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Investigation of transient numerical simulation of solidification and thermal behavior of metal molds with conformal cooling channels

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Abstract. The cooling process in metal molds is one of the important factors in the solidification process of molten metal. Molding defects, such as hot spot defects and warping, are usually present in cast products when cooling is not uniform. However, qualified and faster cooling positively affects product quality. Molding is one of the important processes both in terms of cycle time and product quality, with permanent mold casting, high-quality liquid metal casting, and quality product. Selective Laser Melting (SLM) method was used to design metal mold cores with unique cooling channels to be compactly produced. The effects of the designed cooling channels, heat transfer, and solidification of the molten metal are studied in transient numerical terms. The temperature distributions at the 1st, 3rd, and 5th seconds after casting were obtained, and the solidification processes were investigated according to the standard cooling channels of the original cooling channels. According to the results obtained, it was observed that solidification would function better in the originally designed cooling channels.

1. Introduction

The cooling process in metal molds is one of the important factors in the solidification process of molten metal. Molding defects, such as hot spot defects and warping, occur in cast products when cooling is not uniform. However, qualified and faster cooling affects product quality positively. Molding is one of the important processes both in terms of cycle time and product quality, with permanent mold casting, high-quality liquid metal casting, and quality product. One of the permanent mold casting methods is metal gravity die casting, which is the casting of molten metal by a mold made of steel. Molding is one of the important processes in terms of cycle time and product quality such that permanent mold casting produces high-quality product by casting liquid metal at high temperatures. There are many important problems in classical molding methods where the cooling process is performed by using vertical and horizontal channels formed on the mold body; these important problems such as deterioration and shrinkage of the obtained products arise because the cooling process cannot be homogeneous and sufficient. Therefore, the production period increases, which increases the cost of the product [1]. This is particularly important for parts with high production costs per unit volume (as in the medical, aerospace, space, energy, electronics, and automotive sectors). In recent years of work and developing technology, SLM (Selective Laser Melting) has been shown to be able to produce high-quality metal parts in a shorter production time period than conventional production methods [2-4]. In their stud-

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ies, the molds produced by the conventional method and the conformal injection molds produced by joint manufacturing for 2 different products are economically comparable [5]. It is emphasized that, in the near future, joint manufacturing will dominate other manufacturing methods in mold production. The mold, which can be produced by the joint manufacturing method, makes it possible to construct a complex cooling channel structure of a serial production mold. It has been proved by theoretical and experimental studies where a more uniform heat transfer takes place with appropriate cooling channels [6-9]. The fact that the cost of production is high in metal molds produced by an additive manufacturing method makes it necessary to produce the conformal cooling channel design with the desired performance. By applying the finite element method, the cooling performance of mold cooling channels and the solidification process of liquid metal can be simulated. Numerical studies point out the possibility of an increase in the cooling performance with a decrease in the solidification time through the conformal cooling channel [10-16]. Conformal cooling channels for the plastic injection mold design and the numerical and experimental cooling performance were examined. Numerical analysis and experimental results are consistent with each other and have a 12.8% shorter cycle time period with conformal cooling channels. In addition, Park and Dang [17] developed a conformal cooling channel for plastic injection mold. The results of this study showed 30% shorter cycle time with conformal cooling channels. In an experimental study, they have achieved an injection mold design with a conformal cooling channel through articulated manufacturing in a shorter time period compared to the mold regime temperature [18]. In order to reduce the cycle time in the aluminum metal injection mold (biscuit), the conformal cooling channel in the heel region was designed [19]. The numerical analysis and experimental verification showed that any increase in the cycle time of the original cooling channel with respect to the standard channel was observed. They achieved an increase in an extrusion rate of 300% by producing an aluminum extrusion die with conformal cooling channels with DMLS (Direct Metal Laser Sintering) [20]. According to the recent pieces of research, it was observed that the numerical analyses were verified with experimental studies. In this study, they carried out a time-dependent numerical analysis of solidification melting behavior by using an enthalpy-porosity approach with ANSYS-FLUENT software for sodium nitrate in the case of thermal energy storage [21]. The results of the numerical analysis showed that the discharging process was slower than the charging process. It was suggested that engine parts, such as valves and camshafts, could be manufactured using aluminum alloys [22]. Numerical and experimental studies on aluminum and its alloys were carried out. Aluminum 6061-SiC MMCs (Metal Matrix Composites) were used to investigate the changes in their mechanical properties, microstructure, and hardness properties based on the ratio of SiC, leading to a conclusion that poppet valve could be produced with these findings [23-26].

