Development of a General-purpose Analytical Tool for Evaluating Dynamic Characteristics of Thermal Energy Systems

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Abstract

We present an original tool for analyzing the dynamics of a wide range of thermal energy systems using Modelica, developed by the Central Research Institute of Electric Power Industry in Japan. This tool was originally developed to analyze thermal power generation systems and has been validated against several sets of operational data so far. This paper reports the extension of the tool to the calculation of the thermophysical properties of not only water/steam and air/gas but also various refrigerants implemented by the ExternalMedia library. This addition expands the range of energy systems that can be analyzed with the tool. To validate the simulation data, a comparison between experimental and simulation data targeting a CO_2 heat-pump loop facility was drawn.

Keywords: Modelica, energy system, heat pump

1 Introduction

A great deal of renewable energy sources (REs) must be introduced to electric power grids to reduce CO_2 emissions in the future. However, the fluctuating and unpredictable power output of REs like photovoltaic generation and wind power generation can destabilize an electric power grid. Therefore, it is necessary to establish a realistic approach to compensate for REs load fluctuation. Thermal Power Generation (TPG) systems, which have high efficiency and excellent flexibility, is promising as a power source that handles load fluctuation. If the flexibility of TPG systems can be improved furthermore, it would be possible to introduce a large amount of REs in the electric power grid while reducing CO_2 emissions. In both the design phase and during the operation of such systems, dynamic simulation is an important for determining the limits of flexibility and improving the operability of TPG systems.

The Central Research Institute of Electric Power Industry (CRIEPI) in Japan has developed a dynamic analytical tool based on Modelica for evaluating the dynamic characteristics of a new and an existing TPG systems (Takahashi et al., 2016; Watanabe et al., 2017). The usefulness of this tool has been demonstrated by applying it to evaluate dynamic characteristics and improve the operability of TPG systems (Watanabe et al., 2017).

Meanwhile, another option that adjusts the power demand at the customer-side such as automatic demand response and virtual power plant schemes have been considered to cope with load fluctuation of REs in Japan. Therefore, a dynamic analysis tool will be also needed to evaluate the performance of demand side resources such as cogeneration systems, heat pumps and an air-conditioners that are affected by load-changing operations. Novel customer-side systems will be also needed to facilitate demand management.

In this study, we aimed at improving our original tool more generically to analyze both TPG systems and customer-side equipment systems. Initially, efficiently adding and handling new working fluids such as fluorocarbon-based refrigerants and natural refrigerants posed developmental bottle necks; however, there are already useful open source libraries developed like the External Media library (Casella and Richter, 2008) for the calculation of thermophysical properties, and it was shown that this library could be combined with other libraries (Quoilin et al., 2014; Casella et al., 2013) and proved to be useful. For efficient implementation, using these libraries to incorporate in our tool is also an effective option, but there was a problem about model connection and management between these libraries and our existing tool. Therefore, the External Library was directly implemented and a new package handling a refrigerant fluids was added in our original tool. These changes improve the modeling tool so that it could be used to analyze the dynamic characteristics of various types of energy systems more generically, such as a complex energy system combining existing TPG systems and heat pump systems.

In this paper, the outline of our new developed tool was shown firstly. And then, as a case study for testing the newly added part, a simplified dynamic model of a heat pump system was constructed using this tool. The model results are then compared with experimental data of the CO_2 heat-pump loop facility at CRIEPI for validation.

2 Outline of Analytical Tool

A tool for analyzing TPG systems dynamically was developed at CRIEPI based on the Modelica language using Dymola environment (Takahashi et al., 2016; Watanabe et al., 2017). In this tool, various component

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models (e.g. compressor, gas turbine, combustor, heat exchanger, steam drum, etc) mainly for analyzing TPG systems are already in place along with a node model for calculating the pressure and enthalpy between components, a valve model calculating flows between components, and a control model (e.g., a proportional–integral PI controller). The component models are subjected to mass and energy conservation equations based on physical laws. The models are packaged in a way that makes it easy to construct a dynamic system model.

The original analytical tool could not analyze the dynamic characteristics of equipment that uses either synthetic (e.g., chlorofluorocarbons) or natural (e.g., CO_2 and ammonia) refrigerant as the working medium. Therefore, to model customer-side equipment such as heat pumps or air conditioners, the function that calculates thermophysical properties of the working fluid needs to be extended.

