Development of a Refrigerant Evaluation Tool for Air Conditioners

Yoichi Miyaoka[a,*], Niccolo Giannetti[b], Jongsoo Jeong[a], Kiyoshi Saito[a],
Komei Nakajima[c], Koji Yamashita[c], Shigeharu Taira[c]

[a]Waseda University, 3-4-1 Okubo, Shinjuku, Tokyo, 169-8555, Japan
[b]Waseda University, Waseda Institute for Advanced Study, 1-6-1 Nishiwaseda, Shinjuku, Tokyo, 169-8050, Japan
[c]The Japan Refrigeration and Air Conditioning Industry Association, Tokyo, 105-0011, Japan

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3. Overview of the refrigerant evaluation tool
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    - Model of the Residential Air Conditioner
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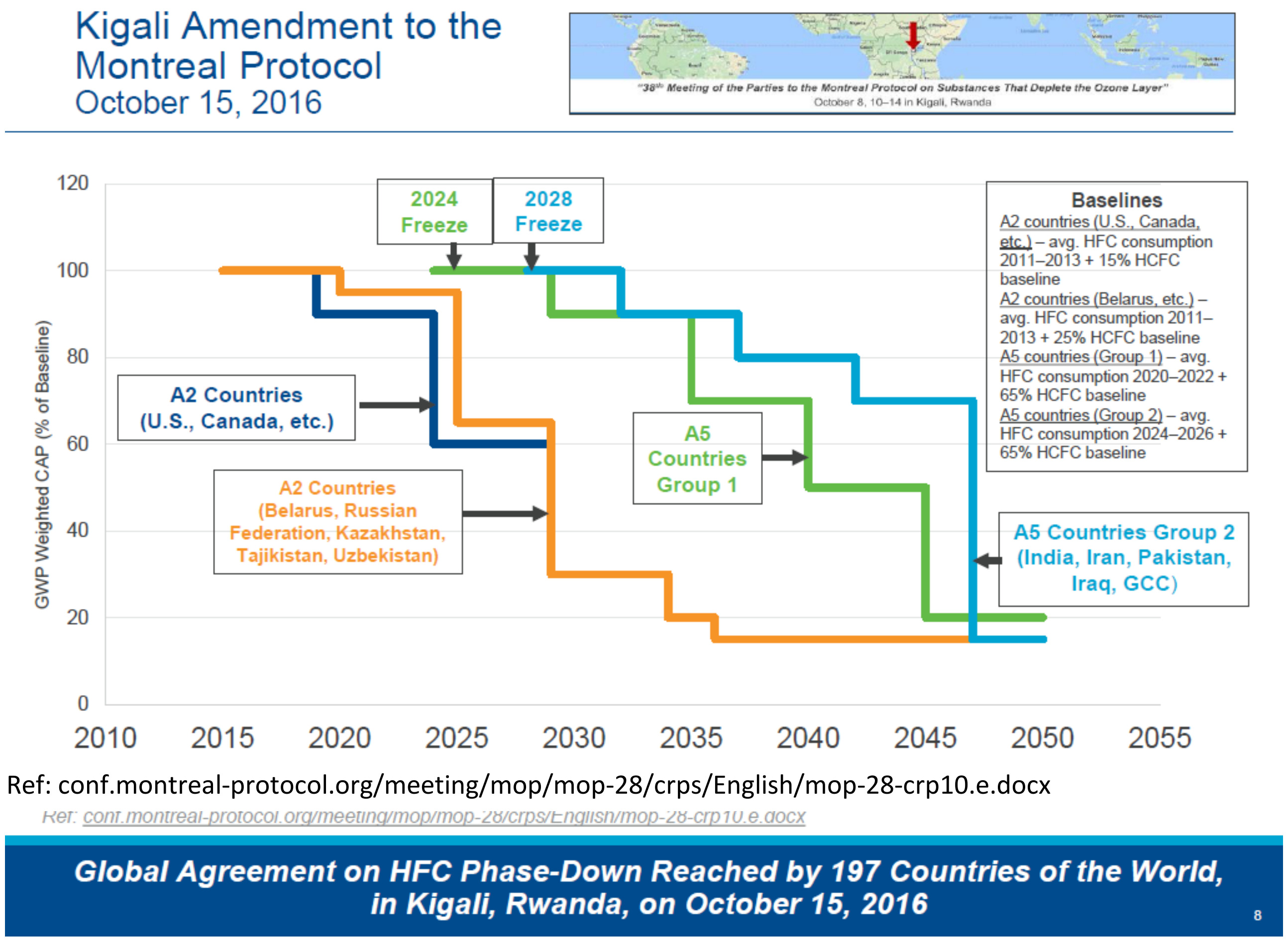
Background

Next Generation Low GWP Refrigerant

- <u>At Kigali's 28th(2016) Montreal Protocol</u>
  Phase-down of hydrofluorocarbons (HFCs) by cutting their production and consumption

- <u>Refrigerant for use of refrigeration & air-conditioning facilities</u>
  Needed for development of next-generation low-GWP refrigerant



Purpose

To develop and select next-generation low-GWP refrigerants, What should we do?

