Proceedings of the 11th World Congress on Mechanical, Chemical, and Material Engineering (MCM'25)
Paris, France - August, 2025
Paper No. HTFF 131
DOI: 10.11159/htff25.131

An Analysis and Optimization of the Cooling Channel Design Of the High-Pressure Die Casting (HPDC) Process Using Computer-Aided Engineering (CAE)

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Abstract - The application of computer-aided engineering (CAE) has grown significantly in the industrial environment, particularly in the manufacturing industry. It is facilitated by computational techniques that allow numerical analysis of partial differential equation models in large quantities. The high pressure die casting industry is one of the manufacturing industries widely used to produce components for machines with high dimensional accuracy and efficiency. During the casting process, heat exchange occurs within the die casting mold. The surface temperature of the mold must be maintained throughout the cavity surface in order to reduce casting defects that may occur during the molding process. Therefore, the cooling channel design has been optimized in order to maintain an even temperature on the cavity surface. The cooling channel has been embedded in the mold based on the amount of heat, and the surface temperature of each part of the mold has been analyzed statistically. The results showed that the cavity surface temperature was evenly distributed throughout each mold part when the parameters and positions of the cooling channel were optimized using computer-aided engineering (CAE), The cover die and ejector die mold surface temperature regions, with increases from 83.88% to 85.60% and 52.86% to 72.83%, respectively. It allows free placement of cooling channel positions, modifying water flow rates, and repeating simulations. This is to obtain the desired surface temperature distribution and to reduce production costs.

Keywords: cooling channel design, cavity surface temperature, high pressure die casting, computer-aided engineering

Introduction

A high pressure die casting process is widely used in numerous industries because of its capability to manufacture components that are dimensionally accurate and efficient. Essentially, this process consists of liquid metal filled, solidified, mold opened, casting ejected, release agent sprayed, air blown, and mold closed (1 cycle) see figure 1. This process involves heat exchange which affects the mold's shape and durability due to thermal stress. Ding et al.[1] investigated the failure analysis of H13 Steel mold for HPDC found that the cavity surface has residual stress up to 555 MPa and numerous thermal fatigue cracks in the range of 1-30 mm from the mold surface. According to Mrvar et al. [2] studied that cracks occurred on the cold surface of the shoot sleeve, and the average crack length increased as the number of HPDC cycles increased.

This phenomenon is caused by thermal stress. Therefore, it is necessary to maintain thermal stability during the casting process. Wu's research revealed a drastic transformation in tensile to compression stresses within the surface mold cavity [3]. Thermal control in molds can be achieved by applying cooling channels and spraying. Cooling channels contribute significantly to releasing heat in HPDC molds. This method, which was known as conventional cooling channels in the past, has long been used to release heat in molds, currently used in simple geometry [4]. The recent introduction of addictive manufacturing technology has enabled cooling channels to be developed into more complex forms. Many studies have shown that conformal cooling channels dissipate more heat than traditional cooling channels. A study by Anand revealed that conformal cooling channels can enhance mold thermal management. It can improve the uniformity of mold cooling, the quality of casting, and the life of dies [5].

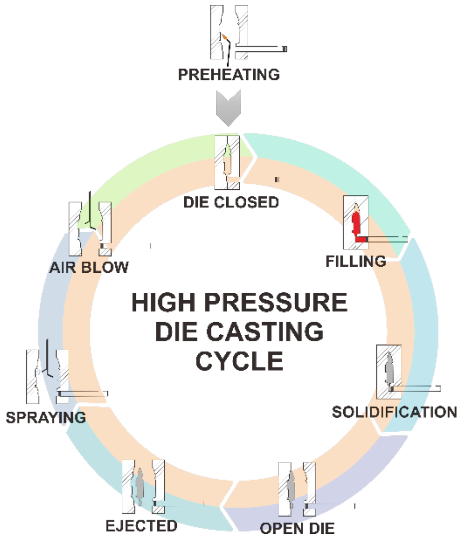


Fig. 1: High pressure die casting cycle.

