Design of Conformal Cooling Channels Using Numerical Methods in a Metal Mold and Calculating Exergy Destruction in Channels

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ABSTRACT

Shorter cycle times, better product quality and less product outage can be possible with faster cooling. But mold cooling channels can only be made in linear directions and limited forms via classical manufacturing methods. Therefore, it limits that performance of mold cooling. Developed in recent years additive manufacturing technologies are capable of building complex geometries and monoblock 3D products. With this technology it is possible to produce metal molds with conformal cooling channels in different forms and capable of qualified cooling. In this study, conformal cooling channels were designed in order to achieve optimum cooling in monoblock permanent mold. In this study, CFD (Computational Fluid Dynamic) analyses are performed to steady stead conditions for designed conformal cooling channels and classical cooling channel mold. Pressure drops, cooling channel outlet temperatures and exergy destructions are calculated depending on the flow velocity rate in channels. The numerical investigations of the cooling process have shown that approximately 5% higher cooling performance can be achieved with conformal cooling channels. However, the pressure drop in the conformal cooling is observed to be higher than classical cooling channel. In addition, exergy destruction in the conformal cooling channel is approximately 12% greater than the classical cooling channel.

KEYWORDS -Metal Mold, Exergy Destruction, Cooling Channel Design.

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1 INTRODUCTION

Cooling process in metal molds is one of the important factors in the solidification of liquid metal. Molding defects such as hot spot defects and distortion occur in the casting products when cooling is not uniform. Conversely, qualified and faster cooling affects product quality positively. With conventional manufacturing methods, mold cooling channels can only be made in linear directions and circular cross sections. This limits mold cooling performance [1]. There are studies in the literature about metal molding techniques and cooling channel design. The cooling performance of hot extrusion dies with conformal cooling channels produced by the additive manufacturing method was examined [2]. Increase of the production speed up to 300 % was observed with the conformal cooling channel mold compared to the standard cooling channel mold. The cycle time in molding effects product cost and quality. It was observed that shorter cycle time, more homogeneous temperature distribution and fewer component distortions. Therefore better product quality was obtained in injection molds with conformal cooling channels [3-9]. The fact that the cost of production is high in metal molds produced with the additive manufacturing method makes it necessary to produce the conformal cooling channel design with the desired performance. Using the finite element method, the cooling performance of mold cooling channels and the solidification process of liquid metal can be simulated. Numerical studies inferred to increase the cooling performance by decreasing the solidification time through the conformal cooling channel [10-12]. A conformal cooling channel for plastic injection mold was designed [1]. The study had been conducted numerically and experimentally.

Numerical and experimental investigations revealed that % 12.8 shorter cycle time with conformal cooling channels. In addition Park and Dang [9] developed comformal cooling channel for plastic injection mold. The study results showed that % 30 shorter cycle time with conformal cooling channels.

Friction losses, heat transfer due to temperature difference, rapid expansion and compression, cause loss of exergy in a system. [13-15] The molten metal heat transfers through the cooling channels. The heat transfer between the molten metal and the cooling channels is similar to the working principle of heat exchangers. There are a lot of studies in the literature about loss of exergy in heat exchangers. However, studies on loss of exergy in metal mold cooling channels are very few in literature. In order to determine the optimum working conditions of the heat exchangers or thermodynamic cycles and reducing exergy destruction, the parameters such as the fluid velocity, the pressure drop, the temperature distribution were examined by researchers. They emphasized that the exergy destruction is reduced by improving these parameters [16-19].

With the additive manufacturing technology developed in recent years, products can be manufactured in complex geometries and compact structures. In this study; cooling channels in a metal mold are designed in different geometries that cannot be produced by conventional manufacturing methods. Two different conformal cooling channel molds are designed and compared with standard cooling channel mold numerically at steady-stead conditions. Heat transfer rates, exergy destructions and pressure drops at different flow rates are calculated for each channel.

2 NUMERICAL MODELING AND MATHEMATICAL METHOD

In this study, a permanent mold (Fig. 1) is modeled for gravity die casting. The mold casting geometry is an exhaust valve of a gasoline internal combustion engine. The hydrodynamic and thermal behavior of the mold cooling channels is investigated numerically. The mold that has conformal cooling channel will be produced by the SLM (Selective Laser Melting) method from stainless steel 316 L powder. Nitriding will be applied to prevent molten aluminum damage the mold surface [20]. Mold consists of two symmetry parts and simulations are conducted for a symmetry part.

