Designing for slag "freeze linings" on furnace sidewalls – an engineering perspective.

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Abstract

The use of stable "freeze linings" to maintain the integrity of furnace sidewalls against liquid slag and metal systems are widely accepted today. A major paradigm shift was needed to move away from using insulating refractory sidewalls to using highly conductive materials combined with more effective cooling systems. The driving force behind this shift include cost effectiveness over the long term, the possibility of higher operating temperatures, and more freedom in optimizing the process chemistry.

In this paper a simple method to design a "freeze lining" on a furnace sidewall hot face is described. The method is based on natural convection calculations for buoyancy driven flow over a vertical plate. The bath is assumed to be liquid slag or metal. It is shown how to estimate the most important and difficult parameter, namely the heat transfer coefficient between the bath and the sidewall/"freeze lining". For complex sidewall lining/cooling systems combining materials with high differences in thermal conductivity the use of Finite Element Analysis techniques are discussed for calculating the heat transfer. An example is presented involving the design and evaluation of a sidewall lining/cooling system for a alumina melting process.

Introduction

A sidewall lining/cooling system is first of all required to maintain a stable "freeze lining" under normal operating conditions. Secondly, and more importantly, the lining/cooling system must be designed to withstand extreme operating conditions. These include slag temperature excursions, sudden loss of the "freeze lining" due to thermal shock or mechanical dislodging, sudden change in the process chemistry and other abnormal and unplanned conditions that inevitably occur. In practice a sidewall campaign life is determined by these deviations, and not by the normal operating conditions itself.

Method

In order to design a sidewall lining/cooling system to maintain a stable "freeze lining", the heat load expected on the sidewall needs to be calculated. If a "freeze lining" is assumed to have formed and to be stable on the sidewall hot face, the heat load on the sidewall is calculated using

$$q = h_{slag} \Delta T = h_{slag} \left(T_{slag} - T_{freezing} \right) \tag{1}$$

where q = heat flux (kW/m^2)
h_{slag} = slag to sidewall/freeze lining heat transfer coefficient
T_{slag} = liquid slag temperature
$T_{freezing}$ = freezing temperature of liquid slag

Thus, as long as the "freeze lining" is maintained, the heat loss from the furnace is a function of the process parameters and not the sidewall lining/cooling system design. In Equation (1) the liquid slag temperature, T_{slag}, is taken equal to the slag tapping temperature. The slag freezing temperature is assumed equal to the average of the liquidus and solidus slag temperatures:

$$T_{freezing} = \frac{T_{liquidus} + T_{solidus}}{2} \tag{2}$$

This is to approximate the effect of the so-called "mushy zone" present on the "freeze lining" hot face. In calculating the heat transfer coefficient, h_{slag}, the additional thermal resistance due to the "mushy zone" is not catered for. Thus, the heat flux or load on the sidewall lining/cooling system is slightly overestimated for design purposes. The calculation of the heat transfer coefficient between the slag bath and the "freeze lining" is discussed in more detail in the next section.

Once the heat load is determined using Equation (1), the sidewall lining/cooling system can be designed to maintain a stable "freeze lining" of specified thickness under normal operating conditions. Equation (3) calculates the maximum allowable sidewall lining/cooling system thermal resistance that will insure that heat is removed from the lining hot face at a rate equal to or higher than that calculated in Equation (1).

$$q = \frac{T_{freezing} - T_{cooling}}{R_{freeze} + R_{lining/cooling}}$$

$$R_{lining/cooling} = \frac{T_{freezing} - T_{cooling}}{q} - R_{freeze} \tag{3}$$

where $T_{cooling}$ = temperature of cooling medium (air, water etc.)

$R_{freeze} = \frac{x_{freeze}}{k_{freeze}}$

x_{freeze} = minimum "freeze lining" thickness required

k_{freeze} = "freeze lining" thermal conductivity

Determination of the thermal conductivity of the slag "freeze lining" is either through estimation from literature [1] or from actual solid slag samples. The thermal conductivity of solidified slag is considerably higher than that of the liquid slag [2]. Values between 1 and 3 W/(mK) are observed depending on the slag composition.

