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Performance Estimation and Optimal Operation of a CO_2 Heat Pump Water Heating System*

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Abstract

The daily performance of a CO_2 heat pump water heating system with a hot water storage tank is affected by the history of daily hot water demand and heat pump operating conditions. To attain the maximum system performance, it is important to estimate the daily changes in the system performance values accurately in relation to those in hot water demand and heat pump operating conditions, and determine the operating conditions optimally based on the estimation. In this paper, neural network models are used for this estimation, and the values of model parameters are identified by a global optimization method. In addition, the outlet water temperature during operation and the inlet water temperature for shutdown are determined to maximize the system efficiency subject to a lower limit for the volume of unused hot water. The validity and effectiveness of this approach are ascertained by a numerical study using a simulated hot water demand.

Keywords: *Heat pump; water heater; thermal storage; natural refrigerant; carbon dioxide; system performance; estimation; optimization.*

1. Introduction

Hot water demand occupies about one-third of the energy consumption in the residential sector in Japan, and energy saving in hot water supply has been an important issue. Under this situation, water heating systems each of which is composed of a heat pump using CO_2 as a natural refrigerant and a hot water storage tank have been developed and commercialized widely (Saikawa, 2004; Hashimoto, 2006). The performance of CO_2 heat pumps has been enhanced dramatically through the technological development of their components such as compressors and gas coolers. On the other hand, importance has also been given to the performance of water heating systems in case they are operated under a daily change in hot water demand.

The performance of the CO_2 heat pump only, or coefficient of performance (COP) is affected by the air temperature as well as the inlet and outlet water temperatures. Many theoretical and experimental studies have been conducted for the performance analysis on CO_2 heat pumps (Hwang and Radermacher, 1998; Nekså et al., 1998; Saikawa et al., 1999; Saikawa and Hashimoto, 2001; Nekså, 2002; White et al., 2002; Skaugen et al., 2002; Richter et al., 2003; Yokoyama et al., 2006; Laipvadit et al., 2008; Yan et al., 2010; Sarkar et al., 2010; Yamaguchi et al., 2011). On the other hand, the performance of the water heating system composed of the CO_2 heat pump and storage tank is affected by many conditions. The ambient conditions such as air and feed water temperatures, the hot water demand, and the operating conditions such as startup and shutdown, and outlet water temperature during operation of the CO_2 heat pump affect the inlet water temperature and resultantly the COP through the temperature distribution in the storage tank. In addition to the COP, the storage and system efficiencies, and the volumes of stored and unused hot water are considered as system performance values, and these are also affected by the aforementioned various conditions through the temperature distribution in the storage tank. As a result, the system performance is affected by the operational history on past several days, and changes complexly with days. Therefore, in order to attain the maximum system performance, it is necessary to estimate the daily changes in system performance values accurately in relation to those in the ambient conditions, hot water demand, and operating conditions, and determine the operating conditions optimally based on them.

Some studies have been conducted for the performance analysis on water heating systems (Cecchinato et al., 2005; Stene, 2005; Minetto, 2011). However, few studies have been conducted in consideration of daily changes in the aforementioned conditions. In order to investigate the daily changes in system performance values, laboratory and field tests have been tried under simulated and practical hot water demands, respectively. However, hot water demands depend on residential houses, and it takes extremely long time to conduct the tests. Thus, it is not necessarily easy to investigate the system performance systematically and obtain useful results only by limited tests. On the other hand, numerical simulations have been conducted in place of the tests (Yokoyama et al., 2007; Yokoyama et al., 2008). The daily changes in system performance values have recently been investigated under a daily change in hot water demand by a numerical simulation (Yokoyama et al., 2010b; Yokoyama et al., 2010a). However, it takes long times to estimate the daily changes in system performance values by numerical simulations with complex computations, and thus it is difficult to determine the operating con-

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ditions optimally by numerical simulations, because the optimization needs to estimate the daily changes in system performance values repeatedly under various operating conditions. Therefore, it is necessary to establish easier methods of estimating the daily changes in system performance values accurately, and determining the operating conditions optimally.

In this paper, a method of estimating the daily changes in system performance values by neural network models is proposed for a CO_2 heat pump water heating system. In addition, the values of model parameters are identified by a global optimization method. Moreover, the operating conditions are determined optimally based on the system performance values obtained by the estimation. This approach is applied to estimating the daily changes in system performance values and determining the operating conditions optimally under a simulated monthly hot water demand, and its validity and effectiveness are investigated through the comparison between estimated and simulated system performance values.

2. CO_2 Heat Pump Water Heating System

Figure 1 shows the configuration of the CO_2 heat pump water heating system investigated in this paper. This system is composed of a CO_2 heat pump and a hot water storage tank. The CO_2 heat pump is composed of a compressor, a gas cooler, an expansion valve, and an evaporator. The system is equipped with a fan, a pump, and motors M1 to M3 as auxiliary machinery. Here, inlet and outlet water is defined as water at the inlet and outlet of the gas cooler, respectively. In the charging mode, the system heats water using the refrigeration cycle of the CO_2 heat pump and stores hot water in the storage tank. In the tapping mode, hot water stored in the storage tank is retrieved and supplied to a tapping site.

3. Performance Estimation and Optimal Operation

3.1 Basic Assumptions

Existing systems are operated under complex conditions. In this paper, however, the performance estimation and optimal operation are considered under simple conditions by setting the following basic assumptions:

- The charging and tapping modes do not arise simultaneously and switch alternately. Namely, the heat pump is operated during the period from 0:00 to 6:00, and the hot water demand arises during the period from 6:00 to 24:00.
- The outlet water temperature during operation and the inlet water temperature for shutdown are considered as fundamental operating conditions of the heat pump. The heat pump is shut down with the shutdown condition that the inlet water temperature attains an appropriate value satisfied, and is started up at an appropriate time so that it is shut down before 6:00.
- Since the system performance is determined certainly by physical characteristics, it may be estimated accurately. However, since the hot water demand affecting the system performance is essentially uncertain, it cannot by predicted accurately by any methods. At the first phase of this research, it is assumed that the hot water demand is certainly given, and it is used to estimate the system performance.
- The system performance depends on ambient conditions such as air and feed water temperatures. However, the system performance during a short period hardly depends on the ambient conditions. Therefore, it is assumed that the ambient conditions are constant.

