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Compare Between the Results of the Casting Simulation and the Results of Experimental Production with Calculating the Interface Heat Transfer Coefficient of the Casting-Mold

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Abstract

Sanitary tapware that can drain hot and cold water from the plumbing systems in the desired proportions by mixing are called faucet. The production of faucets used today is conducted by using a low-pressure casting method. The raw material of the body, which is the main part of faucets, is generally brass alloy (CuZn39Pb1Al-C). The material of faucet molds produced using the casting method is the copper-beryllium alloy (CuCoNiBe). Some casting defects can be raised of used in these different two alloy materials. These defects should be solved before the production phase. Therefore, to be studied to detect these defects in design phase. Although the literature was researched, any study could not be found about the faucet products. Besides this study will be led the faucet field due to missing studies for the faucet products. In this research, K type thermocouples were placed into the mold in such a way that there was a distance of 3 mm to the casting surface, and temperature changes during the production were achieved by the measurement and recording device. 1283,1263,1243,1223,1203,1183,1163 K values of casting temperatures that were identified as critical in Ansys Fluent program and interfacial heat transfer coefficient of the combinations created by casting temperatures of 413,473,533,593,653 K were calculated numerically. Casting simulation was created in Magma program by using calculated IHTC values, and they were analysed by making a comparison between experimental and simulation temperature curves. The match of the defects was controlled by comparing the defect results of simulation in which convergence within temperature curves were provided and the defects of scrap parts in experimental production.

Keywords: Casting defects, casting simulation, CFD, copper-beryllium alloy, interface heat rransfer coefficient (IHTC), low pressure die casting, porosity analysis.

1. Introduction

Producing with casting is the principal method in the production of parts used in many fields of industry. For this reason, scrap rate in the parts produced with casting has also economically great importance. It is possible to develop suitable designs by identifying the areas where defect may occur before the production process to reduce scrap. Accordingly, the contribution of developing technology to the production sector is numerical analysis and simulation programs. These programs allow the examination of defect estimates resulting from simulation and solidification simulation of casting through the correct design of the casting process. Correct parameters must be used to be able to define the production process more realistically in such simulation programs.

Cast copper alloys are very versatile. They are widely used in ship propellers, power plant water impellers, plumbing fixtures, bearing sleeves, bushings because of easy casting. They have a successful history of usage, also can get various physical and mechanical properties and have easily machining, brazing, soldering, polishing or plating. Moreover, it is easy to supply from many sources [1].

Heat transfer lies behind the defects occurring in the parts produced by the casting method. It is necessary to determine the heat transfer coefficients to prevent heat transfer problems. Casting-mold IHTC affects the solidification features of casting and the defects to be occurred in part to a great extent by determining the rate of heat transfer from molten casting metal to mold material. For this reason, many studies were carried out on both experimental and numerical methods, and algorithms for the solution of heat transfer problems. These studies have shown a rapid increase in the last 10 years. Susac et al. [2] determined interface heat transfer coefficients of casting-core and casting-mold by carrying out both experimental and numerical investigation. They used Al-7% Si-Mg alloy as casting metal in their study. They were able to determine the desired interface heat transfer coefficient for the casting-core and casting-mold interfaces as a result of the study. In a similar research, Arunkumar et al. [3] investigated the air gap between casting and mold both experimentally and numerically along a vertical mold wall. Experimental and numerical results at the end of the study indicated that the interfacial heat transfer coefficient of casting-mold increased with the effect of mold coating, and it changed during the entire phase change period in the metal. Taha et al. [4] discussed in their study the contraction occurring during the solidification of casting and the formation of the air gap between casting-mold. The change of interface heat transfer coefficient was also detected by the air gap occurred. Al and Al-Si alloys were used as casting metal, and experimental study was executed in a simple rectangular mold. They reported that air gap occurred as a result of the study realized the heat transfer coefficient for different surfaces with different values. Pathak et al. [5] made a numerical analysis for mold filling and solidification in a two-dimensional rectangular space by conducting a different research. They stated at the end of the analysis that the parameters such as filling speed, filling configuration and cooling rate had effect on the interface heat transfer coefficient. Lan et al. [6] developed a plane stress model to study the thermal-mechanical behavior of a continuous casting bloom for a particular specific steel. A similar study was carried out by Rafique and Iqbal [7]. They developed a mathematical model by using standard transport equations, including all heat transfer coefficients, to calculate the solidification time in the casting operation of zircon coated silica sand mold, and made the computer simulation of the model at C++ for the verification of model. They also reported that changes in heat transfer coefficient affected the solidification time due to the air gap and geometry of molds occurred at mold-casting interface in the consequence of the study. They also explained that the calculated HTC values and the experimental values were in harmony.

In another study, Xuan-xuan et al. [8] investigated the numerical simulation with Fluent software to be able to predict the defects in casting filling operation and provide process optimization. Surface fluctuation of molten metal showed the temperature distributions at the end of filling, and they indicated that numerical data for solidification simulation were obtained. Pehlke and Berry [9] conducted a similar study. They investigated the interfacial heat transfer coefficient of casting-mold in the operations of merchantable casting and permanent mold casting. Both experimental and simulation studies were carried out to be able to make a good estimation of the interfacial heat transfer coefficient. It was then shown that there was a good convergence in temperature curves occurred during the solidification and between experiment and simulations.

