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Development of a Standardized Refrigerant Evaluation Tool for Air Conditioning and Refrigeration Equipment Using a General-Purpose Energy-Analysis Simulator

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ABSTRACT

Various new low-GWP refrigerants are being introduced for refrigeration and air-conditioning equipment, such as residential air conditioners, commercial air-conditioners, refrigerated display cabinets, chillers, and condensing units. 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 refrigeration and 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. To this aim, the joint effort of a consortium representing different views from academia and industry is required to validate the analysis and define common calculation conditions. Consequently, the development of a standardized evaluation tool will minimize inconsistencies between different research efforts and contribute to driving the effective selection of refrigerants and the development of energy-efficient equipment. A general-purpose energy-analysis simulator, "Energy Flow+M", was developed and validated at Waseda University for steady-state, dynamic and control analyses. The cooperation with the Japan Refrigeration and Air Conditioning Industry Association (JRAIA) led to the proposal of standardized analysis conditions and the development of standard refrigerant evaluation models for different air-conditioning and refrigeration systems. Finally, this evaluation tool was used to assess the performance of different systems using next-generation low-GWP refrigerants, including conventional HFC refrigerants, refrigerant mixtures, HFO and natural refrigerants. Comparative results obtained for R32, R410A, R290, R1234yf, and different zeotropic mixtures were presented and discussed.

1. INTRODUCTION

The efficiency of thermal systems rules the systematic use of energy resources and is associated with direct and indirect emissions to the environment. These systems essentially operate by circulating working fluids within different components where heat, mass, and momentum transfer is realized to convert the input energy sources to output effects. The thermophysical, transport (such as heat transfer coefficients), and chemical properties of these working fluids, contextually termed “refrigerants” affect both direct and indirect environmental footprint of these systems during their whole lifecycle. Following the Kigali Amendment to the Montreal Protocol, research and development of next-generation low global warming potential (GWP) refrigerants, as well as their safety and risk assessment are underway. In this context, the development of assessment techniques for next-generation refrigerants with low-GWP values is an essential aspect of the strategy towards environmental sustainability. Nonetheless, common procedures for the selection of refrigerants have been carried out experimentally, with drop-in tests where the refrigerant is replaced without reconsidering the design and control of the system, or numerically, with cycle simulations solely determined by the thermophysical properties of the fluid while disregarding a thorough evaluation of the interrelations between the transport properties of the refrigerant and the equipment performance. Therefore, an unbiased assessment technique should evaluate the potential of each refrigerant in representative conditions while considering the actual transport performance of the components, system operation requirements, and setting of manipulated and control parameters without limiting the search for effective configurations. To this aim, in November 2015 the Japan Refrigeration and Air Conditioning Industry Association (JRAIA) founded the Refrigerant Evaluation Working Group to develop a standardized environment and a corresponding assessment technique for the performance evaluation of most common refrigeration equipment using new refrigerants, thereby eliminating complementary discussions on measurement setup, method and accuracy, and enabling prompt evaluation of the actual potential performance of new refrigerants. This is done by means of the general-purpose energy-analysis simulator, "Energy Flow+M", developed and validated at Waseda University for steady-state, dynamic and control analyses (Saito and Jeong, 2012). The numerical simulator is developed by using the modular analysis theory for representing different refrigeration systems using various refrigerants. This modular tool relies on fundamental thermophysical and transport properties, heat, mass and momentum balances, and allows the investigation of different system layouts and operation strategies, hence, featuring the necessary elements for a comprehensive evaluation.

This study presents a preliminary set of results obtained via the implementation of this refrigerant evaluation tool for different air conditioning and refrigeration equipment. Specifically, residential- and window-type air conditioners, condensing units, and built-in refrigerated display cabinets are hereby investigated. Unbiased simulation settings are proposed and reference equipment models introduced as the baseline reference for the performance evaluation of different refrigerants.

2. SIMULATOR AND SIMULATED EQUIPMENT

The development of a unified simulation platform for the energy analysis of air conditioning and refrigeration equipment relies on the modular analysis theory (Figure 1), which enables stationary, dynamic and control analyses while accounting for the actual transport performance of different refrigerants in relation to the component configurations, operation settings, environmental conditions, and required output demands. The formulation of the fundamental transport phenomena, along with energy, mass and momentum transfer, constitute the mathematical relations which define each module. Under this viewpoint, heat exchangers, compressor, expansion devices, and accumulators are represented by a set of functions relating the inlet, outlet, and internal state quantities of the circulating refrigerant. Consequently, the interconnections of modules according to the system configuration, and the interfacing with the external environment enables the construction of the Jacobian matrix of the whole system, which is managed by Newton-Raphson method towards convergence in steady and unsteady conditions according to dynamic modulations of control parameters. Mathematical details of the models adopted for the fundamentals modules and the validation of steady-state, dynamic, and control simulation results are referred to Saito and Jeong (2012), Ohno et al. (2013), and Saito (2016).

