CRITICAL HEAT FLUX OF MIST-COOLING UNDER HIGH FLOW RATE AND ITS ENHANCEMENT WITH SURFACTANT

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Abstract
Critical heat flux of water-mist cooling under high flow rate is evaluated first to clarify some issues regarding further augmentation of its cooling performance. Then, surfactant-added mist cooling is performed in order to elucidate the possibilities and problems/issues regarding the use of surfactant under the high flow rate and high heat flux conditions. The water-mist cooling experiments under atmospheric pressure prove the heat removal performance of almost 10 MW/m². Evaluation of its cooling efficiency reveals that, to improve the CHF to a higher level, it is necessary to suppress formation of excessively thick liquid film on the heat transfer surface and enhance liquid supply to the surface through the liquid film. From the mist cooling experiments using some kinds of surfactant solution, it is confirmed that the addition of surfactant is effective to increase the CHF especially under the conditions of high flow rate, and much higher CHF can be achieved by adjusting the concentration of surfactant to the order of ppm.

1 Introduction
Technologies to control solid-liquid wettability have been actively developed over recent years in both heat transfer and fluid flow fields. One such a technology is a surface activation utilizing plasma, radioactive rays, and ultraviolet rays for augmenting boiling heat transfer, and the increase of critical heat flux has been confirmed [1-3]. Many such technologies also have combining functions such as disinfection, deodorization, antifouling, and corrosion control, aside from the boiling heat transfer augmentation, so that there is a lot of positive expectation for the future development. Another technology is the one that utilizes surfactant in order to control chemical structure of a solid-liquid interface. This technology, which is sometimes associated with Toms effect [4], is generally used to reduce flow resistance [5, 6]. However, adding the surfactant to liquid generally works negatively in both convective heat transfer and boiling heat transfer. As to the boiling heat transfer, since the onset of nucleate boiling (ONB) falls with decrease in the surface tension of liquid, the heat transfer coefficient will be improved in some cases. However, there has been no report on a substantial increase of CHF, to the best of the author's knowledge.

By the way, utilizing the surfactant in mist cooling [7, 8] may affect the so-called atomization: droplet velocity and droplet size that are major parameters in the mist cooling. It also affects the characteristics of a liquid film formed on the heat transfer surface under the conditions of high water flow rate, and, further, interaction between the droplets and the liquid film, to some extent. Consequently, there is a high possibility that liquid will be actively supplied toward the heat transfer surface and the CHF will increase. In addition, especially under the high heat flux in the order of MW/m², the minimum scale of boiling, the so-called microlayer, is anticipated to shift to a nanometer scale. Therefore, it can also be expected that the self-assembling function of surfactant molecules near the solid surface (e.g. formation of micelle
whose size is in a nanometer scale) will influence the physical mechanism of CHF. The boiling heat transfer by mist cooling and spray cooling is still important in industrial fields; it is frequently used not only to cool hot surfaces in the iron and steel industry, but it is also used at many other plants because of its ease of application. Many researchers have studied the fundamental boiling heat transfer of mist cooling in order to control the wall temperature under relatively low heat loading conditions. It seems that data on the boiling heat transfer characteristics, including the CHF, under high heat flux of several to several dozen MW/m², which inevitably brings to high water flow rate condition, are insufficient at present.

Against this background, this research into the use of surfactant for the mist cooling first evaluates the CHF characteristics of water-mist cooling under the high flow rate, and then evaluates the CHF characteristics in the case that the surfactant is added in the water mist. The purpose of this study is to clarify the possibility for using the surfactant in the mist cooling, and the problems and the issues arising are also looked at.

