Comparison of Analytical Model and Semi Empirical Model of Pressure Die Casting Die

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Abstract— Thermal profile of die for pressure die casting play an important role to manufacturing casting automobile parts. In this process molten metal is poured and applied pressure on it to fix in die. Within 20 second period of time liquid metal is converted into usable product form. This was only successfully possible after various numbers of attempt made on pressure die casting machines. For new product it was quite difficult to forecast thermal profile for die as well as casting parts. Quality of casting parts strongly depends on temperature distribution of die. This distribution can controlled by water mass flow rate applied to die for cooling purpose. This cooling profile neither too sudden nor too gradual. Optimum temperature distribution required in die and casting part contact area. It is necessary to study the process parameters on the performance of the die because the commercial setup is expensive. Hence, an attempt is made to investigate the effect of parameters on the thermal performance (cooling time) of the die. Semi empirical model prepare based on die thermal characteristics and die geometry. It is difficult to understand the effect of each individual parameter via experiments because it demands higher operating and tooling cost. Thus, it is always viable to use analytical or numerical approach. In present study, a semi empirical model and analytical model has been compared. This both model has been developed considering the parameters like density of water, velocity of water, diameter of die, temperature difference (die temperature and water temperature). The response has been selected as cooling time as thermal performance indicator. In order to validate the results, an analytical approach was used. It was observed that the results are found in good agreement between semi empirical model and analytical approach. Therefore, semi empirical model can be effectively used to estimate cooling time for various geometrical and operating conditions.

Index Terms— Pressure die casting, Semi Empirical Model, Analytical Model, Cooling Time.

1. INTRODUCTION

The Pressure die casting process is usually use for mass production and components made from nonferrous alloy. The design of the thermal system is essential because it affects Casting quality Casting production rate (economics) and Die life (economics).Due to the cyclic characteristics and complicated process parameters in the process, the modelling of the thermal system for the process is different from that of conventional methods.[1] During the solidification process the solidified shell is subjected to varying thermal and mechanical load, which can cause defects in the cast products if the resulting stresses and strains exceed critical values.[2] However, defects such as shrinkage, cold shuts and gas pores are often observed in the cast parts. These defects affect the mechanical properties of the casting components, which greatly restrict the application of specific alloys. Huge work has been already done to investigate the casting process, such as the application of CAD/CAE system, the method of numerical simulation, etc.[3] Efforts has been made to predicting relationship of microstructure in real parts and cooling rate associated to the modulus of casting and mold materials. These parameter correlations is used to thermal analysis of pressure die casting die with experimentation work.[4] The density, fracture energy, impact energy, yield strength and ultimate tensile strength of the castings were related to the solidification time of alloys, in the as-cast and precipitation hardening conditions; the shorter the solidification time, the higher is the value of the property.[5] If the thickness of the die layer is thin, the cooling effect is better compared to a thick one. When it is too thin, a ripple-shaped thermal expansion is developed on the surface and the surface quality of the specimen is deteriorated. Therefore, the thickness of the cooling layer should be considered carefully.[6] Various fixed preconditions are required for qualitative casting. Influencing parameters for these are cooling profile of the material, the quantity of the materials, the method of the cooling of the casting die, the thermal conductivity of the die material and cast material, and the time at which die and casted parts contact each other's.[7] Some researchers work on various techniques to predict the cooling or solidification profile of materials, one of them is DSC techniques. Materials melting point as well as latent heat easily calculated by this methods. This techniques is only useful for limited parametric works. It measures the energy evolved/absorbed by a sample as it cools, heated, or held at temperature. However, DSC is limited to small size samples, in the milligram range, and by cooling and heating rates. The uses of this techniques was limited for forecasting of cooling profile of die due to: High cost, requires skilled work experience and is not suitable for casting shop floor operations.[8] From the starting of PDC cycle, the mold is filled with liquid metal. Heat transfer was start through the mold to the atmosphere. So the temperature reduces and solidification starts from the mold wall and progresses instantly in case of pressure die casting. Due that latent heat is

