Open Access Journal of Physics
Volume 2, Issue 3, 2018, PP 5-14
ISSN 2637-5826

Numerical investigation of Cooling Performance in Classic and New Cooling Channels of Mold Core

O. Ipek[1], M. Kan[2]

[1,2]Süleyman Demirel University, Isparta, Turkey

***Corresponding Author:** M. Kan, Süleyman Demirel University, Isparta, Turkey*

ABSTRACT

Thermal management of the cooling process is one of the most important factors in obtaining directional and effective solidification of liquid metal in a metal mold. Various die thermal-related defects, such as localized causing shrinkage, hot tears, suck downs and also warping can occur when cooling is not controlled. This study developed a new internal section for metal die cavities with classical cooling channel, and two original cooling channel metal sections using Laser Sintering Technology (LST) method. These channels were intended to be used together. They were examined numerically to determine their effects on heat transfer and solidification of the molten metal regarding intervals. In the first 0.5-5 seconds after casting, the researchers examined temperature distributions and solidification processes for all channels. The study results revealed that solidification of the heat transfer and the molten metal was better in the original cooling channels. Production quality molding technology in order to solve the problems of mold cooling process directly affects LST method contemplated for applications to do with the specific cooling channels and the mold can be cooled at high efficiency to 70% of the core and would be of substantial improvement of product quality were observed. It is also understood that the production period can be shortened.

Keywords: *CFD Analysis, Conformal Cooling Channels, LTS, Metal Molds*

INTRODUCTION

During gravity die casting, the mold cooling process obtained via proper die design and a controlled thermal management system are critical factors for optimizing production throughput and casting quality. Metal-casting is one of the most prominent sectors that strengthen the economy and show its development level. The added value produced by the industry is much higher than its production costs. Today, classical manufacturing methods are used for molding. However, current LST-based applications are used for cutting and removing material from a block in the manufacturing of parts as well as the forming process, wherein these applications help melt metal powder layer by layer. In contrast, a combination of multiple methods can be used in conventional manufacturing. This technology is employed in a wide range of industries for the production of various parts and components and for manufacturing processes including implant manufacturing, medical equipment, spacecraft parts, satellite systems, aircraft components, mini jet turbines, compressors and engine components, gas turbine equipment and complex geometry products in addition to the products that require precisely designed parts and devices. LST technology applied to classical manufacturing methods allows a rapid and easy production of even very challenging products, and the production processes that typically take a long time. Moreover, this technology will yield even better results in the future as it is developed further. Experimental studies have demonstrated how the microstructure of the manufactured parts is affected by the molding process. The new methods developed in previous studies have optimum conditions for the production of materials that are suitable for the selective laser sintering (SLS) method. The selective laser melting (SLM) method applied with conventional manufacturing injection on steel samples caused the samples to have higher tensile strength. Past studies have made an experimental investigation of the particle mechanical structure and mechanical properties of the parts produced by LST [1-7]. There are studies that made an effort to improve surface quality. Furthermore, researchers have carried out experiments on metal-casting to increase the wear resistance of mold surfaces during casting to increase the heat transfer rate and to obtain a more controlled temperature distribution [8-10].

The microstructure of the materials produced by the casting method needs to be cooled in a rapid and controlled manner to have fine-grained mechanical properties with better quality. Thermally-managed and rapid cooling also increases the production speed. For this reason, this study has designed geometrical cooling channels with special aspects. Correlations are determined to improve the efficiency of uniform (conformal) cooling channels and the quality of production. There are experimental studies which claimed and proved a more uniform heat transfer through conventional cooling channels. In metal-casting process, the efforts to prevent mold defects (e.g., part warpage, bending and hot spot flaws) resulted from an uncontrolled cooling finish. It is possible that stresses, corrosions and structural deformations occur in the materials during metal-casting process. Past research has shown that these problems cause cracks on the surface [11-17]. This study developed a finite element stress model based on the previous studies on these distortions. This new model derived heat transfer correlations from these studies, which investigated the microstructures and mechanical properties of the samples they produced [18-25].

The present study made a numerical investigation of the cooling performance of the metal die cavity's internal section. The thermal and hydrodynamic behaviors of the conventional cooling channels and the original cooling channels (LST method) were investigated to determine their effect on heat transfer and the solidification of the molten metal.

Numerical Modeling

The metal mold core (the internal section of the metal die cavity) that can be produced by the LST method comes from two symmetrical parts. As can be seen in the solid model of the mold core shown in Figure 1, the symmetrical mold parts are designed in the exact same manner. The original cooling channels were designed to yield optimal cooling for castings. Because the symmetry of the cooling channels was symmetrical, the effect of heat transfer and solidification of the molten metal was numerically investigated for half of the mold.

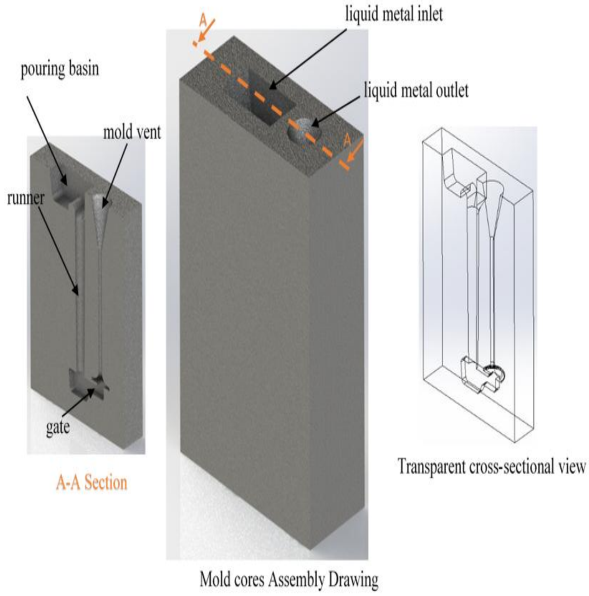

Figure1: *Metal mold core drawing*

For cooling channels [26]:

The heat transfer equation is given below in Equation 1.

$$\dot{m}\Delta H = -hA_s(T_m - T_s) \qquad (1)$$

For intra-channel flows [26]:

The mass conservation equation is given below in Equation 2.

$$div\bar{u} = \frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial z} \qquad (2)$$

The momentum equation is given below in Equations 3, 4 and 5 for X, Y and Z axes, respectively:

$$\rho\left(\frac{\partial u}{\partial t} + u\frac{\partial u}{\partial x} + v\frac{\partial u}{\partial y} + w\frac{\partial u}{\partial z}\right) = \mu\left(\frac{\partial^2 u}{\partial x^2} + \frac{\partial^2 u}{\partial y^2} + \frac{\partial^2 u}{\partial z^2}\right) - \frac{\partial P}{\partial x} + \rho g_x \qquad (3)$$

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

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

The conservation equation of the energy is given below in Equation 6.

$$\rho\left[\frac{\partial(C_pT)}{\partial t}+\frac{\partial(C_puT)}{\partial x}+\frac{\partial(C_pvT)}{\partial y}+\frac{\partial(C_pwT)}{\partial z}\right]=\frac{\partial}{\partial x}(\lambda\frac{\partial T}{\partial x})+\frac{\partial}{\partial y}(\lambda\frac{\partial T}{\partial y})+\frac{\partial}{\partial z}(\lambda\frac{\partial T}{\partial z}) \quad (6)$$

The flow volume models of the flow circulating in the metal mold core are shown in Figure 2.

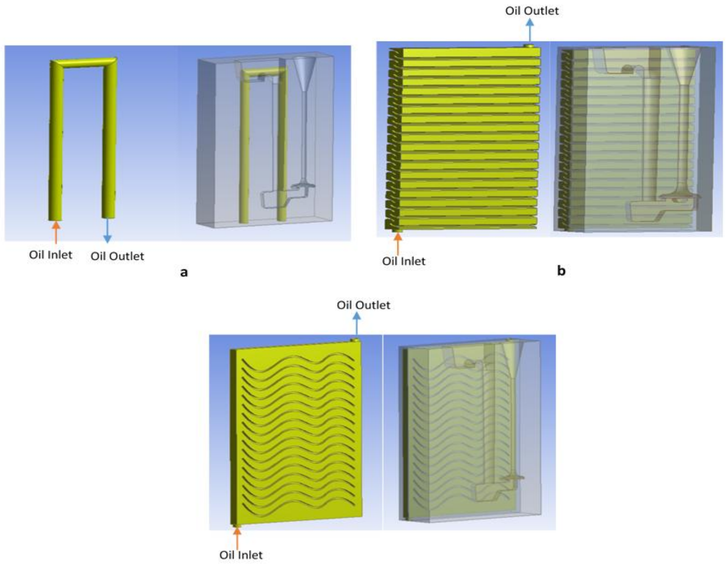

Figure2. *Flow volumes of the designed cooling channels (a. Classical Channel, b. Twist-Type Channel, c. Plate -Type Channel)*

A mesh structure was established for CFD analysis. For each flow volume model (Classical channel (CC), twist-type channel (TTC) and plate-type channel (PTC)), a mesh was placed in the tetrahedral mesh geometry. For these models, CC, TTC and PTC had an average of 9,917,834 elements and 5,694,075 nodes. 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 3. The study also made analyses to determine transient temperature changes and solidification rates for the valve in different types of cooling channels. The numerical model parameters used in the analyses are given in Table 1.

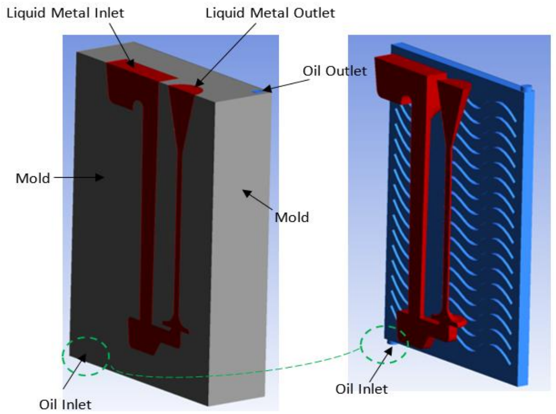

Figure3. *Boundary conditions used in analyzes*

Table1. *Numerical model parameters used in analyzes [26]*

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

Result

For all the symmetrical compact mold cores, the temperature distributions of the 3-D cooling channel, the metal mold core and the molten metal are time-dependent. For this reason, these distributions were analyzed in different periods for each of the 3 different cooling channel designs. The study also compared the melting metal solidification rates for these cooling channels. Figure 4 presents the appearance of the symmetrical mold cores according to their respective temperature and liquid volume ratios [26].

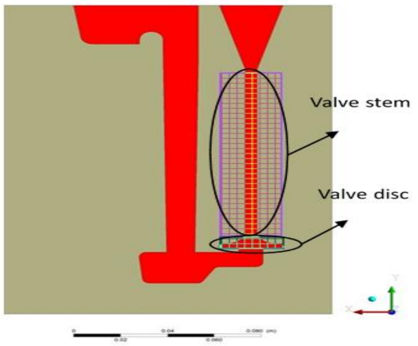

Figure4. *Comparison zones based on the temperature and solid-liquid ratio of the analysis results*

Figure 5 shows the variation of the temperature distribution contours according to the valve height along the valve axis in the first 0.5 - 5 s interval after casting for the classical cooling channel. Here, the temperature between the valve head and the valve stem is noteworthy. Depending on the time, the temperature begins to decrease before stabilizing towards the valve stemonce the cooling is started [26].