Sun et al. [10] examined pores taking place in production engine crankcases by low-pressure casting and performed micrographic analysis to find casting defects. They also simulated crankcase filling. They reported that the gate speed increased suddenly when the liquid metal caused turbulence. Li et al. [11] simulated the microstructure of 17-4PH stainless steel numerically in investment casting. They adopted a cellular automation algorithm to simulate nucleation and grain growth. Park [12] applied finite element method for the analysis of complex phenomena such as melt flow, heat transfer, solidification and plastic deformation occurring in a vertical double roll casting of magnesium alloy AZ31. Next, Jiang et al. [13] researched the casting quality and mechanic properties of A356-T6 aluminium alloy produced with different casting operations for different casting methods in 2013. They indicated that the parts produced by vacuum and low pressure had better mechanical properties and less pore defect than other methods. Long et al. [14] received measurement in their study to determine interfacial heat transfer coefficient of metal-mold by placing K type thermocouple into the beam mold made for carrying motor. They then created simulation in the Magma program with received measurements. They compared experimental and simulation results and obtained their desired results. They urged that they could predict casting defects better with the heat transfer coefficient that they obtained for the simulation model. Hsu et al. [15] investigated the boiling phenomena of water which flows in a cooling channel in a permanent mold. And, they obtained a diagram of the heat flux to the heat transfer coefficient that was formed to examine the heat removal efficiency of water coolant. Katgerman [16] is a comprehensive description of liquid-solid transformation in casting, welding and crystal growth; He has worked on topics such as liquid state, liquid-solid crystallization, solid-liquid interfaces and fast solidification supported by detailed mathematical examples. He stated that casting and solidification were often used for making complex shapes that would be difficult or uneconomical to made by other methods and remain among the most important commercial processes for many materials.

Warriner and Monroe [17] defined an open-source code for specifying generating feeder geometries and metal casting hotspots. Their study shows and elucidates an open-source code that is generating feeder geometries from as-cast geometries. Sui et al. [18] carried out the experiments to affirm the applicability of cooling process for aluminum alloy wheel during low-pressure die casting. But the results indicated that some macro-porosity defects on the linkings of small spokes. They defined the insulation process and rational cooling by examining the solidification times of different phases at some locations of casting. Konrad et al. [19] presented a method for determining the heat transfer coefficient between the alloy and the investment casting mold from recorded transient temperature data directly. Sun et al. [20] designed a special 5-step squeeze casting for understanding casting thickness-dependent IHTC. With measured temperatures, the heat flux and IHTCs evaluated using polynomial curve fitting method and numerical inverse method. They showed the time-dependent curves of IHTCs.

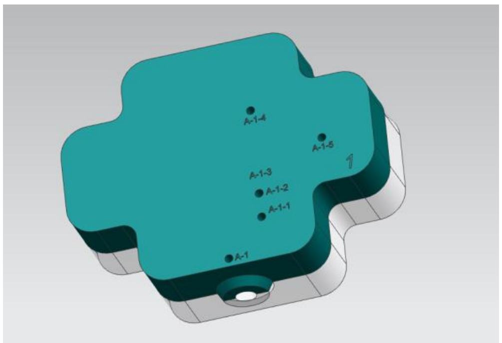
Nişancı [21] studied to find the heat transfer coefficient between casting and mold. In the study, the temperatures were determined during production process with a chosen faucet model and the IHTC between casting and mold was calculated with used a analysis programme. This study was created based on his study.

This study aimed at identifying defects in the simulation phase, and thus reducing the number of parts scraped in production by comparing the defects occurring in the experimental production parts with the simulation for a body of bath mixer produced by low-pressure casting method. Accordingly, K type thermocouples were placed into the mold in such a way that there was a distance of 3 mm to the casting surface, and temperature changes during the production were obtained by the measurement and recording device. 1283, 1263, 1243, 1223, 1203, 1183, 1163 K values of casting temperature that were identified as critical in Ansys Fluent program and interfacial heat transfer coefficient of the combinations created by casting temperatures of 413, 473, 533, 593, 653 K were calculated numerically. Casting simulation was created in a commercial software program (MagmaSoft) by using calculated IHTC values, and they were examined by making a comparison between experimental temperature curves and simulation temperature curves. The match of defects was controlled by comparing the defect results of simulation in which convergence within temperature curves was provided and the defects of scrap parts in experimental production.

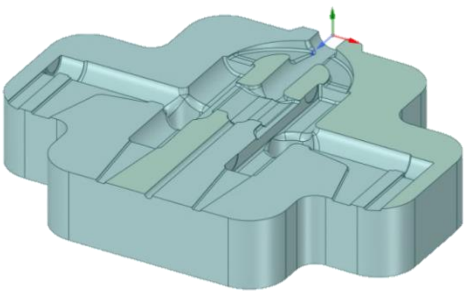
2. Experimental Study

A body of bath mixer faucet was selected for experimental production to be carried out within sanitary tap wares produced by low-pressure casting method. 3D model was created using Siemens NX modelling program in order to measure the temperatures during the production for the mold of bath mixer faucet with CuCoNiBe (copper-beryllium) material.

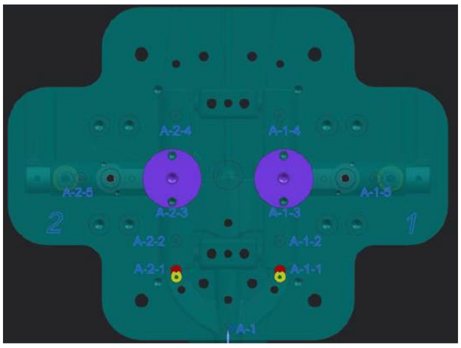
The layout of the thermocouples with the features in Table 1 on the 3D model was conducted as in Figure 1(a-b-c).



(a)



(b)



(c)

Figure 1. 3-D mold model.

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Determined points of totally 6 thermocouples to be placed into the mold are in such a manner that 3 mm left to mold surface as shown in Figure 2.

