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AN ESTIMATION OF PURITY AND YIELD IN PURIFICATION OF CRYSTALLINE LAYERS BY SWEATING OPERATIONS

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ABSTRACT

Sweating operations were explored for various crystalline layers obtained during layer-melt crystallizations. The crystalline layers used in sweating operations were crystallized at different cooling rates of 0.1, 1, and 5K/min, and different feed compositions of 80, 85, and 90 wt% caprolactam–cyclo hexanone mixtures. The purification effects of sweating parameters, including the sweating time, amount of inclusions entrapped during the crystallization operation, and the degree of superheating, were investigated. The effect of crystalline layers, formed under various crystallization conditions, on sweating was studied. A model combining heat-balance equation and mass transfer correlation for the movement of inclusions was developed. The model was verified with the experimental data.

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INTRODUCTION

The crystals in layer-melt crystallization are grown at cooled surfaces, internal or external to the walls of the crystallizer. When a crystal grows on a cooled surface, the growth rate affects the structure of the layer and the inclusion of impurity in the layer (1,2). Very high growth rates are required for economic reasons in industrial applications. Therefore, entrapment of the impure liquid inclusions is inevitable, but the amount of impurity can be reduced to some extent by controlling the growth conditions. The inclusions entrapped in the layer during crystallization are completely inside the crystalline layer. Therefore, an additional purification is essentially required for upgrading the crystal to ultra purity after crystallization.

Washing, sweating, and migration are used as additional purification methods (3–5). Washing was found to be an effective method to remove the impurity from the surface of crystalline layers (5,6). The removal of inclusions, however, inside the crystals cannot be expected by washing. Ulrich et al. reported the migration of inclusions in the crystalline layer by temperature gradient (3,7,8); diffusion accounts for the removal of the inclusions during the migration process. Practical applications of temperature gradients seem difficult as the migration rate is very low—about 10^{-7}–10^{-10} m/sec. Sweating is the most common post-purification process in industrial-melt crystallization. Sweating is based on partial melting of the crystalline layer and the removal of inclusions from the layer. Although many previous works have reported purification of crystals by sweating, most of the studies concentrated on the influences of sweating temperature (4,9,10). Little attention has been paid to optimization of sweating operations and prediction of purity and yield.

A simple mass transfer equation was used for correlation of purification rate in the sweating operations, and the purification rate constant was used to compare the performance of sweating processes (4). Quantitative estimations of the products during sweating operations were not available. Washing of crystals in suspensions was studied by Poschmann and Ulrich (11). The aim was to remove the adhering impurity from the surface of crystals. They showed that inclusion formation does not influence the crystal growth rate when grown on seeds. Although the model correlation presented by Ulrich (10) exhibited a quantitative agreement, it was impossible to determine definitively the applicability of the model for quantitative correlation due to considerable scattering of the raw data.

In this paper, layer-melt crystallization and sweating operations were carried out for caprolactam–cyclohexanon mixture, which is a simple eutectic system. The effect of crystalline layers obtained under various crystallization conditions on the sweating performance was explored. A model for prediction of purity and yield of crystalline layer during sweating operations was developed.

The model along with the heat-balance equation and rinsing of inclusions was presented. The simulated results were compared with the experimental results obtained during a sweating process with a system of carprolactam–cyclohexanon.

EXPERIMENTS

Methods and Procedures

Crystallization and sweating experiments were carried out in this study. Figure 1 shows the experimental apparatus for layer-crystallization and sweating operations. It comprised a layer crystallizer, circulators for controlling temperatures, an image analysis system with camera, and temperature acquisition system for measuring temperatures of coolant and melt sides. The layer

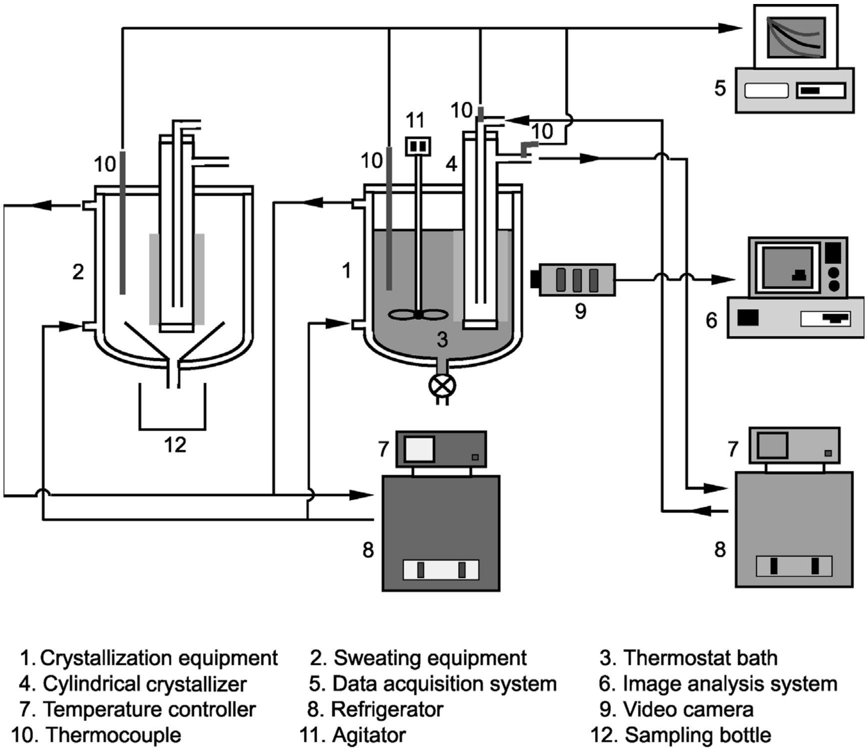

Figure 1. Experimental apparatus for layer crystallization and sweating operations.

crystallizer consisted of a jacketed vessel and cylindrical tube-type crystallizer. The vessel had a volume capacity of 800 mL with an inner diameter of 80 mm and depth of 140 mm. The layer crystallizer had an outer diameter of 26.4 mm and length of 100 mm. Teflon was set at the bottom of the cylindrical crystallizer to prevent the crystal growth on the bottom side. The coolant was circulated on the inside of the layer crystallizer and the crystalline layer was grown at the cooled surface. The temperature of melt side was set constant. The melt in the vessel was agitated with a paddle type impeller at 300 rpm. Thermocouples were placed in the vessel, in the inlet, and outlet of coolant in the layer crystallizer side. The thermocouples were calibrated with a calibrated thermometer from Fisher Scientific (No. 15-078-7) with an accuracy of ± 0.05K. The accuracy of the thermocouple measurements is believed to be ± 0.1K. Thickness of the crystalline layer was measured by an image analyzer (Image-Pro Plus, Media Cybernetics) with a camera. The crystal growth rate of the crystalline layer on the crystallizer was determined by an image analysis of the crystalline layer during the growth of the layer. The image analyzer for measurement of the layer thickness was calibrated by using actual crystalline layer.