If the heat load or flux on the sidewall is calculated at below 20 kW/(m^{2}K), external shell cooling can be combined with a thermally efficient refractory lining. To insure the formation of a stable freeze lining, the sum of the thermal resistances for the different refractory layers and sidewall components must satisfy Equation (3). Thus, the following equation must hold:

$$R_{lining/cooling} \geq \sum \frac{x_n}{k_n} + \frac{x_{shell}}{k_{shell}} + \frac{1}{h_{cooling}} \tag{4}$$

where n = number of different refractory layers present in the sidewall.

x_n = thickness of refractory layer n.

k_n = thermal conductivity of refractory layer n.

x_{shell} = thickness of furnace shell.

k_{shell} = thermal conductivity of furnace shell (For mild steel equal to 45 W/(mK)).

$h_{cooling}$ = thermal heat transfer coefficient between cooling medium and shell.

It is of utmost importance to insure good contact between the refractory lining and the shell. If an air or gas filled gap is to form between the refractories and the shell, an additional relatively high thermal resistance is introduced into Equation (4). Graphite tiles with very high thermal conductivity is sometimes glued to the shell to prevent gap formation [3]. The formation of a gap between the high conductivity tiles and for example high conductivity graphite blocks in the front is not as problematic. This is because the heat could easily be diverted to and removed through those areas where good contact is achieved.

If the heat load or flux on the sidewall is estimated above 20 kW/(m^{2}K), the use of integrated copper sidewall cooling is advised. As there is a considerable difference in thermal conductivity between the copper and the refractory materials, the overall sidewall resistance can not be calculated accurately with a two-dimensional thermal resistance model [4]. Finite Element Analysis (FEA) is used to investigate the heat transfer through and calculate the thermal resistance of the sidewall lining/cooling system [5]. The heat flux calculated in Equation (1) is applied as a boundary condition on the hot face of a three-dimensional FEA model of the lining/cooling system. The resulting maximum hot face temperature together with the cooling medium film temperature and the applied heat flux is then used to calculate an overall thermal resistance for the lining/cooling system. The value of this resistance must be equal to or smaller than the value calculated using Equation (3).

$$R_{lining/cooling} \geq R_{FEAresult} \qquad (5)$$

As discussed earlier, a furnace lining/cooling system must be designed to withstand the extreme operating conditions. For a lining/cooling system behind a “freeze lining” the extreme operating condition is experienced if the “freeze lining” is lost due to thermal shock or mechanical dislodging thereof. The lining/cooling system is then directly subjected to the slag or furnace bath. Although the “freeze lining” will again start forming immediately, it is common knowledge that the time it will take to form a new stable “freeze lining” is measured in hours. Final equilibrium will only be reached after some weeks or even months. The increase in “freeze lining” thickness over time can be calculated solving the following equation:

$$h_{slag}(T_{slag} - T_{freezing}) - \frac{T_{freezing} - T_{cooling}}{R_{freeze} + R_{lining/cooling}} = -rL\frac{dx}{dt} \qquad (6)$$

where r = average density of liquid and solid slag.
L = latent heat of slag changing from liquid to solid
x = varying “freeze lining” thickness also present in R_{freeze} term.
$\frac{dx}{dt}$ = slag freezing rate.

The performance of a lining/cooling system under extreme operating conditions is evaluated by applying the slag bath temperature together with the slag-to-sidewall heat transfer coefficient as a boundary condition directly onto the hot face of the three-dimensional FEA model. A static analysis is done which represents the worse case. In other words, the sidewall hot face is assumed to remain unprotected for a period long enough as to show the maximum effect of the extreme operating conditions on the lining/cooling system. Important results from the model include the maximum hot face temperature, the maximum copper temperature, the maximum temperature gradient across the hot face and a re-check on the effective thermal resistance of the lining/cooling system as a whole. Another important design parameter to be introduced here is concerned with the effective use of copper. The J factor is simply the ratio between the effective heat transfer coefficient for the lining/cooling system and the volume of copper used per unit sidewall area.

