Fayoum University Faculty of Engineering, 2024, Vol: 7(2), 264-271
https://fuje.journals.ekb.eg/
ISSN Online: 2537-0634
ISSN Print: 2537-0626

Estimation of Heat Flux During Spray Quenching Process Using Revision Measured Data

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How to cite this paper: Abdalrahman, K.H.M. & Abo Elyamin, G.R.H. (2024). Estimation of Heat Flux During Spray Quenching Process Using Revision Measured Data. *Journal of Fayoum University Faculty of Engineering, Selected papers from the Third International Conference on Advanced Engineering Technologies for Sustainable Development ICAETSD, held on 21-22 November 2023, 7(2), 264-*271.
https://dx.doi.org/10.21608/fuje.2024.344048

Abstract

Quenching can be defined as, cooling of metals at a rate faster than cooling in the still air which is widely used for controlling the mechanical and metallurgical properties in the metal manufacturing and material processing industries. An experimental and numerical study of transient boiling heat transfer during a cooling of a hot circular aluminum alloy plate AA6082 has been made. A developed technique using the processed readings as a basis in the approach to solving has been applied. This technique depends on the revision of experimental measured data, which used as input of the numerical solutions to calculate the heat flux. On one of its surfaces, a thin heated metal plate is exposed to a nozzle, while on the other, an infrared camera measures the temperature (T). The measured temperature data from the plate hot surface is the primary interest in the metal quenching process for the heat flux estimation. Based on the region of temperature, the heat transfer mechanism during quenching will also change, ie. film boiling, transition boiling and nucleate boiling. Measured temperature data are further processed through the numerical solutions one dimensional (1D) and two dimensional (2D) analyses. The surface heat flux was estimated for both 1D and 2D numerical methods for two different cases data (processed and unprocessed). This confirms clearly that while the behaviors are the same, using processed data is better than employing unprocessed data..

Keywords

Aluminium DC casting; spray quenching; Infrared thermography; Inverse heat conduction problem; Heat flux

1. Introduction (Heading 1)

DC casting is the most common semi-continuous casting practice in aluminum alloy properties it's widely used and it produces high quality of almost any alloy. Multifarious heat and fluid flow models in the continuous casting process have been made. Several physical phenomena take place during the casting process leading to different mathematical models such as the dynamic heat and fluid flow in the startup of ingot casting and, the pressurized air gap between the mold wall and the ingot. In continuous casting, the secondary cooling system has an important influence on the quality of the cast products. A spray quenching method is used as secondary quenching in Direct Chill casting (DCC) of metals where the rate of heat transfer is low in this region e.g. steel (Jeshar et al., 1986) and (Sengupta et al., 2005). The Leidenfrost (LF) phenomenon, which develops as a result of the high surface temperature, may have an impact on the transfer of heat. In the present research, we are interested in the analysis solutions and estimation of heat transfer in the metal during spray cooling. It is very important to analyze the metallurgical effects of quenching. Experimentally capturing the sequence and size of these impacts is difficult due to the complexity of the phenomena' interrelations and their brief quality (Bartosz et al., 2023). Due to ever-increasing processing power and the accessibility of commercial software, numerical simulations of heat treatment processes have been created and are currently used in the industry to analyze transient phenomena like quenching. Numerous systems built using the finite-element method are dedicated to heat treatment procedures (Dowling, 1996) and (Arimoto, 1998). Therefore, it is essential to define the input data precisely for each of the different phases of a system. Software like JMatPro (Guo et al., 2013) or Thermo-Calc (Jo et al., 2002) can be used to specify the temperature-dependent thermo physical and mechanical parameters of each phase. The developed method is applied to the measured data from many experiments; it explains the importance of purification of the measured data before they are used as inputs in the numerical solutions. (Sengupta et al., 2005) suggested that the mathematical models of the DC casting process based on thermo fundamentals it is better including the optimization of water-cooling practices. (Bakken et al., 1986) interested in reducing the measurement error by using a special jag was devolved to ensure that the thermocouples were placed near the surface and axially aligned with each other. Data smoothing techniques are used to eliminate "noise" and extract real trends and patterns. (Schneider et al., 1990) applied a smoothing technique to all measured temperature values to remove any random noise, this technique was found necessary in achieving a stable inverse solution. (Li Huiping et al., 2006) used an inverse heat conduction problem (IHCP) to calculate heat transfer according to the temperature curve gained experimentally during the quenching process, advanced finite element method (FEM) to the inverse heat conduction problem was applied, the optimum values of heat transfer can be easily obtained by a developed method. (Ling et al., 2003) developed a non- iterative, finite element method to solve inverse problems for estimating surface heat flux histories on thermally conducting bodies. The technique Absorbed linear and non-linear problems, the error between measured and computed temperatures was minimized, and the minimization of the instantaneous error led to a linear system. In this research, the heat flux of a quenched aluminum plate is estimated by using experimental results and finite element technique based on an inverse mathematical model. The influence of cooling water velocity on Aluminum hot surface is analyzed.

