Characterization of heat transfer and its effect on solidification in water cooled LPDC of wheels

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Abstract. Computational process modelling has become an important engineering tool in the casting industry to predict the solidification sequence in complex castings. Used properly, this tool can help reduce manufacturing costs. One of the challenging issues in developing casting simulations of the low pressure die casting (LPDC) process for automotive wheels is to quantify the heat transfer coefficients (HTC) within the cooling channels in a die. When water is used as the cooling media, the HTCs exhibit a complex, non-linear behaviour due to the boiling phenomena that occur making it possible to extract a significant amount of heat from the die in a short period of time and influence the solidification of a wheel. Primarily, constant heat transfer coefficients have been used to describe this heat transfer in casting models up until now, but an opportunity exists to improve the transient description of heat transfer in channels cooled with water. In this paper, HTC’s in a lab-scale physical analogue model of die cooling will be characterized as a function of initial die temperatures.

1. Introduction
Wheels are one automotive component where weight reduction may be achieved by selecting lightweight materials over the traditionally used steel. In addition to their structural performance, styling and aesthetic appearance are important characteristics of automotive wheels. The most common process used to manufacture aluminium alloy wheels is the low pressure die casting (LPDC) process. LPDC is a permanent-mould, die casting technique used industrially to produce rotationally symmetric parts such as wheels where cosmetic considerations are important [1]. However, castings produced by this technique are often affected by defects that can compromise structural performance under cyclic loading conditions. These include microporosity, hot tearing, entrained oxide films [2] and cold shuts [3]. The formation of these types of casting defects is closely linked to the casting process. Careful control of solidification can be used to eliminate porosity and to achieve a finer cast microstructure which translates to improved performance for cast aluminium wheels. Controlled solidification may be achieved through superior die design and tuned cooling (cooling channel geometry, cooling media (water, air mist), cooling duration, and cooling media flow rate). Accurate mathematical models of the LPDC process are necessary to allow engineers to develop effective strategies to achieve controlled solidifications and to enhance aluminium wheel quality.

Casting simulations of components produced via the low pressure die casting (LPDC) process are typically based on the Finite Element or Finite Volume Methods. The information required to develop these models includes geometry, material properties, initial conditions and boundary conditions. One of the challenging issues of developing casting simulations is to accurately quantify the boundary conditions involved which are often dependent on time, temperature, location, surface treatment and cooling media [4]. In particular, the HTCs within the cooling channels in the die are one of the most
critical and sensitive model parameters. In the LPDC process, temperatures can reach ~500°C at some locations in the die during steady-state casting conditions. When a fluid, such as water, contacts a surface with a wall temperature, $T_w$, above the liquid saturation temperature, $T_{sat}$, at a specified pressure, a liquid-to-vapor phase change (e.g. boiling) will occur. In a die cooled with water flowing through enclosed channels, internal flow boiling conditions are present where the combined effects of water flow, channel orientation and boiling influence heat transfer. Once the channel surface has cooled down below the saturation temperature forced convection conditions will prevail and will only occur if the cooling cycle is long enough. Forced convective heat transfer is a complex transport process involving the combined effects of heat conduction through a fluid and heat transport due to movement of the fluid. This work aims to characterize heat transfer occurring in a physical analogue of a cooling channel and thereby improve the description of HTCs in cooling channels. The expectation is that this work will enable significant improvement in casting process model accuracy.

2. Experimental Methodology
An experimental apparatus has been designed, fabricated and commissioned to mimic the heat transfer conditions experienced in an LPDC process. The cooling block experimental apparatus consists of an H13-tool steel block (83 x 83 x 305 mm) with a round cooling channel (25 mm dia.) machined into the center of the block. The block is heated by 8 channel heater strips (50 kW/m^2 each) that are bolted to the outside of the block (2 on each side). The block is instrumented with 16 type-K thermocouples and the incoming water flow rate is measured. A schematic of the cooling block setup is shown in Figure 1. A portable data acquisition system using National Instruments CompactRIO hardware and the LabView DAQ software is used to monitor and record temperatures during each experiment. This experimental setup allows the effects of parameters such as fluid type (air and water), flow rate, and initial block temperature to be assessed.