$$J = \frac{h_{lining/cooling}}{V_{copper}/A_{sidewall}} \left[\mathrm{W/(m^3K)}\right] \qquad (7)$$

A lining/cooling system can thus be designed and optimized using this method. This method is based on physical relations, proven empirical relations, actual furnace data and engineering experience. It is ideal to quickly and effectively design and evaluate lining/cooling systems. Other methods include Computational Fluid Dynamic modeling of the furnace bath or physical testing of the process. These should provide more accurate answers but at a much higher cost due to both expensive computer software and time.

Heat transfer coefficient

Determination of the heat transfer coefficient between the slag bath and the sidewall of an electric furnace is very difficult although critical in estimating the heat load on the sidewall. The sidewall heat load as calculated using Equation (1) in turn is critical for the thermal design and evaluation of sidewall lining/cooling systems. Three different routes can be followed for the slag-to-sidewall heat transfer coefficient determination:

1. The use of natural convection empirical relations/formulas based on previous studies in conjunction with experimentally determined data for the variables involved. This is the most economic and time efficient method. The accuracy depends on the applicability of the empirical relations and the reliability of the experimental data used.

2. Computational Fluid Dynamics (CFD) can be used for the numerical modelling of the interaction between the slag bath and the sidewall for the purpose of estimating the heat transfer coefficient. This method can also provide insight into flow patterns in the bath, temperature gradients through the bath, electrical current paths, as well as actual "freeze lining" formation, all relative to furnace geometry. Initial experimental verification is necessary insuring that all contributing factors are considered. Accuracy during application to different processes is still subject to the applicability and reliability of the input data for the various material properties.

3. Specific physical experimentation for every single case will provide the most reliable data for determining the heat transfer coefficient. Although this method is by far the most expensive and time consuming, it can not be substituted during the design of a furnace for a new process.

The first method is the one most frequently used by furnace engineers and designers. It is an easy and cost effective way to quickly estimate furnace sidewall requirements for a specific application. Empirical relations based on those for natural convection next to a vertical plate is employed. The empirical function suggested by Kang [6] for slag against a sidewall was decided on due to its verification by both experimentation and numerical modelling. It takes the form of

$$Nu = C(GrPr)^m \qquad (8)$$

for $8 \times 10^6 < Ra = GrPr < 10^{11}$

where Nu = Nusselt number
Gr = Grashof number
Pr = Prandtl number
Ra = Rayleigh number
C = 0.32
m = 0.3

The Grashof number is calculated as follows:

$$Gr = \frac{g r^2 b \Delta T L^3}{m^2} \quad (9)$$

where g = gravitational acceleration = 9.81 m/s^2
r = density of liquid slag
b = volumetric expansion coefficient of liquid slag
ΔT = temperature difference between sidewall and slag bath
l = height of sidewall covered by slag
m = dynamic viscosity

and the Prandtl number is calculated as

$$Pr = \frac{c_p m}{k} \quad (10)$$

where c_p = specific heat of liquid slag
k = thermal conductivity of liquid slag

The heat transfer coefficient is then calculated using the Nusselts number as follow:

$$h = \frac{k}{l} Nu \quad (11)$$

For estimation and/or determination of the material properties the slag composition must be known. The viscosity, density and slag freezing temperature are estimated using published values for different slags [1]. The specific heat is calculated using the separate values for the slag constituents together with the respective molar coefficients in the molar function [7]. Two methods exist for estimation of the thermal conductivity of liquid slag. The first is based on the molar volume of the liquid slag and calculates the thermal conductivity at its melting point [8]:

$$k = 1.8 \times 10^{-5} V_M^{-1} \quad (12)$$

The second method for estimating the thermal conductivity of liquid slag makes use of the relationship between the thermal conductivity and the so-called network parameter [2,9]. Both these methods require knowledge of the slag composition and in the latter case of the viscosity at the melting point. Experimental determination of the thermal conductivity of liquid slag is difficult and expensive. One well known method is the so-called "laser flash method" [10]. Numerous references are available but the listed one provides a simple explanation as well as a discussion of improvements to the method.

