Design method for reasonable operation of industrial crystallizer using neural network model

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The use of a neural network model to determine the operational conditions for the production of crystals of specific size in a continuous industrial crystallizer with an actual heat exchange area of $400m^2$ is discussed. The product crystal size is well determined by the neural network model consisting of three explanatory variables: steam flow rate, suspension density of crystals in a crystallizer and frequency of the circulation pump. The most suitable learning number of iterations for the neural network model obtained by the leave-one-out cross-validation method is 50,000, and the mean estimated error of the product crystal size is about 0.03mm. From these results, it is believed that the neural network model is sufficiently accurate for practical use, and is effective for the design of the operational conditions required for manufacturing products with a specific crystal size in industrial crystallization. A practical method for constructing the neural network model is proposed.

1. INTRODUCTION

In the operation of an industrial crystallizer for manufacturing salt, there exist various operational conditions that are thought to affect the product crystal size. Toyokura and Aoyama proposed a design theory for the operation of a continuous industrial crystallizer based on the relationship between productivity and product crystal size distribution [1]. It is difficult to determine precisely the relationship between product crystal size and other operational conditions, for example, circulation rate of slurry suspended in a crystallizer or crystallization temperature.

In this study, a neural network model (NN model) constructed with data obtained under various operational conditions is utilized to determine the most suitable operational conditions for the production of crystals of specific size in a continuous industrial crystallizer [2].

2. OUTLINE OF NEURAL NETWORK

The neural network has high capability as a tool for approximating nonlinear data. The neural network is composed of a dependent variable layer, a multiple explanatory variables layer and a calculating network called the intermediate layer, as shown in Figure 1.

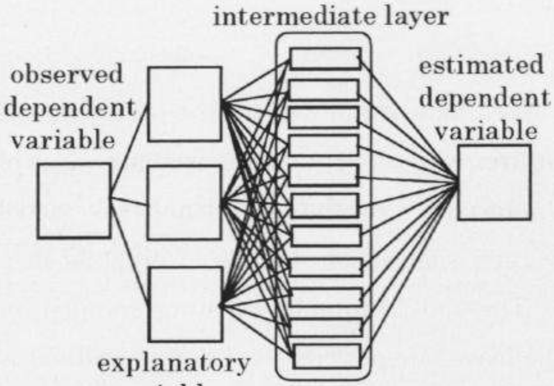

Figure 1 Outline of neural network

To construct a complete NN model, the dependent variables estimated through the intermediate layer are evaluated, then, if the estimated error can not be permitted, this learning is repeated by the back-propagation method [3].

3. EXPERIMENTAL METHOD

The schematic diagram of the evaporating industrial crystallizer with an actual heat exchange area of $400m^2$ used in this study is shown in Figure 2.

In this study, steam flow rate, frequency of a circulation pump and suspension density of crystals in a crystallizer were chosen as the explanatory variables that affected product crystal size.

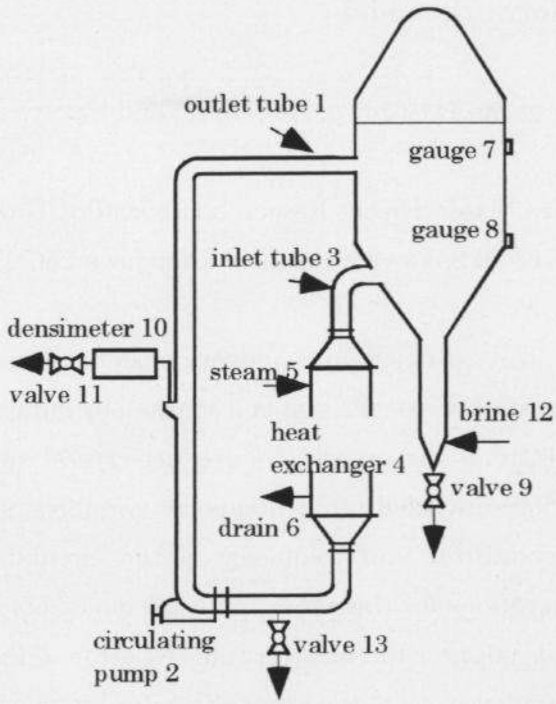

Figure 2 Industrial crystallizer used in this study

The flow rate of drain 6, which is equal to the steam flow rate, was controlled at a constant value within the range of 7~14ton/h. The frequency of circulation pump 2 characterized by the flow rate of slurry in a crystallizer was fixed at 45, 50 or 60Hz. The pressure difference ΔP measured between two pressure gauges 7 and 8 (Δh=2,850mm) was controlled at constant value within the range of 3700~4300mmH_2O, and the density of mother liquor ρ_m observed by densimeter 10 was controlled at 1,200~1,220kg/m^3. The suspension density of crystals in a crystallizer