![Figure 1. Schematic of Cooling Block Experimental Setup. Symbols represent location of thermocouples.](image)

During each experiment, the block is heated to a desired starting temperature and held until a steady state temperature condition is reached. The data acquisition system, which records data from the thermocouples at 20 Hz, is used to verify that the steady-state condition is reached before introducing coolant to the block. The criterion used to assess whether steady-state has been reached is that the block temperature does not change more than ±2°C / min. There are 12 thermocouples embedded in the block at three different axial positions (near the Inlet end, Mid-length and Outlet end of the block). At each axial position, thermocouples were located 3.2, 9.5, 15.9 and 22.2 mm away from the cooling channel interface. The locations of the thermocouples in the cooling block are shown in Figure 1. The temperature of the coolant at the inlet and outlet to the block was recorded by 4 thermocouples (in the fluid near the wall and at the centre of the fitting at each location).

3. Mathematical model
A transient heat conduction model of the cooling block was developed based on the cooling block experiments using the general-purpose finite element modelling software, ABAQUS. The domain of the
model was reduced to a 1/8\textsuperscript{th} section of the block by assuming symmetric heat flow conditions exist during the experiment. To approximate the heat transfer occurring at the boundaries of the cooling block, a common form of the heat transfer coefficient boundary condition was used. The resulting heat flux applied to each surface can be calculated as:

$$q'' = h(T_w - T_\infty)$$

where $q''$ is the heat flux (W/m\textsuperscript{2}), $h$ is the heat transfer coefficient (W/(m\textsuperscript{2}·K)), $T_w$ is the surface temperature of the block (°C), and $T_\infty$ is the temperature of the environment adjacent to the block surface (°C). The $h$ and $T_\infty$ were manipulated to represent the different conditions on the block surfaces. User-written subroutines were used to describe the effects of the heaters and cooling (temperature dependent) from the central channel. Uniform HTCs and a constant ambient temperature were used to describe heat loss to the surrounding environment. A trial and error approach was used to determine appropriate values for the boundary conditions and the end results were verified by comparing the predicted and measured temperatures.

**Figure 2.** Cooling Block Model 1/8\textsuperscript{th} domain

The initial condition (e.g. $t = 0$ s) for the cooling block model, shown in Figure 2 as the block temperature distribution, is based on data obtained from the cooling block experiments. Prior to a test, the cooling block is heated until a steady state temperature is reached. At the time when the coolant first reaches the block, the temperature at 3 points within the block closest to heater boundary layer (22.2 mm from the cooling interface at the Inlet, Mid-length, Outlet locations) and one point (3.2 mm from the cooling interface at the Mid-length location) furthest from the heated surface are used to generate the initial condition.

### 4. Result and Discussion

#### 4.1. Cooling Block Experimental Result

**Figure 3.** Measured temperatures in the cooling block for an initial block temperature of 400°C and a flow rate of 20 l/min.
Experiments were performed with initial block target temperatures of 300°C, 400°C and 500°C. A constant water flow rate of 20 l/min was used for these experiments. The experimental results consist of measured temperatures from the H13 block at different depths from the block/water interface and measured water temperatures at the inlet and outlet of the block. The measured temperatures in the block for the 400°C initial block temperature condition is shown in Figure 3.

During a cooling experiment, the locations nearest to the cooling channel (3.2 mm depth at the Inlet, Mid-length and Outlet) exhibit the first and most rapid temperature decrease followed sequentially by the other thermocouple locations increasing in distance from the H13/ water interface (9.5 and 22.3 mm). At each time during the experiment, the Mid-length position thermocouples at all depths have the highest temperatures while the Inlet positions have the lowest temperatures. This has been attributed to end effects caused by exposure of the ends of the block to the surrounding environment and the fittings connecting the coolant supply to the block (contact cooling), resulting in lower temperatures relative to the Mid-length block temperature. The Outlet positions of the block exhibits higher temperatures than the Inlet positions because the water at the outlet has been heated as it flows through the block.

![Figure 4](image-url) – Measured temperatures in the (a) water for 1000 s and (b) the magnification of (a) for 100s for an initial block temperature of 400°C and a flow rate of 20 l/min.

The measured water temperatures, shown in Figure 4(a), are from the locations within fittings attached at the inlet and outlet sides of the block. The temperatures are measured near the wall (~3 mm) and at the centre of the inlet and outlet fittings. Due to abnormalities in the measured temperature data from the Inlet Wall location, the data from this thermocouple was omitted from Figure 4(a). Previous experimental data has shown that the temperatures at the Inlet Wall and Inlet Centre locations are almost identical. A magnified view of the measured water temperature data is shown in Figure 4(b). At the Inlet Centre, the initial water temperature was measured to be ~100°C and this rapidly decreased to 26°C in the first 3 s during the experiment. The inlet water temperature then decreases to ~12°C. These changes are most likely caused by the initial boiling of water followed by decrease in the source water temperature. The initial water temperature from the source is around 26°C due to heat from the environment being transferred to the water when the water is stationary in the buildings plumbing and a small amount of heat transfer along the apparatus’s inlet pipe during preheating.