Example

To illustrate the use of the above methods for designing a sidewall lining/cooling system to maintain a freeze lining, an example is presented here for an alumina (mullite) melting process. Although mullite has a very high melting point and thus results in a very high liquid slag temperature in the bath, it is ideal for forming "freeze linings" on sidewalls. This is due to being a natural refractory oxide with high strength, therefore providing a competent freeze layer able to withstand high temperature fluctuations even during batch processes. If metal is present in the feed and reduced during the process, problems could be experienced with the lower sidewall area due to a metal layer with a very high superheat.

The slag analysis in mass percentage is assumed as follow for simplicity:

Al_2O_3 = 75 %
SiO_2 = 25 %
Other < 0.5 % (neglected)

The following values were estimated, calculated or obtained for the variables at 2000°C:

r = 2600 kg/m^3
b = 1 x 10^{-4}
T_{slag} = 2000°C
T_{freeze} = 1877.5°C (Liquidus = 1940°C, Solidus = 1815°C)
ΔT = 122.5°C
L = 0.6 m
m = 0.8 Poise (kg/ms)
c_p = 1418 J/kgK
k = 0.5 W/mK (0.54 W/mK first method, 0.45 W/mk second method)

Using the empirical relation proposed by Kang [6], an average heat transfer coefficient between the slag bath and the sidewall of 145 W/(m^{2}K) is obtained. Using Equation (1), the heat flux through the sidewall is calculated at 18 kW/m^2 under normal operating conditions with a stable "freeze lining" in place. For a required "freeze lining" thickness of 50 mm, a combined thermal resistance of 0.078 W^{-1}.m^{2}K is calculated using Equation (4). This thermal resistance can be inverted into an effective heat transfer coefficient required for the sidewall lining/cooling system.

$$h_{lining\ /\ cooling} = \frac{1}{R_{lining\ /\ cooling}} = 12.9\ \text{W/(m}^2\text{K)} \qquad (13)$$

Because the expected heat flux under normal operating conditions is very close to the 20 kW/m^2, it is expected to rise well above this level under extreme operating conditions. Due to this and the higher than normal operating temperatures it is decided to use a copper cooling system in the sidewall suited for medium heat loads ranging between 20 and 130 kW/m^2. It comprises of copper fingers inserted through a steel shell into a refractory castable with the cooling water kept external to the furnace shell. The castable is bauxite based with 15% silicon carbide addition to provide for a reasonable thermal conductivity of ± 3.5 W/(mK).

The next step is to evaluate the chosen lining/cooling system under the extreme operating conditions. A three-dimensional FEA model as shown in Figure 1 is used for this purpose. The slag bath temperature of 2000°C together with the calculated slag-to-sidewall heat transfer coefficient of 145 W/(m^{2}K) is applied as the boundary condition directly onto the lining/cooling system hot face. The resulting temperature distribution is shown in Figure 2.

Some important observations and results from the model include:

1. A maximum hot face temperature of 1405°C which is well below the castable's operating limit of 1550°C.
2. A maximum temperature difference on the hot face of 750°C over a distance of ±200 mm, resulting in a maximum hot face temperature gradient of ± 3.75°C/mm.
3. A maximum copper temperature of 711°C, although this is very local.
4. A maximum copper temperature adjacent to the cooling water channel of 110°C. Thus, the maximum cooling water film temperature will be much lower than this.
5. Resulting average heat flux across the sidewall of 126 kW/m^2.
6. An effective heat transfer coefficient for the sidewall lining/cooling system of 92 $W/(m^2K)$. Inverted this result in a thermal resistance value of 0.011 $W^{-1}m^2K$ that is considerably less than the value of 0.078 $W^{-1}.m^2K$ calculated using Equation (4). Thus, Equation (5) is also satisfied.
7. A J factor equal to 989 $W/(m^3K)$ indicating the effective use of copper in the design. This value is very useful for optimizing a cooling system design or for comparison of different cooling system designs.

