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A Review on Interfacial Heat Transfer Coefficient During Solidification in Casting

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***Abstract*— In recent years, great advances has been made in the field of casting modeling and simulation. But, the accuracy of any software prediction is depends on the process and Input. Casting process is very complex process involving heat transfer problem and fluid flow problem. Interfacial heat transfer coefficient (IHTC) is very important for solving such heat transfer problems. And hence for accurate simulation and modeling of any casting process, sufficient knowledge about IHTC is necessary. This paper gives brief idea about interfacial heat transfer coefficient, its methods of estimation and various factors affecting the IHTC.**

Keywords—IHTC.

I. INTRODUCTION

Casting is an oldest process of manufacturing. It is considered as an additive manufacturing process. Nowadays, various simulation software are available for simulation of casting process. Casting Simulation involves solidification modeling for which mathematical modeling of solidification process of metal has been developed and improved. Solidification modeling consists of following three different modules [1]. They are heat transfer module, fluid flow module and free surface module. Heat transfer module solves energy equation while fluid flow module solves conservation of mass / momentum equation and free surface module solves boundary conditions. For complete solid modeling, all these equation has to be solved simultaneously.

To solve the equations, boundary conditions are necessary and heat transfer at metal mold interface is one of the important boundary condition to solve equation for solidification modelling in casting. Cheng and Tsai [2] developed a numerical method based on control volume finite difference technique for casting solidification problem. This method efficiently solves 2D and 3D casting solidification problem.

In casting, molten metal is poured in mold, which causes the contact between liquid states molten metal and mold wall. As the molten metal starts solidifying, distance between metal in contact with mold wall is gets increased due to shrinkage of metal which leads to formation of air gap between metal wall and mold wall. The heat transfer coefficient at interface is changes with the formation of air gap and hence this affects the solidification process and hence it is one of the important factors responsible for quality of casting.

Consider the following equation

$$Q = hA_s(T_m - T_s) \tag{1}$$

Where, Q is heat transfer from molten metal to mold in w, h is interfacial heat transfer coefficient (IHTC) in w/m^{2}K, A_s is area of surface through which heat is transferred, T_m is metal temperature and T_s is mold temperature.

The magnitude of h is depends of various factor out of which section is important factor as solidification time is higher for thicker section which gives less importance to h but in case of thin section solidification time is small which gives high importance to h.

Beck et al. [3] developed various solution techniques to inverse heat conduction problems. As T_m and T_s is very difficult to measure accurately which leads to inverse heat conduction problem. Beck et al compared several methods for solution of the inverse heat conduction problem of estimating surface heat flux from interior temperature histories. Various methods were Function specification method, iterative regularization, Tikhonov regularization and green's function method. Though all methods gave similar results, function specification method is conceptually simpler.

II. METHODS FOR ESTIMATION OF IHTC

After reviewing the literature, it is found out that two methods are available to estimate IHTC. In first method, gap size is taken in consideration for estimation of IHTC and in second method, temperature data given much more importance for estimation of IHTC. The value of IHTC is depends on method adopted. R. Rajaram and R. Velraj [1] compared these two methods for evaluation of IHTC for cylindrical casting and concluded that control volume technique produces accurate and reliable results.

A. Control volume technique

This method is based on energy balance equation between different control volumes. Energy balance equation is applied to each control volume to determine surface temperature and heat flow. Control volume used in the analysis is as shown in fig. 1 which is rectangular in shape (Rectangular casting and mould wall interface).

Heat Q_E conducted through mold wall is can be found out from known temperatures T_4 and T_4 using heat conduction equation