Fig. 1 outlies the newly extended dynamic analytical tool, which is based on the previous tool for TPG systems and now incorporates the ExternalMedia library (Casella et al., 2008; Trapp et al., 2014) for the calculation of thermophysical properties. By implementing the ExternalMedia library, the range of working fluids that can be handled by this tool is extended. The ExternalMedia library is an open-source library and includes interface functions to return calculation results of the thermophysical property value using external software to the analysis model. The ExternalMedia library links to REFPROP of the National Institute of Standards and Technology (Lemmon et al., 2010), CoolProp (Bell et al., 2014), and FluidProp (Colonna and Stelt, 2004) as reference external databese. In the ExternalMedia library, the thermophysical value is defined as a variable with the same form as the ThermodynamicState variable as it is defined in Modelica.Media. Therefore, the library is relatively easy to inconnect with each model element.

Table 1 lists the packages included in the dynamic-characteristics analytical tool. In addition to the group of packages for TPG systems, the new version of the tool includes the “REFRIGERANT MODEL” package to represent customer-side equipment model and uses the ExternalMedia library for calculating the physical properties of the working fluids. The “REFRIGERANT MODEL” package contains basic and simple modes of dynamic-characteristics of a compressors, heat exchangers, piping, and valves and so on.

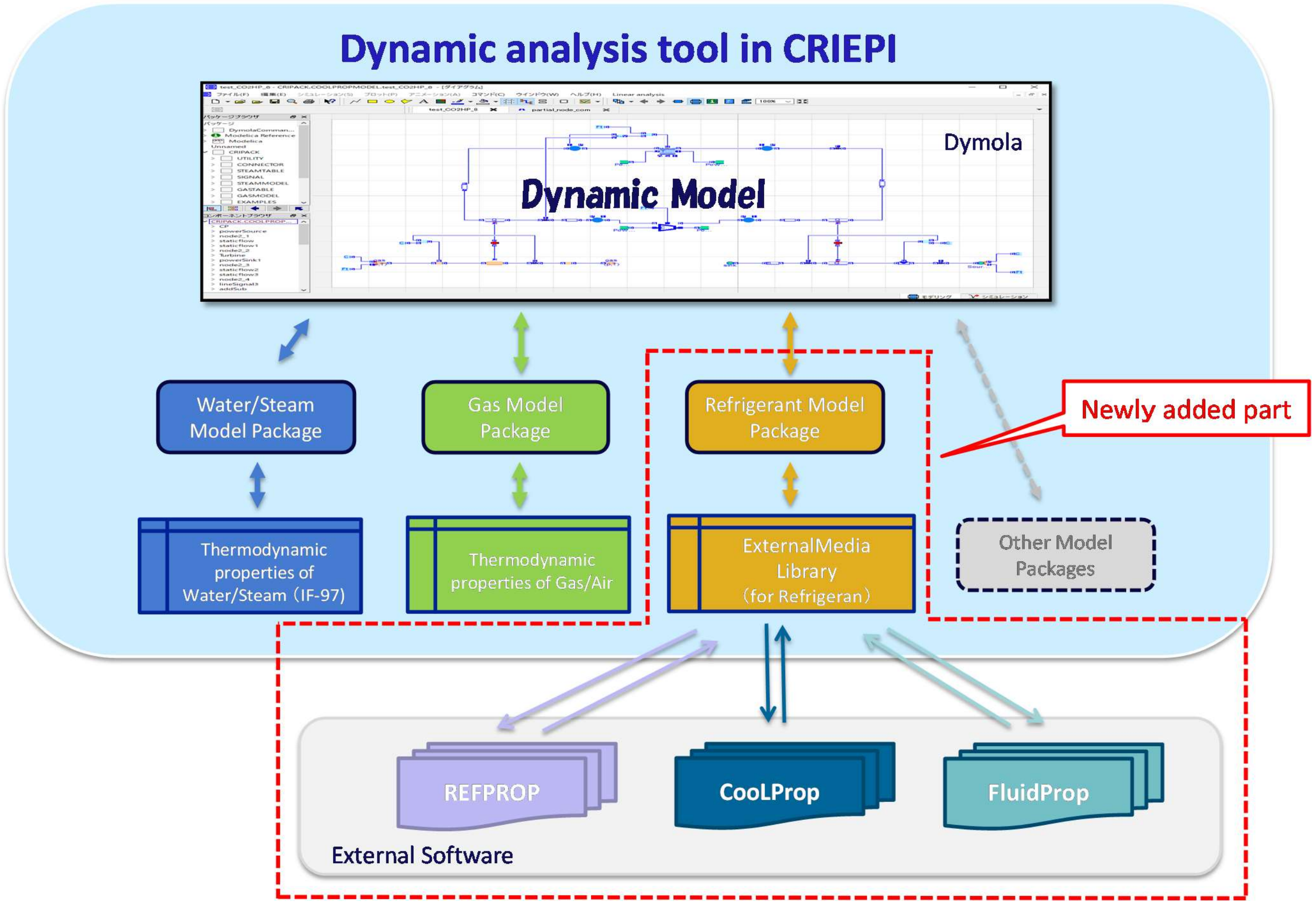


Figure 1. Schematic of the developed tool.

Table 1. Outline of packages in the analytical tool.

Type	**Name**	**Outline**	**Model Example**
Equipment model	STEAMMODEL	Models for fluid dynamics analysis of water and steam instruments	Volume element, Pipe, Valve, Steam turbine, Drum, Heat exchangers, Pump, etc.
	GASMODEL	Models for dynamic analysis of equipment using fluids containing gases other than water vapor	Volume element, Pipe, Valve, Compressor, Combustors, Turbine, Heat exchanger, etc.
	REFRIGERANT MODEL	**Models for dynamic analysis of Freon refrigerant or natural refrigerants**	**Volume element, Pipe, Valve, Compressor, Turbine, Heat exchanger, etc.**