Caprolactam and cyclohexanon were supplied by Aldrich (99.9 wt%). The compositions of feed mixture were 0.8, 0.85, and 0.9 mass fraction of caprolactam, the rest being cyclohexanon. The melt was heated 2°C above its equilibrium temperature. The layer crystallizer was cooled at a constant cooling rate, which was set by a programmed temperature controller. The cooling rates investigated were 0.1, 1, and 5K/min. The difference between the final cooling temperature and the temperature at which crystals started to form was about 30°C. After the crystallization, the layer crystallizer was removed from the residual melt and was inserted into the sweating vessel.

The sweating apparatus consisted of a temperature control system and a measurement system of the melt that drained-out. Draining-out melt was poured into the sampling bottle during sweating. The amount of drained-out melt was measured every 30 min and its composition was analyzed by gas chromatography. The sweating vessel was set at a desired temperature of sweating. The crystalline layer in the vessel gradually sweated and the melt drained into the sample bottle. The sweating temperatures were 74, 80, 85, and 90°C. These measurements were repeated three times for each solution under the same conditions and their average value was taken, the result being consistently reproducible to within 0.4 wt% for the concentrations of melt and layer.

Determination of C_{fi} and Inclusion Fraction I

During crystallization, inclusions are entrapped in the crystalline layer. After crystallization, the residual melt is drained out and then the crystalline layer is stored at a constant temperature of about 25°C for more than 12 hr. It brings the inclusion composition in equilibrium with the temperature of 25°C. Therefore, the inclusion mass fraction I is calculated from the following equation:

$$\begin{aligned} I &= \frac{\text{Mass of inclusions}}{\text{Mass of crystalline layer}} \\ &= \frac{\text{Mass of caprolactam/mass of crystalline layer}}{\text{Mass of caprolactam/mass of inclusions}} = \frac{C_\mathrm{f}}{C_\mathrm{fi}} \end{aligned} \tag{1}$$

where C_f and C_fi are the concentration of crystalline layer obtained during crystallization operation and the concentration of inclusions in equilibrium at 25°C, respectively.

RESULTS AND DISCUSSION

Figure 2 shows a typical result of a sweating operation at a superheating degree of 15K. The starting concentration of the crystalline layer was 91.8 wt% caprolactam with saturation temperature 62.8°C. The crystalline layer used was

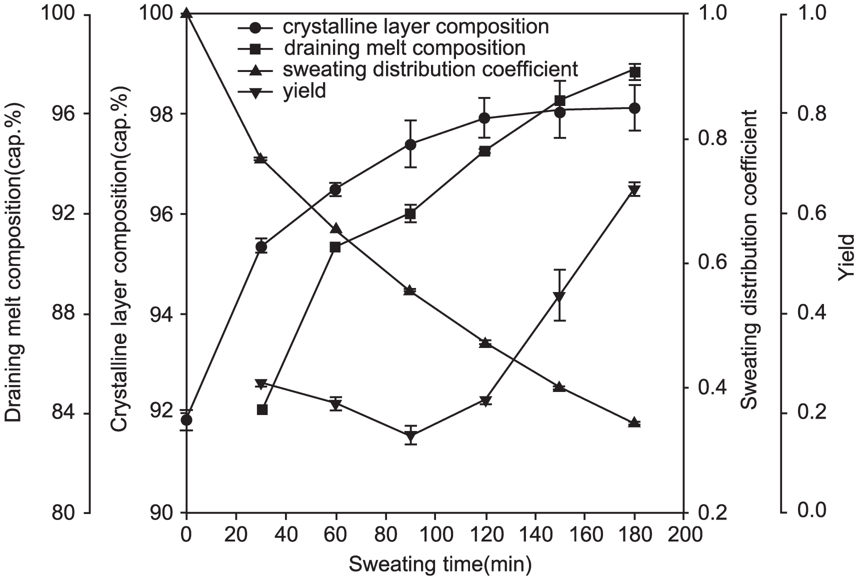

Figure 2. Typical results of sweating operations at superheating degree 15K for the crystalline layer formed at the cooling rate 1K/min and 85 wt% caprolactam mixture.

obtained at the cooling rate of 1K/min for 85 wt% caprolactam mixture by layer crystallization. The time dependence of composition of the drained melt, crystal composition, sweating distribution coefficient, and yield of the crystalline layer are shown in Fig. 2. Compositions of crystalline layer and drained-out melt increase with an increase in sweating time. The composition of the melt drained out increases more rapidly than that of the crystalline layer. The sweating distribution coefficient is defined as the ratio of the impurity fraction in crystal to the impurity fraction of sweated melt drained out. The sweating distribution coefficient decreases with an increase in sweating time and increases at the minimum value of sweating time. From this minimum point, excess melting of the crystals starts. The impurity is mainly adhered onto the crystal surface and can be easily removed. The melt is drained to the outside with melting of the crystal. Therefore, the melt concentration increases with the sweating time. As the liquid melted by partial melting of the crystal is moved outwards and drained down, caprolactam concentrations of the melt increase with the sweating time.

