Determination of heat transfer coefficient for an interaction of sub-cooled gas and metal

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Abstract. Heat transfer coefficient (HTC) for a hot metal surface and their surrounding is one of the need be defined parameter in hot forming process. This study has been conducted to determine the HTC for an interaction between sub-cooled gas sprayed on a hot metal surface. Both experiments and finite element have been adopted in this work. Initially, the designated experiment was conducted to obtain temperature history of spray cooling process. Then, an inverse method was adopted to calculate the HTC value before we validate in a finite element simulation model. The result shows that the heat transfer coefficient for interaction of sub-cooled gas and hot metal surface is 1000 W/m\(^2\)K.

1. Introduction
Heat transfer coefficient (HTC) is not a material property which performs differently within their boundary conditions. It depends on many factors such as the type of flow (laminar or turbulent), the mechanism of the heat transfer (forced or natural convection) and the nature and geometry of the body. In the other word, the HTC must be treated differently at different temperature and time. Theoretically, the HTC is defined in terms of the rate of heat flow per unit area, q and the temperature difference between the contacting media ($T - T_{env}$).

The HTC equations were derived differently based on the cooling technique that can be differentiated by two conditions; i.e. the submerged and the sprayed case. For the former, the whole work-piece undergo instant temperature drop in the fast cooling process. For the details, the related papers on this matter were discussed by Archambault and Sugianto [1, 2]. Meanwhile, the latter studies specifically use coolant that sprayed on the specific area on the hot metal surface. The important types of coolant in their researches were water or cryogenic gases. Among the related researches that can be referred were produced by Buckingham and Shokouhmand [3, 4]. Buckingham revealed that two distinct heat transfer regions exist above the dry wall temperature which are recognized as a radiation-dominated and a convection-dominated region.

Many approaches have been adopted in conducting the HTC determinations. Shokouhmand used the finite element for the HTC investigation and revealed about crack-related problem for the case of a spray-cooled surface at a high temperature. Li used the sub-cooled gas to perform a high pressure quenching and concludes the heat transfer coefficient is the main factor of affect the quenching result [5]. In the direct solution method, a FEM model may be used to calculate temperature distribution in...
the component. In the other research by Hu, he determined the heat transfer coefficient using a combination of the inverse algorithm and the finite element method [6]. In adopting the inverse method to determine the HTC, basic understanding on all the solution methods is very important. It can be easily explained by comparing between the direct solution and the inverse method for the solely case in the FEM application. Inverse method consists of finding an unknown property of a medium, from the observation of it responses to the known parameters. The temperature cooling data was used as input into the inverse heat transfer which calculates the heat flux leaving the metal plate as a function of time.

Since the analysis of the HTC becomes more important especially in the heat transfer system, a lot of programming codes have been developed related to inverse solutions. Among the known codes is an INC-Phatran as discussed by [7]. For broader application, computer software becomes the usual tools for solution of the problems related to heat transfer coefficients.

Instead of the software applications, another solution method for the heat transfer coefficient can be done by an analytical solution method. Many researchers have successfully implemented this method in their studies such as Hu, Prabhu and Nshima [8-10]. Adopting their explanation in our discussion, the proposed method basically involves calculating the temperature using an assumed value of the heat transfer coefficient and then altering that value to reduce the mean difference between the measured and calculated temperatures. The mean difference is summed over all points and over all time at which measurements are made.

2. Inverse method formulation

Starting from the basic Newton’s law of cooling, the heat transfer coefficient is expressed as;

\[ q_c = h_c \Delta T \]  

(1)

Where; \( q_c \) is the heat flux on the area of the surface that is in contact with the fluid, \( \Delta T \) is the temperature difference between the fluid and the solid surface and \( h \) is the heat transfer coefficient.

In general, \( h \) will depend on both the interfacial pressure and the mean interracial temperature. However, in order to describe the procedure being used to find \( h \), this variation will be ignored i.e. \( h \) will be treated as constant. Based on this assumption, the following error function is introduced:

\[ Err = \sum_{\text{time}} \sum_{\text{position}} (T_c - T_m)^2 \]  

(2)

where \( T_c \) and \( T_m \) are calculated and measured temperatures, respectively, at a location near to the surface where the boundary condition is unknown.

Minimizing Equation (2) with respect to \( h \), the following equation is obtained;

\[ \frac{\partial Err}{\partial h} \rightarrow 0 \]  

(3)

This implies that

\[ \frac{\partial}{\partial h} \left( \sum_{\text{time}} \sum_{\text{position}} (T_c - T_m)^2 \right) = 0 \]  

(4)

In inverse modelling, a part of calculation requires determination of the future heat flux value, \( q_{n+1} \) using the present temperatures, \( T_n \) and also the future temperature \( T_{n+1} \). By adopting the Taylor’s series approximation, it can be expressed as;

\[ T^{n+1} = T^n + \frac{\partial T^n}{\partial q^{n+1}} (q^{n+1} - q^n) \]  

