14th IEA Heat Pump Conference
15-18 May 2023, Chicago, Illinois

Development of industrial heat pump simulator

Jongsoo JEONG[a,*] ,So MUTO[b] ,Yoichi MIYAOKA[c], and Kiyoshi SAITO[d]

a Research institute for science and engineering, Waseda University, 3-4-1 Okubo, Tokyo, 169-8555, Japan
b Graduate school of fundamental science and engineering, Waseda University, 3-4-1 Okubo, Tokyo, 169-8555, Japan
c Interdisciplinary institute for thermal energy conversion engineering and mathematics, Waseda University, 3-4-1 Okubo, Tokyo, 169-8555, Japan
d Department of Applied Mechanics and Aerospace Engineering, Waseda university, 3-4-1 Okubo, Tokyo, 169-8555, Japan

Abstract

To improve heat conversion efficiency in the industrial field, this research has focused on heat pump technology, which has low CO_2 emissions and high efficiency, and has developed a simulator that can easily study the effects of introducing the technology and can be used for a variety of systems. To achieve this goal, we have selected a model with a good balance between calculation speed and accuracy, and have built a simulator that is easy for users to use and can flexibly respond to changes in refrigerants, systems, and operating conditions. In this paper, we show, compare and analyze the results of an environmental evaluation, as well as verification of its accuracy using actual measurement data from a factory using the simplified simulator calculated by classification of basic system configuration patterns and the integrated simulators based on general-purpose analysis logic for the model.

Keywords: Industrial heat pump; Simplified simulator; Integrated simulator; economic and environmental evaluation

1. Introduction

The New Energy and Industrial Technology Development Organization (NEDO)[1] reported that 70% of waste heat per fuel is generated in boilers, steam pipes, production facilities, and so on, considering the operation of conventional industrial heat systems in factories. Therefore, the introduction of heat pumps as an alternative to conventional combustion methods is attracting attention as a promising method for energy saving. When introducing an industrial heat pump into an existing process, it is necessary to quantitatively evaluate the cost, effectiveness, and desirable configuration of the heat pump system in advance.

However, the hurdles in terms of cost and time are high to determine these factors through actual demonstration construction using heat pumps, and as a result, this has become a factor hindering the spread and expansion of heat pumps. Considering these problems, a simulation-based evaluation method is preferable for quantitatively evaluating the effectiveness of heat pump installation. However, actual processes and systems have complex equipment configurations and are large in scale, and annual performance evaluations must be conducted in response to fluctuating loads and ambient temperatures, etc. This requires complex calculation inputs and a large amount of calculation time. For this reason, the authors have conducted research with the goal of constructing a simulator that is relatively easy to input calculations, has high accuracy, and can significantly shorten calculation time. [2][3]

This paper reports on two simulators that enable the effects of introducing heat pumps with environmental considerations even in complex systems where multiple devices are installed on factory production lines. Specifically, considering the analysis time and convergence for a large annual calculation in hours, the validity of the analysis results is confirmed by comparing them with field data of heat pump systems obtained

* Corresponding author. Tel.: +81-3-5286-3259; fax: +81-3-5286-3259.
E-mail address: jeong@aoni.waseda.jp.

throughout the year. The primary energy consumption and CO_2 emissions of each simulator were evaluated to quantify the efficiency of the heat pump installation system compared to a conventional combustion system.

2. Simulation overview

2.1. Simplified simulator

We suggested the evaluation method of target systems that are classified as 16 basic patterns to evaluate the effects of introducing a heat pump as shown in Table 1, and constructed a simulator that can be handled easily by users with knowledge of heat pumps as a whole to save energy in the entire industrial field. In order to organize a complicated system configuration, patterning methods were proposed based on four indicators (i.e., used equipment, heating method, introduction use) via surveys of heat pump products developed for existing industries.

The conventional “equipment” is set to “boiler” and the introduced equipment is set to the “heat pump” to compare the use of a conventional boiler or burner with a 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, “heating method” is set to “circulation” and “non-circulation”. Furthermore, the CO_2 hot air generation heat pump can be used for complete replacement of conventional boiler or preheating before conventional boiler. “Introduction use” is set as “replacement” and “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 low temperature side and high temperature side of refrigerant. Therefore, the “thermal utilization” is set as “high-temperature heat utilization” and otherwise “Simultaneous utilization of heat and cold” 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 "thermal utilization" (high-temperature heat utilization, simultaneous utilization of heat and cold).

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.