Effect of Cooling Rate During Crystallization

In this study, crystal growth rate is controlled by adjusting the cooling rate of the coolant. The crystal growth rate decreased with increase in crystallization time. Average crystal growth rates were calculated by dividing the thickness of the layer with the crystallization time. The crystal growth progressed until the coolant temperature was below 30°C from the nucleation start point. Figure 3 shows plots of average crystal growth rates and inclusion fraction in the crystalline layer against the cooling rates for three different feed compositions. As shown in Fig. 3, a linear relationship was found between the average crystal growth rates and the cooling rates. A similar relationship was reported in a previous study on layer-melt crystallizations (13). Mass fraction of the inclusions in the crystalline layer formed during the crystallization process depends on the cooling rate and the feed composition. The mass fraction of the inclusions increases with increasing cooling rates and decreasing feed compositions.

Effect of the Degree of Superheating

Figure 4 shows the purity and the yield of the crystals against the sweating time for four degrees of superheating, which are defined as the difference between melting point and sweating temperature. A crystalline layer formed in a feed composition of 90 wt% caprolactam and a cooling rate of 1K/min was used. It was found that the purity of the crystals depended strongly on the sweating temperature. The purity increased with increase in degrees of superheating. The

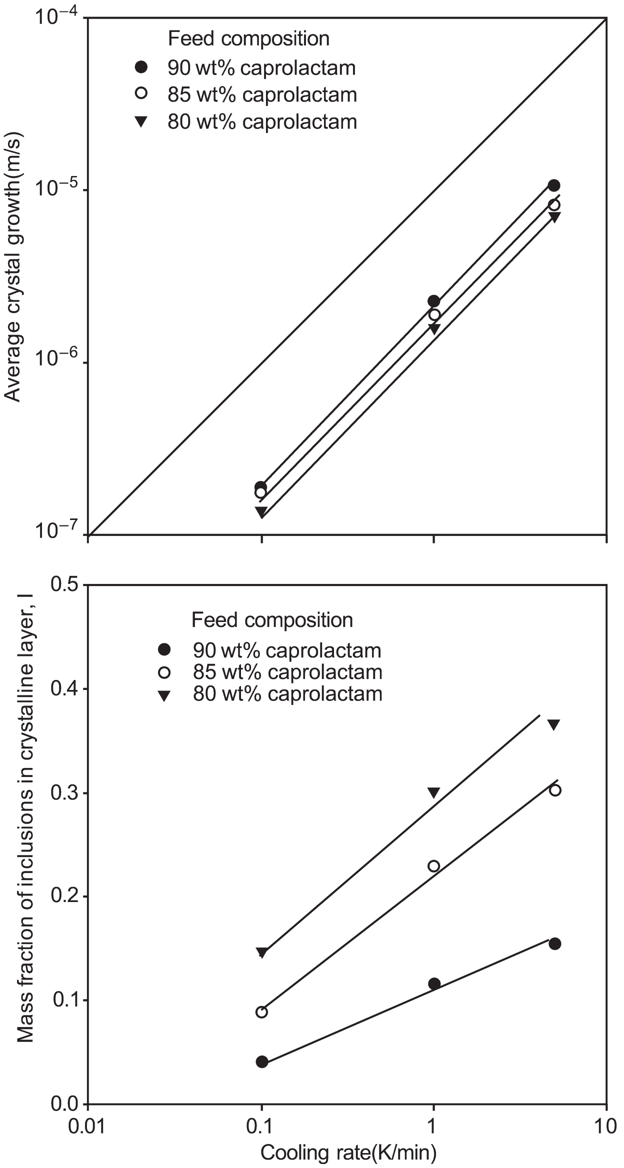

Figure 3. Average crystal growth rate and inclusion fraction vs. cooling rate in layer crystallization operations with various feed compositions.

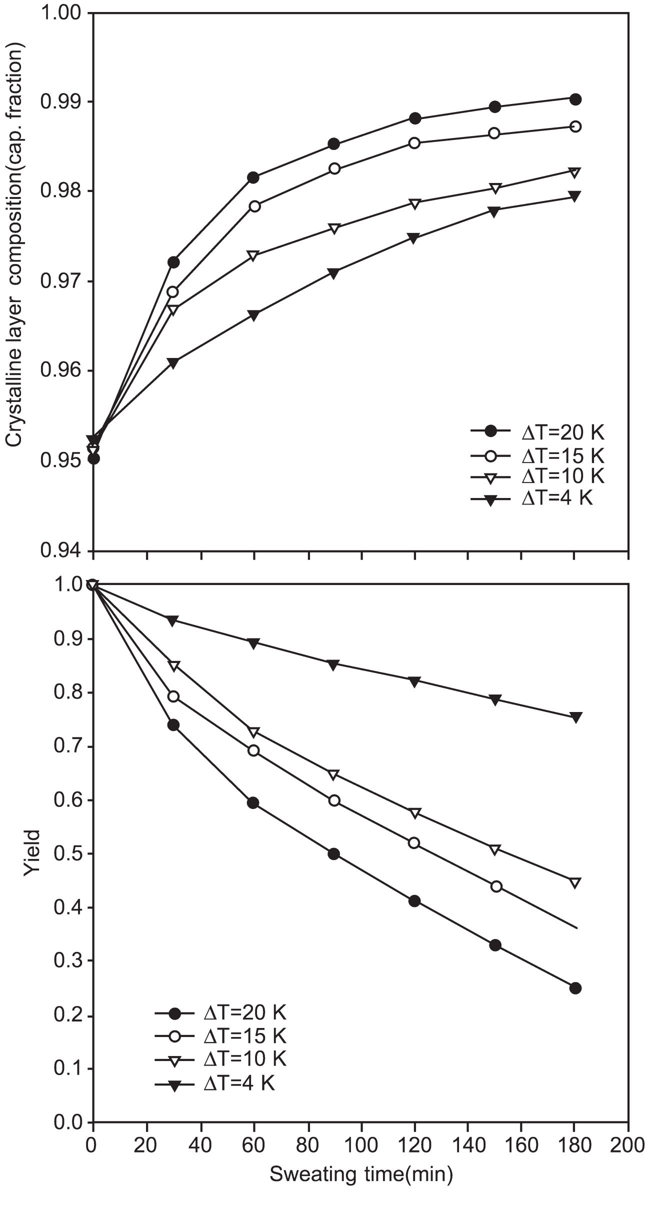

Figure 4. Variations of crystalline layer composition and yield in sweating at different superheating degrees for the crystalline layer formed in 90 wt% feed composition and at cooling rate 1K/min.

yield of crystals was lower at higher degrees of superheating at same sweating time. The purity of the crystals increased rapidly for the first 30 min. The impurity formed on growing crystals is mostly located on the surface of the crystalline layer. Impure inclusions on the outside of the layer are easily drained away at the beginning of the sweating process. This means the crystalline layer starts melting from the surface of the layer. Even after 1 hr, the crystal purity is nearly constant although the sweating operation is still in progress. This means that upgrading the purity of crystalline layer by sweating has a limitation on the amount of melting and time.

