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Development of General Purpose Energy System Simulator

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Abstract

Smart energy system is very large energy system that consists of the windmill, solar panel, heat pump, air-conditioning system, solar thermal panel and so on. To develop efficient smart energy system, it is very important to investigate how to manage the total energy utilization of the total smart energy system. But it is difficult to examine the energy management only with experiment. The simulation is promising technology for the development of the energy management of the smart energy systems. But as this system is too large, we can't analyze this system, unless we analyze this system rationally. Therefore we have established the modular analysis theory that can analyze the large scale energy system. This paper introduces this theory and using this theory, we have developed the energy system analyzing simulator that is called "Energy Flow +M". This simulator has been already opened for the worldwide through Internet. This simulator is expected to be used for the energy saving of the total energy systems.

Keywords: Simulation; Mathematical model; Air-conditioning; Refrigeration; Heating

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1. Introduction

In energy systems, efficiency in each single system is greatly improved by the great efforts of the manufactures, governments and academic organizations in Japan. On the contrary, this means that only the efficiency improvement of each single system doesn't meet the demand of the energy saving policy. It is important to construct the best system combination and optimum energy management of the energy systems. We are just now in the new phase that we have to look for them.

Recently the term "smart" is sometimes used to do so. We always think smart utility of energy is indispensable for the sustainability and enhancement of quality of life. But the definition is vague. In this

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paper, for this term, we imply that smart energy system is the efficient energy system that includes high performance or sustainable energy systems such as wind mill, PV, FC, the air-conditioner, heat pump, solar thermal panel and this system is driven optimally.

In the smart energy, the total energy system management to drive the smart energy system optimally is more important than efficiency improvement of each system. To investigate the method of total energy management, it is not easy to carry out the experiment. In this case, simulation is very effective. However unless we carry out simulation rationally, it is also difficult to realize simulation and optimization.

In my research group, we have developed the modular analysis theory that explains how to develop the model of thermal systems and analyze them rationally. In this theory, whole system model is constructed only by connecting the module that expresses the input & output relations of each element.

From this background, here especially, latest models and analyzing method of thermal system by CO_2 heat pump are introduced because this is indispensable to investigate the optimum combination among many energy system and optimum driving of the smart energy system. Furthermore, this theory can be applied easily to the electric network analysis.

Nomenclature

d	diameter (m)	α	heat transfer coefficient (kW/m^{2}K)
f	friction factor (-)	ρ	density (kg/m^3)
h	specific enthalpy (kJ/kg)	λ	thermal conductivity (kW/mK)
K	overall heat transfer coefficient (kW/m^{2}K)	Subscript	
Nu	Nusselt number (-)	H	helical or homogeneous
P	pressure (Pa)	hyd	hydraulic
Pr	Prandtl number (-)	i	inside
q_i	heat transfer rate per unit length (kW/m)	o	outside
Re	Reynolds number (-)	r	refrigerant
T	temperature (K)	t	tube
u	velocity (m/s)	vap	vapour
z	length (m)	w	water

2. Modular Analysis Theory

Modular analysis theory is the rational whole energy system analyzing theory. We think it is acceptable that whole system model is constructed from the model of each element. Of course, the model of each element is based on the continuity, energy and momentum equations and boundary conditions. However, how to construct the whole system model from each elemental model rationally have not been discussed in detail. In the modular analysis theory, whole system model is constructed by connecting each element model. For this theory, the control engineering way of thinking is put into analysis of the energy systems. The procedure is explained as follows and shown in Fig. 1.

1. Thermal systems are separated into elements such as a heat exchanger, pump and so on.

2. Each mathematical model of the element is constructed based on the equations of continuity, energy, and momentum.
3. Based on the mathematical model of each element, when we make the mathematical module that expresses the relation between input and output variables, input and output variables are based on those that decide the state of working fluids since each element is connected by working fluids.
4. The complete mathematical model of thermal system is constructed by giving connecting conditions among elements and environment.
5. Based on the complete mathematical model, the thermal system is analyzed.

3. Representative System Based on Calculation by Modular Analysis Theory

So far, we have been calculated based on the modular analysis theory in the following systems; CO_2 heat pump water heater [1], Room air-conditioner, VRF system, Absorption refrigerator, heat pump, Desiccant air-conditioning system, Solar thermal system. To calculate these systems, highest precision level model is used. This is because we want to use these models for the actual system design level. Just now we expand the analyzing range from steady state simulation to unsteady state [2]. In this paper, the models of CO_2 the heat pump water heater are introduced. This is indispensable system or element for the smart energy.