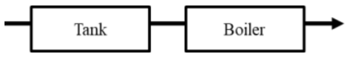
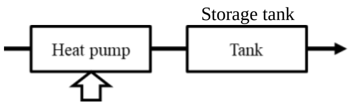
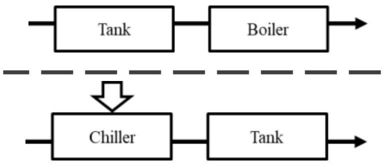
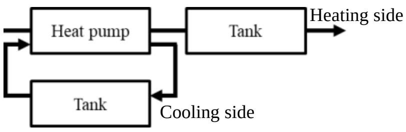
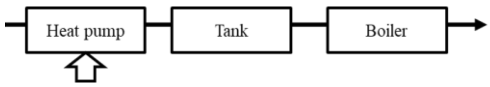
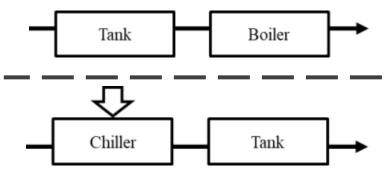
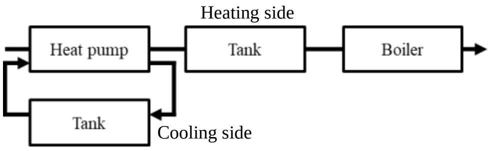
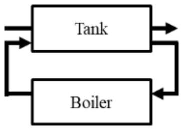
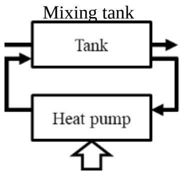
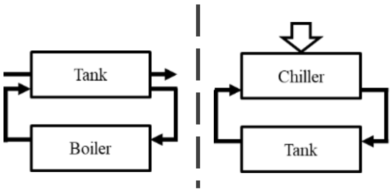
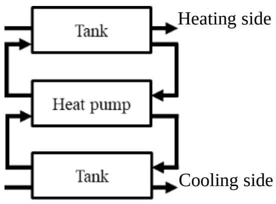
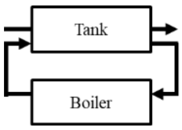
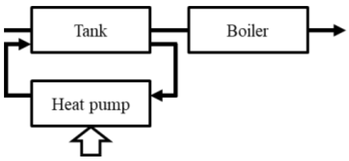
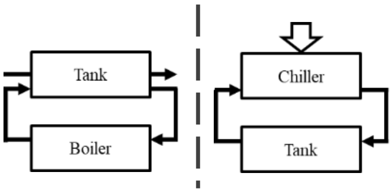
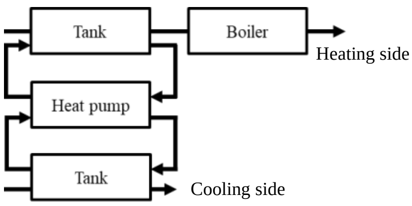
The GUI of the simulator developed using the C++ language is shown in Figure 1. In the simplified simulator, the user first selects one of 16 basic system configuration patterns that correspond to the existing system.

The selected pattern is arranged as the system on the left side shown in Figure 1. The pattern of the heat pump to be newly installed is also selected in the same way, and is placed as the system on the right side shown in Figure 1. Then, input variables for each pattern in csv format (values separated by commas (,)). The input variables are basically the refrigerant type and rated value, as well as the temperature and flow rate at each time point.

Finally, the comparison results are output after running the calculation program. On the screen, the results are displayed in the form of line graphs showing the primary energy consumption during the evaluation period for the input data, and bar graphs and numerical values showing the total primary energy consumption and total CO_2 emissions during the evaluation period, respectively.

In addition, a Moriel diagram of the heat pump is displayed based on the pressure and enthalpy data at the selected time. Since all 16 patterns are used as objective systems for comparison, it is possible to compare the performance of heat pumps with each other, and can respond flexibly to changes in the type of refrigerant and the basic configuration pattern of the system. This simulator is also capable of system economic assessment and LCCP evaluation, however, this paper focuses on the calculation of primary energy consumption and CO_2 emissions. The simulation models are composed of continuity and energy equation in each equipment and the heat transfer performance of the heat exchangers was analyzed as pinch temperature. Details of evaluation assessment are referred to Jeong.[3]

Table 1. Basic pattern of system configuration

Type No.	Conventional type	Heat pump introduction type
Type1 ・Non-circulation ・Replacement ・High-temperature heat utilization		
Type2 ・Non-circulation ・Replacement ・Simultaneous utilization of heat and cold		
Type3 ・Non-circulation ・Preheating ・High-temperature heat utilization		
Type4 ・Non-circulation ・Preheating ・Simultaneous utilization of heat and cold		
Type5 ・Circulation ・Replacement ・High-temperature heat utilization		
Type6 ・Circulation ・Replacement ・Simultaneous utilization of heat and cold		
Type7 ・Circulation ・Preheating ・High-temperature heat utilization		
Type8 ・Circulation ・Preheating ・Simultaneous utilization of heat and cold		