2. Mist Cooling Experiment

2.1 Details of Experimental Apparatus and Test Section

Figure 1 shows the outline of experimental apparatus. The apparatus is composed of a power supply, a mist generator, a data measuring system, and a test section. The working fluids are ion-exchange water and air. The water in a stainless steel pressure tank, which is pressurized by an air compressor, is mixed with compressed air, which is supplied from a separate line from the same compressor, and atomized in the nozzle and then injected as an impinging jet. The nozzle is an internal mixing type of two-fluid nozzle, which has good atomization performance: higher droplet velocity and a wider range of water-flow rate adjustment. Nozzles with different outlet areas (Type A, B, C) are used in accordance with the water flow rate. The nozzle is installed vertically downward, and the horizontally installed target, i.e. a heating body, in the test section, is cooled from above. The mist from the nozzle collides with and cool the target, and then be separated into water and air by a mist trap inside a drain pipe and retrieved separately.

The target in Figure 2 is a nichrome foil, which has good thermostability, corrosion resistance and oxidation resistance, and electrically heated by conducting direct current from copper electrodes that also fix the foil. The nichrome foil is 5 mm in width and 50µm (or 30µm) in thickness. The thickness appropriate for the heat flux level is selected. The surface area of the nichrome target is 208.33 mm². To measure the temperature of the target, three sheathed thermocouples of 0.5 mm in diameter are fitted onto the back surface of foil. Two D.C. power supplies are connected in parallel by master-slave controls, and they are used as constant-voltage regulated power supplies in consideration of the foil's temperature stability against any perturbation.
The maximum current is 100A. Heat loss from the target toward the electrodes and the fixed block, which is heat- and electricity-insulating polytetrafluoroethylene (PTFE), is about 2W when the target temperature is 130°C, which is equivalent to 0.33% or less of thermal dose in this experiment, and can be ignored.

2.2 Experimental Conditions

In order to uniformly cool the rectangle target, the nozzle-target distance is fixed at 53 mm, with consideration given to the injection pattern (sector type), the injection angle and the distribution of droplet impinging force. The water and air flow rates, which are macroscopic factors for the mist cooling characteristics, are in principle determined by water and air pressures. In this experiment, the air and water pressures are so determined that the water volumetric flux \( w \) will be 500, 1000, and 2000 [L/m²/min]. This water volumetric flux \( w \) was measured by sampling the mist with a container with a slit, the same shape and size as the target, at the same location as the target. The air flow rate from the nozzle, \( Q_a \) [L/min.] is measured by an area flowmeter installed between the air compressor and the nozzle. On the other hand, to identify the influences of microscopic factors such as the droplet velocity and the size on the CHF characteristics, it is necessary to change them while maintaining a constant water volumetric flux. Therefore, the influence of droplet velocity and size are evaluated by changing the nozzle type and the air pressure at a constant water volumetric flux. In doing this, it is desirable to establish a predictive equation of droplet size and velocity beforehand. First, the droplet size is generally determined by volume ratio of air to liquid (air flow rate/water flow rate), so that it becomes smaller as the ratio becomes higher. In this experiment, the following predictive equation is established by organizing the droplet size measured by a Fraunhofer diffraction method as Sauter mean diameter \( d_{32} \), with findings on the two-fluid nozzle by Tanazawa et al. [9, 10], J. Gretzinger et al. [11], and K.Y. Kim et al. [22] as a guide.

\[
d_{32} = \frac{135.86 (Q_a / Q_l)^{0.2331}}{(86.135 - Q_a Q_l)}
\]

Here \( Q_a \) and \( Q_l \) represent air and water volumetric flow rates [L/min.], respectively. In this eq., effect relating to the relative velocity between the droplet and the air were ignored because it is expected that the air flow velocity is sufficiently high and the droplets sufficiently responsive to the air flow. The water flow rate \( Q_l \) [L/min.] is, unlike the water volumetric flux \( w \), the volumetric flow rate of all water injected from the nozzle. It is calculated based on the time necessary to inject all water in the water pressure tank. The droplet size generated under this experimental condition is approximately 20 ~ 50μm. Regarding the velocity of these minute droplets, velocity data obtained with a Laser Doppler Velocimeter are organized using the air volumetric flow rate as follows.

\[
v = 3.1896 Q_a^{0.4998}
\]

The droplet velocity in this experiment is approximately 30 ~ 50m/s.