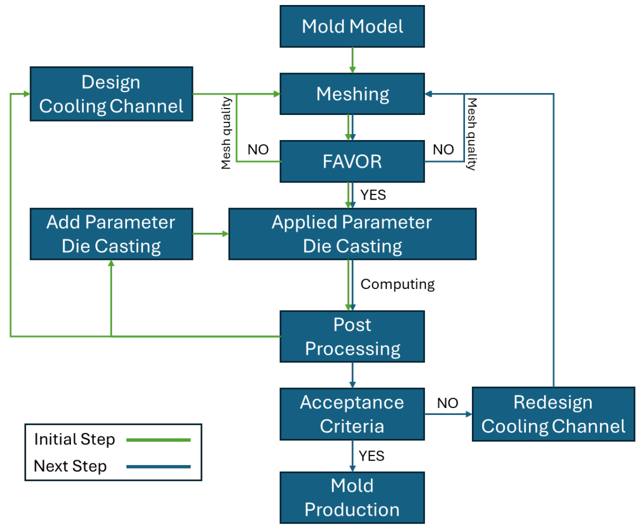


Fig. 2: Flowchart simulation of HPDC process.

Its application requires that the cooling channel be controlled to maintain a thermal balance inside the mold. The governing equation for controlling the cooling channel in the mold is Newton's law of cooling, in this equation the ability of the cooling channel to dissipate heat is obtained. Moreover, it is important to take into consideration the geometry (distance, diameter) and properties of the coolant (flowrate, temperature) to optimize the cooling effectiveness [4].

Spraying is a method used to control the surface temperature of cavities in molds, it typically consists of 1% lubricant agent and 99% water, as a result of its high proportion of water, the solution is used to cool surfaces of mold or is known as a water-based release agent. It has been shown in several studies that, water-based release agent sprays affect mold cracks [6, 7]. Currently, a water free release agent (WFA) has been introduced with its ability to reduce casting defects and extend mold life. According to Aoki et al., water-based die lubricant has a 3% adhesion efficiency compared to WFA's 25%. If electrostatic spraying is applied, the adhesion efficiency increases to 65% [8]. In other words, this solution does not release heat on the mold surface, but rather works as a film layer to release casting parts.

The HPDC process involves heat exchange at every stage of the cycle. To improve casting quality, cycle time, mold life and prevent casting defects, the mold temperature must be controlled at a specific temperature [9, 10]. In several studies, it was found that a mold surface temperature of 180 - 210 ^{o}C is an ideal temperature [10, 11]. The solution to this challenge lies in using computer aided engineering (CAE) as a means of modeling before the mold production procedure.

Computer-aided engineering (CAE) is widely used in high pressure die casting, a CAE simulation can be used to design and develop a casting process, tooling, and identify and predict defects [12]. According to Kwon [13] studied, CAE simulation was used in designing a gate system to reduce die casting defects. Lee [14] studied, CAE simulation to predict shrinkage defects by varying conditions such as liquid metal injection temperature and injection speed. Cornacchia et al. [15] studied Computer-aided engineering (CAE) simulation of the HPDC process was employed to predict and enhance casting quality and confirm foundry feasibility. Essentially, this modeling involves the conservation equations for mass, momentum, and energy. These equations are partial differential equations that can be solved numerically. There are many variations of the Computer Fluid Dynamic solver available, both open source and commercial. The use of this solver must be adjusted to the actual conditions to get appropriate results.

In this study, numerical modeling was carried out to analyze heat exchange on the mold cavity surface starting from die closing, filling, solidification, opening the die, ejecting, spraying, and air blowing stages. The aim of this study is to analyze and optimize cooling channel designs based on heat content and hotspots using computer-aided engineering (CAE).

