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Development of a Refrigerant Evaluation Tool for Air Conditioners

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Abstract

In order to prevent global warming, there is a strong need to reduce greenhouse gas emissions and energy consumption of refrigeration and air conditioning systems. Various new low-GWP refrigerants are being introduced for air-conditioning equipment, such as residential and commercial air-conditioners. The performance of these new working fluids should be effectively evaluated to select their most suitable implementation case and reduce the environmental footprint of this technological field. The actual operation performance of air-conditioning equipment is substantially affected not only by the system design and the properties of the refrigerant, but also by the climate and load conditions of the specific installation. Therefore, a refrigerant evaluation tool may take advantage from the cost effectiveness and flexibility of a reliable simulation platform but requires standardized calculation conditions for achieving unbiased results. Therefore, a system simulator was hence developed for the analysis of next-generation refrigerants, including zeotropic mixtures. This paper discusses about validity verification results of this evaluation tool based on experimental results and assess the performance of residential air conditioners.

Keywords: air-conditioniner; simulator; low-GWP; LCCP; refrigerant;

1. Introduction

In order to curb global warming, it is necessary to reduce greenhouse gas emissions from the refrigeration and air conditioning sector. The operation of such thermal systems leads to both direct and indirect emissions to the environment throughout their life cycle, from manufacturing, through operation, to disposal. In fact, their fundamental functioning is based on the circulation of a refrigerant through various components such as compressors and heat exchangers where heat, mass and momentum transfer take place in order to supply output cooling/heating capacity. The ratio between the magnitude of this output capacity to the corresponding input energy defines the coefficient of performance of the system, which is ruled by the thermophysical and transport properties of the refrigerant. Additionally, the chemical properties define the GWP of the refrigerant, which is commonly used to assess the corresponding direct emissions. Following the Kigali amendment to the Montreal Protocol, research and development of next-generation low-GWP refrigerants and their safety and risk assessment are underway to provide alternative working fluids for refrigerators, air conditioners, and heat pumps. Accordingly, the development of effective refrigerant evaluation techniques is an essential tool for strategizing the decarbonization of this technological field. Contextually, it has been widely recognized that accounting for the sole GWP value cannot comprehensively evaluate the overall environmental footprint of refrigeration and air-conditioning systems. In fact, these systems consume energy during their entire life cycle for equipment manufacturing, operation, and disposal. Energy supply is accompanied by a series of processes that result into corresponding emissions. Under this viewpoint, when selecting optimal refrigerants, LCCP may better represent the performance and environmental footprint of air conditioners and refrigerators. Contextually, the actual operating performance of refrigeration and air conditioning equipment is greatly

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influenced not only by system design and refrigerant characteristics, but also by the climate, load conditions, and characteristics of the energy supply of the installation site [1]. Therefore, to broadly investigate this spectrum of operating conditions, it is important for refrigerant evaluation tools to be cost-effective, flexible, and unbiased.

Common procedures for selecting next-generation refrigerants are either based on the experimental assessment of drop-in tests [2], where refrigerants are replaced without revisiting system design and control, or on the numerical thermodynamic cycle simulations that are determined solely by the refrigerant's thermophysical properties and neglect a thorough evaluation of the interrelationship between the transport properties of the refrigerant and the performance of the equipment [3]. An unbiased refrigerant evaluation approach should assess the potential of each refrigerant under representative operative conditions while also considering the transport performance, component features, and control parameters of the actual equipment. Therefore, a refrigerant evaluation tool may take advantage from the cost effectiveness and flexibility of a reliable simulation platform but requires standardized calculation conditions for achieving unbiased results. To this aim, this study presents the development of a refrigerant evaluation tool based on the integration of a reliable simulation platform with standardized calculation conditions. The validity of the simulator is verified by experimental results, and the performance of residential air conditioners is simulated under some conditions.

2. Overview of the refrigerant evaluation tool

To define representative calculation conditions, it was necessary to bring together different standpoints from academia and industry. Specifically, standardized analysis conditions and equipment models of the most common refrigeration equipment [4] were constructed in cooperation with the Japan Refrigeration and Air Conditioning Industry Association (JRAIA). In November 2015, the JRAIA founded the Refrigerant Evaluation Working Group to develop a standardized environment and corresponding methodology for refrigerant performance evaluation, thereby eliminating complementary discussions on measurement setup, method and accuracy, and enabling prompt evaluation of the actual potential performance of new refrigerants. This will help minimize conflicts between different research efforts and facilitate the effective selection of refrigerants and the development of energy efficient equipment.