2.1 Mathematical Model

In the present work, exergy destructions in the cooling channels are calculated by assuming the melt temperature at 973 K [21]. The theoretical $\dot{Q}_{Al}$ value is calculated assuming that the molten metal Al-A413 has cooled from 973 K to 623 K in 50 seconds. Predicted cycle time is 50 seconds for the selected casting piece which grounds of industrial experience. $\dot{Q}_{Al}$ can be written as Eq. (1). With using this value the heat flux which is contact to mold surface was calculated.

$$\dot{Q}_{Al} = Q_{Al} / dt \tag{1}$$

The heat in the solidification of molten metal is the sum of sensible and latent heat represented as Eq. (2),

$$Q_{Al} = Q_{sensible} + Q_{latent} \tag{2}$$

this study, LH= 500000 J/kg was assumed, sensible and latent heat can be written as Eq. (3) and Eq. (4),

$$Q_{sensible} = m_{Al}.c_{Al}.\Delta T \tag{3}$$

$$Q_{latent} = m_{Al}.LH \tag{4}$$

the heat transferred to the cooling channel represented as Eq. (5),

$$\dot{Q}_{channel} = \dot{m}_{oil}.c_p.(T_{outlet} - T_{inlet}) \tag{5}$$

here, the mass flow rate depends on the velocity in the hydraulic diameters of the designed cooling channels. The mass flow rate is given as,

$$\dot{m}_{oil} = \rho_{oil}.V.A_c \tag{6}$$

Hydraulic diameter in Rectangular, triangular or any profile channels is given as,

$$D_h = \frac{4A_c}{P_w} \tag{7}$$

where “A_c” is the cross sectional area and “P_w” is the wet perimeter.

In Fig. 2, the heat transfer mechanism by the assumptions in the mold cooling channels is shown. The cooling channel is a steady-flow process since there is no change with time and cooling oil inlet temperature is 573 K [22]. Entropy generation can be written as Eq. (8),

$$\sum \frac{\dot{Q}_{Al}}{T_k} + \sum \dot{m}_{oil,inlet} s_{inlet} - \sum \dot{m}_{oil,outlet} s_{outlet} + \dot{S}_{gen} = dS_{CV} / dt \tag{8}$$

where T_k (973 K) is the source temperature of the heat given to the cooling channel by the aluminum melt, $\dot{m}$ is mass flow rate (kg/s) of cooling oil. The right side of Eq. (8) is zero because a steady-flow process. The entropy change for the cooling channel obtained as below,

$$s_{in} - s_{out} = c_{p,oil} \ln(T_{in} / T_{out}) \tag{9}$$

exergy destruction of the system is given in Eq. (10), T_0 is ambient temperature, assumed 300 K.

$$\dot{E}_{des} = T_0 \dot{S}_{gen} \tag{10}$$

2.2 Numerical Modeling

Computational domains of the analyzed cooling channels (standard channel (SC), curved channel (CC) and spherical fin channel (SFC)) are designed (Fig. 3). Tetrahedral mesh structure is created for CFD analysis. Mesh parameters used simulations are given Table 1. For designed models, there are 1,023,000, 1,148,000, 1,356,000 mesh elements in SC, CC, SFC respectively as could be seen on Table 1. Hydraulic diameters and hydraulic diameter cross-sectional areas of the designed cooling channels are shown in Table 2. For each cooling channel, the channel exit temperatures and pressure drops are calculated by changing the cooling oil velocity of the hydraulic cross-sectional areas to 0.2-2 m/s range [23].

Analyzes are performed using ANSYS-FLUENT 16.1 software [24]. In Figure 4, the boundary conditions are depicted. Numerical modeling parameters used solutions are presented in Table 3. "Petro-therm" brand name heat transfer oil specifications are used as refrigerant in the cooling channels. Thermal properties of heat transfer oil used numerical analysis are shown in Table 4. Mold material GGG 50 ductile cast iron is used for SC mold material in the analysis. For CC and SFC mold stainless steel 316 L thermal properties are applied in the analysis. Thermal properties of mold materials used numerical analysis are presented in Table 5.