The inlet temperature of the mist affects the heat transfer and the CHF as the degree of subcool \( \Delta T_{\text{sub}} \). Therefore, the mist is injected for 30 seconds or longer to measure the temperatures of nichrome foil as the inlet temperature of mist before starting to heat the foil. The actual inlet temperature is approximately 20±3°C, that is, the degree of subcool \( \Delta T_{\text{sub}} \) is approximately 80°C.

2.3 Experimental Procedure

Firstly, the air and water pressures are controlled with a pressure control valve to obtain the desired mist flow, i.e. the air and water flow rates. The current to heat the target is increased in steps, and, at each step, the stability of voltage and target temperature shall be confirmed before increasing the current to the next step. This procedure is repeated until the target will be burned out, and the critical heat flux, \( q_{\text{CHF}} \), is calculated based on the product of averaged current and voltage values during the 10 seconds immediately before the burn-out. All data, including voltage drop at the
target, current value that is calculated from voltage drop at a shunt, and the temperatures of target are stored in a computer via an A/D conversion board by differential input. Figure 3 shows an example of monitoring data obtained during the experiment, the last steady state, namely the area marked by the thick line in the figure, is necessary to estimate the CHF.

3. Results and Discussion

3.1 Influences of Air Flow Rate and Water Volumetric Flux on Critical Heat Flux

First, influences of the air flow rate and the water volumetric flux, which are the macroscopic factors in the mist cooling, on the CHF are discussed. Figure 4 represents the influence of air flow rate on the CHF characteristics at each water volumetric flux. Cooling data under a single-phase condition: air flow only, is also shown for comparison. It is obvious that the mist cooling performs far better than the cooling by the air flow only and that the addition of droplets enables highly efficient utilization of the thermal potential of latent heat of vaporization. Most cooling data under these experimental conditions have a heat removal performance of several MW/m² (maximum 8.65MW/m²). Furthermore, the higher the air flow rate, the higher the heat removal performance becomes at every water volumetric flux. At the water volumetric flux of 500L/m²/min., however, the influence of air flow rate is not so apparent compared to the other two water volumetric fluxes. As mentioned before, the air flow rate highly affects the droplet velocity and size, so that it is expected that the influence of droplet size and velocity is not so significant in the case of low water volumetric flux, compared to the cases of higher water volumetric flux. Figure 5 shows the CHF organized by the water volumetric flux. This figure also includes the data for lower water volumetric flux obtained previously [13]. It demonstrates that the CHF strongly depends on the water volumetric flux. Dispersion of data at each water volumetric flux is thought to contain the information on the droplet velocity and size. The following equation was obtained by approximating the CHF data with the water volumetric flux using the least-squares method.

\[ q_{\text{CHF}} = 0.7967w^{0.2876} \]  

Further, the data indicates that the higher the water volumetric flux, the gentler the increase of CHF becomes. To find the cause of this, the experimental data are compared with four straight-lines in the figure, namely A: sensible heat from 20°C to 100°C, B: sensible heat + latent heat of vaporization, C (and D): heat quantity added heat-removal quantity by the air flow to A (and B). In the area where the experimental data are higher than the straight-lines A and C (Area X: w<1000L/m²/min.), it is
obvious that the latent heat of vaporization is utilized effectively by vigorous phase change on the heat transfer surface. On the other hand, in the area where the experimental data are lower than the straight-lines A and C (Area Y: $w > 1000 \text{L/m}^2\text{min}$), it is suggested that while high water flow rate is required to remove high heat flux, a significant amount of water overflows without contributing to the boiling heat transfer. It means that a thick liquid film must be formed on the heat transfer surface under this condition. The discussion becomes clearer by evaluating a cooling efficiency $\varepsilon$ that is defined as the proportion of actual heat removal quantity against potential heat removal quantity by the latent heat, as shown below.

$$\varepsilon = \frac{q_{\text{CHF}}}{\rho_l w \Delta h_{fg}}$$  \hspace{1cm} (4)