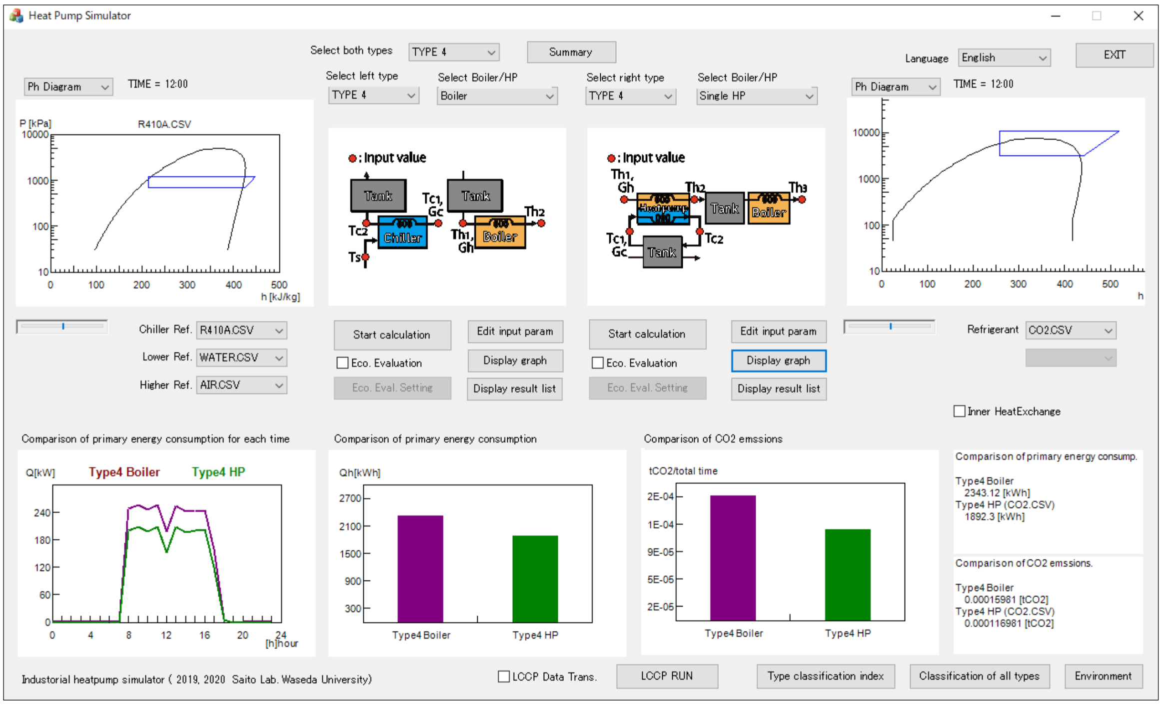
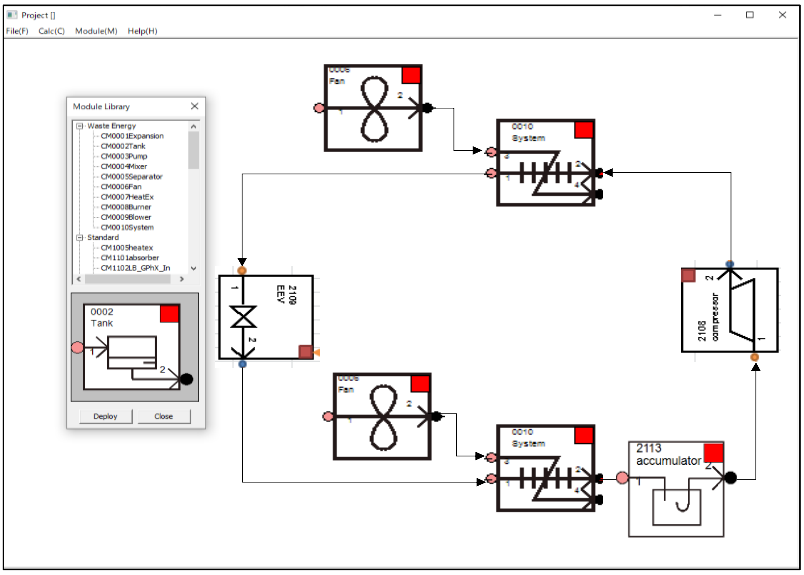


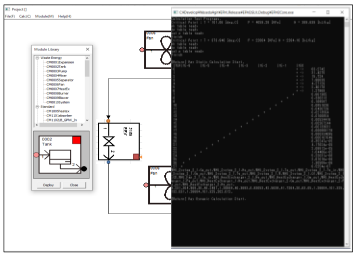
Figure 1. GUI of simplified simulator to compare the effects of installing a heat pump system

2.2. Integrated simulator

Figure 2 shows GUI of integrated simulator, which features high ability in analyzing the performance of system with various refrigerants, and simulation environment being familiar to engineers and researchers that do not specialize in a simulation on industrial and scientific fields. This simulator extends the capabilities of the simplified simulator to analyze systems with complex configurations and is fully capable of not only designing large-scale heat pump systems, but also predicting and verifying the effectiveness of heat pump installations. As for the tool for examining the performance of air-conditioning systems, a general-purpose energy analysis simulator "Energy Flow+M" has been developed at Waseda University for steady state, dynamic, and control analysis [4-6]. Vapor compression type of air conditioning system expressed by GUI is shown in Figure 2-(a) as an example of simulation. In Figure 2-(b), system simulation is carried on GUI. Figure 2-(c) shows simulation results as output using CSV file. The simulation models are basically the same with those of simplified simulator.