We consider

- How low GWP value?
- How large effect of drop-in?
- How satisfactory system performance?
- How superior system design & control method?

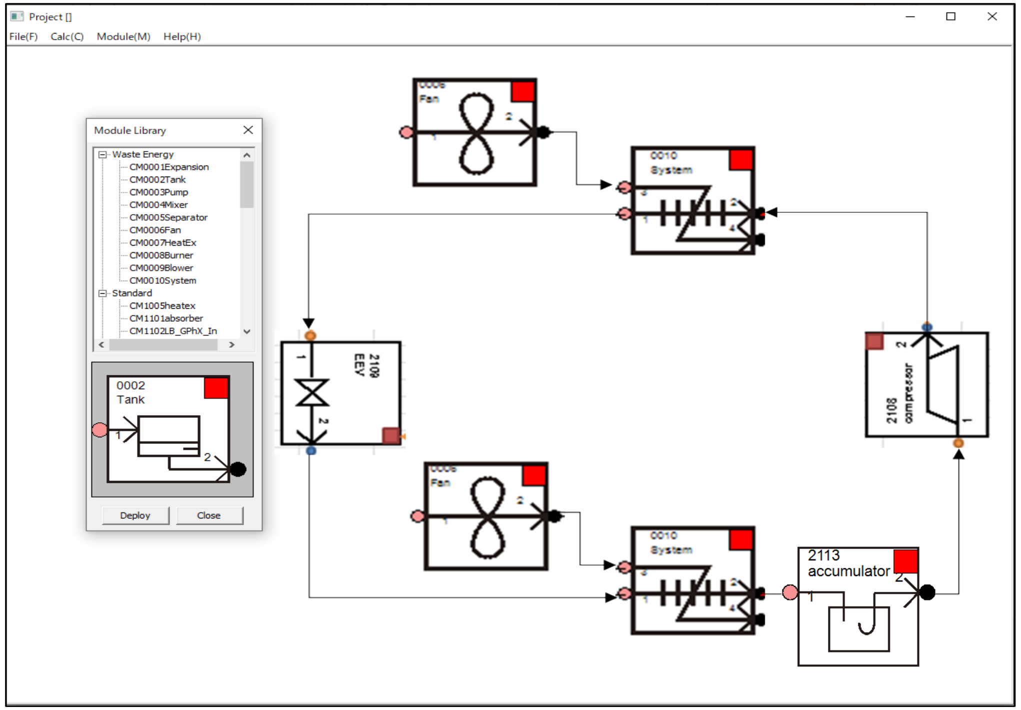
for air-conditioning system

Problems ： Complicated system
System test & introduction cost
Long time operation evaluation

<u>Introduction of simulation technology</u>

<u>Development **of a general-purpose evaluation method** to clarify **effect of refrigerants on** air-conditioning system performance</u>

Overview of the refrigerant evaluation tool



Features

- Versatility
- Standardization
- Specializing in air conditioner
- Calculation of refrigerant charging amount is also possible
- Consider controllability

- Standardized analysis conditions and models of the most common refrigeration equipment were constructed in cooperation with the Japan Refrigeration and Air Conditioning Industry Association (JRAIA).