Another possibility is to calculate how long it will take for a competent "freeze lining" to reform on the sidewall hot face using Equation (6). This gives the designer a further idea of how vulnerable the lining/cooling system will be under attack from the bath once the "freeze lining" is lost. It can also be used effectively by plant personnel to evaluate the condition of an existing lining/cooling system as well as the freeze lining. Figure 3 is a graphical presentation of the "freeze lining" growth relative to time for the present example. It is important to understand that this growth pattern is idealistic and will be influenced by any deviation in operating conditions during the growth period.

Concluding remarks

A simple method is described for the design and evaluation of sidewall lining/cooling systems. The method is both cost and time effective. The accuracy of the results is dependent on the reliability of the input data such as material properties and process conditions. Most of the material properties for liquid slag systems are not freely available and some educated approximations need to be employed, with the thermal conductivity being the most elusive. Two available methods to estimate the thermal conductivity were discussed. Mills [2] also provided two general rules for estimating the thermal conductivity of a liquid slag system:

1. The thermal conductivity of liquid slag systems is appreciably lower than for the solid state.
2. The thermal conductivity of liquid slag systems, as for viscosity, increase with increasing silica content.

For complex sidewall lining/cooling systems it is necessary to employ Finite Element Analysis techniques to calculate the heat transfer through the sidewall. Some important observations and results from the analysis include maximum hot face temperature, maximum temperature gradient on the hot face, maximum copper temperature, maximum cooling water temperature, effective heat transfer coefficient for sidewall lining/cooling system and the J factor indicating the effective use of copper in the design.

Finally it is important to stress the fact that the campaign life of a furnace sidewall is determined by the deviations in operating conditions and the extreme operating conditions. This is especially true for sidewalls designed to be protected by a freeze lining. If the sidewall lining/cooling system is designed for these conditions, and if the conditions on the furnace are effectively controlled, a stable “freeze lining” can be maintained resulting in a theoretically infinite sidewall campaign life.

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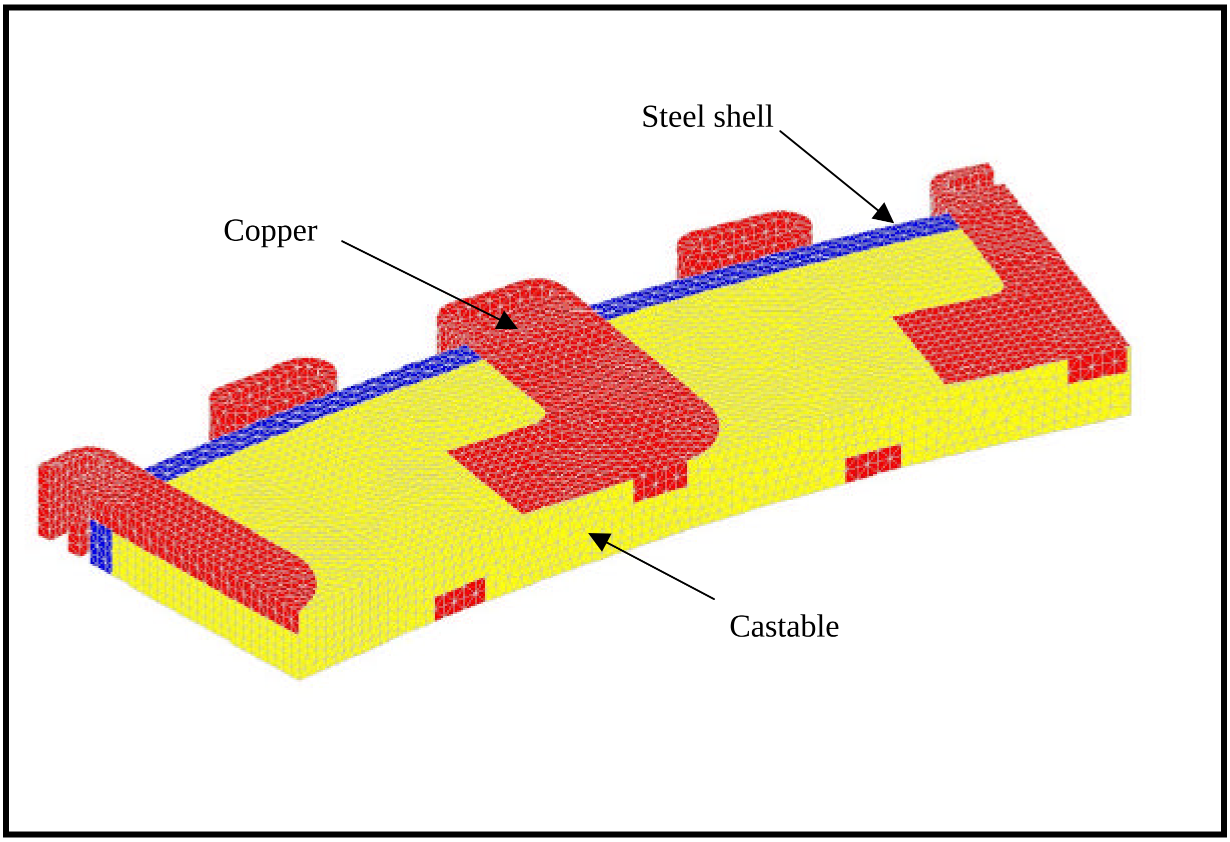

