Effect on the Adhesion of Ice to Characteristic of Cooling Surface and Composition of Aqueous Solution

Jae-Kyoung Suh¹, Hyun Seung¹, Jong-Hyeon Peck², Hiki Hong³ & Chaedong Kang⁴

¹Graduate School of Mechanical Engineering, Chonbuk National University, Jeonju 561-756, Korea

² HVAC/R Research Team, KITECH, Korea

³ School of Mechanical and Industrial System Engineering, KyungHee University, Yongin 449-701, Korea

⁴ RCIT., Division of Mechanical Engineering, Chonbuk National University, Jeonju 561-756, Korea

Keywords: Ice adhesion, Ice slurry, Conversion coating, Additive, Cooling heat transfer rate

Abstract: The phenomenon of ice adhesion or cohesion extremely affects to the decrease of the performance of ice making system, especially to dynamic typed ice thermal storage system(DISS) which mainly forms ice from the flow of an aqueous solution. The ice adhesion is influenced by various parameters concerning with operating or geometric condition. In this study, the effect on the adhesion of ice to the characteristic of cooling surface and to composition of an aqueous solution was fundamentally observed by using batch type cooling device, a beaker. Three patterns of solution in each beaker were cooled with brine. Moreover, the characteristic of cooling surface on each beaker was distinguished to coating materials. Stirring power as the scale of the ice adhesion was measured. In order to compare the stirring power to each beaker cooling heat transfer rate was introduced. At results, the lowest stirring power of 8.9 watts with non-adhesion of ice, occurred to the aqueous solution of EG(4)+PG(1.5)+1,6HD(1.5) in PE coating beaker.

1. Introduction

In dynamic typed ice thermal storage system(DISS) which forms ice continuously on cooling wall, flowing ice, so called ice slurry, is mainly formed. The ice slurry of small particle size has a large heat transfer area, i.e. very rapid response of heat transfer is expected. Moreover, the ice slurry due to fluidity is possible to transport larger cold thermal energy than cold water per unit hour. At present, the diversity has been shown in the field, such as district or industry cooling system, foodstuffs freezing and chilling system, and medical treatment application.⁽¹⁾ However, sudden occurrence of ice adhesion on cooling surface and blockage in tube flow negatively acts to the stability and initial cost-down of the DISS.

Ethylene glycol (EG) or Propylene glycol (PG) as a brine of alcohol, miscible to water has a structure of hydrocarbon group and hydroxyl (EG: HO-CH₂-CH₂-OH, PG: Ch₃-CH-OH-CH₂-OH). And the additive, silane coupling agent (SCA: C₉H₂₃N₂O₃ Si) is wellknown as the substance to suppress the ice adhesion, intervening between inorganic and organic compound or water.^(2,3) Up to the present, most freezing experiment of aqueous solution has been carried out with additives like of the EG, the PG or the SCA, which was reported to ice formation, heat transfer in batch cooling and ice fraction in slurry flow.⁽³⁻⁵⁾ Especially, it was clarified that the concentration of solution and cooling temperature have relations with the ice adhesion on cooling wall or the ice cohesion between ice particles.⁽⁵⁾

1,6-Hexanediol (1,6-HD; 1,6-Dihydroxy-hexane; Hexamethylenediol) is an environment friendly substance rather than the SCA, which has polyalcoholic property. The 1,6-HD has similar structure of the EG, i.e. hydroxyl ion (-OH) is sticked to both sides of hydrocarbon group in element structure (HO-CH₂-(CH₂)₄-CH₂-OH).⁽⁶⁾ Therefore, the 1,6-HD is expected to suppress hydrogen bonding in water, because it has relatively large size of C_mH_n group. Meanwhile, it is well known that nonmetal material such as fluorine resin is hydrophobic material with low friction.⁽⁷⁾

In this paper, an experiment has been performed to investigate the effect of the composition of an aqueous solution and of the characteristic of cooling surface to the ice adhesion. The cooling surface has nonmetal coating such as fluorine resin - Polytetrafluoroethylene (PTFE), Perfluoroalkoxy(PFA) or a plastic - Polytethylene(PE).

2. Experiments

Figure 1 shows the experimental apparatus for ice formation with measurement system. It consisted of low constant temperature bath, stirrer, beaker for vessel of ice slurry formation and measuring equipment for temperature, stirring power.⁽⁵⁾ Beaker with a solution was stirred to 120 rpm by the stirrer(impeller type: perpendicular plate, 3×2 mm², 3 airfoils) and was cooled in the low temperature bath filled with brine which was maintained to -7.5°C. The beaker was insulated at top mount. In order to obtain cooling heat transfer rate the temperature of the solution and the



Fig. 1 Schematic of the experimental apparatus

brine was measured with T-type thermocouple (ϕ 0.3 mm) during cooling. Moreover, stirring power as the scale of the strength to ice adhesion was measured. The cooling was continued to supercooled region of solution. Compulsory dissolution was given by putting ice particles of less than 1 g into the supercooled solution when the solution temperature reached to the target supercooling degree of 1 K.