Features of the simulator

Thermal fluid network

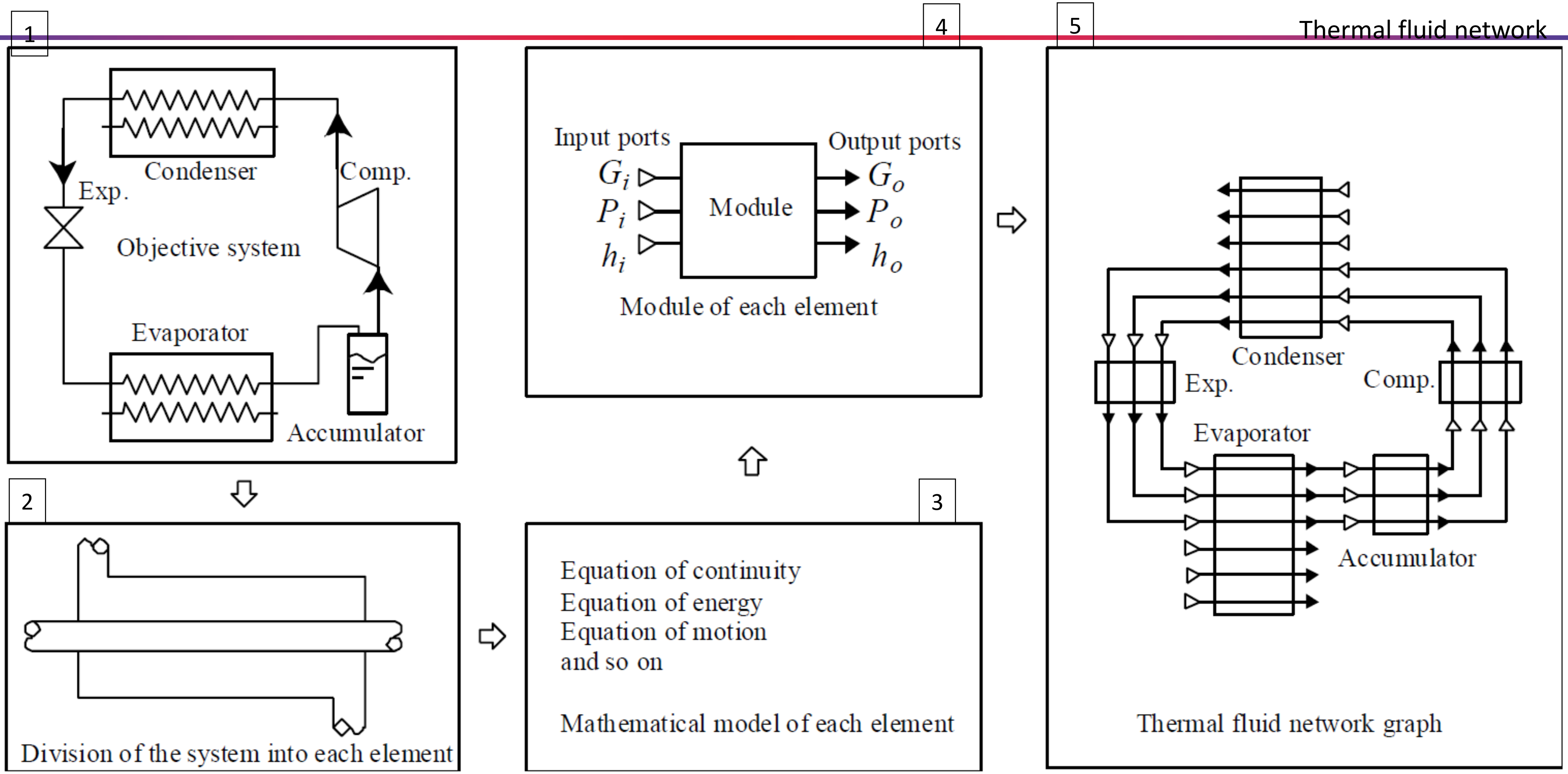
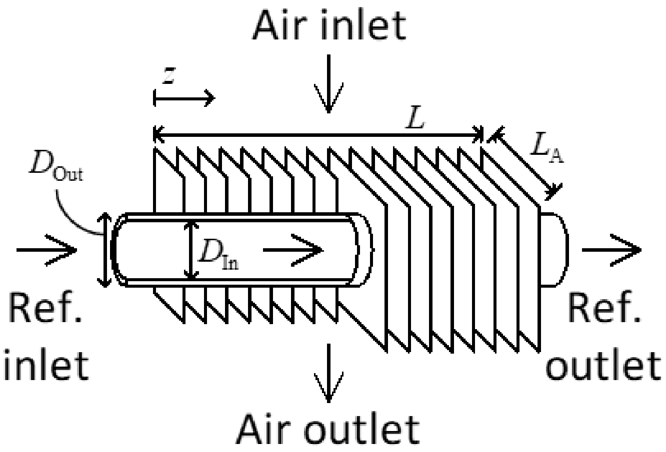


Fig. Procedure of modular analysis

Mathematical Model：Heat exchanger



A	Area	m^2
D	Diameter	m
f	Fanning friction factor	-
G	Mass flow rate	$kg \cdot s^{-1}$
h	Specific enthalpy	$J \cdot kg^{-1}$
j	Mass flux	$kg \cdot m^{-2} \cdot s^{-1}$
L	Length	m
P	Pressure	Pa
q	Heat flux	$W \cdot m^{-2}$
S	Cross sectional area	m^2
t	Time	s
v	Velocity	$m \cdot s^{-1}$
ρ	Density	$kg \cdot m^{-3}$
η	Efficiency	-
hv	Latent heat of vaporization	$J \cdot kg^{-1}$

Refrigerant side continuity equation

$$\frac{\partial \rho_R}{\partial t} + \frac{\partial(\rho_R v_R)}{\partial z} = 0$$