2. Experimental Arrangements

The experimental setup for metal quenching process components are shown in Figure 1. The main parts of the apparatus consists of Infrared camera (IR-camera) with a type ThermaCAM SC 3000, single hydraulic nozzle, water pump, metal plate, and an electric furnace. The metal plate for experiments is aluminum alloy AA6082 deformed in a circular shape with a diameter of 140 mm and thickness of 3 mm. The plate is cooling from one side (quenched side) by the cooling water while the other side (measured side) is painted black coating to improve and raise the surface emissivity (ε) of the measured side to 0.9 approximately. Quenched side of the plate exposed to stream water from the nozzle during cooling process.

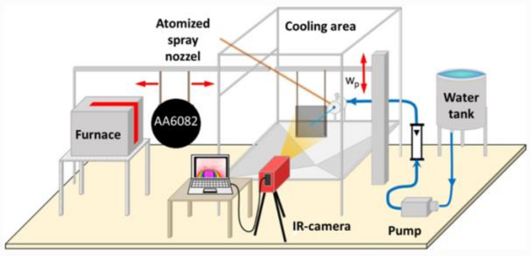

Figure 1. Schematic diagram of the experimental set-up

The cooling water is delivered to the nozzle by a hydraulic pump with flow rate of 20 l/hr controlled by regulating device, and the distance between nozzle orifice and quenched surface of the plate 64 mm. At the beginning of experiments, the plate is heated up in the electric furnace to a high temperature of 560 °C. Due to the requirement for the infrared camera to capture the plate's measured side temperature, the plate is being manually moved from the furnace to the cooling area. An infrared camera captures a changing surface temperature from the plate's measured side. The accuracy of this camera's temperature measurement is about 0.1 Kelvin, and it can take infrared photos of the surface at a frequency of 150Hz. The results of this transient temperature measurement are saved in the computer connected to the camera for every sequence. ThermaCam Researcher 2001 is the software used for operating the camera and analyzing the data afterward. Two different waters (DI water and BF water) are used to cool the plate on the front side and the transient temperature on the back side is recorded by using an infrared camera. Deionized water (Di water) is a type of purified water with mineral ions (salts) removed, and the second is an industrial water used in metal direct chill casting (DC casting) named BF-water. Specifically, the use of these types of water is nothing but it is a case to study the success of the method used to deal with inputs.