Afterwards, thermocouples were placed into the specified points of existing mold in production as in Figure 3, and experimental production was carried out with the production conditions in Table 2. Temperature values measured thanks to thermocouples during the production were recorded by measurement and recording device. According to experimental results, the mold temperatures were determined as 413, 473, 533, 593, 653 K. The beginning temperature of the mold for the process was measured as 413 K. The highest temperature of the mold for the process was measured as 653 K. The middle temperature values were determined by us. Because they should be increased for the parametric analysis as the logical [21].

Table 1: Thermocouple features.

Thermocouple Type	The Type of Thermocouple	Thermocouple Size	Cable Length
K type	Groundless	Ø3 mm X 200 mm	7 m

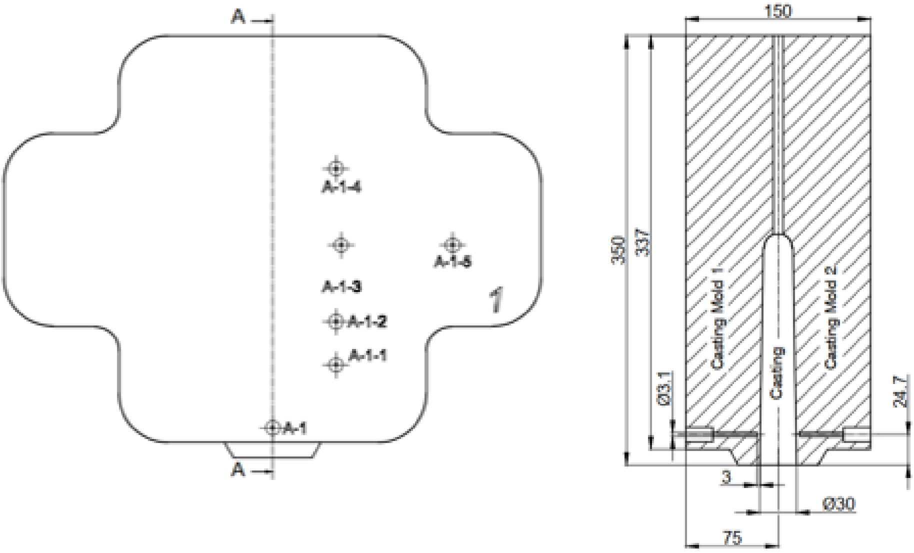

Figure 2. Thermocouple points on mold and distance to casting surface

Table 2. Production parameters.

Process Pressure	Casting Temperature	Mold Temperature	Casting Material	Mold Material
350 Mbar	1283 K	413 K	CuZn39Pb1Al-C	CuCoNiBe

Figure 3. Existing production mold and assembled thermocouples

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3. Numerical Analysis and Numeric Analysis Results

Parametric thermal analysis was carried out for the numerical calculation of the heat transfer coefficient of the casting-mold interface by using temperature values recorded after experimental production and Fluent module of Ansys program.

Temperatures determined as critical within the temperatures obtained by experimental production for thermal analysis were shown in Table 3.

Parametric thermal analysis was executed in Ansys program with 1283, 1263, 1243, 1223, 1203, 1183, 1163 K values of casting temperature and the combination created by mold temperatures of 413, 473, 533, 593, 653 K. First of all, the flow volume shown in Figure 4 (c) was removed from the die geometry demonstrated in Figure 4(b) at the conducted parametric analysis. Flow volume was modelled inside the room as in Figure 4 (a) since the thermal analysis was natural convection analysis.
Mold design was performed as 2 cavities. However, as there was no difference between the mold cavity, the analysis was performed with the symmetric model in thermal analysis. Mesh as shown in Figure 5 was created by using poly-hex core “mosaic” mesh method and Fluent Meshing on analysis geometry. Member number of created mesh structure was 6054015. The quality of the created mesh structure was 0.12 as Orthogonal quality and aspect ratio was 11.98.

Table 3. Casting and mold temperatures specified as critical

Casting Temperature (K)	1283	1263	1243	1223	1203	1183	1163
Mold Temperature (K)	413	473	533	593	653	-	-

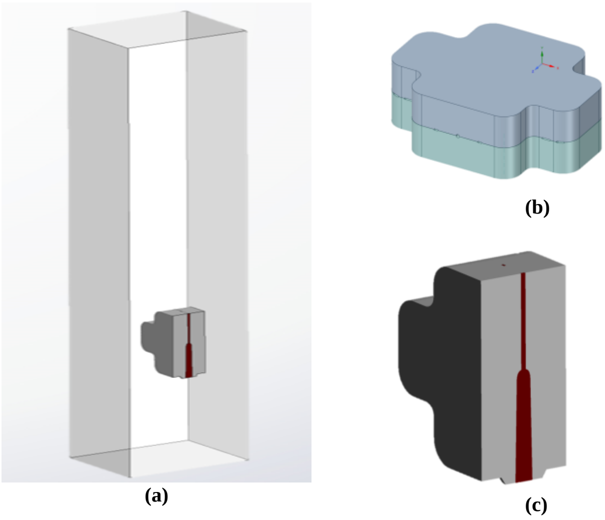

Figure 4. (a) Flow volume inside room **(b)** Analysis geometry **(c)** Flow volume