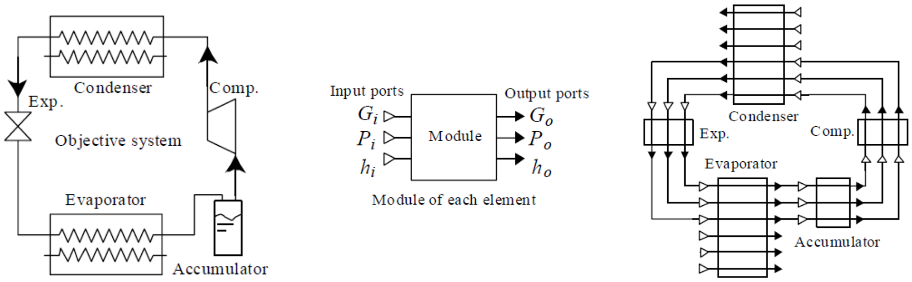


Figure 1: Conceptual representation of the modular theory adopted for the simulator development

The air conditioning and refrigeration systems hereby investigated for the refrigerant performance evaluation are consequently modelled by assembling the fundamental modules according to representative configurations of each equipment and by specifying the refrigerant property database, transfer model, boundary conditions with the external environment, and control method. Given the large variability of the results of this type of investigation in relation to different components and system configurations adopted in the numerical model, standard models were constructed for each equipment type to obtain equivalent results regardless of the user. The main parameters of these models were adjusted to ensure consistency with experimental data from commercially available equipment units. The standard models and their main features are summarized in Table 1. Consequently, different simulation settings are investigated to define appropriate standpoints for the refrigerant performance evaluation. Additionally, for the purpose of refrigerant evaluation, results may be arbitrarily scaled to different cooling capacities.

Table 1: Standard models for refrigerant evaluation

Classification	**Model name**		**Characteristics of the standard model**
Commercial air conditioner	Light commercial air conditioner	Based on R410A	Refrigerant: R410A, Nominal cooling capacity: 12.5 kW, Refrigerant charge: 3.1 kg, Extension pipe: length 7.5 m (diameter 9.52 mm / 15.88 mm)
		Based on R32	Refrigerant: R32, Nominal cooling capacity: 7.1 kW, Refrigerant charge: 3.6 kg, Extension pipe: length 7.5 m (diameter 9.52 mm / 15.88 mm)
	Multi-split-system air conditioner (variable refrigerant flow)		Refrigerant: R410A, Nominal cooling capacity: 26.5 kW, Refrigerant charge: 8 kg, Extension pipe: length 25 m (diameter 9.52 mm / 22.2 mm)
Residential air conditioner	Normal type		Refrigerant: R410A, Nominal cooling capacity: 4.0 kW, Refrigerant charge: 1.2 kg, Extension pipe: length 5 m (diameter 6.35 mm / 9.52 mm)
	Window-type air conditioner		Refrigerant: R410A, Nominal cooling capacity: 2.5 kW, Refrigerant charge: 0.65 kg
	Unit for high ambient temperature	Based on R410A	Refrigerant: R410A, Normal cooling capacity: 3.4 kW, Refrigerant charge: 1.1 kg, Extension pipe: length 5 m (diameter 6.35 mm / 9.52 mm)
		Based on R22	Refrigerant: R22, Normal cooling capacity: 2.8 kW, Refrigerant charge: 0.91 kg, Extension pipe: length 5 m (diameter 6.35 mm / 9.52 mm)
Medium commercial refrigerating appliance	Condensing unit	Based on R404A	Refrigerant: R404A, Nominal cooling capacity: 17.0 kW, Refrigerant charge: 45 kg, Receiver: 55 L, Accumulator: 19 L
		Based on R410A	Refrigerant: R410A, Nominal cooling capacity: 17.4 kW, Refrigerant charge: 59 kg, Receiver: 50 L, Accumulator: 11 L
Small commercial refrigerating appliance	Built-in refrigerated display cabinet (horizontal-type)		Refrigerant: R404A, Normal cooling capacity: 1.0 kW, Refrigerant charge: 1.12 kg (cooling), 1.05 kg (freezing)
Chilling unit	Air cooled modular chiller		Refrigerant: R410A, Nominal cooling capacity: 37.5 kW, Refrigerant charge: 8.6 kg

2.1 Window-Type Air Conditioners

The window-type air conditioners may be considered as the simplest type of AC unit. In this configuration all the fundamental components of a vapor compression refrigeration system are integrated into a single unit, installed on windows and operated at constant compressor speed. Some installations are equipped with the splash (sling) effect mechanism that improves the condenser's heat transfer performance by gathering water from the drain pan with a "slinger ring" placed around the rear fan and by spraying the water on the condenser coils.

Table 2: Reference window-type AC characteristics

Refrigerant	**Nominal cooling capacity**	**Degree of superheat**	**Refrigerant charge**
R410A	2.5 kW	1 K	0.65 kg

Figure 2 illustrates the system, the flow diagram, and the equivalent modular system built through Energy Flow + M simulation platform. Characteristics of the reference system are given in Table 2.