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released at the solidification front if it is pure metal and in the mushy zone if it is alloys. The modelling of solidification technique has remained a subject matter of energetic pastime for numerous decades. Earlier studies were confined generally to one-dimensional models with approximations such as constant for some properties. Recently analytical and computational techniques were develop to increase modelling capability work and improve quality of castings. An aggregate of mould and molten metal temperatures, respectively, either 100°C and 800°C or 200°C and 700°C appears to be the applicable value, for the casting.[9] To achieve the adequate refinement of the primary Si particles, minimum superheat temperature was required. Thermal and chemical modifications effects provides this modifications. The results shows perception of the thermal characteristics for the newly developed hypereutectic Al–20% Si alloy and might be used to optimize the pouring molten metal related parameters handling on casting floor. This techniques has limited capability to get the required alloy micro structural and service characteristics.[10] An empirical relations and human experience provides a feasible solutions in most of the case. But this technique never end up with an optimal solution. For optimization of parameters, Genetic algorithm (GA) along with empirical relationship can be used for limited design considerations.[11] Genetic algorithms and neural networks are used to optimize pressure die casting process parameter by simulation techniques. The partial replacement of the simulation with ANN models also used as simulation meta-models. Simulation techniques have some limitations. Third phase of PDC process was not perfectly modelled. Execution times is large depending on the complexity of the model.[12] For forecasting of thermal system of metals and alloys the semi-empirical equations method can be used for any locations in geometry. This is possible only if the empirical equations related to the heat transfer coefficients is used to applied pressures and 3 phase solidifying temperatures are known. Thermal system of die gives optimum solidification period of casted parts, which was indicate temperature of die was influencing parameter to get qualitative castings.[13] Quality of casting and its cycle time reflects in calculation of casted parts cost. Without taking all parametric considerations it is not possible to reduced direct cycle time by fastest heat removal rate. Melting of liquid of the casting alloy is required during die filling process. Ideal targeted die surface temperatures are discussed but it is critical that analytical logic be incorporated in the design of the thermal system for the die casting die. Die cavity fill time is very sort, it represents only a very little portion of the total cost reflecting cycle time, However, heat removal rate is critical parameter to get optimum cycle speed (shots per hour). Therefore, the important aspects of die thermal system are now offered, this.[14]

II. SEMI EMPIRICAL MODEL

The dimensional analysis is the approach of minimizing the complicated experimental trials. The method can be carried out by two techniques – 1) Rayleigh's method and 2) Buckingham's π theorem. Selection of the method depends on the number of parameters that are involved in the problem. Rayleigh's method is suitable for determining the expression for a variable which depends upon maximum four variables only. When the problem involves higher number of variables, Buckingham's π theorem is more suitable.

Buckingham's π theorem states that "If there are n variables (independent and dependent) in a physical phenomenon and if these variables contain m fundamental dimensions (M, L, T, θ, I), then the variables are arranged into (n-m) dimensionless terms. Each term is called π term" (R.k.Bansal, 2012)

If X1 is a dependent parameter and X2, X3....Xn are independent parameters on which X1 depends, it can be mathematically expressed as under:

$$X_1 = f\left(X_2, X_3 ... X_n\right) \quad \text{--(1)}$$

It can also be written as:

$$f\left(X_1, X_2, X_3 ... X_n\right) \quad \text{--(2)}$$

which is a dimensionally analogous equation which contains n parameters. If there are m elemental dimensions, then the above expression can be written in the form of (n–m) π terms as under:

$$f\left(\pi_1, \pi_2, \pi_3 ... \pi_{n-m}\right) \quad \text{--(3)}$$

Each of the π terms is dimensionless of the system. Division or multiplication by a constant does not alter the character of the π term. Each π term contain m+1 variables, where m is the number of basic dimensions and is also called repeating variables.

The selection of repeating variables is governed by the following considerations (R.k.Bansal, 2012):

1) Dependent parameters should not be selected as repeating factor as far as possible.
2) Repeating factors should be selected in such a way that they belong to different categories.
3) Repeating factors should not form a dimensionless group.
4) Repeating factors jointly must have same number of basic dimensions.
5) Two repeating factors should not have same dimensions.

