractory Lining

In the case of slag contacting with refractory, the Young's equation becomes:

$$\gamma_{AR} = \gamma_{SA} \cos\theta_{ASR} + \gamma_{SR} \tag{2.2}$$

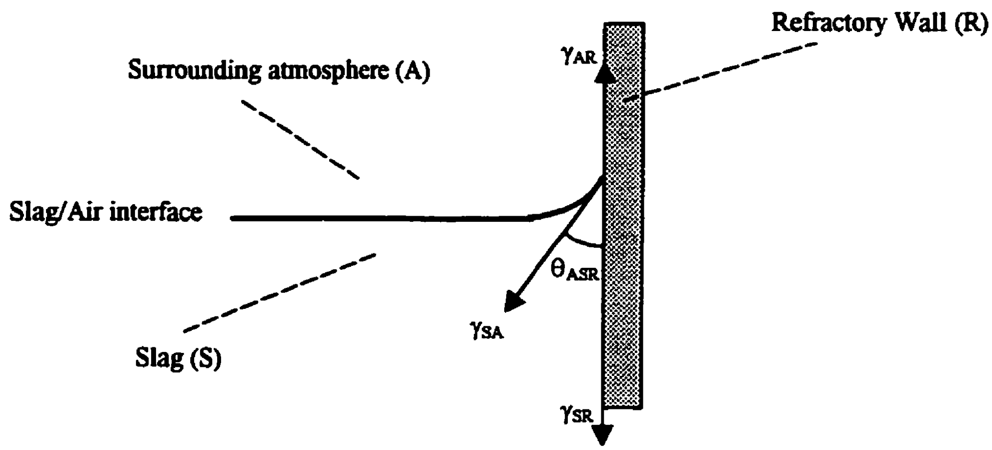


Figure 2.9 Wetting Profile of Slag on Refractory Lining

By rearranging Equations (2.1) and (2.2),

$$\gamma_{SR} - \gamma_{CR} = \gamma_{CA} \cos\theta_{ACR} - \gamma_{SA} \cos\theta_{ASR} \tag{2.3}$$

Considering at the triple point between liquid copper, slag and refractory, Young's equation becomes,

$$\gamma_{SR} - \gamma_{CR} = \gamma_{SC} \cos \theta_{SCR} \tag{2.4}$$

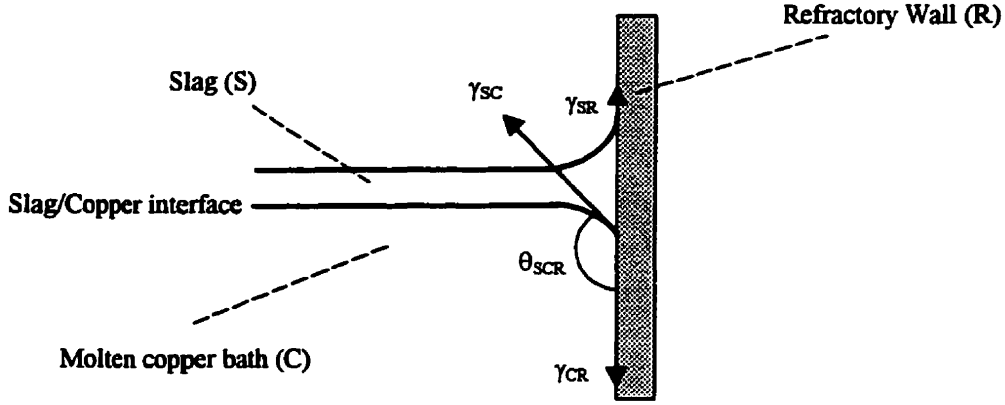


Figure 2.10 Wetting Profile on Slag/Copper Interface on Refractory Lining

Using Equation (2.3), Equation (2.4) becomes:

$$\gamma_{CA} \cos\theta_{ACR} - \gamma_{SA} \cos\theta_{ASR} = \gamma_{SC} \cos \theta_{SCR} \quad (2.5)$$

Since θ_{ACR} is greater than 90° and θ_{ASR} is less than 90°, therefore the LHS of Equation (2.5) has a negative value. On the right hand side of Equation (2.5), since γ_{SC} is a positive value and θ_{SCR} lies between 0 to 180°, therefore θ_{SCR} must be greater than 90°. From this analysis, the contact angle at the copper/slag/refractory triple point must be greater than 90°. In result, the meniscus of the slag/copper interface bends downward at the refractory, Figure 2.7 (B).

From the above analysis, it can be seen that the wetting properties between slag, liquid metal and refractory do not favor the entrainment of underlying liquid metal during skimming. However, the occurrence of entrainment still depends on the velocity of the slag flow across the skimming mouth. In order to ensure that there is no underlying liquid metal entrained in skimming, the velocity of the slag passing the edge of the skimming mouth cannot exceed a certain maximum value.

2.3.1.2 Studies on the Entrainment Phenomenon in Skimming

Many studies have been performed to investigate the entrainment problem in separating two immisible liquids in a container. Two of the researches directly applied to copper industry were carried out by Liow et al [9] and Baird et al [10].

In the work of Liow et al, liquid metal entrained during skimming of Piece-Smith Converter was studied. Skimming of slag was considered as an instantaneous flow of thick layer of liquid over a weir, which represented the skimming lip of the converter. In their experiments, two layers of liquid were held in a tank with the interface at about the level of the weir. A removable gate that located on top of the weir was used to keep the upper liquid layer in the tank before the experiment start. The upper liquid layer was allowed to flow across a weir by sudden removal of the gate. The amount of underlying denser liquid entrained in the flow was measured and was used to validate the prediction by numerical stimulation. The methodology of their experiments failed to stimulate the actual flow of slag during skimming. In the actual skimming operation of a Piece-Smith furnace, the lip is lowered slowly by rotating the furnace. Since the rotation is done carefully and slowly, it will not be possible to have a thick layer of slag available before the slag start to flow out of the furnace. Once the hydrostatic head of the slag layer is high enough to overcome its resistance to flow, it starts to flow out of the furnace. Their study provided a better understanding of the flow of a thick layer of liquid across a weir rather than providing the insight of the behavior of the slag during copper converter skimming.

Another study related to skimming in copper industry was performed by Baird et al. In their study, skimming of slag in the Inco Flash Furnace was stimulated in a cold model with water and mineral oil representing matte and slag in the furnace respectively. The entrainment of water into the stream of mineral oil was investigated during the skimming of the oil through a small circular hole. Their particular interest was in the threshold limit of the distance between the water/oil interface and the bottom of the skimming hole in order to avoid water to be entrained in the oil stream. It was found that the threshold limit increased with the flow rate of the oil. In their study, it was also suggested to modify the geometry of the skimming hole in order to reduce the chance of entrainment occurring. Their suggestion was to increase the entrance area of the skimming hole. By doing this, the velocity of the slag enter the skimming hole can be reduced while maintaining the same flow rate. The idea is to reduce the velocity of the slag at the bottom edge of the skimming hole. Hence, the pressure differential created or the upward suction experience by the slag/liquid metal interface can be reduced also. As a result, the threshold limit of the distance between the slag/liquid metal interface and the bottom of the skimming hole can be extended. It was seen from their study that the level of the skimming mouth cannot be at the same level as the slag/liquid metal interface during skimming in order to avoid entrainment of liquid metal. The allowable level of the skimming mouth depends on the velocity of the slag flow across the skimming mouth.

3. MOVEMENT OF SLAG DURING SKIMMING

3.1 Scope of the Chapter

As mentioned in Chapter 2, skimming of slag comprises of two steps: the slag transportation and the slag removal step. The movement of slag due to the forces acting on or applied to the slag in these two steps is discussed in this chapter. The first part of the chapter focuses on the forces causing the slag to move across the skimming lip in an unassisted skimming operation. The later part of the chapter is devoted to discussing the externally assisted movement of slag in the transportation step resulting from the forced surface circulation. Two methods of generating the surface circulation are explored, by gas injection via submerged tuyere and by impinging gas jet in glancing contact with the metal bath surface. Finally, the behaviors of the slag under the influence of the molten metal bath surface circulation are discussed.

3.2 Movement of Slag in Removal Step

In the slag removal step, slag moves across the skimming lip from the inside of the furnace to the outside. There are two types of flow that may occur in the removal step of an unassisted skimming operation, namely the pressure driven flow and the creeping flow along the skimming mouth surface. The pressure driven flow arises from the thickness of the slag layer above the skimming lip. The creeping flow is a result of the wetting of slag on the refractory at the skimming mouth.

3.2.1 Pressure Driven Flow

When a closer look is taken at the skimming mouth, it can be seen that the overflow of slag can be driven by the hydrostatic head due to the thickness of the slag layer as illustrated in Figure 3.1. As can be seen in the figure, the hydrostatic head at point A, P_A, and point B, P_B, are $\rho g \Delta h_A$ and $\rho g \Delta h_B$ respectively where ρ is the density of the slag and g is gravitation constant. Since Δh_A is greater than Δh_B, P_A is greater than P_B. If the pressure differential between point A and point B is large enough to overcome the resistance to flow, the slag flows from point A to point B. In other words, flow of slag across the skimming lip occurs.

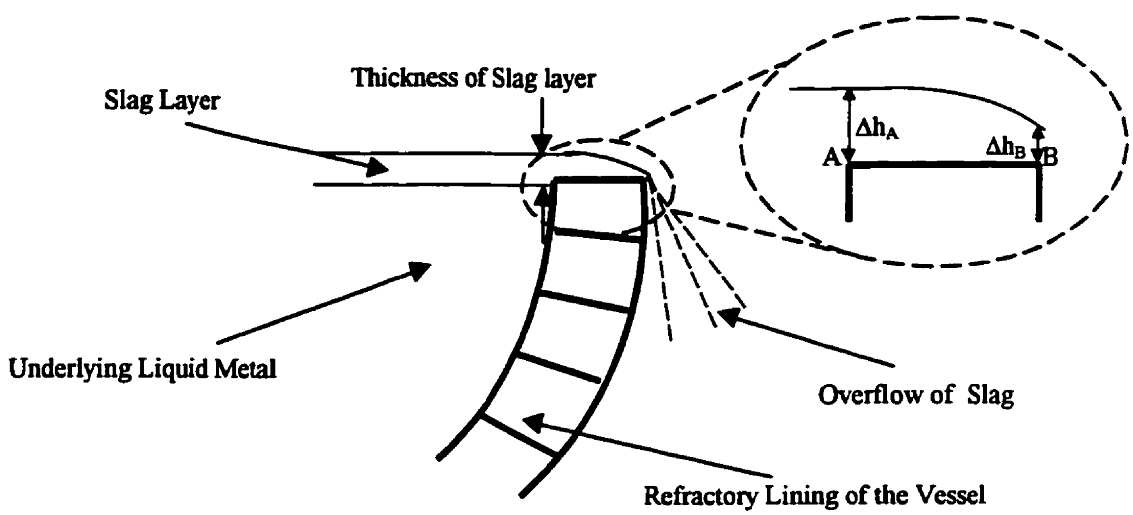


Figure 3.1 Pressure Driven Slag Removal

3.2.2 Creeping Flow on Refractory Surface

The creeping of slag across the skimming lip is due to the wetting of slag on the refractory surface. It is known that the slag produced in copper industry usually wets on the refractory lining. When the skimming lip is at the same level as the slag/metal interface, the level of slag at the wall is slightly above the skimming lip. The slag located next to the vertical end of the skimming mouth spreads along the corner of the mouth and creeps across the skimming lip to form a pool of slag at the corners. If it is assumed that the slag that creeps across the lip can accumulate at the exterior edge of the lip and the skimming lip is horizontal, the creeping stops when the level of slag above the lip at the exterior edge of the vertical end is same as the one at the interior edge. At this point, the slag cannot move further and the system is at equilibrium. In reality, once the slag reaches the exterior edge of the lip, it falls from the furnace under the action of gravity. In other words, the equilibrium cannot be attained and more slag will be drawn from the furnace if there is sufficient slag in the furnace. Therefore, the creeping of slag along the corner of the skimming mouth continues until most of the slag is removed.

3.2.3 Generalization of Slag Movement in Removal Step

In order to analyze the performance of the slag removal during skimming, it was found convenient to categorize the forces that cause slag to flow across the skimming lip as the forces causing slag removal (hereafter called the 'driving force') and the forces resisting the slag flow across the lip as the 'resisting force'. With this terminology, it may be summarized that the removal of slag will occur only when the driving force is greater than the resisting force.

As mentioned above, in an unassisted skimming, the driving forces available are the hydrostatic head of the slag layer and the creeping of slag at the corners of the skimming mouth. The resisting forces include the surface tension and viscosity of the slag and some other interaction that may exist. For slag removal to occur, the driving forces must be greater than the resisting forces. In order to improve the efficiency of the slag removal step, the driving forces must be increased to exceed the resisting force as much as possible. The extent of slag removal is determined by whether the driving force can be maintained greater than the resisting force until all slag is skimmed.

3.3 Movement of Slag in Transportation Step

The transportation step of a skimming process refers to the movement of slag from its original position to the skimming lip. There are two types of slag motion that result in moving the slag to the skimming lip: the creeping flow along the wall and the externally assisted flow.

3.3.1 Classification of Slag

The slag that floats on the liquid metal surface in a furnace can be categorized into two different types, "detached slag" and "attached slag". Detached slag is defined as those pools or islands of slag floating on the surface of the underlying liquid metal without any contact with the refractory lining. Attached slag is those slag pools has contact with the refractory lining. In Figure 3.2, a plan view of a horizontal cylindrical vessel is shown to illustrate the idea of detached and attached slag.

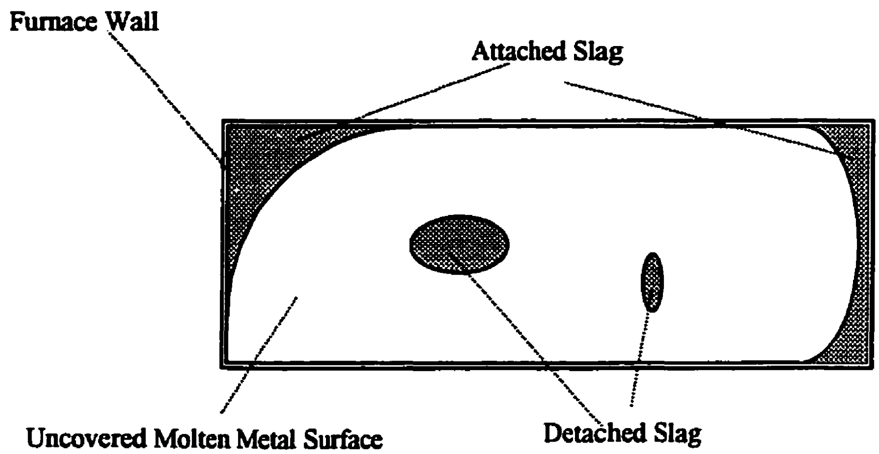


Figure 3.2 Illustration of Attached and Detached Slag (Plan View)

3.3.2 Distribution of Slag

The transportation of slag is only necessary to skim the slag originally located away from the lip. The amount of slag can be skimmed without transportation depends on the distribution of slag before the skimming process start and the location of the skimming mouth. The important factors that affect the distribution of the slag in a furnace are the interfacial properties between the slag and the refractory lining as follows. If the slag does not wet on the refractory lining, there is no preferential place where the slag will locate itself. The distribution of slag before skimming solely depends on the flow pattern of the liquid metal bath when the slag is formed. However, if the slag wets on the refractory lining, the slag will attach to the refractory once there is contact between slag and refractory. Therefore, the distribution of slag is mainly around the wall of the furnace.

Since the slag produced in copper industry usually wets on the refractory lining of the furnaces, the slag will attach to the wall once there is contact with the refractory. Due to the nature of fluids, if enough time is given to the slag, it will arrange itself to minimize its surface area. Therefore, the slag should be mainly located at the two ends of the furnace as illustrated in Figure 3.3.

