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 occur in cast products when the 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. Selective Laser Melting (SLM) method has been 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 for 1, 3 and 5 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 has been observed that solidification is better in originally designed cooling channels.

KEYWORDS - Metal Mold, SLM, Conformal Cooling Channels.
PACS – 81.20.Hy, 44.15.+a, 44.05.+e, 44.20.+b

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 the 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 as well as product quality, in that permanent mold casting produces high quality product by casting liquid metal at high temperature. There are many important problems in classical molding methods where cooling process is performed by using vertical and horizontal channels formed on the mold body, this 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 especially important for parts with high production costs per unit volume (such 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 shorter production period than conventional production methods [2-4]. In their studies, the molds produced by the conventional method with 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 that 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 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 [10-16]. Conformal cooling channels for the plastic injection mold design and examined the numerical and experimental cooling performance. Numerical analysis and experimental results are consistent with each other and have 12.8% shorter cycle times with conformal cooling channels. In addition Park and Dang [17] developed comformal cooling channel for plastic injection mold. The study results showed that % 30 shorter cycle time with conformal cooling channels. In an experimental work they have achieved with an injection mold with a conformal cooling channel designed by articulated manufacture in a shorter time than the mold regime temperature [18]. In order to reduce the cycle time in the aluminum metal injection mold (biscuit), they designed the conformal cooling channel in the heel region [19]. The numerical analyzes 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 extrusion rate of 300% by producing an aluminum extrusion die with conformal cooling channels with DMLS (Direct Metal Laser Sintering) [20]. According to recent researches, it is seen that the numerical analyzes are verified with experimental studies. In this study, they have made time-dependent numerical analysis of solidification melting behavior by using enthalpy-porosity approach with ANSYS-FLUENT software for sodium nitrate for thermal energy storage [21]. Numerical analysis results show that the discharging process is slower than the charging process. It has been suggested that engine parts such as valves and camshafts can be manufactured using aluminum alloys [22]. Numerical and experimental studies on aluminum and its alloys have been carried out. Aluminum 6061-SiC MMCs (metal matrix composites) have investigated the changes in their mechanical properties, microstructure and hardness properties depending on the ratio of SiC and have come to the conclusion that poppet valve can 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 can be produced by the DMLS method were analyzed by ANSYS-FLUENT software. Generally, ANSYS-FLUENT program is used for thermal and flow analysis. [27-30]. Analyzes 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 depending on the time of melting during casting were compared with the original cooling channels.

2 NUMERICAL MODELLING

The metal mold to be produced by the DMLS method of gray cast iron comes from two parts which are symmetry of each other. As seen in the mold solid model given in Figure 1, the symmetry 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 has been numerically investigated for half of the mold. CFD analyses were performed for the designs using CFD software to investigate solidification-melting and cooling channel thermal and hydrodynamic behavior with a consideration of the boundary conditions given in Figure 2.

Equations used for cooling channels in the numerical analyses;

The continuity, momentum and energy equations drawn from the background of the program for the flow analyzes 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 as shown in Eq. (1).

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

$$\dot{m}_{oil} = \rho_{oil} V A_c \tag{1}$$

Hydraulic diameters in the designed cooling channels vary according to the perpendicular to the cross-sectional area. The hydraulic diameter D_h (m) on a non-circle professor is expressed as in follows Eq. (2),

$$D_h = \frac{4A_c}{P_w} \tag{2}$$

Where the "Ac" is the cross sectional area and "Pw" is the wet perimeter.

For flow in channels, Continuity Equation, as shown in Eq. (3) below:

$$\frac{\partial u}{\partial x}+\frac{\partial v}{\partial y}+\frac{\partial w}{\partial z}=0 \tag{3}$$

Momentum Equation, as shown in Eq. (4), Eq. (5) and Eq. (6) below:

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

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

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

Given as. Where g is the acceleration of gravity (m/s^2).