Methodology

In this study, CAE simulations were performed with Flow 3D Cast software using finite volume method (FVM) numerical technique. The simulation flowchart is shown in Fig. 2. Models for molds are created using CAD software, as shown in Fig 3. Importing the mold model file into the flow 3D cast application, the mesh size used is 1.5 mm and the total number of mesh blocks were 55.724.760 cells, as shown in Fig. 4. The next step is to evaluate the meshing using the FAVOR method (Fractional Area/Volume Obstacle Representation). According to this method, meshing is calculated based on the size of the cell that meets the overall representation of the model. Then enter the simulation parameters listed in tables 1 and 2. Material properties for the ADC 12 alloy and the H13 mold were taken from the flow 3d cast software database. When the computation process has been completed, the next step is to perform post-processing, including visualizing and collecting data for use in designing the cooling channel. After the cooling channel design has been completed, re-simulate and add the cooling channel parameters to the flow 3D cast software. After all stages have been appropriated, the computation is carried out. Computational results are processed and evaluated. An analysis of the surface temperature of the mold in direct contact with its liquid metal component only (see Fig. 5) is conducted in this study. and classified into several temperature ranges. The impact of the cooling channel on the mold surface temperature is adjusted according to acceptance criteria, and if appropriate, then the mold can be manufactured.

Table 1: Parameter of simulation

Pour liquid metal temperature	670 ^{o}C
Plunger low / high velocity	0.3 / 3.0 m/s
Type of material liquid metal / mold	ADC 12 / H13
Die cycle time	36 s
Intensification pressure	10.98 MPa
Initial mold temperature	200 ^{o}C

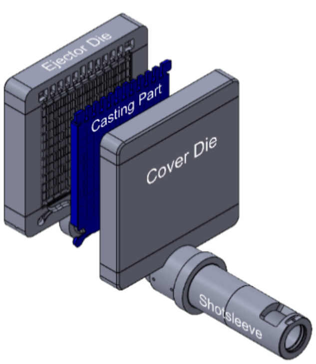


Fig. 3: Mold model.

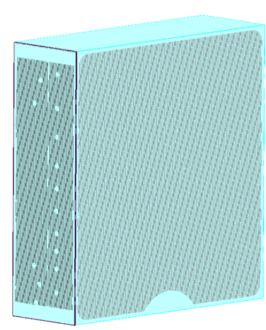


Fig. 4: Meshing of analysis model.

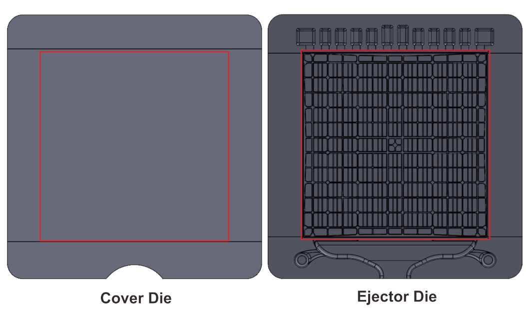


Fig. 5: The area under analysis.

Table 2: Thermal Die Cycling Analysis

No	Name of stage	Duration (s)
1	Solidification	15
2	Open die	2
3	Ejected	4
4	Spraying	8
5	Air blow	5
6	Die closed	2

Mathematical Model

High pressure die casting involves heat exchange at each stage. Referred to Fig. 1, the heat content transfers from the liquid metal to the mold and it is calculated using the finite volume method (FVM) and governing equation was the continuity equation, the momentum equation, and the equation for fluid energy, as shown in Eqs. (1) – (3) and governing equation for wall heat transfer, as shown in Eqs.(4) [16]. The Volume of Fluid (VOF) method is used in this computation to model the sharp interface between liquid metal and gas.

$$V_F\frac{\partial \rho}{\partial t}+\frac{\partial}{\partial x}(\rho u A_x)+R\frac{\partial}{\partial y}(\rho v A_y)+\frac{\partial}{\partial z}(\rho w A_z)+\xi\frac{\rho u A_x}{x}=R_{\mathrm{DIF}}+R_{\mathrm{SOR}} \quad (1)$$

$$\frac{\partial u}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial u}{\partial x}+vA_yR\frac{\partial u}{\partial y}+\ wA_z\frac{\partial u}{\partial z}\right\}-\xi\frac{A_y v^2}{xV_F}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+G_x+f_x-b_x-\frac{R_{\mathrm{SOR}}}{\rho V_F}(u-u_w-u_s)$$

$$\frac{\partial v}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial v}{\partial x}+vA_yR\frac{\partial v}{\partial y}+\ wA_z\frac{\partial v}{\partial z}\right\}+\xi\frac{A_y uv}{xV_F}=-\frac{1}{\rho}\left(R\frac{\partial p}{\partial y}\right)+G_y+f_y-b_y-\frac{R_{\mathrm{SOR}}}{\rho V_F}(v-v_w-v_s) \quad (2)$$