Sweating of Crystalline Layers Formed at Different Cooling Rates

The concentration of caprolactam in a crystalline layer that remains during any operating time after sweating was calculated from the remaining caprolactam. Figure 5 shows the plots of purity and yield of the layer vs. the sweating time for the different crystalline layers. The crystalline layers were prepared at cooling rates of 0.1, 1, and 5K/min for 90 wt% caprolactam mixture. The superheating degree was 10K. As the cooling rate affected the crystal growth rate, the crystalline layer obtained at different cooling rates had different inclusions in the layer (see Fig. 3). The purity of crystals before the sweating was high at lower cooling rates, while the purity of crystals after sweating was nearly the same. Therefore, a combination of both mechanisms—crystallization and sweating—is necessary for optimization of the process in total and for an upgrading of the purity of crystalline layers. Despite consistency in the degrees of superheating, the yield of crystal decreases more rapidly in the crystalline layer formed during the higher growth rate. This means that the inclusion fraction in the crystalline layer affects the sweating rate. The crystallization conditions may be considered as an important factor in purification of the layer by a sweating operation.

Sweating of Crystalline Layers Formed with Different Feed Composition

Figure 6 shows the plots of purity and yield of the layer vs. sweating time for the crystalline layers, respectively, which were formed with feed compositions of 80, 85, and 90 wt% caprolactam mixture at the cooling rate of 1K/min. The sweating operations were carried out at a superheating degree of 4K. For the crystalline layers obtained during crystallization operations with a mixture of 80, 85, and 90 wt% caprolactam, the purity of the resulting crystalline layers were 88.1, 91.6, and 95.4 wt% caprolactam, respectively. Purity of crystals obtained by the crystallization process increases with increase in feed

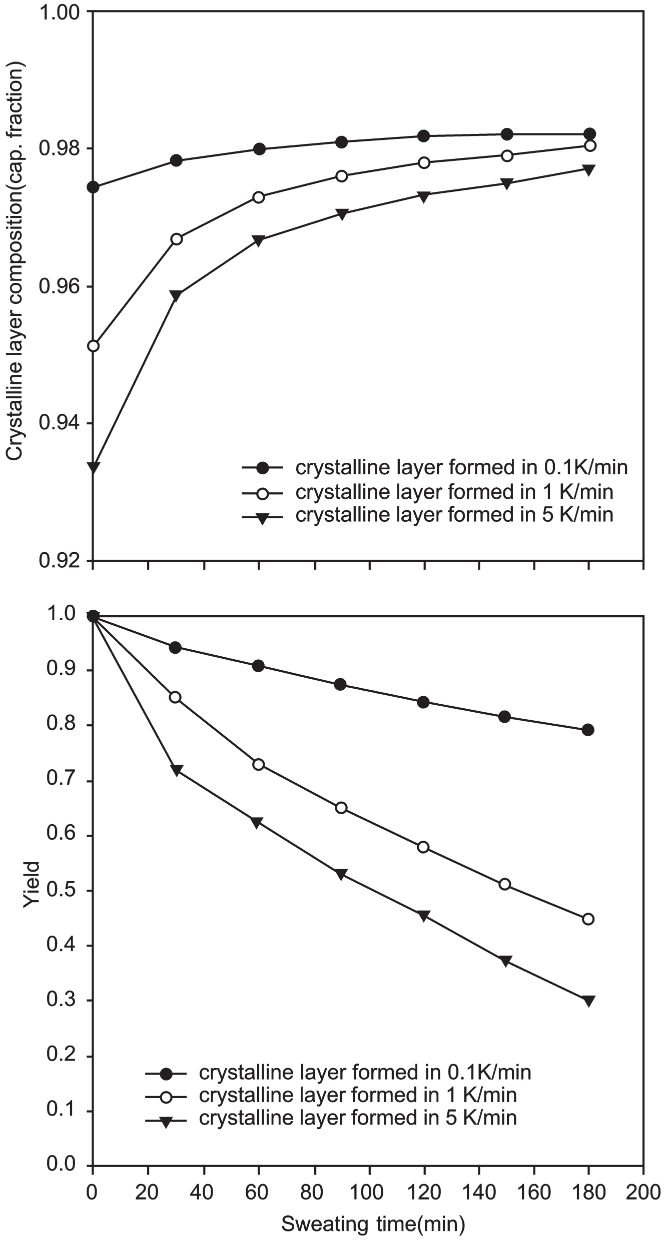

Figure 5. Variations of crystalline layer composition and yield in sweating with $\Delta T =$ 10K for the crystalline layers formed at various cooling rates for 90 wt% feed composition.