Energy Equation, as shown in Eq. (7) below:

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

$C_{p,}$ 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 analyzes 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 analyzes were performed using ANSYS-FLUENT software for designed cooling channels 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 for the smaller time step. The numerical model parameters used in the analyses are given in Table 1. Mesh parameters used simulations are given Table 2. For designed models, there are 1,134,500, 1,262,000, 1,294,000 and 1,428,106 mesh elements in SC, CC, SFC and PTC respectively as could be seen on Table 2. 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. Thermal properties of heat transfer oil used 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 numerical analysis are presented in Table 4. 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 973K. The heat transfer oil was circulated in the cooling channel and the properties of the Petro-Therm commercial product were entered. Mesh structure for cooling channel mold used in analysis in Figure 4.

3. NUMERICAL RESULTS

Numerical analysis results 1, 3 and at the 5 s using the CFD-POST 16.1 program. In the analyzes made, the symmetry for all of the compact molds was obtained for the 4 different cooling channel designs with 3-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 depending on the valve height for the four different types of cooling channel after 1-3-5 th 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 design on the stem is 0.02 m to 0.11. m. After 3 s, it is seen that the temperature decreasing passages from the discrete to the stem are smoother with respect to the valve height from 0.01 m to 0.04 m compared to 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 1 s. At the end of 5 s, the temperature transitions towards the disc stalk seem to be softer than the 3 s. After 5 s, the lowest temperature in the disc for the cooling with the SFC type duct was obtained as 780 K. After 0.02 m, there is no significant difference in temperature change 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 depending on the valve height after 1-3-5 s of casting for 4 different types of cooling ducts. At the end of 1 s, the 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. Liquid fraction data zone center is extended. Complete solidification has been achieved for all channel types at the handle between 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 the 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, the 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 0.15 m. But wherever go towards the ventilation pit this situation is reversed and the SC, CC and SFC type cooling duct molds are less than the liquid fraction PTC. In addition between SC, CC and PTC grooved molds, the SFC type channel mold has the least liquid fraction.

4. CONCLUSIONS

In the study, 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 was investigated. Results of transient numerical analysis 1, 3 and 5 seconds. The effect of cooling performance between cooling channels on solidification could be seen in analyzes made up until the 5 th seconds. Because the model geometries are complex, analysis takes a very long time. That is why the analyzes could be carried out until the 5 th 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 original designed geometry (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 5 th seconds is observed to be lower than the other channels.

According to the numerical results of the solidification process, the solidification rate in SFC type channel design is higher than in other designs. Here, the CC type channel design is contemplated for the conformal cooling of late stiffened parts according to the design of the cast part. However, according to numerical analysis results, there is no significant difference compared to SC. SC performs have better cooling than CC and PTC for 1 - 5 s for casting. At the 5th seconds, solidification for the valve, which is the casting part, is finished. Because the analyzes were very complex and took a long time, they could be run to 5 seconds. In this study, the influence of the cooling channels on the casting part was investigated. The temperature distribution for the mold can be considered separately in further studies. This emphasizes the importance of CFD analysis while designing cooling channels in a metal mold to be produced by joint manufacturing. Numerical analyzes will be compared with real applications in the subsequent studies and the specific cooling channels to be produced by SLM (selective laser melting) will be experimentally examined.

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FIGURE CAPTIONS

Figure 1. Designed metal mold drawing

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

Figure 3. Designed cooling channels flow volumes (a. Standard Channel, b. Spherical Fin Channel, c. Curled Channel, d. Plate Type Channel)

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

Figure 5. Temperature distribution along the valve axis after 1-3-5 s from casting for SC, CC, SFC and PTC type cooling channels
Figure 6. Temperature contours throughout the valve after 1-3-5 s after casting for SC, CC, SFC and PTC type cooling channels