3. Numerical Solutions

3.1. One-Dimensional analysis

The heat transfer coefficients (α) are determined using the one-Dimensional analysis for a specific point on the plate. Since the temperatures of the plate change over time, the heat transfer is unsteady state. Therefore, the following equation of energy balance can be applied

$$\frac{\Delta h}{\Delta t} = \dot{q}_{sp} + \dot{q}_{\lambda} \quad (1)$$

Change of enthalpy (Δh) in the volume calculated by

$$\frac{\Delta h}{\Delta t} = \rho\, c\, s\, \frac{\Delta T}{\Delta t} \quad (2)$$

In case of spray quenching, heat is conducted from the outer radius (r) regions of the plate to the center, the heat flux due to conduction part in the radial direction calculated using Fourier differential equation

$$\dot{q}\,\lambda = -s\,\lambda\,\frac{1}{r}\frac{\partial}{\partial r}\left(r\,\frac{\partial T}{\partial r}\right) \quad (3)$$

The water stream also causes a heat flow outside the volume element regarded. This stream Heat Flux $\dot{q}_{sp}$ is determined by energy balance equation. The heat transfer coefficient of the water stream α_{sp} is defined with the water stream temperature T_{sp} by the equation

$$q_{sp} = \alpha_{sp}\left(T_s - T_{sp}\right) \quad (4)$$

The values of radiation and convection heat flows are small in comparison with the conductive heat flow and heat transfer due to stream, they can be neglected. Now, equation (4) can be written as.

$$\boldsymbol{\alpha_{sp}} = \frac{s\,\lambda\,\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) - \rho\, c\, s\,\frac{\Delta T}{\Delta t}}{\left(T_s - T_{sp}\right)} \quad (5)$$

3.2. Two-Dimensional analysis

A hot metal plate Al6082 with thickness (S) 3 mm is exposed to spray nozzle in the quenching side, the temperature at the measured side can be measured and recorded through the data acquisition system. Using this measurement point temperature, the convective heat flux at the quenching surface can be calculated, while solving the non-linear heat conduction equation in inverse method. A non-iterative finite element method for inverse heat conduction problem is applied to estimate the heat transfer coefficient (HTC) at the quenching surface. Direct Problem Governing differential equation can be given as,

$$\rho c_p \frac{\partial \theta}{\partial t} = \nabla . (k \nabla \theta) \quad (6)$$

Subject to the boundary conditions

$$\theta = \theta_\infty \quad (7)$$

$$k \nabla \theta . n = q \quad (8)$$

And the initial condition

$$\theta(X, t)|_{t=0} = \theta_0(X) \quad (9)$$

Equation (6) represents the energy balance obtained from the First Law of Thermodynamics. Where ρ is the density, Cp is the specific heat capacity, and K is the thermal conductivity which are functions of temperature, and q is the temperature and space dependent normal heat flux (q) due to convection-radiation phenomenon. Applying principle variations and Euler backward time difference (Δt) method, the final form of FEM equation at current time step (n+1) with Capacitance matrix (M) is:

$$(M + \Delta t\, K)\, \theta^{n+1} = M\, \theta^{n} + \Delta t\, f^{n+1} \quad (10)$$

IHCP objective is estimation the surface heat flux at the quenched site using the measurement site temperature data. Assume that.($\tilde{Y}^{n+1}$ and $\tilde{\theta}^{n+1}$)are measured and calculated temperature vectors at the I measurement site nodes. Therefore, the instantaneous error norm is defined as:

$$\boldsymbol{S}^{n+1} = (\widetilde{\boldsymbol{Y}}^{n+1} - \widetilde{\boldsymbol{\theta}}^{n+1})^{T} (\widetilde{\boldsymbol{Y}}^{n+1} - \widetilde{\boldsymbol{\theta}}^{n+1}) \quad (11)$$

4. The Results and Discussion

The thermal properties of circular plate made of aluminum alloy AA6082 as given in Table 1.