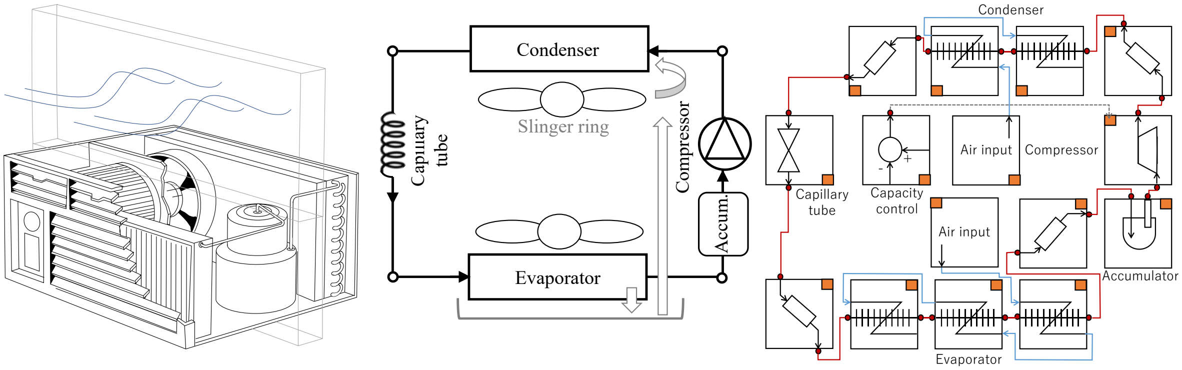


Figure 2: Illustration of the window-type AC system, its flow diagram, and the equivalent modular system built in Energy Flow+M

2.2 Residential Air Conditioners

Residential air conditioners feature a separated outdoor unit connected to the indoor heat exchanger through a refrigerant pipeline. The compressor rotational speed and expansion valve opening are modulated using the PI controllers to achieve target room temperature and superheat at the suction of the compressor (Figure 3).

Table 3: Reference residential AC characteristics

Refrigerant	Nominal cooling capacity	Compressor volumetric flow rate	Liquid/Gaseous refrigerant pipe diameter	Extension piping length	Refrigerant charge
R410A	3.4 kW	2.96 m^3/h	6.35 mm/9.52 mm	5 m	1.1 kg

The corresponding simulation model is constructed according to the reference system characteristics (Table 3) with a compressor, outdoor heat exchanger, expansion valve, accumulator, indoor heat exchanger and extension piping.

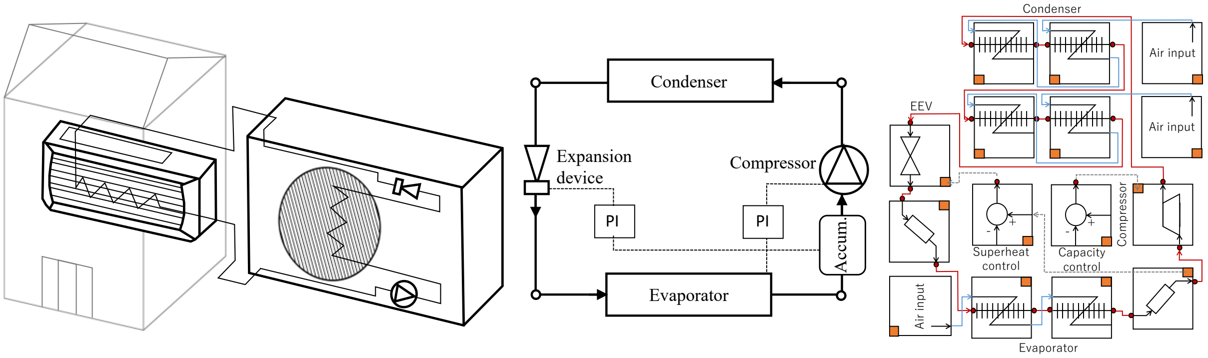


Figure 3: Illustration of the residential AC system, its flow diagram, and the equivalent modular system built in Energy Flow+M

2.3 Condensing Units

Outdoor condensing units are commonly employed for supplying compressed refrigerant to a direct expansion coil for air conditioning or freezing application cases. The investigation of refrigerant performance within this equipment is carried out by defining a reference model for two units using R404A and R410A with liquid injection and the characteristics shown in Table 4.

Table 4: Reference condensing unit characteristics

Refrigerant	Nominal cooling capacity	Receiver tank	Accumulator	Refrigerant charge
R404A	17.0 kW	55L	19L	45 kg
R410A	17.4 kW	50L	11L	59 kg

The corresponding modular simulation model (Figure 4) was constructed on Energy Flow+M simulation platform and validated with reference to experimental performance. This model includes the effect of the internal economizer on the system performance. However, the analysis of the contents related to the economizer is not hereby discussed.