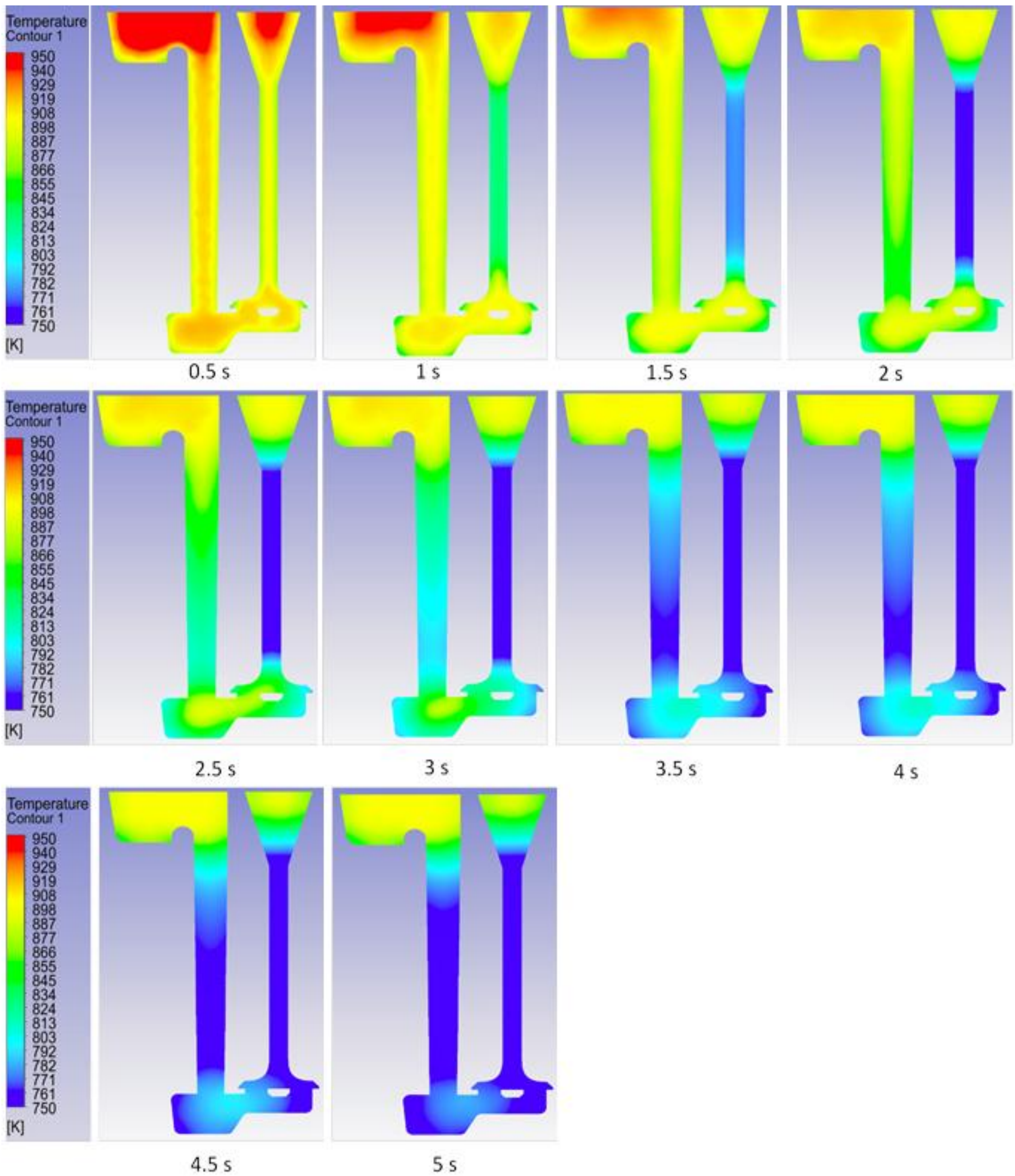

Figure5. *Temperature contours throughout the valve after 0.5-5 s from casting for CC*

In Figure 6, the contour of change according to the valve height of the liquid volume ratio along the valve axis in the first 0.5 – 5 s intervals after casting is given for the classical cooling channel.

