Characteristics of Multiple-Pass Heat Exchanger with Melting of Falling Snow*

Nobuyuki ISHIKAWA**, Kazuo AOKI***,
Masaru HATTORI*** and Yoshiharu KOBAYASHI****

The structure of a multiple-pass heat exchanger composed of pipes and plate fins is similar to that of heat exchangers used for melting snow. In this study, we investigated the characteristics of a multiple-pass heat exchanger having two types, a regular pitch type and an irregular one, focusing on the brine pipe pitch of the multiple-pass heat exchanger. The perfect melting condition and the melting efficiency were related to the dimensionless parameters of the heat exchanger and its operating conditions. The calculated results for the perfect melting condition and the melting efficiency agreed with the results obtained from field tests on melting of falling snow. Applying the irregular pitch extends the critical condition for perfect melting when the flow rate of brine is low or the area for melting of falling snow is large. Also, the melting efficiency of the irregular pitch is higher than that of the regular pitch.

Key Words: Heat Exchanger, Extended Heat Transfer Surface, Heat Conduction, Snow Melting, Pipe Pitch, Falling Snow, Melting Efficiency, Perfect Melting Condition

1. Introduction

Studies on the use of heat exchangers for melting snow in relation to conditions of melting snow on roofs and roads, and the optimization of facilities, are important. In our previous works^{(1),(2)}, we investigated the characteristics of melting of falling snow with a one-dimensional heat exchanger and a two-dimensional heat exchanger to which a plate fin is attached. Among the heat exchangers used for melting snow, multiple-pass heat exchangers composed of plate fins and brine pipes are attractive because the area for melting snow on roofs and roads is large. In general,

brine temperature in the heat exchanger drops in the direction of brine flow due to heat transport in the upstream area. The drop of brine temperature is large when using the multiple-pass heat exchanger, causing the snow-melting ability to differ between the upstream and downstream areas of the brine flow. Accordingly, the pipe pitch of an irregular type is significant for melting snow in the multiple-pass heat exchanger.

In this paper, we discuss the characteristics of the multiple-pass heat exchanger having two types, a regular interval type and an irregular interval one, focusing on the pipe pitch of the multiple-pass heat exchanger. Conditions for perfect melting and melting efficiency are predicted and related to dimensionless parameters. The predicted results are compared with the experimental results obtained from field tests on melting of falling snow. Moreover, it is predicted that the effect of the irregular pipe pitch is related to the operating conditions of the heat exchanger and the optimum pipe pitch.

2. Nomenclature

c_p : specific heat capacity at constant pressure,

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** Department of Mechanical Engineering, Miyagi National College of Technology, 48 Medeshima, Natori, Miyagi 981-1239, Japan. E-mail: ishihawa@miyagi-ct.ac.jp

*** Department of Mechanical Engineering, Nagaoka University of Technology, 1603-1 Kamitomioka, Nagaoka, Niigata 940-2188, Japan

**** Nisshin Steel Company, Ltd., 3-4-1 Marunouti, Chiyoda-ku, Tokyo 100-8366, Japan

- J/(kgK)
- D_i : internal diameter of brine pipe, m
- D_o : outside diameter of brine pipe, m
- F : heat transfer area per unit length, m²/m
- G : fluid mass flow rate, kg/s
- h : heat transfer coefficient, W/(m²K)
- K : overall heat transfer coefficient, W/(m²K)
- L : length of heat exchanger, m
- L_s : latent heat of snow, J/kg
- n : total number of brine path
- NTU: number of heat transfer units
- P : fin width, m
- $\bar{P}$: average fin width, m
- T : temperature, °C
- T_m : fusion temperature of ice (0°C), °C
- x : direction of brine flow, m
- y : direction of fin width, m
- Z : intensity of falling snow, kg/(m²s)
- δ : thickness of fin, m
- ε : heat exchanger effectiveness
- ϕ : surrounding parameter, defined by Eq. (16)
- γ : pipe pitch parameter, defined by Eq. (12)
- $\bar{\eta}$: melting efficiency
- η_f : fin efficiency
- λ : thermal conductivity, W/(mK)
- ξ : initial melting parameter, defined by Eq. (17)
- Subscripts
- a : air
- b : brine (heat source)
- f : fin
- I : brine pipe number
- i : fin number
- in : inlet of heat exchanger for brine
- out : outlet of heat exchanger for brine
- p : brine pipe
- ∞ : surroundings

