The 21st Conference of Mechanical Engineering Network of Thailand
17-19 October 2007, Chonburi, Thailand

Performance of Ice Production System Using Direct Contact Heat Transfer of Carbon Dioxide and Water

S. Thongwik[1*], T. Kiatsiriroat[1], and A. Nuntaphan[2]

[1] Department of Mechanical Engineering, Chiang Mai University, Chiang Mai 50200, Thailand
Tel: 0-5394-4144, Fax: 0-5394-4145, Email: thongwik@yahoo.com
[2] Thermal Technology Research Laboratories
Mae Moh Training Center, Electricity Generating Authority of Thailand,
Mae Moh, Lampang 52220, Thailand
Tel: 0-5425-6932, Fax: 0-5425-6938, Email: atipoang.n@egat.co.th

Abstract

This research studies the heat transfer characteristic during ice formation of a direct contact heat transfer between carbon dioxide and water. In this work, the low temperature carbon dioxide, approximately -15 to -60°C, is injected into water at 28°C and exchanges heat directly. The flow rate of carbon dioxide is varied between 0.003-0.017 kg/s while the volume of water is between 1-3 L.

From the experiment, it is found that the effectiveness of the direct contact heat transfer between carbon dioxide and water is closed to 100%. Moreover, the lumped model can be used for predicting the temperature of water and the mass of ice formation quite well.

Keywords: Direct contact heat transfer, Ice storage, Carbon dioxide, Lumped model

1. Introduction

At present, air-conditioning system of commercial building consumes approximately 60% of electrical demand and it brings to get high electrical cost. To overcome this problem, an ice thermal energy storage has been used. Since, the electrical cost of Thailand during the nighttime is cheaper than that of during the daytime, therefore, ice thermal energy storage system of which the ice is produced in the night and used for air-conditioning during the daytime seems to be appropriate. Chaichana et al [1] reported that an ice thermal energy storage can be reduced the electrical cost approximately 55%. Moreover, Bruan [2] and Carey et al [3] reported that the coefficient of performance (COP) of an ice thermal energy storage system is higher than that of a conventional air-conditioning system.

Ice-on-coil system is a commercial ice thermal energy storage. An evaporator coil of this system is submerged in the water and ice is form around its evaporator tube. Since the thermal conductivity of ice is very low; therefore, the performance of the evaporator is reduced with the increasing of ice thickness. To avoid this problem, direct contact heat transfer technique is proposed. The concept for producing ice is the injection of cold refrigerant into the water and exchange heat directly. Nuntaphan [4] reported that the effectiveness of a direct contact heat transfer between R12 and water is closed to 100%. Moreover, Kiatsiriroat et al [5] investigated the performance of a refrigeration cycle using a direct contact evaporator. In this study, R12 was selected as the refrigerant. They found that the COP of this system was around 3.4-3.6 and the ice looked like slurry. Kiatsiriroat et al [6] proposed the heat transfer correlation for the direct contact heat transfer between R12- water and R22-water in the form of dimensionless parameters which were Stanton number, Stephan number and dimensionless pressure.

In this work, carbon dioxide, one type of natural fluid, is used for the study of direct contact heat transfer for ice production. The information data could serve the applications of ice thermal energy storage for commercial building or other industrial purposes.

2. Mathematical model

From previous studies [4,5,6], it is found that when a refrigerant is injected into water, a high turbulence of water is occurred and the temperature of water is uniform. Therefore, the lumped model could be used for predicting the water temperature and the amount of ice formation. In case of the direct contact between carbon dioxide and water, the energy balance can be written as

$$\frac{d}{dt}\left(m_w h_w\right) = \dot{m}_{CO_2}\left(h_{CO_2,i} - h_{CO_2,o}\right) - (UA)\left(T_a - T_w\right) \qquad (1)$$

The left hand side of the above equation is the enthalpy change of water with time while the first and the second terms of the right hand side are the rate of enthalpy change of carbon dioxide and the rate of heat loss to the environment, respectively.

