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A Refined Thermal Reynolds Analysis to Estimate the Lubricant Film Thickness at the Mould Inlet Region of a Continuous Casting Process

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Abstract

Mould lubrication or strand lubrication is necessary in any continuous casting process. The lubricant known as the mould flux in the meniscus region of continuous casting process flows through the space between the solidified shell and water cooled mould wall under the influence of the mould oscillation, gravity and the casting speed. An inadequacy in mould lubrication may result in producing defects to the surface of the steel cast strand. The tribology aspect in continuous casting upper mould region is characterized as the hydrodynamic lubrication phenomena. The film thickness at this working region zone is considered to be important and it may determine the quality of the surface of the slab during continuous casting. The hydrodynamic equation known as the Reynolds equation can be used to analyse the mould flux in the gap between the mould wall and the steel strand for analyzing an optimum performance of casting. To implement such an analytical method in continuous casting, a modified thermal Reynolds equation with two different surface temperatures where the mould wall surface is cooler than the strand surface is required. Therefore, a refined thermal Reynolds analysis with two different surface temperatures and velocities is developed to estimate the lubricant film thickness at the mould inlet region of a continuous casting process. In fact, it is aimed to investigate how the predicted theoretical film thickness be influenced by the process control parameters. The present work successfully presented an analysis of the lubrication process with unequal surface temperatures and different surfaces velocity which is required in the continuous casting process.

Keywords : *Thermal Reynolds, Film Thickness, Continuous Casting*

Introduction

This work deals with sliding of high temperature slab or billet cast of metal in the mould of continuous casting under hydrodynamic lubrication. There is much to be gained from understanding the mechanics of continuous casting lubrication. Such an understanding will lead to improvements in lubrication practice. This in turn will provide economics benefits from increased casting speed and cast surface quality due to the reduction of metal to metal contact during casting withdrawal.

It is well known that hydrodynamic action can be important in continuous casting lubrication. An inadequacy in mould lubrication may result in producing defects to the surface of the steel cast strand. Currently research on modelling and finding an effective mould lubricant are still in progress for performing higher casting speeds with reduced risk of breakouts (Blevins et al. 2000). McDavid and Thomas (1996) have modelled a three dimensional model for the fluid flow and thermal behaviour on the top of the layer of the continuous casting process. In their model, the fluid flow and heat transfer of the flux layers were coupled with the flow field in the liquid steel through the shear stress distribution at the interface. Lubricant effect on the mould wall can be maintained by ensuring a liquid flux or mould lubricant always exists during withdrawal process. In other words, frictional forces in the mould could be eliminated and smooth sliding between the solid strand and the mould wall can be maintained. Mathematical models to evaluate the hydrodynamic sliding friction condition at the upper portion of the mould in continuous casting has been introduced by Royzman (1997). He has considered two different types of sliding which depends on the speed of the cast. Takeuchi and Brimacombe (1984) have simulated the pressure distribution in the meniscus zone by applying the fluid flow analysis based on the Reynolds equation. It has shown that the viscosity influences the maximum pressure in the layer during casting withdrawal. Upward motion of the mould produced more maximum pressure compared with the downward motion of the mould. It has been indicated by Riboud and Larrecq (1979), the hydrodynamic lubrication was prevalent only at the upper part of the mould. At the lower region of the mould, a solid to solid friction may take place. This condition occurs due to a lower temperature present at the lower region of the mould in comparison to the temperature at the upper part of the mould.

The lubrication process in continuous casting upper mould region is characterized as the hydrodynamic lubrication phenomena. The film thickness at this working region zone may determine the quality of the surface of the slab during continuous casting. The hydrodynamic lubrication equation known as the Reynolds equation can be used to analyse the lubrication in the gap between the mould wall and the steel strand for analyzing an optimum performance of casting. Itoyama et al. (1994) have applied the Reynolds equation to predict the pressure distribution due to the squeeze flow with horizontal oscillation. Bland (1984) has applied the Reynolds equation to examine the mass flow between parallel plates by including the oscillatory velocity of the mould.

This work is focused on the analytical and numerical solution of the hydrodynamic lubrication for estimating the film thickness in the upper mould region of the continuous casting process. The thermal Reynolds equation will be solved simultaneously with the energy equation so the temperature distribution across the film thickness may be determined prior to the calculation for the pressure distribution. The thermal Reynolds equation takes into account the variation of the viscosity across the lubricant film thickness due to the energy dissipation. The most important thermal effect in lubrication process is due to the shear heating between the moving surfaces.