3. Characteristics of Heat Exchanger with Melting Snow

3.1 Classification of heat exchanger

Figure 1 shows the schematic diagram of the structure of the multiple-pass heat exchanger for melting snow. Figure 1(a) shows the regular pipe pitch structure. In this case, brine pipes are arranged at equal pitch on the plate attached to the heat exchanger. In Fig. 1(b), the irregular pipe pitch structure is shown, where brine pipes are arranged in different pitches. The former is called "the regular pitch" and the latter, "the irregular pitch" hereafter. In this classification, the pipe pitch of irregular pitch is restricted by arithmetic progression. Then, the brine pipes are set at a larger pitch in the upstream area of brine flow and a smaller pitch in the downstream area.

(a) Regular pipe pitch (b) Irregular pipe pitch

Fig. 1 Typical intervals of pipe pitch for the multiple-pass heat exchanger

Fig. 2 Model of the multiple-pass heat exchanger for melting of falling snow

3.2 Model and analysis

3.2.1 Model of heat exchanger for melting snow

Figure 2 shows a model of the irregular pitch heat exchanger for melting of falling snow. The structure of the multiple-pass heat exchanger is based on that of a two-dimensional heat exchanger with a pair of plate fins with equal width on both sides of the brine pipe. The two-dimensional heat exchanger is shown in the part with the diagonal lines in Fig. 1(b). The difference in width P_i for the irregular pitch in this study is regulated by arithmetic progression of the common difference ΔP . Then, the fin width P_i attached to both sides of the brine pipe of order " I " is determined by the following equation.

$$P_I = \bar{P} + \Delta P \left(\frac{n+1}{2} - I \right) ; I=1, 2, \dots, n \quad (1)$$

The bent parts of the pipes and the edges of the heat

(a) Element of the heat exchanger

(b) Section of the element

Fig. 3 Basic element in the model of multiple-pass heat exchanger

exchanger are insulated. Plate fin parts are heated by the brine pipes located on both sides of the fin. With the above assumption, the basic element of the multiple-pass heat exchanger is two straight brine pipes and a plate fin put between the brine pipes. Brine in the pipes exhibits counter flow. Figure 3 shows the model of the basic element of the multiple-pass heat exchanger. The multiple-pass heat exchanger is constructed by arranging part of the basic element in parallel to the total of $(n+1)$. The width ΔY_i in the basic element of order “ i ” can be written by

$$\Delta Y_i = Y_i - Y_{i-1} = 2\bar{P} + \{n - 2(i-1)\}\Delta P \quad (2)$$

The width ΔY_i corresponds to the pipe pitch. Temperature in the direction of fin thickness is assumed to be uniform, because the fin is thin. In this analysis, the fin temperature is consists of only the two-dimensional heat conduction on the fin. The melting of falling snow and the convection to the surroundings occur on the surface of fins, by assuming that the reverse sides of the fins are insulated. The intensity of the falling snow and the convective heat transfer coefficient of the surroundings are assumed to be uniform over the surface of the fin on the heat exchanger. Moreover, it is assumed that temperature of falling snow is equal to the surrounding temperature. The influence of water on melting snow is neglected in this analysis by assuming that water for melting snow

drains from the surface of the fin momentarily.

3.2.2 Analysis of the multiple-pass heat exchanger The governing equations are based on the model of the basic element for the irregular pitch. The heat balance equation for brine of order “ I ” of the brine pipe can be written by

$$G_b c_{pb} \frac{dT_{b,I}}{dx} - (-1)^I h_p F_p (T_{b,I} - T_{f,y=Y_i}) = 0 \quad (3)$$

where h_p is shown by

$$h_p = \frac{1}{\left(\frac{1}{h_b} \cdot \frac{D_o}{D_i} + \frac{D_o}{2\lambda_p} \ln \frac{D_o}{D_i} \right)} \quad (4)$$

The heat balance equation for the fin part of the basic element of order “ i ” is shown by the following equation.

$$\lambda_f \delta_f \left(\frac{\partial^2 T_{f,i}}{\partial x^2} + \frac{\partial^2 T_{f,i}}{\partial y^2} \right) - h_a (T_{f,i} - T_\infty) = 0 \quad (5)$$

Now, T_∞ in Eq. (5) is the apparent surrounding temperature and is defined by

$$T_\infty = T_\infty - \frac{Z}{h_a} \{L_s + c_{ps} (T_m - T_\infty)\} \quad (6)$$