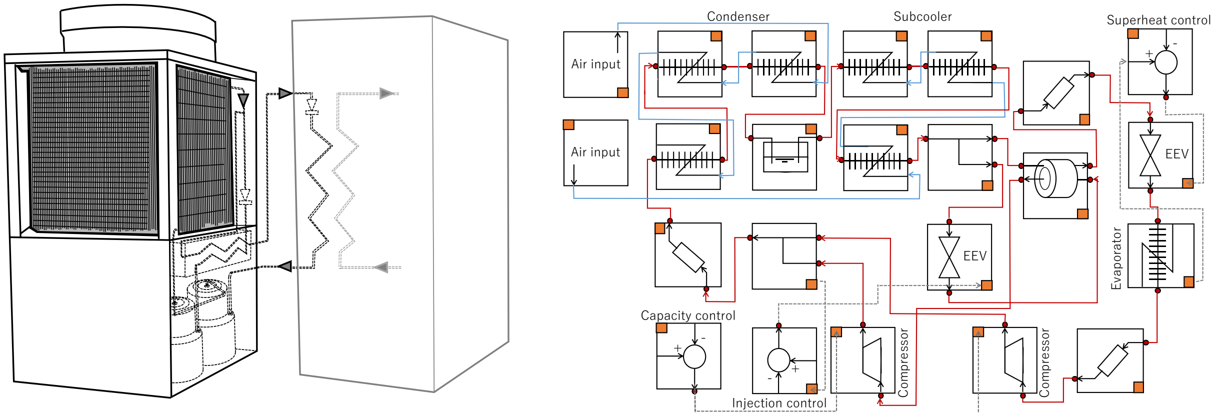


Figure 4: Illustration of the condensing unit and the equivalent modular system built in Energy Flow+M

2.4 Built-in Refrigerated Display Cabinets

Commercial built-in refrigerated display cabinets for fresh products are very common worldwide and, most commonly, use R404A refrigerant. However, HFC refrigerants, such as R404A, will be phased out and will be substituted by current A2L alternatives with GWP lower than 150, including R454C, R455A, R457A, and R459B or natural refrigerants, such as R290. Accordingly, the performance of these refrigerants is evaluated for a commercial built-in refrigerated display cabinet operating in cooling and freezing mode of fresh products (Table 5) while considering thermodynamic and transfer properties, and suitably adjusting the equipment to meet the operation requirements. The physical configuration of the equipment is converted to the corresponding modular system using Energy Flow+M (Figure 5).

Table 5: Reference built-in refrigerated display cabinet characteristics

Type	Refrigerant	Nominal cooling capacity	Refrigerant charge	Degree of superheat
Cooling	R404A	1.0 kW	1.12 kg	8 K
Freezing	R404A	1.0 kW	1.05 kg	8 K

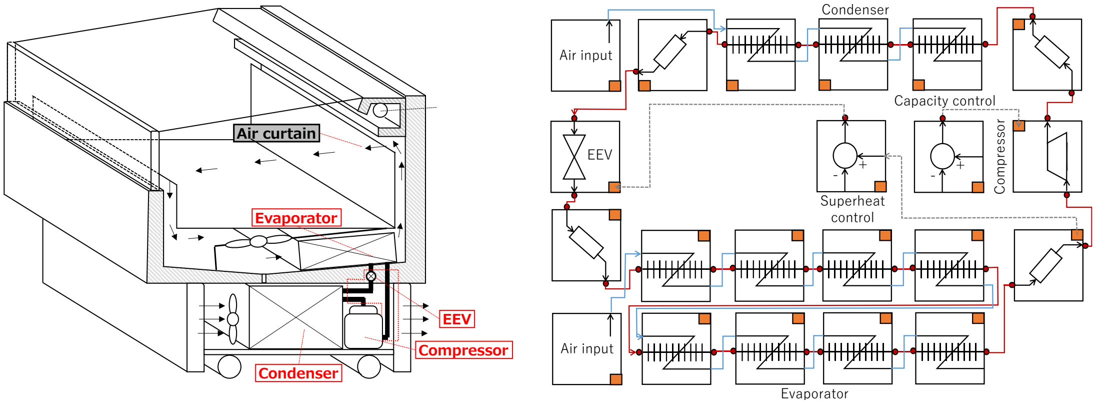
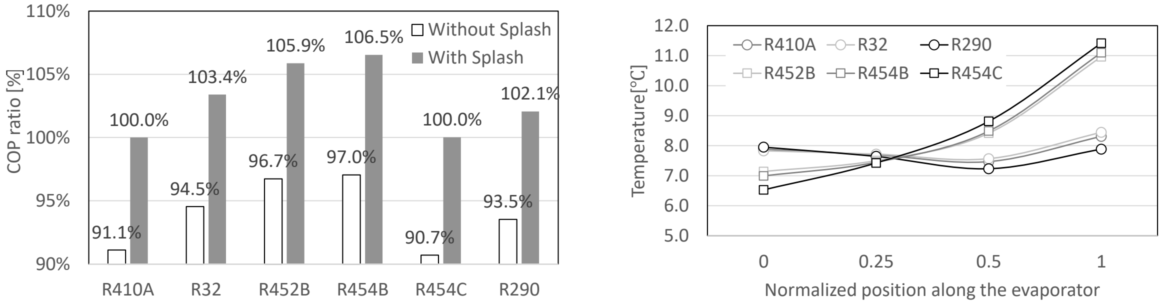