(1-ε) was calculated using equation 1 [4].

The size distribution of the product crystals removed from valve 9 was measured at 2 hour intervals. When the size distribution of the product crystals became almost constant, the operation of the crystallizer was regarded to have reached the steady state, and the experiment was terminated.

$$(1\text{-}\varepsilon)=(\Delta P/\Delta hg\text{-}\rho_m)/(\rho_C\text{-}\rho_m) \quad (1)$$

ρ_C :density of NaCl crystal

g: acceleration due to gravity

4. RESULTS AND DISCUSSIONS

4.1 Most suitable modeling condition

The most suitable learning number for the construction of the NN model was determined by the leave-one-out cross-validation method (LCV method) [5]. In the LCV method, the NN model is constructed with the remaining data after removal of a datum from all the obtained data, and then the dependent variable under each removal condition is estimated using the obtained NN model. When the estimated error was the minimum, the most suitable learning number could be determined.

The change of correlative coefficient and the mean deviation between measured product crystal sizes and estimated ones obtained with the LCV method are shown in Figure 3.

The estimated accuracy was maximum when the learning number was 50,000, and the mean estimated error of the product crystal size was about 0.03mm. Therefore, the most suitable learning number for the construction of the NN model was 50,000.

The main reason that the estimated accuracy decreased after the learning number of 50,000 was due to the phenomenon called the over learning [5].

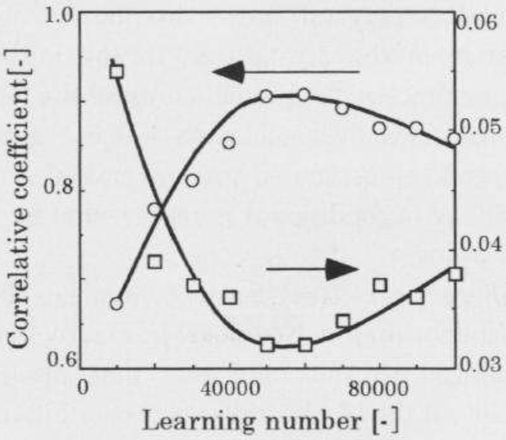

Figure 3 Estimated results

Figure 4 shows the image of over learning. In Figure 4, white circles indicate real values of product crystal size under condition A, and the correlation between the product crystal size and condition A is shown by a dashed line.

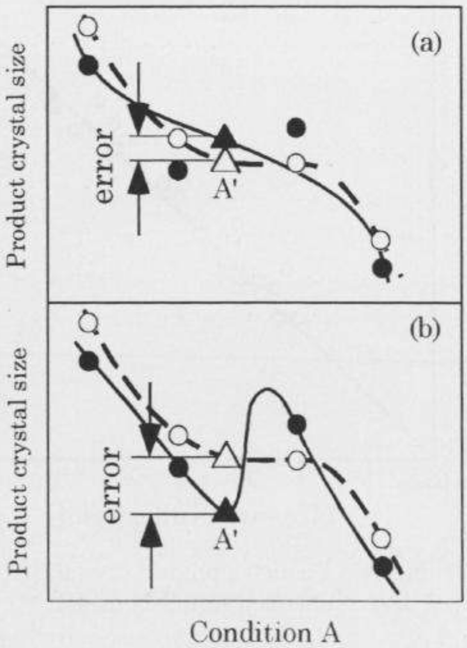

Figure 4 Image of over learning

Black circles represent practically observed values which include errors in measurement of product crystal size distribution or operation of the crystallizer. In the initial learning process, the prediction using the NN model is shown by a solid curve line in Figure 4-(a), and the estimated product crystal size at point A' of condition A is represented by a black triangle.

