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Categorization of industrial heat pump for integrated simulation technology

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Abstract

Recently, the demand for high-temperature heat in the industrial field has increased. Hence, improvement in conversion efficiency to generate thermal power is strongly required for surplus steam heat that is of significant value along with a process with low heat generation efficiency in factories. Given the aforementioned problems, a significant energy saving effect for the complete process is expected by introducing a heat pump to the thermal process. However, it is extremely difficult to experimentally examine the energy saving of the system due to cost and installation space. The final goal of the study is to construct integrated analysis technologies that can realize optimization of the system including the design and control system from the selection of various refrigerants and cycles via simulations. The study compared and examined introduction model cases applied to high temperature heat pump and confirmed that the annual simulation results were reasonable when compared to measured values.

Keywords: Waste heat recovery, Industrial heat pump, integrated simulation, Annual performance evaluation;

1. Introduction

With the development of heat pump technology, there is an increasing interest the introduction of heat pump technology to save energy in the industrial field. However, the existing factory is large in scale and includes a complicated configuration with many devices. Thus, it is necessary to quantitatively clarify several parameters including the type of heat pump and temperature zone that are required for a factory. Therefore, it is difficult to evaluate the effect of experimental heat pump introduction. Hence, the introduction method of heat pump and evaluation method of introduction effect are not established to date.

Therefore, in the study, we propose a heat pump introduction method and evaluation of the introduction effect in the industrial field via simulations. First, it is necessary to model a large and complex factory to realize this type of a simulation. Additionally, annual performance evaluation is performed when conducting simulations in countries with four seasons, such as Japan, and hence a significant amount of calculation is expected from the simulation period and size of the factory. In the analysis logic in the simulation, it is necessary to increase calculation speed while maintaining calculation accuracy. Furthermore, it is necessary for the built simulator to entail ease of use for the user to operate and output energy saving and economic efficiency prior to and after the introduction of the heat pump.

Given the aforementioned factors, the purpose of the study is to construct a general-purpose evaluation tool on the effects of introducing industrial heat pumps. The study focuses on the construction of basic system configuration patterns and construction of general-purpose analysis logic for the model.

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2. Method

2.1. Simulation overview

Fig. 1 shows the overall algorithm to evaluate the effects of introducing a heat pump. In the simulation in the study, the method to evaluate the effect of introducing heat pump is determined via dividing it into three main processes.

First, the target systems are classified by basic patterns. It is difficult to perform calculations with a model that divides element devices such as boilers and heat pumps into smaller elements, such as valves, heat exchangers, and compressors, because of the large scale of the target system. (In this paper, combustion-type heating devices including burners are collectively referred to as “boilers”) Additionally, accuracy can be obtained to analyze long-term performance such as annual performance although it is not practical due to the significant calculation time involved. Therefore, although the details are subsequently described, we aim to increase the calculation time by classifying the basic pattern proposed in the study with the boiler and heat pump as an element. Second, the target system is constructed by combining the classified patterns, and input variables are set for each pattern. Here, in order to correspond to the patterns classified in the previous stage, it is necessary to select variables that can be calculated even if the model of each pattern is divided. Finally, the heat pump introduction effect is calculated from the model of the target system and the input variables. Thus, even if the target is divided and modeled, it is still necessary to construct a method that decreases the calculation time by assuming annual performance calculations. Based on the aforementioned flow, it is possible to verify the effect of introducing the heat pump to the target system. The system before and after the introduction is compared, the performance parameters are graphed and displayed, and the user evaluates the introduction effect. Additionally, we construct a simulator that can be handled easily by any user and experts on heat pumps as a whole to save energy in the entire industrial field.

The following sections describe each process.