Figure 5: Illustration of the refrigerated display cabinet and the equivalent modular system built in Energy Flow+M

3. RESULTS AND DISCUSSION

3.1 Window-Type Air Conditioners

The refrigerant evaluation study of a window type air conditioner compared R410A with five alternative refrigerants that have been listed as potential replacements in recent years. The selection criteria of the alternative refrigerants include similarity of the operating pressure to R410A, zeotropic characteristics with temperature glide, or a lower operating pressure. Accordingly, the refrigerants assessed as potential replacements of R410A are R452B, R454B, R454C, R32, and R290. The comparative performance evaluation of different refrigerants is carried out both with and without splash effect at standard cooling test conditions (ISO 5151-2017), that is, outdoor dry/wet bulb temperature of 35 °C/24 °C and indoor dry/wet bulb temperature of 27 °C/19 °C by means of the reference model built up on Energy Flow + M simulation platform (Figure 2). In the simulation runs the same compressor rotational speed and compressor related efficiencies (volumetric, adiabatic, and mechanical efficiencies) are assigned for all the refrigerants. Contrarily, the compressor displacement is adjusted to achieve identical cooling capacity, and refrigerant charge is optimized to achieve maximum COP for each refrigerant. The simulation results are summarized in Figure 6.



(a) (b)

Figure 6: (a) Simulated COP ratio of the window-type AC for different refrigerants with and without splash effect (b) refrigerant temperature gradient along the evaporator for the case with splash effect

The vertical axis shows the normalized COP with reference to R410A with splash effect. It is shown that the splash effect improved the COP for all refrigerants by roughly 9%. Although the differences are minimal, the COP improvement due to the splash effect appears to be larger for refrigerants with temperature glide, such as R452B, R454B, and R454C. The results with splash effect demonstrate that R452B and R454B, zeotropic refrigerant mixtures with temperature glide, show up to a 6% improvement in COP when compared to R410A. R454C, exhibiting a large temperature glide, shows identical performance to R410A, and the use of R32 achieved a COP enhancement of approximately 3%. This confirms that, even though refrigerants with temperature glide provide possibilities of COP improvement by means of a suitable thermal matching between the refrigerant and the air temperature gradients in quasi-counter flow configuration, if the circuitry arrangement is not properly optimized (Li et al., 2018), the inlet saturation pressure of the refrigerant may have to be reduced to achieve the same capacity (Figure 6b). Finally, R290 (pure refrigerant with a low operating pressure) shows a COP value that is 2% higher than R410A. Figure 6(b) illustrates the temperature variation in the evaporator for each refrigerant, which reflects temperature decline due to pressure drop in azeotropic fluids and the temperature glide of zeotropic mixtures. The horizontal axis shows the position of the evaporator, with the refrigerant flowing from left to right.

3.2 Residential Air Conditioners

The following assessment results for a residential air conditioner are performed while investigating the effect of high outdoor temperature conditions. It is consequently shown that the performance evaluation of different refrigerants with drop-in tests may not be appropriate, and the corresponding results may be invalidated by a reconsideration of the simulation conditions to better represent the actual potential of each working fluid.

A set of 3 A2L refrigerants (R32, R452B, and R454B) is investigated as alternatives for the residential AC designed for R410A (see Table 3). The simulation conditions are summarized in Table 6. The refrigerant charge of the baseline fluid is calculated as the value that maximizes the system COP at the design condition, whilst in the case of alternative refrigerants is determined as the required amount for achieving the same degree of subcooling as the baseline refrigerant.

In Figure 7, experimental drop-in test data obtained for R32 and R410A (Praha II, 2016) are compared to the results of corresponding simulations carried out for the complete set of refrigerants with constant compressor speed (50 Hz) and valve opening. The comparison is illustrated in terms of normalized COP (with reference to the COP of R410A at 35 °C ambient temperature) as a function of the outdoor air temperature, and demonstrates that, consistently with the experimental data, the COP ratio of both R410A and R32 decreases at higher outdoor temperatures. In these conditions, R32 suffers from larger performance deteriorations than R410A.