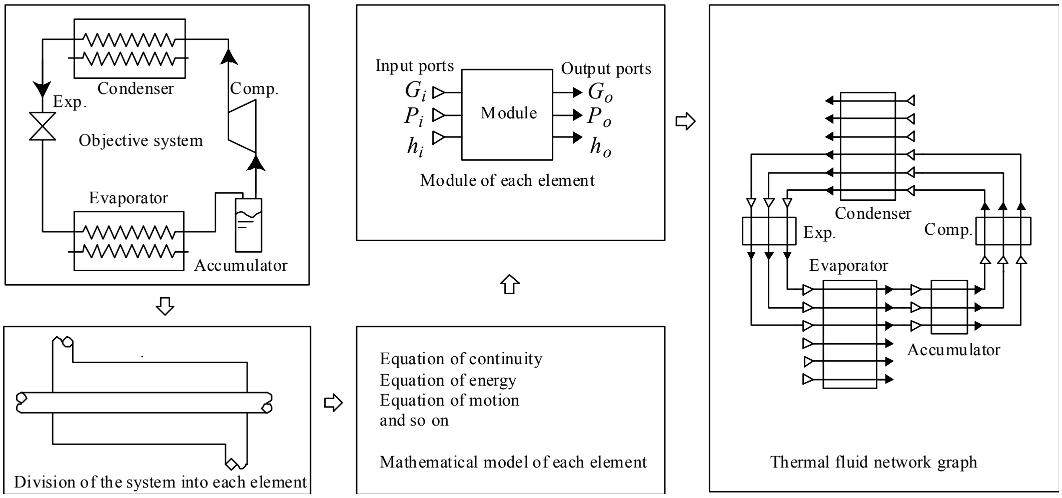

Fig. 1. Modular analysis theory

4. CO_2 Heat Pump Water Heater

4.1. System description

CO_2 heat pump water heater is the compression type heat pump system to heat up the water. This system uses CO_2 as refrigerant. CO_2 is sometimes regarded as green house gas. However, as refrigerant, CO_2 is far better than Freon that is mainly used for refrigerant because GWP of CO_2 is far lower than Freon. CO_2 heat pump is almost the same system with the conventional heat pump. However, the feature of this system is that this system uses the super critical region of the fluid. This increases the pressure too much. On the other hand, as a water heater, the supercritical region is very good to enhance the efficiency.

That's why the market of CO_2 heat pump is getting bigger. The flow of this system is shown in Fig. 2(a). The exterior of the actual system and gas cooler are shown in Fig. 2(b) and Fig.2(c) respectively.

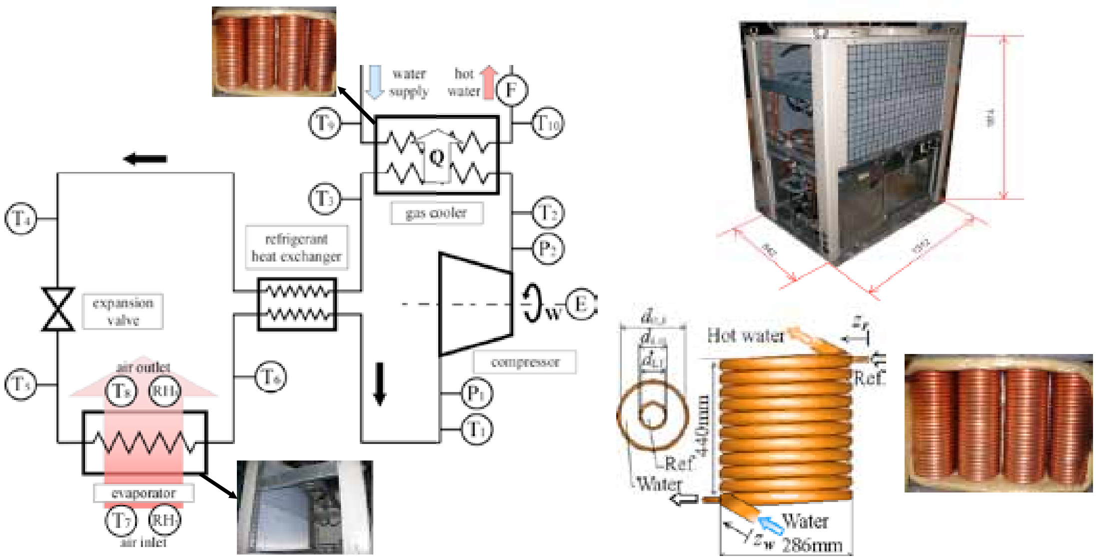

Fig. 2. (a) left picture; Schematic flow of CO2 heat pump water heater (b) top right picture; photo of CO2 heat pump water heater (c) below right picture; gas cooler

4.2. Mathematical model

Due to the limitation of pages, only the model of the gas cooler is shown in Fig.2(c). Authors show the details model in Kato D [1]. This heat exchanger is helical type and water flows outside the inner tube and refrigerant flows inside the inner tube.