Model Development:

Table 1 Parameters and their dimensions

Sr. No.	Name	Unit	Dimension
1	Dynamic Viscosity of Fluid (μ)	kg/m.s	$M^1 L^{-1} T^{-1}$
2	Specific Heat (C_p)	J/kg.K	$M^0 L^2 T^{-2}\theta^{-1}$
3	Thermal Conductivity (k)	W/m.K	$M^1 L^1 T^{-3}\theta^{-1}$
4	Density (ρ)	kg/m^3	$M^1 L^{-3} T^0$
5	Velocity of Fluid (V)	m/s	$M^0 L^1 T^{-1}$
6	Diameter of Die (D)	m	$M^0 L^1 T^0$
7	Convective Heat transfer Coefficient (h)	W/m^2K	$M^1 L^0 T^{-3}\theta^{-1}$

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Sr. No.	Name	Unit	Dimension
8	Length of Die (L)	m	$M^0 L^1 T^0$
9	Cross-section Area of Die (A)	m^2	$M^0 L^2 T^0$
10	Temperature Difference (ΔT)	K	$M^0 L^0 T^0 \theta^1$
11	Mass Flow Rate (m)	kg/sec	$M^1 L^0 T^{-1}$
12	Diameter of Inner Hole (d_1)	m	$M^0 L^1 T^0$
13	Diameter of Outer Hole (d_2)	m	$M^0 L^1 T^0$
14	Heat Transfer Rate (Q^*)	J/sec	$M^1 L^2 T^{-3}$
15	Total Heat transfer (Q_t)	J	$M^1 L^2 T^{-2}$
16	Time for Heat Transfer (t)	sec	$M^0 L^0 T^1$

The input parameters are listed below which are used for model development.

1) Operating Variables

Four operating parameters have been selected based on literature survey and preliminary work. The parameters include Density (ρ),Velocity of Fluid (V),Diameter of Die (D), Temperature Difference (ΔT).These are the major contributory factors as these can be vary by operator therefore, it is required to consider these four parameters.

In present case, Time (t) can be expressed as:

$$t = f\left(\mu, C_p, k, \rho, V, D, h, L, A, \Delta T, m, d_1, d_2, Q^{\bullet}, Q_t\right) = 0 \quad (4)$$

$$f = \left(\mu, C_p, k, \rho, V, D, h, L, A, \Delta T, m, d_1, d_2, Q^{\bullet}, Q_t\right) = 0 \quad \text{-(5)}$$

Fundamental dimensions include: M, L, T

Their are 4 repeating variables. These repeating variables are by using the considerations proposed by Cengel and Cimbala, (2012) and Bansal (2012) as mentioned above.

No. of dimensionless parameters (π- terms) =Total number of parameters – No. of fundamental dimensions

= 16 - 4 = 12

Non-repeating Variables = 12

Now, based on Buckingham’s theorem, equation (2) can be written as,

$$f = \left(\pi_1, \pi_2, \pi_3, \pi_4, \pi_5, \pi_6, \pi_7, \pi_8, \pi_9, \pi_{10}, \pi_{11}, \pi_{12}\right) = 0 \quad \text{- (6)}$$

These π term can be written as follows:

$\pi_1 = \rho^a V^b D^c \Delta T^d\, t$

$= (M^1 L^{-3})^a (L^1 T^{-1})^b (L^1)^c (\theta^1)^d (T^1)$--(v)

$\pi_1 = \rho^0 V^1 D^{-1} \Delta T^0\, t$

The calculations of power indices are evaluated as:

$\pi_1 = \rho^0 V^1 D^{-1} \Delta T^0\, t = M^0 L^0 T^0 \theta^0$

M → a=0 then a = 0

L → $-3a_{12} + b_{12} + c_{12} = 0$ then b = 1

T → $-b_{12} + 1 = 0$ then c = -1

θ → $d_{12} = 0$ then d = 0

$$\pi_1 = \frac{V*t}{D} \quad \text{---(7)}$$

Similarly, other π – terms and corresponding power indices can be calculated. After calculating all the π-terms and their power indices the equation (3) can be written as,

$$\pi = t(\pi_1)^a * (\pi_2)^b * (\pi_3)^c * (\pi_4)^d * (\pi_5)^e * (\pi_6)^f * (\pi_7)^g * (\pi_8)^h * (\pi_9)^i * (\pi_{10})^j * (\pi_{11})^k \quad \text{\_(8)}$$

where, a, b, c, d, e, f, g, h, i, j, k are constants which can be find out using curve fitting. On substitution of the expressions for π terms, we get, The constants in the equation of the resultant force can be found using non-linear estimation.

$$t = \frac{D}{V}\left[\left\{\frac{\mu}{\rho*V*D}\right\}*\left\{\frac{Cp*\Delta T}{V^2}\right\}*\left\{\frac{k*\Delta T}{\rho*V*D^3}\right\}*\left\{\frac{h*\Delta T}{\rho*V*D^2}\right\}*\left\{\frac{L}{D}\right\}*\left\{\frac{A}{D^2}\right\}*\left\{\frac{m}{\rho*V*D^2}\right\}*\left\{\frac{d1}{D}\right\}*\left\{\frac{d2}{D}\right\}*\left\{\frac{Q*}{\rho*V^3*D^2}\right\}\right] \quad \text{---(9)}$$

The common agenda of nonlinear estimation is to established relationship between independent variable with dependent variable. In present case, gauss Newton method has been used for nonlinear estimation.[15]The main attribute of this model is to consider all the variables depending upon the process. Hence, all major variables are considered to estimate the cooling time.

III. ANALYTICAL MODEL

This section presents the analytical model of the cooling time for the pressure die casting mold. The standard methodology has been adopted to establish the relationship. It contains the Prandtl number, Reynolds number, Nusselt number, Heat transfer rate and total heat transfer to determine the cooling time. The cooling time is the critical response because the effectiveness of the process is mainly depending upon cooling time. For different velocity of water, the constant numbers are calculated and based on them the cooling time has been determined.

Prandtl Number:

The Prandtl number is defined as the ratio of momentum diffusivity to thermal diffusivity. The momentum diffusivity or kinematic viscosity which tells us the material resistance to shear-flows in relation to density.

$$Pr = \frac{\mu*Cp}{k} \quad \text{--------------------(9)}$$

Where,

μ = dynamic viscosity [N.s/m2]

Cp = specific heat [J/kg.K]

K = thermal conductivity [W/m.K]

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Reynolds Number:

The Reynolds number is the ratio of inertia force to viscous. It can be predict that when the viscous force is more than it is sufficient to keep all the fluid particle in line , then it can be said that the flow is laminar.

$$Re = \frac{\rho * V * D}{\mu}$$ ---------------(10)

Where,

V = flow velocity,

D = characteristic linear dimension, (travelled length of the fluid)

v = kinematic viscosity (m2/s)

Nusselt Number:

Nusselt number is equal to the dimensionless temperature gradient at the surface, and it provides a measure of the convection heat transfer occurring at the surface.

$$Nu = \frac{h * L}{k}$$ -----------(11)

Where,

h =convective heat transfer coefficient [W/m2.K]

L = characteristic length

k = thermal conductivity of the fluid [W/m.K]

Heat Transfer Rate:

The heat transfer coefficient in thermodynamics and in mechanics is the proportionality constant between the heat flux and the thermodynamic driving force for the flow of heat.

$$Q^{\bullet} = h * A * \Delta T$$ -----(12)

Where,

A = surface area for heat transfer

ΔT = temperature difference

Total Heat Transfer:

The total heat transfer can be estimated based on the following equation.

$$Q_t = m * Cp * \Delta T$$ -------------------------------- (13)

$$m = \rho\left[\left[\frac{\pi}{4} * D^2 * L\right] - \left[\pi * d1^2\right] - \left[\frac{\pi}{4} * d2^2\right]\right]$$ --- (14)

Time for Heat Transfer:

$$t = \frac{Q_t}{Q^{\bullet}}$$ ---- (15)

Mass Flow Rate:

$$m^{\bullet} = A * V * \rho$$ ----(16)

Effect when Change in Velocity:

Based on the methodology described, an analytical model has been developed. The effect of velocity of water has been studied.