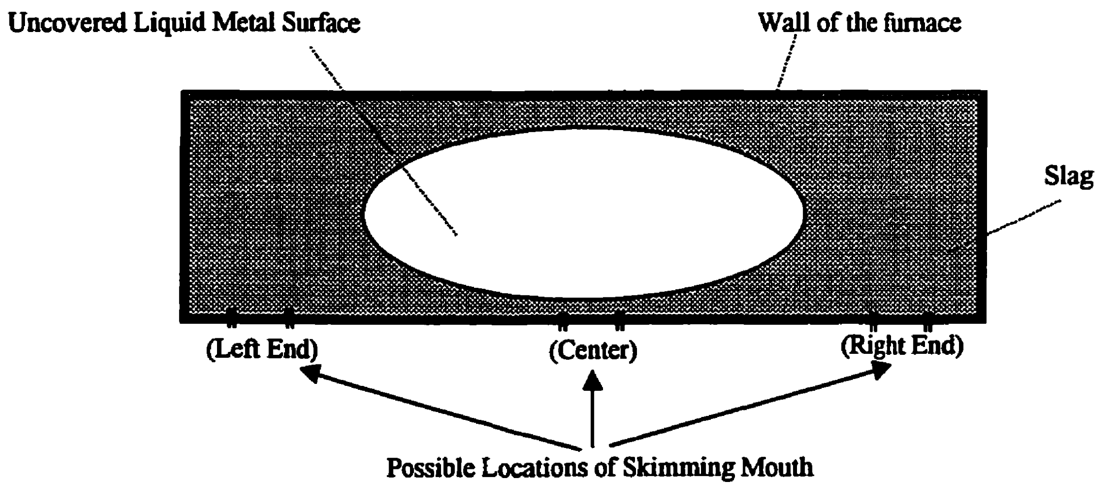


Figure 3.3 Predicted Slag Distribution in Cylindrical Vessel (Plan View)

The area of the uncovered liquid metal surface depends on the amount of slag present in the vessel. If the amount of slag increases, the uncovered area decreases. However, this uncovered area is always located at the middle at equilibrium.

When the initial amount of slag is small and there is some uncovered area in the middle of the furnace, the location of the skimming mouth is a crucial factor determining the amount of slag can be skimmed without forced transportation externally applied since only that slag in the immediate vicinity of the mouth quickly overflows. As can be seen in Figure 3.3, if the skimming mouth is located at the center of the furnace, the slag can be skimmed without transportation is very limited. However, if the skimming mouth is at either end of the furnace, the slag available potentially to be skimmed is greatly increased. When the initial amount of slag is large enough to cover the whole surface, the location of the skimming mouth does not have great influence on the initial amount of slag that can be skimmed by the conventional skimming practice. However, as the slag is being skimmed, the complete slag layer eventually breaks up and creates an uncovered area as shown in Figure 3.3 and the location of the skimming mouth again becomes important as the skimming process continue.

3.3.3 Transportation of Slag by Creeping along the Wall

The slag attached to the vertical end of the skimming mouth creeps along at the corner of the mouth forming a slowly flowing pool of slag at the corner (3.2.2). If this slag is continuously removed, more slag will be drawn from the furnace. As a result, the slag inside the vessel continuously creeps along the walls towards the skimming lip. However, the creeping flow has no effect on detached slag. It can be seen that the attached slag located at the back of the furnace needs to move around the perimeter of the furnace before it can reach the lip, i.e., the distance needed to be traveled is great with the result that the rate of slag transported to the skimming mouth by the creeping flow is small. However, this creeping motion does not stop as long as the slag pools at the skimming mouth corners are continuously removed and there is sufficient slag head to create flow across the lip.

3.3.4 Externally Assisted Movement of Slag

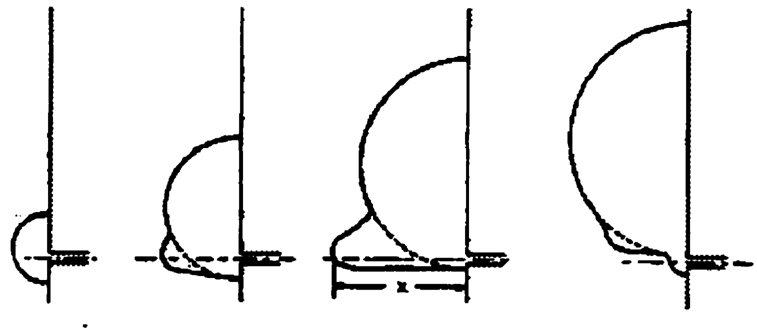
In order to improve the skimming effectiveness, the rate of the slag being carried to the skimming lip needs to be improved. Therefore, an externally assisted flow of slag is needed. The external assistance referred to in this work is the movement or "circulation" of the underlying metal bath surface. When the surface of the molten metal bath is made to circulate, the motion of the metal bath surface moves the slag floating on it. The mechanism by which a very thin layer of moving liquid moves the slag floating on it is outside the scope of this thesis. However, two methods to create the motion of the metal bath surface were explored and compared.

3.3.4.1 Creation of Surface Circulation by Gas Injection

3.3.4.1.1 Submerged Injection

Injection of gas at the bottom of a molten metal bath is a common practice in metallurgical processes. Gas injection is usually done via either a tuyere or porous plug. In terms of slag transportation for skimming, creation of surface movement by bottom gas injection is an industrial used technique. In the research performed by Petrushka and Winters[11], they stated that one of the common problems of raking facilities in steelmaking industry is the inability of the skimmer blade to reach the slag layer at the backwall of the ladle. In order to transport the slag in the transfer ladle to the skimming lip, they suggested mounting bubbling plugs inside the ladle. Inert gas (9.4×10^{-3} m^3/s STP) was supplied to the plugs via a refractory lance. Gas bubbles rise in the ladle promoted the movement of the slag towards the ladle lip. As stated by Petrushka and Winters the porous plug should be mounted as close to the backwall as possible. This suggestion was made because if the gas was not injected next to the furnace wall, part of the slag would be pushed towards the rear wall by the surface circulation instead of towards the skimming lip. In the ideal case, the gas bubble should rise against the furnace wall. However, as the cold gas bubble rises along the wall, the refractory lining experiences a serious thermal shock and cause damage on the refractory bricks. Therefore, the injected gas cannot be too close to the refractory lining in order to minimize damage on the refractory bricks. As a result, there is always some slag being pushed towards the backwall by the surface movement created by bottom gas injection.

Another method to inject gas into the metal bath is by submerged tuyere. Kozlowski and Wraith [12] studied the formation of bubbles during the injection of gas into liquid bath. As gas was injected into a liquid bath via a tuyere, the bubble would expand radically and accelerate upwards under the influence of the buoyancy force until the bubble base passed the source and detached from the gas supply. The jet cavity expands as the bubble grows and reaches a maximum length when the bubble detaches from the nozzle. The cycle of growth and displacement of the bubble would repeat as the gas supply was sustained. Illustration of the growth of the jet cavity during the bubble growth is present in Figure 3.4.



(A) Schematic Representation

(B) Experimental Observation

Figure 3.4 Growth of Jet Cavity and the Bubble Growth Cycle [12]

The size of bubbles created by the submerged nozzle is large. When this large bubble reaches the liquid metal surface and collapse, the surrounding liquid metal moves rapidly to fill the empty space original occupied by the bubble. This rapid movement of the liquid metal creates a strong circulation in the metal bath. If this circulation is strong enough to overcome the surface tension of the slag, the circulation may entrain the slag floating on the surface back into the molten metal bath and cause mixing as shown in Figure 3.5.

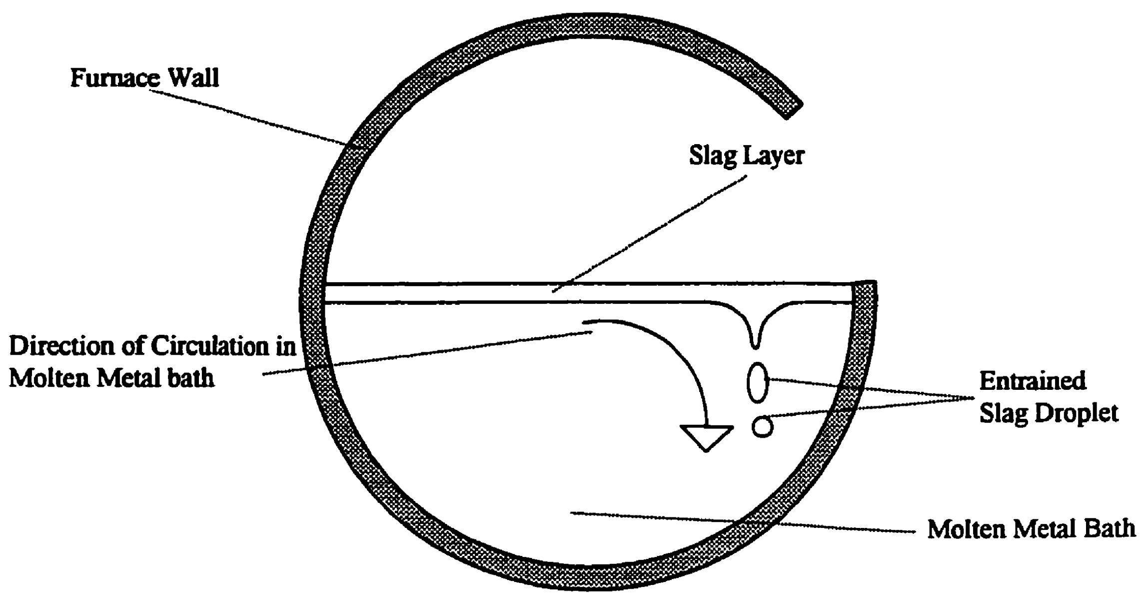


Figure 3.5 Entrainment of Slag by Circulation in Molten Metal Bath

Moreover, as the gas bubbles escape from the molten metal bath, splashing occurs and waves are created on the surface. The waves propagate in all directions away from the location where the bubble collapses. As the wave reaches the wall of the furnace, it reflects back into the furnace and interferes with the wave generated by the next bubble.

After several reflections and interference, the circulation on the liquid metal surface is highly disordered and chaotic. In this case, it is difficult to control the circulation pattern on the liquid metal surface. Since the goal of the gas injection is to transport the slag to a specific location, a controlled circulation pattern on the underlying liquid metal surface is highly desired. Moreover, because of the complex interference pattern on the liquid metal surface, standing waves may be created at certain locations on the liquid metal surface. Once a standing wave is created, the motion of slag floating on the surface is only in the vertical direction. In other words, the slag located at the node vibrates vertically instead of advancing horizontally. Therefore, transportation of slag by wavy motion is ineffective.

3.3.4.1.2 Impinging Gas Jet

In this research, it is proposed to create circulation on the liquid metal bath by an inclined, top- blowing, gas jet in glancing contact with the molten metal bath surface. As a stream of gas impinges on a liquid surface, the liquid surface will deform and form a dimple on the surface. After the gas stream exits from the dimple, it flows roughly parallel to the surface of the liquid. This parallel flow forms a boundary layer along the liquid surface. The velocity of the gas decreases from its main stream velocity (U) to a smaller velocity at the interface ($V_{surface}$) inside the boundary layer. If it is assumed that there is no slip between the gas phase and the liquid phase, the velocity of the liquid at the interface will be $V_{surface}$ also. As momentum moves down into the liquid phase, the velocity further decreases by viscous dissipation and is eventually totally dissipated by the viscosity of the liquid. As a result of the gas jet, only the surface layer of liquid bath is in motion. The underneath bath remains undisturbed in the process.

The thickness of the liquid bath distributed by the gas flow depends on the viscosity of the liquid. As an extreme example, if the viscosity of the liquid η_{liquid} is infinitely high, it behaves like a solid. In this case, the velocity of the gas phase decreases to zero at the interface. Then the thickness of the liquid layer set into motion by the gas flow will be zero. In other words, the whole liquid phase remains stationary. The velocity profile will be similar to one shown in Figure 3.6.

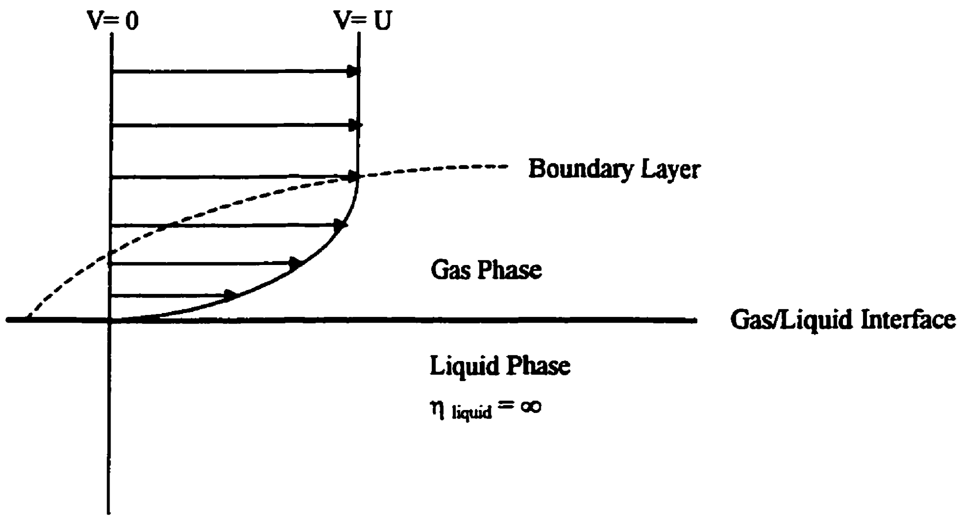


Figure 3.6 Velocity Profile across Gas/Liquid Interface with Highly Viscous Liquid

In the other extreme, if the viscosity of the liquid is very low, it behaves like a gas. In this case, no boundary layer is formed at the interface. The velocity of the liquid phase at the interface is same as the main stream velocity of the gas. The rate of velocity dissipation in the liquid phase will be zero. The thickness of the liquid layer set into motion by the gas will be infinite. In other words, the whole liquid phase will move at a velocity same as the main stream velocity of the gas. The velocity profile will be similar to the one shown in Figure 3.7.

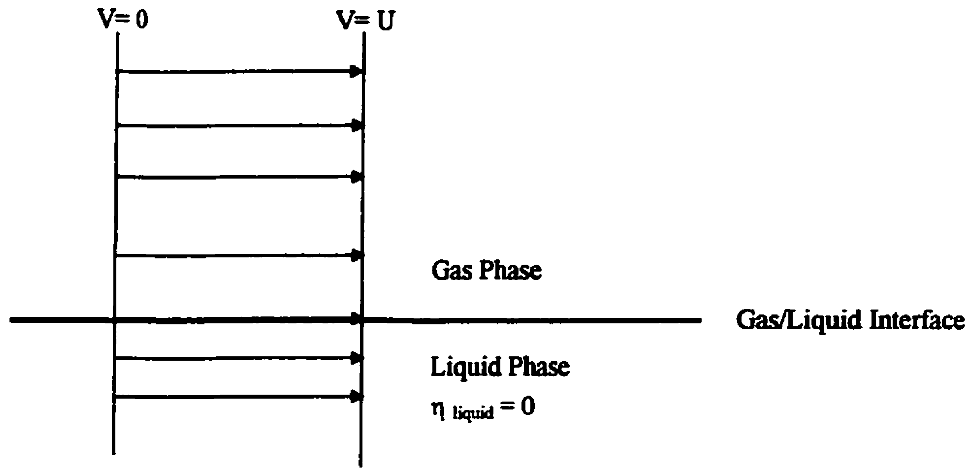


Figure 3.7 Velocity Profile across Gas/Liquid Interface with Inviscid Liquid

When the liquid phase is a molten metal bath in a furnace, the viscosity of the molten metal has a finite value and greater than the viscosity of the gas. Therefore, the velocity of the molten metal surface must be greater zero but smaller than the main stream velocity of the gas flow, U. The velocity of the liquid phase surface, $V_{surface}$, is governed by the ratio of the viscosity of the gas phase and the liquid phase and is given by the following expression:

$$V_{surface} = U\frac{\eta_{gas}}{\eta_{liquid}} \tag{3.1}$$

The thickness of the molten metal bath set into motion is finite and depends on the viscosity of the molten metal. The velocity profile at the gas/molten metal interface will be similar to the one presented in Figure 3.8.

