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Unsteady State Simulation of Vapor Compression Heat Pump Systems With Modular Analysis

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ABSTRACT

Due to worldwide demand for energy saving, many new technologies have been developed in the air conditioning field. Packaged indoor unit and outdoor unit vapor compression refrigerating heat pump system using the change of refrigerant's condition between liquid and gas is a recently developed air conditioning system. The cooling cycle is composed of an evaporator, a condenser, a compressor, an accumulator, pipe and an expansion valve. These components are controlled by the equation of continuity, the equation of energy and the equation of motion and so on. We can solve these equations by giving numerical boundary conditions. In this study, we create the simulation model applied the cooling cycle using theory of modular analysis. In this theory we classify the components into some kinds of module and we structure equations of each component individually and connect by physical continuity and initial condition. To verify the accuracy of simulation model, we tested this system in the stable environmental facility. We set more than 300 sensors of temperature, pressure and quantity of flow. We can analyze the change of the conditions of refrigerant per a couple of seconds. Compared to experimental data and the solution of simulation model, we certain accuracy of model and analyze the influence of the ability of machinery and COP. As a result, we made sure that the constructed simulation model could predict actual behavior of systems. Now we focused the heat exchangers at indoor units and outdoor unit, and we calculated the adequate foam of refrigerant flowing paths by cooling cycle and heating cycle.

1. INTRODUCTION

Most of Japanese area belong to the temperature zones and have rainy season called 'TUYU' from middle of June to July. In Japan in the summer time it is too hot and humid, and in the winter time it is too cold and dry because of continental air flow. Because of environmental change we Japanese are used to use air conditioners which can control to adequate air environmental both summer and winter season. Limited of residential buildings, more than 90% families install them.

In this report we focus air-conditioners for office buildings and shops and hospitals especially VRF (Variable Refrigerant Flow) systems. By Japanese geographical characteristic residence space is narrow because of surrounding mountains and population is too big, half of Japanese people live in just 14% land space. So in the urban area buildings tend to be higher and higher. Because of tendency office buildings and shops are composed of different tenants that differ from business hours. In this background building users tend to install VRF systems which can be controlled individually. In Japan VRF systems shoulder important role of air-conditioner market which are manufactured 800 thousands per year for domestic buildings. The ratio of installing VRF systems increases gradually. In 1983 it showed only 30%, but it rose 58% in 2005. If this tendency continues, VRF systems will monopolize half of all stock of buildings at 2030.

Lately it is popular to use air-conditioners 24 hours for the reason why cut the peak energy load, but commonly air-conditioners turn ON and OFF frequently per a day. Generally speaking, on the way to design the planers considerate safety margin which facilities can manage it the worst circumstances. Piling these reasons, facilities

seldom drive maximum load. The result of survey VRF system's annual load factor in the office building said that only 20～50% VRF systems manage load factor.
The new VRF systems have improved and changed until now for the reason why save energy or increase useful function or progress in high cost performance and so on. In Japan, there are standards for the consumers easy to evaluate the capacity of VRF systems. Japanese most famous standard is JIS (Japanese Industrial Standards), it consist of three parts of standards 'the standard of fundamental' and 'the standard of method' and 'the standard of product' , in 'the standard of method' it is defined to measure and test and analyze. VRF systems standard is JISB8616. It was established in 2006, and in this standard it was mentioned that the VRF systems lord factor is low and it was proposed the way how to evaluate of APF (Annual Performance Factor).

2. Modular Analysis Method

It is important to evaluate VRF systems' capacity and efficiency and actual management, but it is difficult to evaluate all VRF systems for consumers in the experimental room. So we have developed simulation program called 'Modular Analysis Method' by using computers, instead of testing VRF systems. This method is the way to analyze the complicated system. The more VRF systems' fundamental factors increase, the more complex the system are, because of improving the products. But it is unchanging the mathematical model for VRF systems.
Concretely we make a simulation model by three steps. At first we separate the system for every element called 'Module' composed of VRF systems. Secondly we connect each element by physical equations and initial conditions. If the number of variable quantity and the number of equations is same, we can solve the problem step by step. Finally we calculate the VRF systems for parameter study in case of many kinds of initial conditions and many kinds of the each elemental form in steady and unsteady conditions on the computers.
In this report we show the VRF systems' model, there are little difference of the products, basically VRF systems consist of 6 elements. Figure 1 shows the model of whole VRF system. This model has one outdoor unit and four indoor units which are same capacity. Indoor unit equips expansion valve independently.