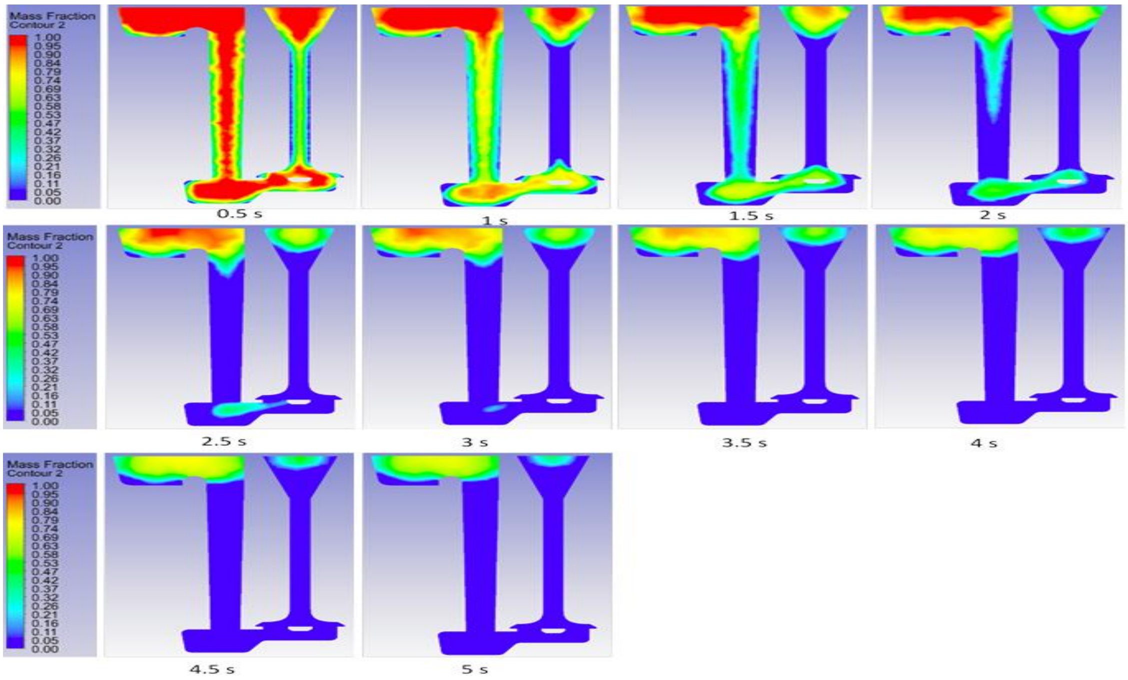

Figure6. *Liquid fraction along the valve axis after 0.5-5 s from casting for CC*

For the twist-type channel, the variations of the temperature distribution contours of the valve profile along the valve axis during the first 0.5 – 5 s time interval after casting are shown in Figure 7.

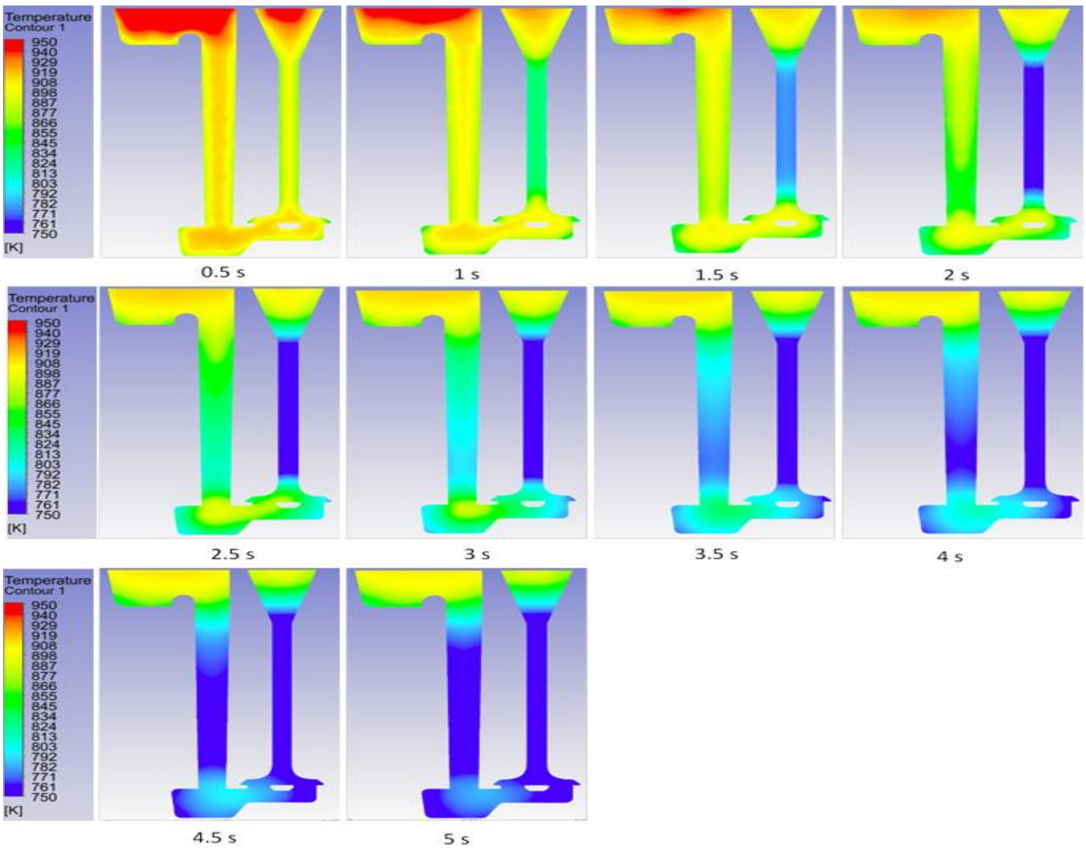

Figure7.*Temperature contours throughout the valve after 0.5-5 s from casting for TTC*

Figure 8 shows the contours of the volume-to-volume variation along the vertical axis of the valve during 0.5 - 5 s time intervals after casting for the twist-type channel. There is a remarkable difference in temperature between the valve head and the valve stem. After the cooling is initiated, the temperature distribution begins to decrease before becoming stable towards the valve stem.