(5)
Then, the partial derivative, $\phi^n$, for the Equation (5) is introduced to measure a change in the estimated temperatures with a small change. This formulation is known as sensitivity coefficient that can be calculated by:

$$
\phi^n = \frac{T_c(q^n(1+\varepsilon)) - T_c(q^n)}{\varepsilon q^n}
$$

The denominator is the difference in the $q$ values, i.e., $\varepsilon$ is a small number and was taken as 0.001 in the present investigation. Substituting equations (5) and (6) in the equation (4);

$$
\frac{\partial}{\partial h} n(\sum \sum (T_c^n + \phi^n(q^{n+1} - q^n) - T_m^2) = 0
$$

which gives

$$
\sum_{time} \sum_{position} \phi^n(T_c^n - T_m + \phi^n(\nabla q^{n+1}))
$$

Rearranging the above equation, the correction term for heat flux was obtained as;

$$
\nabla q^{n+1} = \frac{\sum_{time} \sum_{position}(T_m - T_c^n(\phi^n))}{\sum_{time} \sum_{position}(\phi^n)^2}
$$

and

$$
\Delta q = q^{n+1} - q^n
$$

The iteration of the future heat flux is continued until

$$
\frac{\nabla q^{n+1}}{q^n} < 0.005
$$

3. Experimental works

3.1. Test-piece preparation

In this experiment, the test-pieces were cut to size 100 mm x 30mm. Thirteen locations was selected as measuring point using thermocouples attached to the test-piece. Some of the measured points were considered insignificant since they were used to check proper alignment between the test-piece and the infra-red heater.

The Freon-12 is type of freezer suitable to remove heat at the fastest time since it has a very low evaporated temperature (-30°C). In this study, the volume of freezer applied on the surface was controlled consistently in all experiment by pushing the knob to maximum.

3.2. Test setup

A schematic and actual setup of the heat transfer coefficient test is shown in the Figure 1 and 2. The parabolic infra-red heater produced by Research Inc. Ltd has been used as heat source to supply energy to the bottom surface of specimen. The distance between infra-red heater and specimen were set at infra-red ray’s focal point to maximize energy supplied to the specimen. Therefore, elevated platform has been used to position the specimen height at the correct distance. In this investigation, the focal point distance between the infra-red heater to the specimen was set at 51 mm. On the top of specimen, extended plastic tube with 3 mm outside diameter fitted inside the U-plate on the top of specimen to create uniform line spray condition. The distance between the nozzle to top surface is 10 mm.
3.3. Test procedures

There are two stages of experiments had been planned. The first test was conducted to determine suitable volume of freezer should be used for maximum heat removal at the shortest time at the back surface of specimen. By this, we were able to identify optimum volume of freezer to be used for optimum temperature gradient along the part thickness. The height of the freezer nozzle was set at 15 mm above the test-piece’s top surface. Only two thermocouples have been used, i.e. at top centre and bottom area of test-piece.

It was followed by the specific identification of heat transfer coefficient value. As explained earlier, thermocouples were attached at thirteen locations on top and bottom surface as shown in Figure 3(a). The process sequence for heating and spraying the freezer is shown in Figure 3(b). The coolant spraying was started at instant t=600 sec and the top temperature was 510°C. Freezer was sprayed for 5 and 10 sec. For accuracy of the test results, the test was repeated for three times each.

3.4. Results

The first experiment result is shown in Figure 4. From the result, it is determined that due to freezer application on the back surface could assist to increase temperature gradient between top and bottom surface. In this case, the temperature difference between top and bottom surface could be increased to 200°C. Comparing between the two different time settings, spray time for 5 seconds was identified able to remove enough heat from the specimen at minimum time. As we can see in the figure, the temperature drop sharply for within two seconds before became flat at longer sprayed time. This
indicates that minimum two seconds is required for effectively cooling effect where longer spray time does not improved cooling under the tested condition.

**Figure 4.** Temperature on the heated and back surfaces during spray cooling process

In the second experiment, the objective is to determine heat transfer coefficient value for interaction between Freon12 and hot metal surface. The measured temperatures were obtained from the back surface when the freezer was sprayed on the test-piece as shown in Figure 5(a) and (b). The results show temperature at each point from their distance to the centre line. The rate of temperature drop at point T5 is higher compare to the others due to maximum volume of freezer reach the middle area. It is difficult to control the consistent flow rate of freezer because the used plastic hose is not properly cut with the width. Figure 5(b) also shows that the temperature at point T3 and T6 are almost similar due to the equal distance for both point from the middle of sprayed area. In the other case, it shows temperature drop at point T3 less than T6. This result is also explainable because the location of T3 is 5mm further from the middle area compare to T6.

**Figure 5.** The temperature measured on the back surface (a) Along the cooled area (b) At left and right location to the sprayed area.

### 4. The inverse method

This study is focused on determination of the localised heat transfer coefficient for Freon12-hot surface interaction during the spray cooling using an inversed method. It was started by an initial ho value. The calculation based on the above equation run iteratively until an error defined in eq. (10) is achieved below the selected value. An initial value used is 600w/m2K. By substituting this value into equation (1) and solving iteratively using MS-Excel, the estimation value of HTC was obtained. At the end of analysis, the estimated HTC has been revealed around 1000 W/m2K.