	SIGNAL	Models for signals and control	Step signal model, ramp signal model, PI controller model, etc.
Functions of thermal properties of working fluid	STEAMTABLE	Functions for thermodynamic properties of water and steam based on International Association for the Properties of Water and Steam 1997	Calculation functions of physical properties such as enthalpy, pressure, and specific volume concerning water/steam
	GASTABLE	Functions for thermodynamic properties of gas. Based on IGTC-83 paper (Matsunaga, 1983) and Chemical Properties Hand Book, McGraw-Hill (Yaws, 1999) , create functions necessary for dynamic analysis	Calculation functions of enthalpy, pressure, specific volume, etc. Physical property value concerning gases such as CO_2, O_2, and H_2O and mixed gas
	ExternalMedia (Casella and Richter, 2008)	**Functions for accessing NIST REFPROP, CoolProp, FluidProp and calculating physical property values necessary for dynamic characteristic analysis.**	**Calculation functions of physical properties of the refrigerant provided by external software.**
Models and functions required for model creation or internal computation	CONNECTOR	Models that regulates connection of a device model and a control model	Composition of the working fluid, physical property value, and real number
	UTILITY	General functions for calculation	Number sorting

※Text in bold and red describes components added in the present study

3 Case Study

In this section, the validity and applicability of the tool are verified by comparing results obtained with the dynamic model constructed with the present tool with data obtained from actual machine operation.

3.1 Outline of CO_2 Heat-pump Loop

The target system is the CO_2 heat-pump loop test facility at CRIEPI (Saikawa et al., 1998). Fig. 3 shows a photograph of the experimental apparatus, and Fig. 4 shows a schematic of the equipment. The apparatus includes a compressor, gas coolers, an electro-motion expansion valve, and evaporators. The compressor is an oil-free reciprocating model driven by a variable-speed inverter driven motor and has two pistons and cylinders. The temperature and flow rate of the fluid in each heat exchanger are controlled automatically.

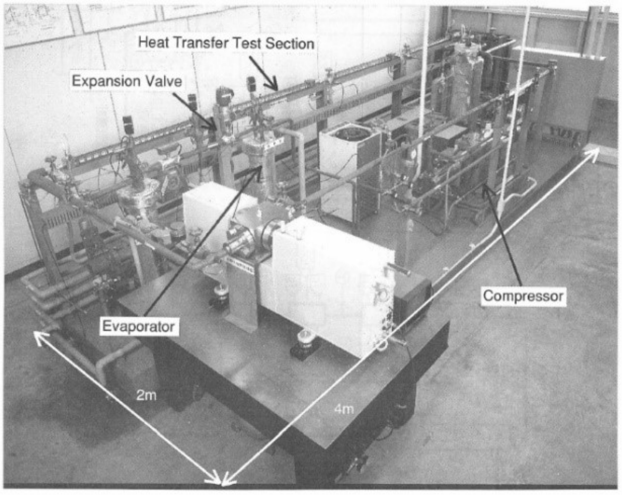


Figure 3. Photograph of the CO_2 heat-pump loop.