Refrigerant side pressure loss

$$\frac{\partial P_R}{\partial z} = -f_R \frac{1}{d_{In}} 2\rho_R v_R^2$$

Refrigerant side energy equation

$$\frac{\partial(\rho_R u_R)}{\partial t} + \frac{\partial(\rho_R v_R h_R)}{\partial z} = -\frac{Lc_{In}}{S_{In}} q_{In}$$

Pipe side energy equation

$$\rho_M C_M \frac{\partial T_M}{\partial t} = \frac{Lc_{In}}{S_M} q_{In} - \frac{A_{Pipe} + \eta_{FIN} A_{FIN}}{S_M L} (q_{Out} + j_{Out} hv_{Wat})$$

Equation for Air Side Continuity

$$\rho_{A,O} v_{A,O} L_{A,O} - \rho_{A,I} v_{A,I} L_{A,I} = \frac{A_{Pipe} + \eta_{FIN} A_{FIN}}{L} j_{Out}$$

$$\rho_{A,O} v_{A,O} L_{A,O} = G_{A,O}$$

$$\rho_{A,I} v_{A,I} L_{A,I} = G_{A,I}$$

Air side pressure loss

$$P_{A,O} - P_{A,I} = -f_A \frac{2L_x \rho_A V_{ac}^2}{D_{ec}}$$

Air side energy equation

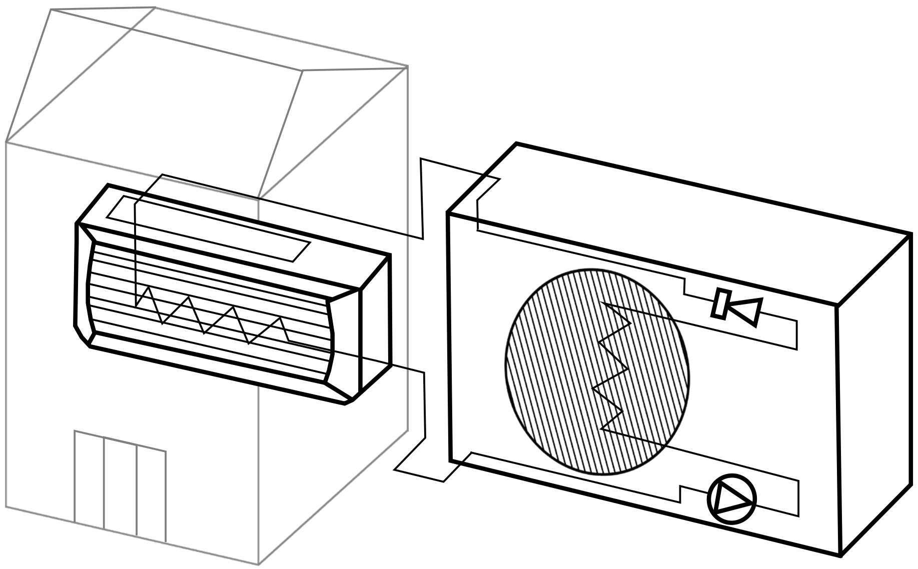
$$\rho_{A,O} v_{A,O} X_{A,O} L_{A,O} - \rho_{A,I} v_{A,I} X_{A,I} L_{A,I} = \frac{A_{Pipe} + \eta_{FIN} A_{FIN}}{L} j_{Out}$$

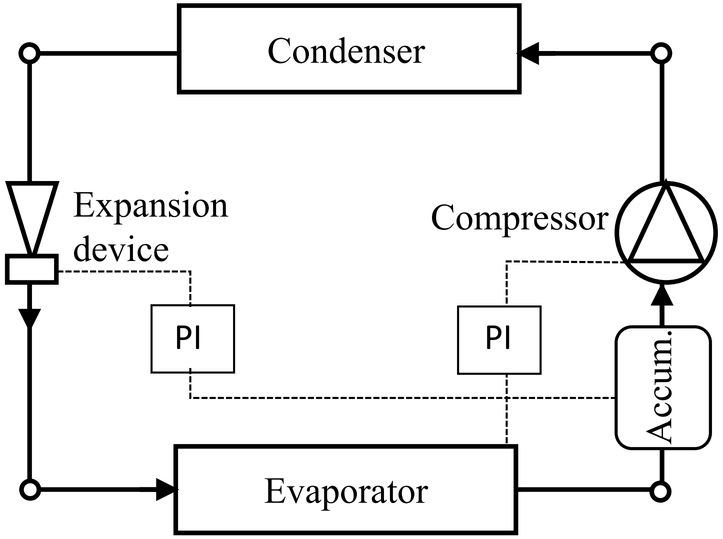
Equation for Air side water vapor balance

$$\rho_{A,O} v_{A,O} h_{A,O} L_{A,O} - \rho_{A,I} v_{A,I} h_{A,I} L_{A,I} = \frac{A_{Pipe} + \eta_{FIN} A_{FIN}}{L} (q_{Out} + j_{Out} hv_{Wat})$$