$$\frac{\partial w}{\partial t}+\frac{1}{V_F}\left\{uA_x\frac{\partial w}{\partial x}+vA_yR\frac{\partial w}{\partial y}+\ wA_z\frac{\partial w}{\partial z}\right\}=-\frac{1}{\rho}\frac{\partial p}{\partial z}+G_z+f_z-b_z-\frac{R_{\mathrm{SOR}}}{\rho V_F}(w-w_w-w_s)$$

$$V_F\frac{\partial}{\partial t}(\rho I)+\frac{\partial}{\partial x}(\rho I u A_x)+R\frac{\partial}{\partial y}(\rho I v A_y)+\frac{\partial}{\partial z}(\rho I w A_z)+\xi\frac{\rho I u A_x}{x}=-p\left\{\frac{\partial uA_x}{\partial x}+R\frac{\partial vA_y}{\partial y}+\frac{\partial wA_z}{\partial z}+\ \xi\frac{uA_x}{x}\right\}+RI_{\mathrm{DIF}}+T_{\mathrm{DIF}}+RI_{\mathrm{SOR}} \quad (3)$$

$$q=hW_A(T_w-T) \quad (4)$$

Location of hotspot

Hotspot is the last solidification area, in which it has a high heat content compared to others. Therefore, this area is one of the factors in designing a cooling channel. In this study the hotspot area was passed through a cooling channel to reduce heat. The equation that governs predicting the hotspot location is the correlation between solidification time and casting modulus also called Chvorinov's rule as shown in Eqs. (5) and (6) below.

$$t = B\left(\frac{V}{A}\right)^n \tag{5}$$

$$B = \left[\frac{\rho_m}{T_m - T_0}\right]^2 \left[\frac{\pi}{4k\rho c}\right] \left[L + c_m\left(T_{pour} - T_m\right)\right]^2 \tag{6}$$

Where t is casting solidification time, B is mold constant, n is a constant (usually equal to 1.5~2), V is volume of the casting part, A is surface area of the casting part, ρ_m is the density of the liquid metal, T_m is metal temperature, T_0 is the initial temperature of mold, ρ is the density of mold, c is specific heat of the mold, L is the latent heat of fusion of metal, c_m is the specific heat of the metal, and T_{pour} is the liquid metal pouring temperature.

Simulation Result and Discussion

Hotspot and heat content

Hotspot computations revealed that the total solidification time is 103.258 seconds, which represents the total solidification time for the casting component including the biscuit part, as shown in Fig. 6A. Fig. 6B shows a visualization of a hotspot particle. Areas marked with a red rectangle have a longer solidification time than other areas of the casting component (except the runner and biscuit). Therefore, this area passes through a cooling channel in order to reduce the surface temperature of the cavity.

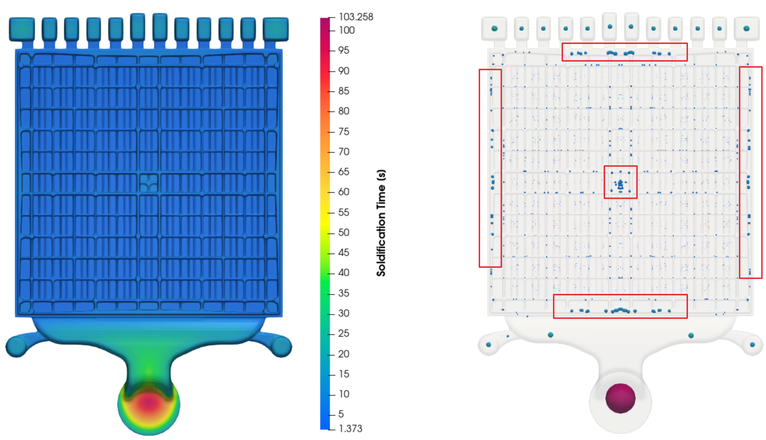
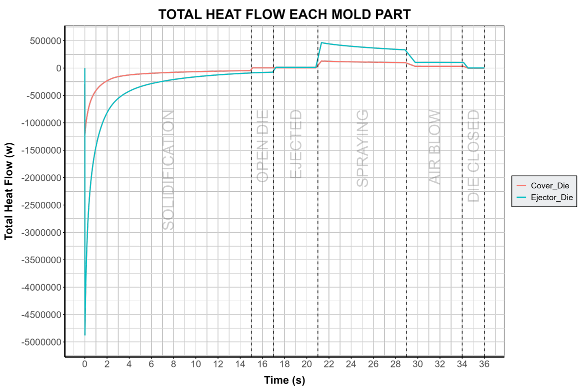