(a) Layout of vapor compression air conditioner


(b) Calculation on GUI

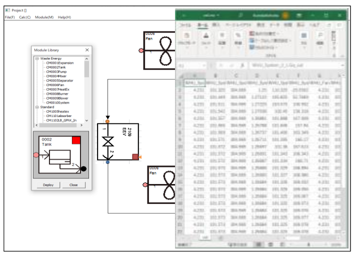

(c) Simulation results on CSV

Figure 2. GUI of integrated Simulator to evaluate the performance of thermal system and effects of installing a heat pump system

Figure 3 shows the analysis process of the integrated simulator. First, the components of the system to be built are selected from the module list and placed on the GUI. Each element or combined pattern is treated as a "module" with its own entrance and exit, and each module is connected to each other with "connections" to construct the system configuration as shown in Figure 2(a). For each of these modules, fixed variables for each device, time-series variables such as temperature conditions, and connection information with each module are stored in xml format, and when the system calculation is executed, the information in the xml file is passed to the calculation main core side. The system is then simulated using the necessary physical properties and convergence algorithms. The final result of the analysis is an environmental assessment of the primary energy consumption and CO_2 emissions of the system and an economic assessment of the life cycle cost. In this paper, it focuses on the calculation of primary energy consumption and CO_2 emissions.

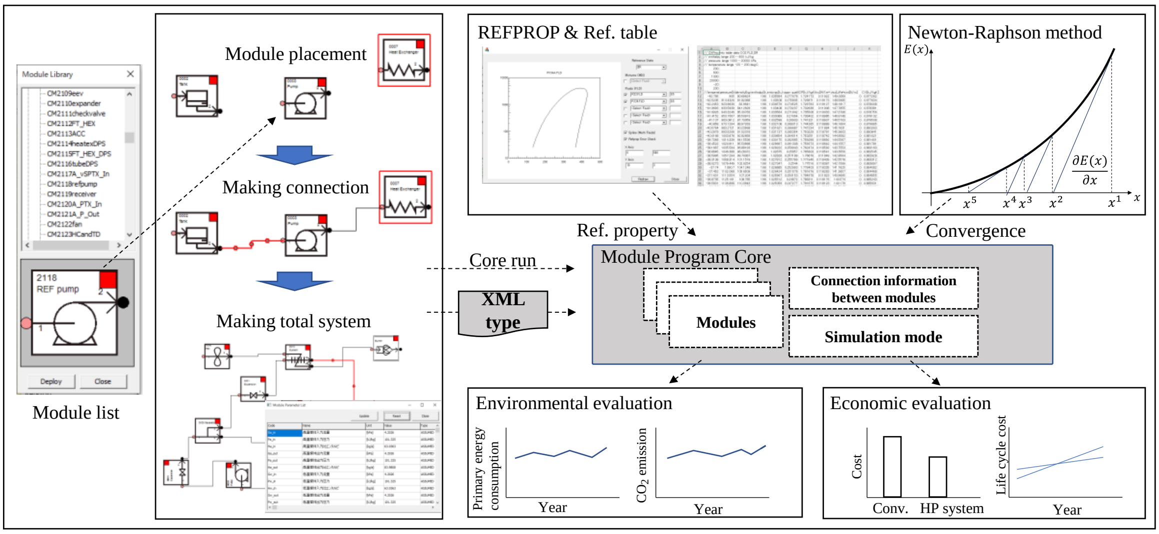


Figure 3. Simulation process of "Integrated simulator" on GUI

3. Simulation example of each simulator

3.1. Objective system

The objective system shown in Figure 4 is a paint drying system in a certain factory. In contrast to conventional combustion-type heating, this system uses a heat pump with CO_2 refrigerant for preheating to generate high-temperature hot air, which is preheated to 90-100°C with the heat pump by the heat pump by taking in outside air at around 15°C, and the heated air is further heated to 170°C by the burner. This system consists of a chiller, a heat exchanger, a burner, and a fan in addition to the heat pump, with multiple heat sources heating and cooling materials in different temperature zones.