The general governing equation for the multiple-pass heat exchanger is based on the simultaneous equation that consists of the equations for the total number n of brine pipes and the equations for the total number $(n+1)$ of fin parts. The boundary conditions for the joint part of the basic element and the edge parts of the heat exchanger are based on the following equations.

$$\left. \begin{aligned} x=0, x=L; (i=1, 2, \dots, n+1): \quad & \frac{\partial T_{f,i}}{\partial x} = 0 \\ y=0: \quad & \frac{\partial T_{f,1}}{\partial y} = 0 \\ y=Y_i (i=1, 2, \dots, n): \quad & \lambda_f \delta_f \left(-\frac{\partial T_{f,i}}{\partial y} \Big|_{y=Y_i} + \frac{\partial T_{f,i+1}}{\partial y} \Big|_{y=Y_i} \right) \\ & = -h_p F_p (T_{b,i} - T_{f,y=Y_i}) \\ y=2n\bar{P}: \quad & \frac{\partial T_{f,n+1}}{\partial y} = 0 \end{aligned} \right\} \quad (7)$$

Next, dimensionless parameters are applied to the governing equations for the multiple-pass heat exchanger and the equations for the boundary conditions. Equation (3) for the brine pipe and Eq. (5) for the basic element are rewritten by

$$\frac{dT_{b,I}^*}{dx^*} - \frac{(-1)^I}{n} \frac{\eta_f NTU}{(\eta_f - H)} (T_{b,I}^* - T_{f,y^*=1}^*) = 0 \quad (8)$$

$$\gamma_i^2 \beta^2 \frac{\partial^2 T_{f,i}^*}{\partial x^{*2}} + \frac{\partial^2 T_{f,i}^*}{\partial y^{*2}} - \gamma_i^2 m^2 T_{f,i}^* = 0 \quad (9)$$

where T^* , x^* and y^* are dimensionless values defined by

$$T^* = \frac{T - T'_\infty}{T_{bin} - T'_\infty}, \quad x^* = \frac{x}{L}, \quad y^* = \frac{y - Y_{i-1}}{Y_i - Y_{i-1}} \quad (10)$$

: $i=1, 2, \dots, n+1$.

The boundary conditions are rewritten by

$$\left. \begin{aligned} x^* &= 0, x^* = 1; \quad (i=1, 2, \dots, n+1) \quad : \quad \frac{\partial T_{f,i}^*}{\partial x^*} = 0 \\ y^* &= 0 \quad : \quad \frac{\partial T_{f,1}^*}{\partial y^*} = 0 \\ y^* &= i \quad (i=1, 2, \dots, n) : \\ &\frac{1}{\gamma_i} \frac{\partial T_{f,i}^*}{\partial y^*} \Big|_{y^*=i} - \frac{1}{\gamma_{i+1}} \frac{\partial T_{f,i+1}^*}{\partial y^*} \Big|_{y^*=i} \\ &= 2m^2 \frac{\eta_f H}{\eta_f - H} (T_{b,i=1}^* - T_{f,y^*=i}^*) \\ y^* &= n+1 \quad : \quad \frac{\partial T_{f,n+1}^*}{\partial y^*} = 0. \end{aligned} \right\} \quad (11)$$

Dimensionless parameters in the above equations are defined by

$$\left. \begin{aligned} NTU &= \frac{KnF_f L}{G_b C_{pb}}, \quad H = \frac{K}{h_a}, \quad \beta = \frac{\bar{P}}{L} \\ \eta_f &= \frac{\tanh(m)}{m}; \quad m = \sqrt{\frac{h_a \bar{P}^2}{\lambda_f \delta_f}} \\ \gamma_i &= \frac{\Delta Y_i}{\bar{P}} = \frac{Y_i - Y_{i-1}}{\bar{P}} \quad (i=1, 2, \dots, n+1) \end{aligned} \right\} \quad (12)$$

NTU represents the number of heat transfer units in the heat exchanger, and K is the overall heat transfer coefficient in the following equation.

$$K = \frac{1}{\frac{F_f}{h_p F_p} + \frac{1}{\eta_f h_a}} \quad (13)$$

The pipe pitch parameter γ is determined by obtaining the total number n of pipes and average fin width $\bar{P}$ based on the relation in Eq. (2). The difference in pipe pitch, therefore, is indicated in the parameter ΔP of the common difference hereafter. The case of the regular pitch is equivalent to the case of $\Delta P=0$, and the governing equations for the irregular pitch include the equations for the regular pitch.