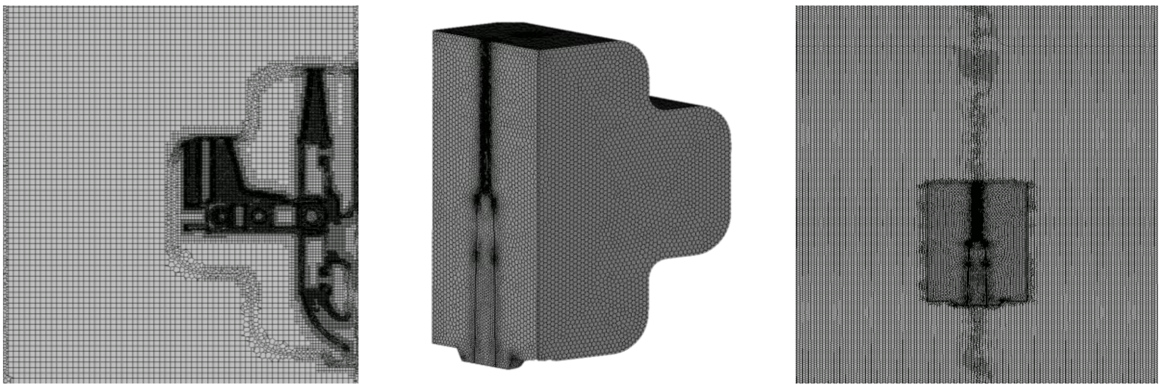

Figure 5. Mesh image of analysis geometry.

Analysis was established with natural convection modelling, and acceleration of gravity was activated as -9,81 m/s^2 in Z axis. Solutions were performed by using Coupled algorithm as laminar model and conducting steady state examination for analyses.

Air density was defined as incompressible-ideal-gas as the natural convection solution was executed. The thermal properties of air, casting (CuZn39Pb1Al-C), mold (CuCoNiBe) materials entered in the limiting conditions of the analysis are as in Table 4.

A velocity value was entered as 0.1 m/s to be relaxed the natural convection modelling. Besides the fluid time scale was determined as 1 in Pseudo Transient.

The results of parametric thermal analysis carried out by finite volumes method are shown in Table 5 [21]. These IHTC values that we found for performing defect detections healthier will be used in the simulation program.

Table 4. Thermophysical properties of air, casting and mold entered in Ansys-Fluent program.

Thermophysical Properties	**Air**	**Casting**	**Mold**
Density (kg/m^3)	Incompressible-ideal-gas	8730	8800
Specific Heat (J/kgK)	1006,43	381	420
Thermal Conductivity (W/mK)	0,0242	109	230
Viscosity (kg/ms)	1,7894e-05	-	-

Table 5. Calculated heat transfer coefficient values [21].

Mold Temp. 413 K		Mold Temp. 473 K		Mold Temp. 533 K		Mold Temp. 593 K		Mold Temp. 653 K	
Casting Temp. K	HTC W/m^{2}K	Casting Temp. K	HTC W/m^{2}K	Casting Temp. K	HTC W/m^{2}K	Casting Temp. K	HTC W/m^{2}K	Casting Temp. K	HTC W/m^{2}K
1283	5001,6	1283	4656,7	1283	4311,7	1283	3966,8	1283	3621,9
1263	4987,9	1263	4635,8	1263	4283,7	1263	3931,6	1263	3579,6
1243	4973,6	1243	4614,1	1243	4254,5	1243	3895	1243	3535,5
1223	4958,7	1223	4591,4	1223	4224,1	1223	3856,8	1223	3489,5
1203	4943,2	1203	4567,7	1203	4192,3	1203	3816,9	1203	3441,4
1183	4926,9	1183	4543	1183	4159,1	1183	3775,2	1183	3391,2
1163	4909,9	1163	4517,1	1163	4124,3	1163	3731,5	1163	3338,7

4. Casting Simulation and Porosity Analysis

4.1. Casting simulation

Casting simulation was created in the software program with casting-mold interface heat transfer coefficient values calculated by Ansys Fluent program and shown in Table 5. Simulations were previously created with the parameters seen in Table 6 in the software program. Nevertheless, defect analyses in the results of practiced simulation were not compatible with the defects occurred in the part as a result of process. The reason for this was considered as the inability to define the correct parameters to the software program. For this reason, temperature-dependent IHTC values were achieved by conducting parametric thermal analysis in the Ansys program.

The 15 times simulations were made with numerically calculated IHTC values. Convergences between simulation temperature curves and experimental production temperature curves were examined in the simulations. The optimum convergence began with the value of 4800 W/m^{2}K HTC for casting initial temperature of 1283 K, and it gradually decreased till the value of 2500 W/m^{2}K for liquidus temperature of 1183 K, and then reached the value of 2300 W/m^{2}K for solidus temperature of 1163 K. HTC value continued to decrease gradually from the value of 2300 W/m^{2}K to 100 W/m^{2}K between 1163 K where the casting starts to solidify and 1073 K in which it gets completely solid. The definition of IHTC values as a temperature dependent variable to the software program is shown in Figure 6. Other values used in the simulation are shown in Table 7.

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Table 6: Software simulation parameters used before calculating IHTC values.