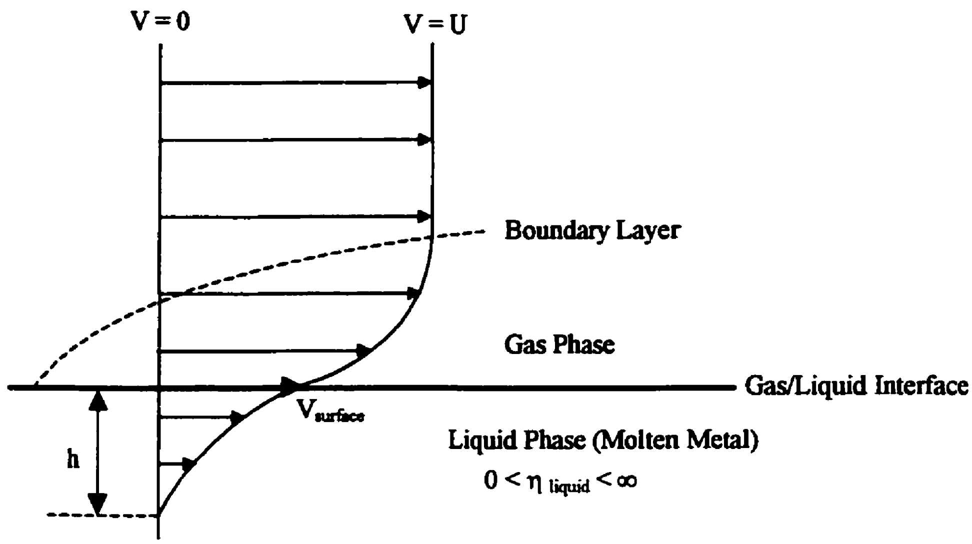


Figure 3.8 Typical Velocity Profile across Gas/Molten Metal Interface

3.3.4.1.3 Comparison of Surface Movement

When comparing the generation of surface movement on a molten metal bath for transportation of slag by submerged gas injection and by impinging gas jet, it can be seen that impinging gas jet avoids several problems created by submerged gas injection.

- The surface circulation pattern on the molten metal bath can be easily controlled via the orientation and configuration of the top blowing jets.

- There is no direct contact between the jets and the high temperature molten metal bath.
- The possible problems of solidification of metal inside the injector and thermal shock on the refractory lining are eliminated.
- The maintenance of a top blowing jet is relatively easy and cheap compared with submerged blowing devices.
- Gas flow from a top blowing jet directly drags and shears the liquid surface without significantly disturbing the underneath liquid.
- The problem of mixing between slag and liquid metal are reduced.
- The surface movement created by a top blowing jet is horizontally across the molten metal bath.
- The wavy motion on the molten metal surface is minimal.

In conclusion, glancing gas jets are more advantageous than submerged gas injection for generating surface circulation on the molten metal bath to transport slag for skimming.

3.3.4.2 Behavior of Slag with Bath Surface Circulation

Detached slag forms isolated islands floating on the underlying liquid metal surface. There is nothing holding the detached slag in its original position when the underlying liquid metal surface is in motion. Therefore, when the surface of the underlying liquid metal bath is in motion, the detached slag will be carried by the circulation and advances in the same direction as the surface circulation. The movement of the detached slag is solely controlled by the movement of the underlying liquid metal surface. Therefore, if the underlying liquid metal surface moves towards the skimming mouth, the detached slag moves to the mouth also.

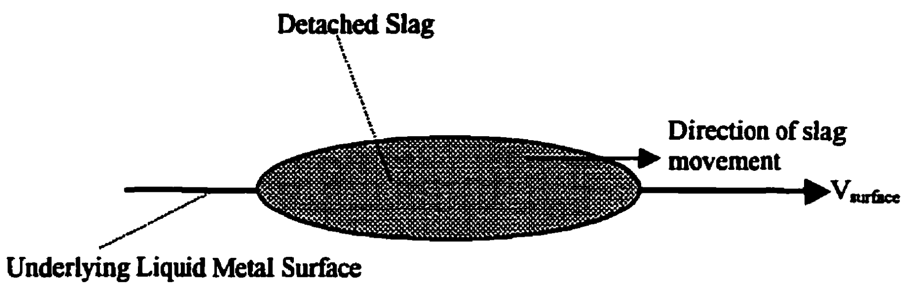


Figure 3.9 Movement of Detached Slag by Liquid Metal Surface Circulation

For attached slag, the behavior of the slag under the influence of the underlying liquid metal surface circulation depends on the interfacial properties between slag and refractory lining as well as the surface tension of the slag. As the underlying liquid metal surface is in motion, a shear stress, τ, is induced on the bottom of the attached slag. The shear force experienced by the slag will be τA, where A is the area of the slag/liquid interface which is in motion. If the slag does not wet on the refractory, there is on force available to oppose the shear force induced on the slag. Therefore, the slag can be easily separated from the wall by the underlying liquid metal surface circulation and forms a detached slag island. Once the attached slag is separated from the refractory wall, the behavior of the slag will be identical to a detached slag.

However, it is known that the slag usually wets on the refractory lining, the interaction between the slag and the refractory lining keeps the slag attached to the furnace wall. In this case, the behavior of the slag will be controlled by the surface tension of the free slag surface. Assuming that the surface tension of the slag is large, the slag does not deform. If the shear force induced by the surface circulation is greater than the interaction between the slag and the refractory lining, the whole piece of attached slag will be separated from the wall. However, in reality, the slag does deform when sheared. The interaction between the slag and the refractory lining is usually greater than the surface tension of the slag. Therefore, once the induced shear force is large enough to overcome the surface tension of the slag, the slag will deform without separating from the wall. If it is assumed that there is no slip between the slag/liquid metal interface, the velocity of the slag (V_{slag}) contacting with the underlying liquid metal will be same as the velocity at the liquid metal surface ($V_{surface}$). Due to viscous dissipation, the velocity of the slag gradually decreases in the upward direction. Eventually, the momentum is totally dissipated. Therefore, a layer of the slag with certain thickness (h) will be in motion in the same direction as the surface circulation and the thickness of this advancing slag depends on the viscosity of the slag.

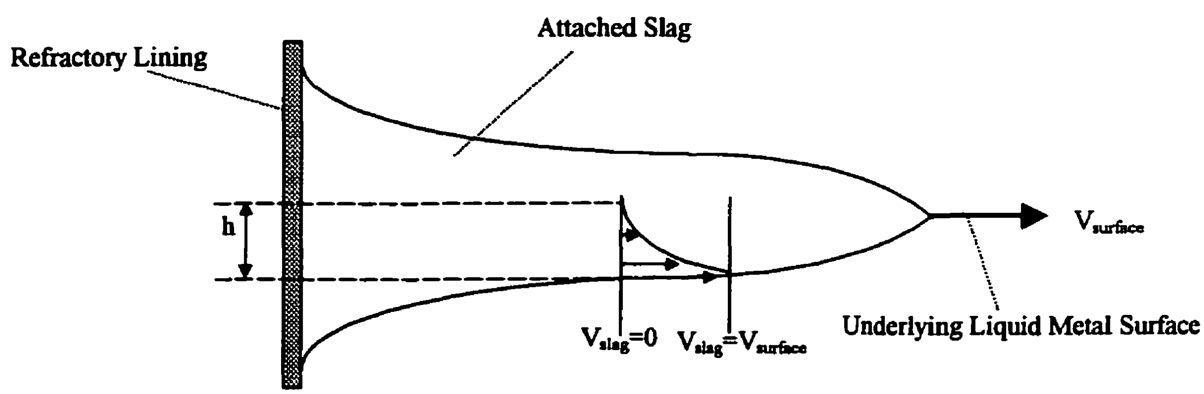


Figure 3.10 Movement of Attached Slag by Liquid Metal Surface Circulation

The result of the deformation of the attached slag by underlying liquid metal surface circulation is the extension of its surface area. However, the nature of a fluid is to minimize its surface area, thus the shearing force at the bottom trends to increase the slag surface area while the surface tension of the slag tries to decrease it. As a result of the two opposing forces acting on the slag, it breaks up to form a piece of detached slag and is carried away by the surface circulation after a certain extension. In other words, part of the attached slag is separated from the wall and carried towards the skimming mouth by circulation on the underlying liquid metal surface. Therefore, by introducing a surface circulation on the underlying liquid metal, it may be possible to detach part of the attached slag and carry it towards the skimming mouth.

3.3.4.3 Desired Surface Circulation

The desired circulation pattern on the underlying liquid metal surface is the one that is able to move all slag floating on the surface towards the skimming mouth regardless of its original position. One of the possible circulation patterns is the left side of the underlying liquid metal surface circulating in an anti-clockwise direction while the right side is circulating in a clockwise direction with the center of the skimming mouth as the dividing line as shown in Figure 3.11.

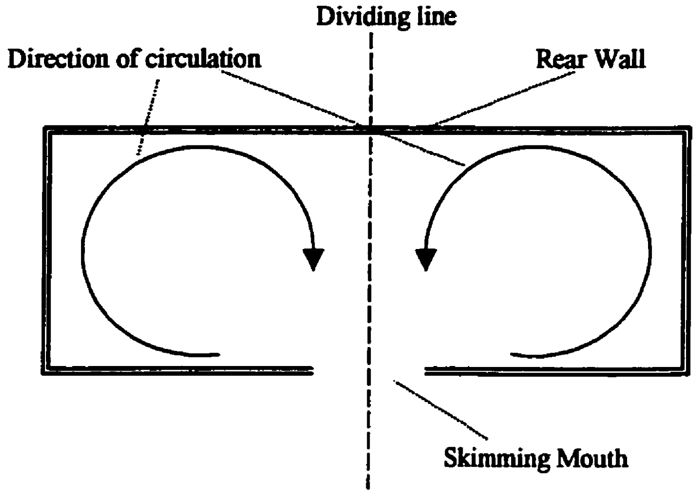


Figure 3.11 Illustration of Desired Circulation Pattern on Bath Surface (Plan View)

This circulation pattern will be able to bring the detached slag, randomly scattered on the underlying liquid metal surface, to the skimming mouth regardless of its original position. For the attached slag, this circulation pattern has the ability to deform the slag along the walls of the furnace and accumulate at the rear wall at the dividing line. The accumulated slag will then be further deformed along the dividing line and move towards the skimming mouth.

4. MODELING SIMILARITY

Physical modeling is a commonly used technique in studying the behavior of the furnaces in metallurgical processes [9,10,13,14,15,16]. However, the similarity between the model and the prototype were seldom discussed. Mazumdar and Guthrie [17] performed an extensive literature review on physical and mathematical modeling of gas stirred ladle. In their paper, the following comment regarding the experimental studies of the gas stirred liquid metal system was made; '*many of these studies, while of considerable fundamental importance to steelmaking, are not of direct relevance to ladle metallurgy operations since experimental conditions applied do not exactly correspond to ladle metallurgy operations. Consequently, an extensive discussion on these has been avoided.*' In another study, Mazumdar [18] also commented about the similarity consideration of physical modeling of a gas stirred system presented in the literature that '*the physical modeling principles, particularly the dynamic similarity criterion between model and full-scale systems, have not been adequately considered*'.

Conventionally physical modeling exercises reported in the literature start by building a 'scale' model, wherein scale refers to the ratio of physical dimensions of the model to the prototype. As will be discussed below, the choice of the parameter that is used to specify the scaling factor is based on similarity considerations; a sophisticated task that need to be well informed. Since, similarity considerations were often ignored in physical modeling studies in the literature, it is difficult to accept the literatures' claims that the experiments faithfully reproduced the behavior of the prototype.

4.1 Similarity Considerations

The primary factor that determines the successfulness of a physical modeling exercise is the ability to correctly stimulate the behavior of the prototype in a model. In order to simulate the fluid flow of the prototype, the model must be "similar" to the prototype geometrically, kinematically and dynamically [19].

- Geometric similarity requires that the model and the prototype be the same shape and all linear dimensions of the model be related to corresponding dimensions of the prototype by a single scale factor.
- Kinematic similarity requires the velocities of the two flows at corresponding points are in the same direction and are related in magnitude by the same scaling factor as in geometric similarity consideration.
- Dynamic similarity requires two flows have force distributions such that identical types of forces are parallel and are related in magnitude by the same scaling factor at all corresponding points.

The requirement of dynamic similar is most restrictive. Two flows must possess both geometric and kinematic similarity to be dynamically similar. Moreover, the primary interest of this work is the forces acting on the slag during skimming. Therefore, the following discussion was focused on the criteria that need to be satisfied to achieve dynamic similarity

It is noteworthy that the prototype has different types of behavior, for example, fluid flow, heat transfer or mass transfer, etc. The situation is often that it is not possible to simultaneously stimulate all types of behavior in a single model. A decision needs to be taken about which behavior to focus on. The model to be constructed must be able to faithfully simulate the interested behavior of the prototype, while the simulation of other behaviors may need to be sacrificed.

The objective of the present modeling exercise was to study, in general terms, the movement of slag and the motion of the underlying liquid metal generated by impinging gas jets in order to facilitate skimming of a rotary cylindrical furnace. In other words, the modeling exercise performed was not to stimulate the flow of the bulk fluids in a particular furnace or to design the necessary jet configuration to create the desired liquid flow. Since the dimensions of the prototype furnaces and fluid properties vary widely in different processes, the present work could not be a direct physical modeling exercise. Rather it became an exercise aimed at visualizing an otherwise unobservable high temperature phenomenon and exploring the means to improve the skimming of fluid slag.

4.1.1 Present Modeling Strategy

The strategy employed in this work was to establish the general similarity relationships in modeling a rotary cylindrical furnace during skimming with the aid of top blowing jets. Typical fluid properties of converter slag and molten copper at their melting points were used in the similarity considerations and are presented in Table 4.1

It was found in the present study that from the observation of this general movement, identification of methods to improve skimming effectiveness was possible. Moreover, the similarity considerations presented below serve as reference for constructing a physical model to reproduce the detailed behavior of a rotary cylindrical furnace during skimming. With these similarity criteria, it will be straightforward to build a model to directly stimulate the detail behavior of a particular prototype.

Table 4.1: Physical Properties of Typical Converter Slag and Liquid Copper [20]

	Slag	Copper
Density	3.8×10^3 kg/m^3	8.0×10^3 kg/m^3
Viscosity	3×10^{-1} Pa s	3×10^{-3} Pa s
Surface tension	6×10^{-1} N/m	3.5×10^{-1} N/m

4.1.2 Present Model

Section 3.3.4 and in particular Section 3.3.4.2 showed that it was believed that top blowing gas jets might produce an improvement in industrial skimming effectiveness. Since there is no industrial furnace equipped with top blowing gas jets for skimming purpose, the configuration of the jets in the prototype referred to in the similarity considerations is uncertain. However, it should be obvious that there is a great deal of freedom with respect to the number of jets could be used and their specifications, such as flow rate, velocity and orientation with respect to the slag/metal interface. After extensive discussion with informed parties and some preliminary test work, but also somewhat arbitrarily, the jet placement as shown in Figure 4.1 was settled upon.