Here $\rho_l$ represents density of water [kg/m$^3$], and $\Delta h_{fg}$ latent heat of vaporization [J/kg]. Changes in the cooling efficiency against the water volumetric flux are shown in Figure 6. The CHF in eq. (4) is calculated based on the eq. (3). It shows that the cooling efficiency shows a high value of 0.873, close to 1, in the case of extremely low water volumetric flux of 69 L/m$^2$/min. It clearly suggests that it is the most ideal heat removal condition where the amount of water, that has almost the same thermal potential as the thermal dose, is supplied to the heat transfer surface. In this case, conceivably the liquid film is either not formed on the heat transfer surface or it is very thin. In such a heat transfer regime, including the area X, single-droplet information might remain strongly, but it is clearly a phenomenon in a wetting region, so that supposedly it does not show very much dependency on We number, namely the droplet size and velocity. This is the reason why the data at the water volumetric flux of 500L/m$^2$/min. show a different tendency from the data of other water volumetric fluxes in Figure 4. The cooling efficiency declines sharply with the increase of water volumetric flux, namely 0.48 at $w = 167 \text{L/m}^2\text{min}$, 0.22 at $w = 500 \text{L/m}^2\text{min}$, and 0.08 at $w = 2000 \text{L/m}^2\text{min}$, the maximum water flow rate condition. In this case, an excessively thick liquid film could be formed on the heat transfer surface, so it is thought that the interaction between the liquid film and the droplets strongly influences the liquid supply toward the heat transfer surface. It is, therefore, not realistic to further increase the water volumetric flux to remove higher heat flux. To cool heat flux of several dozen MW/m$^2$ in a more efficient and economic manner, it is important to suppress the formation of excessively thick liquid film on the heat transfer surface and the overflow, and to identify the conditions for the optimal droplet size and velocity to supply the amount of mist, that has a thermal potential equivalent to the thermal dose, to the heat transfer surface.
Alternatively, innovative technologies should be developed.

3.2 Influence of Droplet Velocity and Size on Critical Heat Flux

Figure 7 shows the influences of droplet velocity on the CHF. It can be observed that the CHF increases with the increase of droplet velocity, especially at the water volumetric flux of 1000 and 2000 L/m²/min. The inclination of the approximation straight-line at the water volumetric flux of 500 L/m²/min is different from the other ones, as in Figure 4. It is thought that the influence of the droplet velocity decreased at w=500L/m²/min. as it is a heat transfer phenomenon in the wetting region though a single droplet strongly contributes to the liquid supply to the heat transfer surface, as mentioned before. To the contrary, a thick liquid film is formed in the case of the other two high water volumetric fluxes, and the interaction between this liquid film and the droplets is an important factor that affects the liquid supply. Due to the characteristics of the nozzle used in this experiment, the droplet size is inversely proportional to the droplet velocity, which makes systematic discussion difficult because the droplet size becomes smaller as the droplet velocity increases, even at the same water volumetric flux. Nevertheless, the CHF increases with increasing the droplet velocity, so that it can be said that the droplet velocity, not the droplet momentum, has a very strong influence on the interaction between the droplet swarm and the liquid film. Figure 8 shows the influence posed by the droplet size on heat transfer coefficient at the CHF. The heat transfer coefficient increases as the droplet size decreases, but systematic discussion is difficult, even if coupled with Figure 7, for the above mentioned reason. However, under the conditions of this experiment, it is apparent that the increase in droplet size works negatively against the CHF. It is important to generalize the optimal droplet velocity and size conditions in order to drastically improve the CHF.

