Simplified CFD Model for Assessing the Cooling Channel Design in 3D Printed High-Pressure Tools for Aluminium Alloy Casting

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Simplified CFD Model for Assessing the Cooling Channel Design in 3D Printed High-Pressure Tools for Aluminium Alloy Casting

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Abstract

Additive manufacturing (AM) provides significant geometric design freedom for the cooling of high pressure die casting (HPDC) tools. Designing cooling channels that can achieve a uniform temperature throughout the tool-cast interface during the moulding process can limit part warping and sink marks, internal part stresses, and increase tool life. However, the design of the embedded cooling channels requires high computational resources to model the heat transfer process for the cast, mould, and coolant from the moment aluminium is injected into the cavity until the injection for the next cycle. To enable the examination of the effect of various parameters, a simplified 3-D CFD conjugate heat transfer model is introduced by considering the experimental observations. The model decouples the cast part from the mould. A volumetric heat source term is added to the energy equation to represent the solidification energy, and accordingly the heat flux is evaluated on its surface that has been set to a uniform temperature. The heat flux is then compared with that obtained from the mould surface for a specific cooling channel layout. With this approach it is possible for the designer to rapidly assess the cooling system without incurring significant computational cost. The model reveals the undercooled and overcooled regions, which are then matched with the observational results obtained by analysing the tools and the aluminium cast surface. The results prove that the model can be employed to develop a baseline design of the cooling channel network for a complex geometry before applying an optimisation technique. It can also be useful for assessing the effect of various parameters, and to carry out a parametric sensitivity study with limited computational cost. The limitations of the model are evaluated and discussed in this work.

1. Introduction

Achieving proper and efficient cooling in HPDC tools during the moulding process can help limit or eliminate many of the resulting aluminium cast part's defects[1], can improve the surface quality and structure [2], and can reduce the cycle time and increase tool lifespan [3]. With 3D printing, it is theoretically possible to generate any channel shape at any location. However, designing a conformal cooling layout that leads to a uniform mould cavity temperature is a challenging task for designers when the die lifetime of the tool is considered. Having very small channels which are necessary to conformally cool small geometrical features may not be possible. Practical experience has shown that flow in these small channels can be partially blocked by contamination from various sources on the pipe surface and can lead to an imbalance within the cooling system. Unwanted deformation of small channels is common in the 3D printing process [4]. The depth of the channels from the cavity surface is another constraint because of high thermal fatigue caused by a temperature gradient that can reach 50^{o}C for each millimetre of depth [5]. The significant amount of heat transfer required to solidify the aluminium cast part in addition to the relatively high inlet water temperature limits the length of cooling pipes to avoid boiling.

The 3D printed tool or insert provides flexibility in designing the cooling channels and can yield better quality cast parts by eliminating many of the defects. However, for a 3D printed tool to be economically viable its lifecycle must extend to over 100,000 shots before replacement [6]. Thermal fatigue and temperature gradient should be limited to extend the tool's lifespan; both are linked to the layout of the internal cooling system. Simulations to compare the various designs and configurations are important for engineers when modifying the baseline design or introducing new cooling layouts.

Numerical simulation of HPDC is challenging, particularly for a complex part. The high computational cost arises not only because of the geometry, but also because of the complex physics and varying time- and length-scales of the process. The internal cooling cycle encompasses the injection of the molten aluminium, the solidification process, demoulding, air and lubricant spraying, and mould closing [7]. Each of these stages require different boundary conditions to capture the varying physical processes and conditions that will affect the internal cooling process. In addition, the cycle should be repeated until a steady average mould temperature is achieved. In practise, at the beginning of the HPDC process, the mould is usually too cold and can potentially produce faulty parts, until the mould reaches this thermally stabilised condition [8]. The transient nature of the process and the novel complexity restricts the capacity of designers to have multiple iterations or to assess various design options.

Even after considering all of the physics and taking into account the boundary conditions and changes for each stage of the cycle, the model will still fail to quantitively represent reality if there is no accurate presentation of the cast/mould interface heat transfer coefficient. It is therefore a common practice to calibrate the model using the inverse method [9]. In many cases, design engineers need to quickly compare different cooling channel layouts for an insert without having to carry out thermal simulation for the complete CAD and the full cycle. It is therefore useful to have a simplified model for the engineers that allows a quick comparative analysis to examine the various design options, particularly in the utilisation of novel 3D printing processes to improve the quality of the products and extend the tool lifetime [10].

Having a uniform interface temperature entails the design of a cooling system that can allow various heat fluxes depending on the cast part thickness and geometry. Various design parameters can be considered to achieve temperature uniformity at the interface by changing the thermal resistance and therefore the local heat flux from the cast to the cooling channels. These parameters include: the depth of the channel from the interface; the distance between the channels (pitch); coolant type; coolant temperature; coolant flow rate; and the channel cross-sectional shape and size [11]. Each of these parameters have associated physical and technical constraints, that can limit the optimisation of the internal cooling system during solidification, required to predict the effect of various changes within a computationally viable number of iterations. Although achieving a uniform temperature is a challenging task, setting a correct rate of heat flux is equally important for enhancing the cast part's mechanical and surface properties [14]. The trade-off between the temperature uniformity, heat flux, or solidification time is a decision to be made.