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

TABLE CAPTIONS

Table 1. Numerical modelling parameters used solution

Table 2. Mesh parameters used simulations

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

Table 4. Thermal properties of Al 6061 used numerical analysis

FIGURES

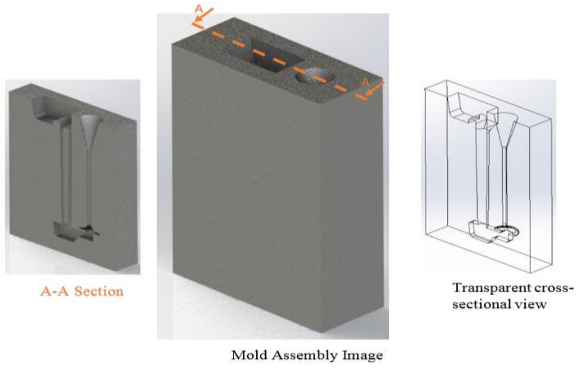


Fig. 1

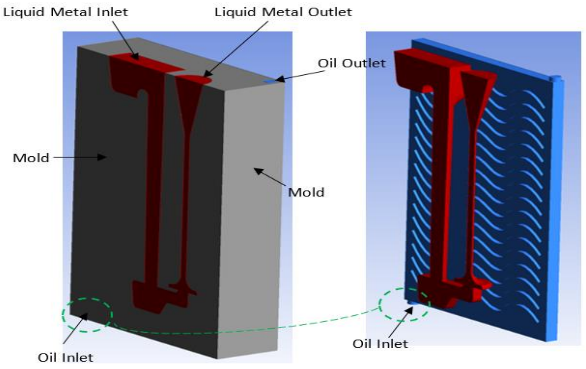


Fig. 2

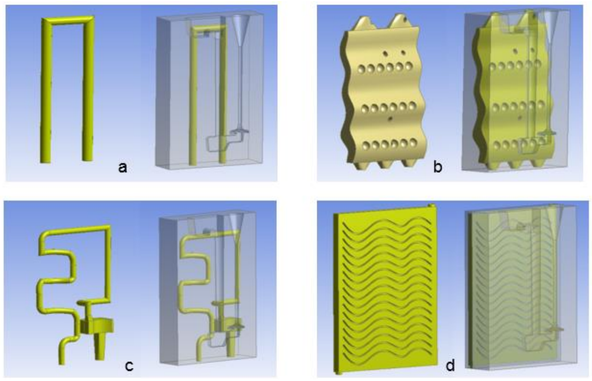
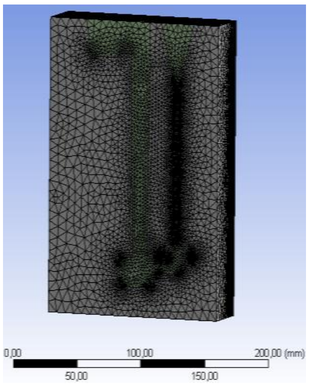

a
b
c
d

Fig. 3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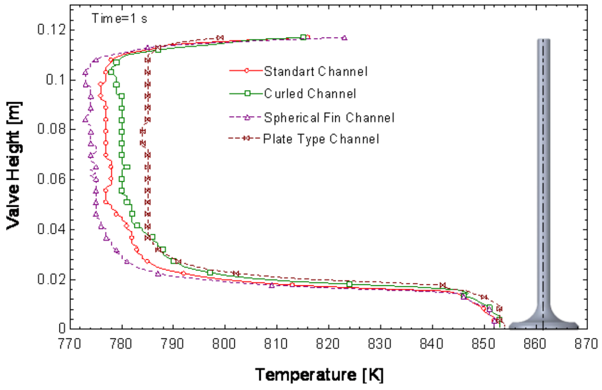
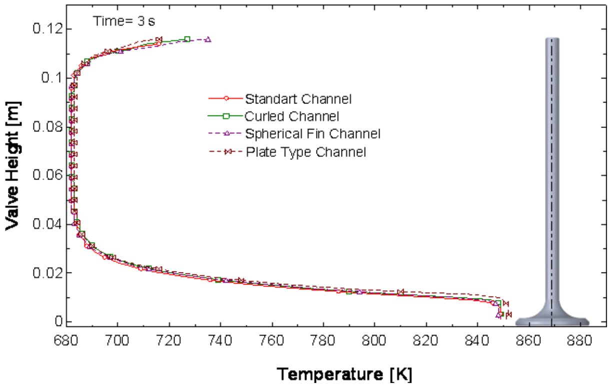
200,00 (mm)
50,00
150,00