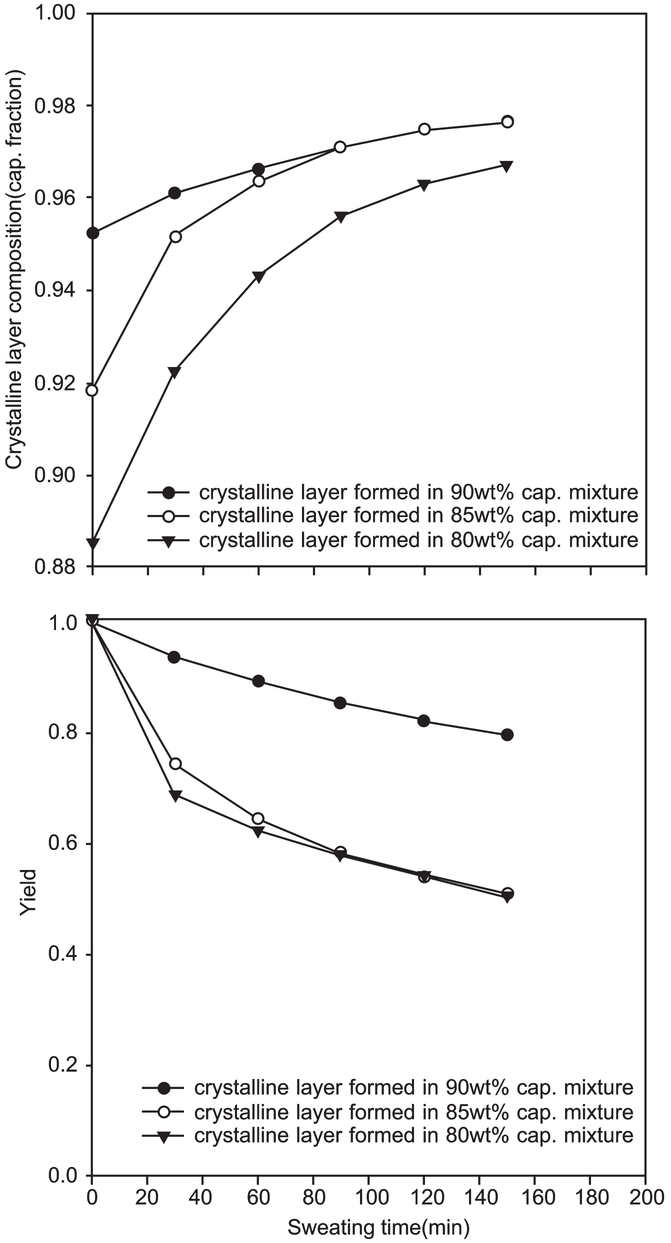

Figure 6. Variations of crystalline layer composition and yield in sweating with $\Delta T =$ 4K for the crystalline layers formed in various feed compositions at cooling rate 1K/min.

composition. Amount of inclusions trapped in the crystalline layer increases by decreasing feed composition. Despite different concentrations in the crystalline layer, the purity of the layer was found to be near to 98 wt% caprolactam after the sweating operation. Therefore, the effect of sweating is higher in the crystalline layers with higher inclusions. The time needed to attain a steady state of composition is faster in higher concentrations of the layer. Despite constant degrees of superheating, the yield of the crystals decreased more rapidly in the higher inclusion fraction. This means that inclusion fraction of the crystalline layers affects the sweating rate.

Model for Sweating Operation

Figure 7 shows a block diagram for material flows during a sweating operation. The crystalline layers obtained after the crystallization operation consisted of a solid and the inclusions entrapped in it. The inclusions exist in the form of entrapped liquid impurities inside the layer and occluded impurities on the surface of the crystalline layer. The amount of inclusions and crystals present in the layer after crystallization can be expressed based on the balance material as follows.

$$M_c + M_i = M \tag{2}$$

$$M_c C_{fc} + M_i C_{fi} = M C_f \tag{3}$$

where M, M_c, and M_i are total mass of crystalline layer, the amount of pure crystal phase, and inclusion phase, respectively. C_f, C_{fc}, and C_{fi} represent compositions of the crystalline layer, pure crystal, and inclusions entrapped in a crystal, respectively.

In case of a eutectic system, composition of the crystal phase C_{fc} is unity. Combining Eqs. (2) and (3), one can obtain Eq. (4).

$$M_c = \frac{M(C_f - C_{fi})}{1 - C_{fi}} \tag{4}$$

C_{fi} can be estimated from the temperature of the crystalline layer before sweating. The concentration of inclusions can be assumed to be in equilibrium at a given temperature if the layer stays at that constant temperature for a few hours. In a eutectic system, the relationship between concentration and temperature is expressed by

$$C_{fi} = \alpha T_o + \beta \tag{5}$$

which is valid for concentrations above 60% in a caprolactam–cyclohexanon mixture. In this system, α and β are 0.0145 and 0.00706, respectively (12), T_o means temperature of the crystalline layer retained for 12 hr before sweating of the crystalline layer, in Celcius.

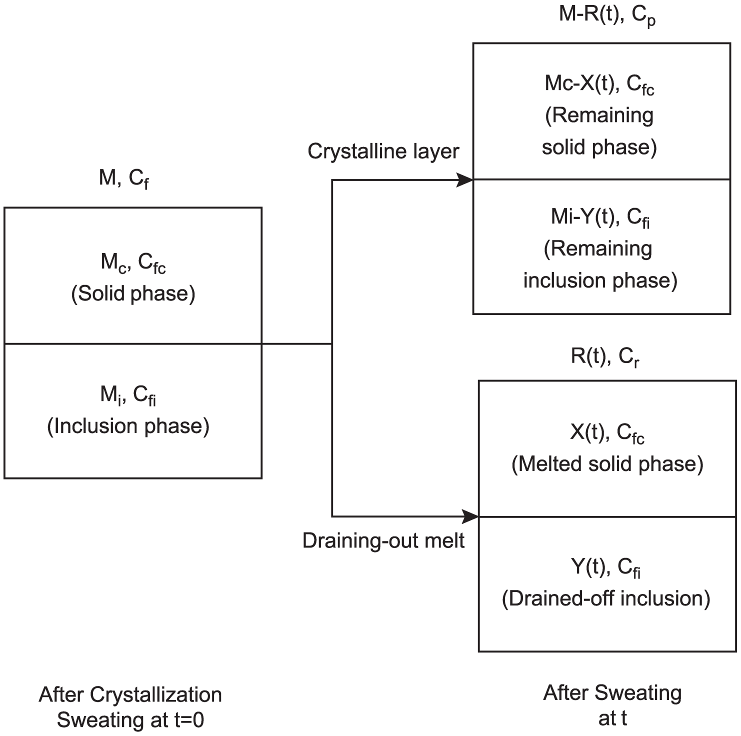

Figure 7. Block diagram for material flow in sweating operation.

During the sweating, crystal phase is melted partially, while the inclusion phase is drained-out with the melted crystalline material. The material that remains in the residual melt drained out during the sweating operation can be expressed as:

$$X(t) + Y(t) = R(t) \tag{6}$$

$$X(t)C_{\mathrm{fc}} + Y(t)C_{\mathrm{fi}} = R(t)C_{\mathrm{r}}(t) \tag{7}$$

where $X(t)$, $Y(t)$, and $R(t)$ are the amount of partially melted crystal, amount of drained out inclusions with the melted crystal, and the amount of sweat drained out at sweating time t, respectively.