Table 1. Thermal properties of aluminum alloy AA6082

Properties	Value	SI unit
Thermal conductivity	160	W/m/K
Density	2270	Kg/m3
Specific heat	1050	J/kg/K

During experimental cooling process the plate heated to an initial temperature of 560 °C. Then, it is cooled by sprayed water from spray nozzle. At a very high frame rate of 150 Hz, data obtained from an IR camera in the form of thermal pictures can be recorded. The thermal image data of several distinct points that are plotted on the thermal image can be transferred by the IR camera software to temperature-time data (input data of numerical solution) of these points. Twenty points from the plate center to the radial direction were chosen for this study. The distance between each point and a point is equal to two pixels (one-pixel distance 10/11 mm). Twenty spots are chosen and plotted on the thermal image of the IR cam in Figure 2. These valuable temperatures with time measurements from the IR cam are taken for these twenty points.Twenty temperature profiles for twenty points can be plotted as shown in Figure 3. It is clear that every point begins at a temperature of 560 °C. Film, transition, and nucleate boiling are the three distinctive phases of cooling that typically occur. All points pass through these phases with the existence of differences in the time of cooling. In film boiling the cooling water from the spray nozzle cannot wet the plate surface because the water evaporates immediately.

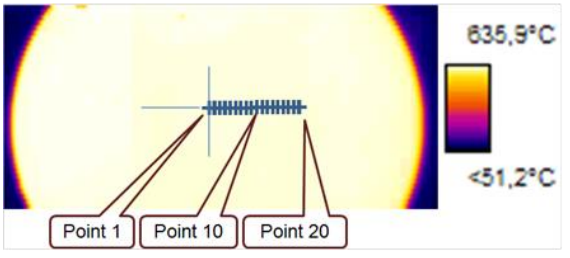

Figure 2. Twenty points selected on thermal image of IR cam

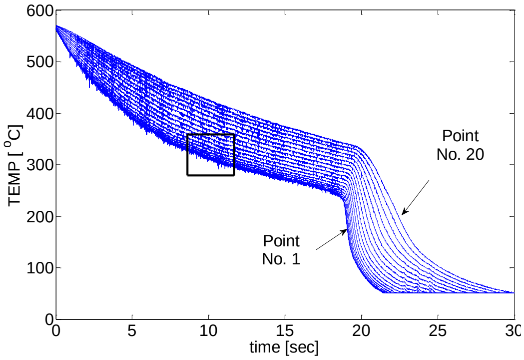

Figure 3. Twenty temperature profiles for Di water

As the plate is cooled, the amount of heat extracted follows the transition portion of the cooling curve up to the maximum value. A more reduction in plate surface temperature lead to the intensity of nucleate boiling decreases until the temperatures drops below boiling point of water Figure 4 represents a re-plotting of the area (A) in Figure 3 on a smaller scale. As the temperature profiles of the different locations become closer, minor fluctuations start to occur.

Through actual studies using a spray nozzle, it was discovered that the cause for the long cooling time and the relatively low amount of heat loss from the metal's surface was the long cooling time. The developed approach makes use of the MATLAB software program, which provides procedures for eliminating of illogical data, cleaning it up, and then using it again. This makes it easier to employ numerical solutions.

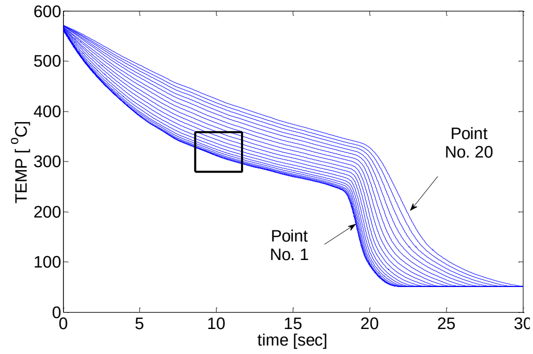

Figure 5. A revised twenty profiles for Di water

The same twenty points are shown in Figure 5 using the MATLAB program, and the temperature profiles are visible there without any fluctuations. Similarly, a repotting for the same Figure 5 with a small scale of the two axes as shown in Figure 6. To confirm the results the error of cooling rate was calculated between the two cases (revised data and not revised data) for three different points at different regions. The cooling time rate unit is temperature/time ^{0}C/sec and defined by dividing each temperature data point by its corresponding time data point, then the average all of your answers to achieve a cooling rate.