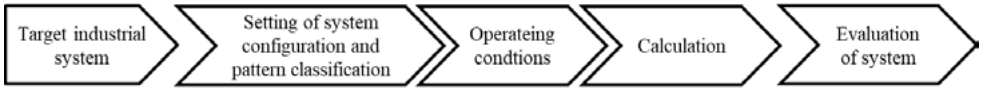


Fig. 1. Overall logic in the study

2.2. Pattern classification

In order to organize a complicated system configuration, a basic pattern is constructed based on various systems in which heat pumps are already introduced. In the study, we propose a patterning method based on four indicators (i.e., device, heating method, introduction use) via surveys of heat pump products developed for existing industries, literature surveys, and interviews with experts.

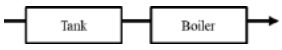
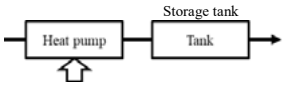
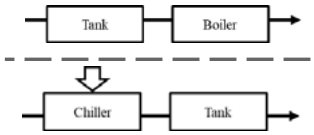
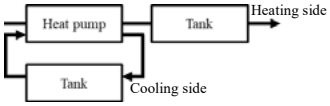
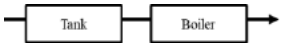
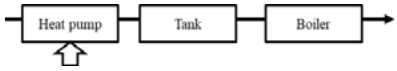
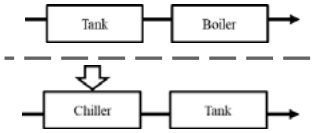
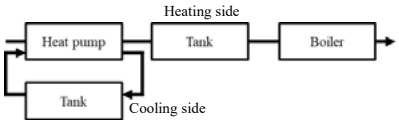
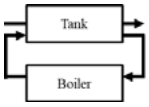
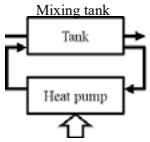
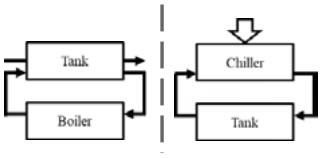
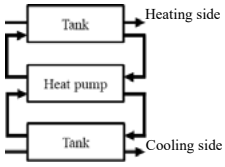
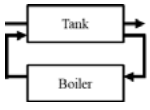
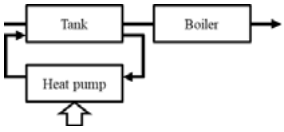
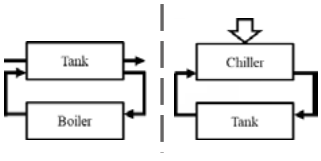
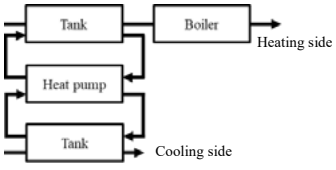
First, in order to compare the use of a conventional boiler with a heat pump, the former “device” is set to “boiler” and the latter is set to the “heat pump”. We then consider an eco-cute system that supplies hot water as a system that includes a heat pump. Household water heaters are popular although large-scale industrial eco-cutes were developed to generate hot water instead of boilers. This corresponds to an introduction example targeted in the study. In this type of a water heater, there is a difference in the heating method between storing hot water in the tank and temporarily supplying hot water. Therefore, the former “heating method” is set to “circulation” and the latter is set to “non-circulation”. Furthermore, the CO2 hot air generation heat pump was developed as an industrial heat pump that generates hot air without burning fuel like a boiler. The product makes it is possible to generate hot air at a higher temperature that consumes less fuel than before by replacing the boiler with a heat pump or heating the hot air preheated with a heat pump with a conventional heater. Therefore, the former “introduction use” is set as “replacement” and the latter is set as “preheating”. Finally, heat pumps that can realize applications including cold / hot water generation, hot water supply, and hot water tank heating with a single unit were developed using waste heat recovery technology. The heat pump can simultaneously extract cold and warm heat from the high temperature side and low temperature side such as recovering the heat released to the atmosphere during cooling operation by a conventional air conditioning system and using it as a heat source for hot water supply. Therefore, the “cold heat utilization” is set as “cold heat generation” and otherwise “hot heat generation” is set.