$$Q_E = k_m \times A \times \frac{(T_3 - T_4)}{\Delta x}$$

On rearranging above equation, we get

$$T_4 = T_3 - \frac{Q_E \Delta x}{k_m A} \quad (2)$$

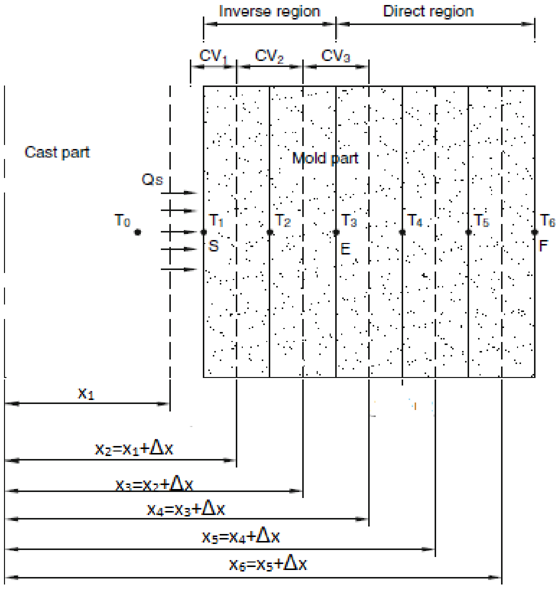

Fig.1. 1 D heat conduction problem with control volume grid (Rectangular wall)

Relation between mold surface temperature T_1 and casting temperature at any particular moment can be found out using heat conduction equation at mold surface. Here, Q_E is heat flow at mold surface.

$$\mathrm{Q_S} = \mathrm{k_c} \times \mathrm{A} \times \frac{(\mathrm{T_0} - \mathrm{T_1})}{\Delta \mathrm{x}}$$

On rearranging above equation, we get

$$\mathrm{T_0} = \mathrm{T_1} + \frac{\mathrm{Q_S} \Delta \mathrm{x}}{\mathrm{k_c} \mathrm{A}} \quad (3)$$

In the present method, energy balance is first applied to control volume 3. The unknown temperature T_2 is determined from known temperature T_2 by using heat conduction equation Q_E.

$$A \Delta x \rho_m C_m \frac{dT_3}{dt} = \frac{A k_m (T_2 - T_3)}{\Delta x} - \frac{A k_m (T_3 - T_4)}{\Delta x}$$

On substitution of T4 and rearranging above equation, we get

$$T_2 = T_3 + \frac{\Delta x^2}{\alpha_m} \frac{dT_3}{dt} + \frac{Q_E \Delta x}{k_m A} \quad (4)$$

Applying energy balance equation for control volume 2, we get

$$A \Delta x \rho_m C_m \frac{dT_2}{dt} = \frac{A k_m (T_1 - T_2)}{\Delta x} - \frac{A k_m (T_2 - T_3)}{\Delta x}$$

On substitution of dT2/dt and rearranging above equation, we get

$$T_1 = T_2 + \frac{2\Delta x^2}{\alpha_m} \frac{dT_3}{dt} + \frac{\Delta x^4}{\alpha_m^2} \frac{d^2 T_3}{dt^2} + \frac{Q_E \Delta x}{k_m A} + \frac{\Delta x^3}{\alpha_m k_m A} \frac{dQ_E}{dt} \quad (5)$$

On substitution of T_2 and rearranging above equation, we get

$$T_1 = T_3 + \frac{3\Delta x^2}{\alpha_m} \frac{dT_3}{dt} + \frac{\Delta x^4}{\alpha_m^2} \frac{d^2 T_3}{dt^2} + \frac{2 Q_E \Delta x}{k_m A} + \frac{\Delta x^3}{\alpha_m k_m A} \frac{dQ_E}{dt} \quad (6)$$

Applying energy balance equation for control volume 1, we get,

$$\frac{A \Delta x (\rho_m C_m + \rho_m C_m)}{2} \frac{dT_1}{dt} = \frac{A k_c (T_0 - T_1)}{\Delta x} - \frac{A k_m (T_1 - T_2)}{\Delta x}$$

On substitution of T_0, T_1, T_2, and dT_1/dt in above equation, we get

$$Q_S = Q_E + \Delta x A \times \left(\frac{Z}{2} + \frac{2k_m}{\alpha_m}\right) \frac{dT_3}{dt} + \frac{\Delta x^3 A}{\alpha_m} \left(\frac{3Z}{2} + \frac{k_m}{\alpha_m}\right) \frac{d^2 T_3}{dt^2} + \frac{\Delta x^5 Z A}{2\alpha_m^2} \frac{d^3 T_3}{dt^3} + \Delta x^2 \left(\frac{Z}{k_m} + \frac{1}{\alpha_m}\right) \frac{dQ_E}{dt} + \frac{\Delta x^4 Z}{2\alpha_m k_m} \frac{d^2 Q_E}{dt^2} \quad (7)$$

Where, $\mathrm{Z} = (\rho_\mathrm{m} \mathrm{C_m} + \rho_\mathrm{m} \mathrm{C_m})$

Equation (7) gives heat flows from cast surface to mold surface and IHTC (h) can be evaluated using equation (1).