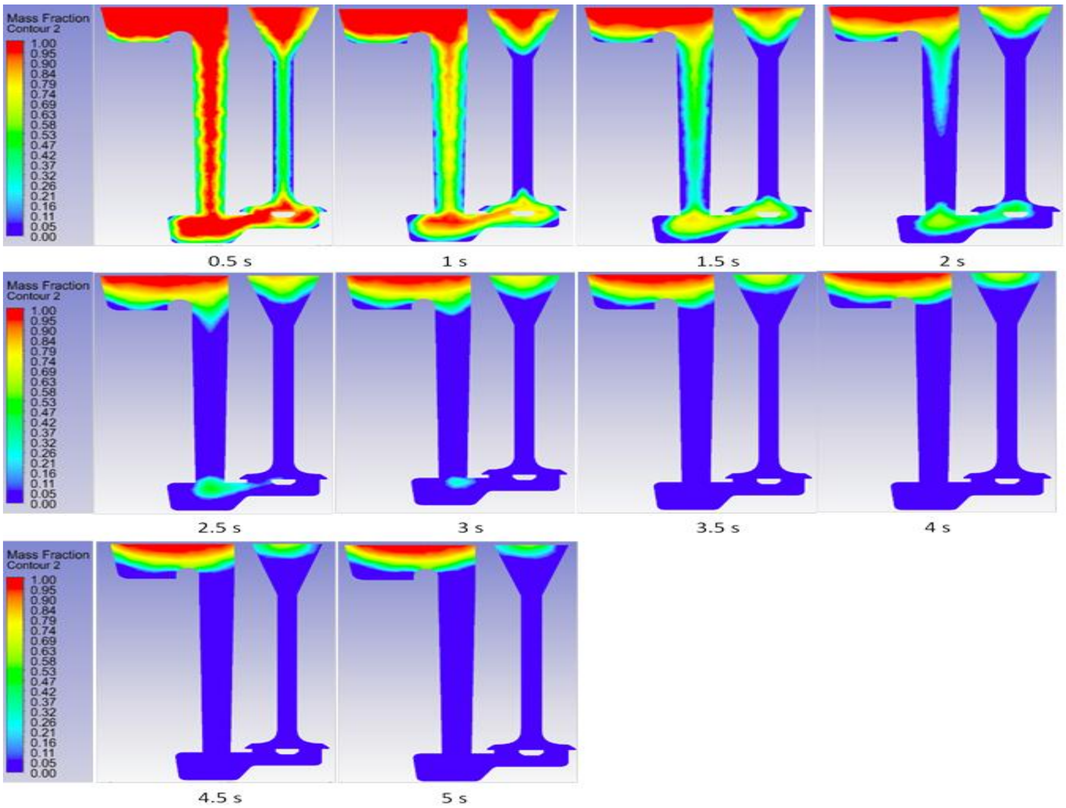

Figure8. *Liquid fraction along the valve axis after 0.5-5 s from casting for TTC*

Figure 9 shows the variation of temperature distribution contours along the vertical axis of the valve during time intervals of 0.5-5 s for the plate-type channel.

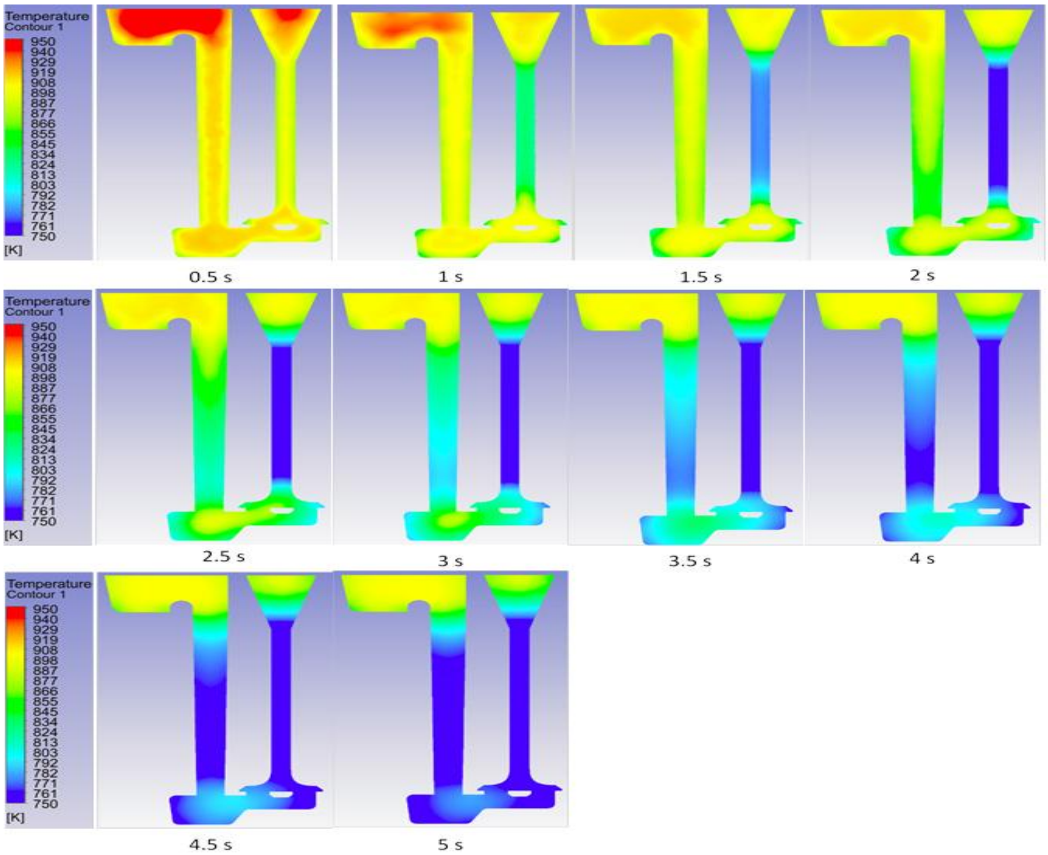

Figure9.*Temperature contours throughout the valve after 0.5-5 s from casting for PTC*

Variations of liquid volume ratio contours along the valve vertical axis of the valve during 0.5 - 5 s time intervals for the plate-type channel are shown in Figure 10.