Fig. 4


Time=1 s
Standart Channel
Curled Channel
Spherical Fin Channel
Plate Type Channel
Valve Height [m]
0
0.02
0.04
0.06
0.08
0.1
0.12
770
780
790
800
810
820
830
840
850
860
870
Temperature [K]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Standart Channel
Curled Channel
Spherical Fin Channel
Plate Type Channel
Valve Height [m]
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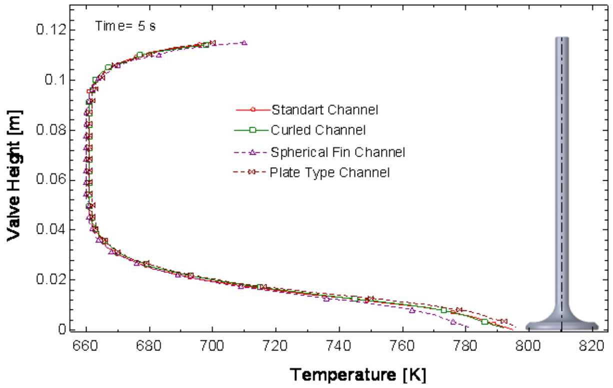
0.02
0.04
0.06
0.08
0.1
0.12
680
700
720
740
760
780
800
820
840
860
880
Temperature [K]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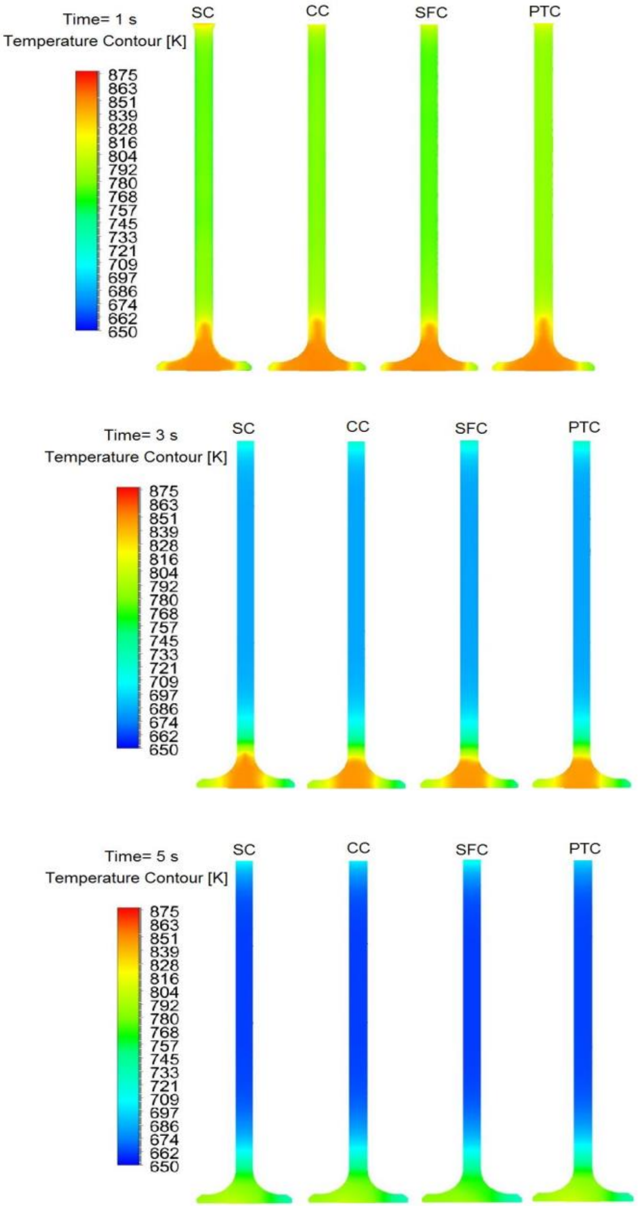
Valve Height [m]
0.12
0.1
0.08
0.06
0.04
0.02
0
Temperature [K]
660
680
700
720
740
760
780
800
820
Standart Channel
Curled Channel
Spherical Fin Channel
Plate Type Channel