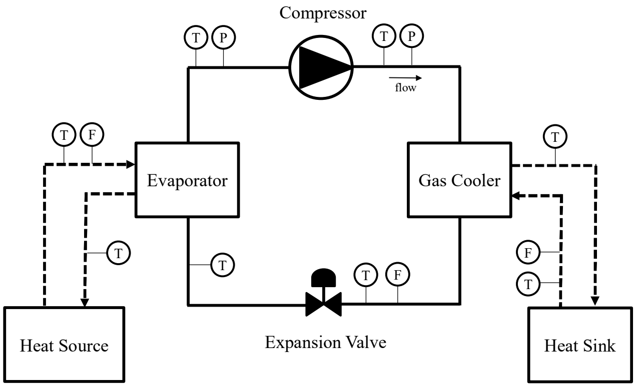


Figure 4. Schematic of the CO_2 heat-pump loop.

Table 2. Specifications of the CO_2 heat-pump loop.

Cycle	Single-stage compression cycle
Power input to compressor	<3 kW (variable by inverter)
Compressor	Reciprocating two oil-free cylinders (D48 × L70 [mm])
Heating capacity	4 - 7 kW
Working pressure	Low pressure: 3 - 4 MPa High pressure: 8 - 12 MPa
Heat source	Brine
Heat sink	Water

3.2 Dynamic Model of CO_2 Heat-pump

A system model of this facility was constructed using the extended analysis tool. Fig. 5 shows an outline of the dynamic model of the CO_2 heat-pump loop facility. In construction of the dynamic model, the refrigerant circuit is used in the “REFRIGERATORMODEL” package, the water side circuit of the heat exchanger is used in the “STEAMMODEL” package, and the controller model is used in the “SIGNAL” package. The calculation equations of the main component models are as follows.

Compressor model:

The flow of the working fluid and the output temperature considering the adiabatic efficiency are calculated with Eqs. (1) and (2), respectively, and the compressor power is calculated as Eq. (3):

$$F = f(N_{comp}), \tag{1}$$

$$h_{out} = h_{in} + \frac{(h_{ad} - h_{in})}{\eta}, \tag{2}$$

$$W_{comp} = F \cdot (h_{out} - h_{in}). \tag{3}$$

Gas cooler and Evaporator model:

The mass and energy equations for the refrigerant side pipe and the water side pipe are represented as Eqs. (4)-(7) (e.g. (Quoilin,2011)). The energy-balance and heat transfer equations for the metal wall on the heat transfer side are represented as Eqs. (8)-(10). These models are also divided vertically and into sections *i* and *j*.

Refrigerant side:

$$V_{r,i}\left(\frac{\partial \rho_{r,i}}{\partial p}\frac{dp_r}{dt} + \frac{\partial \rho_{r,i}}{\partial h}\frac{dh_{r,i}}{dt}\right) = F_{r,i-1} - F_{r,i} \tag{4}$$

$$V_{r,i}\left(-\frac{dp_r}{dt} + \rho_{r,i}\frac{dh_{r,i}}{dt}\right) = F_{r,i-1}\left(h_{r,i-1} - h_{r,i}\right) + Q_{r,i} \tag{5}$$

Water side:

$$V_{w,j}\left(\frac{\partial \rho_{w,j}}{\partial p}\frac{dp_w}{dt} + \frac{\partial \rho_{w,j}}{\partial h}\frac{dh_{w,j}}{dt}\right) = F_{w,j+1} - F_{w,j} \tag{6}$$

$$V_{w,j}\left(-\frac{dp_w}{dt} + \rho_{w,j}\frac{dh_{w,j}}{dt}\right) = F_{w,j+1}\left(h_{w,j+1} - h_{w,j}\right) - Q_{w,j} \tag{7}$$

Metal wall:

$$cp_{m,i}M_{m,i}\frac{d}{dt}T_{m,i} = Q_{r,i} - Q_{w,i} \tag{8}$$

$$Q_{r,i} = K_{r,i} \cdot (T_{m,i} - T_{r,i}) \tag{9}$$

$$Q_{w,i} = K_{w,i} \cdot (T_{w,i} - T_{m,i}) \tag{10}$$

Expansion valve model:

The flow rate is calculated with Eq. (11). The coefficient varies depending on the valve-opening signal:

$$F = C(u) \cdot \left(\sqrt{\rho_{in} \cdot (P_{in} - P_{out})}\right). \tag{11}$$

In this model, the controller model (PI controller) is used to control (i) the opening rate of the expansion valve in response to the difference between the inlet and outlet temperatures of the evaporator and (ii) the flow rate of the water in the heat exchangers.