3 NUMERICAL RESULTS

3.1 Validation of Numerical Analysis

In this study, a permanent mold is modeled for gravity die casting. The study has not been conducted experimentally however it is not possible to find studies that have similar geometry like this study in the literature. Therefore, the validation of the numerical results was performed for Imran et al. [23] study. They practiced similar methods and boundary conditions that used in this study. Experiments were conducted to determine the effect of water mass flow rate and heat load on thermal and hydraulic performances of the heat exchanger. Considering the full geometry of the heat exchanger (configuration a), all presumptions and boundary conditions of the system, modeling and simulation of that experimental study was conducted. The comparison was carried out the base plate temperature and pressure drop of the channels. In Figure 5 Imran et al. and current study results for different mass flow rate of working fluid are compared to base temperature. The deviation between the numerical and the experimental results is found 10%. In Figure 6 demonstrates comparison of numerical and experimental results the pressure drop for different mass flow rate of working fluid. The difference between numerical and experimental results is observed % 8. The difference between the pressure drop of current research and Imran et al study is observed almost same values. It is observed that there is a consistency between numerical and experimental data.

3.2 Numerical Simulations Results

In Figure 7.a, the comparison of heat transfer rate and pressure drops of SC, CC and SFC depending on flow rates is presented. SFC transfers more heat than CC and SC. As the fluid velocity increases, there is no significant change in the amount of heat transferred in the SFC, while there is a decrease in SC and CC. As the velocity increases, the pressure drop is around 1-4 kPa in SC. In SFC, this value is up to approximately 50 kPa.

Exergy destruction is calculated using the Engineering Equation Solver (EES) software [25]. In Figure 7.b, the comparison of channel outlet temperatures and exergy losses of SC, CC and SFC depending on flow rates is presented. For SC, the exergy destruction increases up to 0.6 m/s value and then decreases as the speed increases. The outlet temperature of the cooling oil decreases from 625 K to 580 K as the velocity increases. Exergy destruction increases up to 1 m/s for CC and then decreases. Exergy destruction changes between 0.286-0.332 kW and is similar to SC. The outlet temperature of the cooling oil decreases from 680 K to 582 K as the velocity increases. The exergy destruction for SFC fluctuates around 0.37 kW. As the speed increases, a significant change in the destruction of the exergy for this channel does not occur. The outlet temperature of the cooling oil decreases from 577.5 K to 573.5 K as the velocity increases. The difference between the inlet temperature and the outlet temperature of the cooling channel is 4 K and it is in a small temperature range.

4 CONCLUSION

In the present work, CFD analyses are performed in steady stead conditions for designed cooling channels and classical cooling channel mold. Pressure drops, cooling channel outlet temperatures and exergy destructions are calculated depending on the flow velocity rate in channels. Numerical analysis investigations revealed that, for 1 m/s reference velocity, the heat transfer rate in SFC is 5% higher than SC. Accordingly, heat transfer rate increases as the cycle time decreases. These results have accordance with existing literature [1-9]. For 1m/s velocity rate, the SC and SFC required pump power is 0.157 W and 11.7 W respectively. On the other hand, 40 W more heat transfer rate is obtained by SFC. However, as the flow rate in hydraulic diameters increases, the pressure drop is the greatest in this channel. As the flow rate decreases in SC and CC, the temperature difference between T_{outlet} and T_{inlet} is higher than in SFC. Numerical calculations have shown that the exergy destruction in the SFC occurs almost constantly with small fluctuations and is 12% higher than the SC. Decreasing of the exergy destruction could be improve the efficiency and increase the cooling channel heat transfer rate. The design of the cooling channel can be developed in future studies.

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FIGURE CAPTIONS

Figure 1. The solid model of metal mold symmetry part

Figure 2. The assumptions in the mold cooling channels heat transfer mechanism

Figure 3. Computational domains of the analyzed cooling channels

Figure 4. Boundary conditions used for the analyzed mold configuration

Figure 5. Comparison of Imran et al. [23] and current study results for base temperature

Figure 6. Comparison of Imran et al. [23] and current study results for pressure drop

Figure 7 a. Comparison of heat transfer rate and pressure drops of SC, CC and SFC depending on flow rates, **b.** Comparison of channel outlet temperatures and exergy losses of SC, CC and SFC depending on flow rates

TABLE CAPTIONS

Table 1. Mesh parameters used simulations

Table 2. Hydraulic diameters and hydraulic diameter cross-sectional areas of the designed cooling channels