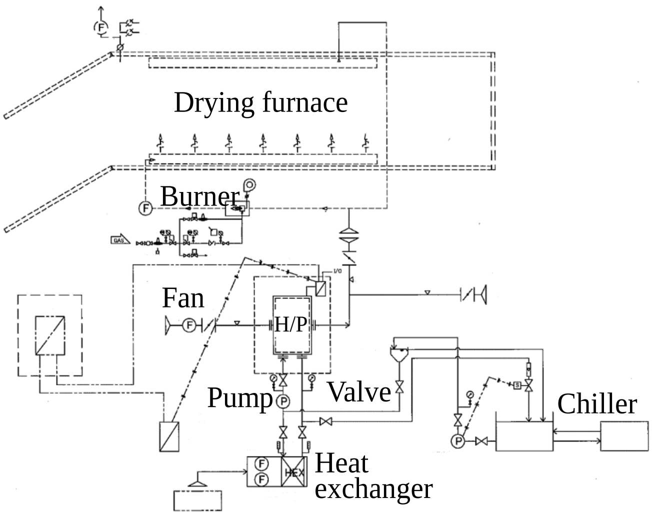


Figure 4. Flow of the target factory

Figure 5 shows annual actual operation data for the objective system with a heat pump as shown in Figure 4, including the temperature and airflow rate of the fan on the hot-air process side, the temperature of the heated hot-air from the heat pump at about 100°C, and the temperature of the hot-air provided by the burner to the drying furnace at about 170°C. Compared to a conventional combustion system, the heat pump is used to raise the temperature from the ambient air to about 100°C. When assessing environmental and economic performance using the simulators, the actual operation data shown in Figure 5 are used as input values for analysis, and energy consumption is calculated to evaluate the effect of the heat pump installation. The heat pump installation system operates for approximately 11 hours from 7:00 to 18:00 on weekdays, with system shutdown on weekends and holidays.

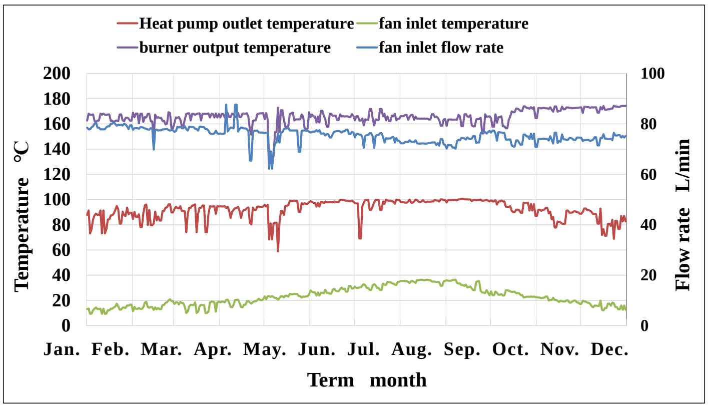
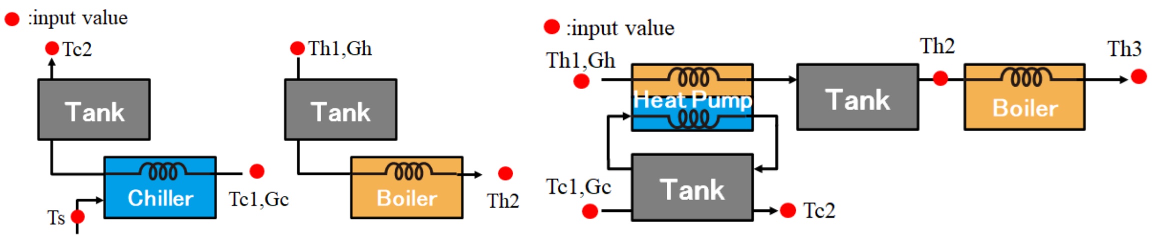


Figure 5. Annual actual operation of heat pump installation system

3.2. Analysis by simplified simulator

For analysis of objective system, the simplified simulator enables evaluating the effects of introducing the industrial heat pump proposed above. The classification for simulation described in Table 1 corresponds to Type 4. This type is without hot water circulation between heat pump and tank and heat pump is for use of preheating in front of boiler or burner to get the target temperature into drying furnace. In addition, to operate efficiently this system, cold and hot water are utilized for drying furnace and electrodeposition process by the heat exchanger in Figure 4. Figure 6 shows the setting of input values for conventional type and heat pump introduction type. Power consumptions are calculated by these input values, for example, final target temperature (Tc1, Th2, Tc2, Th3), environmental air temperature (Th1), air flow rate (Gh), cooling water temperature (Ts), chilled water temperature(Tc1), chilled water flow rate (Gc).