Casting-Mold Interface HTC (W/m^2K)	Mold -Mold Interface HTC (W/m^2K)	Casting-Core Interface HTC (W/m^2K)	Mold-Core Interface HTC (W/m^2K)
Constant 7000	Constant 300	Constant 400	Constant 200

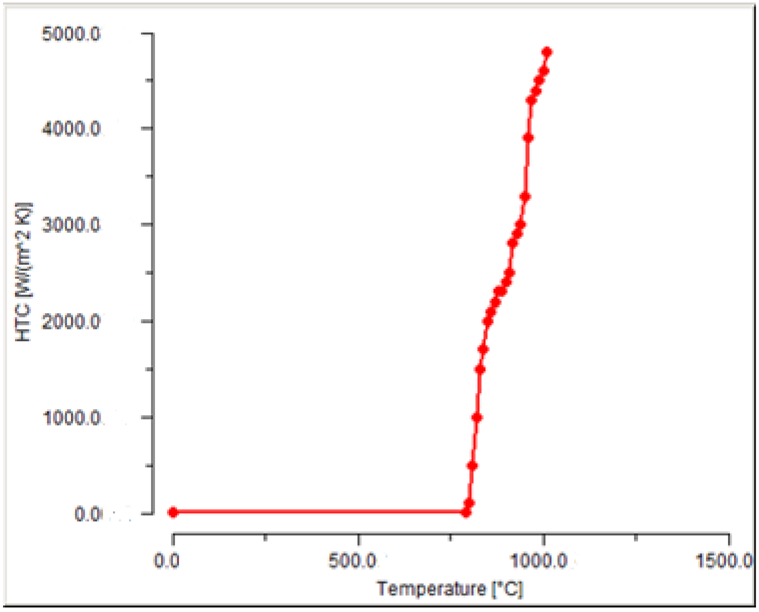

Figure 6. Heat transfer coefficient values defined in commercial software program.

Table 7. Other parameters of simulations created in commercial software program.

Casting-Mold Interface HTC (W/m^2K)	Mold -Mold Interface HTC (W/m^2K)	Casting-Core Interface HTC (W/m^2K)	Mold-Core Interface HTC (W/m^2K)
Values in Table 5 as 'Temperature Dependent'	Constant 300	Constant 400	Constant 200

The most efficient measurement in the experimental production was executed with A1-1 and A1-3 thermocouples. While A1-1 thermocouple is on the runner side, A1-3 thermocouple is on the side of in the middle of the faucet body. This area is called the cartridge region and defect of castings occurs most here. Therefore, measurements taken from A1-1 and A1-3 thermocouples and convergences of curves were examined.

The convergence obtained from experiments is shown in Figure 7. The difference between the simulation and experimental temperature curves was 274 K as seen in Figure 7.

Figure 8 shows the temperature curves of A1-1 point for the first 3 cycles. These curves demonstrated the production cycle of a complete casting as filling and solidification. The 1st cycle in the simulation was defined as the preheating operation of the mold in the commercial software program and filling operation could not be performed. Other 2 cycles were identified as the cycle in which filling operation and the production of 2 parts were carried out. Experimental measurements at the point of A1-3 and simulation values were compared for the 3rd Cycle in Figure 9.

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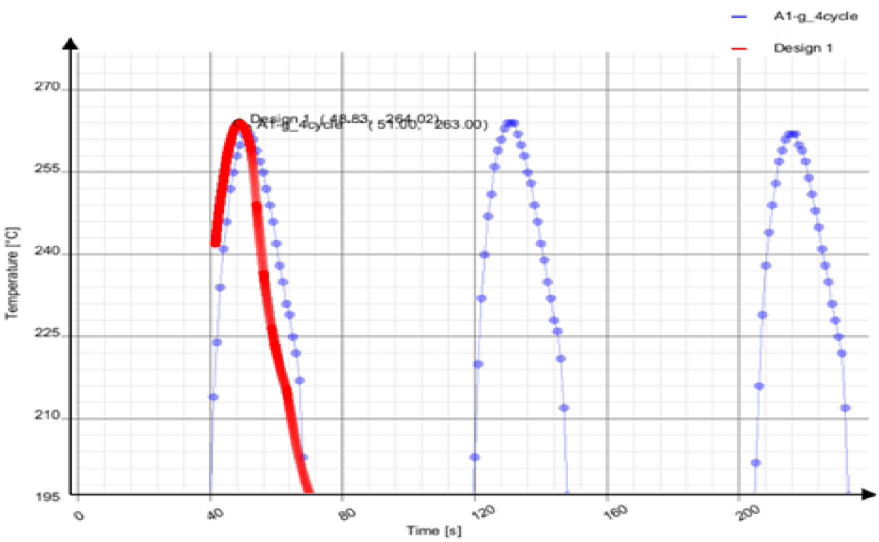

Figure 7. Temperature curve achieved during experimental production (red-flat) and temperature curve obtained as a result of simulation (blue-dotted).

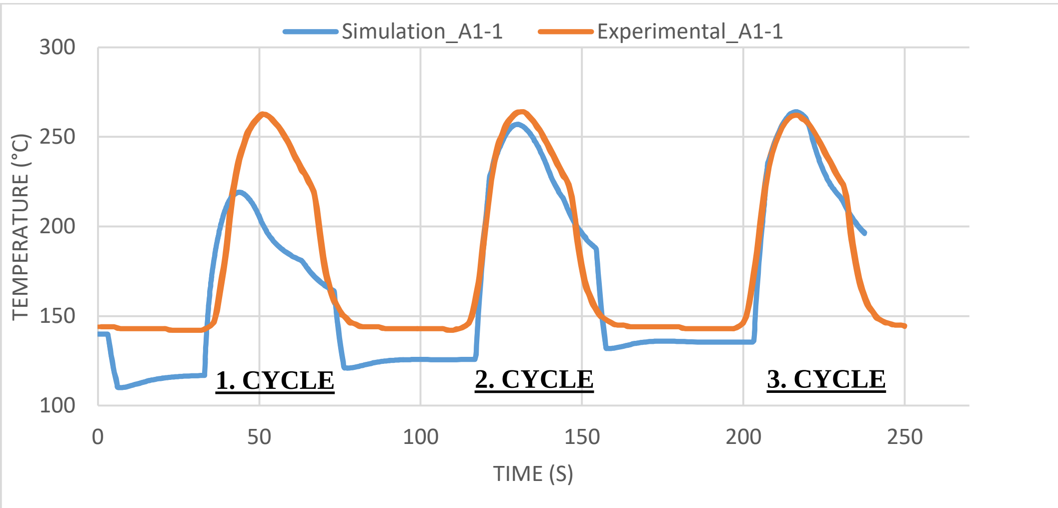

Figure 8. A1 Temperature curves for the first 3 cycle.