Fig. 5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Temperature Contour [K]
875
863
851
839
828
816
804
792
780
768
757
745
733
721
709
697
686
674
662
650
SC
CC
SFC
PTC
Time= 3 s
Temperature Contour [K]
SC
CC
SFC
PTC
Time= 5 s
Temperature Contour [K]
SC
CC
SFC
PTC

Fig. 6

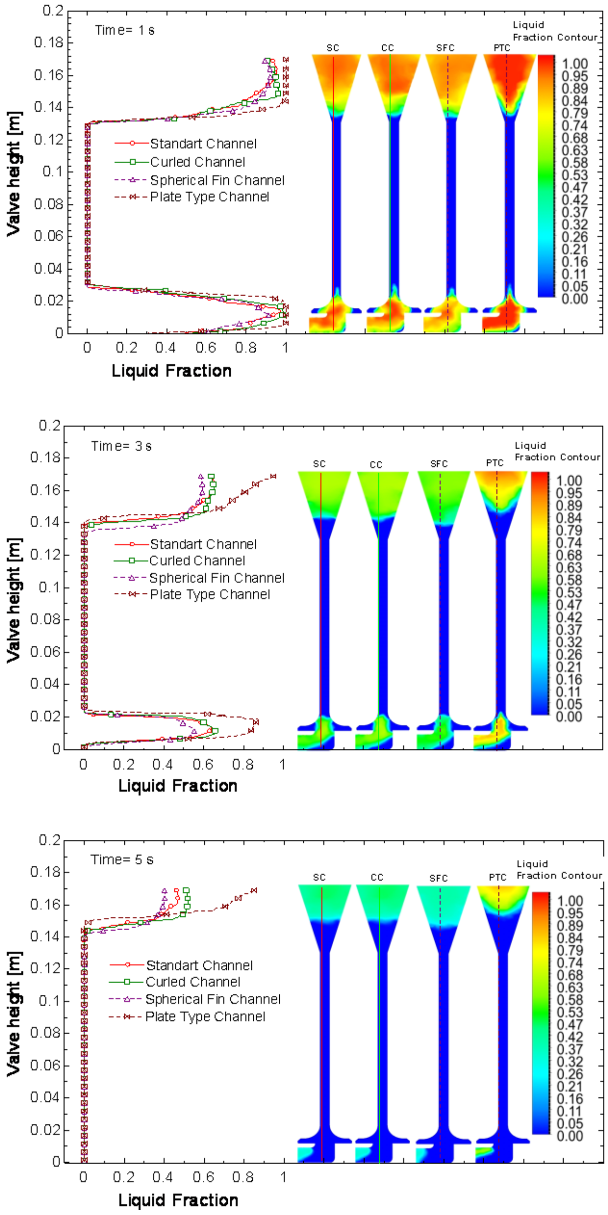

Fig. 7

TABLES

Table 1

Simulation Condition	Transient-state
Solver Type	Pressure Based
Mesh Structure	Tetrahedral
Turbulence Model	RNG-Enhanced wall treatment standard k-ε Turbulence Model
Wall-Turbulence Interaction	Standard Wall-function
Speed - Pressure Interaction	COUPLED algorithm
Decomposition Method	Second Order Upwind

Table 2

	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

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	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	-	-

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		

BIOGRAPHIES

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