Figure 1: Three-dimensional FEA model of lining/cooling system

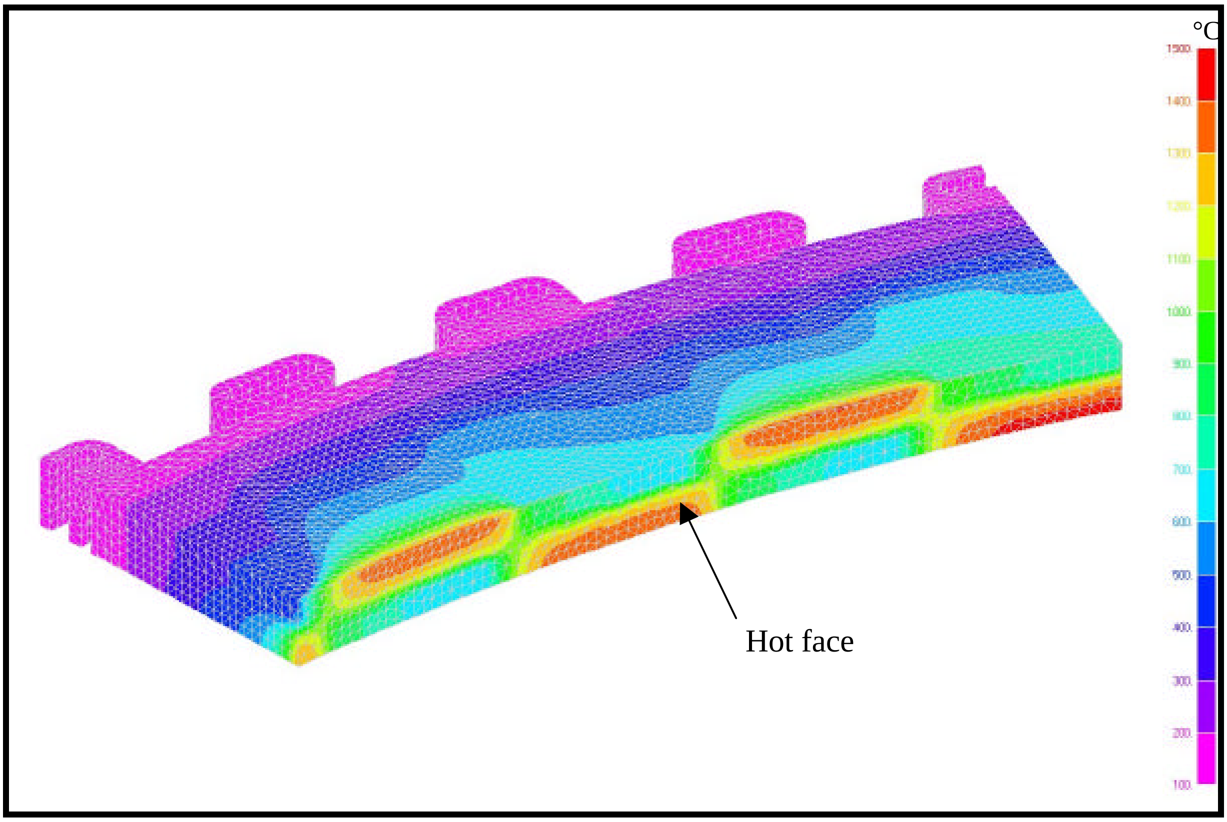

Figure 2: Results of FEA