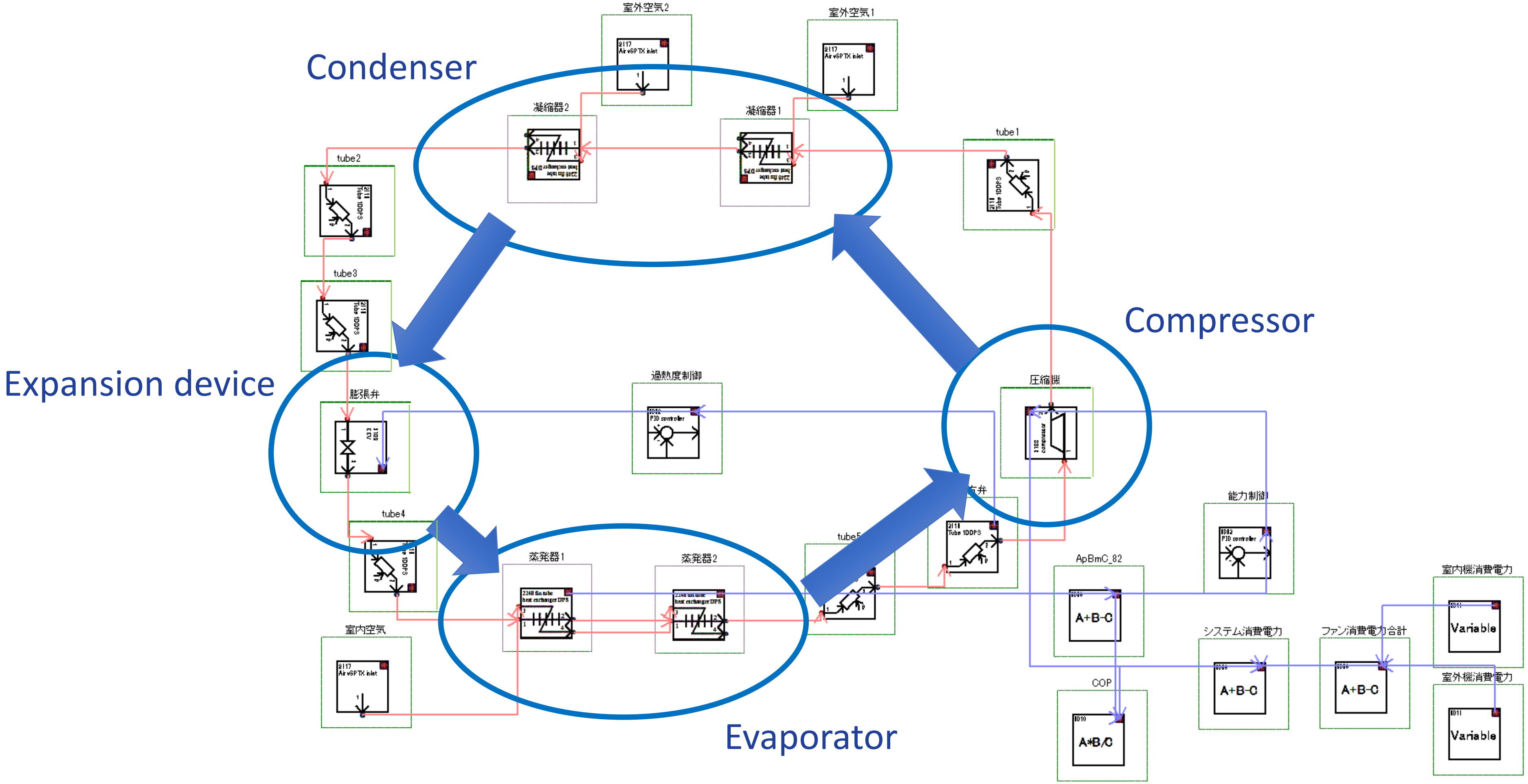
Model of the Residential Air Conditioner