In the present study, a total of 16 patterns are proposed by combining the aforementioned "used equipment" (boiler, heat pump), "heating method" (circulation, non-circulation), "introduction use" (preheating, replacement), and "cool use" (cold heat generation, heat generation). However, if it corresponds to “cold heat

generation" and the device used is a boiler, then it is assumed that a refrigerator is present at the same time. The outline of the 16 patterns is listed in Table 1.

The user inputs the target system configuration via a combination of the 16 basic patterns. Similarly, it is possible to perform a comparison with the case where the heat pump is introduced by using the basic pattern and to clarify various effects of introduction.

Table 1. Basic pattern of system configuration

Type No.	Conventional type	Heat pump type
Type1 ・Non-circulation ・Replacement ・Hot heat generation		
Type2 ・Non-circulation ・Replacement ・Cold/Hot heat generation		
Type3 ・Non-circulation ・Preheating ・Hot heat generation		
Type4 ・Non-circulation ・Preheating ・Cold/Hot heat generation		
Type5 ・Circulation ・Replacement ・Hot heat generation		
Type6 ・Circulation ・Replacement ・Cold/Hot heat generation		
Type7 ・Circulation ・Preheating ・Hot heat generation		
Type8 ・Circulation ・Preheating ・Cold/Hot heat generation		

In these patterns figure, a white arrow indicates a heat source input. Each tank functions either as a storage tank or as a mixing tank, which is indicated in Table 1. If there is no tank, apply the pipe model to the tank. In all patterns proposed in this study, heating source is basically needed for heating process in the system, and cooling heat source is adjusted to get hot water or air as much as possible considering the heat balance between high and low temperature heat sources.

2.3. Simulation input and calculation

After classifying the target system configuration into patterns, input variables for boiler and heat pump elements in each basic pattern are set. Input and output variables for each element are shown in Tables 2 and 3, and the expressions used are shown below. Given that each pattern consists of a boiler, heat pump, and tank, models were created for the same. Various methods are available for mathematical model creation. In the study, in order to evaluate the annual performance, a model based on the pinch temperature was established in the heat transfer part of the heat pump to ensure sufficient validity while focusing on the calculation speed. As an example, the heat pump calculates variables including the heating capacity, COP, and primary energy consumption from the input variables listed in Table 3. In order to quantitatively evaluate the introduction effect under the same temperature and flow conditions in the heat pump type as compared with the boiler type, the simulator in the study mainly calculates the primary energy consumption as the output of each pattern.

Table 2. Input and output variables (Boiler)

Input			Output		
Variable	Code	Unit	Variable	Code	Unit
Boiler efficiency	η_{Boiler}	%	Heating capacity	Q	kW
Rated heating capacity	Q_{rated}	kW	Primary energy consumption	W_{prim}	kW
Inlet temperature	T_{in}	℃	Load factor	η_{load}	%
Outlet temperature	T_{out}	℃			
Mass flow	G	kg/s			

$$Q = G c_p (T_{out} - T_{in}) \tag{1}$$

$$W_{prim} = \frac{Q}{\eta_{boiler}} \times 100 \tag{2}$$

$$\eta_{road} = \frac{Q}{Q_{rated}} \tag{3}$$

Table 3. Input and output variables (Heat pump)

Input			Output		
Variable	Code	Unit	Variable	Code	Unit
Rated heating capacity	Q_{rated}	kW	COP	COP	
Inlet temperature at condenser	$T_{con,in}$	℃	Heating capacity	Q	kW
Outlet temperature at condenser	$T_{con,out}$	℃	Load factor	η_{load}	%
Mass flow	G	kg/s	Energy consumption	W	kW
Source temperature	T_{source}	℃	Primary energy consumption	W_{prim}	kW
Refrigerant	-	-			
Isentropic efficiency	η_{ad}	%			
Pinch point temperature at condenser	ΔT_{con}	℃			
Pinch point temperature at evaporator	ΔT_{eva}	℃			
Primary conversion efficiency	η_{prim}	%			