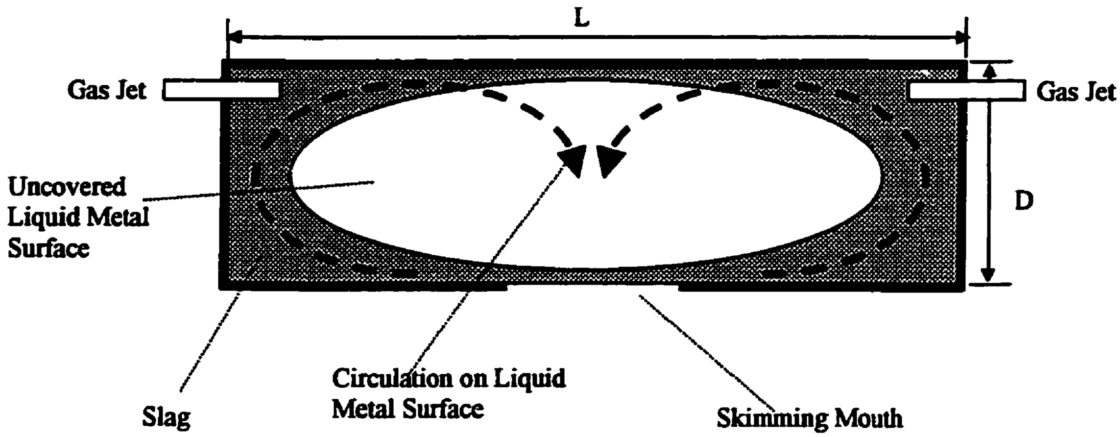


Figure 4.1 Illustration of Configuration of Model

As can be seen from the Figure 4.1, the jets were aligned parallel to the furnace axis and placed close to the rear wall. In addition, the jets were oriented 50 ° to the slag/metal interface. Preliminary studies revealed that this configuration generated the desired circulation pattern on the liquid metal surface towards the furnace mouth as discussed in Section 3.3.4.3 and as shown in the figure. This configuration was used in the following similarity considerations.

In practice, the fluid system of the prototype consists of three parts; the gas, the slag and the underlying liquid metal. However, the movement of gas was not the primary interest in this work. This modeling work focused only on the motion of the slag and the underlying liquid metal

Since the requirement of dynamic similar is most restrictive, the following focused on the criteria must be satisfied to achieve dynamic similarity. For simplicity, these two parts are considered below individually.

4.1.2.1 Underlying Liquid Metal

In order to achieve geometric similarity, the following relationship must be satisfied.

$$(D)_p = \lambda\,(D)_m \;\; ; \;\; (L)_p = \lambda\,(L)_m \tag{4.1}$$

Where the subscripts m and p represent the model and prototype respectively and λ is the scaling factor. The dimensionless numbers, which govern the flow of the liquid metal, are Re, Fr and We.

$$\text{Re} : \frac{\text{Inertia Force}}{\text{Viscous Force}} : \left(\frac{\rho_M UD}{\eta_M}\right)_m = \left(\frac{\rho_M UD}{\eta_M}\right)_p \tag{4.2}$$

$$\text{Fr} : \frac{\text{Inertia Force}}{\text{Gravitational Force}} : \left(\frac{U^2}{gD}\right)_m = \left(\frac{U^2}{gD}\right)_p \tag{4.3}$$

$$\text{We} : \frac{\text{Inertia Force}}{\text{Surface Tension}} : \left(\frac{\rho_M U^2 D}{\gamma_{MA}}\right)_m = \left(\frac{\rho_M U^2 D}{\gamma_{MA}}\right)_p \tag{4.4}$$

It can be seen that there is a parameter in Equations 4.1 to 4.4 represents the length of the system, which is called the "characteristic length of the system". The characteristic length is a length scale of the system that is able to describe the size of the system. Also, the characteristic length is usually defined as a length scale that is perpendicular to the fluid flow. Since the proposed gas jets of the prototype would be installed in the end wall of the vessel parallel to the axial direction, the characteristic length was defined as the diameter of the vessel. Movement of slag was found in preliminary studies to be determined by the surface movement of the liquid metal, therefore the characteristic velocity was defined as the velocity of the metal surface. It is worth mentioning that the surface velocity was found not uniform. Therefore, the characteristic velocity of the liquid metal surface of the prototype defined here cannot be represented by a single value. However, since the surface velocity was created by the gas flow from the jet and relates to the momentum and the orientation of the gas jet, it was assumed that the velocity on the liquid metal surface can be characterized by the velocity of the gas exiting the jet. However, the relationship between the gas jet velocity and the liquid metal surface velocity is beyond the scope of this work and will not be discussed further.

For practical and economic reasons, water was selected to be used in the cold model to represent the liquid metal in the prototype. To satisfy Froude criteria and using Equation 4.1, Equation 4.3 becomes,

$$(U)_p = \sqrt{\lambda}\,(U)_m \qquad (4.5)$$

In order to satisfy Froude and Reynolds criteria simultaneously, Equations 4.1 and 4.5 is substituted into Equation 4.2 and the following relation is obtained.

$$\left(\frac{\rho}{\eta}\right)_m = \lambda^{3/2}\left(\frac{\rho}{\eta}\right)_p \qquad (4.6)$$

Density and viscosity of water at 20 °C are 1000 kg/m^3 and 1x10^{-3} Pa s, respectively. By substituting properties of molten copper as shown in Table 4.1 and properties of water into Equation 4.6, it was found that the scaling factor is about three. This means that the size of the model must be three times greater than the size of the prototype in order to satisfy both Froude and Reynolds criteria. However, further analysis of the three dimensionless numbers using typical properties of molten copper presented in Table 4.1 and with a characteristic length of 1 m and characteristic velocity of 1 ms^{-1} revealed that inertia force in the prototype was about two million times greater than viscous force and ten thousand times greater than the surface tension.

$$Re : \frac{\text{Inertia Force}}{\text{Viscous Force}} = 2 \times 10^{6}$$

$$Fr : \frac{\text{Inertia Force}}{\text{Gravitational Force}} = 1 \times 10^{-1}$$

$$We : \frac{\text{Inertia Force}}{\text{Surface Tension}} = 1 \times 10^{4}$$

Therefore, the flow in the prototype is dominated by inertial forces and gravitational force rather than viscous forces or surface tensions and consideration of Re and We can be omitted without significant error. Thus Fr governs the dynamic similarity of the underlying liquid. The surface velocity of the underlying liquid in model and the prototype are related as follows:

$$(U)_p = \sqrt{\lambda}\,(U)_m \tag{4.7}$$

4.1.2.2 Slag

As mentioned in Section 3.3.1, slag in a furnace can be classified as "detached" or "attached" slag. The movement of the detached slag was solely determined by the underlying liquid metal surface circulation. Therefore, it was not necessary to consider the similarity of the detached slag once the similarities of the underlying liquid metal were satisfied. Thus, the discussion presented below is for attached slag only. In the rest of this chapter, slag refers to the attached slag in the prototype.

The slag in the prototype does not necessarily cover the whole liquid metal surface. However, from the discussion in Section 3.3.2, the slag in a cylindrical furnace in the copper industries is mainly distributed at the two ends of the furnace as shown in Figure 4.1. Therefore, the characteristic length of the slag was also defined as the diameter of the furnace and the geometric similarity of the slag was automatically satisfied once the geometric similarity of the liquid metal was established.

Similar to the liquid metal system, the dynamic similarity consideration was based on Re, Fr and We numbers. The characteristic velocity was taken as the velocity of the slag at the slag/underlying liquid metal interface. As a starting point, a no slip condition was assumed at the slag/ liquid metal interface and the characteristic velocity of the slag was taken same as for the liquid metal system.

In order to successfully simulate the behavior of slag in the prototype, the properties of material used to represent the slag in the model are crucial. Based on the consideration of the three dimensionless numbers and using Equations 4.1 and 4.7, the material must have physical properties that satisfy the following relationships:

$$\left(\frac{\rho_S}{\gamma_{SA}}\right)_m = \lambda^2\left(\frac{\rho_S}{\gamma_{SA}}\right)_p \tag{4.8}$$

$$\left(\frac{\rho_S}{\eta_S}\right)_m = \lambda^{3/2}\left(\frac{\rho_S}{\eta_S}\right)_p \tag{4.9}$$

One of the factors governing the movement of slag under the influence of underlying liquid metal surface circulation in the prototype is the wetting of the slag on the refractory and on the liquid metal surface. In order to stimulate the movement of the slag in the prototype by a cold model, the wetting of the material representing the slag in the model on the wall of the model and on the underlying liquid must be similar to the one in the prototype. The similarity of the wetting behavior is governed by the Bond number since the wetting here is manifested by the rise of the slag/refractory/air triple point up the interior wall of the vessel:

$$\text{Bo}: \frac{\text{Gravitational force}}{\text{Surface tension}} = \frac{\rho g D^2}{\gamma} \tag{4.7}$$

Thus, in order to achieve similarity of the wetting behavior, the choices of material to construct the model and the fluid to represent the slag must be chosen that the following two relationships are satisfied.

$$\left(\frac{\rho_S}{\gamma_{SW}}\right)_m = \lambda^2\left(\frac{\rho_S}{\gamma_{SW}}\right)_p \tag{4.10}$$

$$\left(\frac{\rho_S}{\gamma_{SM}}\right)_m = \lambda^2\left(\frac{\rho_S}{\gamma_{SM}}\right)_p \tag{4.11}$$

Finally, it can be seen that several similarity criteria, Equation 4.8 to 4.11, related to the physical properties of the slag needed to be satisfied. It is simpler to first select the material of the fluid representing the slag in the model. Then, the scaling factor can be determined from these similarity criteria. The size of the model to be constructed can be evaluated using Equation 4.1.

5 EXPERIMENTATION

The objective of the experiments was to visualize the movement of the slag during skimming in order to gain a better insight of the process. Different from the direct simulation of the prototype, the similarity criteria required for the present purpose were relaxed. However, material to be used representing the slag and the material of construction of the model were selected carefully in order to reflect the characteristics of the slag and the furnace.

5.1 Materials Selection

5.1.1 Slag in the Model

The material to be used in the model to represent the slag in the prototype had to satisfy the following four criteria:

1. The density of the material must be less than that of water since it must float on water, which was used to simulate the liquid metal.
2. The material must be liquid at room temperature.
3. The material must be immiscible with water.
4. The material must wet the wall of the model.

After reviewing the physical properties of about 200 common liquids, it was decided to use 1-decanol to represent the slag. As can be seen from the physical properties of 1-decanol presented in Table 5.1, 1-decanol satisfied the first three criteria listed above. The forth criterion depended on the material of construction of the model.

Therefore, the material to be used in construction of the model was selected based on the last of the four criteria above.

Table 5.1: Physical properties of 1-decanol [21]

Property	1-decanol
Molecular formula	$CH_3(CH_2)_8CH_2OH$
Molecular weight	158.28 g/mole
Melting point	6.9 °C
Boiling point	231.1 °C
Density	829.7 kg/m^3
Surface tension	28.51 x 10^{-3} N/m
Viscosity	10.9 x 10^{-3} Pa s
Solubility in water	Insoluble

5.1.2 Material of Construction of the Model

In order to stimulate skimming in a physical model, the material representing the slag must wet on the material of construction of the model. Since 1-decanol has been selected to represent the slag, the material of construction was selected based on its wetting by 1-decanol.

It was found that when a drop of 1-decanol was put on the horizontal surface of an acrylic sample (Plexiglas MC acrylic sheet manufactured by Atohaas), it spread quickly on the surface. Ultimately the thickness of the droplet was almost negligible.

Another test was performed to demonstrate the wetting behavior of a 1-decanol droplet, while floating on water surface, on a vertical surface of the acrylic. It was observed that the 1-decaonl droplet spread spontaneously on the sample. Figure 5.1 illustrates the evolution of the 1-decaonl droplet once it contacted the acrylic sample. The border of the droplet was manually highlighted for easier visualization.

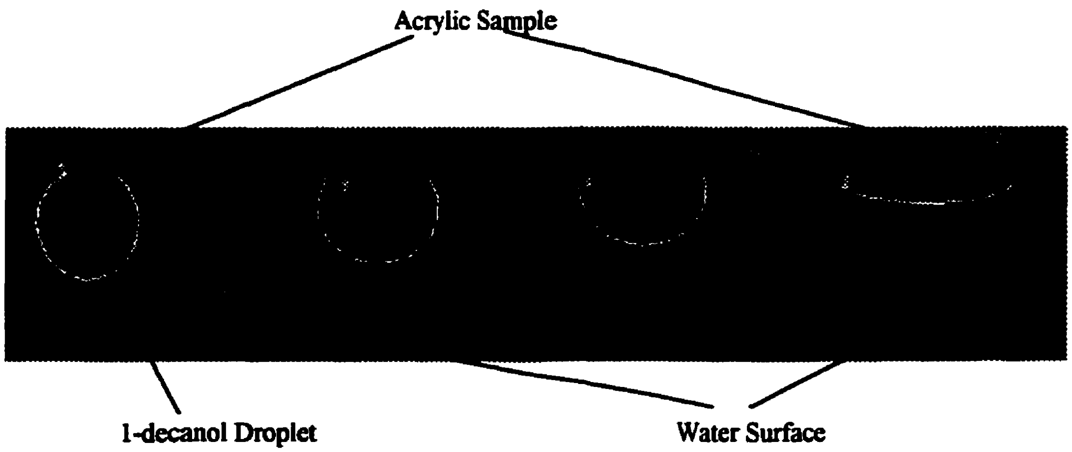


Figure 5.1 Spreading of 1-decanol on Acrylic (Plan View)

In order to ensure that the acrylic/water/1-decanol triple point was similar to that in the copper production furnace, the 1-decanol/water interface profile at a partially submerged vertical acrylic surface was studied. The 1-decaonl/water interface at the acrylic surface is shown in Figure 5.2. As can be seen from the figure, the contact angle of the 1-decanol/water interface on a vertical acrylic surface was greater than 90°. This profile is similar to the one discussed in Section 2.3.1.1 of the slag/underlying liquid metal wetting profile on the refractory. Therefore, it was concluded that the combination of 1-decanol and acrylic was able to reproduce the wetting behavior of the slag in a furnace.

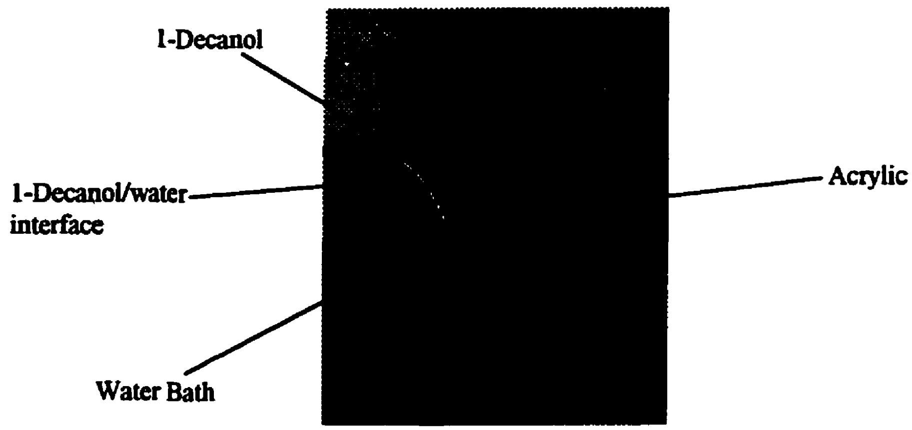


Figure 5.2 Wetting Profile of 1-decanol/Water Interface on Acrylic (Side View)

5.2 Experimental Setup

5.2.1 Fluid Container

Experiments were performed with a model constructed with acrylic (Plexiglas MC acrylic sheet manufactured by Atohaas with thickness of 6mm). The model was rectangular in shape with dimensions as illustrated in Figure 5.3 which represent roughly at 1/12 scale factor if a standard 3.4m x 12m copper anode furnace was taken as the prototype. In order to reproduce the geometric characteristic of a rotary cylindrical furnace, the width to length ratio of the model was set to be kept the same as the diameter to length ratio of a typical furnace, about 11: 40.