3.2 Evaluation of System Performance Values and Hot Water Demand

To investigate the daily changes in system performance values, each system performance value is evaluated daily as follows:

- The COP is evaluated as the ratio of the total heat output to the total power consumption during the period from 0:00 to 6:00.
- The storage efficiency is evaluated as the ratio of the total hot water demand during the period from 6:00 to 24:00 on the previous day to the total heat output during the period from 0:00 to 6:00 on the current day.
- The system efficiency is evaluated as the ratio of the total hot water demand during the period from 6:00 to 24:00 on the previous day to the total power consumption during the period from 0:00 to 6:00 on the current day. Thus, the system efficiency is equal to the product of the COP and storage efficiency.
- The volumes of stored and unused hot water are defined as the volumes of hot water which can be used for its supply at 6:00 after the charging mode and at 24:00 after the tapping mode, respectively. Here, the volume of hot water is defined as the one with a temperature of 42 °C obtained by mixing the hot water with temperatures higher than 42 °C and the feed water.

The total hot water demand during the period from 6:00 to 24:00 is also evaluated as the volume of hot water with a temperature of 42 °C similarly as the volumes of stored and

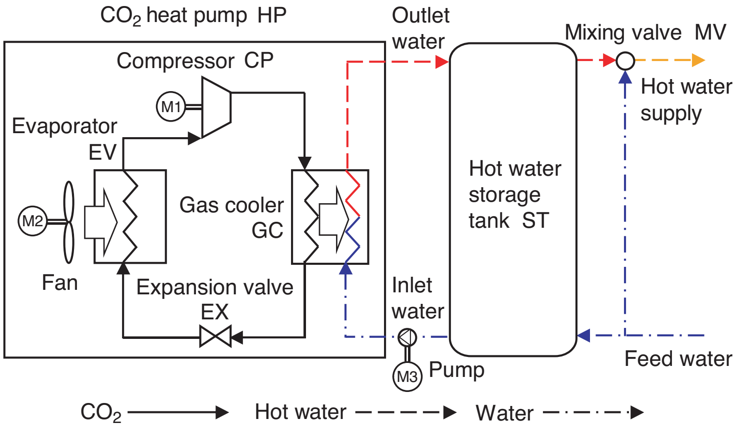


Figure 1. Configuration of CO_2 heat pump water heating system.

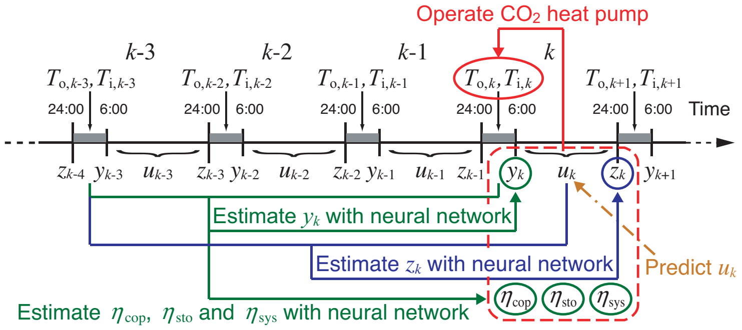


Figure 2. Procedure for performance estimation and optimal operation.

unused hot water.

3.3 Procedure for Performance Estimation and Optimal Operation

A procedure is presented to estimate the system performance values accurately and determine the operating conditions optimally.

Figure 2 shows the procedure in which the operational history on the past three days is used as an example. The outlet water temperature during operation and the inlet water temperature for shutdown of the heat pump are designated by T_o and T_i, respectively. The volumes of hot water stored at 6:00 and unused at 24:00 are designated by y and z, respectively. The total hot water demand during the period from 6:00 to 24:00 is designated by u. The subscript k denotes a value on the kth day. In addition, the COP, storage efficiency, and system efficiency are designated by η_{cop}, η_{sto}, and η_{sys}, respectively.

First, at 0:00 on the kth day, the volume of hot water stored at 6:00 on the kth day y_k is estimated using the outlet water temperature during operation, the inlet water temperature for shutdown, the volumes of stored and unused hot water, and the total hot water demand on the (k–3)th to (k–1)th days as well as the candidates for the outlet water temperature during operation and the inlet water temperature for shutdown on the kth day. Next, the volume of hot water unused at 24:00 on the kth day z_k is also estimated using the estimated value for the volume of stored hot water y_k and the predicted value for the total hot water demand u_k on the kth day in addition to the aforementioned values. Finally, the COP η_{cop}, storage efficiency η_{sto}, and system efficiency η_{sys} on the kth day are also estimated similarly as the volume of stored hot water y_k. This is based on the following reasons: The COP depends on the inlet water temperature, and the inlet water temperature depends significantly on the temperature distribution in the storage tank at 24:00; The storage efficiency depends on the temperature distribution in the storage tank throughout the day, and is roughly expressed by the temperature distributions in the storage tank at 6:00 and 24:00; The system efficiency is equal to the product of the COP and storage efficiency, and is also roughly expressed by the temperature distributions in the storage tank at 6:00 and 24:00.

The optimal operating conditions are determined as follows: The aforementioned system performance values are estimated under all the possible combinations of the candidates for the outlet water temperature during operation and the inlet water temperature for shutdown of the heat pump as operating conditions; Based on the estimated system performance values, the optimal combination of the candidates for the operating conditions is selected so that an objective function is optimized subject to constraints. Figure 3 shows a flow chart for the concrete procedure of determining the optimal operating conditions based on the estimated system performance values. In this paper, the objective function to be maximized is the system efficiency so that the system performance can be enhanced as much as possible, and the constraint to be satisfied is that the volume of unused hot water is larger than a certain value so that the shortage in hot water supply can be avoided.

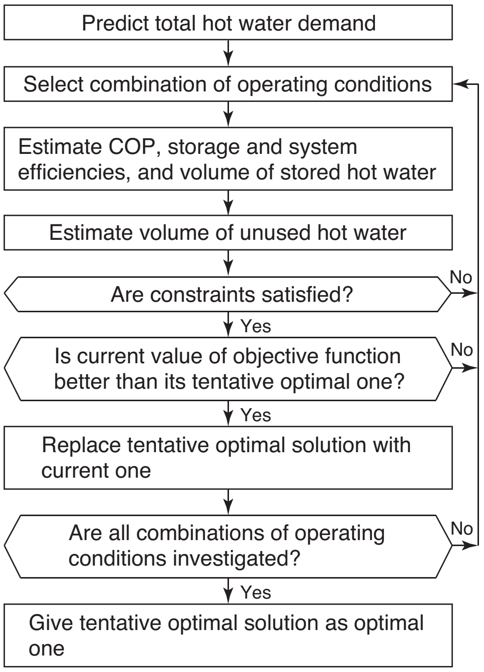


Figure 3. Flow chart for concrete procedure of determining optimal operating conditions.