Lubricant Infiltration in the Mould

Figure 1 represents the physical system of the inlet upper mould region near the meniscus of a continuous casting process. A lubricant film of thickness *h* is being transported in the x direction which is the casting direction against a pressure gradient *dp/dx=p'*. Both surfaces have different temperatures, T_1 and T_2, and move in the casting direction with velocity, U_1 and U_2 as shown in Figure 1.

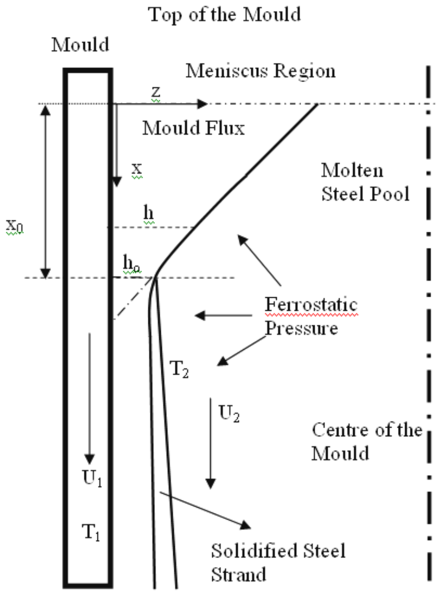

Figure 1. Infiltration of the lubricant known as mould flux

The solidified steel strand in the continuous casting mould is separated by a hydrodynamic lubricant film from the mould surface. The solidified shell of the cast is stressed and deformed due to the action of the thermal load and the ferrostatic pressure as reported by Grill et al. (1976). This ferrostatic pressure produces an external load to the solid shell which is in contact with the liquid metal core. As the casting descends, the deformation due to pressure continues and progressively a wider part of the face comes in contact with the mould. Finally, an equilibrium condition is reached where only the skin near the corners is not in contact with the mould.

Thermal Reynolds Continuous Casting Analysis

The thermal Reynolds equation is equivalent to the steady one dimensional incompressible Reynolds equation which takes into account the variation of the viscosity across the lubricant film thickness due to the energy dissipation. The derivation of the thermal Reynolds problem includes the viscosity variation across the film thickness and velocity differences at the surfaces. The adapted heat transfer equation deals with the situation where the convection of heat is assumed unimportant (low Peclet number). Therefore, the conduction across the lubricant film is the dominant mode of heat transfer in the present analysis. Some assumptions are taken for applying the developed thermal Reynolds equation in the continuous casting inlet zone analysis. The assumptions are:

1. The lubricant flow is two dimensional
2. Inertial effects can be neglected
3. The lubricant pressure is constant across the film
4. The component of lubricant velocity across the film is small compared with that along the film
5. The lubricant is Newtonian
6. The viscosity of the mould lubricant is assumed to be defined as an exponential function of the temperature which can be described as,
   $\mu = \mu_s \exp\left\{-\alpha\left(T - \frac{T_2 - T_1}{2}\right)\right\}$ where μ_s is the viscosity at the average temperature of the surfaces and α is the viscosity temperature coefficient. T_2 and T_1 are surfaces temperature of mould's wall and the slab
7. The lubricant film thickness is small compared with the slab cast length.

Assumptions (1) to (5) are usually applied to the unsteady one dimensional Reynolds equation. The viscosity temperature model described in assumption (6) is valid for a wide range of temperatures in lubrication analysis. The viscosity model does not ignore the variations of the viscosity with pressure.

It is more convenient to continue this analysis in a non-dimensional form by introducing some non-dimensional parameters which are,

$R = \dfrac{p' h^3}{12\mu_s (Uh - Q)}$ Non-dimensional Pressure Gradient **(1)**

$F = \dfrac{\mu_s \alpha (Uh - Q)^2}{kh^2}$ Non-dimensional Thermal Backflow parameter **(2)**