Generally, the obtained result consistent with some conducted studies related to the spray cooling condition. The similar test by Suganita reveals the heat transfer coefficient in the range 1200 to 3000 W/m2K [11]. In the other research, Holman reveals in his study the heat flux value for Freon-12 is between 5000 to 26000 W/m2-K [12]. It is difficult to obtain the exact heat flux dissipation value since it depends on various factors such as the distance between nozzle and the heated surface, the impacting droplets density and pressure.
This can be explained from the perspective of the forced evaporative heat transfer condition which is not much dependent on the coolant type. In this case, the coolant is not reach the hot surface example because high temperature different. The accuracy of the procedure is strongly dependent on where the temperature measurements are made. In general, the closer that these measurements are made to the interface, the more accurate will be the derived value of the heat transfer coefficient.

5. Verification of the obtained HTC value
In order to verify the reliability of the obtained result, subsequent finite element analysis was established based on the temperature history and the known heat transfer coefficient. For comparison, six selected nodal points which is at similar position in respect to the experiment have been used. Figure 6 shows the location of the selected points on the both surfaces.

![Figure 6](image)

**Figure 6.** Selected points from both experiment and simulation

5.1. The finite element model
Finite element analysis was modelled to obtain heat transfer coefficient through trial and error by comparing to the obtained temperature history in experiment work. The geometrical and the meshed model of a metal plate are shown in the Figure 7(a) and (b).

![Figure 7](image)

**Figure 7.** (a)The geometrical model (b) The meshed model

In this analysis, the thermal and mechanical properties of the test-piece exactly similar to the completed heat transfer experiment. Moreover, similar setting for the boundary condition and interaction properties had been used as implemented in the previous heat transfer analysis. Another important parameter in the model is the freezer heat flux on both of the surface. In the developed model, a heating zone at the bottom surface was set at 2 mm width. It was determined based on recommendation of manufacturer’s technical manual. The total heat flux for the heated surface is 1.18 x10^6 W/m^2-K for 6.5 mm^2 heating area and the total heat dissipation on the spray cooling area is 1.05 x 10^7 W/m^2-K for 1 mm^2 cooling area. Instead of using the Gaussian distribution method, the heat flux distribution is divided into four zones inside the heating area as in Table 1. It shows heat flux value in the respective zone as it has been used in the finite element model.

| Top Surface | Width(x10^-3) (m) | Length(x10^-3) (m) | HF value (W/m^2.C) |
|-------------|-------------------|--------------------|-------------------|
| 1st row     | 0.25              | 15                 | 1.8x10^6          |
| 2nd row     | 0.25              | 15                 | 1.4x10^6          |
| 3rd row     | 0.25              | 15                 | 1x10^6            |
| 4th row     | 0.25              | 15                 | 5x10^5            |
The analysis comprised of a heating and spray cooling steps. Initially, a plate was heated to peak temperature with the infrared heater. Total time for this analysis is equal to used heating time in the experiment. As in the experiment, the specimen was heated for 10 minutes before was cooled for 5 and 10 seconds. In this case, the targeted temperature after 10 minutes was estimated around 500°C. Then, it was followed by the cooling process by spraying the Freon-12 on the back surface. Selection of the time increments to use in calculating the behavior of the roof will affect the run time of the model and its accuracy.

Along this process, the heat flux on the heated surface was continuously activated along the process in both process steps. It is important to highlight that the main consideration of this analysis is to identify an appropriate heat transfer coefficient during the spray cooling process. The simulation result will be used in the inverse method to determine the estimated heat transfer coefficient for the spray cooling of the Freon-12 on the hot metal surface.

5.2. The results
From this analysis, the temperature histories of the selected points on the test-piece are shown in the Figure 8(a) – (c).

![Figure 8. Comparison between simulation and experiment results for the determined heat transfer coefficient at spray cooling surface= 1000 W/m².K](image)

From the graphs, it shows a good agreement between the measured temperatures and the temperatures in the finite element analysis. It is more obvious on the spray cooling surface as the main concerned in this analysis. From the Figure 8(a), the simulation result at the centre point of the spray cooling surface shows almost similar cooling rate at the initial process only. When the process continues, the simulation result shows slower temperature drop until they reach similar minimum temperature around 200°C. Similar explanation can be used for the other points as shown in the Figure 8(b) and (c) which show similar temperature pattern but at smaller discrepancies compare to the experiment result.

The obtained simulation result is acceptable under constant heat transfer coefficient. At the end of this study, it shows that optimum heat transfer coefficients can be obtained by comparing the nodal temperatures of both experimental and simulation analysis.

6. Conclusion
This study successfully obtains the HTC for interaction of subcooled gas and metal surface. An inverse method is one of suitable approach to determine the HTC. The HTC plays a major effect on determine total heat removal from the hot metal surface. The temperature drops very fast at the beginning and become constant after a few seconds. The obtained HTC value is consistent with some previous researches. It is difficult to obtain the exact value due to a lot of factors that contribute to temperature variation during spray cooling process.

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