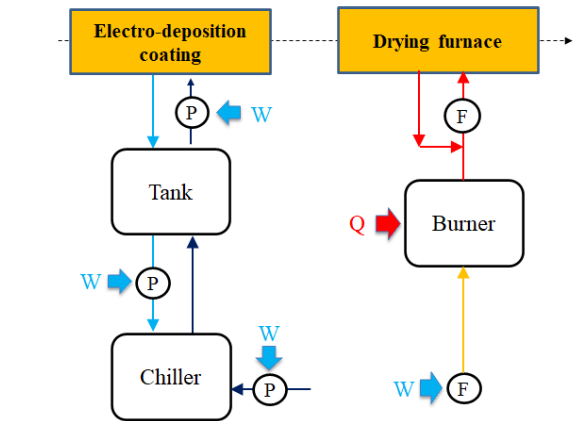


(a) Conventional type   (b) Heat pump introduction type

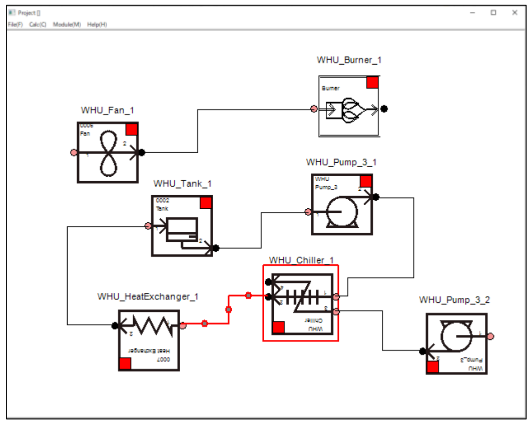
Figure 6. System type classification for simplified simulator

3.3. Analysis by integrated simulator

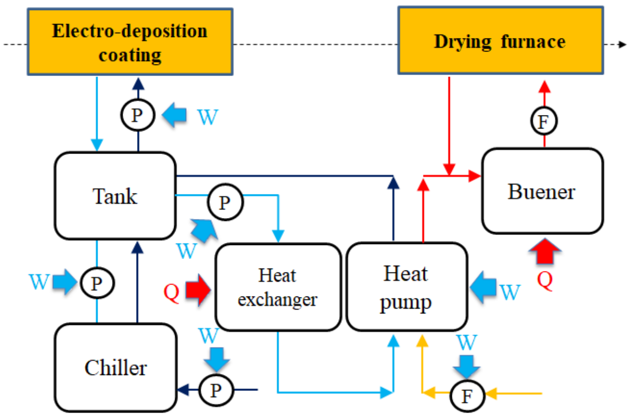
The integrated simulator is based on the concept of modular analysis as a general-purpose analytical theory for energy systems, particularly thermal-fluid systems. This theory enables the numerical analysis of a wide variety of energy systems using a unified method, and Figure 7(a) shows a flow diagram of a chiller and burner used in conventional industrial process cooling and drying processes. To analyse these systems, the modules of each component of the system are arranged on the graphic user interface (hereinafter referred to as GUI) of the integrated simulator, as shown in Figure 7(b). Figure 7(c) shows a flow diagram of a system that simultaneously utilizes cold and heat by introducing a heat pump, in contrast to the conventional system shown in Figure 7(a). Figure 7(d) shows this system represented as a module of each element in the GUI of the integrated simulator. As shown in Figure 7(b) and Figure 7(d), the integrated simulator was developed in the C++ language, and the GUI was designed to simplify the main screen and make the calculation procedure easy to understand. In addition, the code is structured in a calculation core with independent system analysis, module analysis, convergence calculation, refrigerant properties, and other sections, making it easy to modify and add to the code. The code incorporates a new convergence calculation method to increase speed, and maps refrigerant properties based on the latest REFPROP to improve accuracy and increase speed.



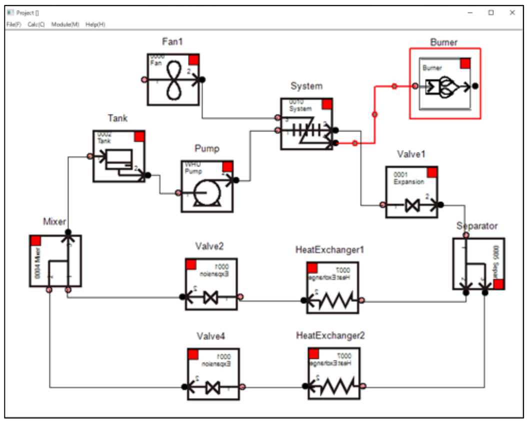
(a) Conventional industrial drying system



(b) Conventional industrial drying system on GUI



(c) Industrial heat pump drying system



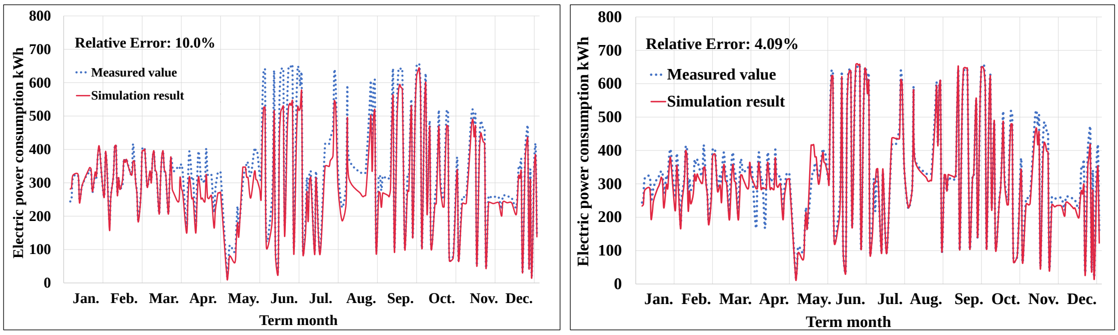
(d) Industrial heat pump drying system on GUI