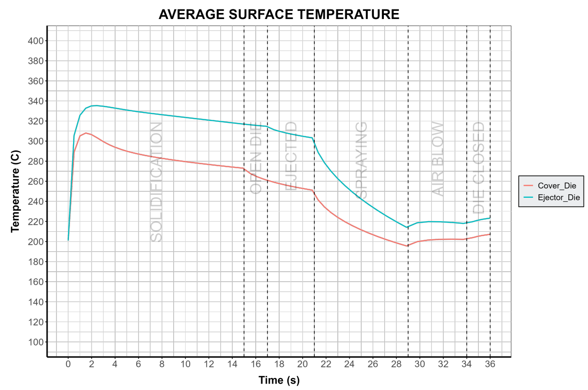
Fig. 6A: Solidification time. Fig. 6B: Hotspot particle.

In Fig. 7A, it can be seen that during the casting process the amount of heat transferred from the liquid metal to the mold fluctuates, while during solidification the amount of heat transferred increases significantly (negative indicates that heat is being transferred from the liquid metal to the mold). During open die stages, the cover die releases heat into the environment, whereas the casting component remains attached to the mold at the ejector die. During the ejected stage, the ejector die releases heat into the environment. During the spraying stage, the cover die and ejector die release heat by spraying, with the ejector die releasing more heat than the cover die. At the air blow stage the heat dissipation tends to be smaller than spraying stage, this is because the heat transfer coefficient of water is much higher than air, and at the die closed stage, the cover die and ejector still dissipate heat slowly. This phenomenon can also be seen in Fig. 7B, this graph shows the average surface temperature in direct contact with the liquid metal of the casting component. It can be seen that the temperature fluctuates during high pressure die casting.



A

Fig. 7A: Total heat flow.



B

Fig. 7B: Average surface temperature.

Cooling Channel Design

This study cooling channel design can be seen in Fig. 8. Cooling channels were located near hotspots and had high surface temperatures. Optimizing the cooling channel was carried out by changing the water flow rate.

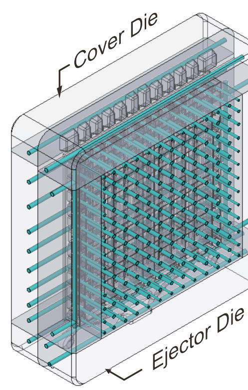


Fig. 8: Design of Cooling Channel.

Temperature Distribution

The surface temperature distribution on the mold has been analyzed statistically. See Table 3In the initial design, the cover die and ejector die had regions 83.88% and 52.86%, respectively, at a temperature range of $150 \leq T < 200$ ^{o}C, thereby the flow rate of cooling channel on the ejector die needs to be adjusted. According to the results of the design optimization on the cover die and the ejector die, the region of the temperature range between $150 \leq T < 200$ ^{o}C was 85.60% and 72.83%, respectively. The result indicates that the temperature uniformity area increases at temperature within the range $150 \leq T < 200$ ^{o}C. In Fig. 9, showed a comparison graph of surface temperature between the initial design and the optimized design in the 20th cycle and in Fig. 10A and Fig. 10B showed the model distribution of surface temperature of the initial and the optimized design at die closed stage.

Table 3: Classification surface temperature of mold in the 20th cycle at die closed stage.