The calculation for percentage error is used to evaluate the degree of error in measured data. Here are the steps for assessing percentage error where the formula for calculating percent error is: real measured values   revised measured values / real measured values × 100 %.

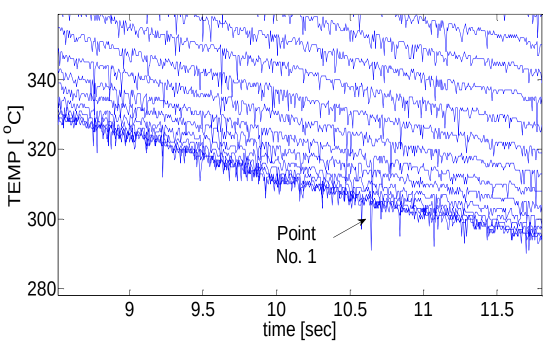

Figure 4. Temperature profiles with a small scale for Di-water

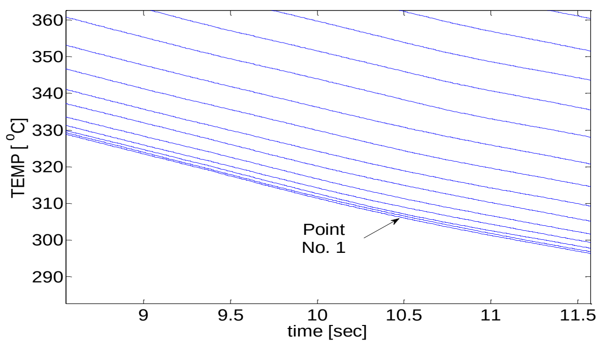

Figure 6. A revised T profiles in small scale for Di-water

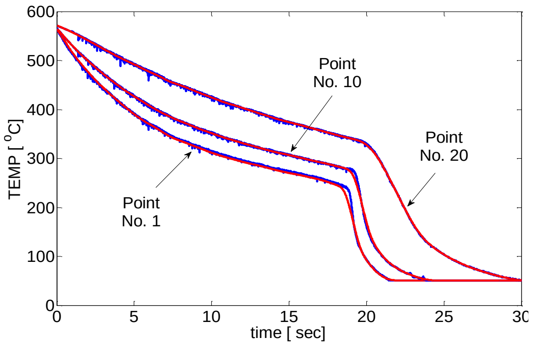

Figure 7. Three different points of measured data before and after using a revision

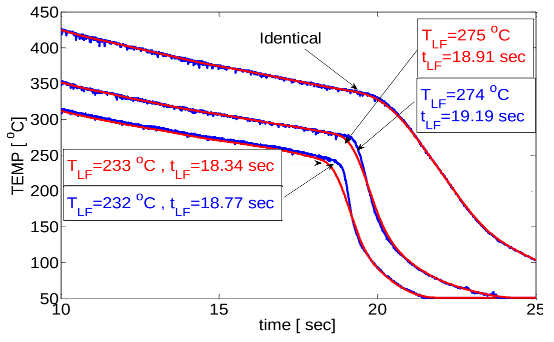

Figure 9. Errors of LFP regions of three pistons

Figure 7 shows three different points of measured data (point No. 1, point No. 10 and No. 20) are plotted and compared with the same three different points of revised data (point No. 1 is the center point). As can be seen, the trend in the data is unaffected and only the localized fluctuations and curves are identical. The percentage of cooling rate error was calculated in two important zones: film boiling region and the second zone at Leidenfrost point (LFP). Figure 8 shows real measured values and revised measured values of three points (points No.1, 10 and 20). The curves have been plotted from initial surface temperature 560 ^{0}C and extended until they reached 18 sec.

The calculated inaccuracy percentage for the film's boiling regions' cooling rates was equal to zero. While the absolute values of calculated cooling rate error at LFP regions for three points (No.1, No. 10 and No. 20) equal to 2.79%, 1.85%, and 0.0% respectively.