By iteration of the learning number, the prediction using the NN model in Figure 4-(a) is changed to the solid line that passes through all the black circles as shown Figure 4-(b), and the estimated error increases comparing with one in the initial learning process.

4.2 Construction of NN model

The NN model was constructed using all data obtained in this study at a learning number of 50,000. The predicted product crystal size using the NN model is plotted against measured ones in Figure 5.

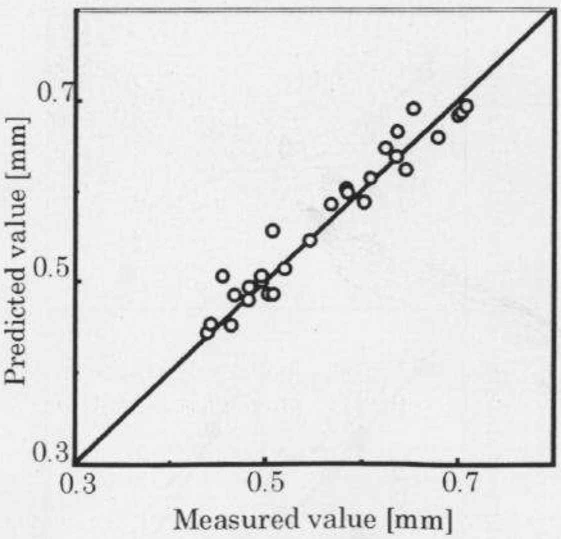

Figure 5 Predicted product crystal sizes obtained from NN model

The product crystal size obtained from the multiple regression model, which utilizes product crystal size as the independent variable, and steam flow rate, frequency of circulation pump and suspension density of crystals in a crystallizer as the explanatory variables, is shown in Figure 6.

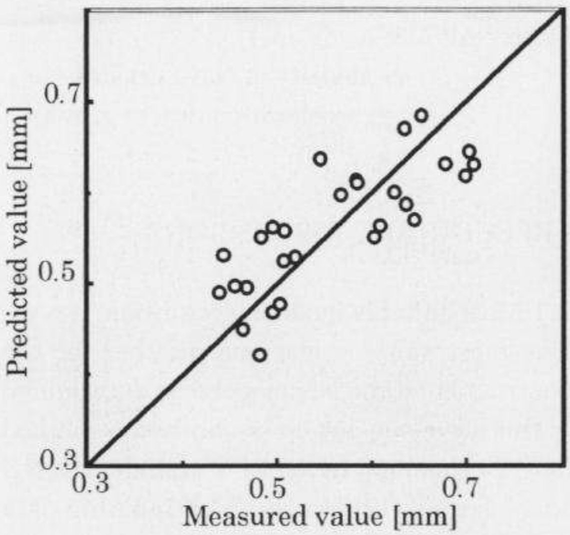

Figure 6 Predicted product crystal sizes obtained from multiple regression model

In the NN model, the product crystal size was well correlated with the three explanatory variables: the correlative coefficient between predicted values and measured ones was above 0.97. On the other hand, the predicted values using the multiple regression model showed poor correlation with the measured values, i.e., the correlative coefficient was below 0.8.

From these results, it is thought that the NN model is effective as a design method of the operation for production of crystals of specific size in industrial crystallization.

4.3 Characteristic of the NN model

The change in product crystal size with the steam flow rate and the suspension density of crystals in a crystallizer at the circulation pump frequency of 45Hz predicted using the NN model is shown in Figure 7. The product crystal size rapidly and directly increased with the suspension density of crystals in a crystallizer, but increased in a curve with the steam flow rate.