External cooling and lubrication can help in achieving a more uniform interface temperature after demoulding, in addition to their main function, which is to release the casting without soldering or deformation, and to enhance the injection of the molten metal without causing lamination in the casting [12]. Nevertheless, it is difficult to control the lubricant spray to achieve a target temperature distribution on the die cavity surface. The lubrication process is therefore treated as a separate process to meet its main function of lowering the die surface temperatures to 150 °C from a maximum of 320 °C, before injecting the molten aluminium, to improve the quality of castings and its surface [13]. It is therefore not usually considered in detail during the casting modelling process despite its contribution to cooling by 20-50% in older HPDC systems [14] which is reduced significantly in the new designs.

Some attempts have been made to simplify the model [10]. The most common assumption is to neglect the initial aluminium injection process, because the associated complex physics require expensive unsteady flow simulation for what represents a very short time duration (0.5 second) relative to the solidification time [15]. External convective cooling of the mould assembly is also commonly neglected even though it can represent up to 20 % of the total cooling load in recent designs. Replacing the water with an equivalent heat transfer coefficient is a common approximation which can save much of the computation time, because of the computational expense of having a small mesh size to capture the thermal boundary layer.

Previous work showed that once the molten aluminium is injected into the tool, in less than a second, it forms a thin layer of solidified aluminium called a 'skin', and the tool surface reaches a temperature of 400°C – 450°C [16]. The quick formation of the thin solidified layer has been attributed to the much lower temperature of the mould when the molten aluminium is injected [17]. Other work showed that for a typical thermal cycle of an aluminium HPDC die, the surface of the mould cavity reaches a peak temperature of 457°C [18]. The skin thickness then grows with a rate that depends upon the rate of heat transfer, which in turn is affected by the cooling channel design and the interface thermal resistance.

Existing literature indicates that the temperature of the interface does not change much during the cooling stage inside the mould; a change of less than 30°C from the initial formation of the solidification layer until the end of the solidification time [19]. The heat flux reaches its peak during the injection because of the intimate contact of the molten aluminium with the mould surface. However, this high peak drops significantly within 1-2 seconds [20] because of the formation of an interface void caused by aluminium shrinking and pulling away from the mould surface as it cools, leading to an increased interface thermal resistance and an decrease in mould temperature (Chilling effect). As solidification progresses, the heat flux rate tends to level off. The cooling process therefore approaches a steady state at the time of part solidification. This is true, so long as the pipes are close enough to the cavity to allow the mould region located between the cavity and pipe to reach its steady temperature. Under these conditions, the heat from the cast is transferred to the cooling water.

In this work, we will examine and utilise this condition to assess various cooling channel layouts using a steady thermal model and we will discuss the limitations of this methodology.

2. Methodology

In this work, a steady assumption has been made for the casting part in building our model to assess the cooling system. We also assume isothermal surface of the mould through the solidification period. The assumption of steady conditions is only valid under specific design conditions; for example it is not correct to use this assumption in deeply located cooling channels where casting heat is mostly absorbed in the mould during the solidification stage before it eventually passes to the water at later stages of the cycle, (i.e. after demoulding). To be able to identify the criteria for using a steady model, a transient model has been developed first, and validated using a gravity casting experiment.

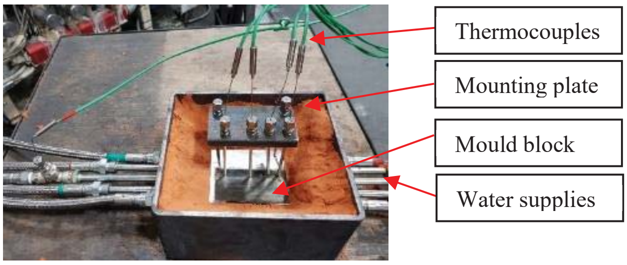
The constant temperature mould surface assumption was then used to develop an allocation table to identify the location and conditions of the cooling channels for various cast thicknesses under various cooling conditions. The allocation table is then used to locate the cooling pipes for a cast part with two different thicknesses. The heat flux from two cooling pipe depth locations are compared to explore the effect of shifting the pipe depth from its design value. A similar case study was also considered for a full transient model to evaluate the interface temperature for two cooling designs.

In this section, the experimental test rig for validating the transient model will be introduced followed by the transient model itself, and finally the simplified model will be discussed (with its limitations).

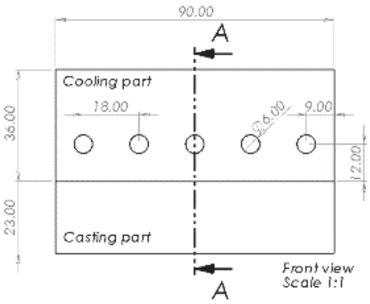
2.1 Experimental setup

To validate the mathematical model an experimental test has been carried out by pouring molten aluminium over a flat block of 3D printed tool steel with five cooling pipes, each of 6 mm diameter, cooled using water at 67°C as shown in Figure 1a. The temperatures at various locations within the 3D printed block have been measured as shown in figure 1b. Temperatures were recorded using 1mm diameter k-type thermocouples at a rate of 5 samples per second using a Pico-TC08 data acquisition system. To ensure the correct measurement of the temperatures, water was allowed to flow for sufficient time for the block temperature to reach a steady state condition, so that all of the thermocouples were measuring the same temperature before the aluminium was poured over the block surface.