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 [5-7]. Specifically, the features of the developed evaluation tool and the experimental verification of its computational accuracy are hereby presented and discussed.

3. Features of the simulator

The development of the simulator "Energy Flow+M" is based on the modular analysis theory to consistently represent different thermal systems using different refrigerants on the same simulation platform for energy analysis (Figure 1). Fundamental transport phenomena, together with the laws of energy conservation, mass conservation, and momentum transfer, make up the mathematical relationships that define each module. From this point of view, heat exchangers, compressors, expansion valves, and accumulators are represented as sets of functions that relate the inlet and the outlet states of the circulating refrigerant. As a result, it is possible to construct the Jacobian matrix of the entire system by interconnecting modules according to the system configuration and interfacing with the external environment. Newton-Raphson method drives the simulation towards convergence in stationary conditions and non-stationary conditions with dynamic parameter modulations. For mathematical details of the model formulation employed for the fundamental modules [5-7].

The modular analysis theory as a general-purpose analysis method focused on thermal fluid energy system Modular analysis. Consequently, it was clarified that the modular analysis theory facilitated the numerical analysis of various thermal energy systems, for example, vapor compression system, absorption system, desiccant system, solar thermal application system, etc. by unified methodology. For this theory, the concept of engineering control methods is put into analysis of the energy systems. The user can analyze the thermal system without mathematical procedure. Large scale smart energy system can be also easily analyzed and the user's burden to make the simulation code can be reduced by using this simulator.

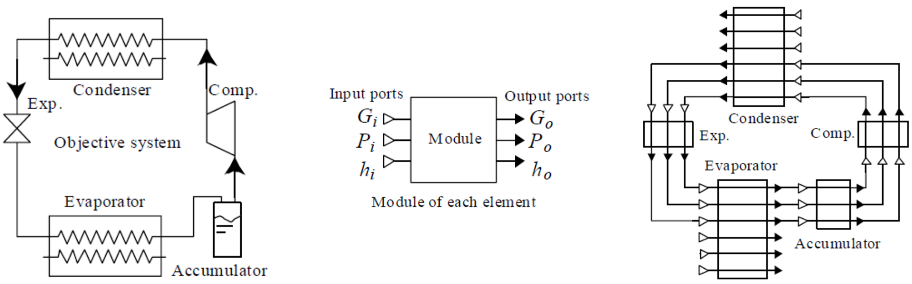


Fig. 1. Conceptual representation of the modular theory adopted for the simulator development

4. Model of the Residential Air Conditioner

Here, we will present the model of a residential air conditioner as a representative example. Single-split residential air conditioner generally feature an independent outdoor unit connected to the indoor heat exchanger with refrigerant pipelines as shown in Figure 2. Additionally, the rotational speed of the compressor and the opening of the expansion valve are adjusted using a PI controller to achieve target room temperature and degree of superheat at the suction of the compressor. The corresponding simulation model is built by assembling compressor, outdoor heat exchanger, expansion valve, accumulator, indoor heat exchanger and extension piping modules according to the reference system characteristics (summarized in Table 1).

Table 1. Reference residential air conditioners characteristics

Refrigerant	Nominal cooling capacity	Extension piping length	Refrigerant charge
R22	2.2 kW	5 m	0.9 kg

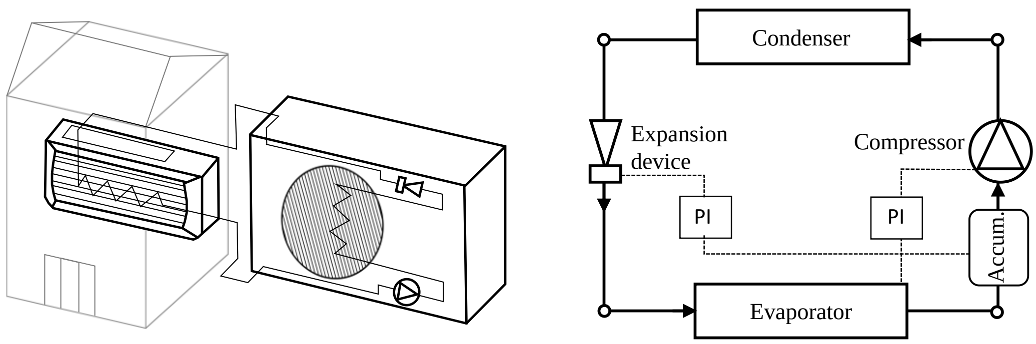
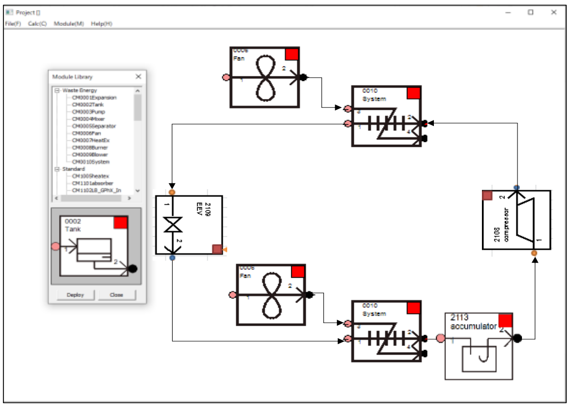