In this study, the cooling performance of a permanent mold was numerically investigated. Thermal and hydrodynamic behaviors of conformal mold cooling channels and standard cooling channels that could be produced by the DMLS method were analyzed by ANSYS-FLUENT software. Generally, ANSYS-FLUENT program was used for thermal and flow analysis [27-30]. Analyses were made for an engine exhaust valve, which was produced by pouring in permanent mold aluminum alloy material (Al 6061) with a mold. In this work, the casting piece is an exhaust valve of an internal combustion engine. It is mentioned in the study that the Al 6061 alloy automobile engine valve could be made [31]. Therefore, this alloy was chosen as a casting in this study. Temperature distribution and solidification rates based on the time of melting during casting were compared with the original cooling channels.

2. Numerical modeling

The metal mold to be produced by the DMLS method of gray cast iron comes from two parts that are symmetrical with respect to each other. As seen in the mold solid model given in Figure 1, the symmetrical mold parts are compactly designed. Original cooling ducts are designed for optimum cooling for cast parts. Due to the symmetry of the designed cooling channels, the effect of heat transfer and solidification of the molten metal was numerically investigated for half of the mold. CFD analyses of the designs using CFD software were carried out to investigate solidification-melting and

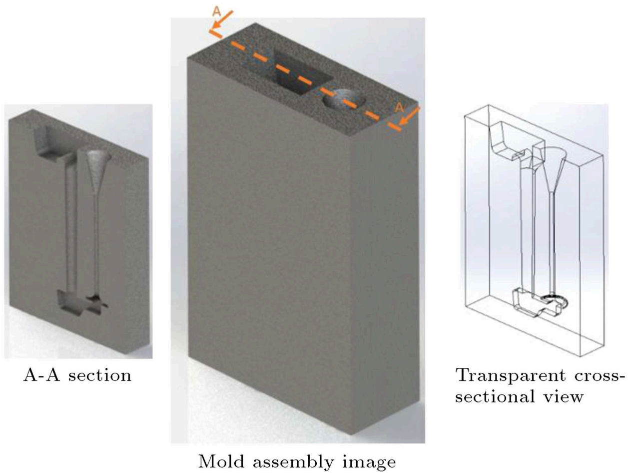

Figure 1. Designed metal mold drawing.

cooling channel thermal and hydrodynamic behaviors, considering the boundary conditions given in Figure 2.

The following equations are used for cooling channels in the numerical analyses.

The continuity, momentum, and energy equations drawn from the background of the program for the flow analyses in the channel are presented below. The equations used by the background program to account for the hydrodynamic behavior of the cooling channels are presented below:

$$\dot{m}_{oil} = \rho_{oil} V A_c. \quad (1)$$

The mass flow of the circulating fluid in the channel is $\dot{m}_{\text{oil}}$ (kg/s), channel cross-sectional area is A_c, and mean the average velocity is V (m/s).

Hydraulic diameters in the designed cooling channels vary according to being perpendicular to the cross-sectional area. The hydraulic diameter, D_h (m), is expressed in Eq. (2):

$$D_h = \frac{4A_c}{P_w}, \quad (2)$$

where A_c and P_w are the cross-sectional area and the wet perimeter, respectively.

For flow in channels, continuity equation is as follows:

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} = 0. \quad (3)$$

Momentum equations are shown below:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{\partial P}{\partial x} + \rho g_x, \quad (4)$$

$$\rho\left(\frac{\partial v}{\partial t} + u\frac{\partial v}{\partial x} + v\frac{\partial v}{\partial y} + w\frac{\partial v}{\partial z}\right) = \mu\left(\frac{\partial^2 v}{\partial x^2} + \frac{\partial^2 v}{\partial y^2} + \frac{\partial^2 v}{\partial z^2}\right) - \frac{\partial P}{\partial y} + \rho g_y, \quad (5)$$