3.3 Establishment of Predictive Equation on Critical Heat Flux under High Flow Rate

Here various factors involved in the CHF of mist cooling are reexamined in order to establish a predictive equation with regard to the CHF of several MW/m², provided that the degree of subcool is 80°C. In mist cooling, not only the water volumetric flux, the droplet size and droplet velocity, which are evaluated in this study, but also number density of droplet [1/m³] that reflects the collective effect of droplet swarm, as well as We number that represents interaction between the droplets and the liquid film, not the heat transfer surface, are thought to be effective. However, the collective effect of droplets is included in the water volumetric flux, and as to the We number, it is desirable that it
shall be introduced after quantitative evaluation of the interaction of a single droplet with the liquid film. Thus it is assumed that these factors should be included in the water volumetric flux, the droplet velocity and the droplet size at present. On the other hand, in a multiple regression analysis, mutually correlated factors will be avoided to use together simultaneously. As mentioned before, the influence of droplet velocity, rather than the influence of droplet size, is dominant in the range of this experiment. Furthermore, research by Takimoto et al. [14], Toda [8], Chen et al. [15], and Nishio et al. [16] show that there are few cases where the influence of droplet size is remarkably apparent. Accordingly, the influence of droplet size is supposed to be included in the water volumetric flux $w$ and the droplet velocity $v$, so that the droplet size is excluded from the evaluation. Results by the multiple regression analysis are shown in Figure 9 and the regression line is represented by the following equation.

$$q_{\text{CHF}} = 0.02541 w^{0.298} v^{0.304}$$  \hspace{1cm} (5)

More than 90% of experiment data on the CHF fall in the range of ±15% from the regression line, and can be sufficiently evaluated by the water volumetric flux and the droplet velocity. To establish a more accurate predictive equation, it is necessary to evaluate the CHF in each heat transfer regime of mist cooling mentioned before. Therefore, a regression analysis was performed only under the high water volumetric flux condition that has a relatively large number of data (1000 $< w <$ 2000). The result is shown in Figure 10. It shows that most data is in the range of ±15% from the regression line

$$q_{\text{CHF}} = 0.051 w^{0.399} v^{0.563}$$ \hspace{1cm} (6)

It is interesting in observing convergence of data to the line under higher flow rate and further a tendency similar to the one obtained by Nishio et al. regarding the CHF under the high water flow rate conditions, namely the CHF is proportionate to the 0.33rd power of water volumetric flux and showing strong dependency on the droplet velocity [16]. More accurate prediction will be possible with more data on the water volumetric flux.

4 Enhancement of the Critical Heat Flux by Adding Surfactant

4.1 Surfactant

Surface activation is a phenomenon that significantly changes the properties of interface, and surfactant is any substance that produces the surface activation by the surfactant molecules gathering at the interface between two phases. The surfactant has hydrophobic group and hydrophilic group in the molecule and can be classified into anionic surfactants, cationic surfactants, nonionic surfactants, and
ampholytic surfactants according to the type of hydrophilic group. When dissolved into water, the surfactant molecules are in a monodispersion state first, and then the hydrophobic groups try to escape from the water molecules and form a monolayer at the gas-liquid and solid-liquid interfaces. In particular, in the case of solid-liquid interface, a hydrophilic adsorption layer is formed on the solid surface, with the hydrophilic groups facing the liquid side, which improves wettability of the solid surface. As the concentration of surfactant increases, the number of interface absorbing molecules increases, and when it exceeds the critical micelle concentration (cmc), the hydrophobic groups get together and form a molecular aggregate such as micelle in the order of several nanometers. Generally, because of the surface activation as described above, water added the surfactant has a lower surface tension. Shown below are the expected advantages of using the surfactant in the mist cooling.

1. Reduced pressure loss in a water transportation line by Toms effect
2. Improved atomization performance brought by lower surface tension (change in droplet size and velocity)
3. Suppression of excessively thick liquid-film formation and overflow at a high water flow rate and Supply of the amount of mist with the same thermal potential as thermal dose to the heat transfer surface
4. Augmentation of nucleate boiling heat transfer by accelerated vapor bubble formation brought by decreased surface tension
5. Active supply of liquid to the heat transfer surface brought by higher solid-liquid wettability

When such factors intricately influence each other, interaction between the liquid film formed on the heat transfer surface and the droplets becomes more active, which might produce unexpected effects.