During the sensible heat period, eq.(1) is modified and the temperature of water in the storage tank could be

$$T_w^{t+\Delta t} = T_w^t + \frac{\dot{m}_{CO_2}\left(h_{CO_2,i} - h_{CO_2,o}\right) - (UA)(T_a - T_w)}{m_w C p_w}\Delta t \quad (2)$$

Moreover, during ice formation period, the water temperature is constant at its freezing point and the mass of ice during a time interval could be predicted from

$$m_{ice} = \frac{\dot{m}_{CO_2}\left(h_{CO_2,i} - h_{CO_2,o}\right) - (UA)(T_a - T_w)}{\lambda_w}\Delta t_{ice} \quad (3)$$

3. Experiment set-up

Fig. 1 shows the schematic sketch of the experimental setup. Low temperature carbon dioxide from a storage tank is injected into water in a storage tank and exchanges heat directly.

In this work, the initial water temperature is around 28ºC while the inlet temperature of carbon dioxide is varied between -15 ºC to -60ºC. The mass flow rate of carbon dioxide is varied between 0.003-0.017 kg/s. The water is stored in a cylindrical test tube of 0.0762 m in diameter and 2 m in height. The volume of water is between 1-3 L.

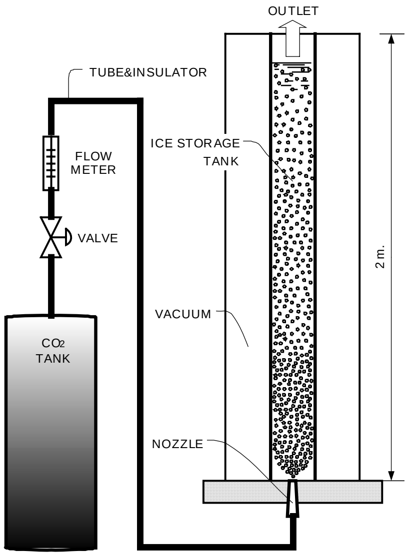


Fig. 1 Schematic sketch of the experimental set-up.

The temperature of water, the inlet temperature of carbon dioxide and the ambient air are measured by a set of K-type thermocouples having ±0.1ºC accuracy and recorded every 10 s. Notice that the carbon dioxide is injected into the water till most of water become ice. The mass of ice in a storage tank is measured by a high precision weighing machine having ±0.1 g accuracy.

4. Results and Discussion

Fig.2 shows the effect of the mass flow rate and the inlet temperature of carbon dioxide and the volume of water on the decrease of water temperature in the storage tank. Notice that the volume of water is 1-3 L, the mass flow rate and the inlet temperature of carbon dioxide is varied between 0.003-0.017 kg/s and approximately 28°C respectively. The undoubtedly result shows that the decrease of water volume is directly proportional to the mass flow rate of carbon dioxide and inversely proportional to the volume of water and the inlet temperature of carbon dioxide.

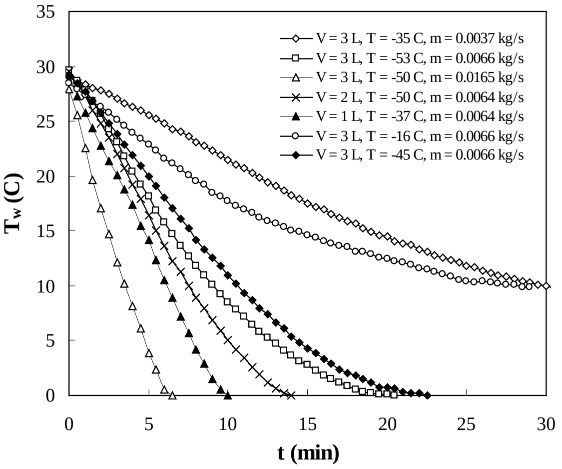


Fig. 2 The decrease of water temperature in a storage tank at various conditions.

Moreover, the lumped model can predict the temperature of water in the storage tank quite well and the example of this result is also shown in Fig. 3. It should be note that, in case of sensible heat period the lumped model can be predicted approximately 70% of the experimental data within ±20% variation.