By combining Eqs. (6) and (7), $X(t)$ can be expressed by

$$X(t) = \frac{R(t)C_{\mathrm{r}}(t) - R(t)C_{\mathrm{fi}}}{1 - C_{\mathrm{fi}}} \tag{8}$$

$Y(t)$ can be calculated by combining Eqs. (6) and (8). Thus, $X(t)$ and $Y(t)$ can be obtained from the experimental data of the residual melt.

When the crystalline layer is melted from its surface, the heat balance for melting of the crystalline layer as far as the sweating process is concerned can be expressed as:

$$-\lambda \frac{\mathrm{d}X(t)}{\mathrm{d}t} - kS\frac{\mathrm{d}T}{\mathrm{d}x} = hS\Delta T \tag{9}$$

The first term on the left-hand side is the heat transfer rate derived by melting of the crystalline layer, the second term on the left-hand side is the heat transferred by conduction in the solid phase, and the term on the right-hand side is the heat transferred by convection from the warm side onto the surface. The second term is neglected when compared to the first latent term.

$$-\lambda \frac{\mathrm{d}X(t)}{\mathrm{d}t} = hS\Delta T \tag{10}$$

where surface area of the crystalline layer S is varied with the sweating time t. Surface area of the layer is expressed as:

$$S = \left(\frac{4\pi L}{\rho_s}\right)^{1/2} (V_{\mathrm{cry}}\rho_s + M_c - X(t))^{1/2} \tag{11}$$

where V_{cry}, L, λ, k, h and ΔT are volume of the crystallizer, length of the crystallizer, latent heat of the crystal, thermal conductivity, heat transfer coefficient, and driving force for sweating process, i.e., the difference between the melting point of caprolactam and sweating temperature. When λ, h, L, and ΔT are considered to be constant during the sweating period, one can combine Eqs. (10) and (11) with an initial condition of $X(0) = 0$ and derive the following equation:

$$X(t) = -A(0.25At^2 + B^{1/2}t) \tag{12}$$

where $A = (-h/\lambda)(4\pi L/\rho_s)^{1/2}\Delta T$, $B = M_c + V_{\mathrm{cry}}\rho_s$, and $V_{\mathrm{cry}} = (\pi D_{\mathrm{cry}}^2/4)L$.

From the results, it can be said that the effect of sweating on purity of crystalline layers depends on the configuration of the crystalline layer, which affects the inclusion fraction of the layer. In addition, degree of superheating can be used to control the sweating rate. Many authors reported the fact that the purity of crystals was related to the ratio of crystal mass to sweated crystals mass (1,4,6). The mechanism of purification of sweating is: first, the crystalline layer with impurity inclusions are melted and impurity inclusions are moved into the surface of layer, and second, the melted sweat rinses the surface of crystalline layer and the drained out impurity inclusions adhere to the surface. Optimization of the sweating process leads to minimization of the production cost by controlling the amount of sweating. A model is required to predict the purity and yield of a crystalline layer for any sweating time. During a sweating operation, inclusions entrapped in the crystalline layer are removed partly by the melted sweat. The rate of removal of inclusions is related to the rate of melting of crystals.

Figure 8 shows a semi-log plot of $Y(t)/M_\mathrm{i}$ vs. $X(t)/M_\mathrm{c}$ in which sweating is carried out for the crystalline layers obtained at three cooling rates for three feed compositions. As shown in Fig. 8, despite the conditions of crystallization and sweating operations, the plots of all data in log–log coordinates give a straight line with a little scattering. As a result, the amount of inclusions drained-out during sweating is found to depend on the amount of crystal melted in the crystalline layer. The drained-out amount is related to the melting amount for any sweating time t. From Fig. 8, $Y(t)/M_\mathrm{i}$ can be correlated with function of $X(t)/M_\mathrm{c}$

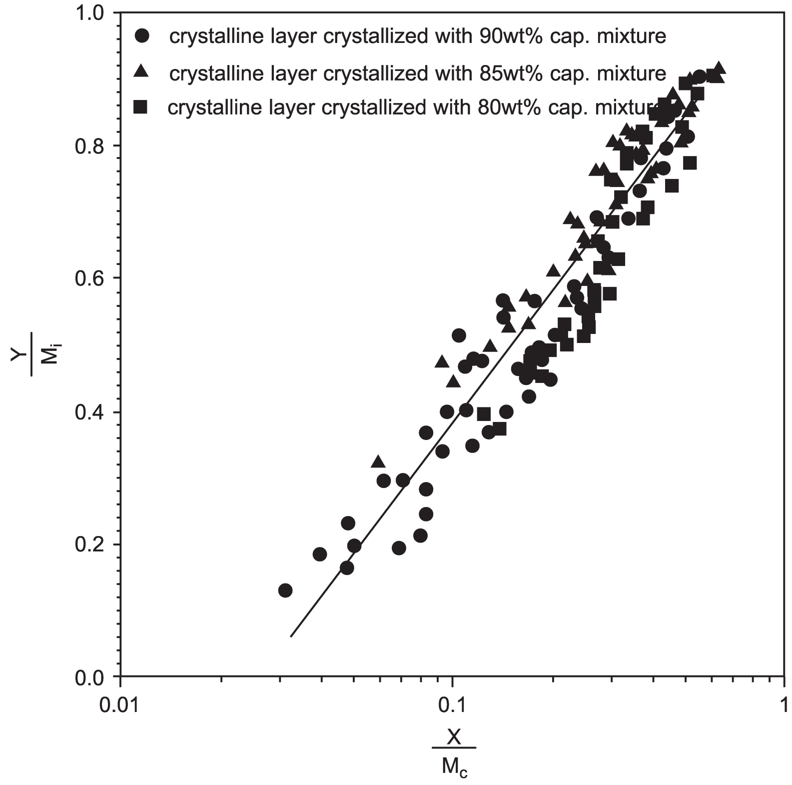

Figure 8. Y/M_i as a function of X/M_c.

as follows:

$$\frac{Y(t)}{M_\mathrm{i}} = a \ln\left[\frac{X(t)}{M_\mathrm{c}}\right] + b \tag{13}$$

where a and b are constants for correlation between draining-out rate and melting rate. The values of correlation constants a and b defined in Eq. (13) are found to be 0.292 and 1.028, respectively.