3.3 Simulation Conditions

To assess the validity of the dynamic CO_2 heat-pump model, the calculation values were compared with previously reported experimental data from the CO_2 heat-pump loop (Saikawa et al., 1998). Fig. 6 shows the scenario used to assess the validity of the dynamic model. In this case, the inverter frequency of the compressor was varied, which changes the flow rate of the CO_2 working fluid is changing.

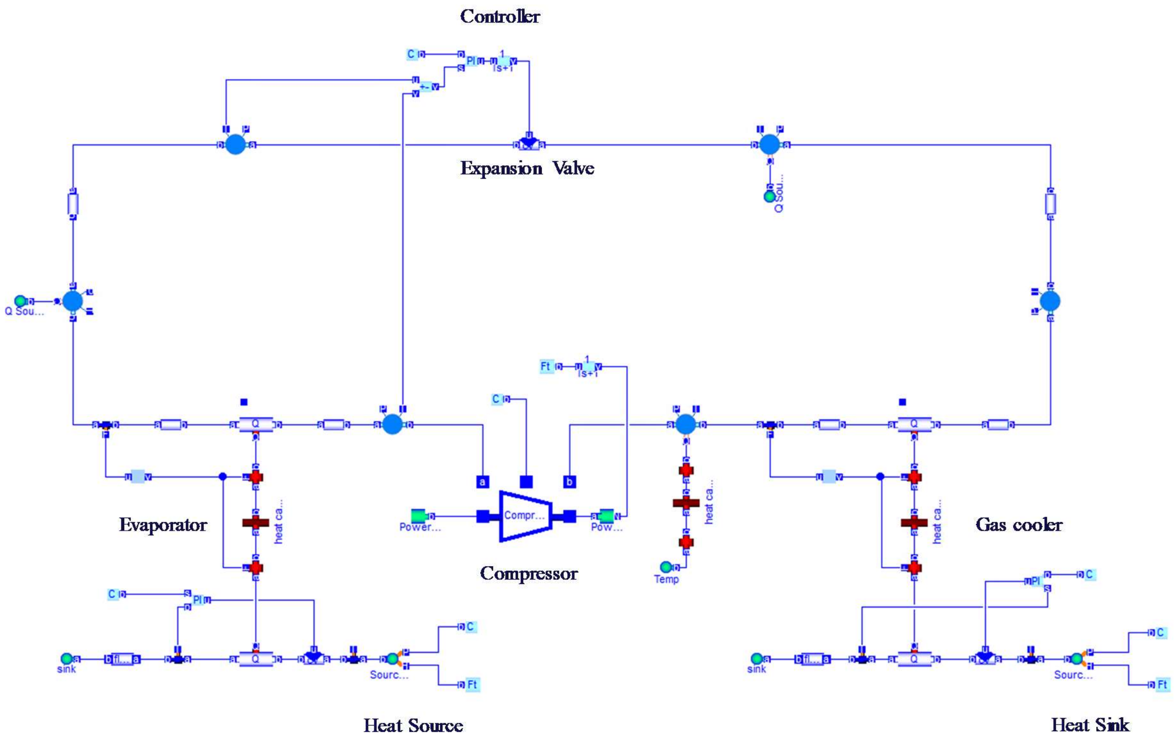


Figure 5. Dynamic model of CO_2 heat-pump-loop facility.

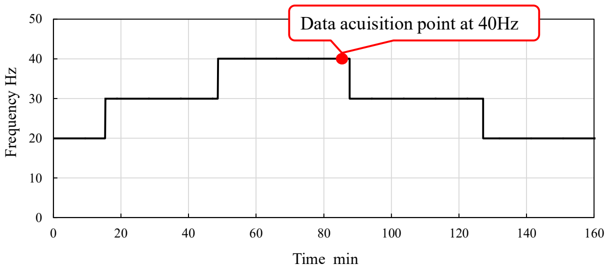
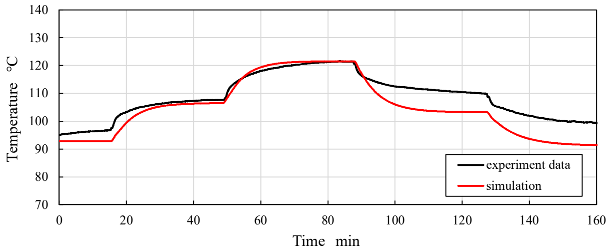


Figure 6. Test scenario for validation: the inverter frequency of the compressor is changing.