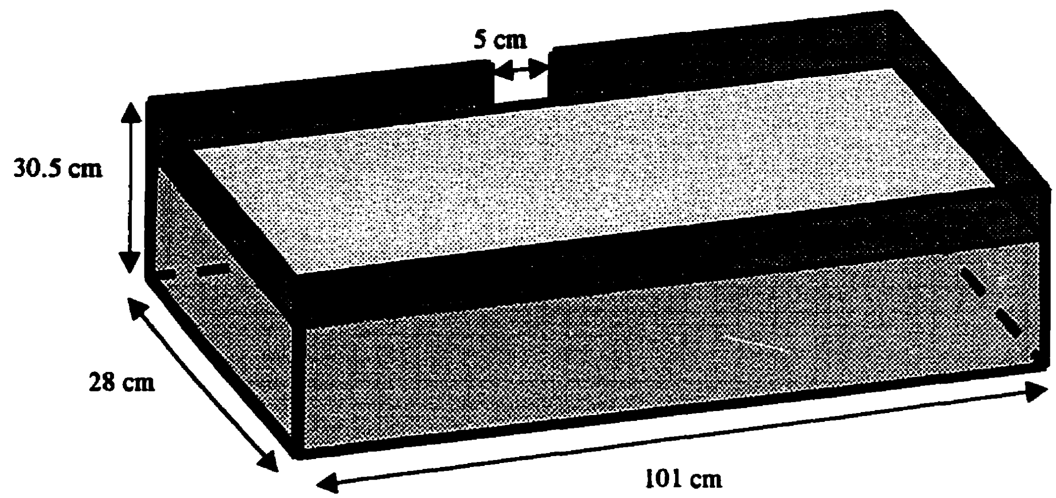


Figure 5.3 Dimensions of the Physical Model

The most noticeable difference between the model and the prototype is the shape of the underlying liquid pool. The prototype is in the shape of a partially filled horizontal cylinder while the model tank is a rectangular box.

The motion of the slag, which floats on the underlying liquid bath, is a result of the movement of the bath surface. Therefore, attention was focused on the underlying liquid/slag interface only and the shape of the bottom of the liquid pool was not simulated. Moreover, the overflow of the slag at the skimming lip of the vessel is a result of the movement of the slag at the bath surface. Only a thin layer of the underlying liquid pool at the surface is affected by the overflow of slag. The bottom of the bath is effectively stationary. It was believed that the overflow of slag across the skimming lip was independent on the shape of underlying liquid pool. Therefore, the present shape of the model tank did not affect the overflow of slag across the skimming lip.

5.2.2 Model Operation Mechanism

The modeling tank was supported by a flat wood platform. The platform was supported by three screws. The three screws formed a triangle with its base parallel to the front edge of the platform and vertex close to the rear edge. By adjusting the two screws at the front of the platform, the water level in the tank could be set parallel to the bottom of the skimming month. The tank was tilted by adjusting the screw at rear. A stopper was put at the front edge to prevent the tank from sliding down when the platform was tilted.

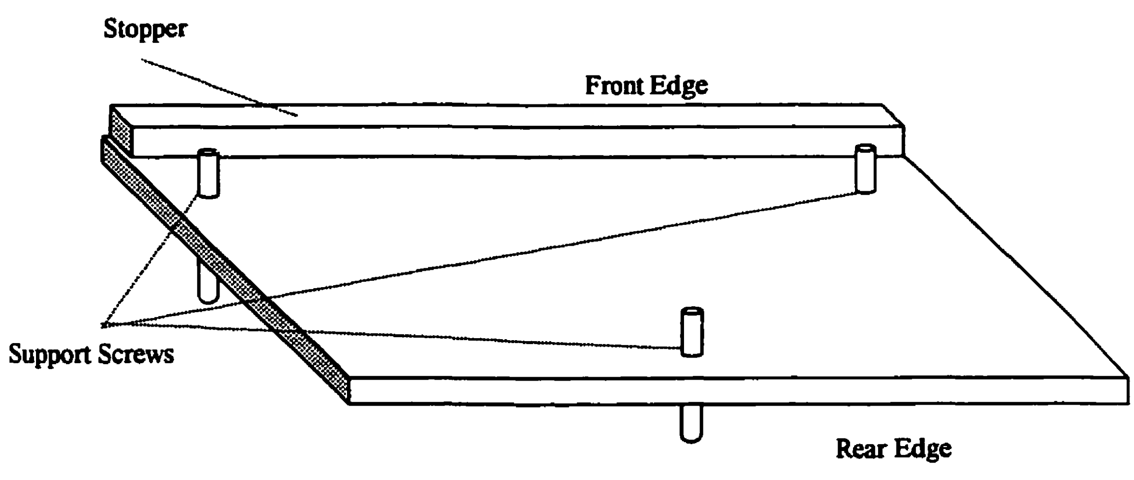


Figure 5.4 Schematic Representation of the Supporting Platform

The jets used in experiments were galvanized steel circular pipe; inner diameter of 1 cm, with length of 12.7 cm. The jets were supported by stands and clamps sitting on the platform. The jets were orientated parallel to the front edge of the tank, at 50° with respect to the horizontal water surface and with the outlet 8 cm above the water surface. A Tee joint split the compressed air supply into two streams. In each stream, the compressed air was directed to a calibrated rotameter then to the jet by PVC tubing. A valve was installed in each stream at the exit of the Tee joint. The valves were carefully adjusted in each experiment to ensure the flow rates as shown by the rotameters in each jets were at the desired level, which was 7×10^{-4} m^3/s (STP). This flowrate was chosen because it was found the movement generated on the water surface was able to carry the 1-decanol to the skimming lip without creating significant wave motion on the water surface.

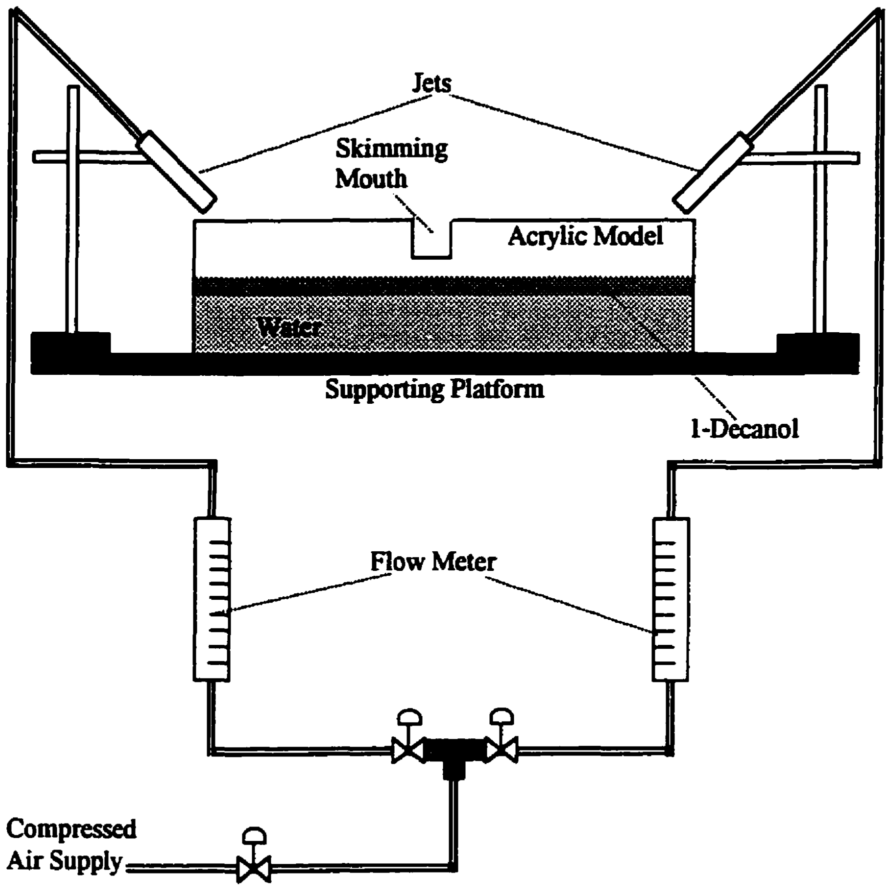


Figure 5.5 Schematic Diagram of the Gas Flow System in the Experimental Set Up

5.3 Experimental Procedure

Experiments were carried out in pairs as follows. The first of the experiment pairs was performed without the gas flowing from the jets. The procedure was as follows. A known amount of 1-decanol was charged to the tank. The tank was left undistributed for about 30 minutes to allow the 1-decanol to stabilize and distribute itself around the inside of the apparatus to its steady state shape. At the start of an experiment, the tank was tilted by slowly turning adjustable screw threaded mounts on one side of the apparatus supporting plate until water was seen to just start to overflow the skimming mouth as well as 1-decanol. At that instant, the screws were turned back just enough to stop water overflow. Thereafter, 1-decanol floating on the water surface continued to overflow. The amount of 1-decanol collected was recorded at regular time intervals.

In the second of the experiment pairs, skimming of 1-decanol under the influence of the action of the gas jet and by the tilting of the tank was studied. The procedure was as follows. All 1-decanol collected at the end of the first experiment was recharged into the model and the tank was again allowed to stabilize for 30 minutes. Compressed air was then first supplied to the jets, creating a circulation of the water surface before the model was tilted. The amount of tilting during skimming was adjusted to be as close as possible to the first of the experiment pairs. The amount of 1-decanol collected was again recorded at regular time intervals and compared with the result obtained from the first part of the experiment pairs. Four sets of pairs were performed and represented four repeats of skimming without gas jetting and with gas jetting at a jet velocity of 9 ms^{-1}. No other conditions were examined because the objective of the experiments was to gain a better insight of the skimming process rather than to investigate the effect of the specification and orientation of the gas jets on the skimming effectiveness.

6 EXPERIMENTAL RESULTS

6.1 Preliminary Experiments

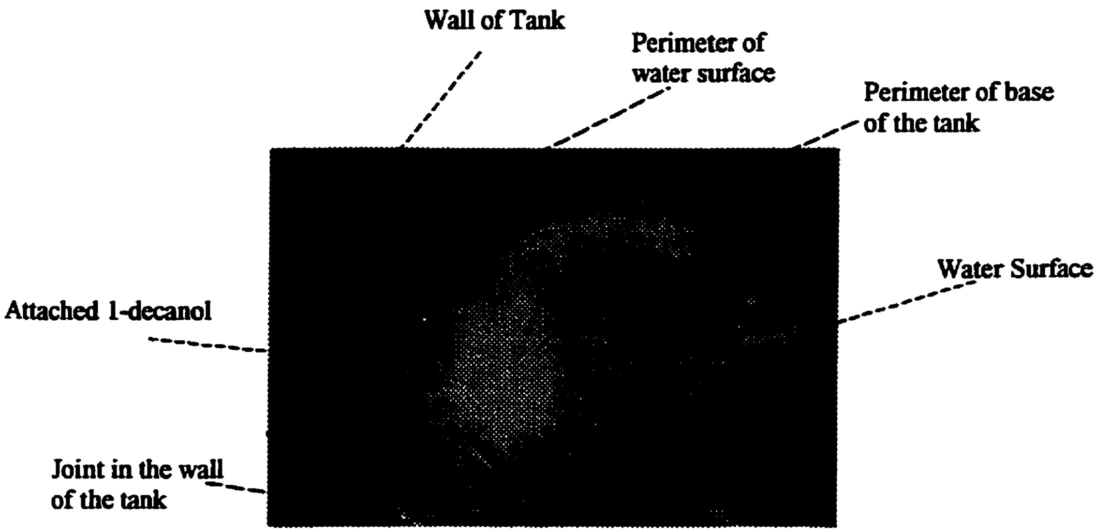
Preliminary experiments were performed to examine the movement of slag on a moving liquid bath surface. Different methods of gas injection to create the surface movement were studied. Experiments were carried out in a cylindrical tank filled with water. About 20 ml of 1-decanol was charged into the tank along the wall to form an attached pool representing an attached slag. The water surface was set into motion by submerged gas injection and by impinging compressed air on the water surface. The movement of the 1-decanol on the water surface was visually observed.

6.1.1 Submerged Gas Injection

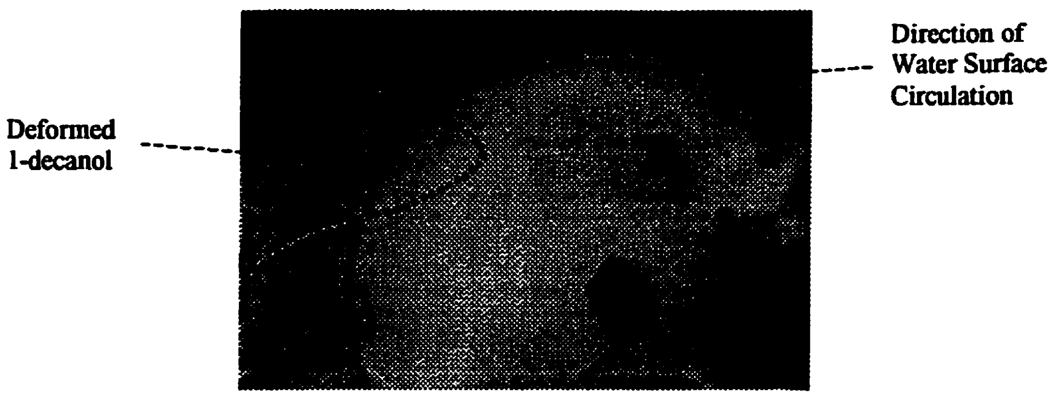
In these experiments, compressed air with flowrate of 7×10^{-4} m^3/s (STP) was injected into the water bath at 5 cm below the attached slag via a steel pipe (I.D. 0.01m). It was observed that as air was injected into the water bath, bubbles formed at the point of injection, rose and collapsed at the water surface. The attached slag broke into many pieces of detached slag immediately. Some 1-decanol remained in contact with the wall throughout the test. The movement of the detached slag was mainly in vertical direction due to the waves. The rate of advancement in horizontal direction was small and the direction of advancement was disordered. Some of the 1-decanol that was detached reattached when it came back in contact with the wall at another point. But mostly, it was found that the slag carried by the wavy surface did not reach the wall again because the waves reflected from the wall moved the 1-decanol back into the center of the bath once it came close to the wall. For slag able to reach the wall, the position was inconsistent. It was clear that the reflection of waves from the wall interfered with the waves generated by the collapsing bubbles and produced a neither consistent nor predictable circulation pattern on the water surface.