Combination of Eqs. (12) and (13) gives the following equation:

$$Y(t) = M_\mathrm{i}\left\{a \ln\left(-\frac{0.25A^2t^2 + AB^{1/2}t}{M_\mathrm{c}}\right) + b\right\} \tag{14}$$

Purity and Yield in the Sweating Operation

From the balance material of the crystals remaining during sweating (see Fig. 7), composition of the remaining crystals $C_\mathrm{p}(t)$ is obtained by the following equation.

$$C_\mathrm{p}(t) = \frac{1 + KC_\mathrm{fi}}{1 + K} \tag{15}$$

where $K = (M_\mathrm{i} - Y(t))/(M_\mathrm{c} - X(t))$

K is rewritten by combining Eqs. (12) and (14).

$$K = \frac{(F - M_\mathrm{c})\left\{1 + a \ln\left(-\frac{0.25A^2t^2 + AB^{1/2}t}{M_\mathrm{c}}\right) + b\right\}}{(0.5At + B^{1/2})^2 - V_\mathrm{cry}\rho_\mathrm{s}} \tag{16}$$

The yield of remaining crystals is expressed by

$$P(t) = \frac{(1 + K)(M_\mathrm{c} - X(t))}{M} \tag{17}$$

where $P(t)$ is the yield of crystalline layer during the sweating operation. Purity and yield of the crystalline layer during sweating operations can be predicted by physical properties like h, λ, and ρ, the operating conditions like ΔT, and correlation constants a and b by Eqs. (15) and (17), respectively.

The sweating process includes partial melting of the crystal phase and draining out of the inclusions. In sweating, the path for the melt to go out of the crystal line material is enlarged, which accelerates draining-out of inclusions from the layer. It depends on the sweating temperature and the amount of inclusions. Therefore, sweating time can be optimized by adjusting these two variables.

Figure 9 shows a comparison between the calculated and experimental values for melted fractions of crystals and removed inclusion fraction during sweating at a superheating degree of 10°C. The crystalline layer was formed for 90 wt% caprolactam mixture at a cooling rate of 0.1K/min. The lines are calculated from Eqs. (14) and (16), in which the heat transfer coefficient is estimated to be 1.5 W/m^{2}K. Similar results are also obtained from all tests. Heat transfer occurs between the crystalline layer and its surrounding atmosphere as the dry sweating is carried out. A heat transfer coefficient for a cylindrical tube with motionless gas fluid can be considered in this sweating operation. In this case, $hD_{\mathrm{cry}}/k_{\mathrm{gas}} = 2$ is approximately available (14). The calculated heat transfer coefficient is then about 1.9 W/m^{2}K. As a result, the experimental data are lower than the calculated value. This suggested that during heat transfer in a sweating operation, a heat transfer resistance of the

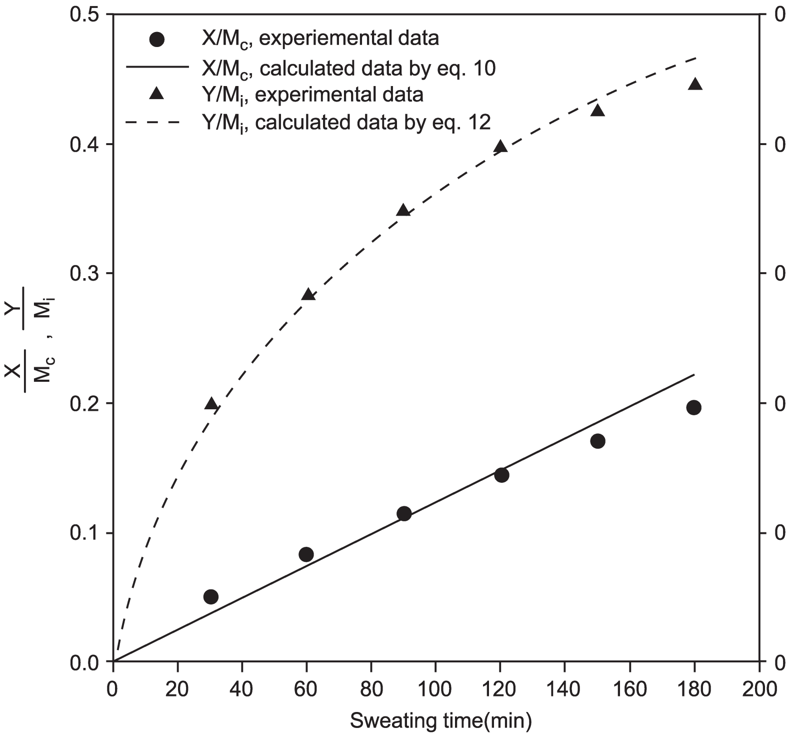

Figure 9. Comparison between the calculated and experimental data for Y/M_{i} and X/M_{c}.

drained out melt exists. Eventually, the heat transfer coefficient obtained during sweating operations can be used as a scale-up parameter for sweating operations.

For sweating operations, purity and yield of crystalline layers were calculated from Eqs. (15) and (17), respectively. Figure 10 shows plots of purity and yield of the layer against any sweating time, when the superheating degree was 10°C. The crystalline layer was obtained for 85 wt% caproalctam at the cooling rate of 0.1K/min. According to the model expressed by Eqs. (15) and (17), it can be expected that the crystalline layer can be purified by sweating operation. Figure 11 shows a comparison between the calculated and all experimental data for the composition of the crystalline layers purified during the sweating operations. In all the runs, heat transfer coefficients were in the range from 1.5 to 2.8 W/m^{2}K. The correlation model can, therefore, be used for a quantitative estimation of the sweating operation.