Three types of component ratio to aqueous solution were used as following; EG 7 mass % one (solution 1), EG 4 + SCA 3 mass%(solution 2) and EG 4 + 1,6-HD 1.5 + PG 1.5 mass%(solution 3). Total mass fraction of additives for each solution of 300 g was fixed to 7 %. Table 1 shows each component ratio of solution.

Table 2 shows a part of the thermophysical property of coating materials. It is remarkable that the dynamic coefficient of friction and critical surface tension of the fluorine resin are smaller than those of the PE and SS. Beakers used in the experiment are shown in Fig. 2, which consisted to a stainless steel(304SS) base one and to three others with conversion coating based on 304SS. The coating was done on base beaker (75 × 120 × 1 mm³ (D_o × H × t), 500 ml) with PTFE, PFA and PE that treated by electric resistance and conversion coating (electrochemical treatment of the metal surface) below 100 μ m thickness.

The cooling heat transfer rate to beaker has relations with ice formation, i.e. ice amount in solution. Time average of cooling heat transfer rate was calculated



Fig. 2 Picture of the inside of coating vessel

 Table 1 Component ratios of three aqueous solutions

 (mass%)

Solution No.	EG	SCA	PG+HD	Water
1	7	-	-	93
2	4	3	-	93
3	4	-	3 (PG1.5,HD1.5)	93

 Table 2 Thermophysical property for coating ⁽⁸⁾

Material Property	PTFE	PFA	PE	304SS
Thermal conductivity [W/m·K]	0.25	0.25	0.33	16.3
Dynamic coefficient of friction	0.04	0.08	0.08 ~0.18	0.19
Critical surface tension [dyne/cm]	18	18	31	47

with equation (1). In the equation, the amount of ice at a time was expressed to equation (2). Also, the concentration of the solution in ice slurry was presumed from the measured freezing point of the solution, which was approximated with a first order function of freezing point as equation (3).

$$\overline{q} = \frac{1}{\Delta \tau} \left[(m_{ice,n} - m_{ice,n-1}) L_{ice} + m_s \overline{C}_s (T_{fp,n} - T_{fp,n-1}) \right]$$
(1)
$$x(\tau) = x_n = \frac{m_a}{m_{total} - m_{ice,n}} \times 100 [\%]$$

where $m_{total} = m_w (0) + m_a$, $m_a = m_{FG} + m_{SCA}$ (2)

$$u_{\alpha}$$
 u_{α} u_{α

$$T_{fp,n} = Ax_n + B$$

(EG, EG + SCA soln.: A = -0.35, B = 0.068)
(EG + PG + HD soln.: A = -0.35, B = 0.36) (3)

3. Results and discussion

3.1 Freezing of solution

Figure 3 shows the time history of temperature for the solution 1(EG 7 mass % aqueous solution) cooling with stirring power in stainless steel (304SS) beaker. The solution was dissoluted compulsorily when it reached to supercooling degree of 1K. During one hour from the dissolution the stirring power increased. At the time of 2 hours 30 minutes from the dissolution, the settlement of stirring power was shown to 12 W, which follows the easement of ice formation due to the decrease of temperature difference between an aqueous solution and brine. At the end of cooling the ice slurry was discharged from the beaker by inclining the beaker. Therefore, it was estimated that non-adhesion of ice occurred. It was compared that the stirring power increased 15 W above when the ice adhesion occurred to cooling wall.



Fig. 3 Time history of temperature and stirring power for solution 1(EG 7 mass%, SS beaker)

3.2 Ice formation to component ratio and cooling surface

Although the data of stirring power to the solution 1 with PTFE or PE coating wall was not shown, the maximum stirring power in the solution 2 was smaller 1 W than that in the solution 1. Thus the SCA is more effective to suppress the ice adhesion on the polymeric coating wall than on the metal one. Figure 4 shows that the stirring power increased as the time average cooling heat transfer rate increased. However, the stirring power decreased at the end of freezing process because the concentration of solution correlated to the growth velocity of ice particle, i.e. non-uniform ice particle might be uniform with the decrease of cooling heat transfer rate. Unfortunately, it was not confirmed because the time variation of the particle size distribution of ice was not measured with the restriction of measurement system.

In Fig. 5(solution 3) the falling of the stirring power after the maximum point was greater than that in Fig. 4(solution 2). The final stirring power was 8.9 W. Therefore, it is more effective on the polymeric coating wall to suppress ice adhesion and to make more uniform particle size with 1,6-HD than with the SCA. Figure 6(a) shows the picture of the ice slurry with the

solution 3 (1,6-HD with PG) at the end of cooling in the PTFE coating beaker. And Fig. 6 (b) shows when the ice slurry poured out.