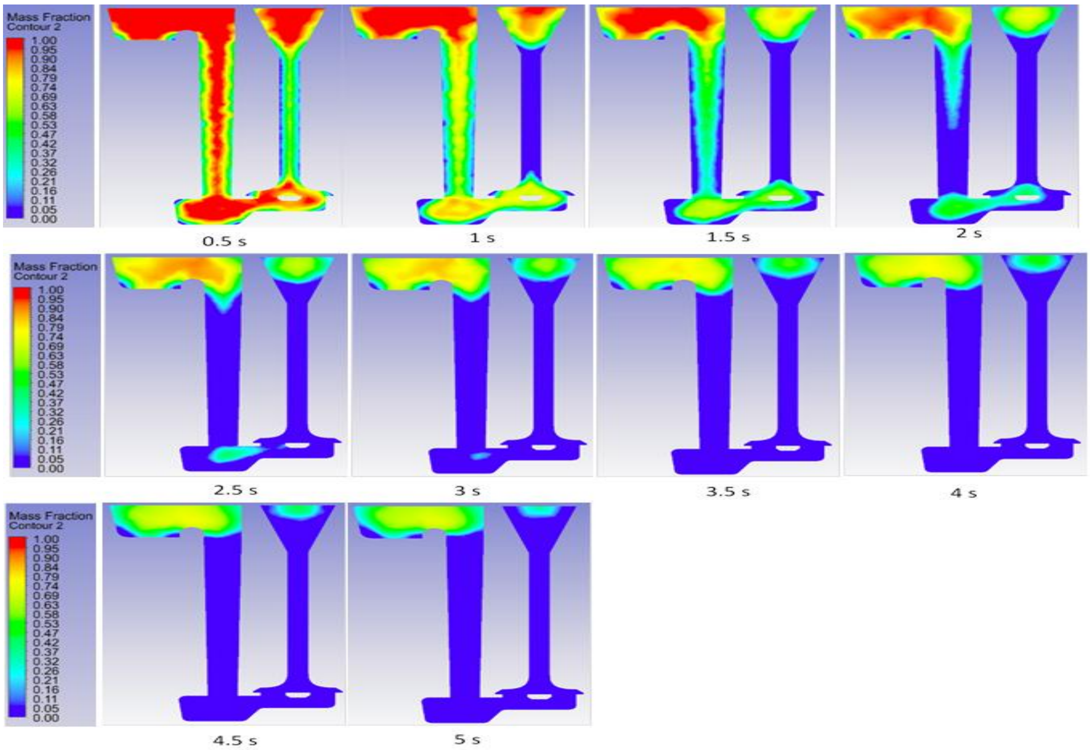

Figure10. *Liquid fraction along the valve axis after 0.5-5 s from casting for PTC*

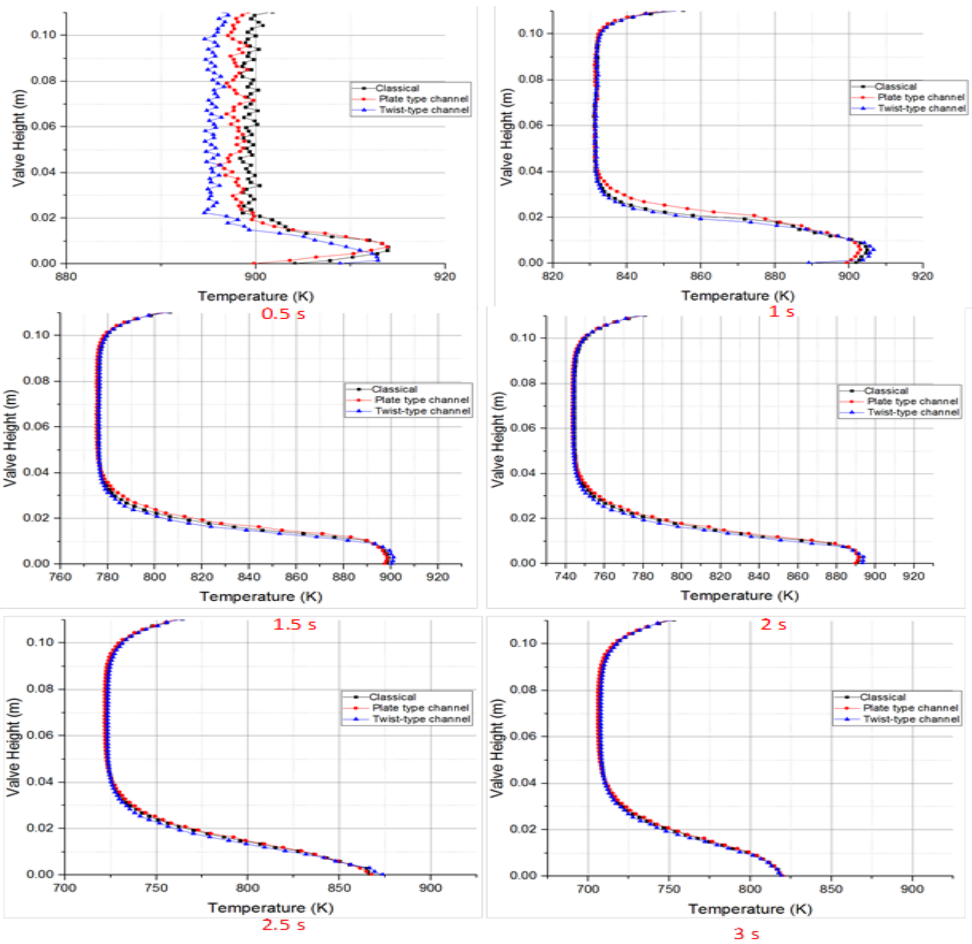

Figure11a. *Temperature distribution along the valve axis after 0.5-5 s from casting for CC, PTC, TTC*

