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Dropwise evaporative cooling of hot water: A novel methodology to enhance heat transfer rate at very high surface temperatures

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ABSTRACT

Newly developed cooling techniques including spray cooling and air-atomized cooling are oriented on one basic phenomenon, i.e., dropwise evaporative cooling. The dropwise evaporative cooling is mainly controlled by the physical and thermal properties of the coolant and the droplet dynamics during evaporation. Different researchers have tried to enhance dropwise evaporation process by enhancing any one of the aforesaid characteristics and as consequence the achieved heat transfer rate is lower than the quenching rate required for the fast cooling operation. In addition to the above, the open literature does not disclose any methodologies, which consider simultaneously all the above-mentioned properties in the enhancement of heat transfer. Therefore, in the current research, an attempt has been made to augment the heat transfer rate in case of dropwise evaporative cooling process by altering simultaneously the thermal properties, physical properties and the flow dynamics of the droplet. The current proposed methodology to obtain fast evaporation is by altering thermal, physical and flow properties and this is achieved by increasing the water temperature. The experimental investigation considers water temperature and the substrate temperature as the independent variables. The heat transfer analysis depicts that the increment in initial plate temperature and water temperature have significant effects on evaporation time. On increasing water temperature from 10 to 60 °C, the evaporation time is reduced by ~200% due to the chances of reduction of recoiling characteristics after impingement, creation of high heat transfer area and decrement of sensible heat extraction period. With the increasing substrate temperature, the evaporation time decreases due to the increment of the thermal conductivity of the coolant. In addition to the above, the mechanism for the aforesaid enhancement process is tried to reveal by developing the mathematical models. In addition to the above, the enhancement capability of the hot water is compared with different potential coolants. From the comparison, it is concluded that the heat removal capacity of hot water is significant and it can also replace the considered coolants without depicting the disadvantages of the considered coolants in the literature. For the verification, experimental results are compared with the numerical results. The comparison discloses that the developed model is quite accurate and shows insignificant variation from the experimental results. A suitable model and vapour film thickness are also determined from the numerical investigations.

1. Introduction

The heat transfer rate in case of dropwise evaporation is controlled by the physical and thermal properties and the flow dynamics of coolant during evaporation. The physical properties such as surface tension, viscosity and density are related to heat transfer. On decreasing surface tension of the coolant, the contact angle of the coolant droplet decreases [1–8]. This process creates high heat transfer. Furthermore, the decrement of viscosity and density lead to finer atomization and this is favourable for heat transfer.

The thermal properties such as specific heat and thermal conductivity are the controlling parameter in case of dropwise evaporation. The decrement of specific heat and the increment of thermal conductivity enhance the dropwise evaporation rate by decreasing the sensible heat extraction period and increasing the conductive heat transfer rate. In addition to the above, the flow dynamics of the droplet such as recoiling behaviour and vapour bubble coalescence also regulates the heat transfer rate. The increment in the recoiling characteristic of droplet after impingement on the hot substrate and the enhancement of vapour bubble coalescence during evaporation are detrimental for heat transfer. Bernardin et al. [9] studied the heat transfer mechanism in case of dropwise evaporation at various

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conditions. They experimentally observed the above discussed phenomena during impingement and evaporation. In addition to the above, they also noticed that the substrate temperature and Weber number are the two important parameters, which decide the boiling regimes, and in turn the heat transfer mechanism. The droplet evaporation mechanism is also theoretically investigated by Baumeister et al. [10]. At very high surface temperature, the dropwise evaporation occurs through a vapour film insulating the droplet from the hot plate and this process is considered very similar to Leidenfrost effect [11–14]. Due to this, the droplet evaporation rate drastically reduces.

The dropwise evaporation is tried to enhance by various researchers by altering one or more of the above-discussed factors. Chandra et al. [8] and Qiao and Chandra [16] studied the effect of droplet contact angle with the solid surface on droplet evaporation rate by adding SDS (surfactant) to water. They reported that on reducing contact angle from 90°-20°, the droplet evaporation time was reduced by 50%. Sadhal and Plesset [17] also reported similar results. The dropwise evaporation rate is enhanced by droplet spreading which increases the heat transfer area [1]. Furthermore, the spreading of the droplet also decreases the evaporation time by reducing the height of the droplet [19,20]. The initial droplet diameter individually alters the droplet evaporation rate as reported by Crafton and Black [21]. They investigated the evaporation rate of a water droplet on aluminium and found that with increasing initial droplet diameter, the evaporation rate increases almost linearly. Chandra and Avedisian [22] investigated the collision of n-heptane droplet (fixed weber number of 43) on a polished stainless steel surface. They reported that with increasing surface temperature, population of bubbles inside the droplet increases. If the surface temperature of the substrate is high ($> 170\,^{\circ}\mathrm{C}$), then recoiling of the droplet occurs. The aforesaid reported characteristics are detrimental for heat transfer. Cui et al. [23] conducted dropwise evaporation experiments by carbon dioxide in water and found that it enhanced the evaporation rate by forming bubbles. Researchers also tried to reduce the evaporation time by increasing the thermal conductivity of water droplet by dissolving various salts such as sodium carbonate, sodium bicarbonate [23], magnesium sulphate, sodium chloride and sodium sulphate [24]. Most of the salts showed insignificant improvement in evaporation rate except sodium bicarbonate, which reduced the evaporation time by 50% to that of water. Moreover, some additives discussed earlier gets deposited on the solid surface being cooled which changes the surface profile of the metal. This sometimes alter the properties of the metal. Hence, some new alternatives are essential to be adapted for further significant enhancement of the heat transfer rate, which is appropriate for the fast cooling operations.