3.4 Application of Neural Network Models

As shown in Figure 4, three-layered neural network models are used to estimate the system performance values. As aforementioned, each system performance value is estimated independently by the corresponding model. For long-term operation of existing systems, it is necessary to measure necessary data continuously and identify model parameter values repeatedly, and estimate system performance values correspondingly. Here, the estimation only for short-term operation is considered.

In the input layer, the operating conditions, the volumes of stored and unused hot water, and the total hot water demand on the past days as well as the operating conditions on the current day are adopted commonly as the inputs to the model to estimate all the system performance values. The estimated volume of stored hot water and the predicted total hot water demand on the current day are adopted additionally to estimate the volume of unused hot water. In the other layers, each neuron has multiple inputs and single output, and converts the weighted sum of the J inputs X_j minus the threshold θ to the output Y by the following response function:

$$Y = g\left(\sum_{j=1}^{J} w_j X_j - \theta\right) \qquad (1)$$

where w_j is the weight for each input. The sigmoid function is usually used as the response function $g(x)$. In this paper, however, the hyperbolic tangent function $g(x) = \tanh x$ is used to obtain positive and negative values from the output. Here, the value from the output ranges only from –1.0 to 1.0 by normalizing the values to the inputs and from the output in advance.

3.5 Identification of Model Parameter Values

To estimate the system performance values by the neural network models, it is necessary to identify the values of model parameters, weights and thresholds in Eq. (1). The squared error between the estimated value and the corresponding measured value is evaluated for each pattern, and its summation for all the patterns is minimized as the objective function to identify the values of model parameters. In the back propagation method, the error function for each pattern is minimized sequentially. Here, to secure the local optimality of solutions and make the convergence faster, the total error function for all the patterns is minimized simultaneously.

The search for local optimal solutions can be conducted by gradient methods for unconstrained nonlinear programming problems such as steepest descent, conjugate gradient, and quasi-Newton methods. However, these methods have the significant drawback that they can derive only local optimal solutions. In this paper, the modal trimming method proposed for nonlinear programming problems is adopted as a global optimization one (Yokoyama and Ito, 2005). This method has been applied to a neural network model for energy demand prediction, and its validity and effectiveness have been ascertained (Yokoyama et al., 2009).

The concept of the modal trimming method is shown in Figure 5. This method is composed of the following two procedures: A local optimal solution is searched to obtain a tentative global quasi-optimal one; A feasible solution with the value of the objective function equal to or smaller than that for the tentative global quasi-optimal one is searched to obtain an initial point for finding a better local optimal one. These procedures are repeated until a feasible solution with the value of the objective function equal to or smaller than that for the tentative global quasi-optimal one cannot be found, and the tentative global quasi-optimal one is adopted as the global quasi-optimal one. A local optimal solution is searched by a conventional gradient method. On the other hand, a feasible solution is searched by an extended Newton-Raphson method based on the Moore-Penrose generalized inverse of the Jacobi matrix of the objective function. The method can have a high possibility of deriving global optimal solutions, if it has the capability of global search for feasible ones.

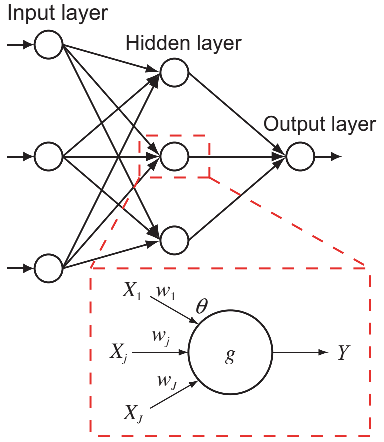


Figure 4. Three-layered neural network model.

The renewal of the values of the variables based on the extended Newton-Raphson method has the following features: In the region with a feasible solution, the renewal can have the convergence to it; In the region with no feasible solution, the renewal can create a chaotic behavior and has the capability of global search; In the region with no feasible solution, the renewal can also create a cyclically vibrating behavior and has the possibility of trap into a local optimal solution. To prevent the trap, a decelerating parameter is changed randomly in the range from 0.0 to 1.0 at each renewal.

4. Numerical Study on Performance Estimation

First, the parameter values of the neural network models are identified based on the system performance values obtained by numerical simulation, and their validity is investigated by comparing the estimated and simulated system performance values.

4.1 Numerical Simulation

It is necessary to use some system performance values to identify the values of model parameters. In applying the method of performance estimation to existing systems, measured data on system performance values must be used. In this paper, values obtained by numerical simulation are used in place of measured values. Here, only a summary on the numerical simulation is described as follows:

A simplified static model is adopted for the CO_2 heat pump (Yokoyama et al., 2010b): Although the heat pump includes several components, they are not taken into account explicitly, and it is expressed by one model. The mass flow rates and temperatures of water at the inlet and outlet, COP, heat output, power consumption, and air temperature are adopted as basic variables whose values are to be determined. The mass and energy balance relationships as well as the energy input and output relationship are adopted as basic equations to be satisfied. The remaining equations to be considered are approximate functions of the power consumption and COP, and they are expressed in relation to the air and inlet/outlet water temperatures.

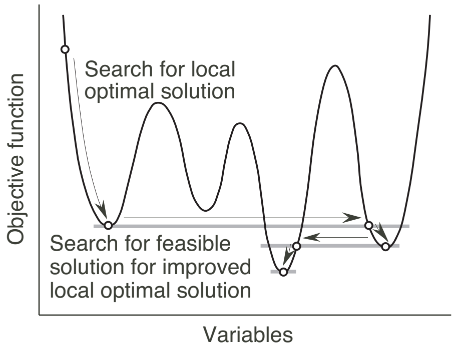


Figure 5. Concept of modal trimming method.