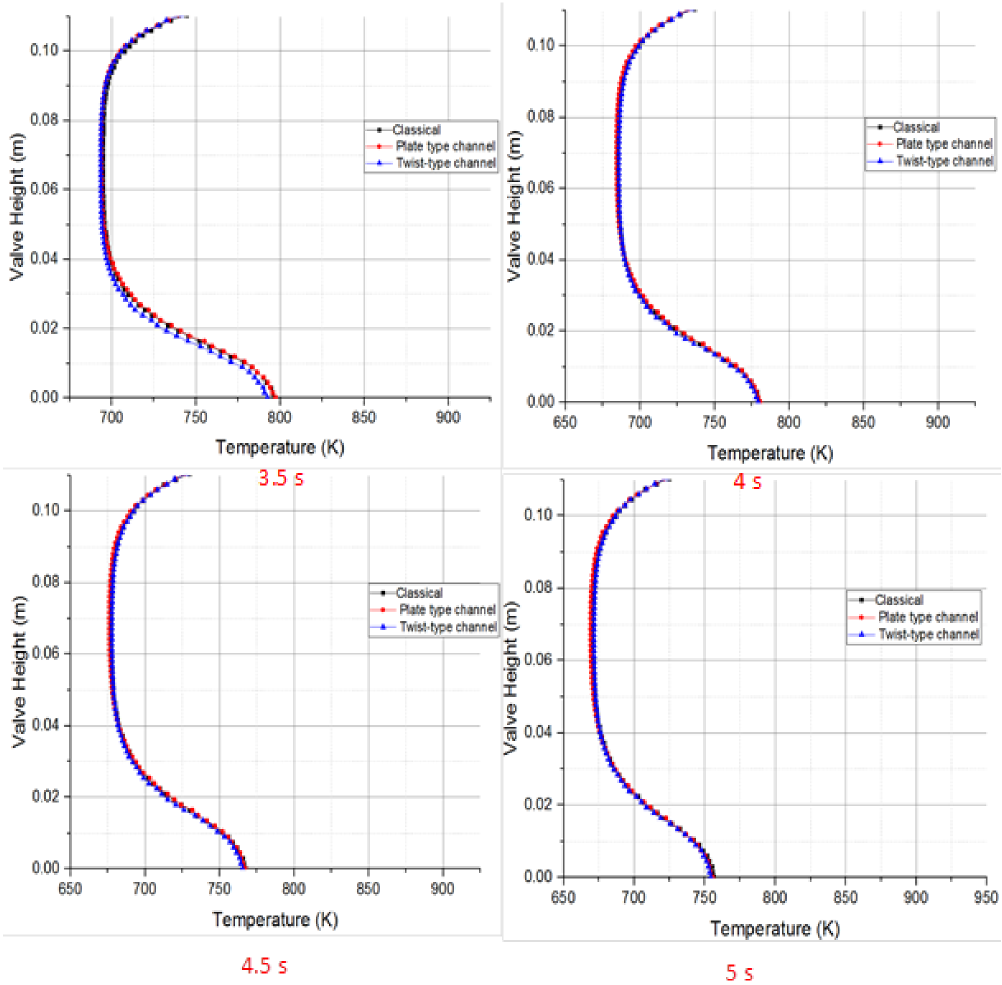

Figure11b. *Temperature distribution along the valve axis after 0.5-5 s from casting for CC, PTC, TTC*

Figure 11 presents the temperatures in the cooling channel during the 0.5 - 5 s time interval distribution. As can be seen from the graphs, the thermal balance between the channel geometries in the first 0.5 s and the internal section of the metal die cavity is not precise, which leads to the fact that they fluctuate in temperature. Therefore, the change in temperature throughout the valve is not big. The temperature distribution in the valve stem region showed a steady trend once solidification started after 1 s. At the end of 5 s, however, it was observed that the cooling of the valve stem resulted in better cooling. At 2 cm down from the valve height, the temperature drops sharply toward the valve stem. An observation of the temperature distributions in the cooling channels revealed that the molten metal with a plate-type channel went through a better cooling than the other cooling channels.

Conclusions

This study invstigated the effect of different types of cooling channels on the solidification rate and heat transfer for a material made of Al alloy in a metal mold. In examining the numerical transient analysis results of the 0.5 to 5 s interval, the researchers concluded (based on the temperature distributions of the casting) that it is possible to achieve faster cooling with the PTC-type channel than with the other channels. According to the numerical results of the solidification process, the solidification rate of the PTC-type channel design was higher than that of the other designs, which shows the importance of CFD analysis in designing cooling channels in a metal mold to be produced by joint manufacturing. The effects of the designed cooling channels, heat transfer and solidification of the molten metal were studied in transient numerical terms. This work will close the gap in the literature for heat transfer in cooling channels and solidification and melting for gravity die casting.

References

[1] Manilal, P. I., Singh, D. P. K. and Chen, Z. W., “Computer Modeling And Experimentation For Thermal Control Of Dies In Permanent

Mold Casting", **AFS Trans** 2003. V111p125-135_ AFS Library20030337A.

[2] Biswas S., Monroe C. Prucha T. , "Use of Published Experimental Results to Validate Approaches to Gray and Ductile Iron Mechanical Properties Prediction", International Journal of Metalcasting.Volume 11, Issue 4, pp 656–674. 2017.

[3] Muñoz-Ibáñez C. A., Alfaro-Ponce M., Perez-Lechuga G., Pescador-Rojas J.A., "Design and Application of a Quantitative Forecast Model for Determination of the Properties of Aluminum Alloys Used in Die Casting", **International Journal of Metalcasting**.pp 1–14, 2018.

[4] Amend, P.,Pscherer, C., Rechtenwald, T., Frick, T., Schmidt, M., "A fast and flexible method for manufacturing 3D molded interconnect devices by the use of a rapid prototyping technology", **Physics Procedia**, 5.561–572, 2010.

[5] Deckers J., Meyers S., Kruth J.P., Vleugels J., "Direct selective laser sintering/melting of high density alumina powder layers at elevated temperatures", **Physics Procedia** 56. 117 – 124. DOI: 10.1016/j.phpro.2016.01.002, 2014.