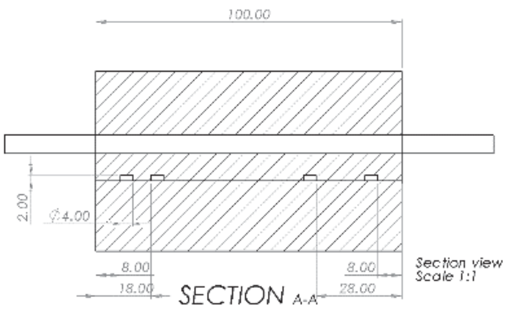
Four monitor points were used to measure the temperature at a 2mm depth from the block interface near the inlet and outlet of the cooling channel. The temperature of the aluminium 3mm above the contact interface was also monitored. All of the thermocouples were protected using stainless steel sleeves that passed through the cast. Cooling water inlet and outlet temperature, as well as the flow rate were recorded. Inlet water temperature was held constant during the experiment at a value of 67°C ± 0.2°C, as the water was circulated via a water pump connected to a large tank. All of the thermocouples were located under the block's central pipe, which was adjacent to two pipes on both sides to enable the use of periodic boundary conditions in the numerical model. Special attention was paid to the location of the thermocouples, to fix them in position before the experiment commenced. Nonetheless, it is believed that there may have been up to 0.2 mm error because of the tip size of the thermocouples that were utilised. The protective stainless-steel pipe may also have contributed to some error in measuring the interface temperature as it will have acted as heatsink, slightly altering the heat flux direction.



a) The block and thermocouples before pouring the molten aluminium



b) Block size and pipes



c) Thermocouple locations

Figure 1 – Experimental test rig and locations of the thermocouples in the 3D printed block and cast

2.2 Transient Model

The commercial CFD software StarCCM+ by Siemens was used to simulate the heat transfer in the cast aluminium part, the 3D printed H13 steel mould, and the cooling channels. The model uses the finite volume discretization approach to solve the energy equation in the cast and mould. Although the experiment was carried out on a much wider flat surface with five parallel cooling channels, in the simulation surfaces associated with only one pipe were used by applying periodic boundary conditions as shown in Figure 2. The outside surfaces of the 3D printed block were assumed to be adiabatic since they were encased in sand. Convective heat transfer with a heat transfer coefficient of 8 W/m^2 K was applied to the upper and side surfaces of the cast on the top of the block. Heat transfer by radiation was neglected in this study.

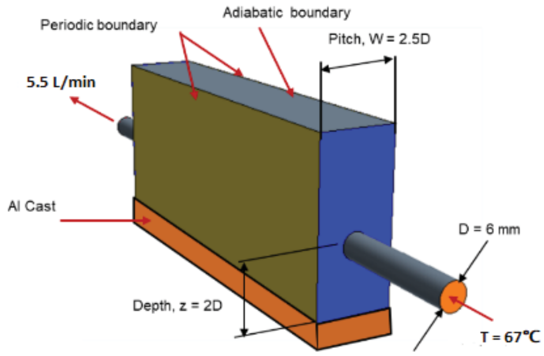


Figure 2 – Transient model with similar conditions to the experiment

When modelling the heat transfer from the cast to the mould a contact resistance is considered. An estimated mean interface heat transfer coefficient of 5000 $W/m^2.K$ was adapted from the existing study [21].

The boundary and initial conditions that were used in the model have been listed in Table 1 below:

Table 1. Boundary and initial conditions of the steady model

Boundary & operating Conditions	
Water inlet temperature (°C)	67
Casting solidus temperature (°C)	538
Casting liquidus temperature (°C)	593
Casting injection temperature (°C)	650
Coolant flow rate (L/min)	5.5
Channel diameter, d (mm)	6
Channel depth, h (mm)	12
Channel pitch, W (mm)	18
Cast thickness, t_c (mm)	23
Initial block Temperature, (°C)	67°C

The heat transfer from the mould to the cooling channels has been simplified by using the following equation to calculate the heat transfer coefficient for turbulent flow on a smooth surface.

$$Nu = \frac{\left(\frac{f}{8}\right)(Re - 1000)Pr}{1 + 12.7\left(\frac{f}{8}\right)^{0.5}\left(Pr^{\frac{2}{3}} - 1\right)} \quad and \quad f = (0.79 \ln Re - 1.64)^{-2}$$

Where; (1)

$$Nu = \frac{hD_h}{k}, \qquad Re = \frac{\rho V D_h}{\mu}, \qquad Pr = \frac{\mu C_p}{k_f} = \frac{v}{a}$$

The above equation can be modified to account for the fouling effect and internal coolant channel surface roughness for 3D printed tools upon the Nusselt number and the heat transfer coefficient [22]. However, to enable the comparison of two different cooling channel layouts in this study a smooth surface has been used.

Physical properties were varied with temperature as listed in Table 2 for the essential thermal properties of aluminium and steel. Both specific heat and thermal conductivity of steel are linearly correlated and varied with temperature. The heat transfer coefficient of water was calculated using water properties at 67°C and for a water flow rate of 5.5 L/min. The initial temperature of the mould was similar to the experimentally measured value, which was the same as the cooling water temperature of 67°C. The transient analysis was not only used for validating the model but also employed to identify the solidification time for various design parameters. Solidification time is defined as the time when all cells reaches the solidus temperature or lower.