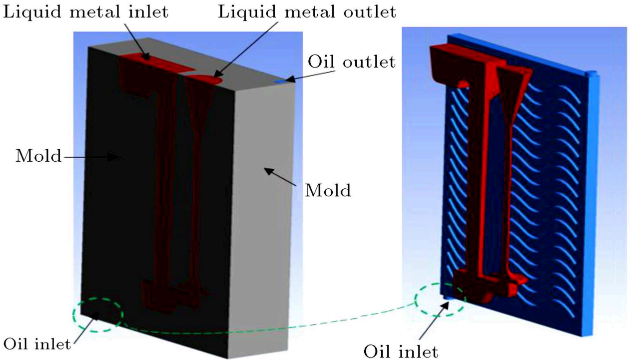

Figure 2. Boundary conditions for cooling channel mold used in analysis.

$$\rho\left(\frac{\partial w}{\partial t} + u\frac{\partial w}{\partial x} + v\frac{\partial w}{\partial y} + w\frac{\partial w}{\partial z}\right) = \mu\left(\frac{\partial^2 w}{\partial x^2} + \frac{\partial^2 w}{\partial y^2} + \frac{\partial^2 w}{\partial z^2}\right) - \frac{\partial P}{\partial x} + \rho g_z, \quad (6)$$

where, g is the acceleration of gravity (m/s^2).

Energy equation is shown below:

$$\rho\left[\frac{\partial(C_pT)}{\partial t} + \frac{\partial(C_puT)}{\partial x} + \frac{\partial(C_pvT)}{\partial y} + \frac{\partial(C_pwT)}{\partial z}\right] = \frac{\partial}{\partial x}\left(\lambda\frac{\partial T}{\partial x}\right) + \frac{\partial}{\partial y}\left(\lambda\frac{\partial T}{\partial y}\right) + \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right), \quad (7)$$

where C_p, is the specific heat (kJ/kgK), and λ is the heat transfer coefficient (W/mK).

After forming the flow volume models of the fluid circulating in the metal mold, the numerical network structure for the CFD analyses was established. For each flow volume model (Standard Channel (SC), Curved Channel (CC), Spherical Fin Channel (SFC), and Plate Type Channel (PTC)), a mesh is placed in the tetra hedral mesh geometry. For these designs, CFD analyses were performed using ANSYS-FLUENT software for designed cooling channels in flow volumes, given in Figure 3. The analyses were carried out to determine transient temperature changes and solidification rates for the valve in different types of cooling channels. In the analyses, the time step was set to 0.001 s, and no significant change was observed in the results at the smaller time step. The numerical model parameters used in the analyses are given in Table 1. Mesh parameters used in simulations are given in Table 2. For designed models, there are 1,134,500, 1,262,000,

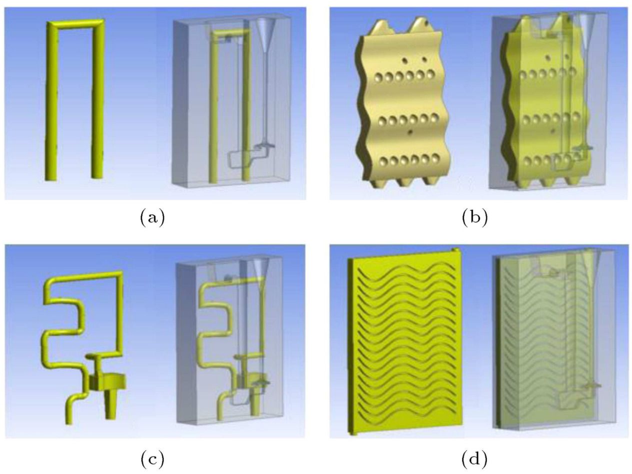

Figure 3. Designed cooling channels flow volumes: (a) Standard channel, (b) spherical fin channel, (c) curled channel, and (d) plate type channel.

Table 1. Numerical modelling parameters used in solution.

Simulation condition	Transient-state
Solver type	Pressure based
Mesh structure	Tetrahedral
Turbulence model	RNG-enhanced wall treatment standard $k-\varepsilon$ turbulence model
Wall-turbulence interaction	Standard wall-function
Speed-pressure interaction	Coupled algorithm
Decomposition method	Second-order upwind

Table 2. Mesh parameters used in simulations.

	SC	**CC**	**SFC**	**PTC**
Mesh element number	1134500	1262000	1294000	1428106
Aspect ratio	1.84	1.86	1.86	1.88
Jakobian ratio	1.0132	1.0	1.0	1.0
Skewness	0.22379	0.21682	0.23578	0.26659

Table 3. Thermal properties of heat transfer oil used in numerical analysis.