The outlet water temperatures for both the centre (Outlet Centre) and wall (Outlet Wall) locations generally exhibit a period of rapid decrease initially (for times < 50 s), followed by a reduction in the cooling rate. Significant fluctuations (very short pulses, high fluctuations in temperatures) in the outlet water temperature are observed at the Outlet Wall location during the first 10 s. This may be due to transient phenomena taking place at the start of the experiment and / or due to boiling phenomena. After 10 s, fluctuations in the measured water temperatures at the Outlet location are present but at a reduced level as boiling phenomena are fully established at this time. An additional cause of these fluctuations may be the turbulent flow conditions (e.g. based on Reynold’s number) that exist in the cooling channel. The Outlet Wall thermocouple was placed at a location within the channel where high temperature...
gradients were expected due to the boundary layer formed at the wall. During boiling and/or turbulent flow, significant mixing will occur resulting in fluctuations in the measured temperatures.

4.2. Cooling Block Model Result

The model was used to estimate the HTCs for each initial block temperature by adjusting the HTCs at the H13/heater interface and H13/water interface, in the form of data tables, until a reasonable fit was achieved. The predicted temperatures (model) are compared with the measured temperatures (experiment) for each initial block temperature at the Mid-length axial position in Figure 5. The model curves (solid lines) and the experimental curves (dashed lines) are observed to correlate closely. The biggest difference between the model and experiment at each thermocouple location ranges from approximately 0.6°C to 6.95°C.

The heat flux at the cooling channel interface at the Mid-length position has been plotted in Figure 6(a) for the first 100 s of the cooling process for initial block temperatures of 300, 400 and 500°C. The heat flux increases rapidly to a high value within the first ~5 seconds before decreasing approximately 80 – 90% (t < 15s) and then slowly decreasing linearly after that. The heat fluxes are observed to be higher for higher initial block temperatures because of the increased driving force for heat transfer (e.g. ΔT) and larger amount of enthalpy in the cooling block at the start of the experiment which continues to diffuse to the cooling channel interface.

The HTC values as a function of wall temperature used to obtain the fits shown in Figure 5 are shown in Figure 6(b) and range from 2300 - 7509 W / (m²·K), 2000 - 9074 W / (m²·K),

Figure 5 - Comparison of the predicted and measured temperatures at different depths from the water channel at the Mid-length position in the block for an initial block temperature of (a) 300, (b) 400 and (c) 500°C, for a flow rate of 20 l/min.
Figure 6 - (a) Corresponding heat flux history and (b) comparison of the HTC values for initial block temperatures of 300°C, 400°C and 500°C and a flow rate of 20 l/min

2200 - 9355 W / (m²·K) for initial block temperatures of 300, 400 and 500°C, respectively. The maximum HTC value increases with increasing initial block temperature. The minimum HTC for the 300°C, 400°C and 500°C cases are similar. The high heat extraction rates at higher block temperatures is consistent with the transient boiling phenomena, and the lower heat extraction rates suggest the occurrence of convective heat transfer. Between 74°C – 175°C, the HTC values drop significantly (e.g. from ~8600 W / (m²·K) to around 3800 W / (m²·K) for an initial block temperature of 500°C). The decrease in HTC values at temperatures within this range result from transition from boiling to convective cooling.

5. Summary
An experimental apparatus has been developed to quantify the HTC occurring within cooling block apparatus as function of relevant process parameters. The cooling block experiment is meant to be a physical analogue of a cooling channel in a LPDC die. A mathematical model has been developed of the experiment to facilitate the calculation of the HTCs. The measured temperatures and modelling results indicate that internal flow boiling heat transfer is very nonlinear and sensitive to changes in the initial block temperature. The calculated HTC values for different initial block temperatures show that maximum HTC values increase as the initial block temperature increase however minimum HTC values show minimal change and remain within the lower range of HTC. Further investigation is needed to quantify the boiling phenomena in greater detail. Additional experiments and modelling are planned to examine the effects of other process parameters. It is expected that the knowledge developed from the experimental characterization of heat transfer can be adapted for use in the industrial LPDC applications and that this improved description of the heat transfer occurring in the LPDC process will enable improvements to the manufacturing process through reduced casting defects.

References
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