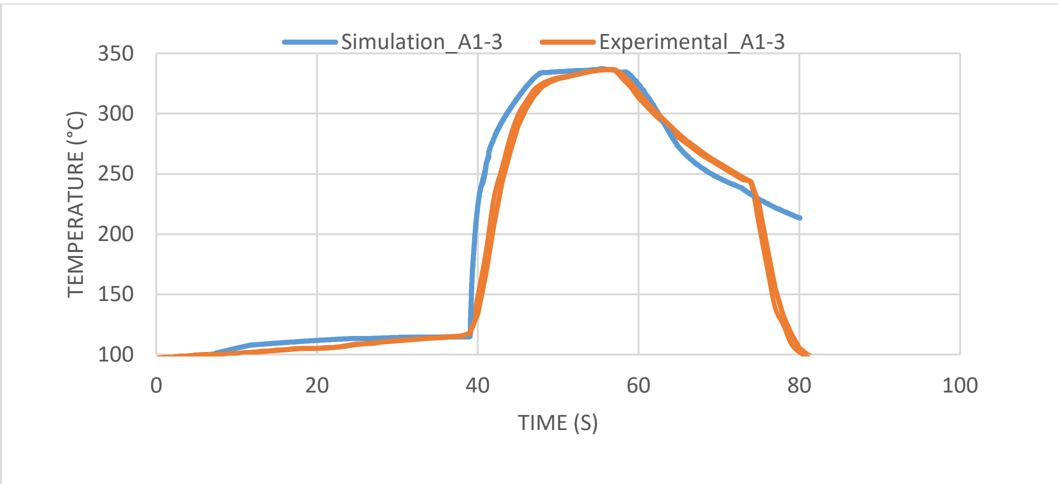

Figure 9. A3 temperature curve for 3rd cycle.

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4.2. Porosity analysis

Most of the defects occurring in the casting process take place during solidification. When solidification begins, a solid shell develops on the exterior surface of the casting and contact with the mold surface is cut. Since the solidification continues inside the casting, defects such as shrinkage or deflection due to gas entrapment or temperature difference occur at that moment. Therefore, the convergence of experimental and simulation temperature curves was examined. As the convergence between experimental and simulation temperature curves was also successfully carried out, defect analyses of simulation, in which convergence occurred were investigated and then compared with the reasons of defect of the castings separated as scraped in experimental production.

Porosity analysis results in Figure 10, Figure 11, and Figure 12 were analyzed based on the simulation of the commercial software program. The results of this analysis showed us the height of color value in the area where defect will occur in the color scale on the right side of screen indicates that defect will definitely take place there.

The defects of the castings which were scraped during the experimental production, were analyzed in 13th, 14th and 15th Figures. Next, simulation and experimental production defect areas and types were compared. Furthermore, the defect regions in experimental production were shown in macro images taken by stereo microscope. As it is understood from the figures, we observe that the areas, where defect may occur, identified as a result of the simulations that we made using the IHTC values which we calculated numerically and areas where the defect occurred after production coincided.