Table 6: Simulation conditions for the refrigerant evaluation in the reference model of a residential AC

Simulation	Outdoor temperature	Room temperature	Compressor rotational speed	Valve opening
1	35~52 °C	27 °C	Fixed (50 Hz)	Fixed
2	35~52 °C	27 °C	Fixed (50 Hz)	Achieve 5 K superheat at 35 °C
3	35~52 °C	27 °C	Controlled to achieve 3.4 kW	Controlled to achieve 5 K superheat

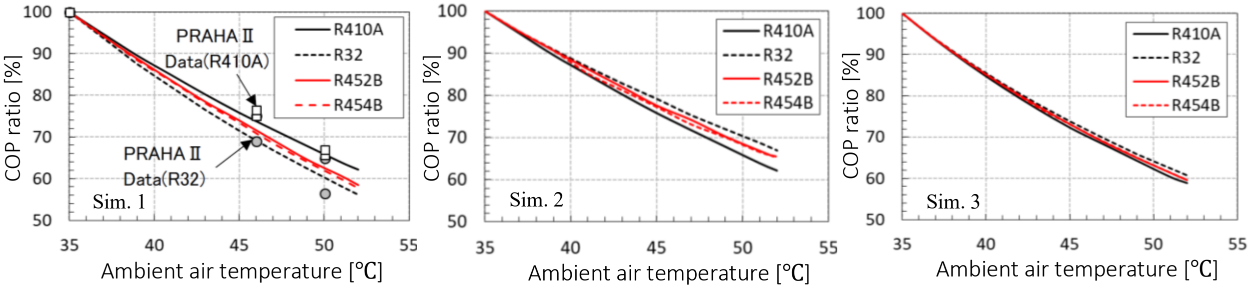


Figure 7: Results of the simulations conducted according to the setting shown in Table 6

This simulation setting assumes fixed compressor rotational speed and valve opening, which are not adjusted with reference to the specific refrigerant. Consequently, due to different thermophysical and transport properties of different refrigerants, such operation does not achieve the same output capacity and required degree of superheat at the compressor inlet. Therefore, the setting of simulation 2 and 3 (Table 6) are suggested as reasonable standpoints to be adopted for the refrigerant performance evaluation, namely under the conditions at which the expansion device alone is designed to achieve the target degree of superheat, and both rotational speed of the compressor and valve opening are adjusted to achieve the target values of output capacity and degree of superheat, respectively.

The results obtained for the settings of Sim. 2 in Figure 7 demonstrate that, if the throttling of the expansion device was optimally set according to each refrigerant, at constant-speed operation of the system, the rate of decrease in COP the A2L refrigerants with respect to the rise in outside air temperature will be smaller than that of R410A. The results obtained for the settings of Sim. 2 in Figure 7, again, confirms that R32, R452B, and R454B exhibit lower decrease in COP than R410A with respect to the rise in outdoor air temperature, while maintaining output capacity and degree of superheat by means of controlled compressor rotational speed and valve opening. Results from these 3 simulation settings are summarized in Figure 8 at 52 °C outdoor temperature condition.

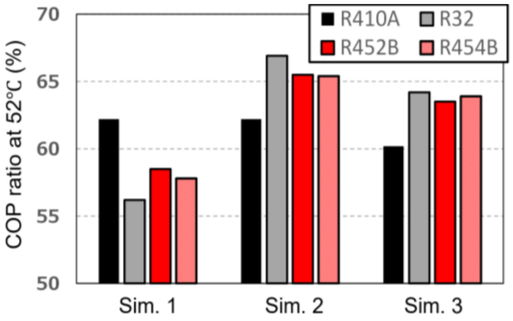


Figure 8: Summary of the results at 52 °C outdoor temperature

3.3 Condensing Units

The performance evaluation of different refrigerants as possible alternatives to R404A and R410A for condensing units is conducted under the simulation conditions presented in Table 7. The compressor discharge temperature is adjusted to 105 °C by modulating the injection ratio. In this case, as the system features a receiver tank where strictly unnecessary refrigerant amount is stored, the refrigerant charge of different refrigerant is matched to the amount of the baseline fluid. Therefore, as the simulation model disregards the local variations of the composition of refrigerant mixtures, the amount of refrigerant does not affect the system performance unless the receiver tank is emptied or overflowed.

Results are summarized in Figure 9 for a given size of the subcooler. It is shown that these low-GWP refrigerant alternatives exhibit comparable performance with the reference case of R404A and that the lower the injection ratio is the higher is the COP. When the calculation conditions of the standard model were modified to the evaporation midpoint method and compared with the results of the dew point method, larger COP improvements are achieved for refrigerants with larger temperature glide. As the result, alternative refrigerants such as R448A, R449A, R407H and R454C all achieve similar performance to the reference system using R404A.

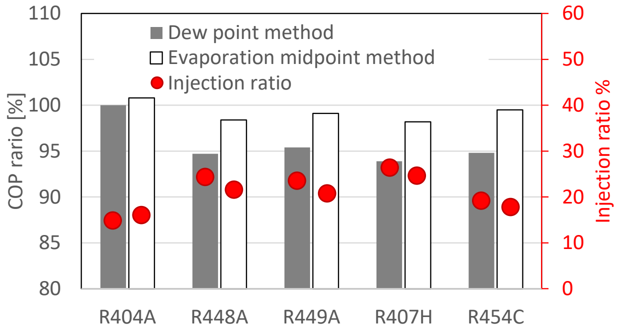


Figure 9: Simulated COP ratio (with reference to R404A) and injection ratio according to the setting of Table 7

Considering the reference simulation model of an R410A condensing unit (see Table 4), the assessment of a lower GWP alternative refrigerant R463A is investigated. Simulations are conducted with reference to the conditions summarized in Table 7 to explore the effect of the subcooler size on the performance of the condensing unit.