3.2.3 Numerical method The dimensionless governing equations and the equations for the boundary conditions of the multiple-pass heat exchanger are computed by the finite difference method. Discretized simultaneous equations are solved by the Gauss-Seidel iterative method, and dimensionless temperature in each grid point is calculated. The number of grids is 20×20 in the fin part of the basic element and 20 in the brine pipe, and the convergence condition is 10^{-6} .

3.3 Condition for perfect melting and efficiency of melting snow

3.3.1 Perfect melting condition In the melting of falling snow, it is important determine whether or not the falling snow is perfectly melting over the surface of the heat exchanger. In general, perfect melting of the falling snow on the heat exchanger

occurs when the surface temperature of the heat exchanger is higher than the fusion temperature of ice. This perfect melting condition is shown by the following equation.

$$T_f \geq 0 \quad (14)$$

Although the perfect melting condition depends on fin temperature, it is difficult to calculate the analytic solution of fin temperature from governing equations (8) and (9). However, the above governing equations (8) and (9) are linear homogeneous equations regarding the temperature, and the independent variables x^* , y^* and the function of the dimensionless parameters are given as the dimensionless temperature of the plate fin. Then, the perfect melting condition is explained by formulating Eq. (15) with the dimensionless parameters for melting of falling snow in the same way as that in a previous paper⁽³⁾. By defining the lowest dimensionless temperature $T_{f,min}^*$ at position (x_c^*, y_c^*) on the fin, the perfect melting condition is given by

$$\frac{\xi}{\phi} \leq \frac{T_{f,min}^*}{H} = \frac{f_{Fin}(NTU, H, \eta_f, \beta, \frac{\Delta P}{\bar{P}}, n, x_c^*, y_c^*)}{H} \quad (15)$$

where ϕ represents the degree of intensity of falling snow on the apparent surrounding temperature and is defined by the surrounding parameter⁽²⁾.

$$\phi = \frac{Z\{L_s + c_{ps}(T_m - T_\infty)\}}{h_a(T_m - T_\infty)} = 1 - \frac{T_\infty}{T_m} \quad (16)$$

Also, ξ represents the ratio of heat needed to melt the falling snow to heat transferred from the brine at the inlet and is defined by the initial melting parameter⁽²⁾.

$$\xi = \frac{Z\{L_s + c_{ps}(T_m - T_\infty)\}}{K(T_{bin} - T'_\infty)} \quad (17)$$

Finally, although the calculation of dimensionless temperature by the numerical method is required, the perfect melting condition is related to the following equation, using the dimensionless parameters.

3.3.2 Melting efficiency Part of the heat supplied becomes heat lost to the surroundings during melting of falling snow. Namely, part of the heat supplied by hot brine is used to melt the snow, but the rest of the heat transfers to the surrounding as heat loss. The snow-melting ability is expressed as melting efficiency, which is the ratio of the heat ideally needed to melt snow to the heat actually transferred through the heat exchanger, and is represented by the following equation.

$$\bar{\eta} = \frac{Z\{L_s + c_{ps}(T_m - T_\infty)\} n F_f L}{G_b C_{pb} (T_{bin} - T_{b,out})} = NTU \frac{\xi}{\varepsilon} \quad (18)$$

ε is the heat exchanger effectiveness, which is calculated from the dimensionless outlet temperature of the brine, defined by

$$\varepsilon = \frac{T_{bin} - T_{b,out}}{T_{bin} - T'_\infty} = 1 - T_{b,out}^* \quad (19)$$

4. Experimental Apparatus

The melting of falling snow was investigated by using a heat exchanger set on the roof of an experimental house in the field. The outline of the experimental house is shown in Fig. 4. Two heat exchangers, one with the regular pitch and the other with the irregular pitch, were used in the experiment. The brine is an aqueous solution (50% concentration) of ethylene glycol. The brine is heated by the heat

Fig. 4 Schematic diagram of experimental apparatus

(a) Shape of the heat exchanger

(b) Section of the heat exchanger

Fig. 5 Structure of the multiple-pass heat exchanger used for melting of falling snow

pump, and the hot brine is distributed in the heat exchanger for melting snow with the pump. Temperature at the inlet and the outlet of the brine and temperature in the surroundings were measured by using copper-constantan thermocouples of 0.2 mm diameter. The mass flow rate of brine was measured by weighing the brine at certain intervals.