B. *Beck's Method*

This method is widely used by the researcher to evaluate interfacial heat transfer coefficient though this method was introduced by beck for the aerospace application. This method uses the temperature data measured inside the cast and mold.

In this method, first the equation of T in terms of "x" and "t" i.e. distance and time respectively is derived to find estimated value of T. "q" is assumed to be constant for particular time step in this method temperature distribution id determined using that value of "q".

Using steady state heat conduction equation without any internal heat generation,

$$k \frac{\partial^2 T}{\partial x^2} = \rho C \frac{\partial T}{\partial t} \quad (8)$$

The introduction of finite difference term in Equation (8) gives,

$$\rho C \left(\frac{T_i^{n+1} - T_i^n}{\Delta t}\right) = k_m \left(\frac{T_{i-1}^n - 2T_i^n + T_{i+1}^n}{\Delta x^2}\right)$$

Where, subscripts indicates, number denoted to thermocouple and superscripts indicate time.

On rearranging above equation, we get

$$T_i^{n+1} = T_i^n + F_o(T_{i-1}^n - 2T_i^n + T_{i+1}^n) \qquad (9)$$

Here, Fourier No. $\mathrm{F_o} = \frac{\mathrm{k_m}}{\rho \mathrm{C}} \frac{\Delta t}{\Delta x^2}$

But heat conducted is,

$$q = k_m \left(\frac{T_{i-1}^n - T_{i+1}^n}{2\Delta x} \right)$$

On rearranging above equation, we get

$$T_{i-1}^n = \frac{2q\Delta x}{k_m} + T_{i+1}^n$$

Substituting value of $\mathrm{T_{i-1}^n}$ in equation (9) and rearranging, we get

$$T_i^{n+1} = T_i^n + 2F_o\left(T_{i+1}^n - T_i^n + \frac{q\Delta x}{k_m}\right) \qquad (10)$$

The assumed value of "q" is changed by small fraction "εq" where "ε" is small fraction and new $\mathrm{T_{est}}$ is determined. Using these value, sensitivity coefficient is calculated for all iteration as follows,

$$X^{n+j-1} = \frac{T_{est}^{n+j-1} q^n (1+\varepsilon) - T_{est}^{n+j-1} q^n}{\varepsilon q^n}$$

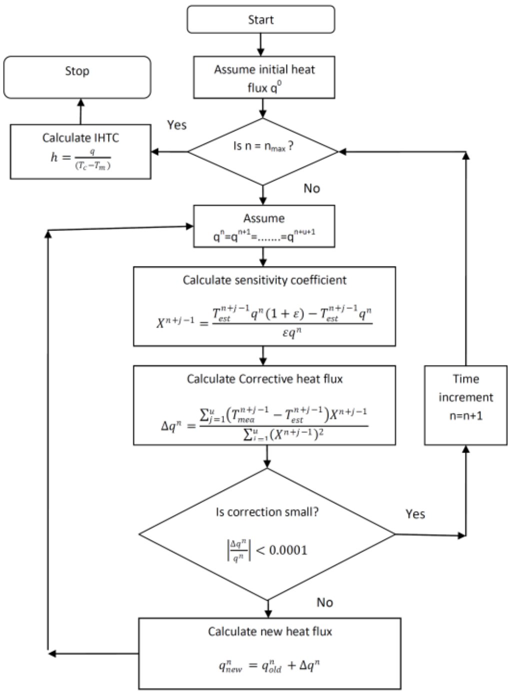

Fig.2. Flowchart of Beck's Method in simplified form

Again,

$$\Delta q^n = \frac{\sum_{j=1}^{u} (T_{mea}^{n+j-1} - T_{est}^{n+j-1}) X^{n+j-1}}{\sum_{j=1}^{u} (X^{n+j-1})^2}$$

Where, j is time step, $\mathrm{T_{mea}^{n+j-1}}$ is measured temperature value and $\mathrm{T_{est}^{n+j-1}}$ is estimated temperature value.