Table 7: Simulation conditions for the refrigerant evaluation in the reference model of a condensing unit

Outdoor temperature	Evaporation temperature	Compressor rotational speed	Subcooler size	Compressor suction temperature	Compressor discharge temperature
32 °C	-40 °C	Controlled to achieve 17.4 kW	100 ~ 0 %	20 °C	105 °C

Results obtained for R410A and R463A are correspondingly reorganized with reference to the degree of subcooling in Figure 10. It appears that, as there is a temperature glide in the evaporation process for the case of R463A, the same degree of subcooling cannot be achieved unless the subcooler size is correspondingly adjusted. Alternatively, appropriate circuitry modification may take advantage of the temperature glide with an efficient thermal matching with the temperature gradient of the air stream (Li et al. 2018).

Accordingly, performance evaluation may be conducted while achieving corresponding degrees of subcooling, hence simulation settings are being adjusted to match these conditions when comparing the performance of different refrigerants (Figure 10). As a result, if the subcooler is resized to obtain a degree of subcooling equivalent to R410A, the performance of alternative refrigerants may become equivalent to that of R410A.

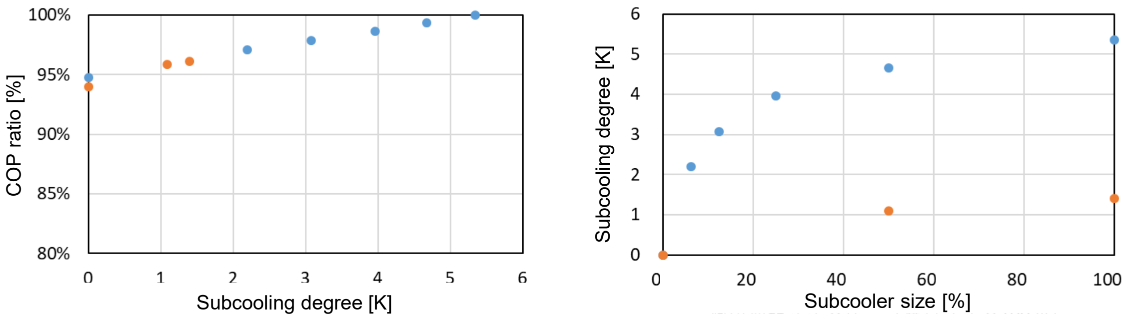


Figure 10: Results of the simulations conducted according to the setting shown in Table 7

3.4 Built-in Refrigerated Display Cabinets

Refrigerant performance assessment for built-in refrigerated display cabinets is carried out according to the simulation settings summarized in Table 8. The reference model developed for this refrigeration equipment (Table

5) is investigated to evaluate the performance of different refrigerants in three sets of conditions representing drop-in tests with fixed compressor speed at freezing operation and two alternative sets of representative conditions for assessing the potential of each refrigerant with reference to equivalent output and operation requirements in both freezing and cooling operation cases. In the latter case, it is assumed that the compressor performance is equivalent for different refrigerants, the expansion valve opening is adjusted to meet a given degree of superheat, and the rotational speed of the compressor to supply the target cooling capacity.

In each of the following simulation settings, the refrigerant charge of alternative refrigerants is determined as the required amount for achieving the same degree of subcooling as the baseline refrigerant at the design condition.

Table 8: Simulation conditions for the refrigerant evaluation in the reference model of a refrigerated display cabinet

Simulation	Room temperature	Refrigerated space temperature	Compressor rotational speed	Valve opening
1	27 °C	-15 °C	Fixed (as R404A)	Controlled to achieve 8 K superheat
2	27 °C	-15 °C	Controlled to achieve 1.0 kW	Controlled to achieve 8 K superheat
3	27 °C	10 °C	Controlled to achieve 1.0 kW	Controlled to achieve 8 K superheat

Figure 11 demonstrates that, for the case represented by the settings of simulation 2 (Table 8), the use of R459B and R455A leads to slightly lower performance than R404A, whereas R290 exhibits the best performance among the set of refrigerants investigated.

For the settings of cooling use (simulation 3), R290 and R457A exhibit better performance than R404A, while other refrigerants lead to comparable COPs. The simulation results at setting 1 (Table 8), representing drop-in at constant compressor speed, show higher COP values, which are, nonetheless, associated to lower output cooling capacities than that of the baseline operation with R404A. The corresponding degree of subcooling for this set of refrigerants in the simulation settings of Table 8 are illustrated in Figure 12.