Figure 5 shows the fundamental structure of the heat exchanger for the experiment. The heat exchanger consisted of stainless steel plate fins (1.5 mm thickness) and copper pipes (12.7 mm outside diameter, 0.5 mm thickness) as the brine path. The straight copper pipe was set in the plate fin, and was strongly adhered to the plate fin with adhesive cement. The bent part of the brine path was connected to a rubber hose. The reverse side of the fin was insulated with Styrofoam. Melting of snow occurred only on the surface of the plate fin with a straight copper pipe set on it. The number of copper pipes was 15 for one heat exchanger.

Both the regular pitch and the irregular pitch had an average fin width of 100 mm. Although the pipe pitch of the regular pitch was 200 mm, that of the irregular pitch decreased gradually from the upstream area with a common difference of 4 mm. In order to eliminate water present in the falling snow, all experiments were performed with the surrounding temperature below 0°C. The intensity of the falling snow was obtained by weighing falling snow at certain intervals. The convective heat transfer coefficient of the surroundings was obtained in relation to the average wind velocity during the experiments⁽⁴⁾. Also, the convective heat transfer coefficients of the brine were obtained from a preliminary experiment conducted at a uniform fin temperature of 0°C, corresponding to the melting of piled snow.

5. Results and Discussion

5.1 Distribution of fin temperature

First, the effect of the irregular pitch on the distribution of fin temperature is discussed, because the perfect melting condition depends markedly on the fin temperature. Figure 6 shows the distributions of fin temperature along the center of the heat exchanger for the regular pitch and the irregular pitch with a difference in NTU . Fin temperature is the highest in the fin area to which the brine pipe is attached, and the lowest in the middle of the fin area between the brine pipes. The regular pitch in the above figure always shows a low temperature of the fin in the downstream area. When NTU increases by decreasing the quantity of brine, the tendency of the distribution of fin temperature becomes more remarkable. Fin temperature decreases gradually with the irregular pitch in

Fig. 6 Comparison of calculated results of the distribution of dimensionless fin temperature between regular pitch and irregular pitch

Fig. 7 Comparison between experimental and calculated results of the perfect melting conditions

the bottom figure, because fin width is reduced in the downstream area. The minimum temperature of the fin occurs in the inlet part of the irregular pitch with the smaller NTU , and in the outlet part of the regular pitch with the larger NTU .

5.2 Perfect melting condition

Figure 7 shows critical conditions for perfect melting in the case of the regular pitch and the irregular one in terms of the relationship between NTU and the dimensionless parameter ratio ξ/ϕ . Experimental results were obtained by observing the existence of the piled snow on the fin of the heat exchanger in various conditions of the melting snow. The calculated results are the critical conditions for perfect melting. In this figure, the regular pitch is shown by the solid curve, and the irregular one is shown by the dotted curve. The area below the critical condition is of perfect melting, and the area above is of partial melting. The critical conditions of ξ/ϕ for perfect

Fig. 8 Comparison of melting snow on the heat exchanger between regular pitch and irregular pitch

melting decrease by increasing NTU in both the regular and the irregular pitch. However, in the smaller range of NTU , the critical condition of ξ/ϕ for the perfect melting of the regular pitch is higher than ξ/ϕ for perfect melting of the irregular pitch. At larger NTU , the critical condition of ξ/ϕ for perfect melting of the irregular pitch becomes high. This is because the position of minimum fin temperature of the irregular pitch moves from the downstream area to the upstream area at smaller NTU . Accordingly, the experimental results for condition "A" in this figure indicate perfect melting with the regular pitch and partial melting with the irregular one. The experimental and calculated results show good agreement regarding the perfect conditions for melting snow.

For example, a photograph of the heat exchanger for melting snow under condition "A" is shown in Fig. 8. Falling snow is completely melted by the heat exchanger with the irregular pitch shown on the right of the photograph. However, piled snow is observed on top of the roof in the downstream area of the brine flow with the regular pitch, which is shown on the center of the photograph. The heat exchanger shown on the left of the photograph should be omitted from the discussion because it was used to examine the influence of using different plate fin materials.