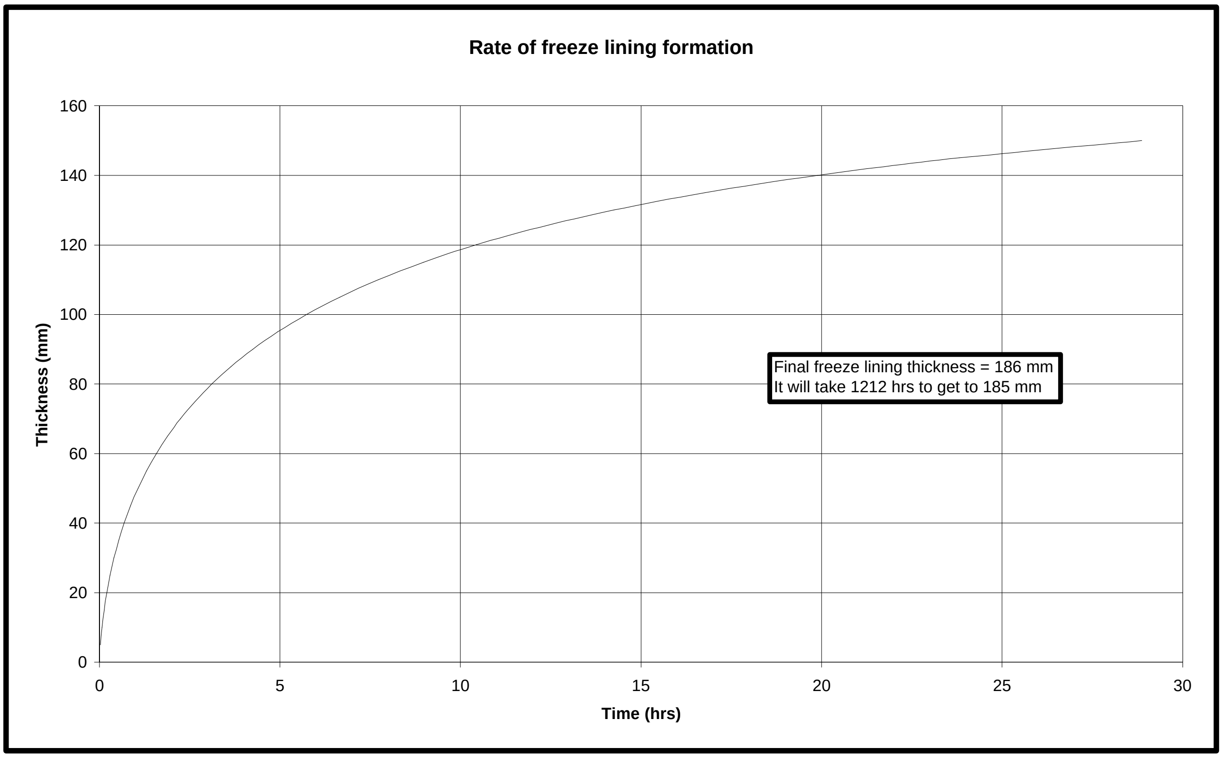

Figure 3: Graphical presentation of rate of "freeze lining" formation