6.1.2 Impinging Gas Jet

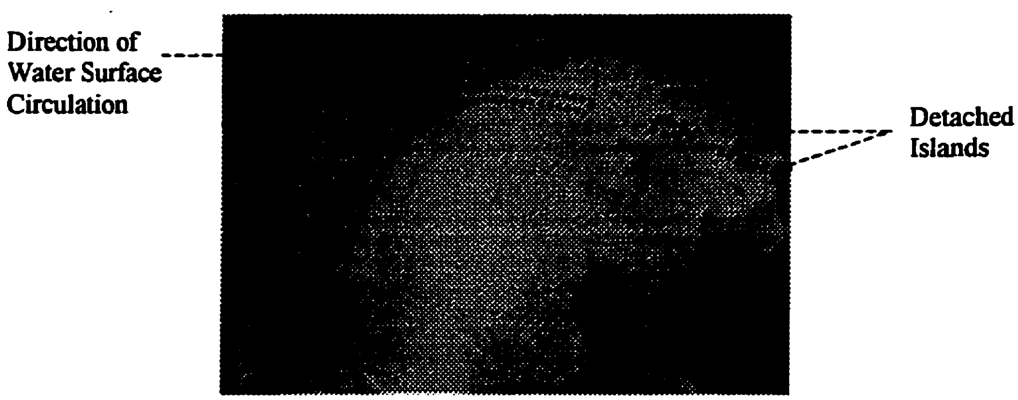
In these experiments, the water surface movement was created by an impinging gas jet in glancing contact with the surface. The water surface was found to remain calm throughout the experiment. The direction of circulation could be easily controlled by the orientation of the jet. It was observed that the 1-decanol pool started to deform as soon as the water surface started to move. The attached 1-decanol pool extended along the path of the water surface circulation. At some point, the attached 1-decanol broke up to form several detached 1-decanol islands. These detached islands continued to advance with the water movement. As the water surface circulation continued, more 1-decanol was drawn with the water surface flow and was detached from the wall. This cycle continued until the attached 1-decanol became quite small. This small piece of attached 1-decanol could only be extended slightly and remained stationary despite of the movement of the underlying water circulation. A series of pictures are presented in Figure 6.1 to demonstrate the evolution of the attached 1-decanol. The border of the 1-decanol was outlined for easier visualization.



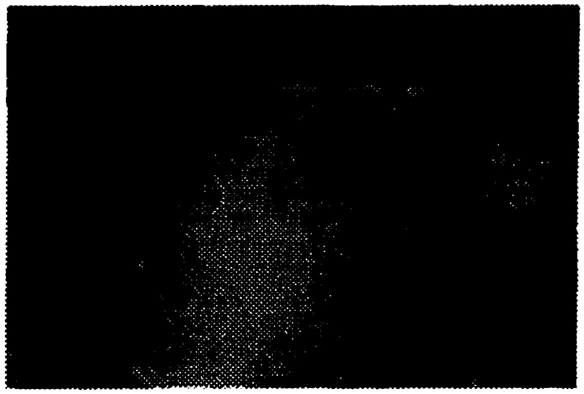
(a) Initial distribution of the 1-decanol



(b) Deformation of 1-decanol by water surface circulation

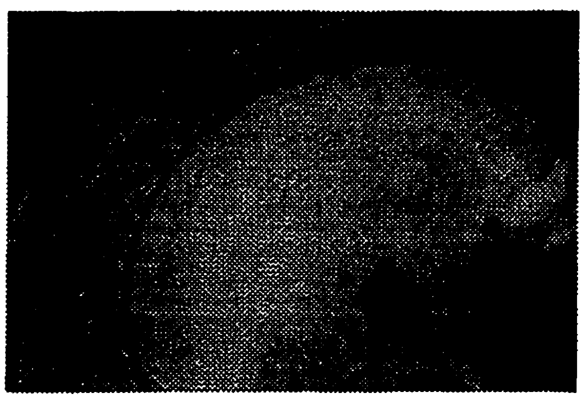


(c) Breakage of attached 1-decanol to form detached islands



(d) Continue deformation of remaining attached 1-decanol after breakage

(e) Second breakage of the attached 1-decanol



(f) Final distribution of 1-decanol

Figure 6.1 Evolution of Attached 1-decanol with Underlying Water Surface Circulation

6.2 Movement of 1-decanol in the Modeling Tank

Experiments were performed to investigate the circulation pattern generated by impinging gas jet in the modeling tank. Experiments were carried out with the apparatus described in Section 5.2. When the 1-decanol was charged into the tank, it spread quickly along the wall. After stabilization, the 1-decanol was mainly distributed at the two end of the tank.

Water surface movement was created by the jet configuration as shown in Figure 6.2 and flowrate of air from each jet was 7×10^{-4} m^3/s. The circulation pattern on the water surface was observed. It was found that this jet configuration was able to produce the desired circulation pattern on the water surface as discussed in Section 3.3.4.3, which was the left side of the underlying liquid surface circulating in an anti clockwise direction while the right side circulated in a clockwise direction with the center of the skimming mouth as the dividing line. However, there were two major dead zones at the both front corners of the tank as shown in Figure 6.2. The 1-decaonl located at these dead zones were not be deformed and transported by the water surface circulation.

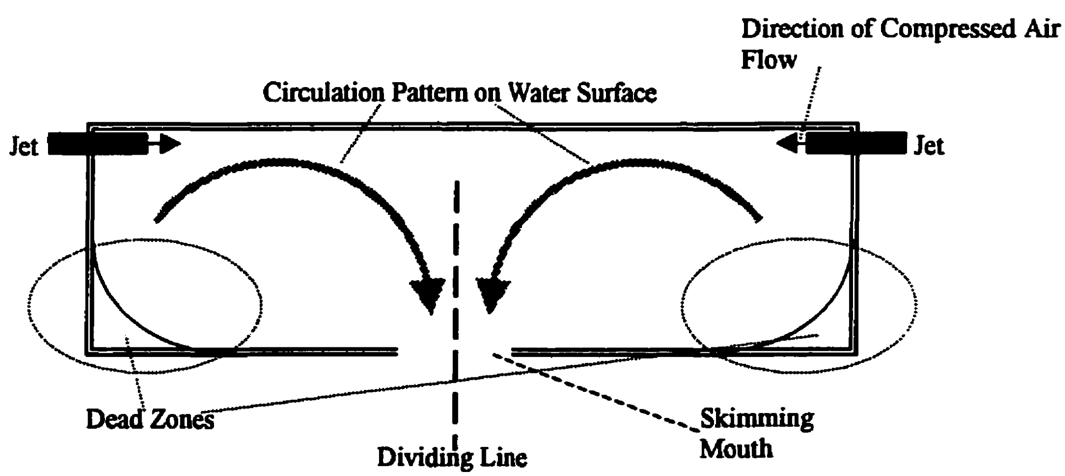


Figure 6.2 Dead Zones on Water Surface

It should be obvious that installing more jets along the wall of the tank could further reduce the dead zones, but an alternative method to minimize the dead zone was to increase of the flow rate of the gas jet. However, it was observed that as the flow rate increased, the water surface became unstable. Waves were generated. As discussed in Section 3.3.4.1.1 and observed in the preliminary experiments, a wavy surface is not an effective way to carry the slag to the skimming mouth. Therefore, subsequent experiments were performed with minimal wave motion on the water surface, and a jet flow rate of $7x10^{-4}$ m^3/s (STP) from both jets, which equivalent to a jet Re at the jet exit of 6100, was used.

It was also observed that the 1-decanol deformed along the centerline when it was leaving the rear wall. As the deformed 1-decanol approaching the skimming mouth, the direction of flow was unstable. Quite often it deviated from the centerline and moved away from the skimming mouth when it reached the front wall. This was due to the fact that movement of the 1-decanol close to the skimming mouth was sensitive to the air currents that passed over the water surface in the tank. In the region close to the skimming mouth, the force that was required to deflect the movement of the 1-decanol was small. A weak air current parallel to the front wall was being sufficient to deflect the 1-decanol from the centerline and causing the 1-decanol to move away from the skimming mouth. Since it was desired that the 1-decanol always reached the front wall at the skimming mouth, it is necessary to increase the momentum of the underlying water circulation in the direction of the mouth. The solution that employed in the following experiments was to install an additional jet pointing parallel to the model short axis at the middle of the skimming mouth as shown in Figure 6.3. The additional jet also inclined at

50° with respect to the horizontal water surface and passing air at a rate of 7×10^{-4} m^3/s giving the same Re as the two rear jets.

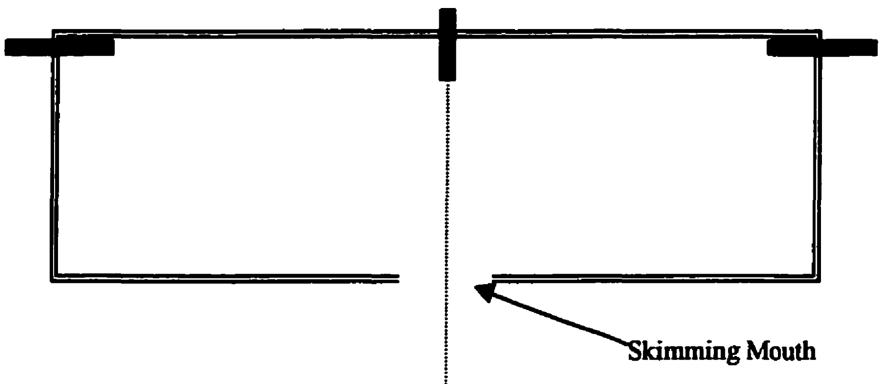


Figure 6.3 Configuration of Jets in Skimming Experiments (Plan View)

With the jet configuration as shown in Figure 6.3, the momentum of the water surface circulation when approaching the front wall was increased without generating significant wave motion on the water surface. After the installation of the center jet, it was observed that the movement of 1-decanol was much less sensitive to the surrounding air currents and consistently reached the front wall in the skimming mouth region.

6.3 Skimming Experiments

Skimming experiments were carried out in pairs, with and without jets. As will be discussed below, it was observed that the skimming of 1-decanol did not stop throughout the experiment. However, the skimming rate became quite small when the experiments proceeded towards the end. Another observation was that the initially high skimming rate decreased rapidly as the experiment proceeded when gas jets were used. After a certain time, it was found that the skimming rate was the same with or without jets. Since the goal of the experiments was to investigate the improvement of the skimming effectiveness with the assistance of the jets using the unassisted one as a point of reference, it was decided to use the time at which the skimming rate of both cases were identical as the point of comparison instead of using an arbitrary chosen cut-off time. The overall skimming efficiency was quantified by averaging the rate of 1-decanol being skimmed up to the comparison point. The extent of skimming is reported here as the fraction of the originally charged 1-decanol removed from the tank up to the comparison point.

6.3.1 Skimming Efficiency

A plot of the instantaneous skimming rate verses time is presented in Figure 6.4. In the plot, the data points corresponded to the average value obtained from four replications of the skimming experiments. The error bar represented the 95% confidence interval of the average values. As can be seen from the graph, in both cases, the initial skimming rates were highest as compared with the rest of the data. Also, the skimming rate decreased gradually. However, the skimming rate was initially higher and decreased more rapidly in the case of skimming with gas jets. As can be seen from the graph, the skimming rate when jets were used reduced to same as that for skimming without jet in 10 minutes. After this point, the skimming rates of the both cases were statistically indistinguishable. Therefore, this point was taken as the point of comparison of the skimming effectiveness. It was found that the when gas jets were used the average skimming rate was 40 ml/min ± 6 ml/min in comparison to 9 ml/min ± 2 ml/min when no jet was used.

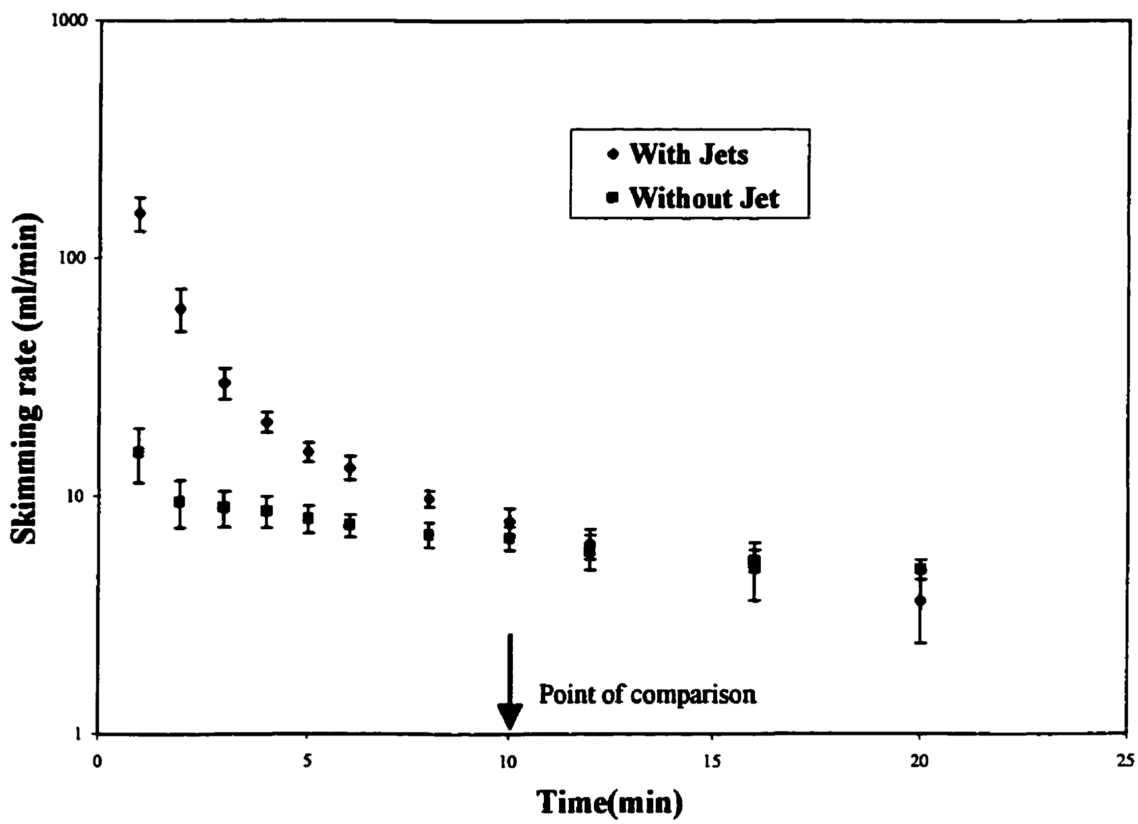


Figure 6.4 Comparison of Skimming Rate

6.3.2 Extent of Skimming

In this section, the extent of skimming is compared. A plot of the fraction of the originally charged 1-decanol skimmed versus time is presented in Figure 6.5. As can be seen from the graph up to the point of comparison, about 70% of 1-decanol was removed using jets but only 20% of the 1-decanol was skimmed without jets. A closer examination revealed that in only the first minute, about 30% of 1-decanol was skimmed with jets in comparison to about 4% without jets. The improvement of the extent of skimming with jets was found mainly due to the significantly improved initial skimming rate.