Figure 7. Flow diagram and expression on integrated simulator of conventional and heat pump introduction industrial drying system

3.4. Simulation results by simplified simulator and integrated simulator

3.4.1. Comparison of simulation results and field data

Figure 8 compares the simulated and measured power consumption of heat pump only by simplified simulator and of heat pump and auxiliary equipment by integrated simulator on a monthly power basis. Integrated simulator considered pump and fan power consumption as auxiliary equipment in addition to heat pump power consumption. The actual measured daily power consumption values used for verification are accumulated as kWh, and data for 365 days are shown. For the simulator analysis, calculations are performed at one-hour intervals throughout the year and compared with the actual measured data. The time required for analysis by the simplified simulator and integrated simulator is about 2 minutes (based on Intel(R) Core(TM) i5) and 7 hours (based on Intel(R) Core(TM) i5) respectively. For the integrated simulator, considering the user's environment, it is assumed that the analysis results can be checked when the user finishes work in the evening and starts work the next morning. The accuracy of the calculation was about 10.0% and 4.1% relative error, confirming the validity of the analysis using the simplified and integrated simulator, respectively.

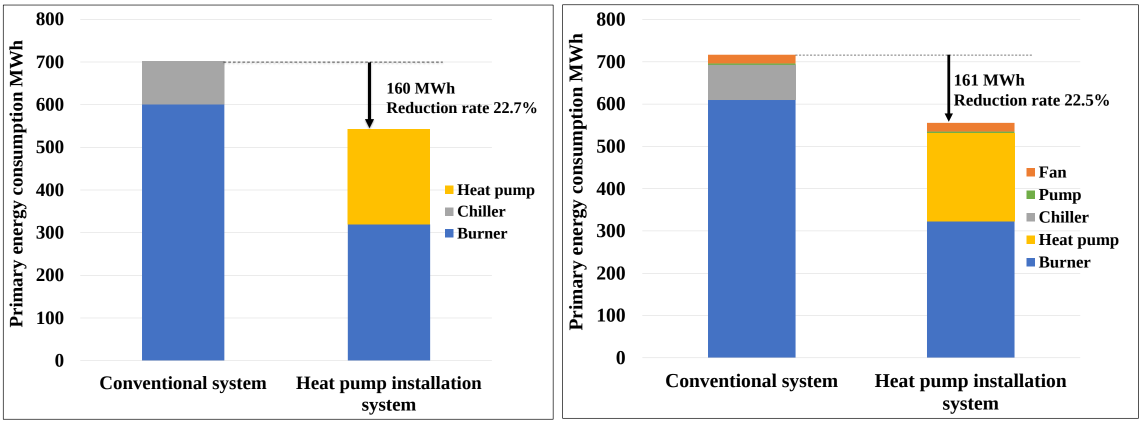


(a) Result by simplified simulator (b) Result by integrated simulator

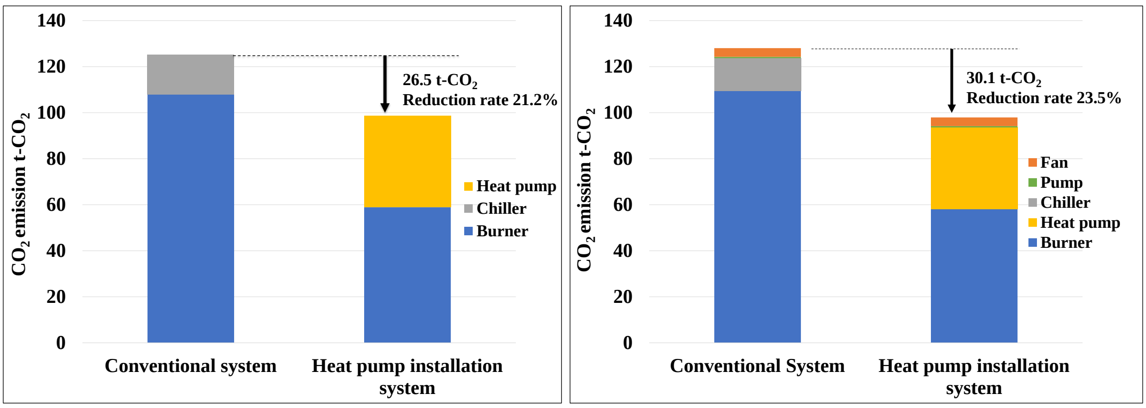
Figure 8. Comparison of simulation and measurement results on electric power consumption of heat pump installation system