Table 3. Numerical modeling parameters used solution

Table 4. Thermal properties of heat transfer oil used numerical analysis

Table 5. Thermal properties of mold materials used numerical analysis

FIGURES

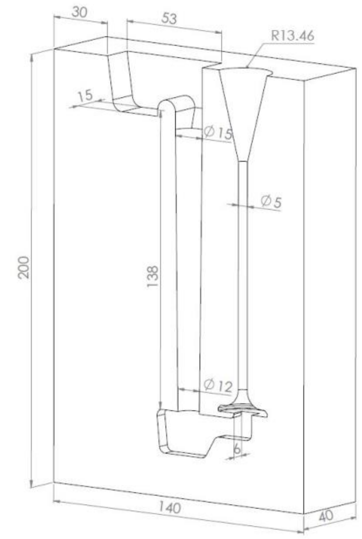


Fig. 1

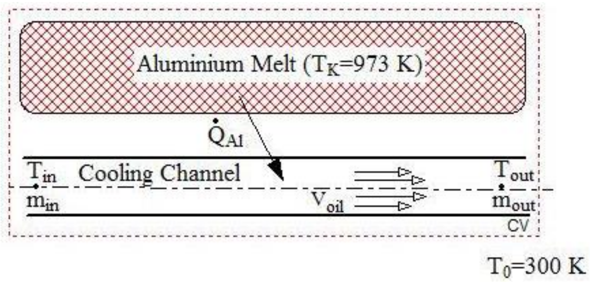


Fig. 2

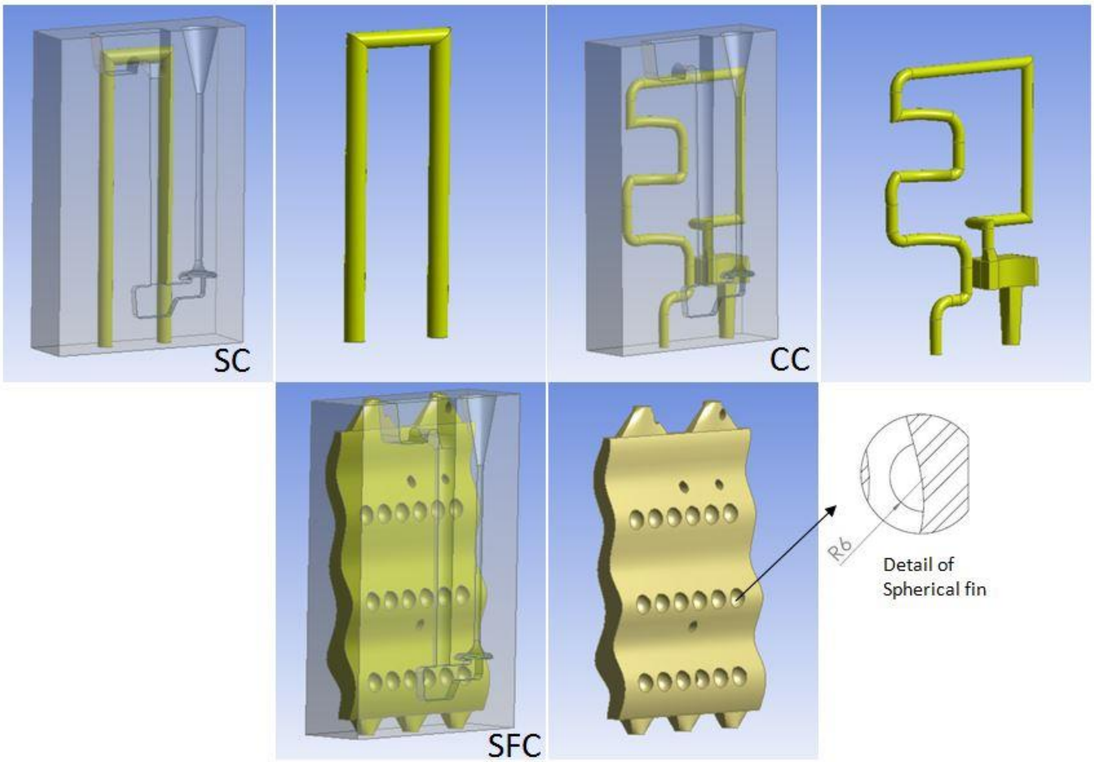
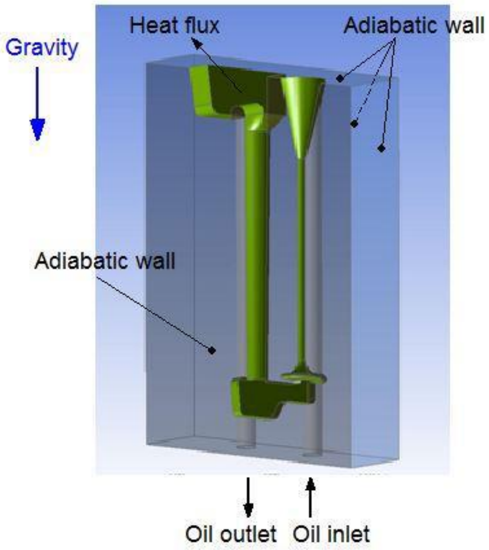