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	0.00307
311	855	1970	0.142	373	0.00048735
533	714	2690	0.13	598	4.753×10^{-5}
559	679	2880	0.128	-	-

Table 4. Thermal properties of Al 6061 used in numerical analysis.

Temperature (K)	**Density (kg/m^3)**	**Specific heat (J/kgK)**	**Thermal conductivity (W/mK)**	**Temperature (K)**	**Viscosity (kg/ms)**
298.15	2705	870	192	894	0.00151
373.15	2695	950	195		
473.15	2675	980	203	1073	0.001012
573.15	2655	1020	211		
673.15	2635	1060	212		
773.15	2610	1150	225		
873.15	2590	1160	200		
915.15	2415	1170	90		
973.15	2400	1170	91		
1073.15	2372	1170	92		

1,294,000, and 1,428,106 mesh elements in SC, CC, SFC, and PTC, respectively, as can be seen in Table 2. Numerical modeling parameters used in solutions are presented in Table 3. Heat transfer oil specifications of "Petro-Therm" brand name are used as refrigerant in the cooling channels. Thermal properties of heat transfer oil used in numerical analysis are shown in Table 4. Thermal properties of heat transfer oil used in numerical analysis are shown in Table 3. For SC, CC, SFC, and PTC mold, Al 6061 thermal properties are applied in the analysis. Thermal properties of Al 6061 used in numerical analysis are presented in Table 4.

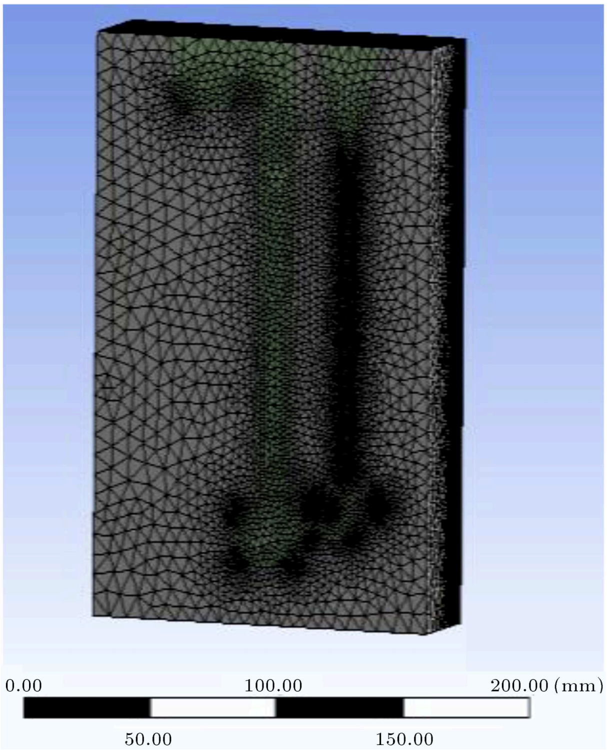

Figure 4. Mesh structure for cooling channel mold used in analysis.

The mass flow is calculated separately for each channel so that the hydraulic velocity at the cooling channels is 1.5 m/s. The molten metal casting temperature was 973 K. The heat transfer oil was circulated in the cooling channel, and the properties of the Petro-Therm commercial product were added. Mesh structure for the cooling channel mold used in the analysis is shown in Figure 4.

3. Numerical results

Results of numerical analysis at the 1st, 3rd, and 5th seconds are obtained in the CFD-POST 16.1 program. In the analyses made, the symmetry of all of the compact molds was obtained for 4 different cooling channel designs with a three-dimensional temperature distribution of the cooling duct, metal mold, and molten metal (Figure 5). Again, the molten metal solidification rate was similarly compared. Figure 6 shows the variation of the temperature distributions along the valve axis based on the valve height for the four different types of the cooling channel after the 1st, 3rd, and 5th seconds of casting.