For the enhancement of heat transfer, the above-discussed factors are altered. Different researchers have enhanced the heat transfer rate by altering the thermal properties, physical properties or flow dynamics in the favourable directions of heat transfer. They have not altered all the factors simultaneously in the favourable direction of heat transfer; therefore, the heat transfer rate of the reported methodology becomes inappropriate for the fast cooling operation. The literature does not reveal any methodology, which enhances the heat transfer rate by simultaneously altering the abovementioned parameters in the favourable direction of heat transfer. Hence, in the current research, an attempt has been made to develop an appropriate process in which the previously mentioned alterations are possible.

One of the promising methodology is the use of water as a coolant at higher temperatures. The rise in water temperature decreases surface tension of water. This adds to the reduction of evaporation time by enlarging the heat transfer area and reducing intensity of recoiling characteristics of the droplet during the evaporation. Apart from surface tension, there are various other properties such as specific heat, density, viscosity and thermal conductivity, which are affected by temperature variation. The previously mentioned properties have significant impact on evaporation of a droplet. The sensible heating period of a droplet decreases with specific heat capacity and hence, the time required for the complete evaporation of a droplet declines. Similarly, rise in thermal conductivity of water increments the heat transfer rate, in turn increasing the evaporation rate. Moreover, the viscosity and density alteration have also significant effect on evaporation rate. As the increment of the water temperature alters the aforesaid properties in the favourable directions of the heat transfer, it is expected that the net effect of the abovementioned changes is significantly enhance the evaporation rate. Therefore, in the current work, the researchers have tried to enhance the dropwise evaporation of water droplets by varying water temperature.

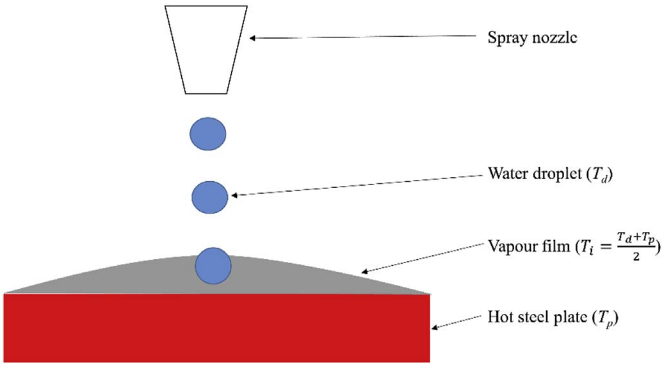

Fig. 1. Schematic view of water droplet penetrating the vapour film.

From the literature review [25–27], it can also be concluded that no research work on the modelling of evaporation of water at different temperatures are reported. Therefore, in the current work, the modelling of the aforesaid process is performed.

2. Modelling

In case of high temperature difference between coolant droplet and hot plate, the vapour formation between the droplet and the plate provides additional resistance to heat transfer and it reduces the cooling rate of the plate significantly (Fig. 1). Considering only convective mode of heat transfer taking place, a model of fast cooling of steel plate is developed with the following assumptions:

a. The temperatures of the plate and droplet vary only with time.
b. The heat loss to the surrounding is negligible.
c. Only a single drop is participated at any moment in the cooling process.
d. Droplet is assumed to be spherical in shape.
e. Temperature of the droplet remains constant after reaching the saturation temperature.

Mathematically, for a droplet,

$$\frac{d}{dt}\left(m_d C_{p_d} T_d\right) = h_d A_c (T_i - T_d) - \dot{m_v}\,\lambda;\ \text{if } T_d = T_s \tag{1}$$

$$\frac{d}{dt}\left(m_d C_{p_d} T_d\right) = h_d A_c (T_i - T_d);\ \text{if }\ T_d < T_s \tag{2}$$

Mass of droplet, m_d and temperature of plate, T_d both are varying with time. Hence, solving left hand side of Eqs. (1) and (2), Eqs. (3) and (4) can be obtained as

$$m_d C_{p_d} \frac{dT_d}{dt} + T_d C_{p_d} \frac{dm_d}{dt} = hA_c (T_i - T_d) - \dot{m_v}\,\lambda \tag{3}$$

$$m_d C_{p_d} \frac{dT_d}{dt} = hA_c (T_i - T_d) \tag{4}$$

From the mass balance of the droplet,

$$\frac{dm_d}{dt} = -\dot{m_v} \tag{5}$$