Table 2 Effect of Water Mass Flow Rate on Other Variable

Sr. No.	v [m/sec]	Pr	Re	Nu	h [W/m^2.K]	Initial Temperature[K]	Steel Temperature[K]	Water Temperature[K]	Q1 [J/sec]	Qt [J]	Time [sec]
1	0.25	6.977	2500	26.15	1569	623	550	300	15470	280679	18.14
2	1	6.977	10000	79.28	4757	623	513	300	43579	756183	18.19
3	2.5	6.977	25000	165	9901	623	430	300	75214	1370000	18.22

Table 2 shows the calculated results through the analytical model. The cooling time for different velocity of the flow is found to be 18.14 s (0.25 m/s), 18.19 s (1 m/s) and 18.22 (2.5 m/s). It was observed that the cooling time is slightly increasing with the increase in the velocity of water. The analytical model has been developed to estimate the cooling time. These results are validated with the proposed semi empirical model. The results are found in good conformity.

RESULT AND DISCUSSION

In present research, a semi empirical model has been proposed to estimate the cooling time for the pressure die casting mold. The dimensional analysis concept was used to develop the semi empirical model. The results are validated with the analytical model. The comparison of results between analytical and semi empirical model are presented in Fig. 1

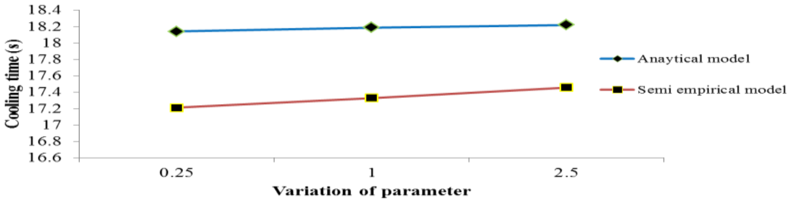

Figure 1: Comparison of cooling time between analytical and semi empirical model

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It can be observed that as the velocity of the water increases then cooling time increases slightly. The results of the each individual reading are presented in Table 3. It can be seen that the maximum percentage error is found to be 5.12 for the velocity of 0.25 m/s. Further, other error percentage for 1 m/s and 2.5 m/s are found to be 4.72% and 4.17% respectively. This variation is due to the approximate nature of the both methods. It means analytical model and semi empirical model both are required certain assumptions. Thus the convergence of the method is depending upon the nature of the process and it may be the probable reason for the variation.

Table 3: Comparison of results between analytical and simulation

Velocity (m/s)	Cooling Time (sec.)		Error (%)
	Analytical	Semi Empirical	
0.25	18.14	17.21	5.12
1	18.19	17.33	4.72
2.5	18.22	17.46	4.17

The parameters and their values which are used for the analytical model, the same are used in semi empirical model to maintain the uniformity. The results are found in good accordance between the analytical and semi empirical model.

IV. CONCLUSION

The semi empirical model has been developed based on the dimensional analysis concept. Based on the present study, following conclusions can be drafted.

- Semi empirical model can be effectively used for estimating the cooling time of pressure die casting mold. The method is very simple and easy to implement. Thus, expensive experimental runs related to pressure die casting can be eliminated.
- The proposed model is able to handle wide variety of the variables which are related to the PDC process. Therefore, effect of individual parameter along with the combined effect of the parameters can be predicted for cooling time.
- An analytical model is proposed considering the fundamental governing equations of heat transfer. The results obtained through analytical model and semi empirical model are checked for adequacy. The results are found in good agreement with reasonable error.
- The maximum percentage error was found to be 5.12 for 0.25 m/s flow rate. It is due to the nature of approximation for both the approaches i.e. analytical and experimental.
- The semi empirical/analytical model can be used to unveil the issues related to the PDC process like temperature variation, surface integrity, defects etc.

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