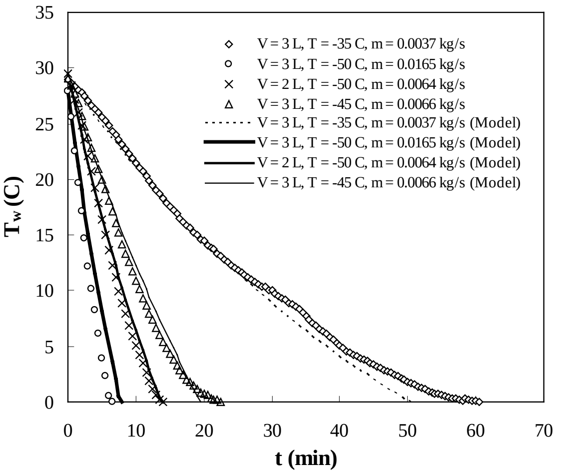


Fig. 3 Comparison of water temperature from experiment and lumped model.

Fig.4 shows the effectiveness of a direct contact heat transfer between water and carbon dioxide. Notice that the effectiveness can be calculated from

$$\varepsilon = \frac{\dot{Q}_{CO_2}}{\dot{Q}_{\max}} \quad (4)$$

$$\dot{Q}_{CO_2} = (\dot{m}C_p)_{CO_2}(T_{CO_2,out} - T_{CO_2,in}) \quad (5)$$

$$\dot{Q}_{\max} = (\dot{m}C_p)_{CO_2}(T_w - T_{CO_2,in}) \quad (6)$$

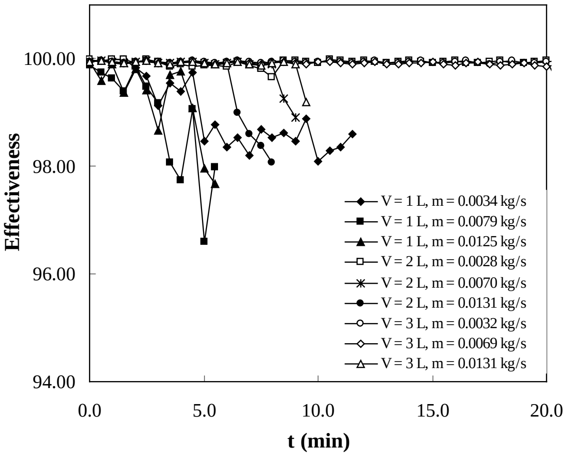


Fig. 4 Effectiveness of the direct contact heat transfer between water and carbon dioxide.

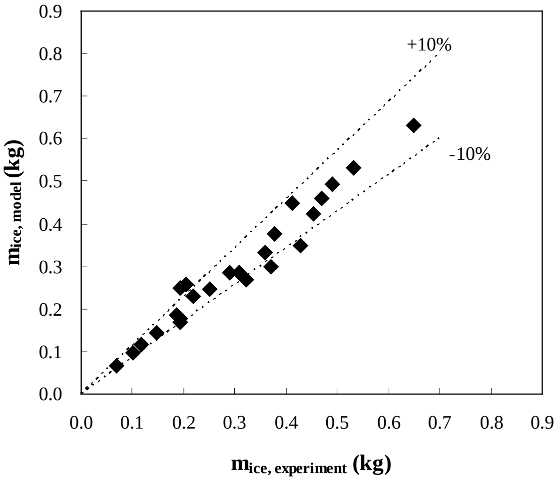
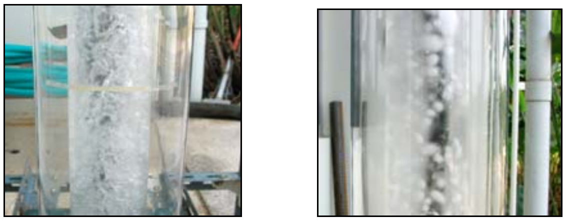


Fig. 5 The comparison of mass of ice from the experiment and the model.