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





Module Connection for System Analysis



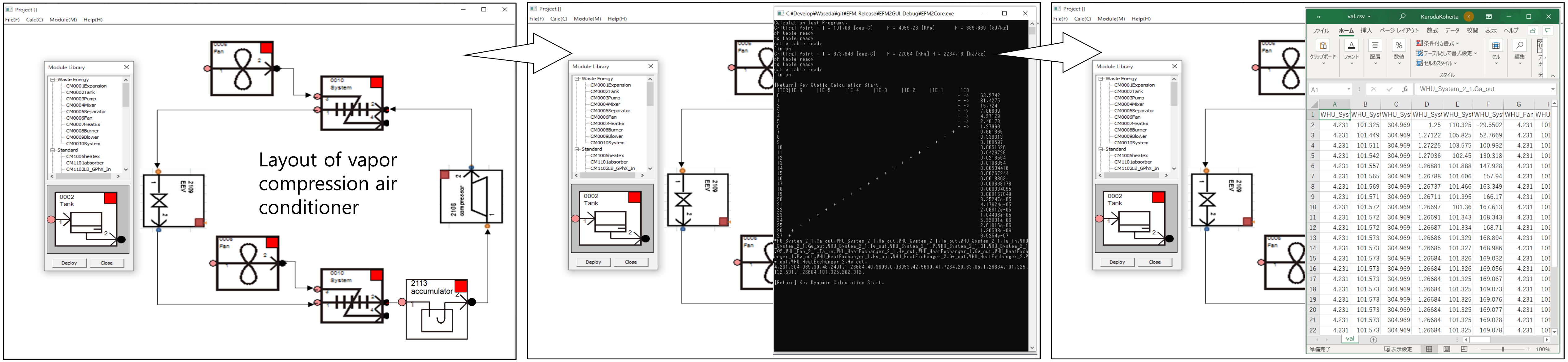
Characteristics of the GUI

・<u>Who utilizes this simulator？</u>

Engineers and researchers with no required background in industrial and scientific simulations.

・<u>Feature？</u>

Ease of simulation and analysis using GUI without coding

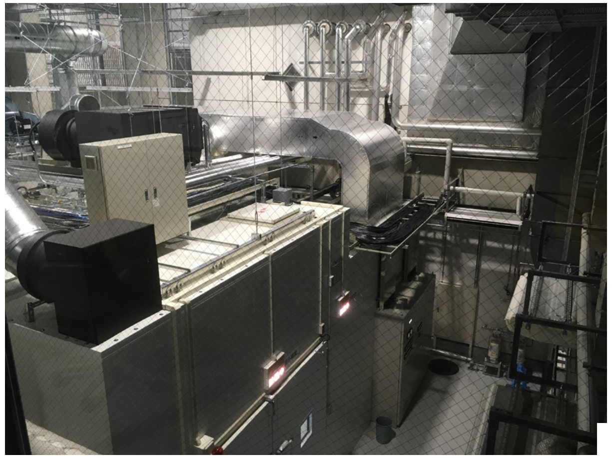


(a) Main screen of GUI (b) Calculation on GUI (C) Output data CSV(EXCEL) file

Fig. Feature of Energy flow +M II

Experimental Validation
Performance evaluation facility

Building exterior



Appearance of the facility

Indoor unit room

Measuring chamber

Experimental Validation

Appearance of actual testing equipment

Indoor unit installed

Outdoor unit installed

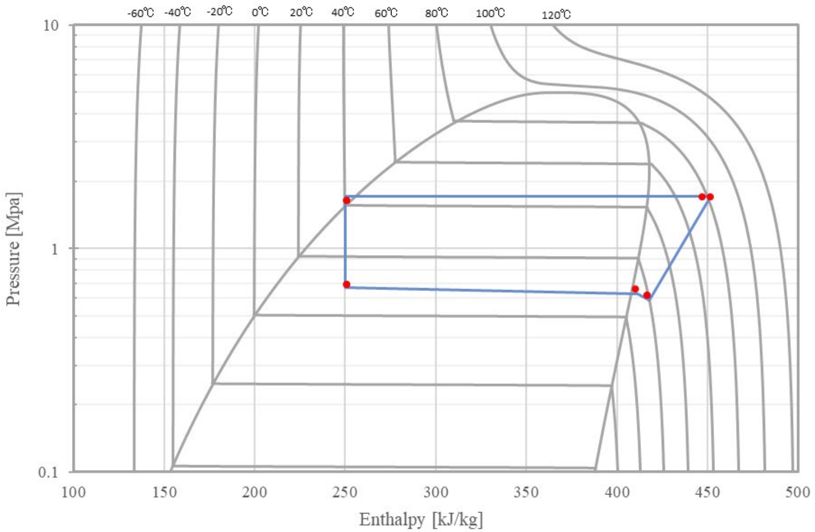
Experimental Validation

Test conditions

<table>
<tr><th colspan="3">Test condition</th><th>Indoor temperature (℃) Dry / Wet</th><th>Outdoor temperature (℃) Dry / Wet</th><th>Partial load ratio (%)</th></tr>
<tr><td>(a)</td><td rowspan="4">Cooling</td><td>Standard cooling
Full-capacity test</td><td rowspan="4">27 / 19</td><td>35 / 24</td><td>100</td></tr>
<tr><td>(b)</td><td>Standard cooling
Half-capacity test</td><td>35 / 24</td><td>50</td></tr>
<tr><td>(c)</td><td>Low-temperature cooling
Half-capacity test</td><td>29 / 19</td><td>50</td></tr>
<tr><td>(d)</td><td>Low-temperature cooling
Minimum-capacity test</td><td>29 / 19</td><td>25</td></tr>
</table>