At the end of 1 s, the temperature between the valve head (disc) and the valve stem is noteworthy. After 0.02 m of valve height, the temperature towards the stem decreases sharply. Temperature drop SFC is the largest in the type channel, while, at least, in the PTC, the fixed temperature zone for the 4-channel

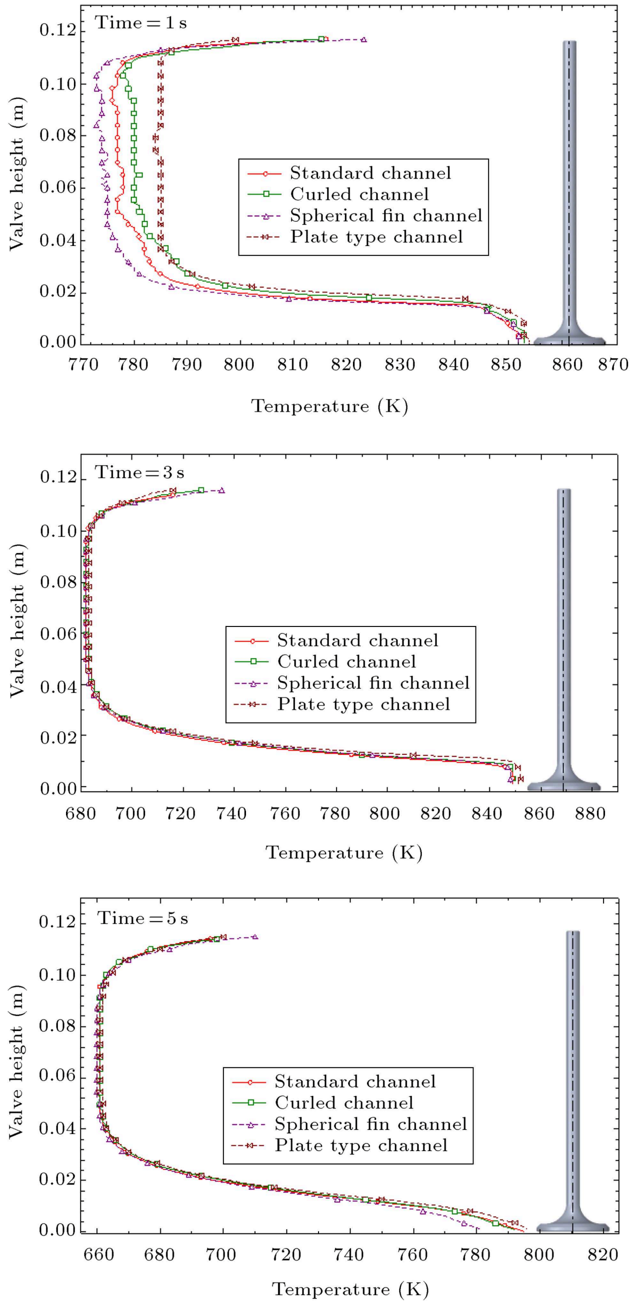

Figure 5. Temperature distribution along the valve axis after 1st, 3rd, and 5th seconds from casting for SC, CC, SFC, and PTC type cooling channels.

design on the stem ranges from 0.02 m to 0.11. m. After 3 s, it is observed that the passage of the decreasing temperature from the discrete to the stem is smoother with respect to the valve height from 0.01 m to 0.04 m compared to those at 1 s. Although there is no significant difference in temperature change for four different types of channels, the constant temperature zone in the stem is shorter than 0.04 m to 0.1 m in comparison to that at 1 s. At the end of 5 s, the temperature transitions towards the disc stalk seem to be softer than those at 3 s. After 5 s, the lowest temperature in the