SC
CC
SFC
R6
Detail of
Spherical fin

Fig. 3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Heat flux
Adiabatic wall
Adiabatic wall
Oil outlet
Oil inlet

Fig. 4

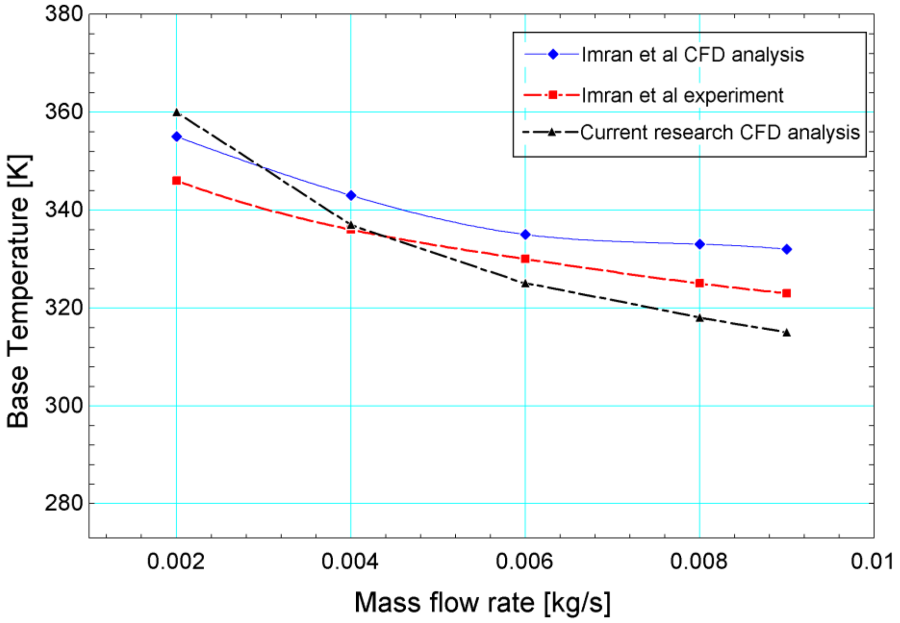
Imran et al CFD analysis
Imran et al experiment
Current research CFD analysis
Base Temperature [K]
380
360
340
320
300
280
0.002
0.004
0.006
0.008
0.01
Mass flow rate [kg/s]

Fig. 5

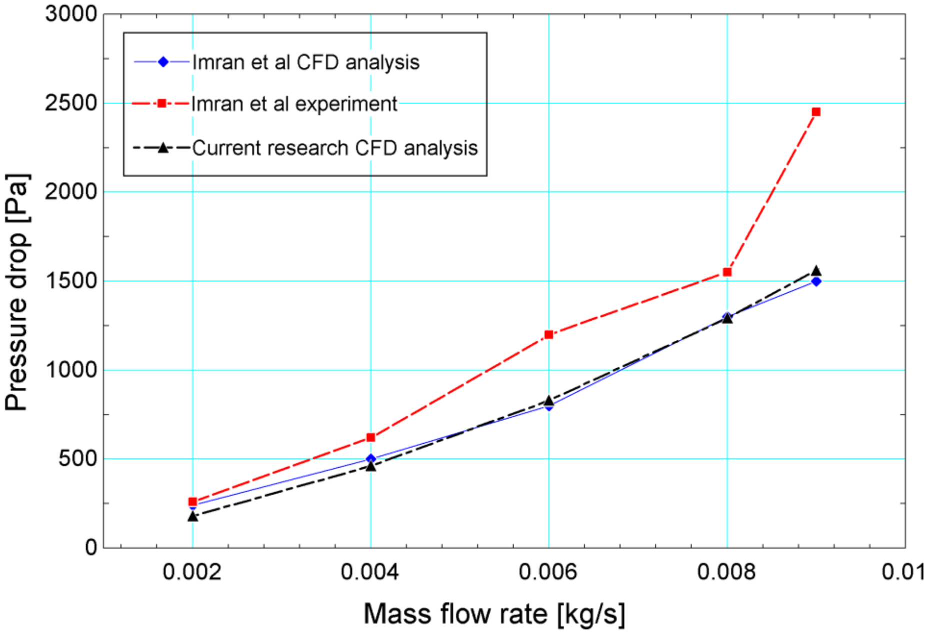
Imran et al CFD analysis
Imran et al experiment
Current research CFD analysis
Pressure drop [Pa]
3000
2500
2000
1500
1000
500
0
0.002
0.004
0.006
0.008
0.01
Mass flow rate [kg/s]