Table 2. Physical properties of the casting part and tool steel

Aluminium A380.0-F Die Casting Alloy [24]	
Density	2760 kg/m^3
Specific Heat	963 J/kg-K
Thermal Conductivity	130 W/m-K
Tool Steel, H13 [25]	
Density	7750 kg/m^3
Min Specific heat	587 J/kg-K @ 300 K
Max Specific heat	777 J/kg-K @ 700 K
Min Thermal Conductivity	24.86 W/m-K @ 300 K
Max Thermal Conductivity	28.7 W/m-K @ 700 K

2.3 An Isothermal Interface Model and Steady model

We observed that a quasi-steady condition occurred towards the end of solidification, close to the demoulding stage for most of the conformal cooling pipes that are located close the surface. The mould interface temperature reaches an almost constant value very early after few seconds when compared to the heat flux that takes much longer. It is therefore possible to decouple the cast from the mould and run the mould separately using an isothermal boundary at its interface. For a comparative study it is not necessary for the temperature on the surface to be accurate, so long as it is applied consistently in all cases under investigation. However, to obtain a correct temperature value, a complete transient simulation needs to be considered and a correct interface heat transfer coefficient should be used as it has a significant effect on mould surface temperature [20]. The model has then to be calibrated based on experimental data. In our case we used the temperature based on our experimental validation for the complete transient model, 396°C. In some other studies the interface temperature was taken as the Riemann interface temperature which is calculated using the initial mould temperature [26]. For the final analysis using an insert the interface temperature was taken to be 450°C isothermal surface, and the heat flux evaluated accordingly.

The heat flux from the cast has been evaluated as steady state by considering the rate of average volumetric heat generation. This approach has only been used for our comparative study. The average heat flux at the interface is correlated with the volume of the cast to achieve a specific solidification time (t). To solidify a unit volume from a melting temperature T_{melt} to an average demoulding temperature T_{demold} the following equations can be used:

$$\dot{Q} = \frac{\rho[h_{fs} + Cp_{Al,s}(T_s - T_{demold}) + Cp_{Al,l}(T_{melt} - T_L)]}{t} \qquad (2)$$

Where $Cp_{Al,s}$ and $Cp_{Al,l}$ are the specific heat of the solid and liquid aluminium phases respectively. T_s and T_L are the solidus and liquidus temperatures of the cast part. The injection kinetic energy and flow energy of the molten aluminium have been neglected. The surface temperature was assumed to be uniform throughout the cast interface,

3. Results and Analysis

The results are divided into 3 sections. The first section includes the experimental results and the comparison with the transient CFD model. The second section includes the transient results that have been carried out over two cycles. The third section relates to the transient model without cast.

3.1 Experimental versus the transient model.

The results from the temperature measurements in the mould and cast are compared with the transient model to validate the model and to ensure that it is set up correctly. Figure 3 shows close agreement between the simulation and experimental measurements for the temperature of the cast and 2 mm depth from the cavity if the first 6 seconds are excluded. The discrepancy at the early stage can be attributed to the slow pouring of the molten aluminium on the surface of the block as it is carried out manually. During this early stage adjustment must be considered for the interface heat transfer coefficient and thermal properties to calibrate the model. However, as the manual pouring process was an additional error that cannot easily compensated, adjustment in the model was limited to the interface heat transfer coefficient to match the steady conditions. A value of 500 W/m^{2}K was found to be suitable for our case.

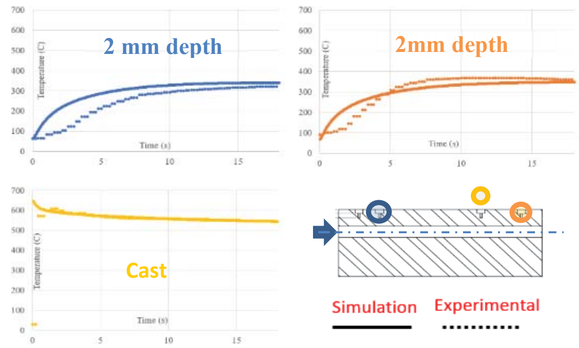


Figure 3 – Temperature between experiment and simulation at four monitor locations

The spatial distribution of the temperature across block and cast after 40 seconds is shown is Figure 4. The temperature gradient at the interface is also shown in left side of the figure and it shows a maximum temperature variation of 4.5°C. This change in temperature difference can be reduced by modifying the cross-sectional shape of the pipe by having a flat surface on the top of the pipe. The temperature gradient in the mould above the pipe reaches a value of 33°C/mm. This value is calculated at steady state conditions. A much higher value is expected when initially injecting the molten aluminium.