Refrigerant continuity, energy and pressure drop are as follows.

$$\frac{\mathrm{d}}{\mathrm{d}z_r}(\rho_r u_r)=0 \quad , \frac{\mathrm{d}}{\mathrm{d}z_r}\left(\rho_r u_r \frac{\pi d_{i,i}{}^2}{4} h_r\right) = -q_i \, , \frac{\mathrm{d}P_r}{\mathrm{d}z_r} = -f_{r,H}\frac{1}{d_{i,i}}\frac{\rho_r u_r{}^2}{2} \qquad (1), (2),(3)$$

Hot water continuity, energy and pressure drop are as follows.

$$\frac{\mathrm{d}}{\mathrm{d}z_w}(\rho_w u_w)=0 \quad , \frac{\mathrm{d}}{\mathrm{d}z_w}\left[\rho_w u_w \left(\frac{\pi d_{o,i}{}^2}{4} - \frac{\pi d_{i,o}{}^2}{4}\right) h_w\right] = q_i \quad , \frac{\mathrm{d}P_w}{\mathrm{d}z_w} = -f_{w,H}\frac{1}{d_{hyd}}\frac{\rho_w u_w{}^2}{2} \qquad (4), (5),(6)$$

Heat transfer rate is derived from the following equations.

$$q_i = K_i \pi d_{i,i}\left(T_r - T_w\right) \quad , \frac{1}{K_i \pi d_{i,i}} = \frac{1}{\xi_{gc}\cdot \alpha_i \pi d_{i,i}} + \frac{1}{2\pi\lambda_t}\ln\left(\frac{d_{i,o}}{d_{i,i}}\right) + \frac{1}{\alpha_o \pi d_{i,o}} \qquad (7),(8)$$

ξ is the degradation factor by the oil contamination. Some paper showed that there isn't small affect when the tube size is larger than 4.0 mm. Therefore, we adopt 1.0 for ξ . Heat transfer performance and friction factor of refrigerant side is as follows.

$$\mathrm{Nu}_r = \frac{\left(f_{r,H}/8\right)\left(\mathrm{Re}_b - 1000\right)\mathrm{Pr}}{1.07 + 12.7\sqrt{f_{r,H}/8}\left(\mathrm{Pr}^{2/3} - 1\right)},\quad f_{r,H} = f_{r,S}\left\{\mathrm{Re}\left(\frac{d_{i,i}}{D_H}\right)^2\right\}^{0.05} \qquad (9),(10)$$

$$f_{r,S} = \left[1.82\log\left(\mathrm{Re}\right) - 1.64\right]^{-2} \qquad (11)$$

Heat transfer performance and friction factor of hot water side is as follows.

$$\mathrm{Nu}_w = \left\{0.65\,\mathrm{Re}_w^{1/2}\left(\frac{d_{hyd}}{D_H}\right)^{1/4} + 0.76\right\}\mathrm{Pr}_w^{0.175},\ f_{w,H} = f_{w,S}\left\{\mathrm{Re}_w\left(\frac{d_{o,i}}{D_H}\right)^2\right\}^{0.05},\ f_{w,S} = \frac{64}{\mathrm{Re}_w} \qquad (12),(13),(14)$$

For the evaporator and internal heat exchanger, heat transfer coefficient that depends on the flow pattern of the refrigerant is considered. For the compressor, isentropic and volumetric efficiencies are derived based on the experiment.

4.3. Simulation and experimental results

Simulation results are shown in Fig. 3. From this, simulation results agree with experimental ones very well. Therefore, we confirmed the validity of our model.