4.2 Mist Cooling Experiment using Surfactant-Added Water

The surfactant first used in this experiment is JEMTECH's SC-1000, a nonionic surfactant. Table 1 shows the physical properties and features of SC-1000. It includes glycerine fatty acid ester, sorbitan fatty acid ester, polyoxyethylene sorbitan fatty acid ester, polyoxyethylene fatty acid ether and fatty acid glucoside etc, but exact composition is unknown. First, a cooling experiment is performed using the surfactant solution of ion-exchange water and SC-1000 in a 50:1 ratio. The decomposition temperature of SC-1000 is supposedly 348ºC or above, so that the thermal decomposition will not occur in this experiment. Table 1 suggests that specific gravity, boiling point and specific heat do not change significantly at this mixture ratio. However, when looking at droplets of ion-exchange water and surfactant solution placed lightly on a nichrome foil (see Figure 11), a substantial decrease in surface tension can be confirmed. Accordingly, this concentration is supposedly well above the critical micelle concentration.

Figure 12 shows how the addition of surfactant influences the CHF. Although it was expected that the addition of surfactant would bring increase of CHF, the CHF is almost the
same or lower than the water-mist cooling. A possible reason for this is foaming resulting from the addition of surfactant. As vigorous foaming of surfactant solution was observed when it collided with the heat transfer surface in the experiment, it would appear that the foaming hindered the liquid supply toward the heat transfer surface. It is also possible that a decrease in the surface tension accelerated transition to the CHF. To cope with this problem, an experiment using the surfactant solution whose concentration was decreased to the order of ppm to suppress the foaming was carried out. The results are shown in Figure 13. The nozzle used in this experiment is Type A with the lowest water flow rate, and only the water pressure is adjusted with the air pressure fixed at 0.5MPa. In addition, several types of other surfactants, which are frequently used for the drag reduction and other purposes (ethanol, butanol, SDS, HC, etc.), were also tested apart from SC-1000. Results show that while the CHF is almost the same as that of water-mist cooling under the conditions of low water pressure, i.e. at a lower water flow rate, drastic improvement of CHF is observed at a high water flow rate (e.g. 1.4 times higher than the water mist at the \( P_{\text{water}} \) of 0.35MPa in a case of SDS). This increase in the CHF at the same water pressure suggests that decrease in the surface tension reduced the liquid film thickness, and coupled with the interaction with droplets, effectively augmented the liquid supply to the heat transfer surface. There are other possible reasons, such as the assembled structure of surfactant molecules in the microlayer worked favorably, but it is not clear and there is much of value to be learnt from future study.

5. Conclusion

In this study, the critical heat flux of mist cooling under high flow rate was evaluated first to clarify some problems regarding further augmentation of the cooling performance. Then, several types of surfactant solutions were introduced to evaluate the CHF of each surfactant-added mist in order to grasp possibilities and problems/issues regarding the use of surfactants in the mist cooling under high heat flux conditions. Findings are summarized as follows:

1. Water-mist cooling experiments under atmospheric pressure demonstrated heat removal performance of maximum 8.65 MW/m².
2. Evaluation of cooling efficiency revealed that, to improve the CHF to a higher level, it is necessary to suppress excessively thick liquid-film formation on the heat transfer surface and enhance liquid supply to the surface through the liquid film.
3. Experimental formula applicable under high water flow rate and high heat flux conditions (several MW/m² level) were established, using water volumetric flux and droplet velocity as the parameters.

4. Mist cooling experiments using some kinds of surfactant solution revealed that addition of surfactant is effective, particularly under the conditions of high heat flux, and very high CHF can be achieved by adjusting the concentration to the order of ppm.

The main advantages of using surfactants are, (1) addition of a small amount of surfactant can significantly improve cooling performance and, (2) flow resistance declines significantly. This suggests that it is possible to drastically improve economic efficiency of various existing cooling systems without large-scale modification of the equipment. It is important to evaluate detailed characteristics of heat transfer coefficient and CHF of surfactant-added mist cooling in order to define the surfactant suitable for the heat removal and its optimal conditions such as concentration etc. More microscopic analyses also seem necessary, including evaluation of the influence of assembled structure of surfactant molecules at the optimal concentration on the physics of CHF.

References