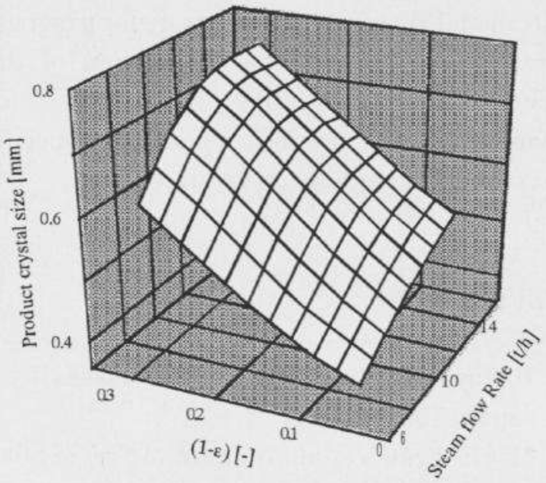

Figure 7 Change of product crystal size at circulation pump frequency of 45Hz

Figure 8 shows the change in product crystal size at the circulation pump frequency of 50Hz. The product crystal size is increased in the same manner as that in the case of 45Hz.

Figure 9 shows the change in product crystal size at the circulation pump frequency of 60Hz. The product crystal size slightly decreased with an increase in the suspension density of crystals in a crystallizer, and was almost constant with the increase in steam flow rate.

From these results, it is thought that the complicated relationship among product crystal size and various operational conditions is well correlated by the NN model.

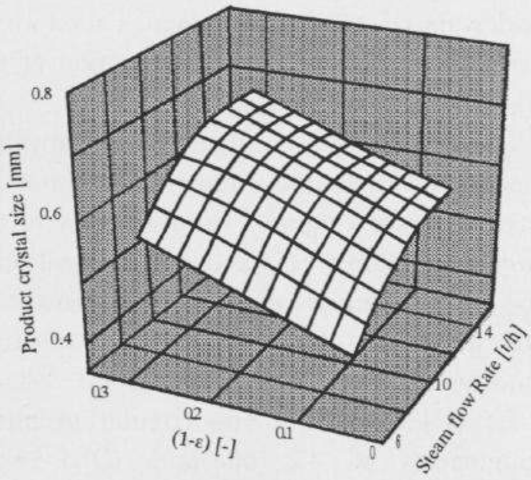

Figure 8 Change of product crystal size at circulation pump frequency of 50Hz

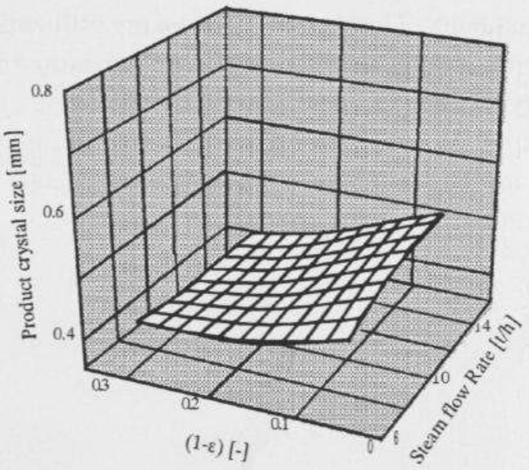

Figure 9 Change of product crystal size at circulation pump frequency of 60Hz

4.4 Practical method for construction of NN model

The NN model requires many crystallization data to improve its accuracy for the determination of the most suitable operational condition. However, it is difficult to obtain such data quickly in a salt-making factory because each product is manufactured under fixed set of conditions. Therefore, a practical method for the construction of the NN model is proposed in this study.

The NN model is divided into multiple models to reduce the number of explanatory variables. For example, the frequency of the circulation pump was fixed in the operation of the industrial crystallizer. In this case, the NN model could be divided into multiple models.

The NN models at the circulation pump frequencies of 45, 50 and 60Hz were constructed, and the correlative coefficient between the measured product crystal size and the predicted one exceeded 0.98. This was because these models were hardly affected by the non-linear effect of the circulation pump frequency. The accumulation of crystallization data in the daily operation of an industrial crystallizer is facilitated by reducing the number of explanatory variables, and finally a complete NN model can be constructed by joining the data used in each model.

5. CONCLUSIONS

The use of a NN model to determine the operational conditions for the production of crystal of specific sizes in a continuous industrial crystallizer with an actual heat exchange area of $400m^2$ was discussed. The product crystal size was well determined by the NN model consisting of three explanatory variables: steam flow rate, suspension density of crystals in a crystallizer and frequency of the circulation pump. It is believed that the NN model is sufficiently accurate for practical use, and is effective for the design of the operational conditions required for manufacturing products with a specific crystal size in industrial crystallization.

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