A detailed dynamic model is adopted for the storage tank (Yokoyama et al., 2007; Yokoyama et al., 2010b). To consider the one-dimensional vertical temperature distribution in the storage tank, it is vertically divided into many control volumes with the same volume, in each of which the water temperature is assumed to be constant. It is also assumed that the heat transfer occurs by water flow and heat conduction as well as heat loss from the tank surface. The mass flow rates and temperatures of water for each control volume are adopted as basic variables whose values are to be determined. The mass and energy balance relationships for each control volume are adopted as basic equations to be satisfied.

A static model is adopted for the mixing valve. The mass flow rates and temperatures of water at the inlets and outlet are considered as basic variables, and the mass and energy balance relationships are considered as basic equations.

At the connection points among the heat pump, storage tank, and mixing valve, connection conditions are taken into account to equalize the values of the corresponding variables. The outlet water temperature is given as a control condition. The feed water temperature as well as the mass flow rate and temperature of hot water to the tapping site are given as boundary conditions. The air temperature is given as an ambient condition.

For the concrete formulation of the simulation model, refer to reference (Yokoyama et al., 2010b). The validity of the simulation model has been verified through an experiment and a three-dimensional thermo-fluid numerical simulation. For this verification, also refer to reference (Yokoyama et al., 2010b).

The aforementioned modeling for the performance analysis by numerical simulation is conducted by a building block approach. The equations for the heat pump and mixing valve are static, while those for the storage tank are dynamic. Therefore, the modeling results in a set of nonlinear differential algebraic equations. It is solved by a hierarchical combination of the Runge-Kutta and Newton-Raphson methods.

4.2 Conditions for Numerical Simulation

A numerical simulation is conducted to obtain the daily changes in system performance values under a daily change in a simulated hot water demand. The following are the conditions used in the numerical simulation:

Table 1 shows the specifications of the CO_2 heat pump water heating system. The values of model parameters included in the aforementioned equations for the CO_2 heat pump and storage tank are estimated based on measured data for an existing system. The rated heat output of the heat pump is set at 4.5 kW. As an example, Figure 6 shows measured values and approximate functions for the power consumption, COP, and their resultant heat output of the heat pump in relation to the inlet water temperature for the air and outlet water temperatures of 16 and 85 °C, respectively. Here, each value is relative to its rated one for the air and inlet/outlet water temperatures of 16, 17, and 65 °C, respectively. This is because the existing system used here was developed initially by a manufacturer, and the values of COP of existing systems have been enhanced significantly afterwards.

Table 1. Specifications of CO_2 heat pump water heating system.

Equipment	Specification	Value
CO_2 heat pump	Heat output	4.50 kW*
	Power consumption	1.11 kW*
	COP	4.05*
Hot water storage tank	Volume	370 L
	Height	1.45 m
	Diameter	0.57 m
	Overall heat transfer coefficient	0.80 W/(m²·°C)

*Rated values for air and inlet/outlet water temperatures of 16, 17, and 65 °C, respectively

The volume of the storage tank is set at 370 L. The number of control volumes for the storage tank is set at 200, and the sampling time interval for the Runge-Kutta method is set at 10 and 180 s for the cases with and without water flow, respectively.

The mid-season is selected, and the corresponding air and feed water temperatures are set at 16 and 17 °C, respectively, which are prescribed by the Japanese Industrial Standards (Japanese Industrial Standards Committee, 2011).

The numerical simulation is conducted for 6 representative days and a month, or consecutive 30 days composed of the 6 representative days (Ukaji et al., 2004). On each representative day, an hourly change in a simulated hot water demand is prescribed. Figure 7 shows the total hot water demands on the 6 representative days. The 1st and 2nd representative days correspond to holidays with smaller and larger hot water demands, respectively, on which residents are out of the house. The 3rd and 4th representative days correspond to weekdays with smaller and larger hot water demands, respectively. The 5th and 6th representative days correspond to holidays with smaller and larger hot water demands, respectively, on which residents are in the house. As an example, Figure 8 shows the hourly change in the hot water demand on the 4th representative day. Here, the

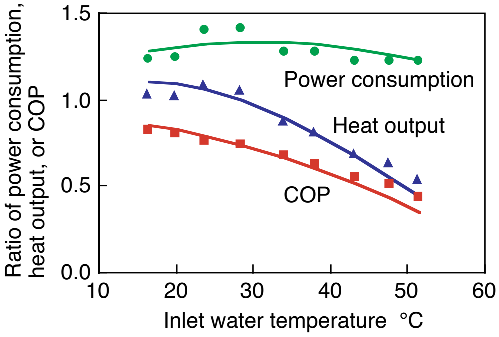


Figure 6. Performance characteristics of CO_2 heat pump

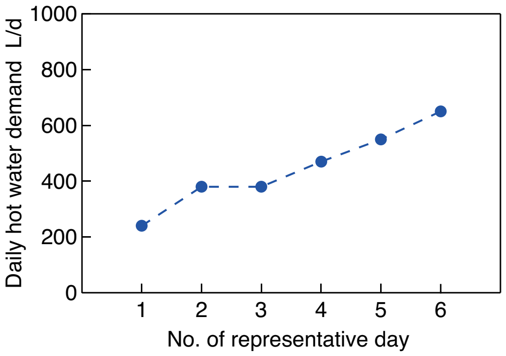


Figure 7. Total hot water demands on 6 representative days.

height and thickness of each vertical line means the flow rate and duration, respectively. The temperature of hot water supplied to the tapping site is set at 42 °C. Figure 9 shows the daily change in the total hot water demand on the 30 consecutive days.

The heat pump is started up at 0:00 and 1:00, when the total hot water demand on the previous day is larger than or equal to and smaller than 500 L/d, respectively. The outlet water temperature during operation is selected among 65, 75, and 85 °C, and the inlet water temperature for shutdown is selected among 30, 40, and 50 °C. The daily operating conditions are set by combining these values. 72 cases are investigated by the numerical simulation. Table 2 shows the conditions on the outlet water temperature during operation and the inlet water temperature for shutdown in cases 1 to 72. Cases 1 to 71 are used to identify model parameter values, while case 72 is used to verify the validity of model parameter values. In cases 1 to 54, the numerical simulation is conducted for the periodically steady state on each representative day under each combination of the constant outlet and inlet water temperatures. In cases 55 to 63, the numerical simulation is conducted on the consecutive days under each combination of the constant outlet and inlet water temperatures. In cases 64 to 66, the numerical simulation is conducted on the consecutive days under variable outlet water temperature and each constant inlet water temperature. In cases 67 to 69, the numerical simulation is conducted on the consecutive days under each constant outlet water temperature and variable inlet water temperature. In cases 70 to 72, the numerical simulation is conducted on the consecutive days under variable outlet and inlet water temperatures.