Corrected q is calculated using

$$q_{new}^n = q_{old}^n + \Delta q^n$$

The resultant value of temperature and q is taken as initial value for next cycle and this process is repeated till the following condition reached.

$$\left|\frac{\Delta q^n}{q^n}\right| < 0.0001$$

III. FACTORS AFFECTING IHTC

IHTC has always very important in design point of view. Many feeding system design decisions such as insulation pad, chills are depends on IHTC values. IHTC is depends on various factors like temperature of melt, mold and casting material, width of air gap formed between mold and casting during solidification, surface roughness, mould temperature etc. In gravity die casting, graphite based die coat is very commonly used. Graphite has good thermal conductivity, and thus it helps to produce dense smooth surface to cast product by allowing rapid solidification. In addition it also acts as lubricants to reduce wear and leading longer mold life. K. Narayan Prabhu and K.M. Suresha [4] studied the effect of superheat, mold and casting material on IHTC for graphite lined permanent mold. They conclude that, increased in the melt superheat resulted in higher heat flux due to increased in fluidity and wettability of liquid metal at higher temperature. Increased in superheat resulted in finer microstructure.

A. Hamasaiid et al. [8] conducted an experiment to compare the effect of coating material and thickness on heat transfer in permanent mold casting process for aluminum alloy. In permanent mold casting process die coating is used for many reasons like protection from wear, lubrication, easy removal and heat transfer rate control. Among which die coating is the most important single factor controlling heat transfer rate in permanent mold casting and hence its effect becomes very much important to study for producing defect free casting. Heat transfer coefficient during solidification in casting is decreases as the coating thickness increases. But the graphite base die coating gives higher heat transfer coefficient for same thickness than ceramic based die coating.

Netto et al [5] studied the heat transfer between solidifying light metal strip moving substrate and conclude that the interfacial heat flux depends on thickness of strip, initial superheat and coating material. Lewis et al [6] studied various factor affecting IHTC to allow for optimum design via thermal stress model. Their study mainly involves thermo-elasto-visco-plastic analysis for predicting air gap widths, use of interface element, to account for metal mold relative motion, equation to relate an air gap width to IHTC.

The relation between air gap widths to interfacial coefficient used by many authors

$$h = \frac{k_a}{\delta_{ag}}$$

In this technique, a user defined constant heat transfer value is used until the formation of air gap and later that value is decreases according to above equation.

Lewis et al [6] proposed a modification to above equation

$$h = \frac{k_a}{\delta_{ag} + \frac{k_a}{h_{ini}}}$$

Where, k_a is conductivity of air, δ_{ag} is air gap width and h_{ini} is initial value of interfacial heat transfer coefficient.

Lewis and Ransing [7] proposed a correlation which can capture any realistic heat transfer coefficient variation with respect to casting interface temperature. The empirical equation has three constant which can be used as design variable.

$$h = \frac{e^{a_1} e^{-a_2/x_2}}{x^{a_3}}$$

$$x = \sqrt{2a_2/a_3} + max(0, T_L - T_{int})$$

Where, a_1, a_2, a_3 are arbitrary constant. T_L Is liquidus temperature and T_{int} is the casting interface temperature. With proper value of arbitrary constant, the above correlation can match any experimentally observed variation of interfacial heat transfer coefficient with respect to casting interface temperature.

IV. CONCLUSION

Interfacial heat transfer coefficient is an important parameter which is very important for solving heat transfer problem in casting solidification process. Hence, it is an input in various casting simulation software.

Various methods are available to estimate IHTC value but Beck's algorithm is widely used by researcher. Another method available is control volume technique. Control volume technique uses the air gap size for estimation of IHTC while Beck's algorithm uses measured temperature data inside cast and mold.

IHTC value is depends on various factors like pouring temperature, mold temperature, surface roughness, die coat material and die coat thickness. If die coat thickness increases the IHTC across that portion decreases. Hence, in actual casting process, die coat thickness is increases here slow solidification required and die coat thickness can be decreases where high solidification rate required for producing defect free casting

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