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# A MATHEMATICAL MODEL TO PREDICT SPRAY COOLING HEAT FLUX

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## ABSTRACT

This paper analyses the spray heat flux based on energy conservation and presents a simple mathematical model to predict the spray cooling heat flux. The concept of evaporation ratio is defined. The predicted maximum heat flux is compared with published CHF data and a reasonable agreement is achieved.

## NOMENCLATURE

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|---|---|
| $C_p$ | Specific heat, J.kg$^{-1}$.K$^{-1}$ |
| CHF | Critical heat flux |
| $h_{fg}$ | Latent heat, J.kg$^{-1}$ |
| $h_L$ | Liquid specific enthalpy, J.kg$^{-1}$ |
| $h_{run\text{-}off}$ | Run-off liquid specific enthalpy, J.kg$^{-1}$ |
| $h_{sat}$ | Saturation liquid specific enthalpy, J.kg$^{-1}$ |
| $h_{vapor}$ | Vapor specific enthalpy, J.kg$^{-1}$ |
| $\dot{m}_L$ | Liquid mass flux, kg.s$^{-1}$.m$^{-2}$ |
| $\dot{m}_{run-off}$ | Liquid run-off flux, kg.s$^{-1}$.m$^{-2}$ |
| $\dot{m}_{vapor}$ | Vapor mass flux, kg.s$^{-1}$.m$^{-2}$ |
| q | Heat flux, W.m$^{-2}$ |
| $r_e$ | Evaporation ratio |
| $T_{Sat}$ | Liquid saturation temperature, K |
| $T_L$ | Liquid temperature, K |

## INTRODUCTION

In a high-pressure die casting processes, water-based lubricants are sprayed onto the die surface to lubricate as well as cool the die. Properly spraying lubricants to a die surface is very important to maximise part quality and die life as well as to reduce cycle time. Despite the importance of die sprays in high-pressure die-casting, the heat removal characteristics of the die sprays are not well understood. As a result, there is no computer software available in the market that incorporates the total simulation of the spray cooling mechanism of the die. The mechanism of spray cooling is investigated by Mesler[1, 2], Bonacina et al.[3], Choi and Yao[4], Deiters and Mudawar[5], and Yang et al.[6,7]. Due to the complexity of involved mechanisms, there has been no comprehensive model established for the heat transfer of the spray cooling process. No correlations have been developed to predict the spray cooling heat flux in high-pressure die casting process. A project currently conducted at Swinburne University of Technology, Centre for Research and Technique Development is to investigate the spray cooling process involved in high pressure die casting and quantify this process with correlations to predict the spray cooling heat flux. This paper is the first step towards this purpose.

## ANALYSIS

The physics inside the control volume shown in Fig. 1 is quite complicated. It involves the impingement of the droplets on the hot surface, the interaction among the liquid droplets, the interaction between the liquid droplets and the generated vapour, the different heat transfer regimes depending on the spray and surface conditions. The exact mechanisms involved and how each mechanism contributes to the heat transfer are still not clear.

From energy conservation, we have:

$$\dot{m}_L h_L + q = \dot{m}_{run-off}\, h_{run-off} + \dot{m}_{vapour}\, h_{vapour} \quad (1)$$

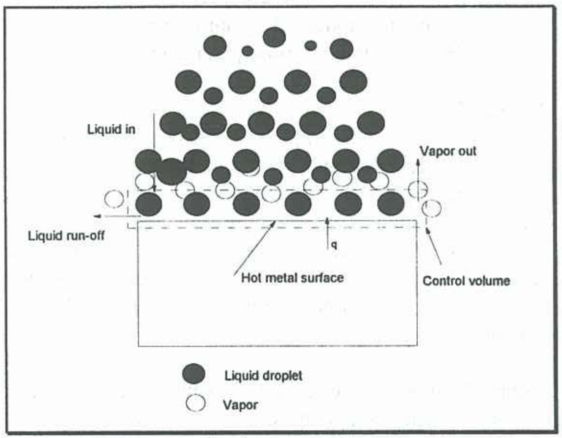

**Figure 1:** The control volume

The following assumptions are made: Firstly, vapour escapes as saturation vapour. The process is occurring at ambient pressure, and the air stagnation flow field can always blow the vapour molecule off. Secondly, in most industrial applications, the hot surface temperature is higher than the liquid saturation temperature, and therefore it is reasonable to assume that the temperature of the run-off liquid is at the liquid saturation temperature; Thirdly, the liquid specific heat remains constant throughout the process. Thus we have

$$h_{vapor} = h_{sat} + h_{fg} \quad (2)$$

$$h_{run\text{-}off} = h_{sat} \quad (3)$$

Substituting equation (2) and (3) into equation (1)

$$\dot{m}_L h_L + q = (\dot{m}_{run-off} + \dot{m}_{vapor}) h_{sat} + \dot{m}_{vapor} h_{fg} \quad (4)$$

According to mass conservation, the mass flux of liquid impinging on the hot surface should equal to the mass flux of the evaporated vapour plus the liquid mass flux that is running off.

$$\dot{m}_L = \dot{m}_{run-off} + \dot{m}_{vapor} \quad (5)$$

and then

$$\dot{m}_L h_L + q = \dot{m}_L h_{sat} + \dot{m}_{vapor} h_{fg}$$

$$q = \dot{m}_L (h_{sat} - h_L) + \dot{m}_{vapor} h_{fg} \quad (6)$$

$$h_{sat} - h_L = \int_L^{Sat} C_p(T)dT = C_p(T_{Sat} - T_L) \quad (7)$$

Substitution of (7) into (6), the following equation emerges

$$q = \dot{m}_L\ C_p(T_{Sat} - T_L) + \dot{m}_{vapor}\ \mathrm{hfg} \qquad (8)$$

Define an evaporation ratio

$$r_e = \dot{m}_{vapor} / \dot{m}_L \qquad (9)$$

which is the ratio of the evaporated liquid and the liquid impinging on the hot surface.