Figure 9. in small scale of axes shows the LFP regions of three different points of measured data are plotted and compared with the same three different points of revised data.

The results of two types of cooling water to estimate the heat flux by using 1D and 2D methods, then compare the results when measured data without revision and again when the measured data are revised. Figure10 shows the heat transfer coefficients (at the position of 5.43 mm from the center point) of Di and BF water in the film boiling region were calculated by using the 1D analysis method and then plotted as a function of the temperature. There are difficulties with the values identified, with the values at the beginnings and ends having most issues differentiating between two average values for heat transfer coefficients in two cases. In Fig. 10 generally, the heat transfer coefficient value of BF water is higher than the value of Di water, in each case it is difficult to detect exact values for the heat transfer in the film region.

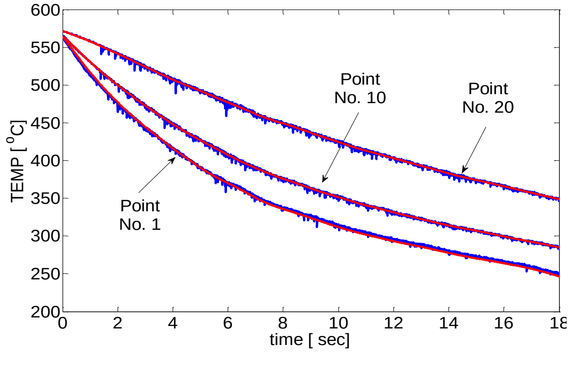

Figure 8. A real measured values and revised measured values of three points during film boiling.

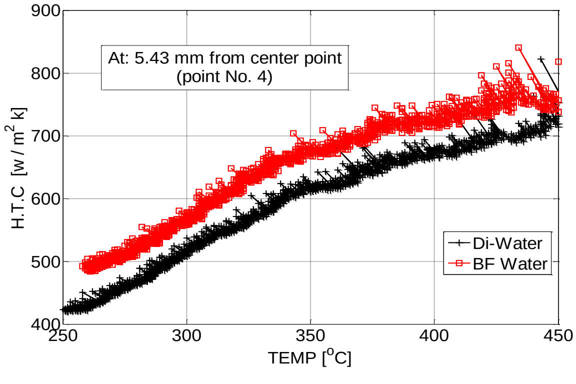

Figure 10. Heat transfer coefficients (at 5.43 mm from center point) of Di water and BF water in film boiling region

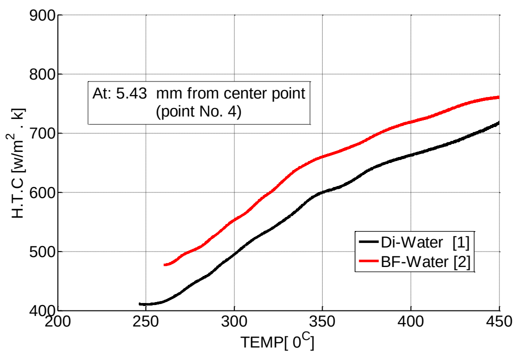

Figure 11. Heat transfer coefficients (at 5.43 mm from center point) of Di water and BF water in film boiling region

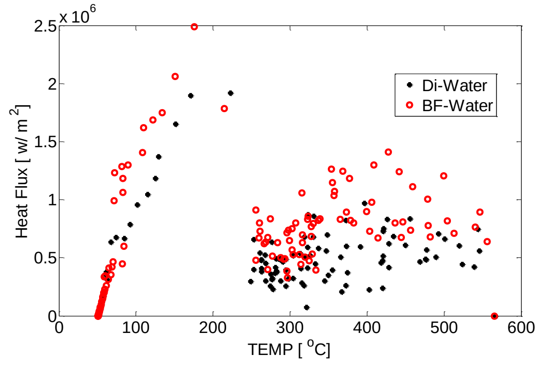

Figure 12. Heat fluxes of Di water and BF water (at 5.43 mm from center point) using IHCP method