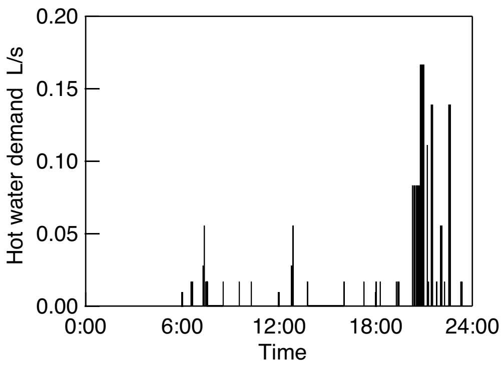


Figure 8. Hourly change in hot water demand on 4th representative day.

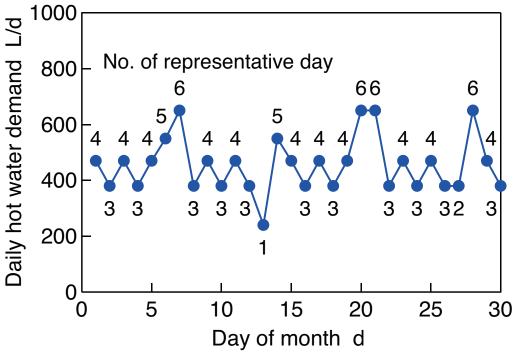


Figure 9. Daily change in total hot water demand on consecutive 30 days.

In cases 1 to 54, the initial temperature in the storage tank at 0:00 on the 1st day is set at 17 °C. In cases 55 to 72, the initial temperature distribution in the storage tank at 0:00 on the 1st day is set as follows: Since the 1st day corresponds to the 4th representative day as shown in Figure 9, the temperature distribution in the storage tank at 0:00 obtained for the periodically steady state on the 4th representative day is adopted as the initial temperature distribution in the storage tank at 0:00 on the 1st day.

4.3 Conditions for Performance Estimation

The numbers of neurons for the neural network models used for the performance estimation are set as follows: The data on the past two days are used; The numbers of neurons in the input and output layers are 12 and 1, respectively, for the models to estimate the COP, storage and system efficiencies, and volume of stored hot water; The numbers of neurons in the input and output layers are 14 and 1, respectively, for the model to estimate the volume of unused hot water; The number of neurons in the hidden layer is 3 commonly for all the models.

4.4 Results and Discussion

Figure 10 shows the operating conditions and the system performance values in case 70. Figure (a) shows the operating conditions given in advance, and Figures (b) and (c) show the system efficiency, and the volumes of stored and unused hot water, respectively, estimated by the neural network models under the given operating conditions. These figures also show the corresponding values obtained by the numerical simulation. The system efficiency is shown as the ratio of the system efficiency to its value on the 1st day. The estimated system performance values coincide well with the simulated ones. This result shows that the values of model parameters are identified properly by the global optimization method, and that the system performance values are estimated with high accuracy.

Figure 11 shows the operating conditions and the system performance values in case 72. Figures (a) to (c) show the same items as aforementioned. Although these simulated system performance values are not used to identify the values of model parameters, the estimated system performance values coincide well with the simulated ones. This result shows that the system performance values are estimated with high accuracy by the same neural network models even under different daily changes in the operating conditions.

Table 2. Operating conditions for identification and verification of neural network models.

Case	Purpose	Hot water demand	Outlet water temperature during heat pump operation	Inlet water temperature for heat pump shutdown
1 ~ 54	Identification	Each of 6 representative days	Constant (each of 65, 75, and 85 °C)	Constant (each of 30, 40, and 50 °C)
55 ~ 63		Pattern of consecutive 30 days	Constant (each of 65, 75, and 85 °C)	Constant (each of 30, 40, and 50 °C)
64 ~ 66		Pattern of consecutive 30 days	Variable (comb. of 65, 75, and 85 °C)	Constant (each of 30, 40, and 50 °C)
67 ~ 69		Pattern of consecutive 30 days	Constant (each of 65, 75, and 85 °C)	Variable (comb. of 30, 40, and 50 °C)
70, 71		Pattern of consecutive 30 days	Variable (comb. of 65, 75, and 85 °C)	Variable (comb. of 30, 40, and 50 °C)
72	Verification	Pattern of consecutive 30 days	Variable (comb. of 65, 75, and 85 °C)	Variable (comb. of 30, 40, and 50 °C)

5. Numerical Study on Optimal Operation

Next, the operating conditions are determined optimally based on the estimation by the neural network models whose parameter values are identified previously.

5.1 Conditions for Optimal Operation

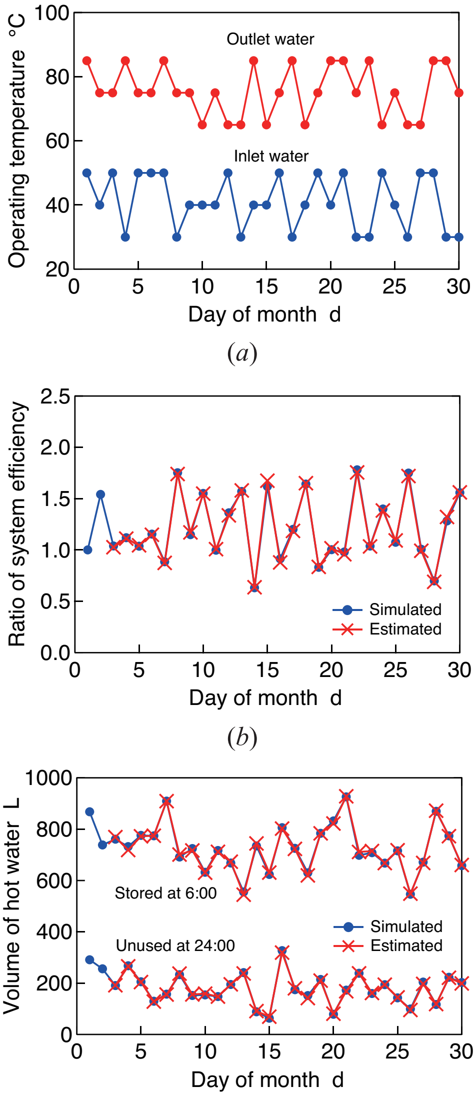
It is important to enhance the system efficiency and prevent the shortage in hot water supply. In this paper, therefore, the system efficiency is maximized subject to a lower limit for the volume of hot water unused at 24:00. The outlet water temperature during operation and the inlet water temperature for shutdown are adopted as the variables, and their values are determined so as to attain the objective and satisfy the constraint. Here, the lower and upper limits for the outlet water temperature during operation are set at 65.0 and 85.0 °C, respectively, and those for the inlet water temperature for shutdown are set at 30.0 and 50.0 °C, respectively.