$$COP = \frac{h_{con,in} - h_{con,out}}{h_{con,out} - h_{eva,in}} \quad (4)$$

$$Q = Gc_p(T_{con,out} - T_{con,in}) \quad (5)$$

$$W = \frac{Q}{COP} \quad (6)$$

$$W_{prim} = \frac{W}{\eta_{prim}} \times 100 \quad (7)$$

2.4. Simulation output

By passing the system configuration and input variables with the aforementioned patterns to the analysis algorithm, simulation results including the total primary energy consumption and reduction rate of the entire system are output from each basic pattern of the input system. From the results output from the simulator, the effect varies based on how the heat pump is introduced into the target system, it is possible to evaluate and examine the overall system configuration that can achieve the maximum effect after the introduction of the heat pump. Additionally, it is possible to compare systems that already include heat pumps installed and changing the type, cycle configuration, and refrigerant used. For annual performance evaluation, there is a method to evaluate from the performance of each season, a method to evaluate from the performance of the representative day set every month, and a method to evaluate 365 days every minute or every hour. Thus, it is necessary to output data that can correspond to the output desired by the user and evaluation method. The simulator constructed in the study outputs time-series calculation results for each variable of the input system.

2.5. Verification

A prototype was specifically constructed for the simulator that enables evaluating the effects of introducing the industrial heat pump proposed above. Using the simulator, the measurement data of a factory where an industrial heat pump is already introduced was input to the simulator, and the analysis logic and calculation accuracy were verified. Figure 2 shows the flow chart of the target factory. In the factory, hot air from a gas burner is mainly used in the product drying process although a heat pump is used as part of the heating. Therefore, the classification described in 2.2 corresponds to Type4. Given that the measured values corresponding to the input items set in 2.3 are 1-minute intervals, the power consumption of the heat pump at 1-minute intervals is calculated for each representative day of 12 months. Furthermore, given that the measured value of power consumption corresponds to the total every 30 min, the calculated value was converted to an average every 30 minutes for comparison purposes. The results and measured values are compared to verify the accuracy of the simulator constructed in the study. The annual performance by the representative day of each month was calculated, and the representative day was set on the third Wednesday, which is used as the average value of each month. Additionally, we analyze the case of assuming a system configuration in which heating by a heat pump in the target factory is performed by a boiler. Based on the results, we evaluate the extent to which the primary energy consumption as a heat pump introduction effect can be annually reduced from the use of conventional boilers.