$D = \alpha(T_2 - T_1)$ Non-dimensional Temperature difference **(3)**

$S = \dfrac{\mu_s \alpha (u_1 - u_2)^2}{k}$ Non-dimensional Velocity **(4)**

$E^* = \dfrac{E\alpha\, h^2}{k}$ Non-dimensional Energy Dissipation **(5)**

The non-dimensional parameter, *S,* is a measure of the effect of energy dissipation due to slip (Couette Flow) on the lubricant viscosity. It should be noted that if *S* is equal to zero pure sliding occurs in the lubricant. *D* is the non-dimensional surface temperature. In the case when both surfaces have equal temperature the parameter *D* become zero. *Q* in Eq. 1 is the flow rate and *E* is the total energy dissipation and *k* is the conductivity of the lubricant. In applying the developed thermal Reynolds equation, it is more useful to consider the non-dimensional parameter, *R,* as the correction factor applied to the conventional Reynolds equation. The conventional Reynolds equation with the correction factor, *R*, is defined as,

$$\frac{dp}{dx} = 12\,\mu_0\, e^{\gamma p} U \frac{\left(h(x) - h_0\right)}{\left(h(x)\right)^3} R \qquad \textbf{(6)}$$

where μ_o is the viscosity of the lubricant. The non-dimensional film thickness in the meniscus region of a continuous casting process could be rewritten as,

$$H = \frac{q}{\sqrt{2}} \ln\left[\frac{\bar{x}}{\sqrt{2q^2} - \sqrt{2q^2 - \bar{x}^2}}\right] - \sqrt{2q^2 - x^2} + q\left(1 + \frac{\ln\left(\sqrt{2} - 1\right)}{\sqrt{2}}\right) \qquad \textbf{(7)}$$

where the parameter *q* is defined as $q = a/h_o$ where a is defined as

$$a = \left(\frac{2\gamma}{(\Delta\rho)g}\right)^{1/2} \qquad \textbf{(8)}$$

γ is the surface tension (N/m), *g* is the acceleration due to the gravity and $\Delta\rho$ is the density. Thus the thermal Reynolds equation in Eq. 6 with the non-dimensional film thickness parameter, *H*, becomes,

$$\frac{dB}{d\bar{x}} = \frac{G}{H_0 {A_0}^2} \frac{\left(H - 1\right)}{H^3} R \qquad \textbf{(9)}$$

where some new introduced non-dimensional parameters defined in Eq. 9 applied to this analysis are,

$$B = e^{-\gamma p} \qquad \textbf{(10)}$$

$$\bar{x} = \frac{x}{h_0} \qquad \textbf{(11)}$$

$$G = \gamma P_{Fer} \qquad \textbf{(12)}$$

$${A_0}^2 = x_{tot}^2 \left(\frac{P_{Fer}}{12\,\mu_0\, U\, x_{tot}^2}\right)^{2/3} \qquad \textbf{(13)}$$

$$H_0 = h_0 \left(\frac{P_{Fer}}{12\,\mu_0\, U\, x_{tot}^2}\right)^{1/3} \qquad \textbf{(14)}$$

The thermal Reynolds equation with the correction factor defined in Eq. 9 was integrated numerically using the fourth order Runge Kutta program. The non-dimensional pressure gradient, *R*, used in Eq. 9 is a function of the *S, D*, and *F* which must be described in the non-dimensional form. Some new parameters are again introduced here which are,

$$L = \frac{\mu_0\, \alpha\, U^2}{k} \qquad \textbf{(15)}$$

$$c = \frac{u_1 - u_2}{u_1 + u_2} \qquad \textbf{(16)}$$

L is defined as the thermal loading parameter and *c* is the non-dimensional velocity. The non-dimensional parameters *F* and *S* could be written in more compact form as,

$$F = \frac{L}{B}\frac{(H-1)^2}{H^2} \quad \textbf{(17)}$$

$$S = \frac{4Lc^2}{B} \quad \textbf{(18)}$$

Results and Discussion

Increasing the thermal loading parameter, *L,* at certain location *x* in the mould tends to increase the value of *B*. It is necessary to apprehend the significance of the parameters used in this analysis. The non-dimensional parameter *G* is the viscosity pressure coefficient, which is defined as a measure of the importance of the pressure induced viscosity changes on the film formation process. The non-dimensional parameter *L* is described as the thermal loading parameter, which is a measure of the temperature induced viscosity changes on the process. Another important non-dimensional parameter is the non-dimensional film thickness, H_0. This parameter H_0 is the ratio of the initial film thickness at the mould meniscus region if no pressure or temperature induced viscosity changes occurred.

Fig. 2 shows the variation of the non-dimensional initial film thickness H_0 at the mould meniscus region with the non-dimensional viscosity pressure coefficient, *G*, or various thermal loading, *L*. As illustrated in Fig. 2 the variation of the film thickness with velocity, *U*, (represented by thermal loading parameter *L*) is difficult to account. Therefore, an alternative variation of the mould lubricant film thickness, H_0, with the thermal loading, *L*, has been chosen. The new defined film thickness, $H_0.L^{(1/6)}$, is proportional to h_o and does not contain the velocity, *U*. The thermal loading, $L^{(1/6)}$, is proportional to the velocity, *U*. The relationship between the film thickness with the velocity for various value of the pressure coefficient of viscosity, *G*, is shown in Fig. 3 and Fig. 4.