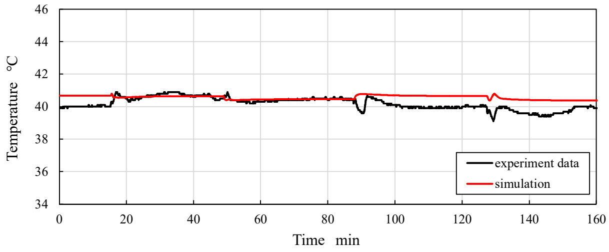
The unmeasured model parameters in the dynamic model, such as the adiabatic efficiency of the compressor and heat transfer coefficient of the heat exchanger, the heat and mass balance calculation using measured operational data of 40Hz (seen in Fig.6) was carried out using the EnergyWin software (Koda and Takahashi, 1999), and these estimated values are set as the initial conditions. The performance parameters of each component set as a function depending on flow rate using the calculation results from steady-state operational data at 20, 30 and 40 Hz. The volume and weight of each equipment and the heat capacity of the heat exchangers were set with reference to the design specifications.

3.4 Results and Discussion

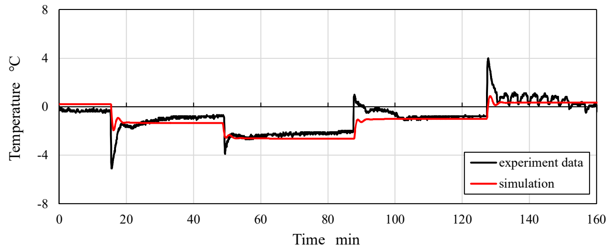
Figs. 7–9 compare the experimental data with the simulation results for the CO_2 heat-pump loop. As shown, the dynamic simulation reproduces the behavior of the operational process. In Figs. 7 and 8, the experiment data and simulation results from the compressor outlet disagree when the frequency decreases. The simplification of the compressor model likely decreased the simulation accuracy, and the model leaves out some phenomena such as volume elements and heat loss. Therefore the model of the compressor characteristics should be prepared with more detail. In Figs. 9(a) and (b), the simulated flow rate shows greater error when the frequency decreases, likely because of the above-mentioned error of the compressor outlet temperature. In addition, the delay factor of the water side-circuit volume element is not considered in the model. Although the inlet temperatures of water from the heat source and heat sink fluctuate slightly in experimental data, the setting parameter of constant inlet water temperature also seems to affect the quantitative results of the simulation, except when the compressor is driven at 40 Hz. The delay in the measuring instruments can be explains this error because the responding speed of this system is quickly. Regarding the quantitative difference when the compressor is under a partial load, the state quantity of working fluid in the heat exchanger and the change of the heat transfer coefficient following the phase change needs to be modeled in greater detail.