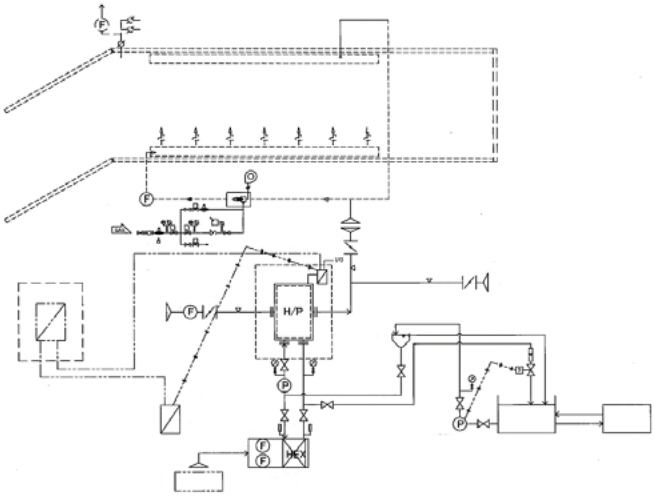


Fig. 2. Flow of the target factory

3. Simulation results and discussion

With respect to the power consumption of the heat pump, Fig. 3 shows the simulation results and measured values of daily transition for each representative day of the month and the total relative error of the day. Based on the results, in the analysis logic constructed in the study, the total annual power consumption multiplied by the number of factory operating days in each month corresponds to 5.47 GWh for the simulation result, 5.76 GWh for the measured value, and the relative error corresponds to 5.19%. With respect to Fig. 3, the power consumption on the representative day of each month is calculated lager than measured value except for March although the analytical values and the measured values exhibit similar fluctuation trends. Most of the time when the heat pump is operating in a stable manner, it exhibits an error of approximately 5%. Therefore, the analysis logic and calculation model of the simulator constructed the time exhibit sufficient calculation accuracy in practice. The reason why the calculated value exceeds the measured value is that the pinch temperature in the heat exchanger was set as constant to match the capability under the rated operating conditions defined by JIS. The COP is calculated as low, and thus it is necessary to set the pinch temperature as the performance of the heat exchanger smaller than the value determined in the rated operating conditions and set it based on the conditions of every minute. Hence, more accurate calculation results can be obtained via correcting the fluctuation of the heat exchanger pinch temperature under actual operating conditions. Henceforth, in order to achieve the specifically, we plan to set the pinch temperature input and investigate and correct the calculation logic.

Additionally, Fig. 4 shows a comparison of changes in the primary energy consumption before and after the introduction of the heat pump in June, when the relative error was the smallest, as the output of the simulator. Fig. 5 shows a comparison of annual primary energy consumption before and after the introduction of the heat pump.

As shown in Fig. 4, the primary energy consumption decreases by 35% per year with an error of 5.19% per year by introducing the heat pump to the target factory. In the simulation, a heat pump with a single-stage vapor compression cycle was modeled. However, in order to quantitatively evaluate the effects of introducing the heat pump in a wider range, it is necessary to model other models in the same manner as the proposed method.