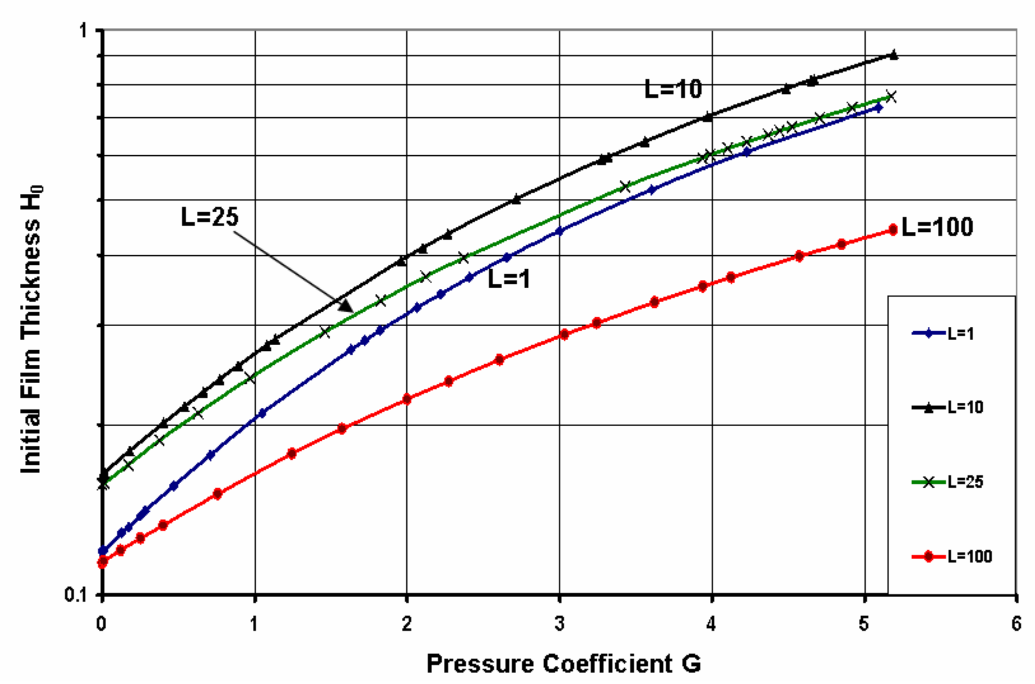

Figure 2. Variation of the initial film thickness Ho versus G with various thermal loading D = 1, S = 100, Various L (in logarithmic scale)