On each day, each system performance value is estimated for all the combinations for the outlet and inlet water temperatures. For simplicity, the outlet water temperature is selected among its discrete values set by 1 °C from 65.0 to 85.0 °C, and the inlet water temperature is selected among its discrete values set by 1 °C from 30.0 to 50.0 °C. Here, the outlet water temperature is constrained so that the stratification in the storage tank is kept. Based on this estimation, the combination of the outlet and inlet water temperatures is selected so that the estimated system efficiency has its maximum and the estimated volume of unused hot water is equal to or larger than its lower limit. In case there is no combination by which the estimated volume of unused hot water is equal to or larger than its lower limit, the combination by which the estimated volume of unused hot water is the closest to its lower limit is selected.

In the numerical study, the lower limit for the volume of unused hot water is changed by 50 L from 50 to 250 L in cases 73 to 77, respectively, and its influence on the system performance is investigated.

5.2 Results and Discussion

Before optimization results are shown, the procedure of dermining the optimal operating conditions is shown using an example. Figure 12 shows the system efficiency and volume of unused hot water as the objective function and constraint, respectively, estimated on the 3rd day in relation to

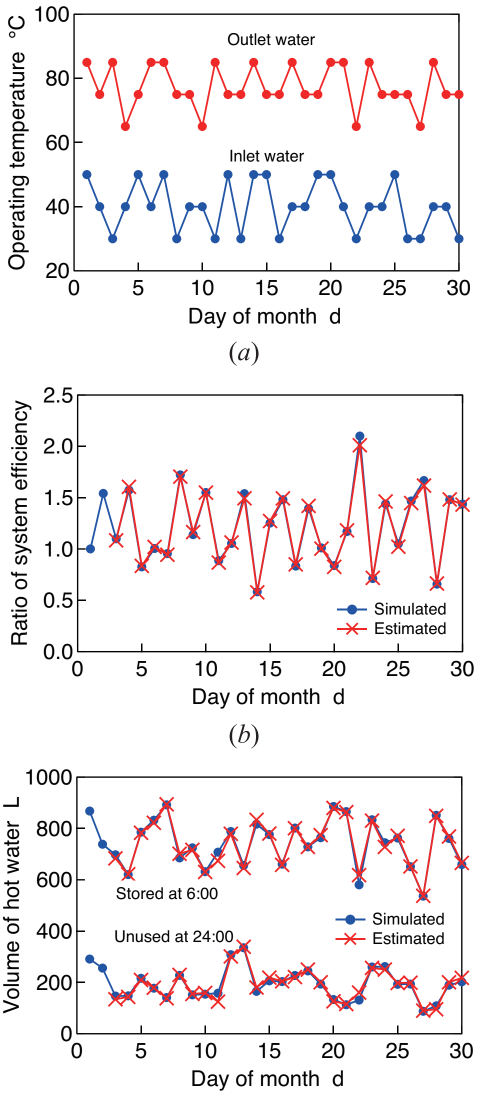


(*a*)

(*b*)

(*c*)

Figure 10. Daily changes in operating conditions and system performance values in case 70: (a) operating conditions, (b) ratio of system efficiency, and (c) volumes of stored and unused hot water.



(*a*)

(*b*)

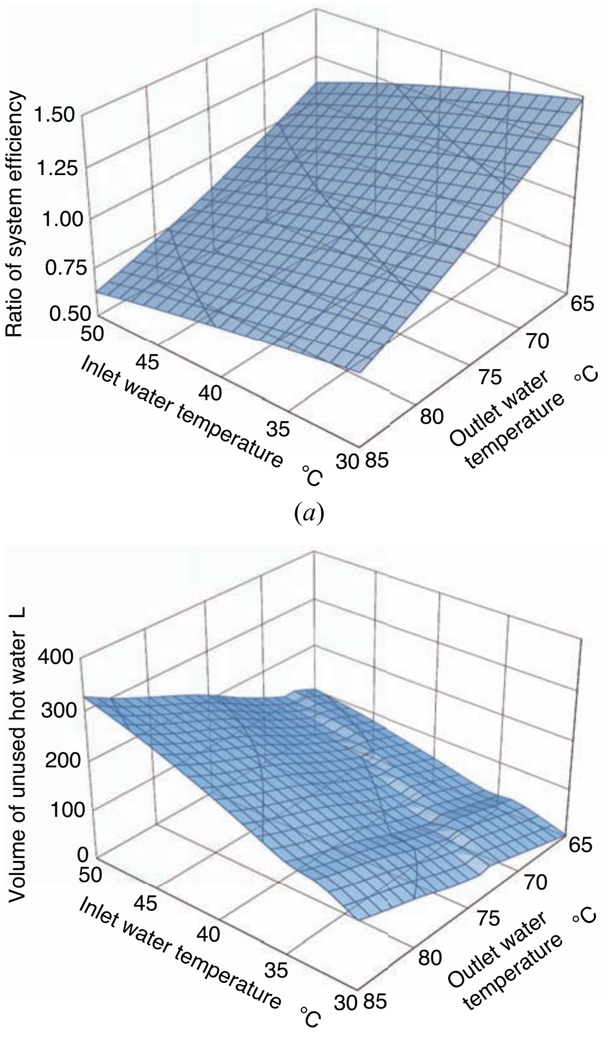
(*c*)

Figure 11. Daily changes in operating conditions and system performance values in case 72: (a) operating conditions, (b) ratio of system efficiency, and (c) volumes of stored and unused hot water.

the operating conditions. This figure shows that the system efficieny decreases and the volume of unused hot water increases with increases in the operating temperatures. Based on these relationships, the operating temperatures are selected to maximize the system efficiency subject to the lower limit for the volume of unused hot water.