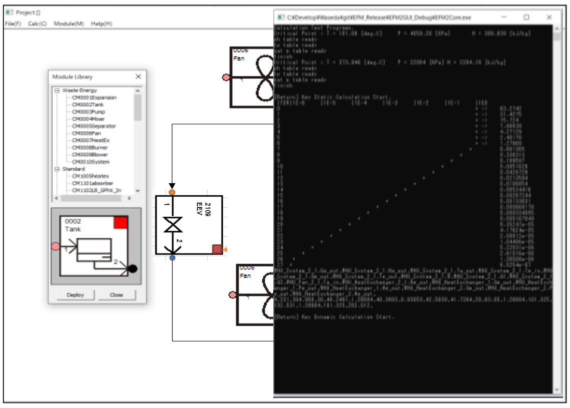
Fig. 2. Illustration of the residential air conditioner system and its flow diagram

5. Characteristics of the GUI

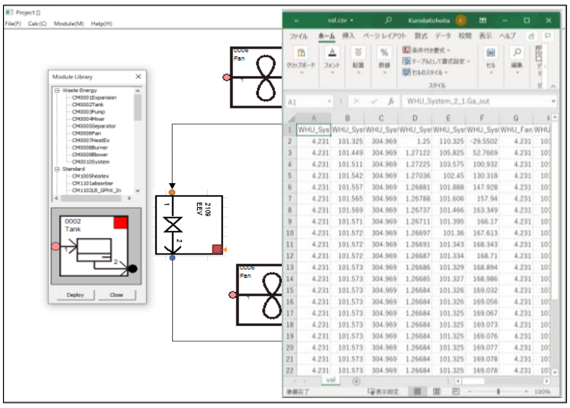
Figure 3 shows the graphic user interface (GUI) of "Energy Flow+M" simulator. The simulation environment makes it user-friendly even to engineers and researchers with minimal background experience in technical and scientific simulations. The combination of modules required to simulate a vapour compression type air conditioning system is shown in Figure 3-(a). Figure 3-(b) shows the appearance of the GUI during system simulations. Figure 3-(c) shows the simulation output in a CSV file format.



(a) Layout of vapor compression air conditioner on GUI



(b) Calculation



(c) Simulation results

Fig. 3. Illustration of the equivalent modular system built in Energy Flow+M

6. Experimental Validation of the Simulation Accuracy

6.1 Experimental test of the air conditioner

6.1.1 Background and purpose of the experiment

When introducing next-generation refrigerants into refrigerating and air conditioning equipment, not only the must the safety and environmental GWP (direct impact) of the refrigerant used in the equipment be considered, but also the impact on global warming owing to energy-derived CO2 emissions (indirect impact). Therefore, the actual operating performance of the refrigerant and air conditioning equipment needs to be evaluated. To fully illustrate the potential of low-GWP refrigerants, an optimized air conditioning unit should be fabricated for each refrigerant and employed to conduct accurate performance tests under actual operating conditions. However, there are a number of next-generation refrigerant candidates; the corresponding financial and time costs required to produce a series of specifically optimized air conditioning units is unrealistic. Therefore, in this study, objective [3] “Simulator development and utilization” was pursued to construct various simulators for heat exchangers and air conditioning systems to shorten the period and cost required for system examination and production. Before using such simulators, the validity and accuracy of the calculated values employed in their construction must be verified. Therefore, the R290 and R454C low-GWP refrigerants were dropped-in to air conditioners designed for use with the R22 refrigerant and their performances were evaluated accordingly.