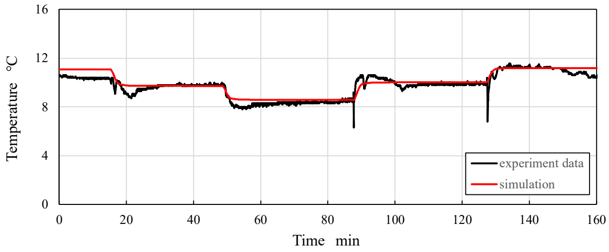
(a) Compressor outlet



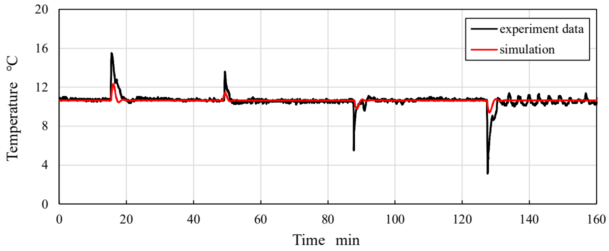
(b) Expansion valve inlet



(c) Evaporator inlet

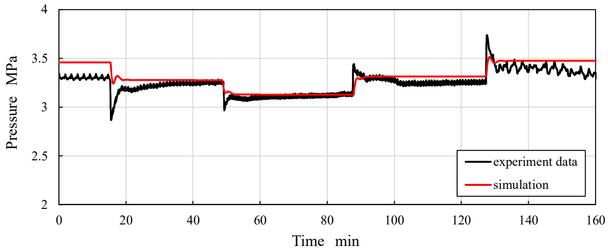


(d) Evaporator outlet

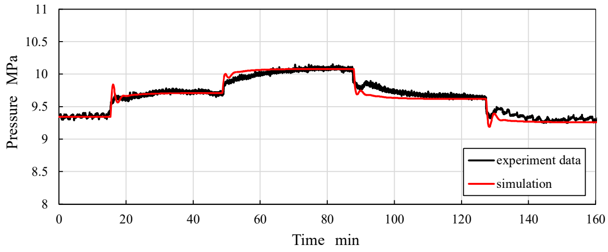


(e) Difference in evaporator inlet/outlet temperature

Figure 7. Results of temperature behavior.

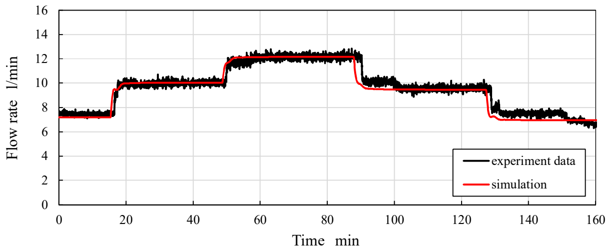


(a) Compressor inlet

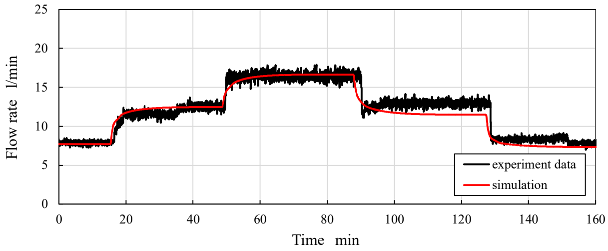


(b) Compressor outlet

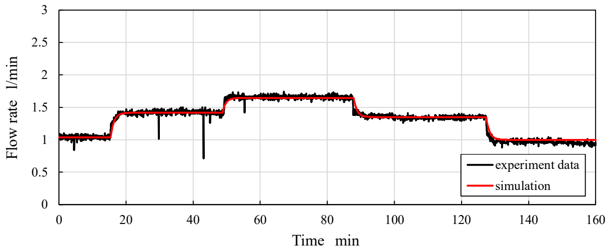
Figure 8. Results of pressure behavior.



(a) Heat source



(b) Heat sink



(c) CO_2 working fluid

Figure 9. Results of flow rate behavior.

These results suggest that the accuracy of some model elements needs to be improved, but it is useful for evaluating the operating performance at the system level.

4 Summary and Future Work

A new function for modeling refrigerant working fluids was added to the CRIEPI's Modelica dynamic-characteristics analytical tool by integrating the ExternalMedia library. The innovations discussed above yield an analytical tool that can be used to more general-purpose energy systems. The validity of the tool was assessed via comparison with experimental data measured from a hot-water supply system with CO_2 refrigerant. The model accuracy of some elements of the system needs further improvement, though sufficiently accurate results for constructing a dynamic model were obtained. In future work, we plan to assess the validity of the tool for other refrigerant types and systems, develop more advanced tools, and challenge the operability evaluation for complex systems that comprise devices with various working fluids. In addition, to promote application to real machines, data calibration and data assimilation as a function to utilize actual operational data will be carried out and models will be developed for the purpose.

NOMENCLATURE

F	Flow rate [kg/s]
h	Specific enthalpy [J/kg]
P	Pressure [Pa]
M	Mass [kg]
V	Volume [m3/kg]
Q	Heat flow [W]
T	Temperature [K]
K	Global Heat transfer coefficient [W/K]
ρ	Density [kg/m3]
W	Power [W]
C	Flow coefficient [-]
u	Input
N	Rotation signal
η	Adiabatic efficiency [-]

Subscript

r	Refrigerant
m	Metal
w	Water
comp	Compressor
ad	Adiabatic change

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