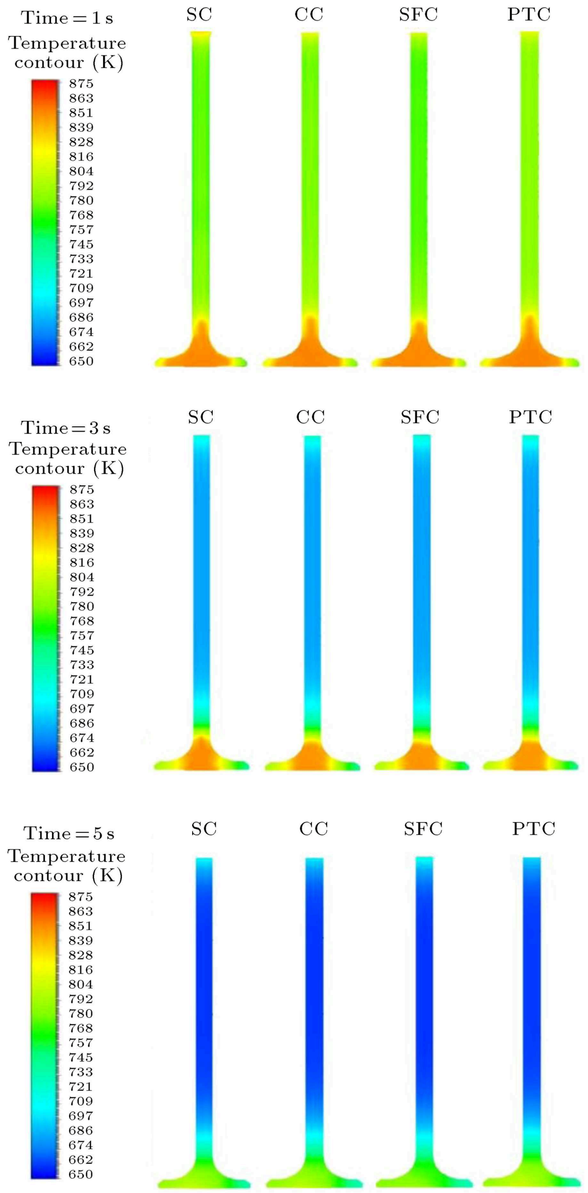

Figure 6. Temperature contours throughout the valve after 1st, 3rd, and 5th seconds after casting for SC, CC, SFC, and PTC type cooling channels.

disc for cooling with the SFC type duct was obtained as 780 K. After 0.02 m, there is no significant difference in temperature variations for 4 different types of channels along the central axis of the valve.

Figure 7 shows the variation of the liquid fractions along the valve axis based on the valve height after 1st, 3rd, and 5th seconds of casting for 4 different types of cooling ducts. At the end of 1 s, solidification in the SFC type cooling channel for the disc entrance area (gate) in the runner is the earliest, while the liquid fraction 1 is observed in the PTC. The same is true for the mold vent. The liquid fraction data zone center is extended. Complete solidification has been achieved for all channel types at the handle between 0.02 m and 0.13 m. At the end of 3 s, the valve disc corresponds to the center axis of 0 to 0.02 m, while the liquid fraction is the least for the SFC channel mold, while, for PTC, it is the largest. Solidification is complete when the center axis is between 0.02 m and 0.14 m. For SC, CC, and SFC type cooling channels in the airway, the liquid fraction is close to 0.5-0.6, while it reaches up to 1 for the PTC type channel. For all cooling channel designs, the solidification was fully realized for the valve after 5 s. At the end of 5 s, solidification in the PTC type cooling channel mold could reach up to 0.14 m in other cooling channels, with the center axis extending approximately to 0.15 m. However, in proximity to the ventilation pit, this situation is reversed, and SC, CC, and SFC type cooling duct molds are less than the liquid fraction PTC. In addition, among SC, CC, and PTC grooved molds, the SFC type channel mold has the least liquid fraction.

4. Conclusions

The study investigated the effect of different types of cooling channels on the solidification rate and heat transfer for a material to be manufactured from Al alloy in a permanent mold. Results of the transient numerical analysis were achieved at the 1st, 3rd, and 5th seconds. The effect of cooling performance between cooling channels on solidification could be seen in analyses made up until the 5th seconds. Because model geometries are complex, the analysis takes a very long time to carry out, which is why the analyses could be carried out until the 5th seconds.

According to the temperature distributions after 1 s from the casting, the SFC type channel can cool faster than the other channels. However, there is no significant difference between the originally designed geometries (CC, SFC, PTC) for the 3rd type according to the cooling channel (SC) of the standard type. The temperature in the SFC channel for the base temperature of the base of the valve at the 5th second was observed to be lower than that in the other channels.