6.1.2 Overview of the air conditioner used in this experiment

Table 2 shows the specifications of the air conditioner operated during the experimental test. The experimental tests are preliminarily conducted at steady-state for an R22 air conditioner and for drop-in tests of R290 within the same unit.

As the production of the R22 air conditioner had already been discontinued about 10 years ago, it was not possible to obtain a new system. Therefore, tests were conducted on a second-hand wall-mounted room air conditioner with a rated capacity of 2.2 kW. Pressure sensors and thermocouples are installed after thoroughly cleaning the heat exchangers of the outdoor and indoor units. Every time the refrigerant is replaced, the inside of the refrigerant circuit is cleaned and the refrigeration oil is replaced s with one suitable for each refrigerant, mineral oil for R22 and PAV for R290. In order to measure the refrigerant flow rate, two Coriolis flowmeters were installed for measurements in both cooling and heating modes. In addition, a compressor and expansion valve drive tools were provided by the air conditioner manufacturer to enable free control of the rotational speed of the compressor and free adjustment of the expansion valve opening in 50 steps. Figure 4 shows the mounting positions of the pressure sensors, thermocouples, and refrigerant flow meters. Further details of the equipment and instrumentation of the testing facility are referred to [8]. Fig.4 shows mounting locations of pressure sensors, thermocouples, and flow meters. Figure 5 shows test setup in the dynamic performance evaluation facility.

Table 2. Specification of the room air-conditioner

Item		Contents
Type		Room air-conditioner
Year of manufacture		2001
Original refrigerant		R22
Rated capacity(W)	cooling	2200
	heating	2500

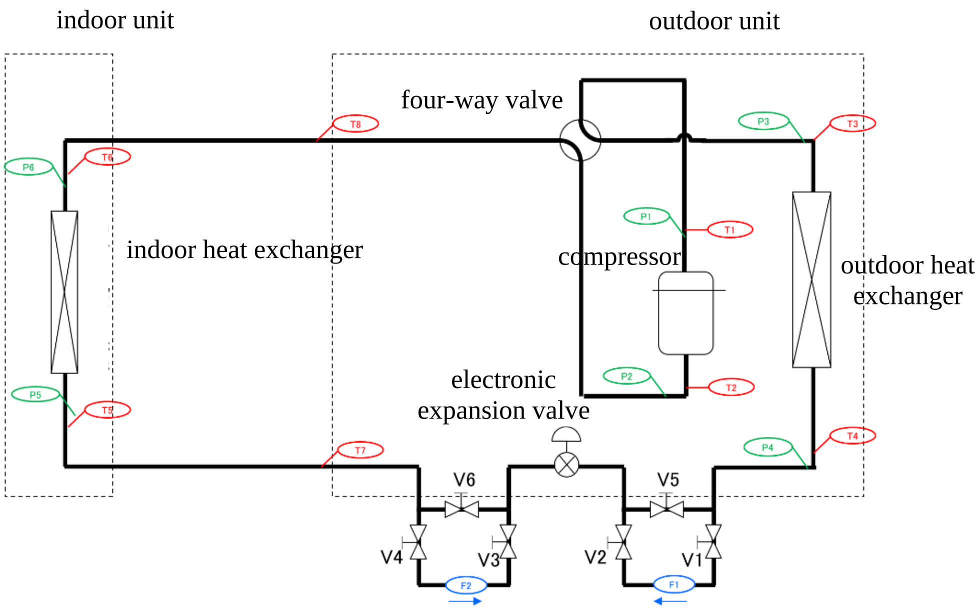


Fig. 4 Mounting locations of pressure sensors, thermocouples, and flow meters

(a) Indoor unit (b) Outdoor unit

Fig. 5 Test setup in the dynamic performance evaluation facility

6.1.3 Test conditions

Four test conditions comprising four cooling conditions and four heating conditions were evaluated in accordance with the temperature conditions for the outdoor and indoor units provided by JIS C 9612:2013 [3] for room air conditioners. The specific temperature and load conditions are listed in Table 3.