Temperature Range (C)	Initial Design		Optimized Design	

	Cover Die (%)	Ejector Die (%)	Cover Die (%)	Ejector Die (%)
< 100	0	0	0	0
100 ≤ T < 150	3.37	6.32	3.49	11.93
150 ≤ T < 200	83.88	52.86	85.60	72.83
200 ≤ T < 250	12.75	40.21	10.91	15.23
250 ≤ T < 300	0	0.61	0	0.01

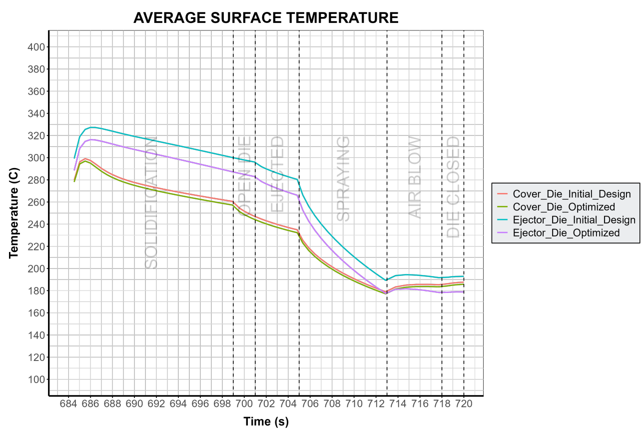


Fig. 9: Comparation average surface temperature of initial and optimized cooling channel design.

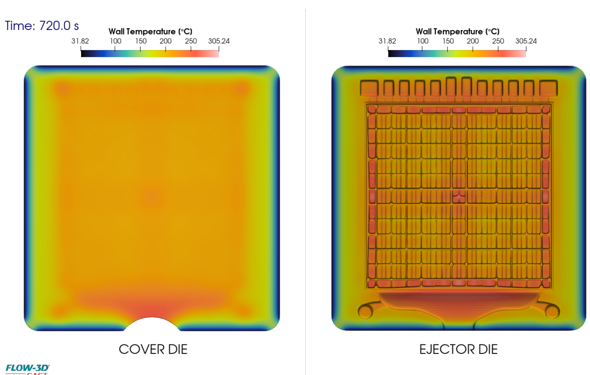


Fig. 10A: Distribution Temperature Initial Design in the 20th cycle at die closed stage.

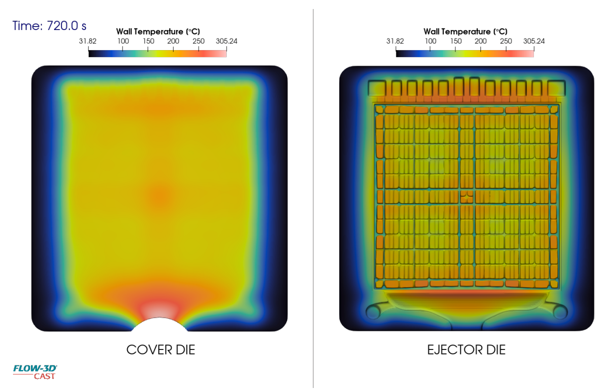


Fig. 10B: Distribution Temperature Optimized Design in the 20th cycle at die closed stage.

Designing the cooling channel requires consideration of several factors in order to achieve a uniform surface temperature, this is a challenge since the surface temperature on the mold varies greatly. Moreover, the cooling channel location and the cooling channel water flow rate play a significant role in determining how fast the surface temperature on the mold decreases, which affects the optimization of the thermal die cycling time. Nevertheless, if the cooling channel is too close to the surface of the mold cavity, it can crack as a result of thermal stress. Hence, it is necessary to perform a Computer-Aided Engineering simulation in order to obtain a more uniform temperature, improve mold durability, and reduce production costs.

Conclusion

The high-pressure die casting process was thoroughly analyzed using computer-aided engineering (CAE) software, revealing the significant role of heat exchange during the process. The shape of the mold model directly influences the amount of heat it absorbs, which affects the surface temperature of the mold. The analysis showed that optimizing the cooling channel design improved the uniformity of the cover die mold surface temperature, with an increase from 83.88% to 85.60% and 52.86% to 72.83% for ejector die mold. This revealed that proper cooling channel placement and water flow rate were factors in achieving an even surface temperature. Overall, CAE proves to be an essential tool for modelling and analyzing thermal dynamics during the die casting cycle, serving as a valuable reference for the design and optimization of cooling channels.

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