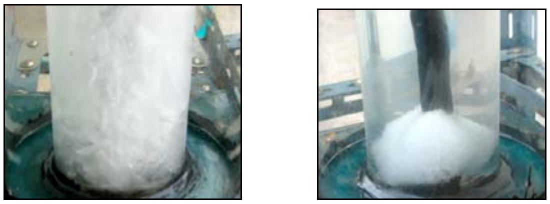
From Fig. 4, it is found that the effectiveness from this work agrees well with the results of Nuntaphan [4] which is closed to 100%. However, at the water volume of 1 L the effectiveness is slightly lower than those of 2 L and 3 L. This result comes from the retention time of exchanging heat. At low volume of water, the height of water column is a little bit short; therefore the retention time of carbon dioxide is rather short too which results in lower effectiveness.

In case of latent heat period, Fig. 5 shows the comparison of mass of ice from the experiment and the model. It is found that the lumped model can predict the mass of ice approximately 77.3% within ±10% variation. Notice that the ice from the direct contact heat transfer process has high porosity. Fig. 6 shows the ice formation at various conditions. In some conditions, there is a blockage of ice around the injector and it obstructs the flow of carbon dioxide.



a. Sensible heat period.

b. Initial state of latent heat period, small flake of ice is occurred.



c. Final state of latent heat period, most of water becomes ice.

d. The blockage of ice around an injector.

Fig. 6 Ice formation at various states.

5. Conclusion

From this research, it could be concluded as

- The decreasing of water volume is directly proportional to the mass flow rate of carbon dioxide and inversely proportional to the volume of water and the inlet temperature of carbon dioxide.
- The effectiveness of a direct contact heat transfer between carbon dioxide and water is close to 100%.
- The lumped model can predict the water temperature and the amount of ice in case of sensible heat and latent heat periods quite well.

Acknowledgments

This research were performed at Thermal Technology Research Laboratory, Mae Moh Training Center, Electricity Generating Authority of Thailand**.**

References

[1] Chaichana, C., William, W.S.C., and Lu A., 2001. An ice thermal storage computer model. Applied Thermal Engineering. Vol. 21, pp. 1769-1778.

[2] Braun, JE., 1990. Reducing energy cost and peak electric demand though optimal control of building thermal storage. ASHRAE Transaction, Vol. 96, No. 2.

[3] Carey, C.W., Mitchell, J.W., and Beckman, W.A., 1995. The control of ice storage system. ASHRAE Transaction, pp. 32-39

[4] Nuntaphan A., 1998. Performance Analysis of a Refrigeration Cycle Using a Direct Contact Evaporator. M.Eng. Thesis, Department of Mechanical Engineering, Chiang Mai University, Thailand.

[5] Kiatsiriroat, T., Siriplubpla, P., Nuntaphan, A., 1998. Performance Analysis of a Refrigeration Cycle Using a Direct Contact Evaporator. Int. J. Energy Research, Vol. 22, pp. 1179-1190.
[6] Kiatsiriroat, T., Vorayos, N., Vithayasai, S., Nuntaphan, A., Vorayos, N., 2003. Heat Transfer Prediction for a Direct Contact Ice Thermal Energy Storage. Energy Conversion & Management, Vol. 44, pp. 497-508

Nomenclatures

Cp_w	Specific heat of water (J/kg K)
$h_{CO_2,i}$	Inlet enthalpy of carbon dioxide (J/kg)
$h_{CO_2,o}$	Outlet enthalpy of carbon dioxide (J/kg)
h_w	Enthalpy of water (J/kg)
m_{ice}	Mass of ice (kg)
m_w	Mass of water (kg)
$\dot{m}_{CO_2}$	Mass flow rate of carbon dioxide (kg/s)
Q_{CO_2}	Heat transfer rate of carbon dioxide (W)
Q_{max}	Maximum heat transfer rate of direct contact process (W)
t	Time (s)
T_a	Ambient temperature (ºC)
T_w	Water temperature (ºC)
Δt	Time duration (s)
Δt_{ice}	Time duration for producing ice (s)
UA	Overall heat loss coefficient and area (W/K)
ε	Effectiveness
λ_w	Latent heat of freezing of water (J/kg)