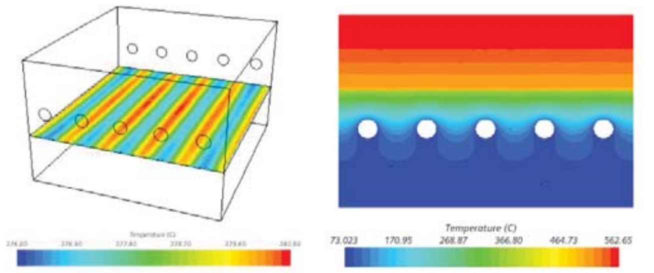


Figure 4 – Temperature distribution between mould/cast interface and cross-section at 40s

The cast interface temperature reaches the solidus temperature in less than a second. The mould interface temperature is lower than the cast temperature and that difference depends on the interface resistance. Figure 5 shows a comparison in cast and mould interface temperatures between a case of constant interface heat transfer coefficient of 5000 W/m^{2}K and a case with initial heat transfer coefficient of 12000 with linear drop to 5000 within one second. Having high heat transfer coefficient at the beginning leads to a higher temperature response at the cast and mould surfaces to reach the steady temperature earlier.

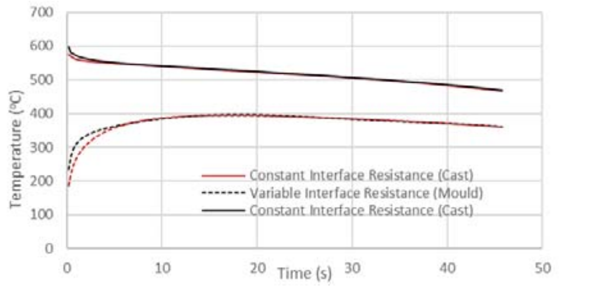


Figure 5 – Mould, cast average interface temperature with constant and varying interface resistance for the 45s period

3.2 Case study for the Transient Model with cast and mould

A comparative study between a cast part with two cast thicknesses can be carried out to compare how the cooling pipe depth can affect the deviation in temperature uniformity and heat flux distribution. A step cast part is chosen with a thickness 23 mm and 11.5 mm and pipe depths of 6 mm and 12 mm pipe as shown in Figure 6. The results of these simulation are compared with another simulation that has a pipe location of 6 mm and 10 mm depth from the interface. In both simulations the interface thermal resistance is neglected. The temperature distributions at the interface and along the cast, pipe and mould are shown in Figures 6 and 7. Because of the absence of the interface heat transfer coefficient or the interface resistance, the mould interface temperature will have much high value than that obtained from previous simulations.

The temperature variation shows a maximum difference of 5°C throughout the interface surface for the optimum pipe locations case while for the case with a 2 mm shift in the pipe depth toward the interface the difference increases to 9°C as shown in the Figure 7.

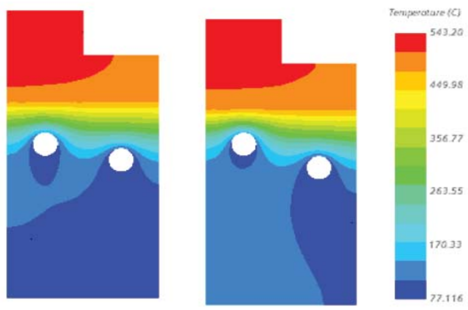


Figure 6 – Cross-section temperature distribution with cast thickness 23mm and 11.5mm at pipe depth 6mm, 12mm (left) and 6, 10mm (right)

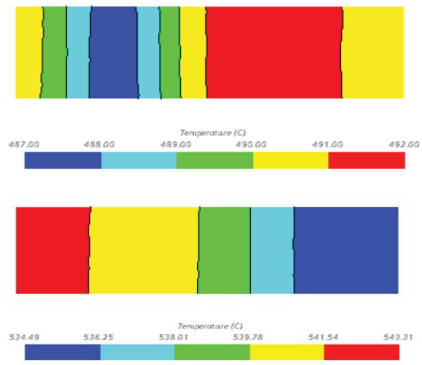


Figure 7 – Mould/cast interface temperature distribution at pipe depth 12mm (top) and 10mm (bottom)

The temperature uniformity can be improved using an adjoint optimization approach that is currently under investigation by the research team that changes the pipe surface geometry. With this technique it was possible to improve the temperature uniformity for ideal case and have a maximum temperature variation of 3°C with a small deformation in the pipe as shown in Figure 8.

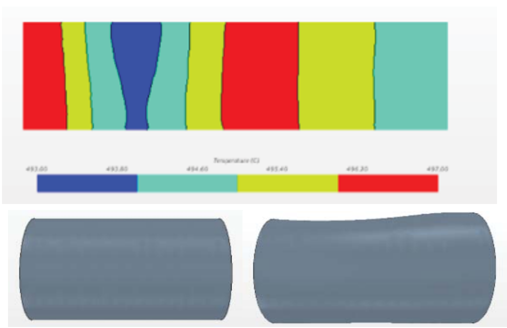


Figure 8– Interface temperature distribution of the optimised cooling channel using the adjoint method and shape deformation of the pipe

The heat flux is also increased as shown in Figure 9 when the pipe depth is reduced in the small cast section interface. However, it was interesting to see a lower heat flux occurring on the thick part. This could be attributed to the higher temperature gradient from the thick part to the thin part at the interface.