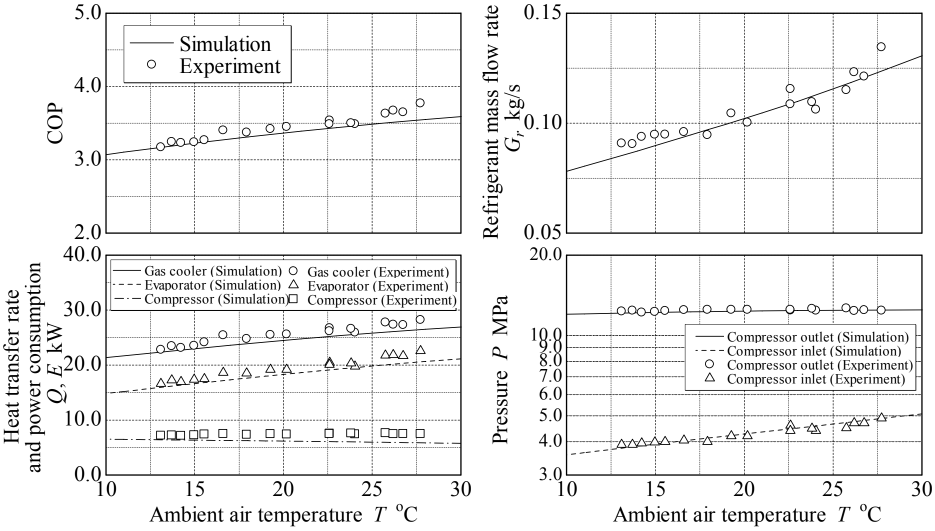

Fig. 3. Simulation and experimental results for CO2 heat pump system

5. Model Level

The necessary precision and permissible calculation time depends on the users. Therefore, three simulation levels are just now considered.

First one is design level model. This level is the highest level model that considers heat and mass transfer in detail. In this model, steady and unsteady state model can be calculated and can be applied to the system design and control system design.

Second level is the engineering level model whose user target is engineering company and so on. In this level, for example, the overall heat transfer performance is constant, whole system performance is calculated directly.

Third level is called the user level that can be calculated large scale system such as whole building and area air-conditioning. For this level of model, performance curve shown in catalog as a model of each system is used. This model is very simple and our analysis theory can be easily applied to this model.

6. Development of Simulator

Modular analysis theory is the one that based on the model of each element. Therefore, using this theory, we can easily develop the general purpose analyzing simulator by adding the GUI. Fig. 4(a) and 4(b) show the simulator we have developed that is called "Energy flow + M".

"Energy flow +M" is based on the mathematical logic we have developed and the user can analyze the thermal system without mathematical procedure. This simulator consists of the following data input part, calculation control part, system calc. part, module calc. part and data output part.

To open this simulator, client can manipulate input and output layer. To communicate the output data, output data is moving from the calculation control part to the client through internet. The calculation control part, analysis part and module calc. part are carried out on server. Fig. 4(b) shows the graphical module on the screen pallet. Using this simulator, large scale smart energy system can be also easily analyzed and the user's burden to make the simulation code can be reduced.

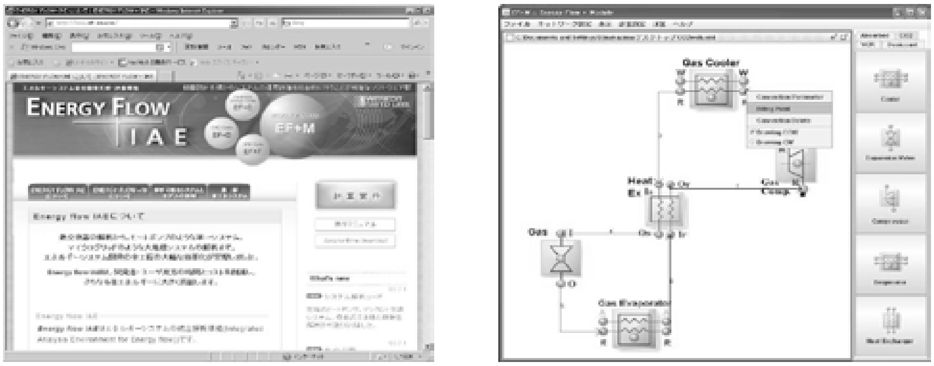

Fig. 4. (a) left picture; homepage of simulator (b) right picture; GUI of simulator

7. Conclusion

In this paper, the mathematical models and simulation method of thermal system by CO_2 heat pump were introduced. These are needed for the simulation of large scale smart energy system. And, not only thermal and fluid systems but also electric network analysis needs to be expanded with simulator. We are just now thinking to expand our simulator to coupled problem between thermal and electric network systems. We will introduce our results soon.

References

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