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

Comparison of experiment and simulation results (R22)

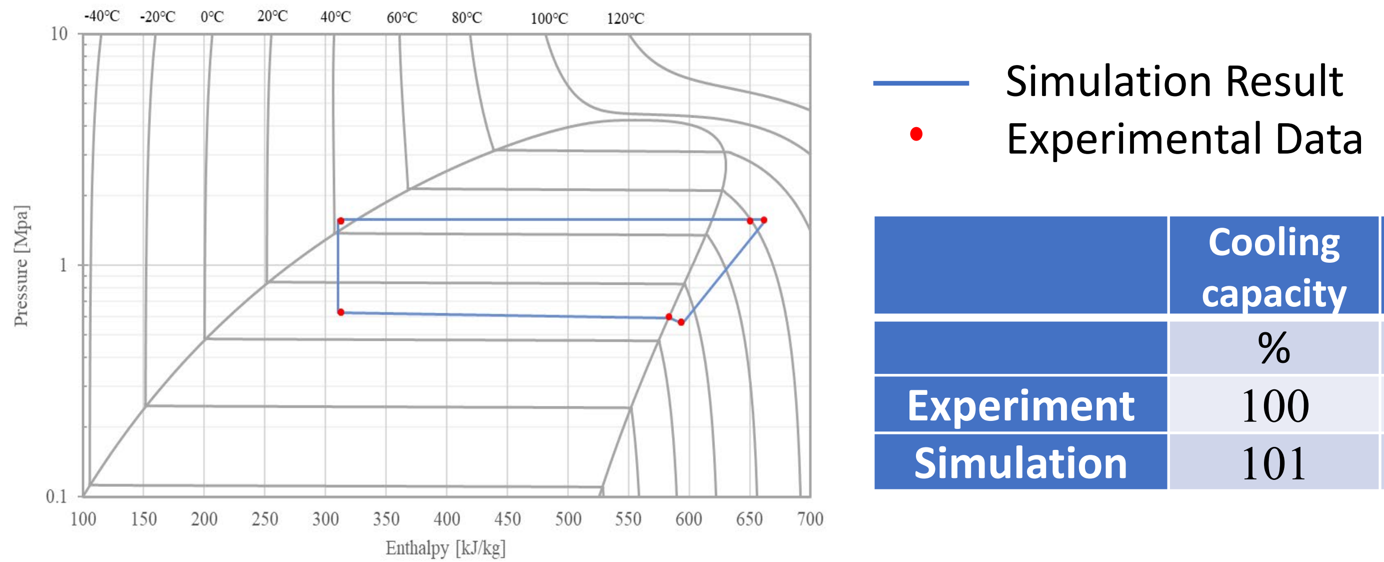


Simulation Result
Experimental Data

	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	Compressor discharge pressure	Compressor suction temperature	Compressor discharge temperature	Degree of superheat	Degree of subcooling
	MPa	MPa	℃	℃	℃	℃
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

Comparison of experiment and simulation results (R290)



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

	Compressor suction pressure	Compressor discharge pressure	Compressor suction temperature	Compressor discharge temperature	Degree of superheat	Degree of subcooling
	MPa	MPa	°C	°C	°C	°C
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

Conclusion

1． This study presented the recent development of a simulation platform adopted for the use in refrigerant performance evaluation analyses.

2． 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.

3． Numerical simulations with R290 were validated with corresponding drop-in tests of the same air conditioning unit.

4． It was shown that the simulation results accurately represent the operating performance of actual systems with different refrigerants and may be effectively used for evaluating the performance of new low-GWP fluids.

Acknowledgements

The results of '6. Experiments to confirm simulation accuracy' in this paper were obtained as a result of commissioned work (JPNP18005) by New Energy and Industrial Technology Development Organization (NEDO), and we would like to express our gratitude to everyone involved.

Researches related to this presentation

1． LCCP Evaluation for Air-to-Air Heat Pumps using Next-Generation Refrigerants - Residential Air Conditioners –

⇒The power consumption of room air conditioners were calculated by this simulator.

2． Development of Industrial Heat Pump Simulator

⇒Based on this simulator, simulators specialized for industrial heat pumps have been developed.

3． Load-based Performance Characterization of Air Conditioners Using an Emulator-type Assessment Technique (at the poster session)

⇒This facility was used as an experimental device to verify the accuracy of the simulator.