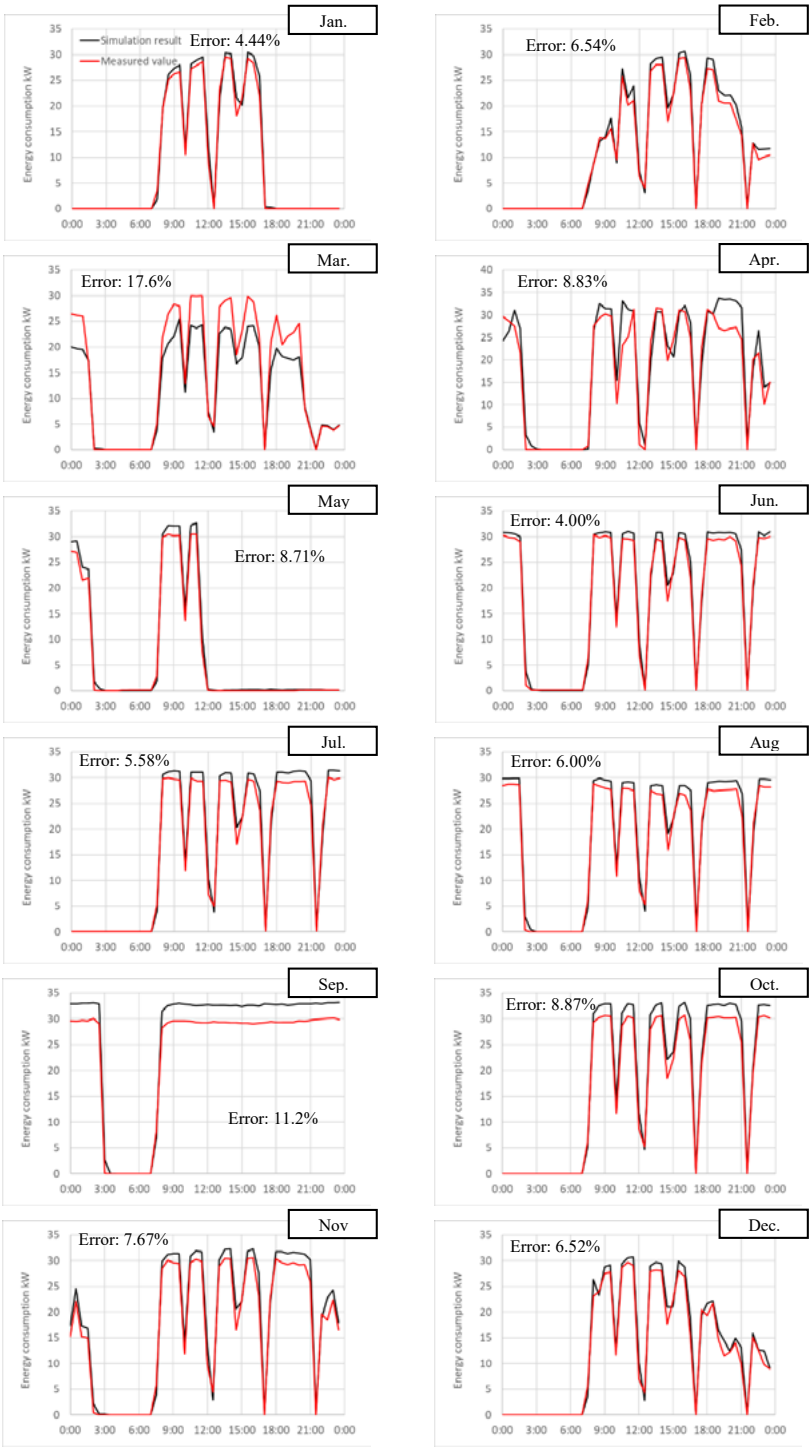


Fig. 3. Annual energy consumption fluctuation

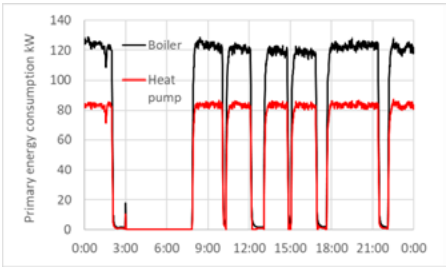


Fig. 4. Primary energy consumption fluctuation (June)

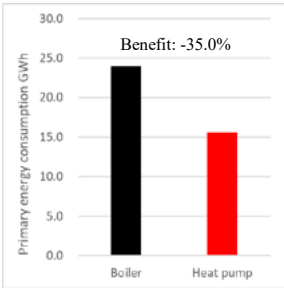


Fig. 5. Annual effect of introducing heat pump

4. Conclusions

In the study, we proposed 16 basic patterns that can categorize heat utilization systems including almost all boilers and heat pumps. Additionally, by incorporating the basic pattern model into the analysis logic, various system simulations are possible. Therefore, it was possible to quantitatively compare the primary energy consumption between a conventional system and new heat pump introduction system. In the study, we created an example that served as the basis for a simulator that incorporated the basic patterns and the built model and verified the accuracy by comparing the actual measurement data and simulation results at a factory where an industrial heat pump was already installed. Thus, the results that the annual power consumption (which is the output of the simulator) can be calculated with a relative error of 5.19% when compared to the actual measurement. Under the accuracy, the results indicated that the primary energy consumption decreased by 35% per year when compared to the case where the target factory was operated with a boiler under similar operating conditions. Henceforth, in order to further improve the accuracy of simulation calculations, we plan to develop and extend the model and specifically develop a simulator.

Acknowledgements

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Nomenclature

c_p	specific heat at constant pressure, kJ·kg^{-1}·K^{-1}
G	mass flow, kg·s^{-1}
h	specific enthalpy, kJ·kg^{-1}
Q	cooling capacity, kW
W	energy consumption, kW
T	Celsius temperature, ℃
η	efficiency, %

Subscript

In	inlet
Out	outlet
source	heat source

Air	air flow
Con	condenser, condensation
Eva	evaporator, evaporation
prim	primary
rated	rated
load	load

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