Figures 13 to 15 show the operating conditions and the system performance values in cases 73, 75, and 77, respectively. Figure (a) shows the operating conditions determined optimally, and Figures (b) and (c) show the system efficiency, and the volumes of stored and unused hot water, respectively, estimated by the neural network models under the optimal operating conditions. These figures also show the corresponding values obtained by the numerical simulation. Although these operating conditions and the corresponding system performance values are not used to identify the values of model parameters, the estimated system performance values coincide well with the simulated ones. This result shows that the system performance values are estimated with high accuracy by the same neural network models even under daily changes in the optimal operating conditions.

In case 75, as shown in Figure 14, although the volume of unused hot water changes around 150 L, it becomes larger than 150 L on a few days. This is because both the operating conditions attain their lower limits, or the outlet water temperature attains the temperature at the top of the storage tank on those days. As a result, the daily change in the volume of unused hot water is small. In case 73, as shown in Figure 13, the volume of unused hot water changes above 50 L on many days. This is also because both the operating conditions attain their lower limits, or the outlet water temperature attains the temperature at the top of the storage tank on those days. As a result, the daily change in the volume of unused hot water is larger. On the other hand, in case 77, as shown in Figure 15, the volume of unused hot water changes below 250 L on several days. This is because the operating conditions attain their upper limits on those days. As a result, the daily change in the volume of unused hot water is slightly larger.

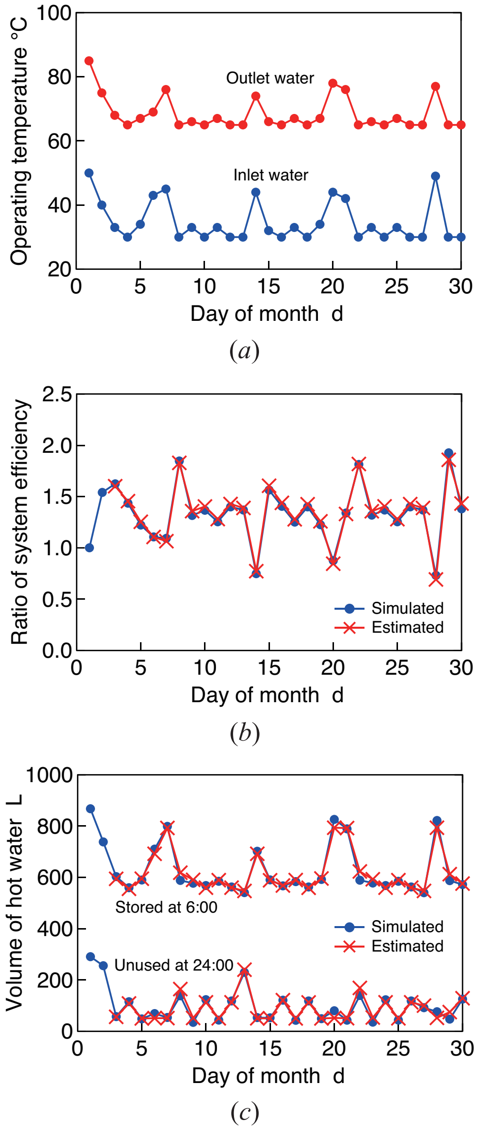


(*a*)

(*b*)

Figure 12. System performance values estimated on 3rd day in relation to operating conditions: (a) ratio of system efficiency and (b) volume of unused hot water.

Figure 16 shows the relationship between the lower limit for the volume of unused hot water and the monthly values of the ratio of system efficiency and the volume of unused hot water. The average value is adopted for the ratio of system efficiency, and the average, maximum, and minimum values are adopted for the volume of unused hot water. The average values of the ratio of system efficiency and the volume of unused hot water have a trade-off relationship. However, the average value of the ratio of system



(*a*)

(*b*)

(*c*)

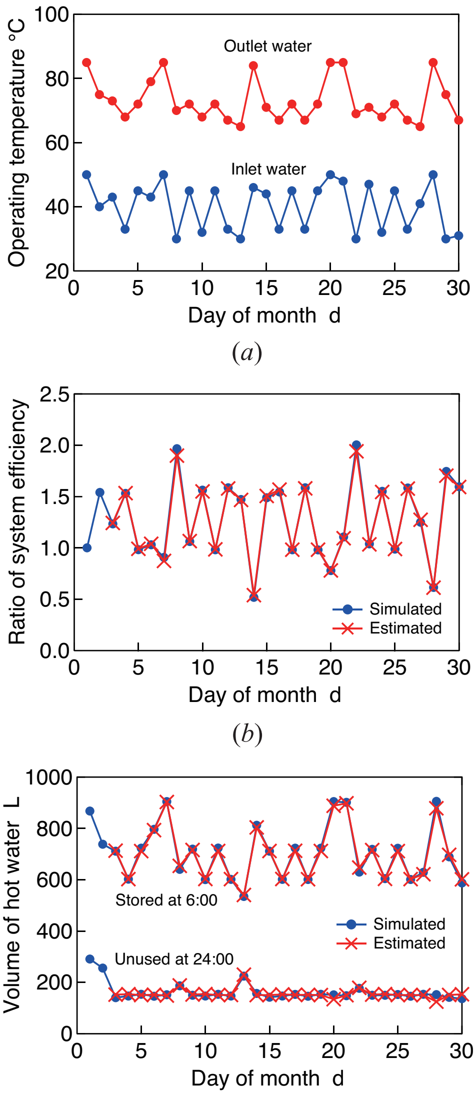
Figure 13. Daily changes in operating conditions and system performance values in case 73: (a) operating conditions, (b) ratio of system efficiency, and (c) volumes of stored and unused hot water.

efficiency and the maximum or minimum value of the volume of unused hot water do not have a trade-off relationship. This is because, as shown in Figures 13 and 15, in case the lower limit for the volume of unused hot water is small or large, the daily change in the volume of unused hot water becomes large, and the difference between the maximum and minimum values of the volume of unused hot water also becomes large.