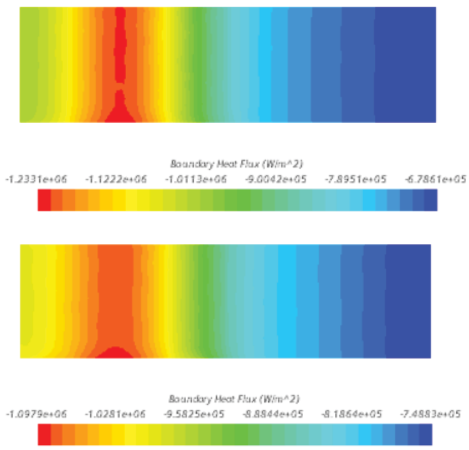


Figure 9 – Interface heat flux distribution for 11.5mm thin (top) and 23mm thick (bottom) cast thickness

3.3 Transient Model without Cast.

From the experimental data and simulation, it was clear that the temperature in the mould takes a short time relative to the solidification time to reach a temperature that is almost constant with relatively small variation. If the early stage is neglected and we assume that the temperature is constant at the mould surface, then it is possible to compare the heat flux from different cooling system designs without the need to simulate the cast each time.

Figure 10 shows the surface average heat flux at each time step for different pipe depths. The highest heat flux occurs upon initial pouring of the aluminium due to the cold block and the chilling effect. The heat flux then reduces as the block temperature increases and reaches an asymptotic value. The simulation was initially run for 10 seconds with a mould surface temperature of 250°C before changing the boundary conditions to a temperature of 396°C. The reason for having two cycles is to ensure that there is a temperature gradient in the region between the block surface and water channel surface. This is usually the case before injection of the molten aluminium.

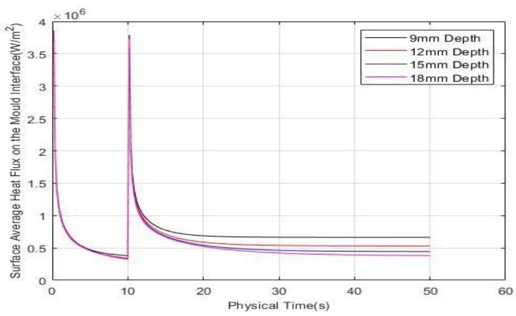


Figure 10 – Two cycle results of the surface average heat flux at 9, 12, 15, and 18mm pipe depth for 40s

The effect of pipe depth on surface average heat flux at different times 15, 20, 25, 30, 35 and 40 seconds is shown in Figure 11. This figure indicates that increasing the pipe depth lowers the rate of heat flux at the interface from the start of the simulation up to the solidification time. Nevertheless, the effect of depth becomes more pronounced at a later stage, close to the solidification time. It is, therefore, possible to compare the heat flux during the moulding stage from various cooling pipe depths or design parameters.

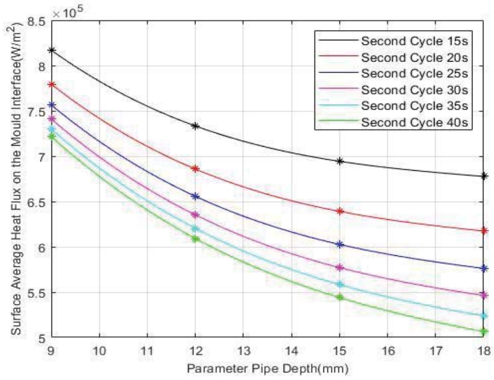


Figure 11 – Surface average heat flux at mould/cast interface against different pipe depth locations for different times of the second cycle

Similar figures have been generated for the effect of pipe diameter, cast thickness, pipe pitch, initial mould temperature and water velocity. The data provides the expected heat flux on the surface for various combinations of parameters that can provide initial cooling channel design before carrying out more rigorous optimisation.

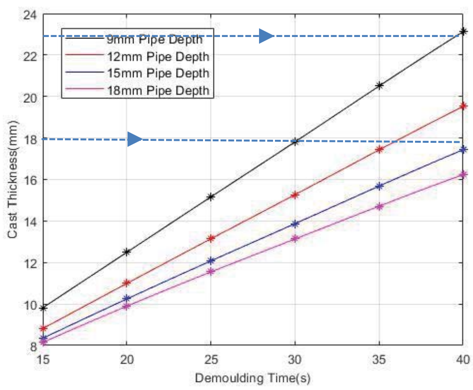
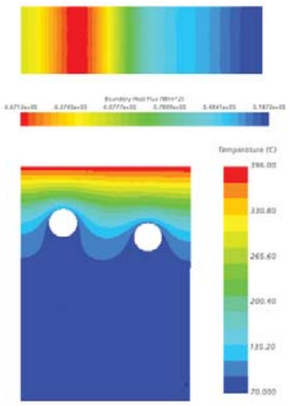


Figure 12 – Cast thickness against solidification time for 9, 12, 15, and 18mm cooling channel depths

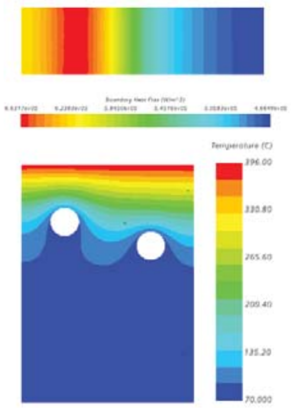
The time-averaged heat flux value over the solidification time divided by the volumetric heat generation that is calculated from equation 2 will provide the average cast thickness to be solidified for a given cooling configuration. Figure 12 shows cast thickness versus solidification time for various pipe depths. This curve is built assuming a constant interface temperature of 396°C. Changing the interface temperature will lead to a different value here.