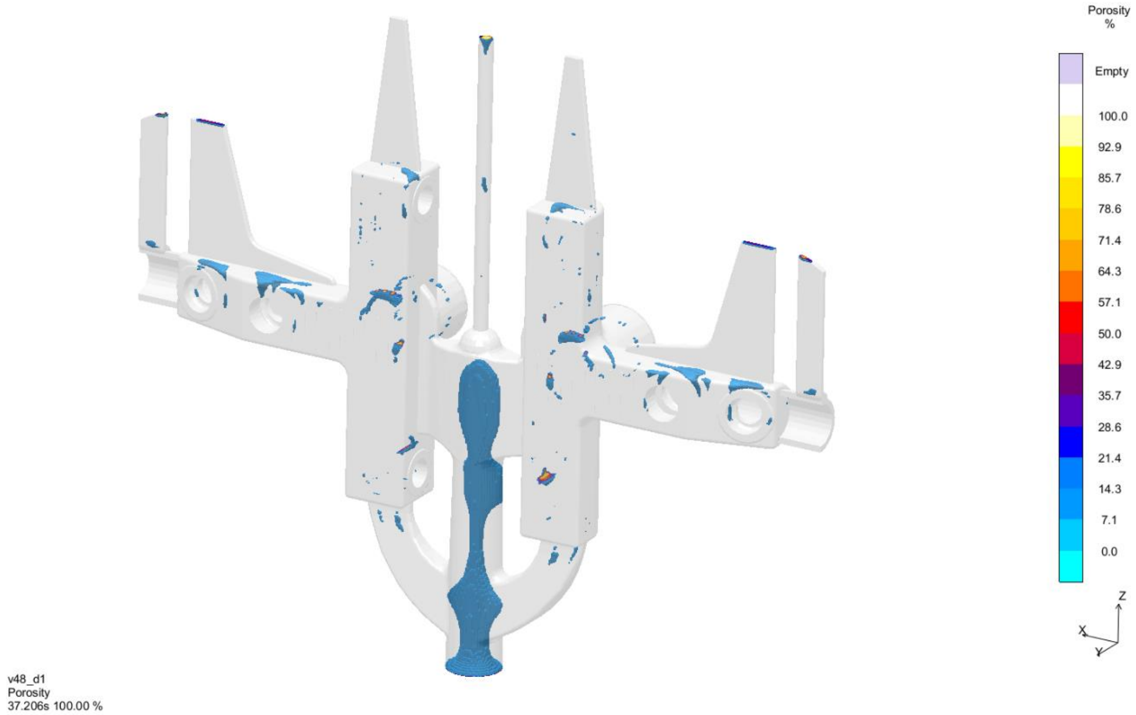


Figure 10. Porosity analysis

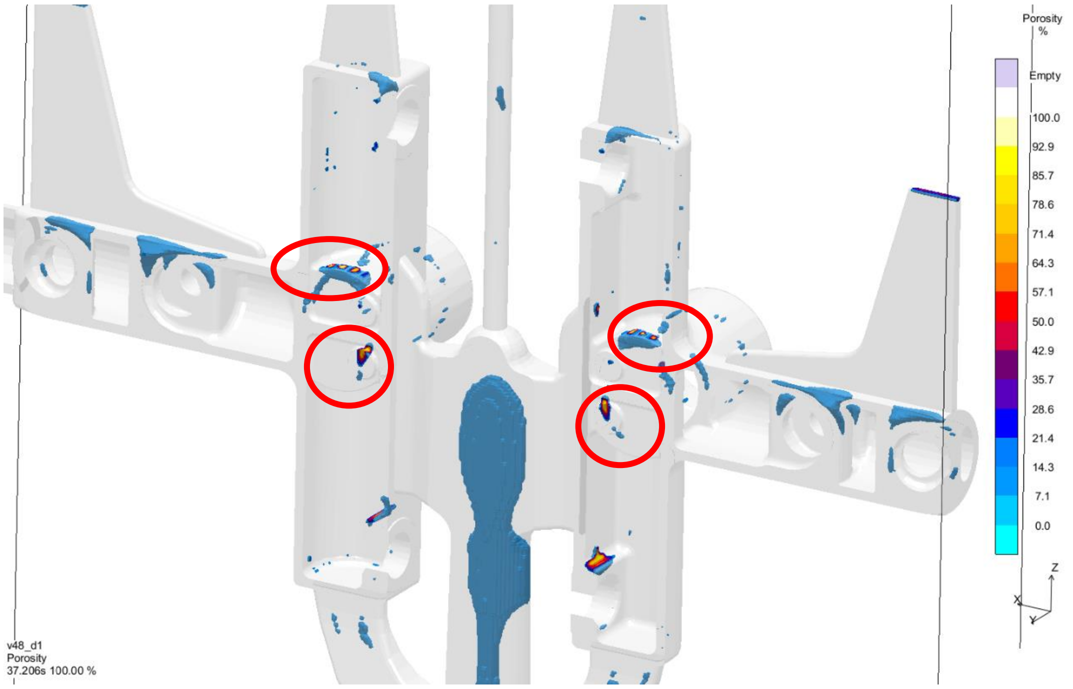


Figure 11. Porosity analysis (sectional view 1)

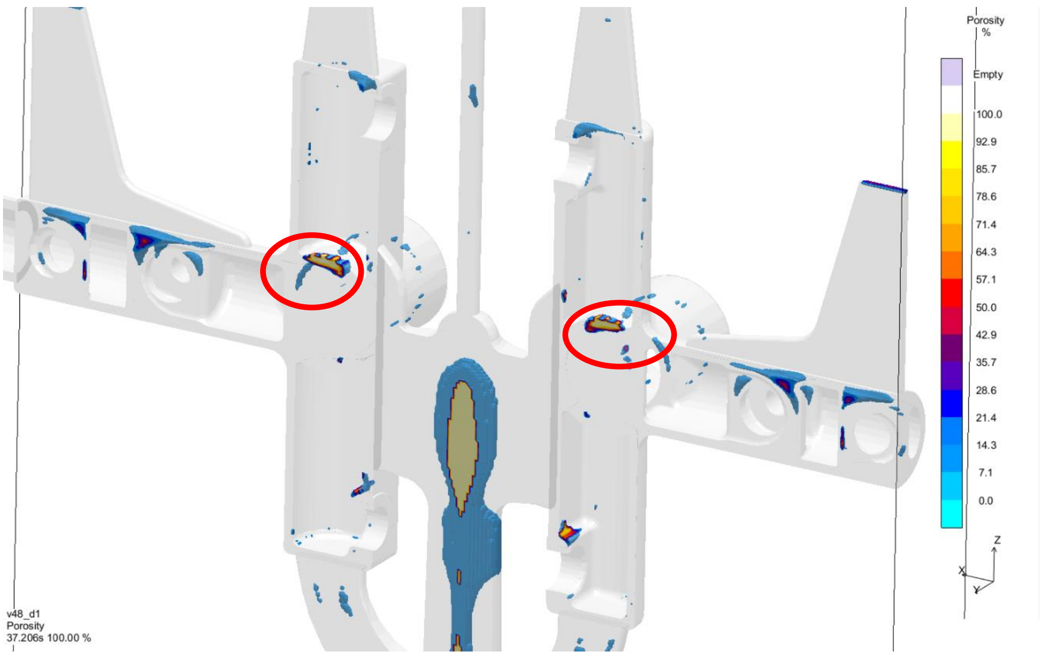
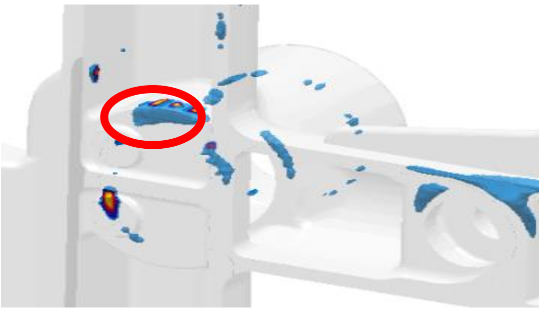