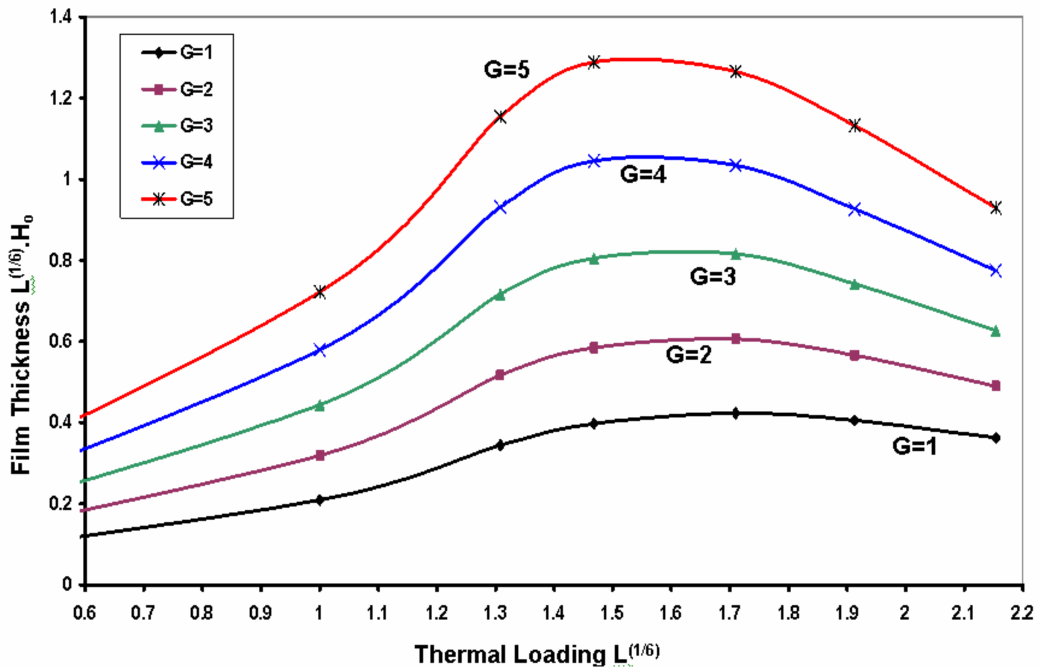

Figure 3. Film thickness variation for D = 1, S = 100 and various G

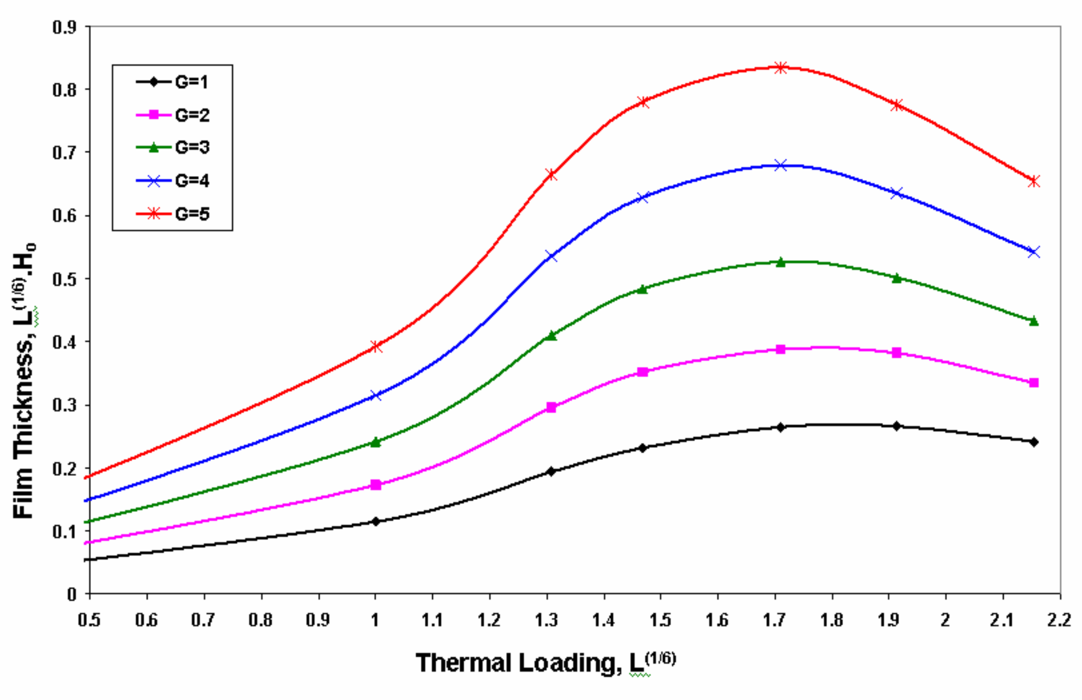

Figure 4. Film thickness variation for D = 2, S = 200 and various G

Apparently as shown in Fig. 2 to Fig. 4, increasing of film thickness results from increasing of G. Increasing of the slip parameter S tends to decrease the film thickness and increasing of temperature parameter, D, results in decreasing of the film thickness of the lubricant.

Conclusions

An analysis of the lubrication process in the meniscus region of a continuous casting process has been performed. A new derived thermal Reynolds equation which is similar to the unsteady, one-dimensional Reynolds equation has been developed. The developed thermal equation takes into account the temperature induced viscosity variation across the film thickness and variation of the surface velocity. The differential equation of the thermal Reynolds equation was derived analytically by inclusion the exponential viscosity temperature model and the sliding effects. The developed equation is further implemented for the analysis of the lubrication process in a continuous casting process.

In this analysis the conduction across the film thickness is the dominant mode of the heat transfer where viscous heating leads to a substantial viscosity variation across the film in the flow of the liquid lubricant. The present work successfully presented an analysis of the lubrication process with unequal surface temperatures. The complicated meniscus profile in the mould of a continuous casting process introduced by Jimbo et al. (1991) has been successfully applied with the new developed thermal Reynolds equation for cases where both surface velocities and temperature are different to analyze the film thickness in this region. The result denotes that the surface velocity and the thermal induced viscosity play an important role in the film thickness formation of a continuous casting process

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