However, it is Figure 11 shows the heat transfer coefficients at the same position of two water types in film boiling regions calculated using revised measured temperatures as inputs. At a distance of 5.43 mm from the center point, clear values could be seen for two different water types using revised data same from the two figures. It is easy to identify two average values heat transfer coefficients, and the values at the beginnings and endings. The beginnings and endings Leidenfrost temperature of Di water at position of 5.43 mm from center point is lower than Leidenfrost temperature of BF water, and also the average heat transfer coefficients is lower in case of Di water. Table 2 shows the values of LFP temperatures and HTC which inferred from Figure 11.

Two-dimensional analysis was applied to calculate the heat flux at the quenched side using the experimental revised and not revised data for two different waters. Because the temperature of the circular plate is different between the quenched and measured sides an Inverse Heat Conduction Problem (IHCP) method is used in 2D analysis where the boundary conditions are unknown and some part of the domain solution is known through experiments. At the same position, two heat flux curves of aluminum alloy AA6082 cooled by two different waters are plotted together as shown in Figure 12.

Table 2. Values of LFP and HTC

Water Type	LFP	HTC
Di Water	250	400 - 710
BF water	260	480 - 750

In Figure 12 IHCP is employed and measured data input was not revised. The typical cooling regimes: Film boiling, nucleate boiling, natural convection and the transitions in between. There are difficulties to determine and compare the flux values for two types of water as used. Determine the value of heat flux in different regions on the curve is one of the biggest difficulties. Therefore, the process is fitted but not accurate to calculate the values and compare them. IHCP method used to estimate heat fluxes of Di and BF-water together using revised measured data as input as shown in Figure 13. it is observed that the maximum heat flux is higher in case use BF-water than the case use Di water, the film boiling region more clearly, and There are no difficulties to determine and compare the heat fluxes values. The values of LFP, Critical Heat Flux (CHF), and Critical T from Figure 13 are estimated and compared as shown in Table 3.

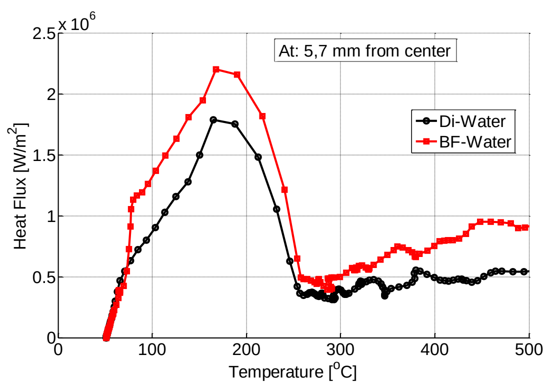

Figure 13. Heat fluxes of Di water and BF water (at 5.43 mm from center point) using IHCP method revised input

Table 3. Values of CHF and Critical T

Water type	**CHF** MW/m2	**Critical T** ºC
Di water	1.7	180
BF water	2.2	186

5. Conclusion

The experimental setup for studying and estimating the heat flux is established. The boiling heat transfer would prove most useful in an industrial setting during the DC casting process, and serve to better quenching quantify. The numerical simulation of the heat treatment processes could accelerate new procedures. Although it required validations and some modifications the simulation of the quenching process using revised data obtained with the input data of aluminum alloy AA6082 types produced a satisfactory correlation with the experimental results for all studied variables. Some improvements could be made to the measured data to make results more useful and clear without there being any differences between the results of revised data and the results without data revision. For solution accuracy, the measured data in two cases (revised and not revised) could be identical. This is demonstrated by calculating a very small percentage of error between the two cases. As seen in this experiment, there is a definite need for characterization of the measured data, as its behavior impacts heat flux estimation. This research is guiding to use of revised data for numerical solutions of heat flux.

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