5.3 Melting efficiency

The comparison of the melting efficiency obtained experimentally with the calculated results under the perfect melting condition is shown in Fig. 9. From this figure, it was found that the melting efficiency increased with increasing ξ and NTU . The increase in ξ represents the decrease in temperature of the brine inlet. When the brine inlet temperature decreases, heat loss to the surroundings is decreased, thereby improving the melting efficiency. In addition, the increase in NTU represents the decrease in the quantity of brine. When the quantity of brine decreases, the amount of heat supplied is decreased, thereby improving the melting efficiency. The calculated and experimental results show good agreement. The melting efficiency by the regular pitch was similar to the efficiency by the irregular pitch in the range of

Fig. 9 Comparison between experimental and calculated results of the melting efficiency of the irregular pitch

Fig. 10 Melting efficiency as a function of NTU considering perfect melting conditions

the experimental conditions investigated, and the difference between them is small.

Figure 10 shows the melting efficiency that considered perfect melting conditions. Curves in this figure with the environmental parameter ϕ indicate the critical conditions for perfect melting. Perfect melting conditions are satisfied in the area below the curve with the environmental parameter ϕ . Although the melting efficiencies of the regular pitch and the irregular one increase with increasing NTU and ξ , the increase in melting efficiency is restricted under perfect melting conditions. Accordingly, the highest melting efficiency is found by obtaining the maximum values of NTU and ξ , located on the curve representing critical condition for perfect melting.

The region of the perfect melting condition increases with increasing NTU with the irregular pitch, and that region decreases with decreasing NTU . Also, the maximum value of the melting

Fig. 11 Optimization of pipe pitch as a function of $\Delta P/\bar{P}$ considering the perfect melting conditions

efficiency with the irregular pitch increases with increasing NTU , and decreases with decreasing NTU . The changes of the conditions for perfect melting of the irregular pitch become more remarkable by increasing $\Delta P/\bar{P}$, which changes the optimum conditions for the melting of falling snow. Accordingly, use of the multiple-pass heat exchanger with the irregular pitch for melting of falling snow requires an optimum $\Delta P/\bar{P}$ corresponding to the condition for the melting of falling snow and the surrounding conditions.

5.4 Optimization of pipe pitch

The pipe pitch of the multiple-pass heat exchanger is optimized for improving the conditions for perfect melting and the melting efficiency. Figure 11 shows the relationship between ξ/ϵ of the critical condition for perfect melting and $\Delta P/\bar{P}$. When $\Delta P/\bar{P}$ increases under constant NTU , ξ/ϵ of the critical condition for perfect melting is increased to reach a maximum value. After that, ξ/ϵ decreases with further increase of $\Delta P/\bar{P}$. From this figure, it is found that $\Delta P/\bar{P}$ indicating the maximum value of ξ/ϵ is changed by increasing NTU . Therefore, the pipe pitch is optimized by setting $\Delta P/\bar{P}$ such that ξ/ϵ is maximum as the critical conditions for perfect melting corresponding to NTU .

Figure 12 shows the relationship between melting efficiency and ξ . In this figure, the curve with ϕ represents the critical condition for perfect melting that conforms to the surrounding conditions. The melting efficiency is improved by increasing ξ with decreasing brine inlet temperature. However, the increase in ξ is regulated by the critical conditions, for the given surrounding parameter ϕ . The maximum value of ξ is 0.455 for the conditions shown in this figure. Accordingly, the highest melting efficiency is realized at the maximum value of ξ under the given surrounding parameter ϕ obtained from the maximum

Fig. 12 Optimization of pipe pitch as a function of $\Delta P/\bar{P}$ considering the melting efficiency

value of ξ/ϕ indicated by $\Delta P/\bar{P}$ for the optimization of the pipe pitch.

6. Conclusion

The characteristics of the multiple-pass heat exchanger for melting of falling snow were examined, and the influence of pipe pitch on melting snow was clarified. The following conclusions are made:

(1) The characteristics of the multiple-pass heat exchanger used for melting of falling snow were investigated experimentally and theoretically. The perfect melting conditions and the melting efficiency were related to the dimensionless parameters defined from the model of the multiple-pass heat exchanger with melting of the falling snow.

(2) The perfect melting conditions and the melt-

ing efficiency were predicted by the presented model of the multiple-pass heat exchanger. The predicted results were in good agreement with the experimental results obtained for melting of falling snow in the field.

(3) The restriction of the perfect melting conditions for the multiple-pass heat exchanger used for melting of falling snow was relaxed by using the irregular pipe pitch, and melting efficiency was increased.

(4) The optimum pipe pitch of the multiple-pass heat exchanger was determined given for obtaining the highest melting efficiency, and was related to the dimensionless parameters.

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