Among the maximum stirring power, the lowest power of 10.3 W was shown to the solution 2 with the PTFE coating beaker at the time average heat transfer rate of 15.5 W. Moreover, a lower stirring power of the solution was shown in the PTFE coating beaker with the dynamic coefficient of friction comparatively lower than that of the PFA. On the other hand, the stirring power of the PTFE coating was lower than that of the PFA one, though the thermal conductivity, the dynamic coefficient of friction and the critical surface tension in the PTFE are higher than those in the PFA one. The result was against the experimental expectation. The contribution of the thermal conductivity and the dynamic coefficient of friction to the ice adhesion are not clear if the two physical properties coexisted. However, it was found that the critical surface tension contributed clearly in the interface between metal(304SS) and non-metal(PTFE, PFA and PE) surface, i.e. the stirring power of the non-metal surface was smaller than that of the metal one.

Figure 7 shows the stirring power at the end of each cooling process with respect to the dynamic coefficient of friction of cooling wall (PTFE, PFA, PE and SS). The stirring power increased in the solution 2 and 3 as the dynamic coefficient of friction increased, except in the PFA coating beaker. In the SS beaker the stirring power was 12.5 W at the solution 2 and 14.5 W at the solution 3, which is greater than that of the solution 1. It might be shown that the SCA and the HD on the SS wall would be acted to as the contributor rather than the suppressor for the ice adhesion. Meanwhile, the 1,6-HD was more effective to suppress the ice adhesion on polymeric surface than the SS one. The minimum stirring power was shown in the solution 2 and 3 which involve the SCA or 1.6-HD with the PTFE coating beaker. Thus the additives have good affinity to polymeric surface.

In Fig.8, the stirring power of the solution 2 and 3 increased except in the PFA coating beaker as the critical surface tension increased, which is similar to the result of Fig. 7.



Fig. 4 Comparison of stirring power with respect to heat transfer rate for different cooling surfaces (EG 4 _ SCA 3 mass%)



Fig. 5 Relationship between cooling heat transfer rate and stirring power for the solution 3 (EG 4 _ PG 1.5 _ 1,6-HD 1.5 mass%)



Fig. 6 Non-adhesion of ice on cooling wall (inside wall and bottom of the PTFE vessel)

From the result, the additive, 1,6-HD showed the suppression of ice adhesion on polymeric cooling surface, which will be adopted to a fundamental data on heat exchanger for ice making and thermal storage materials.

4. Conclusion

An experimental study of ice slurry formation was performed with an aqueous solution containing additives. The following characteristic of ice adhesion was obtained.

Time average cooling heat transfer rate removed from inside of beaker decreases, stirring power increases. In coating beaker, a comparatively lower stirring power was obtained with 1,6-HD containing solution. Moreover, using PG and 1,6-HD instead of SCA, the stirring power decreased to the amount of 2 W. The additive, SCA or 1,6-HD is more effective to suppress the ice adhesion on polymeric surface than stainless steel one. In the solution containing SCA or HD, the stirring power increased as the dynamic coefficient of friction and the critical surface tension increased, except in the PFA coating beaker. Minimum stirring power of 8.9 W was obtained by the solution containing 1,6-HD in the PTFE coating beaker.

Ice slurry sliding out from the beaker was shown at the stirring power below about 15 W, which was considered as non-adhesion of ice.

Acknowledgements



Fig. 7 Comparison of stirring power to different material

This paper was supported by the Research Centre of Industrial Technology Grant of Chonbuk National University

References

- 1. Saito, A., 2002, Recent advances in research on cold thermal energy storage, *International Journal of Refrigeration*, Vol. 25, pp. 177-189
- Kang, C., Okada, M., Oda, S., Matsumoto, K. and Kawagoe, T., 2001, Investigation of effective factor on ice formation process of ice thermal energy storage using water-oil emulsion effective of wall material and cool-ing rate to ice adhesion on cooling wall, *Trans. of the JSRAE*, Vol. 18, No. 1, pp. 51-59.
- Hirata, T., Kato, M., Nagasaka, K., Ishikawa, M., 2000, Crystal ice formation of solution and its removal phenomena at cooled horizontal solid surface Part II: onset of ice removal condition, *International Journal of Heat and mass transfer*, Vol. 43, pp. 757-765.
- 4. Park, K.W., Inaba, H. and Horibe, A., 2001, Study on ice making behavior of water solution with surfactant, *Korean Journal of Air-Conditioning and Refrigerating Engineering*, Vol. 13, No. 12, pp. 2001-2012.
- Seung, H., Peck. J. H., Hong. H. K., and Kang, C. D., 2004, Evaluation of Ice Adhesion in an Aqueous Solution with Functional Materials by Stirring Power, *Korean Journal of Air-Conditioning and Refrigerating Engineering*, Vol. 16, No. 8, pp. 720-727.
- 6. HDO[®]1,6-Hexanediol, BASF Intermediates (http://www.basf.com/businesses/chemicals/diols/pdfs/hdo _brochure.pdf)
- Tsuchida, D., Kang, C. D., Okada, M., Matsumoto, K., and Kawagoe, T., 2002, Ice formation process by cooling water-oil emulsion with stirring a vessel, *International Journal of Refrigeration*, Vol. 25, pp. 250-258.
- 8. Kariyone, T., 1980, Properties and Application of surfactant Saiwai-shobo Co., p. 39.



Fig. 8 Comparison of stirring power to different material