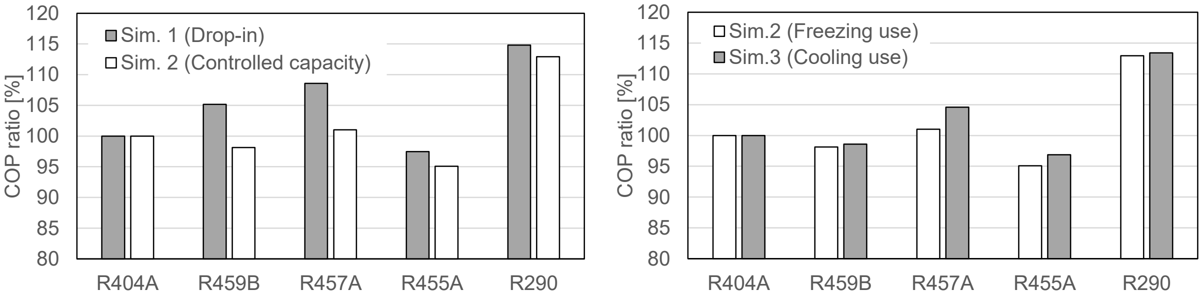


Figure 11: Normalized COP of the simulations conducted according to the settings shown in Table 8

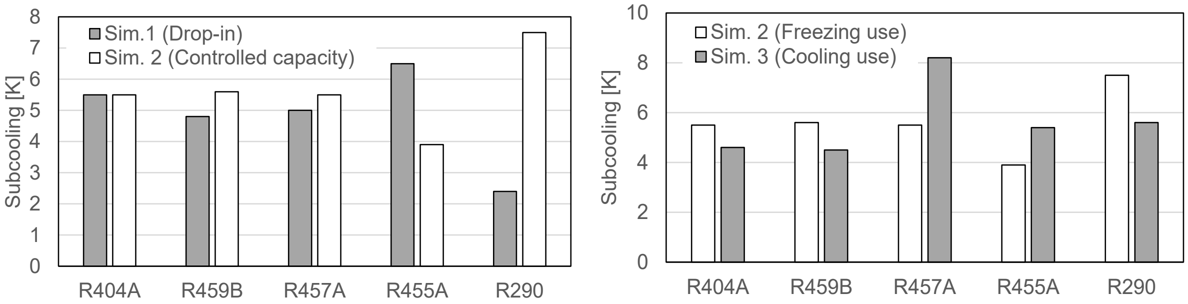


Figure 12: Degree of subcooling of the simulations conducted according to the settings shown in Table 8

4. CONCLUSIONS

The present effort towards the development of a standardized refrigerant evaluation tool for air conditioning and refrigeration equipment took advantage of the flexibility of a general-purpose energy-analysis simulation platform.

This modular simulation environment enabled steady, dynamic and control analyses while accounting for the actual transport performance of different refrigerants in relation to the component configurations, operation settings, environmental conditions, and required output demands. Accordingly, standard models of various air conditioning and refrigeration systems were constructed. Reference models and simulation settings of these systems were developed for guiding the performance evaluation of different refrigerants and the results obtained via the implementation of this evaluation tool were presented for some models.

From the preliminary set of results presented in this study, the following conclusions were extracted:

- The standard model developed for window-type air conditioners with splash effect demonstrates that alternative low-GWP refrigerants exhibit better performance than R410A while operating at equivalent output capacity. Although the differences are minimal, the COP improvement due to the splash effect appears to be larger for refrigerants with temperature glide (R452B, R454B, R454C). Additionally, it was shown that zeotropic mixtures with moderate temperature glide (R452B, R454B) operate with higher COP than R410A and R32, but the efficient operation of refrigerants with larger temperature glides (such as for R454C) requires dedicated optimization procedures for the refrigerant circuitry to appropriately follow the gradient of the air-side temperature.
- The standard model developed for refrigerant performance evaluation in residential e air conditioners shows that, when compressor speed and valve opening are fixed according to the operation characteristics of R410A, A2L refrigerants (R32, R452B, R454B) exhibit lower performance than R410A at high outdoor temperature conditions. However, the rate of decrease in COP of the A2L refrigerants with respect to the rise in outside air temperature will be smaller than that of R410A if evaluated while controlling compressor rotational speed and valve opening for achieving equivalent output capacity and degree of superheat.
- The performance evaluation of different refrigerants as possible alternatives to R404A for condensing units shows that R448A, R449A R407H and R454C may achieve competitive COPs, especially under the conditions consistent with the evaporation midpoint method. Regarding R410A alternatives, R463A may achieve competitive COPs, especially if the subcooler is designed to achieve comparable degrees of subcooling.
- The development of a standard model for built-in refrigerated display cabinets has demonstrated that, when the compressor speed and valve opening are adjusted to achieve 1.0 kW capacity and 8 K superheat, respectively, the use of R459B and R455A leads to slightly lower performance than R404A, whereas R290 and R457A exhibit higher performance than R404A at both freezing and cooling operation.

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