Figure 12. Porosity analysis (sectional view 2)


(a) Simulation


(b) Experimental

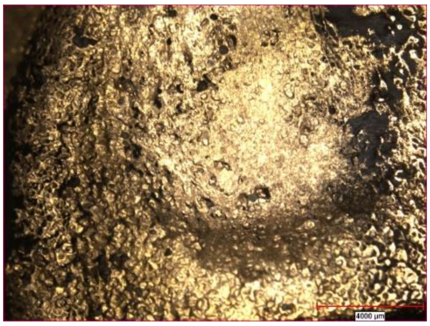
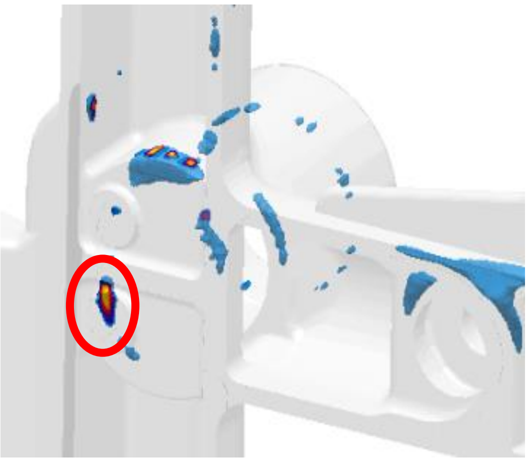

(c) Macro Image Taken with Stereo Microscope

Figure 13. Outer wall of cartridge area in the faucet body


(a) Simulation


(b) Experimental

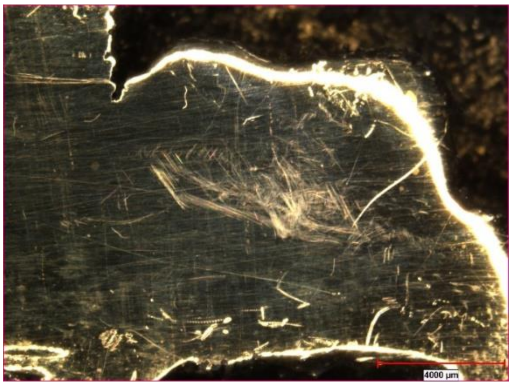
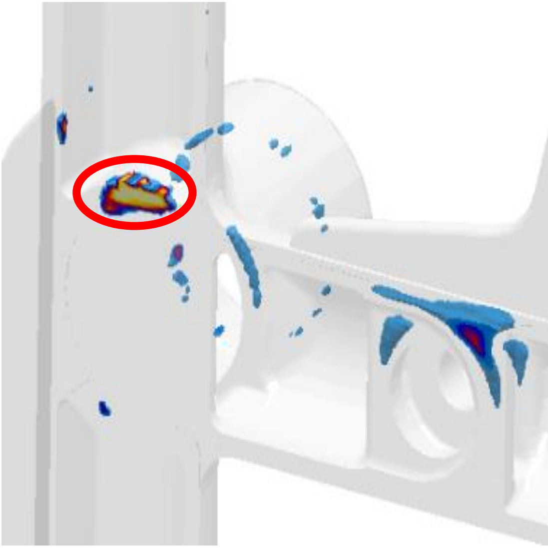

(c) Macro Image Taken with Stereo Microscope

Figure 14. Bottom of cartridge area in the faucet body



(a) Simulation

(b) Experimental

Figure 15. Inner wall of cartridge area in the faucet body

5. Conclusions

It was observed as a result of the thermal analysis that the IHTC values varied depending on the temperature. IHTC value was entered as a temperature dependent variable in the simulation created in commercial software program, and calculated IHTC values were used. Many experiments were made in simulation studies. These experiments examined the convergence of temperature curves obtained by measuring with thermocouple during experimental production and the temperature curves resulting from the simulation.

Defect analyses were investigated in the simulation where convergence took place and experimental and simulation temperature curves. Later, defects of the castings that were scraped at the time of experimental production were examined and they were compared with simulation results.

Defect results of the simulation, in which convergence occurred between experimental and simulation temperature curves, corresponded to the defects of castings scraped in the experimental production. Areas where defects occur, can also be seen in simulation in the same respect.

The fixed value of 7000 W/m^2K was previously entered as the HTC value between casting-mold in commercial software program within the scope of the company where this study was carried out. Since IHTC values were entered invariantly, defects in many castings, of which design verification was performed with the simulation in commercial software program, did not correspond to the defects of castings in the present production. Therefore, actions such as design revisions and correction operations in produced mold were executed and the company lived financial and time loss as a result of these actions.

As a result of this study, heat transfer coefficient for the simulation program of any casting process should not be entered as fixed. Because the alloy, which is in liquid state at first, becomes solid by changing its state over time while the casting process is in progress. Change of state occurs in the casting metal with heat transmission between the metal which was initially at high temperature, and the mold at low temperature. For this reason, the defects in the casting parts emerge at this stage.

Design verification studies are carried out without any financial or time loss thanks to the simulations performed in computer environment by correct determination of the heat transfer coefficient value, which is the most important factor in the creation of defect, during solidification.

Author's Contributions

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Authors' Contributions

Murat Can Nişancı: Drafted and wrote the manuscript, performed the experiment and result analysis.

Ali Yurddaş: Supervised the experiment's and analysis progress, result interpretation and helped in manuscript preparation.

Ethics

There are no ethical issues after the publication of this manuscript.

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