[6] Zeng, K., Pal, D. and Stucker, B., "A Review of Thermal Analysis Methods in Laser Sintering and Selective Laser Melting", Utwired. **http://utwired. engr.utexas.edu/lff/ symposium/proceedingsArchive/pubs/Manuscripts/2012/2012-60-Zeng.pdf**, Available date: 12.08.2015,2012.

[7] Thomas, D., "The Development of Design Rules for Selective Laser Melting", Cardiff Metropolitan University. **https://repository.cardiffmet.ac.uk/dspace/handle /10369/913.**Available date: 12.08.2015,2009.

[8] Thompson, S.M.,Aspin, Z.S., Shamsaei, N., Elwany, A. ve Bian, L., "Additive manufacturing of heat exchangers: Acasestudy on a multi-layered Ti–6Al–4V oscillatingheatpipe", **Additive Manufacturing**, 8, 163-174,2015.

[9] Atzeni Eleonora and Alessandro Salmi, "Study on unsupported overhangs of AlSi10Mg parts processed by Direct Metal Laser Sintering", **Journal of Manufacturing Processes**,2015.

[10] Hanzl P.,Zetek M., Baksa T., Kroupa T., "The Influence of Processing Parameters on the Mechanical Properties of SLM Parts", **Procedia Engineering** 100. 1405 – 1413,2015.

[11] Sachs, E., Wylonis, E., Allen, S., Cima,M., Guo, H., "Production of Injection Molding Tooling With Conformal Cooling Channels Using the Three Dimensional Printing Process", **Polimer Engineering and Science**, 40-5, 2000.

[12] Wang, Y., Yu, K.M., Wang, C.C.L., "Spiral and conformal cooling in plastic injection molding", **Computer-Aided Design**, 63, 1-11. DOI: 10.1016/j.cad.2014.11.012, 2015.

[13] Xia, C., Fu, F., Lai, J., Yao, X., Chen, Z., "Conjugate heat transfer in fractal tree-like channels network heat sink for high-speed motorized spindle cooling", **Applied Thermal Engineering**, 90, 1032-1042.DOI: 10.1016/j.applthermaleng.2015.07.024 ,2015.

[14] Hu, P., He, B., Ying, L., "Numerical investigation on cooling performance of hot stamping tool with various channel designs", **Applied Thermal Engineering**, 96, 338-351. DOI: 10.1016/j.applthermaleng.2015.10.154, 2016.

[15] Au K.M., Yu K.M. and Chiu W.K., "Visibility based conformal cooling channel generation for rapid tooling", **Computer-Aided Design**, 43, 356-373, 2011.

[16] Du F., Wang X., Liu Y., Li T., and Yao M., "Analysis of Non-uniform Mechanical Behavior for a Continuous Casting Mold Based on Heat Flux from Inverse Problem", **Journal of Iron and Steel Research**, 23 (2): 83-91, 2016.

[17] Eimsa-ard. K and Wannisorn. K, "Conformal bubbler cooling for molds by metal deposition process", **Computer-Aided Design,** 69, 126-133. DOI: 10.1016/j.cad.2015.04.004,2015.

[18] Ahammed, N., Asirvatham, L.G., Wongwises, S., "Thermoelectric cooling of electronic devices with nano fluid in a multiport mini channel heat exchanger", **Experimental Thermal and Fluid Science**, 74, 81-90, 2016.

[19] Al-Asadi, M.,Alkasmoul, F.S. and Wilson, M.C.T., "Heat transfer enhancement in a micro-channel cooling system using cylindrical vortex generators", **International Communication in Heat and Mass Transfer**,2016.

[20] Fang, W., He, X., Zhang, R., Yang, S., Qu, X., "Evolution of stresses in metal injection molding parts during sintering", **Transaction of Nonferrus Metals Society of China**, 25, 552-558, 2015.

[21] Hölker, R., Haase, M., Khalifa, N.B., Takkaya, A.E., "Hot extrusion dies with conformal cooling channels produced by additive manufacturing", **Aluminum Two Thousand World Congress and International Conference on Extrusion and Benchmark ICEB 2015**, 4838-4846. DOI:10.1016/j.matpr.2015.10.028, 2015.

[22] Jimenes, C.A.R.,Guerrero, A.H., Cervantes, J.G., Gutierrez, D.L. ve Valle, C.U.G. "CFD study of constructal microchannel networks for liquid-cooling of electronic devices", **Applied Thermal Engineering**, 95, 374-381, 2016.

[23] Koller, M., Walter, H., Hameter, M., "Transient Numerical Simulation of the Melting and Solidification Behavior of NaNO3 Using a Wire Matrix for Enhancing of the Heat Transfer." **Energies**, 9, 205. DOI: 10.3390/en9030205 , 2016.

[24] Djendel M. , Allaoui O., Boubaaya R., "Characterization of Alumina-Titania Coatings Produced by Atmospheric Plasma Spraying on 304 SS Steel", **Acta Physica Polonica A.**, Vol. 132-3, page 538. DOI: 10.12693/APhysPolA.132.538, 2017.

[25] Silverio, V., Cardoso, S., Gaspar, J., Freitas, P.P. ve Moreira, A.L.N., "Design, fabrication and test of an integrated multi-microchannel heatsink for electronics cooling", **Sensors and Actuators,** A 235, 14-27, 2015.

[26] FLUENT Manual, Chapter 21: Modeling Solidification and Melting; ANSYS, Inc.: Canonsburg, PA, USA, 2001.

Citation: *O. Ipek, M. Kan," Numerical investigation of Cooling Performance in Classic and New Cooling Channels of Mold Core", Open Access Journal of Physics, vol. 2, no. 3, pp. 05-14, 2018.*