The gradient in heat flux will be different if the pipes are not located in the correct position to achieve a uniform interface temperature. It is therefore possible to compare the heat flux generated from a different cooling system. This heat flux distribution can be compared with the rate of energy needed to solidify different thicknesses. The actual case is that the interface temperature will not be the same if the pipes are not located correctly and the heat flux will also be different.

To examine the methodology using this constant interface temperature approach, the transient simulation was carried out for a step cast with a step thickness 80% lower the experimental configuration. Figure 13a shows the pipe depth for the two cast thicknesses 23mm and 18mm, two pipe depths can be evaluated assuming a demoulding time of 40 seconds accordingly, the coolant pipe depth should be at 9 and 14 mm. This case has been compared with another case where the coolant pipes were not correctly located, we chose to use a 9mm and 17mm depth to show the difference in heat flux and temperature as shown in Figure 13b.



a) Distribution of heat flux and cross-section temperature at 9 and 15mm depth



b) Distribution of boundary heat flux and cross-section temperature at 9 and 17mm depth

Figure 13 – Comparison of interface boundary heat flux and cross-section temperature distribution at difference pipe depth locations

The heat flux distribution on the interface surface after 40 seconds shows a higher heat flux at the large thickness interface by almost 20%. The drop in the heat flux was found to be 10% at the smaller cast thickness section due to the extra 2 mm in pipe depth. Having a deeper pipe not only leads to lower heat flux but also caused a drop in the heat flux through the interface of the higher cast thickness section by 2%. This comparison shows clearly that there is undercooling in the deeper pipe section if the ideal heat flux distribution is known.

3.4 Complex Geometry Cooling Assessment

Since it is difficult to identify the ideal heat flux, it would be more realistic to compare with an independent variable that is proportional to the ideal heat flux. As the heat flux should be correlated with the cast thickness, it is easier to take the cast thickness as a parameter. However, there is not a straightforward method to identify the cast thickness distribution for a complex geometry. Instead, a uniform volumetric heat generation can be applied as a source term on the cast part and using a steady model, it is easy to evaluate the heat flux on the surface of the cast. With this method the cast can only be simulated once using steady conditions and the heat flux can then be compared with that evaluated from different designs. The heat flux is not expected to be the same at that from the transient model, but it will have a comparable value. Using a scale values can be compared.

Figure 14 shows the heat flux distribution in one of the inserts and also the heat flux generated on the cast. Areas with a similar colour on the cast and mould means there is a match and that the cooling pipes are at their correct location in the design. Areas that appear to have more heat flux than the corresponding value on the cast means they are overcooled and require modification. The method has been applied to various inserts and appears to be a good method for assessment so long as the pipes are close enough to the cavity and the mould reaches a steady condition before solidification.

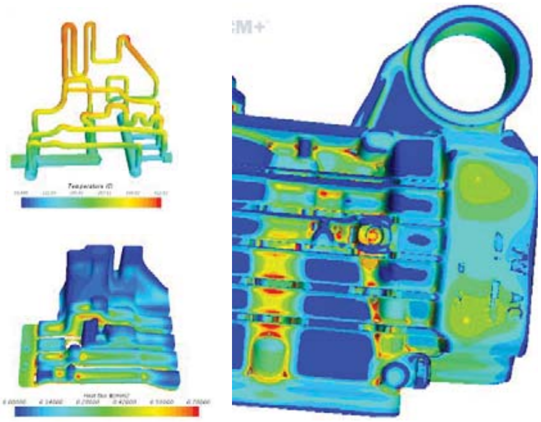


Figure 14 – Temperature distribution around cooling channels and heat flux at the mould/cast interface for one industrial inserts

4. Summary/Conclusions

This study employed commercial CFD software to create a simplified model that can be utilised to assess different cooling systems particularly for 3D printed inserts with complex geometry. The assessment model is based on achieving a uniform mould interface temperature and can be applied when the pipes are closed enough to the cavity for the mould to reach steady conditions before solidification. The model can be utilised in building the baseline cooling design before applying an optimisation technique. The spatial distribution of the heat flux on the mould/cast interface is evaluated by assuming a constant and uniform temperature at the mould interface throughout the solidification period without the cast. The evaluated heat flux is then compared with the cast part heat flux to identify the overcooled or undercooled region. The model has been successfully tested on simple flat surface and step cast part before applying it on a complex geometry. The simulation highlighted that interface thermal resistance can significantly affect the selection of the interface temperature.