Figure 17 shows the comparison of the monthly values of the ratio of system efficiency and the volume of unused hot water in cases 70 to 77. The average value is adopted for the ratio of system efficiency, and the average and minimum values are adopted for the volume of unused hot water. As aforementioned, the average values of the ratio of system efficiency and the volume of unused hot water under the optimal operating conditions in cases 73 to 77 have a trade-off relationship. In addition, those under the non-optimal operating conditions in cases 70 to 72 are very close to the trade-off relationship. Thus, the optimal operation is not effective from the viewpoint of the average system performance values. On the other hand, the average value of the ratio of system efficiency and the minimum value of the volume of unused hot water under the optimal operating conditions in cases 73 to 77 have a trade-off relationship partly in cases 73 to 75. In addition, those under the non-optimal operating conditions in cases 70 to 72 are far from the trade-off relationship. As for the the volume of unused hot water, the minimum value is more important than the average one to prevent the shortage in hot water supply. Thus, as shown by arrows, it is possible to enhance the average value of the system efficiency with the minimum value of the volume of unused hot water kept constant. The increases in the average value of the system efficiency are expected to be about 9.0, 9.9, and 8.2 % in cases 70 to 72, respectively.

6. Conclusions

In this paper, a method of estimating the daily changes in system performance values by neural network models is proposed for a CO_2 heat pump water heating system. In addition, the values of model parameters are identified by a global optimization method. Moreover, the operating conditions are determined optimally based on the system performance values obtained by the estimation. This approach is applied to estimating the daily changes in system performance values and determining the operating conditions

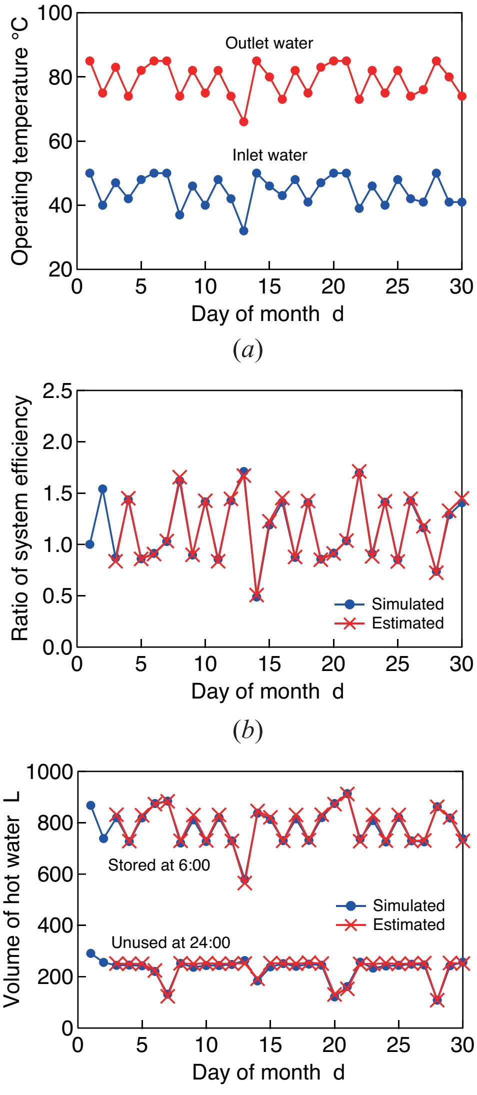


(*a*)

(*b*)

(*c*)

Figure 14. Daily changes in operating conditions and system performance values in case 75: (a) operating conditions, (b) ratio of system efficiency, and (c) volumes of stored and unused hot water.



(*a*)

(*b*)

(*c*)

Figure 15. Daily changes in operating conditions and system performance values in case 77: (a) operating conditions, (b) ratio of system efficiency, and (c) volumes of stored and unused hot water.

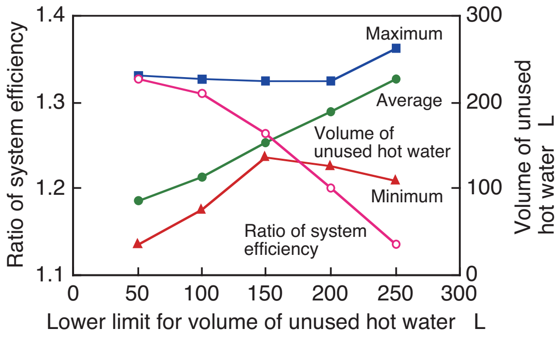


Figure 16. Relationship between monthly system performance values.

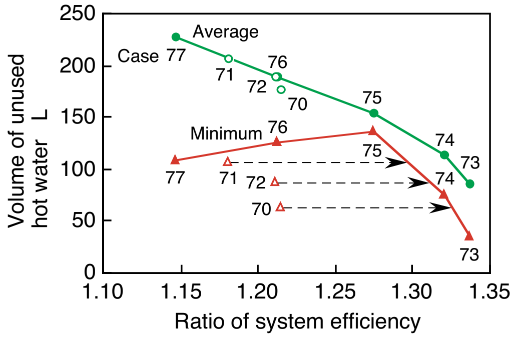


Figure 17. Comparison between monthly system performance values under optimal and non-optimal operating conditions.

optimally under a simulated monthly hot water demand, and its validity and effectiveness are investigated through the comparison between estimated and simulated system performance values. The following main results are obtained:

- It is possible to estimate all the system performance values, or COP, storage and system efficiencies, and volumes of stored and unused hot water with high accuracy not only under the operating conditions used for identifying model parameter values but also under different operating conditions including the optimal ones.
- It is important to enhance the system performance and prevent the shortage in hot water supply. It is possible to determine the operating conditions optimally so as to maximize the system efficiency subject to a lower limit for the volume of unused hot water for the purpose.
- It is possible to enhance the average value of the system efficiency with the minimum value of the volume of unused hot water kept constant by changing the non-optimal operating conditions to the optimal ones. The increase in the average value of the system efficiency is expected to be 8 to 10 % under the conditions investigated in the numerical study.

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Nomenclature

g : response function of neuron
J : number of inputs to neuron
T_i : inlet water temperature for heat pump shutdown, °C
T_o : outlet water temperature during heat pump operation, °C
u : total hot water demand during period from 6:00 to 24:00, L/d
w : weight for inputs to neuron
X : input to neuron
Y : output from neuron
y : volume of hot water stored at 6:00, L
z : volume of hot water unused at 24:00, L
η_{cop} : coefficient of performance (COP)
η_{sto} : storage efficiency
η_{sys} : system efficiency
θ : threshold for neuron

Subscripts

j : index for inputs to neuron
k : index for days

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