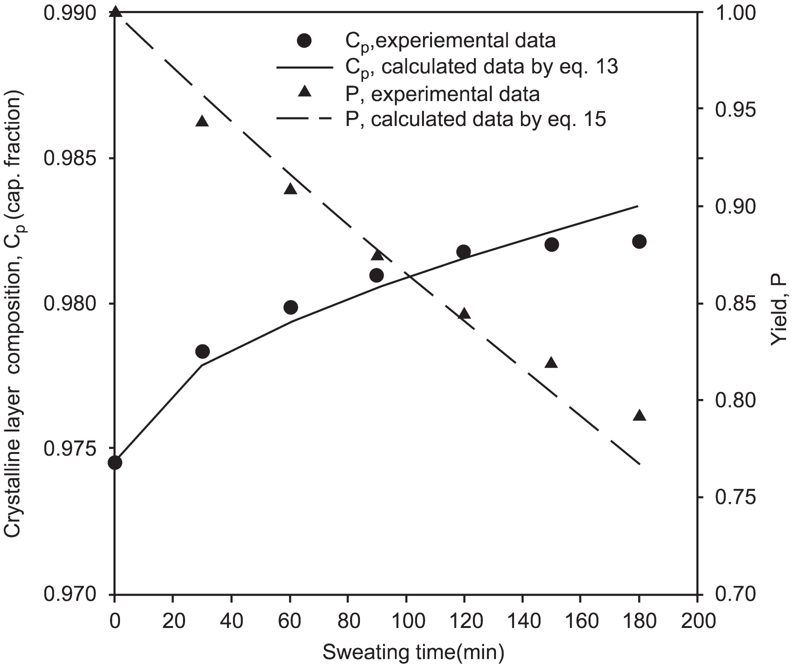

Figure 10. Comparison between the calculated and experimental data for purity and yield of crystalline layer during sweating operations with $\Delta T = 10$K (crystalline layer used was formed in 85 wt% mixture and cooling rate 0.1K/min).

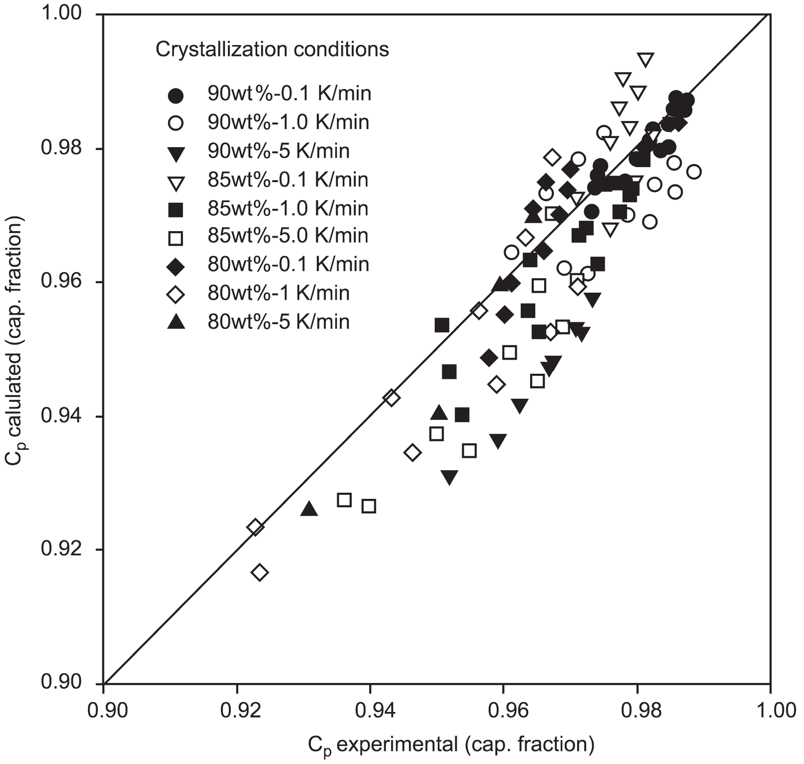

Figure 11. Comparison between the calculated and experimental data for purity of crystalline layer during sweating operations (for all the crystalline layers used in this study).

CONCLUSIONS

Sweating operations were carried out for various crystalline layers obtained in the layer-melt crystallizations. The layer-melt crystallizations were carried out at various cooling rates and various feed compositions of a caprolactam mixture. Inclusion fractions were obtained for both parameters. The purification effects of sweating parameters including sweating time, initial inclusion amount before sweating and sweating temperature were studied. The degree of superheating was investigated to control the sweating rate. A model combining heat balance and mass transfer for the movement of the inclusions was developed. The model was verified with experimental data.

NOMENCLATURE

a	constant in Eq. (13)
A	parameter defined in Eq. (12) ($\mathrm{kg}^{0.5}$/sec)
b	constant in Eq. (13)
B	parameter defined in Eq. (12) (kg)
C_f	concentration of the crystalline layer before sweating (kg/kg)
C_fc	concentration of pure crystal phase before sweating, unity in eutectic mixture (kg/kg)
C_fi	concentration of inclusions in the crystallization layer before sweating (kg/kg)
C_p	concentration of the crystalline layer during sweating operation (kg/kg)
C_r	concentration of sweat drained out (kg/kg)
D_cry	diameter of cylindrical tube crystallizer (m)
h	heat transfer coefficient ($\mathrm{W/m^2K}$)
I	ratio of inclusion amount to total mass of crystalline layer (kg/kg)
K	parameter defined in Eq. (16)
k	thermal conductivity (W/mK)
k_gas	thermal conductivity of gas phase (W/mK)
L	height of crystallizer (m)
M	total mass of crystalline layer before sweating (kg)
M_c	amount of pure crystal phase before sweating (kg)
M_i	amount of inclusion phase before sweating (kg)
$R(t)$	amount of draining-out sweat at the sweating time t (kg)
S	surface of the crystalline layer ($\mathrm{m^2}$)
t	sweating time (sec)
T_o	temperature before sweating (°C)
ΔT	superheating degree (°C)
V_cry	volume of crystallizer ($\mathrm{m^3}$)
$X(t)$	amount of crystals melted partially at the sweating time t (kg)
$Y(t)$	amount of inclusions drained out at the sweating time t (kg)
α	constant in Eq. (5) (1/K)
β	constant in Eq. (5) (kg/kg)
λ	heat of melt (J/kg)
ρ_c	density of crystal ($\mathrm{kg/m^3}$)

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