References

1. Z. P. Guo, S. M. Xiong, B. C. Liu, M. Li et al., "Development of thermal boundary condition model at metal/die interface of high pressure die casting process", International Journal of Cast Metals Research, 24:3-4, 151-157, 2011, DOI: 10.1179/136404611X13001912813825
2. Liang, G., Ali, Y., You, G. and Zhang, M.X. "Effect of cooling rate on grain refinement of cast aluminium alloys. " *Materialia*, *3*, pp.113-121, 2018
3. Long, A., Thornhill, D., Armstrong, C. and Watson, D. "Predicting die life from die temperature for high pressure dies casting aluminium alloy. " Applied thermal engineering, 44, pp.100-107, 2012

4. Vedant Chahal, Robert M. Taylor, "A review of geometric sensitivities in laser metal 3D printing ". Virtual and Physical Prototyping, 15:2, 227-241, 2020, DOI: 10.1080/17452759.2019.1709255
5. Damjan Klobcar, Janez Tuesk "Thermal stress in aluminium alloy die casting dies". Computational Materials Science, 43, 1147-1154, 2008
6. C. Mitterer, F. Holler, F. Ustel, D. Heim "Application of hard coatings in aluminium die casting – soldering, erosion and thermal fatigue behaviour" Surface and Coating Technology 125, 233-239, 2000.
7. Elena Fiorese, Franco Bonollo, Eleonaora Battaglia and Giorgio Cavaliere. "Improving die casting process through optimization of lubrication " International Journal of Cast Metals Research, 30:1, 6-12, 2017 DOI: 10.1080/13640461.2016.1162387
8. Anglada, E., Meléndez, A., Vicario, I., Arratibel, E. et al, "Adjustment of a high pressure die casting simulation model against experimental data. " Procedia Engineering, *132*, pp.966-973, 2015
9. Anglada, E., Meléndez, A., Vicario, I., Idoiaga, J.Ket al., "Prediction and validation of shape distortions in the simulation of high pressure die casting. " Journal of Manufacturing Processes, 33, pp.228-237, 2018
10. E. Anglada, A. Melendez, I. Vicario, E. Arratibel, et al., "Simplified models for high pressure die casting simulation ". The Manufacturing Engineering Society International Conference, Procedia Engineering 132, 974-981, 2015
11. Hong-Seok Park, Huan-Phuong Dang. "Optimization of conformal cooling channels with array of baffles for plastic injection mold" International Journal of precision engineering manufacturing. Vol. 11, No. 6, pp.879-890, 2010
12. S. Asthana. "Innovative die lubricant trends for evolving productivity and process requirements", Holbrook, AZ, NADCA Die casting Cong, 2013
13. L. X. Kong, F. H. She, W. M. Gao, S. Nahavandi, et al. "The effect of die lubricant spray on the thermal balance of dies" J. Mater. Process. Technol. 201(1–3), 629–634. 11. 2008.
14. James L. Graff, Lothar H. Kallien, "The effect of die lubricant spray on the thermal balance of dies", Cleveland, OH, NADCA Cong., Paper T93–083, 239–246, 18–21 October 1993
15. M.F. Horstemeyer, N. Yang, K. Gall, D.L. Mcdowell, Jet al., "High cycle fatigue of a die cast Az91e-T4 magnesium alloy, " Acta Mater. 52 (5)1327–1336, 2004
16. A.J. Norwood, P.M. Dickens, R.C. Soar, R.A. Harris, "Surface temperature of tools during the high-pressure die casting of aluminium" Journal of Engineering Manufacture. 221, 2007
17. Chen, Z.W, "Skin solidification during high pressure die casting of Al–11Si–2Cu–1Fe alloy" Materials Science and Engineering: A, 348(1-2), pp.145-153, 2003
18. A. Srivastava, V. Joshi, R. Shivpuri, R. Bhattacharya, et al, "A multilayer coating architecture to reduce heat checking of die surfaces" Surface and Coating Technology, Elsevier, 2003.
19. Wang, F., Ma, Q., Meng, W. and Han, Z., "Experimental study on the heat transfer behavior and contact pressure at the casting-mold interface in squeeze casting of aluminum alloy" International Journal of Heat and Mass Transfer, 112, pp.1032-1043, 2017.
20. A. Hamasaiid, G. Dour, T. Loulou, M.S. Dargusch. "A predictive model for the evolution of the thermal conductance at the casting-die interfaces in high pressure die casting" International Journal of Thermal Sciences 49, 365-372, 2010.
21. Alastair Long et al. "Determine of the heat transfer coefficient at the metal-die interface for high pressure die cast AlSi9Cu3Fe", Applied Thermal Engineering 31, 3996-4006, 2011.
22. K. Ceylan, and G. Kelbaliyev. "The roughness effects on friction and heat transfer in the fully developed turbulent flow in pipes". Applied thermal engineering, 23 (5), pp 557-570,2003.
23. W.D. Griddiths, K. Kawai. "The effect of increased pressure on interfacial heat transfer in the aluminium gravity die casting process", Journal of Material Science., 45:2330-2339, 2010.
24. John M. Tim Holt, Technical Ed, C. Y. Ho, Ed, "Structural alloys Handbook". CINDAS/Purdue University, West Lafayette, IN, 1996.
25. E. Baril, P. Labelle, M.O. Pekguleryuz, "Elevated temperature Mg–Al–Sr: creep resistance", Mechanical properties and microstructure, JOM 55, 34–39, 2003. doi:10.1007/s11837-003-0207-7
26. G. Dour, M. Dargusch, C. Davidson, A. Nef, "Development of a non-intrusive heat transfer coefficient gauge and its application to high pressure die casting: effect of the process parameters" Journal of Materials Processing Technology 169.2, 223-233, 2005.

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Definitions/Abbreviations

AM	Additive Manufacturing
HPDC	High Pressure Die Casting
CFD	Computational Fluid Dynamics
IHTC	Interface Heat Transfer Coefficient