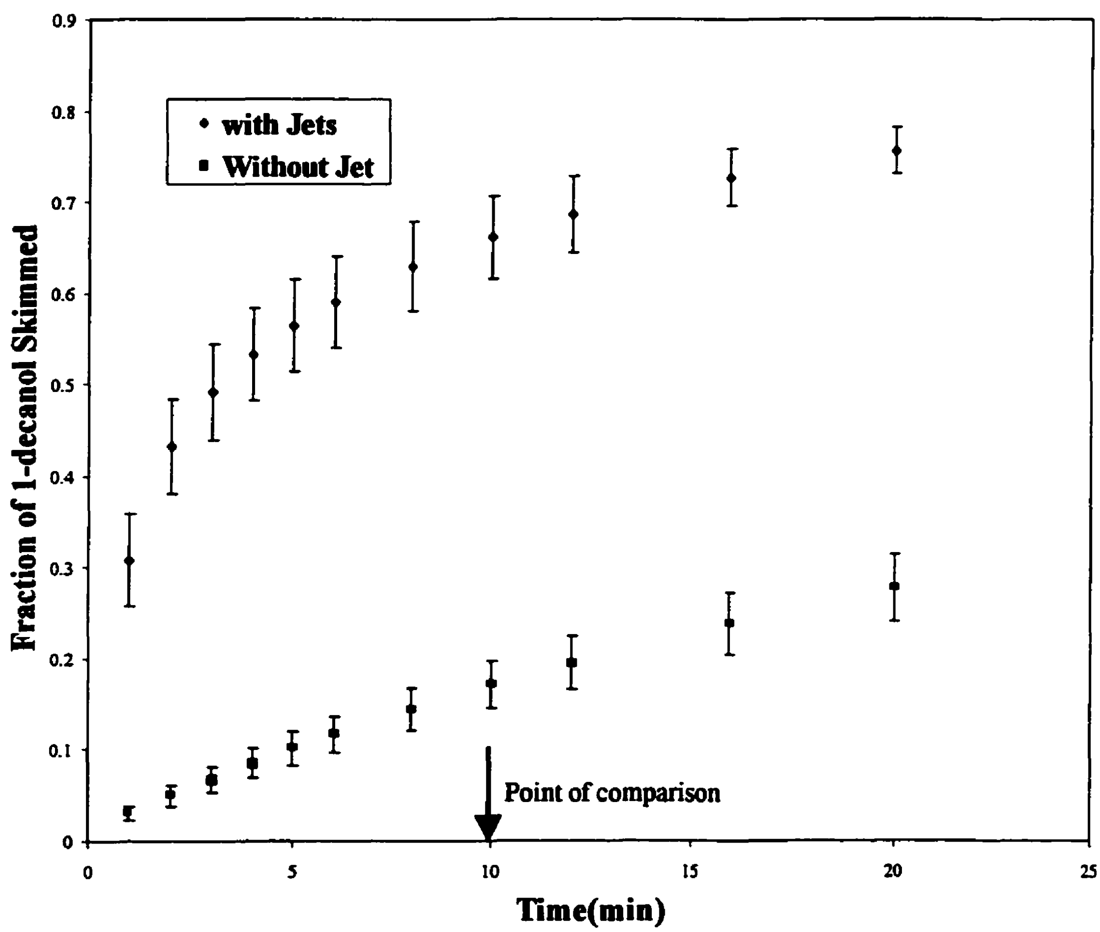


Figure 6.5 Comparison of Extent of Skimming

7. DISCUSSION

7.1 Structure of the Chapter

In this chapter, the causes of the observed enhancement of skimming effectiveness are discussed and some methods to further improve the skimming effectiveness are presented.

The discussion of the improvement of the skimming effectiveness is divided into a discussion of the enhancement of the transportation step and of the removal step.

The discussion of the enhancement of the transportation step is further sub-divided into a discussion of:

- The transportation efficiency: the rate of slag being carried to the skimming lip.
- The extent of transportation: the completeness of separating the attached slag from the wall by the underlying liquid surface circulation.

Discussion about the improvement of the removal step focuses on the increase of driving force for slag removal with the presence of the gas jets and methods to further enhance the driving force for removal based on observations in the experiments.

7.2 Transportation of Slag by Bath Surface Circulation

There are two types of flow that may occur in the slag transportation step, creeping flow along the wall and externally assisted flow (Section 3.3). In this section, discussion focuses on the effectiveness of slag transportation by underlying liquid bath surface circulation as a result of the gas jetting. Also, the efficiency of carrying slag to the skimming lip by the surface motion generated by submerged gas injection and impinging gas stream are compared. Finally, the limitation on separating the attached slag from the furnace wall by surface circulation is discussed.

7.2.1 Efficiency of Transportation

A key factor that determines the efficiency of slag transportation by underlying liquid bath surface movement is the controllability of the circulation pattern. The goal of creating the surface motion is to move the slag to a specific location, i.e. the skimming lip. The transportation efficiency cannot be high if the liquid surface moves randomly. As observed in the preliminary experiments, the surface motion of the underlying liquid bath was highly disordered when submerged gas injection was employed to create the motion. The random motion of the bath surface failed to carry the slag to a specific location. The amount of slag that could be moved to the skimming lip relied on chance more than the design of the gas injection system.

Moreover, submerged gas injection generates waves on the bath surface. The wavy motion reduces the rate of the advancement of the slag in horizontal direction. Also, with a wavy surface, the level of the bath surface vibrates vertically at the wall. Therefore, the position of the skimming lip must be maintained at a level at least as high as the crest of the wave in order to avoid the loss of valuable material. Slag can only be rapidly skimmed when it arrives the skimming lip at the moment of the bath surface at the wall is at its maximum level. In order to gain benefit from submerged gas injection, there has to be back and forth manually controlled rotation of the furnace such that the lip is at the lowest reasonable level without excessive melt carry over when slag arrives at the lip. Thus, the operator needs to visually monitor the motion of the slag on the metal bath surface via the skimming mouth and lower the skimming lip to allow the slag approaching the lip to overflow. Consequently, the skimming effectiveness heavily depends on the skill of the operator and may vary significantly from batch to batch.

As observed in the present experiments, the surface circulation generated by impinging gas jet was highly controllable. By altering the configuration and orientation of the jets, the circulation pattern generated can be easily modified to cope with the design of the furnace and hence direct the slag to the skimming lip. Also, wave generation is minimal, i.e., the skimming process can be operated with a calm bath surface, and expense and variability associated with the human factor can be minimized.

7.2.2 Limitation on the Extent of Transportation

In the experiments, it was observed that the water surface circulation could transport the 1-decanol very effectively to the skimming lip. Most of the 1-decanol originally distributed at the two ends of the tank was carried to the lip. However, as the experiment proceeded, the rate of 1-decanol reaching the lip decreased. Eventually, the 1-decanol along the wall was found not be transported to the lip despite the water surface circulating. An explanation of this is as follows.

As discussed in Section 3.3.4.2, the underlying liquid surface circulation induced a shear force at the bottom of the attached slag. The magnitude of the shear force experienced by the slag was directly proportional to the contact area between the slag and the underlying liquid. As the attached slag was continuously skimmed, the contact area between the slag and the bath continuously decreased. Even though the shear stress induced on the attached slag remained relatively constant, the shear force experienced by the slag decreased. Eventually, the shear force was not enough to overcome the surface tension of the slag and the slag remained stationary and attached to the wall.

Moreover, because of "no-slip" at the metal/wall interface, there is a stagnant region at the wall in the bath. As a result, the slag close to the wall can not be sheared by the bath surface circulation.

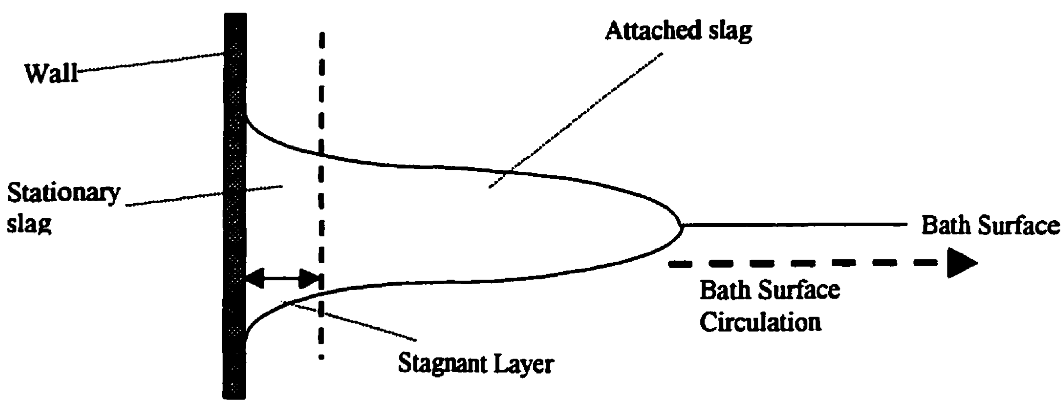


Figure 7.1 Illustration of Stationary Slag at the Wall

Increasing the strength of the bath surface circulation can reduce the thickness of the stagnant layer. However, it cannot be completely eliminated. Moreover, the increase of the bath surface circulation strength implies the increase of the flowrate of the gas jets. As observed in the experiments, an increase of the flowrate of the gas jets generated waves on the water surface. The wavy motion on the water surface resulted in an uncontrollable circulation pattern, which was against the primary goal of the installation of the jets. The presence of the stagnant layer limited the completeness of separating the attached slag from the wall and hence limited the completeness of transporting attached slag to the skimming lip by bath surface circulation.

Even though underlying liquid surface circulation would fail to completely detach slag from the wall of the furnace, the attached slag is transported to the lip by creep along the wall. If the slag at the lip is continuously removed, the creeping of attached slag along the wall continues until almost all slag is skimmed. The rate of transport along the wall depends on the rate of removal at the lip. However, the transportation efficiency is expected to be small in comparison to the one induced by external assistance.

7.3 Removal of Slag

The flow of slag across the lip occurred only when the driving force for flow exceeded the resisting force. It was found that the driving force was improved with the proper configuration of the gas jets. Also, by continuous rotation of the furnace, the high initial skimming rate can be maintained through out the process, though this was not tested here as there was no mechanism to do this.

7.3.1 Enhancement of Slag Removal by Gas Jet

The installation of the jets was primarily for the transportation of the slag. However, if the role of the jets was only to carry the slag to the lip, the initial skimming rate with or without the assistance from the jets would expected to be similar but the duration of the initial skimming rate without jets would have been extended by the presence of the jets. Experimental results revealed that the initial skimming rate with the assistance from the jets was significantly increased. Thus, on top of transporting the slag to the skimming lip, the gas jets played another important role, which was to enhance the flow of the slag across the lip.

7.3.1.1 Role of the Center Jet

As the gas flow from the center jet exiting the skimming mouth, the free surface of the 1-decanol pool located at the skimming mouth experienced a shear force as shown in Figure 7.2.

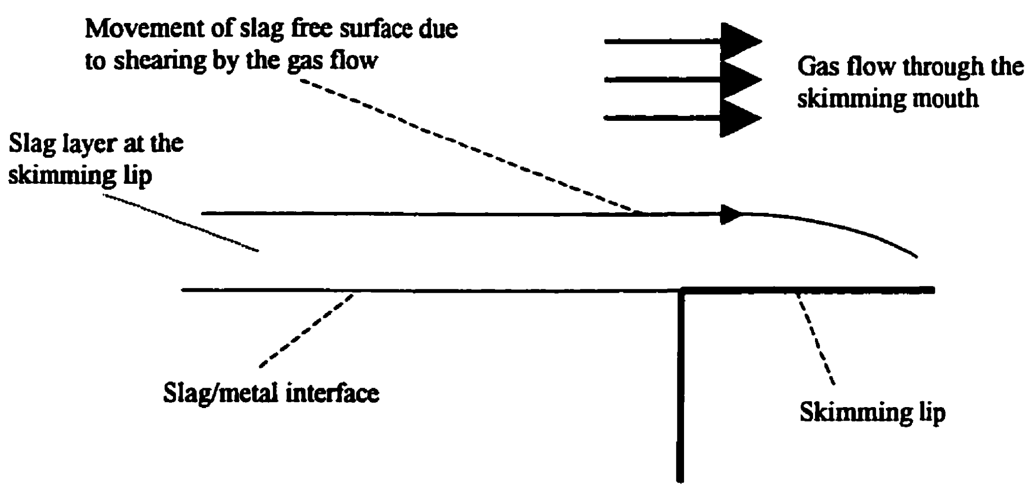


Figure 7.2 Enhancement of Slag Overflow by Gas Jet

On top of the driving forces available when no jet was used, the slag in front of the skimming lip was driven by the shearing due to the gas flow from the center jet to move across the lip faster. Furthermore, the shearing of the slag was an additional driving force that caused the slag to flow across the skimming lip.

As is discussed below, the underlying liquid bath level decreased continuously as the skimming process proceeded. This reduction of bath level resulted in a decrease of the hydrostatic head driving the slag to flow across the skimming lip. With the additional driving force due to the gas flow from the center jet, the skimming process continued after the point when other driving forces were insufficient to cause the slag to overflow across the skimming lip. Thus the center jet not only increased the initial skimming rate but also sustained the skimming for longer as compared to skimming without the center jet.

7.3.1.2 Gas Requirement

In the experiments, the modeling tank was open to the atmosphere. The gas flow from the jets exited the tank from the top and through the mouth. The out flow through the top weakened the shearing on the slag layer at the skimming lip. In a prototype, the only opening through which the injected gas can leave is the skimming mouth. Due to this fact, the shearing effect on the slag layer at the skimming mouth is expected to be stronger in the prototype than observed in the experiments.

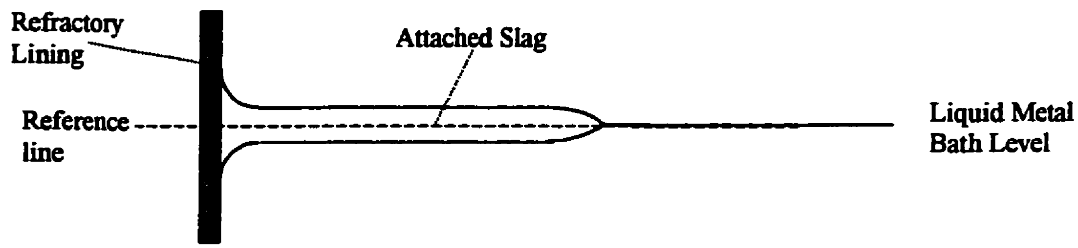
The ratio of the gas stream velocity (U) and the velocity of the liquid surface ($V_{surface}$) is same as the ratio of the liquid viscosity and the gas viscosity, Section 3.3.4.1.2, i.e.:

$$\frac{U}{V_{surface}} = \frac{\eta_{liquid}}{\eta_{gas}} \quad (3.1)$$

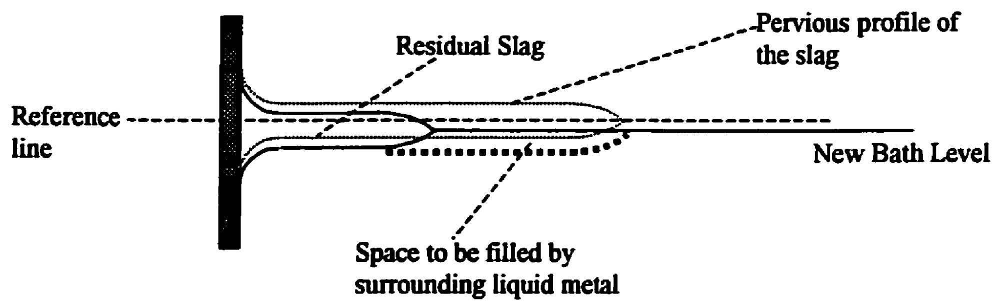
As observed in the experiments, the velocity of the water surface approaching the lip was of order of magnitude of 10^{-2} m/s. To generate a movement on the molten copper bath with a similar speed, the superficial gas velocity (U) through the skimming mouth could be estimated by putting the viscosity of molten copper ($\eta_{liquid} = 10^{-3}$ Pa s) and viscosity of air ($\eta_{gas} = 10^{-5}$ Pa s) into Equation 3.1 with $V_{surface} = 10^{-2}$ m/s. The speed of air passing through would need to be about 1 m/s. If it is assumed that the area of the skimming mouth is 1 m^2, the total gas flow rate required would be about 1 m^3/s.

7.3.2 Enhancement by Skimming Lip Position Control

The slag in a furnace floats on the underlying liquid metal bath because of its lower density than the liquid metal. However, part of the slag is submerged in the liquid metal bath. As some of the slag is removed, an empty space is created in the bath. The surrounding liquid metal fills up this empty space immediately as shown in Figure 7.3.



(a) Before part of slag is skimmed



(b) After part of slag is skimmed

Figure 7.3 Reduction of Bath Level

Thus, the level of the liquid metal bath continuously reduces as the skimming process proceeds. If the position of the skimming lip is kept constant throughout skimming, the reduction of the liquid metal bath level reduces the thickness of the slag above the lip, with the result that the hydrostatic head available to drive the slag to flow across the lip decreases as the skimming proceeds. The faster the slag being removed, the more rapid the bath level decreases and the more rapid the skimming rate decreases. Therefore, as observed in the experiments, the skimming rate decreased more rapidly when jets were used than when no jet was used.