3.4.2. Environmental evaluation

The introduction of heat pumps into the industrial heat system field is expected to save energy in industrial processes. This chapter presents a quantitative comparison and evaluation of the degree to which the introduction of heat pumps can save energy and reduce CO_2 emissions for the entire system compared to conventional combustion-type heating equipment such as boilers and burners. The primary energy consumption and converted CO_2 emissions are compared between the conventional system and the heat pump system, including the gas consumption by the gas burner. To calculate the primary energy consumption, the energy conversion efficiency of thermal power generation is 36% and that of burners and boilers is 90%. For the calculation of CO_2 emissions, the emission factor for electricity is set to 0.000462 [t-CO2/kWh] [7] and that for city gas to 0.00017964 [t-CO2/kWh] [7]. Fig. 9(a) and Fig. 9(b) show the monthly primary energy consumption of the conventional system and the system with heat pumps. In the results, it was found that the calculation results of the simplified simulator and the integrated simulator were almost identical, with the only difference being the presence or absence of power consumption by the auxiliary equipment-pump and fan.



(a) Result on primary energy consumption by simplified simulator (b) Result on primary energy consumption by integrated simulator



(c) Result on CO_2 emission by simplified simulator (d) Result on CO_2 emission by integrated simulator

Figure 9. Comparison of conventional and heat pump installation system on primary energy consumption and CO_2 emission

As shown in Fig. 9(a) and Fig. 9(b), although the heat pump system provides the chiller's cooling capacity for the conventional system, the heat pump provides heating up to about 100°C out of the heating capacity of the gas burner up to 170°C. Therefore, the reduction effect cannot be said to be large. Fig. 9(c) and Fig. 9(d) show the monthly CO_2 emissions of the conventional system and the system with heat pumps in the simplified and integrated simulators. It can be seen that CO_2 emissions are reduced by using a heat pump for preheating, which is more efficient than a gas burner, even though the electricity emission factor is about 2.5 times larger than the city gas emission factor.

Based on the above results, it is not important which simulator is better between the simplified simulator and integrated simulator that have been developed so far. The simplified simulator can be effectively used to estimate the effect of installing a heat pump in a short calculation time. The integrated simulator should be used for system design purposes when the energy distribution of the entire system, including auxiliaries, and greater calculation accuracy are required. In this way, we believe that the real strength is found in using different simulators according to the user's application.

4. Conclusions

In this study, we developed a "Simplified simulator" and an "Integrated simulator" that can study the effects of introducing heat pumps from both environmental and economic perspectives in order to help expand the use of heat pumps in the industrial field toward the targeted energy conservation.

As a result of the verification of the accuracy of the analysis, it became possible to calculate with a relative error of approximately 10.0% on simplified simulator and 4.1% on integrated simulator from the annual measured values of the objective system. In addition, a comparison study was conducted between a conventional combustion-type system and a system with a heat pump, and the effects of the introduction were quantitatively compared and evaluated in terms of environmental performance indicators such as energy consumption and CO_2 emissions. This means that the simplified simulator and the integrated simulator can contribute to improving the efficiency of existing systems in the industrial field. Especially, the integrated simulator extends the capabilities of the simplified simulator to analyze systems with complex configurations and is fully capable of not only designing large-scale heat pump systems, but also predicting and verifying the effectiveness of heat pump installations.

Looking ahead, we will continue to develop these simplified and integrated simulators to increase its usefulness and practicality.

Acknowledgements

These results were obtained as a result of the commissioned work (JPNP15007) of the New Energy and Industrial Technology Development Organization (NEDO), and we would like to express our gratitude to all concerned.

References

[1] Industrial Heat Pump Exposition, 2020. New Energy and Industrial Technology Development Organization (NEDO), https://www.nedo.go.jp/content/100925495.pdf. (in Japanese)

[2] J. Jeong, S. Muto, Y. Miyaoka, K. Saito, "Economic and environmental assessment of integrated industrial heat pump simulator", JSRAE Annual Conference, 2022, Sep. 7-9, Okayama, Japan, A22. (in Japanese)

[3] J. Jeong, Y. Miyaoka, S. Yamaguchi, K. Saito, "Categorization of industrial heat pump for integrated simulation technology", 13th IEA Heat Pump Conference, 2021,April 26-29, Jeju, Korea, 322.

[4] Ohno K, Saito K, Yamaguchi S, Kishimoto T, Matsumoto K. Intermittent driving simulation of compression type heat pump-1st report: Mathematical model and simulation of single-stage vapor compression type heat pump. *Trans. JSRAE* 2013;**30(2)**:107-122.

[5] Saito K, 2016. "Unified Refrigeration Cycle Evaluation Simulator with Various Refrigerants," Proceedings of the JRAIA international Symposium 2016, Tokyo, Japan, Japan, pp.369-372.

[6] Saito K, Jeong J. Development of General Purpose Energy System Simulator. *Energy Procedia* 2012;**14**:1595-1600.

[7] Greenhouse Gas Emissions Calculation, Reporting and Publication System, Ministry of the Environment, http://www.env.go.jp/earth/ghg-santeikohyo/index.html, (2021). (in Japanese)