Substitution of (9) into (8), we have

$$q = \dot{m}_L\ C_p(T_{Sat} - T_L) + \dot{m}_L\ r_e\,\mathrm{hfg} \qquad (10)$$

Equation (10) is the basic equation to predict the spray heat flux. The evaporation ratio $r_e$ combines all the parameters involved in the spray cooling process. It is a function of the liquid properties, the droplet diameter and velocity, the liquid volumetric flow rate, the surface temperature, the surface material properties and the surface roughness. Extensive experimental investigation is currently being conducted by our group to correlate the evaporation ratio with all those parameters.

## RESULTS

Figure 2 shows the comparison between the calculated maximum heat flux at different liquid volumetric flow rates using eq. (10) assuming an evaporation ratio of 1 and the corresponding critical heat flux at the same liquid volumetric flow rates measured by Mudawar and Valentine[8]. We can see that in most cases the measured critical heat flux is in good agreement with the calculated maximum heat flux.

Figure 3 shows the comparison between the calculated maximum heat flux at different liquid volumetric flow rates using eq. (10) assuming an evaporation ratio of 1 and the corresponding critical heat flux at the same liquid volumetric flow rates at different air pressure measured by Yang et al.[7]. The measured critical heat flux is in reasonable agreement with the calculated maximum heat flux.

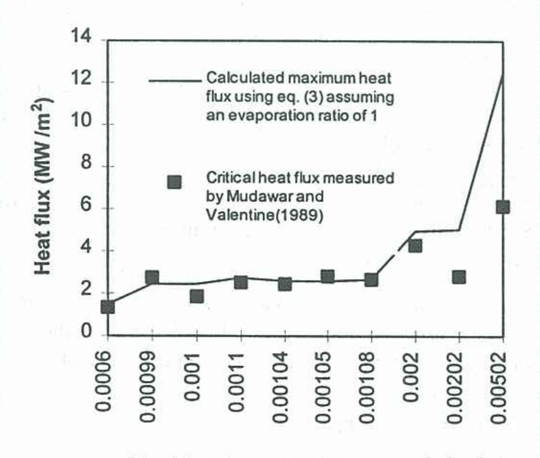

**Figure 2:** Comparison between the calculated maximum heat flux and the critical heat flux measured by Mudawar and Valentine (1989)

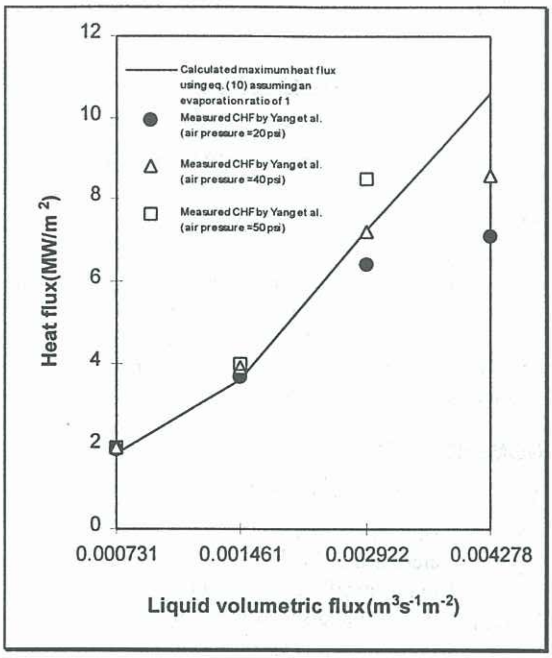

**Figure 3:** Comparison between the calculated maximum heat flux and the critical heat flux measured by Yang et al. (1993)

## CONCLUDING REMARKS

The mathematical model presented in this paper is capable of predicting the spray cooling heat flux. The evaporation ratio $r_e$ combines all the parameters involved in the spray cooling process and is currently under further research.

## REFERENCES

[1] Mesler, R., *A mechanism supported by extensive experimental evidence to explain high heat fluxes observed during nucleate boiling*, AIChE Journal, 22 (1976), pp. 246-252.

[2] Mesler, R., *Research on nucleate boiling*, Chemical Engineering Education, 16 (1982), pp. 152.

[3] Bonacina, C., Del Giudice, S., Comini, G., *Dropwise Evaporation*, Journal of Heat Transfer, 101 (1979), pp. 441-446.

[4] Choi, K. J., Yao, S. C., *Mechanisms of film boiling heat transfer of normally impacting spray*, Int. J. Heat Mass Transfer, 30 (1987) No. 2, pp. 311-318.

[5] Deiters, T. A., Mudawar, I., *Optimization of spray quenching for aluminum extrusion, forging, or continuous casting*, J. Heat Treating, 7(1989), pp. 9-18.

[6] Yang, J., Ph.D. Thesis, University of Kentucky, 1993.

[7] Yang, J., Pais, M. R., Chow, L. C., *Critical heat flux limits in secondary gas atomized liquid spray cooling*, Experimental Heat Transfer, 6(1993), pp55-67.

[8] Mudawar, I., Valentine, W. S., *Determination of the local quenching curve for spray-cooled metallic surface*, J. Heat Treat., 7(1989), pp.107-121.