Thank you for your kind attention

Appendix

Heat transfer coefficient, coefficient of friction, slip ratio

Heat transfer coefficient (refrigerant)

$$\alpha_{In} = Nu_R \lambda_R / D_{In}$$

- Condensation heat transfer coefficient in tube: Notsu et al. equation

$$Nu_R = \max\{Nu_{R,b}, Nu_{R,f}\}$$

$$Nu_{R,b} = 0.725\left(\frac{Ga\,\mathrm{Pr}_{R,Liq}}{H_{R,Liq}}\right)^{0.25}\left\{1.0+0.003\sqrt{\mathrm{Pr}_{R,Liq}}\,C_3^{\,3.1-\frac{0.5}{\mathrm{Pr}_{R,Liq}}}\right\}^{0.3}(1.0+C_2C_4)^{-0.25}$$

$$Nu_{R,f} = 0.018\left(\mathrm{Re}_{R,Liq}\sqrt{\frac{\rho_{R,Liq}}{\rho_{R,Vap}}}\right)^{0.9}\left(\frac{x_R}{1-x_R}\right)^{0.1x_R+0.8}\left(\mathrm{Pr}_{R,Liq}+\frac{8.0\times10^3}{\mathrm{Re}_{R,Liq}^{1.5}}\right)^{1/3}\left(1.0+\frac{C_1H_{R,Liq}}{\mathrm{Pr}_{R,l}}-\frac{0.2H_{R,Vap}}{\mathrm{Pr}_{R,Vap}}\right)$$

- Evaporative heat transfer coefficient in tubes: Yoshida et al. equation

$$\frac{\alpha_{\mathrm{In,TP}}}{\alpha_{\mathrm{In,SP,LIQ}}} = 3.7\left\{Bo\times10^4+0.23\left(Bo\times10^4\right)^{0.69}\left(\frac{1}{X_{\mathrm{tt}}}\right)^2\right\}^{0.44}$$

- Single-phase flow: Dittus-Boelter equation

$$Nu_{R,SP} = 0.023Re_R^{0.8}Pr_R^n$$

Heat transfer coefficient (air)

$$\alpha_{\mathrm{Out}} = Nu_{\mathrm{A}}\,\lambda_{\mathrm{A}}/D_{\mathrm{ec}}$$

- Heat transfer coefficient outside the tube and fin efficiency: Equation of Seshimo and Fujii et al.

$$Nu_{\mathrm{A}} = 2.1\left(\frac{Re_{\mathrm{A}}Pr_{\mathrm{A}}D_{\mathrm{ec}}}{L_{x_{\mathrm{A}}}}\right)^{0.38}$$

Pressure drop (refrigerant)

- Two-phase flow : Chisolm's equation with Lockhart-Martinelli parameters

$$E_{dpi} = P_{RPi}^t - P_{RPi+1}^t \mp \left\{f_{RBi}^t \times \frac{L/n}{D_i}\rho_{Liq,RBi}^t \frac{1}{2}\left(\frac{G_{RBi}^t(1-x_{RBi}^t)}{S_i\rho_{Liq,RBi}^t}\right)^2\right\}$$

$$f_{\mathrm{R,TP}} = 0.079\mathrm{Re}_{\mathrm{R,LIQ}}^{-0.25}\phi_{\mathrm{L}}^2$$

$$\mathrm{Re}_{R,Liq} = \frac{(1-x_R)G_RD_{In}}{S_{In}\mu_{R,Liq}}$$

$$\phi_{Liq}^2 = 1+\frac{20}{X_{tt}}+\frac{1}{X_{tt}^2} \qquad X_{tt} = \left(\frac{1-x_R}{x_R}\right)^{0.9}\left(\frac{\rho_{R,Vap}}{\rho_{R,Liq}}\right)^{0.5}\left(\frac{\mu_{R,Liq}}{\mu_{R,Vap}}\right)^{0.1}$$

- Single-phase flow: Blasius equation

$$E_{dpi} = P_{RPi}^t - P_{RPi+1}^t \mp \left\{f_{RBi}^t \times \frac{L/n}{D_i}\rho_{RBi}^t \frac{1}{2}\left(\frac{G_{RBi}^t}{S_i\rho_{RBi}^t}\right)^2\right\}$$

$$f_{\mathrm{R,SP}} = 0.079\mathrm{Re}_{\mathrm{R}}^{-0.25}$$

$$Re_R = \begin{cases}\dfrac{G_RD_{In}}{S_{In}\mu_{R,Liq}} & (x_R < 0)\\[2ex] \dfrac{G_RD_{In}}{S_{In}\mu_{R,Vap}} & (1 < x_R)\end{cases}$$

Slip ratio

- Smith equation

$$s = \varepsilon + (1-\varepsilon)\times\sqrt{\frac{\rho_L/\rho_G+\varepsilon(1/x-1)}{1+\varepsilon(1/x-1)}}$$

ε: Virtual average liquid ratio, $\varepsilon = 0.4$