Table 3 Test conditions

Test condition			Indoor temperature (℃) Dry / Wet	Outdoor temperature (℃) Dry / Wet	Partial load ratio (%)
(a)	Cooling	Standard cooling Full-capacity test	27 / 19	35 / 24	100
(b)		Standard cooling Half-capacity test		35 / 24	50
(c)		Low-temperature cooling Half-capacity test		29 / 19	50
(d)		Low-temperature cooling Minimum-capacity test		29 / 19	25

6.1.4 Test results

The results of the standard cooling full-capacity test conditions represented by (a) at Table 3 are described Table 4 when the refrigerant charge was optimized by fixing the compressor rotation speed to achieve a capacity of 2.2 kW.

Table 4 Comparison of standard cooling full-capacity test results for R22 and R290

Refrigerant type	Refrigerant charge (g)	Compressor speed (Hz)	Mass flow rate (Kg/h)
R22	910	55.0	51.0
R290	400	62.5	28.2

6.2 Experimental results and simulator validation results

6.2.1 Background and purpose of validation

The actual operating performance of refrigeration and air conditioning equipment is the most critical factor in system operation evaluations. As system simulators offer an extremely effective approach for such evaluations, the effects of applying the R290 refrigerants to air conditioners designed for use with the R22 refrigerant, as discussed in previous section, were analyzed using the EF+M system simulator, which is being developed at our university. The differences between the experimental values and simulation results were then evaluated to validate the simulator.

6.2.2 Simulation results for R22 refrigerant and R290 refrigerant drop-in

Table 5 compares the experimental and simulation results for R22 refrigerant at standard cooling full-capacity test conditions represented by (a) at Table 3, Table 6 compares the experimental and simulation results for R290 refrigerant at standard cooling full-capacity test conditions represented by (a) at Table 3.

Table 5 Comparison of system experiment and simulation results (R22)

	Cooling capacity (%)	Power consumption (%)	Mass flow rate (%)	Condensing temperature (℃)	Evaporating temperature (℃)
Experiment	100	100	100	44.6	6.99
Simulation	99.1	100	101	44.7	8.4

	Compressor suction pressure (MPa)	Compressor discharge pressure (MPa)	Compressor suction temperature (℃)	Compressor discharge temperature (℃)	Degree of superheat (℃)	Degree of subcooling (℃)
Experiment	0.621	1.71	19.3	81.8	2.83	2.11
Simulation	0.587	1.72	19.8	82.1	2.14	4.32

Table 6 Comparison of system experiment and simulation results (R290)

	Cooling capacity (%)	Power consumption (%)	Mass flow rate (%)	Condensing temperature (℃)	Evaporating temperature (℃)
Experiment	100	100	100	46.0	6.13
Simulation	101	100	99	46.2	7.43

	Compressor suction pressure (MPa)	Compressor discharge pressure (MPa)	Compressor suction temperature (℃)	Compressor discharge temperature (℃)	Degree of superheat (℃)	Degree of subcooling (℃)
Experiment	0.570	1.57	12.8	64.5	0.10	3.89
Simulation	0.564	1.58	13.2	65.5	0.82	5.00

These numbers are in good agreement overall. However, there is a difference compressor suction pressure and degree of subcooling. The reason for these is that although the former is considered to be affected by the refrigerating machine oil in the actual machine, it is not considered in the simulation. One of the reasons for the latter is thought to be that the fins of the air heat exchanger have slits in the actual machine, but are treated as flat plates in the simulation. In the future, we would like to further investigate and improve the accuracy.

6.2.3 Summary of model validation

A system simulator was applied to reproduce the results of a test in which a room air conditioner designed for use with the standard R22 refrigerant was charged with R22, R290, the latter two of which are low-GWP refrigerants. Comparisons of the experimental values and simulation results confirmed suitable simulation accuracy. In the future, we will also consider dropping in R454C.

7. Conclusions

This study presented the recent progresses in simulation platform adopted for the use in refrigerant performance evaluation analyses. The GUI of the simulator was upgraded with precisely structured and completely independent calculation codes, which enables prompt modification of each component and system module. The new GUI and internal code structure constitute a user-friendly simulation platform that does not require technical experience in coding and numerical simulation development to run accurate air conditioning and refrigeration system simulations with different refrigerants. A standard model for a single-split residential air conditioner was developed and validated with dedicated experimental tests conducted on a 2.2 kW R22 air conditioner. Additionally, numerical simulations with R290 were validated with corresponding drop-in tests of the same air conditioning unit. As a result, it was shown that the simulation results accurately represents the operating performance of actual systems with different refrigerants and may be effectively used for evaluating the performance of new low-GWP fluids.

Acknowledgements

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