7.3.2.1 Continuous Rotation of the Furnace

As mentioned above, a continuous reduction of skimming rate is due to the lowering of underlying liquid level as the slag is being skimmed. If the furnace is rotated continuously at the rate same as the underlying liquid level decreases, the relative position between the slag/underlying liquid interface and the edge of the skimming lip would be maintained the same as the beginning of the process. The high initial skimming rate as observed in the experiments could be maintained throughout the whole process.

For a certain volume V of slag skimmed, only a fraction of the volume is below the level of the liquid metal bath. Assuming the volume of slag submerged in the underlying liquid bath is V'. The ratio of V' and V is same as the density ratio of the slag and the underlying liquid.

$$\frac{V'}{V} = \frac{\rho_s}{\rho_m} \tag{7.1}$$

In order to fill up an empty space with volume V', the surrounding liquid level has to be decreased by Δh. V' and Δh is related by:

$$V' = A\Delta h \tag{7.2}$$

where A is the area of the bath surface.

Substituting Equation 7.2 into Equation 7.1, the following equation is obtained relating the mass of slag skimmed (M) and the reduction of liquid metal bath level (Δh).

$$\Delta h = \frac{1}{\rho_m A} M \tag{7.3}$$

Equation 7.3 allows calculation of the lowering of the skimming lip required to maintain the same relative position between the skimming lip and the slag/underlying liquid metal interface as at the beginning of the process.

In order to use Equation 7.3 to calculate the position of the skimming lip, the surface area of the liquid metal bath must be known. However, due to the cylindrical shape of the rotary furnace, the surface area of the liquid metal bath changes with the depth of the bath. As the depth of the liquid metal bath changes, the area can either increase or decrease. The direction of variation depends on the initial depth of the liquid metal bath whether it is above or below the centerline. If the initial depth of liquid metal bath is above the centerline, the area increases as the depth of the bath decrease until the depth of the bath is same as the radius of the furnace. Then, the area of the bath decreases as the depth further reduced.

For a cylindrical vessel, the area of the liquid metal bath is given by:

$$A = WL \tag{7.4}$$

where W: width of the bath

L: length of the vessel

As illustrated in Figure 7.4, the width of the bath is related to the radius of the vessel (R) and the initial depth of the bath (H) by

$$W = 2\sqrt{R^2 - (R - H)^2} \tag{7.5}$$

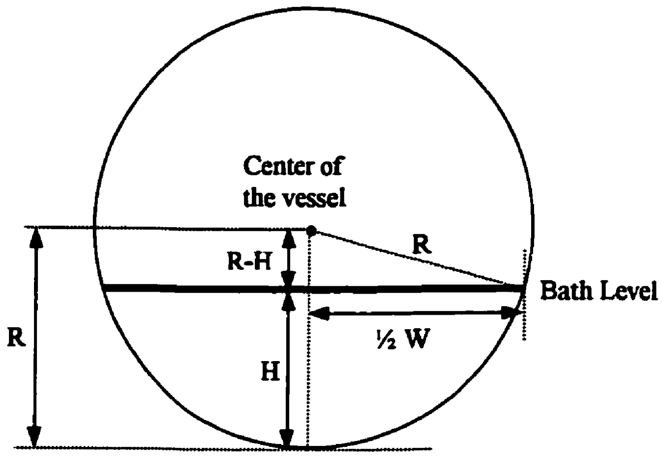


Figure 7.4 Relationship between Bath Width and Depth

The area of the bath surface as the depth decreases by Δh is given by:

$$A = 2L\sqrt{R^2 - (R - H + \Delta h)^2} \tag{7.6}$$

The control of skimming lip position in a rotary furnace is achieved by rotation of the vessel. The angle of rotation (θ) of the furnace is defined here as the line joining the interior edge of the skimming lip and the center of the furnace with respect to vertical as shown in Figure 7.5.

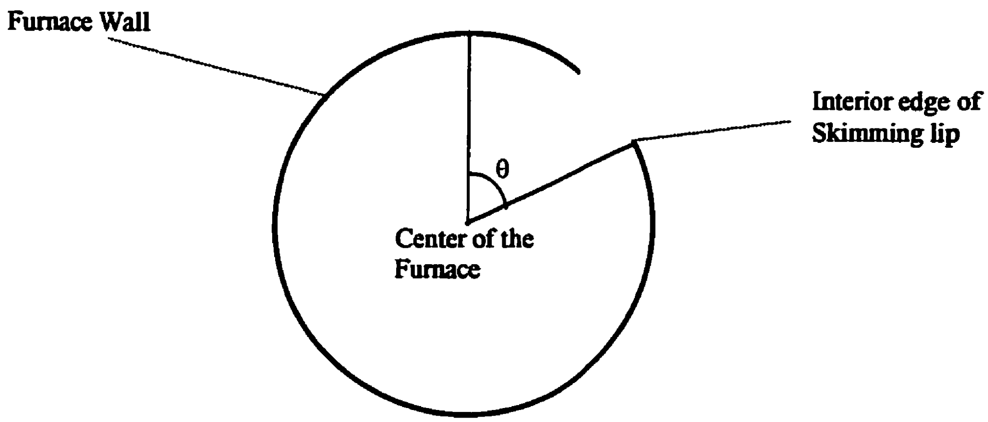


Figure 7.5 Angle of Rotation of the Furnace

Assuming that the furnace is initially in the position with θ_i, in order to lower the skimming lip by Δh, the angle of rotation need to be increased to $\theta_i + \delta\theta$. The change of angle of rotation and the decrease of skimming lip level is related by:

$$\delta\theta = \cos^{-1}\left[\cos(\theta_i) - \frac{\Delta h}{R}\right] - \theta_i \qquad (7.7)$$

Combining Equations (7.3), (7.6) and (7.7), the necessary rotation of furnace can be calculated by knowing the amount of slag skimmed.

In practice, the rotation of the furnace could be controlled by a stepwise loop as shown in Figure 7.6. With a known initial depth of the liquid metal bath and the weight of slag skimmed in the first step, the reduction of bath level could be calculated using Equation 7.3. The area of the bath could be updated and be used in the next calculation step. Using the obtained reduction of bath level, the necessary rotation could be determined using Equation 7.7. The angle obtained could then use to control the rotation mechanism.

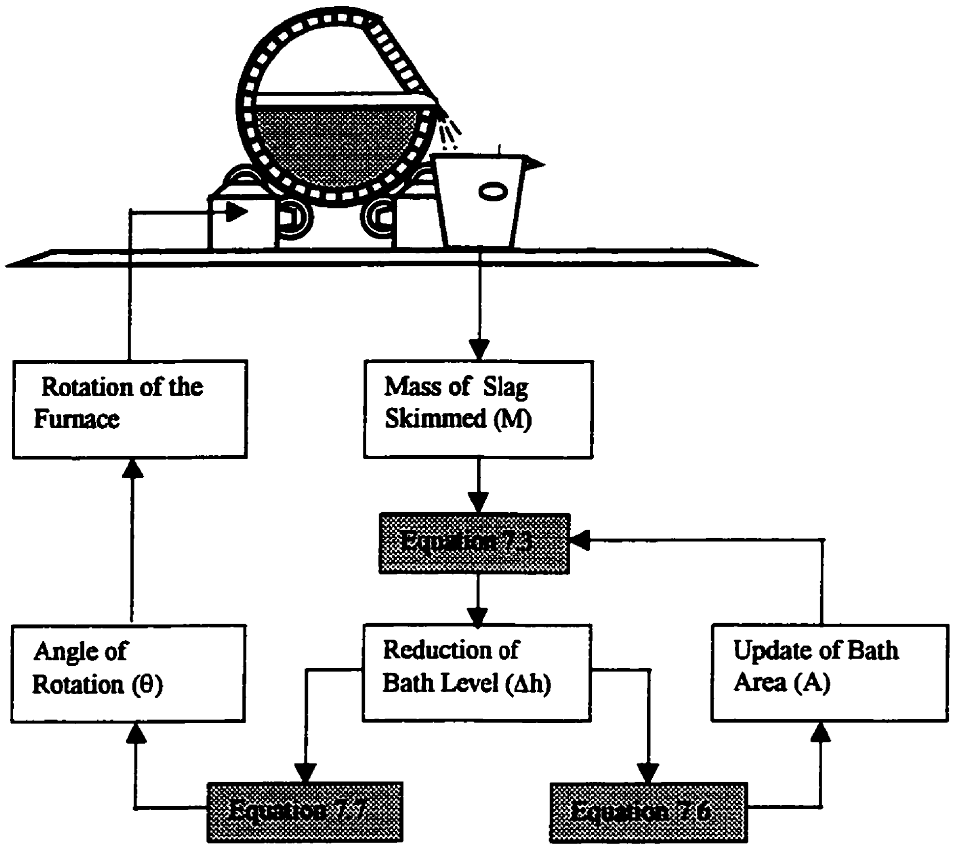


Figure 7.6 Control Strategy of Skimming Lip Position

7.3.2.2 Practical Considerations

The most important factor that governs the successfulness of using the above-mentioned strategy to control the skimming lip position is the precision of the rotation mechanism of the furnace. If the precision of the rotation mechanism is high, the minimum allowable rotation step is small and the lip position can be controlled precisely and the system could respond to a small amount of slag skimmed. As the precision of rotation decreases, the minimum allowable rotation step increases. The system can only respond to a larger amount of slag skimmed in order to avoid loss of valuable material.

An analysis was performed to demonstrate the relationship between the minimum allowable rotation angle and the amount of slag need to be skimmed before the furnace can respond to the change. In the calculation, the size of the furnace was assumed to be 2m in diameter and 12m in length and initially half filled with molten copper. Physical properties of slag and molten copper presented in Table 4.1 were used. Moreover, the level of the skimming lip was assumed to be at the same level of the slag/molten copper interface initially. The value of Δh was calculated with a chosen rotation step ($\delta\theta$) using Equation 7.7. Then, the amount of slag skimmed was obtained using Equation 7.3.

Calculation results revealed that the weight of slag need to be skimmed was directly proportion to the rotation step. When rotation step was 1°, the system could start to respond when 2390 kg of slag is skimmed. However, as the minimum rotation increased to 3°, 7290 kg of slag needed to be skimmed. If the rotation step further increased to 5°, 12350 kg of slag needed to be skimmed before the furnace is allowed to rotate.

The above analysis demonstrated that the precision of the furnace rotation plays an important role in skimming mouth level control. Depending on the precision of the rotation mechanism, the amount of slag need to be skimmed before the furnace is allowed to rotate varies. This amount of slag also depends on the size of the furnace. With a fixed minimum allowable rotation, the amount of slag need to be skimmed increase with the size of the furnace decrease.

8. CONCLUSION AND RECOMMENDATION

8.1 Concluding Remarks

Skimming is a necessary procedure in many metallurgical processes. However, to date there has been little published research on the mechanisms and kinetics of the skimming process. In this work, a physical modeling exercise was performed to gain a better insight into the skimming process of fluid slag in order to identify methods to improve the effectiveness of the process.

The skimming process was found comprised of two steps, namely the transportation step and the removal step. In order to allow a skimming process to proceed, slag must be continuously carried to the skimming lip and the slag accumulated in front of the lip must be continuously flowed across the skimming lip. The effectiveness of the skimming process was determined by the effectiveness of the transportation step and the removal step. With the failure of either step, the skimming process could not be proceeded to completeness.

For the transportation step, creation of bath surface circulation was found an effective way to carry the slag to the skimming lip. However, due to the presence of stagnant regions on the bath surface close to the wall, fluid metallurgical slag can not be completely detached from the wall by bath surface circulation. Moreover, method to create the bath surface movement was a crucial factor that determined the performance of the transportation step. It was found that bath surface movement generated by submerged gas injection was ineffective in carrying slag to the skimming lip because of the uncontrollable circulation pattern created on the bath surface. Also, the waves generation problem require the skimming process to be operated manually. As a result, the copper anode furnace skimming process is more a matter of operator "intuition" and experience than the application of science. On the other hand, it was found that bath surface movement generated with impinging gas jets in glancing contact with the bath surface created a very controllable circulation pattern and was able to carry slag to the skimming lip effectively. The bath surface remained calm through out the process. With this gentle movement, most of the slag located originally at the two ends of the furnace could be carried to the skimming lip.

For the removal step, it was found that the role of the gas jets was more than only moving the slag to the skimming lip. With a proper configuration of the gas jets, the skimming rate could be improved because of the shearing of the slag by gas stream exiting the furnace. It was also observed that as the skimming process proceeded, the skimming rate continuously decreased due to the reduction of the bath depth. It was proposed that to rotate the furnace continuously to maintain the same relative position between the skimming lip and the slag/metal interface as the beginning of the process. A strategy was suggested to control the position of the lip by measuring the weight of slag skimmed. However, the applicability of this strategy was limited by the precision of the rotation mechanism of the furnace.

At first glance, slag skimming appears to be a very simple process, that is, a gravity driven flow that separates immiscible stratified liquids. However, detailed analysis of the process reveals that skimming is a dynamic process. The parameters that governing the performance of the process, i.e. the skimming rate and the distance between the skimming lip and the slag/metal interface, are inter-related. To increase the skimming rate means to increase the velocity of the slag to flow across the skimming lip.

The maximum velocity attained is limited by the relative position of the skimming lip and the slag/metal interface (Δh_w). Otherwise, it leads to entrainment of the underlying liquid metal. The occurrence of entrainment problem can be reduced by increasing Δh_w. However, an increase of Δh_w decreases the hydrostatic head of the slag layer above the lip and reduces the skimming rate. Also, as the slag is skimmed, the level of the underlying liquid metal bath decreases. The faster the slag is skimmed, the faster the bath level decreases. The increase of Δh_w also limited the extent of skimming. As a result of the inter-relationship of the governing parameters, skimming is not a steady process.

Although this work was focused on the skimming of slag from a horizontal, cylindrical, rotary furnace in copper industry, the idea presented to enhance skimming effectively is applicable to other type of skimming process, i.e. from removal of molten grease from turkey juice in the kitchen to cleaning up of oil slick in the ocean.

8.2 Recommendation for Future Works

For the ease of analysis the performance of a skimming process, it is suggested to develop a mathematical expression to describe the skimming process. The expression is expected to be analogous to the governing equations in heat and mass transfer. In other words, the skimming rate is written as a product of a coefficient and the operating parameters. The coefficient is expected to be a function of the fluid properties of the slag. The operating parameters include the size of the furnace, the distance between the skimming lip and the slag/metal interface and the specification of the external assistance to transport the slag to the skimming lip.

The bath surface circulation was found unable to detach slag from the wall. In order to identify method to separate slag from the wall and achieve complete skimming, the evolution of the attached slag at the wall during skimming is important. It is recommended to study the evolution of the triple points of the slag at the wall during skimming. With the understanding of the behavior of the attached slag, identification of method to detach slag from the wall becomes possible.

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APPENDIX I

EXPERIMENTAL DATA

Experimental Data

Total Volume of 1-decanol charged into the modeling tank: 500ml

Time (min)	Skimming With Jets Volume of 1-decanol Collected (ml)				Skimming Without Jets Volume of 1-decanol Collected (ml)			
	Exp 1	Exp 2	Exp 3	Exp 4	Exp 1	Exp 2	Exp 3	Exp 4
1	148	192	144	134	15	14	21	11.5
2	51	62	54	79	10.5	7	12	8.7
3	26	28.5	29	36.5	10	7	10.5	8.5
4	21	18	20.5	23	9.5	7	10	8.3
5	17	15	13.5	16	9	7	9	7.25
6	15	14	12	11.8	8	7	8.5	6.75
8	22	19	19.2	18.5	15	12	15.5	13
10	18	13	16.5	16	15	12	14.5	12.2
12	14	10	13.5	13.5	14	10	13	10.2
16	24	12	24	20.5	24	20	23	19.2
20	14.5	7.5	18.4	18	20	20	22	17.2