Fig. 6

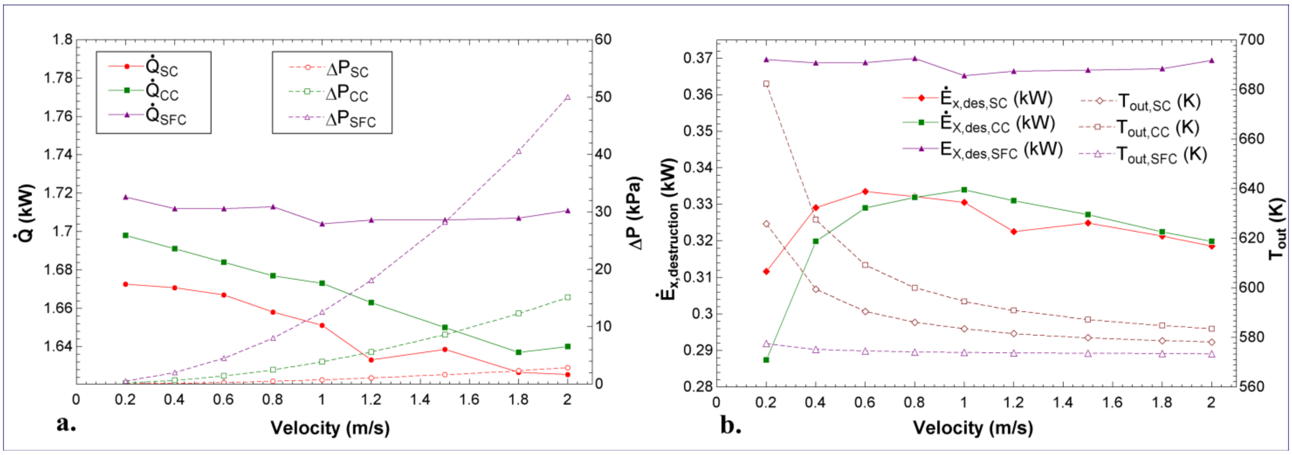

Fig. 7

TABLES

Table 1

	SC	CC	SFC
Mesh element number	1023000	1148000	1356000
Aspect Ratio	1.841	1.8468	1.8646
Jakobian Ratio	1.0132	1.0	1.0
Skewness	0.23437	0.22976	0.23697

Table 2

Cooling Channel	Hydraulic diameter (m)	Hydraulic diameter cross-sectional area (m^2)
Standard Channel (SC)	0.01	0.00007854
Curled Channel (CC)	0.009437	0.00003848
Spherical Fin Channel (SFC)	0.015	0.00096

Table 3

Simulation Condition	Steady-state
Solver Type	Pressure based
Mesh Structure	Tetrahedral
Turbulence Model	RNG-Enhanced wall treatment stand. k-ε Turb. Model
Wall-Turbulence Interaction	Standard Wall-function
Speed - Pressure Interaction	SIMPLE algorithm
Decomposition Method	Second order upwind

Table 4

Temperature (K)	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)	Temperature (K)	Viscosity (kg/ms)
288	869	1890	0.143	313	$3.07x10^{-3}$
311	855	1970	0.142	373	$4.8735x10^{-4}$
533	714	2690	0.13	598	$4.753x10^{-5}$
559	679	2880	0.128	-	-

Table 5

Mold type	Mold material	Density (kg/m^3)	Specific heat (J/kgK)	Thermal conductivity (W/mK)
SC	GGG 50 ductile cast iron	7200	500	35.2
CC and SFC	Stainless steel 316 L	7990	550	16.3

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