According to the numerical results of the solidification process, the solidification rate in the SFC-type channel design was higher than that in other designs. Herein, the CC-type channel design was considered for the conformal cooling of the lately stiffened parts according to the design of the cast part. However, according to the results of numerical analysis, there is no significant difference between CC and SC. SC outperformed CC and PTC at the 1st-5th seconds for casting in terms of better cooling. At the 5th second, solidification for the valve, which is the casting part, was finished. Because the analyses were very complex and took a long time, they could be run up to 5 seconds. In this study, the influence of the cooling channels on

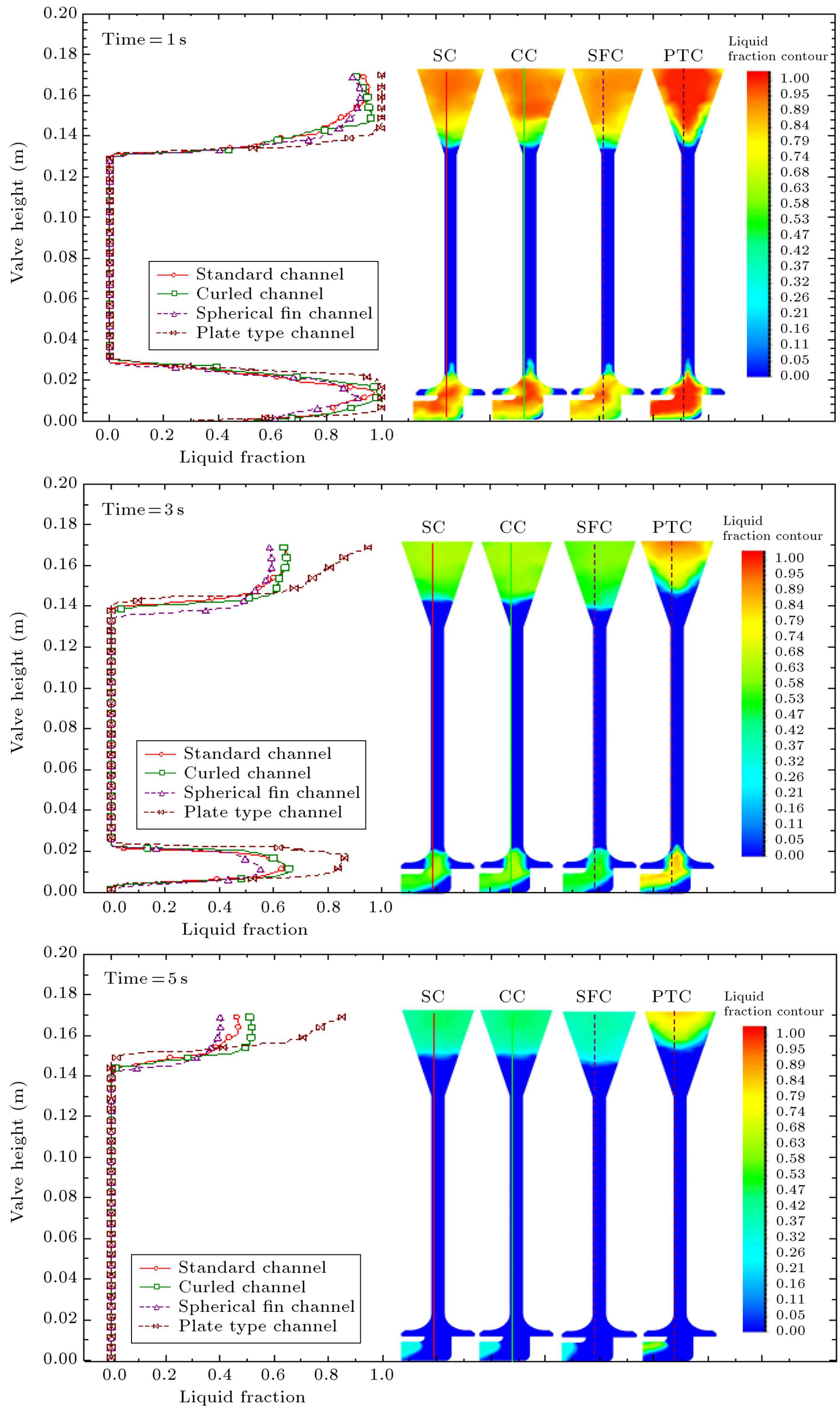

Figure 7. Liquid fraction along the valve axis after 1st, 3rd, and 5th seconds for casting for SC, CC, SFC, and PTC type cooling channels.

the casting part was investigated. The temperature distribution for the mold can be considered separately in further studies. The importance of CFD analysis is emphasized while designing cooling channels in a metal mold to be produced by joint manufacturing. Numerical analyses should be compared with real-world applications in the subsequent studies, and the specific cooling channels to be produced by SLM (Selective Laser Melting) should also be experimentally examined.

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