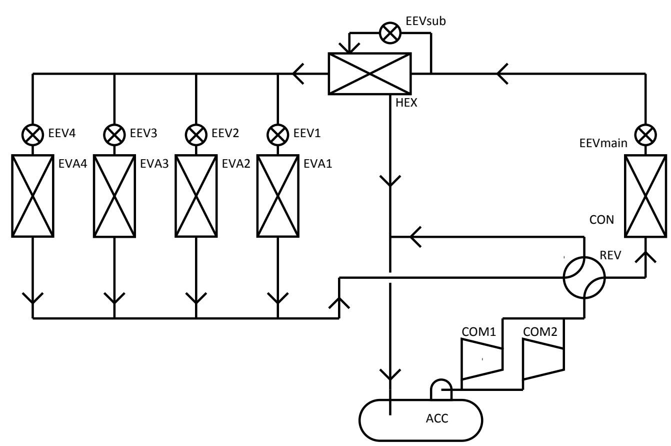

Figure 1: model of VRF System

2.1 Pipe

VRF systems compressed the refrigerant directly, and the pipe is role of the path of refrigerant between two elements. When we create the mathematical model, we assume the two premises. Firstly the refrigerant never eliminate, secondly there is not energy exchange (the pipe is covered by the perfect insulation). We create the mathematical model of three type of the pipe depending on the number of inlet and outlet. The straight pipe has only one inlet and outlet, and the mixing pipe has multiple inlets and one outlet, and the diverging pipe has one inlet and multiple outlets. Figure 2 shows the model of mixing pipe which has two inlets and one outlet. This element is restricted by equations (1)～(4).

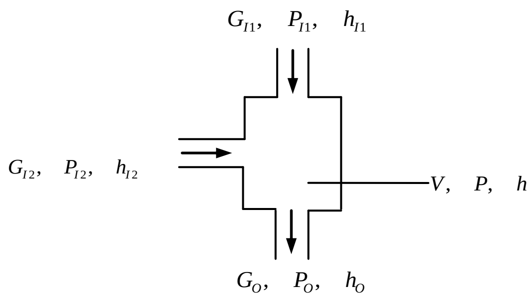

Figure 2: model of mixing pipe

$$\frac{d\rho}{dt}V = G_{I1} + G_{I2} - G_O \quad (1)$$

$$\frac{d\rho u}{dt}V = G_{I1}h_{I1} + G_{I2}h_{I2} - G_O h_O \quad (2)$$

$$P_{I1} = P_{I2} = P_O = P \quad (3)$$

$$h_O = h \quad (4)$$

2.2 Compressor

Compressor is the machine for compressed refrigerant, and it is role of changing pressure conditions. Many kinds of compressors are used for the VRF system, and there forms and physical characteristics vary individually. We focus on the single vapor compressed type. When we create the mathematical model, we assume the two premises. Firstly, when the refrigerant is compressed, it occurs that the loss of entropy and mass volume and energy which the ratio of loss is stable. Secondly, compressor can be controlled among wide range of output, and the refrigerant mass volume depends on the rotational speed of compressor relatively. Figure 3 shows the model of compressor. This element is restricted by equations (5)～(13).

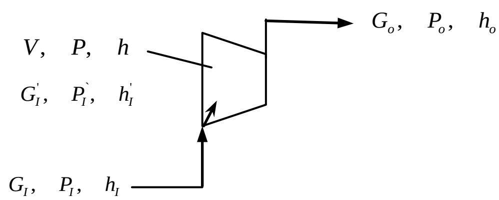

Figure 3: model of compressor

$$\frac{d\rho}{dt}V = G_I - G_O \quad (5)$$

$$\frac{d\rho u}{dt}V = G_I' h_I' - G_O h_O \quad (6)$$

$$\eta = \frac{h_{Iad}' - h_I}{h_I' - h_I} \quad (7)$$

$$s_{Iad}' = s_I \quad (8)$$

$$G_I = \frac{n\rho_I \eta V}{60} \quad (9)$$

$$G_I' = G_I \quad (10)$$

$$G_I' h_I' = G_I h_I + W \quad (11)$$

$$P_O = P \tag{12}$$

$$h_O = h \tag{13}$$

2.3 Heat exchanger

Heat Exchanger is the machine for transferring heat from high temperature medium to low temperature medium, and it is role of promote changing the conditions of refrigerant. Depending on the cooling cycle and heating cycle, it is used for an evaporator and a condenser. Generally speaking, their forms and physical characteristics vary individually. We focus on the fin and tube type. When we create the mathematical model, we assume the two premises. Firstly, heat transfer coefficient is changeable depend on the case of refrigerant conditions. We treated three types of equation. In case of single phase refrigerant, we adopted Dittus-Boelter equation, and in case of double phase refrigerant, we adopted Yoshida equation and Nozu equation. Secondly, the loss of pressure passing through the heat exchanger is changeable depend on the case of refrigerant's conditions. We treated two types of equation. In case of single phase refrigerant, we adopted Blasius equation, and in case of double phase refrigerant, we consider Lockhart-Martinelli parameter. Figure 4 shows the model of heat exchanger. This element is restricted by equations (14)～(23).

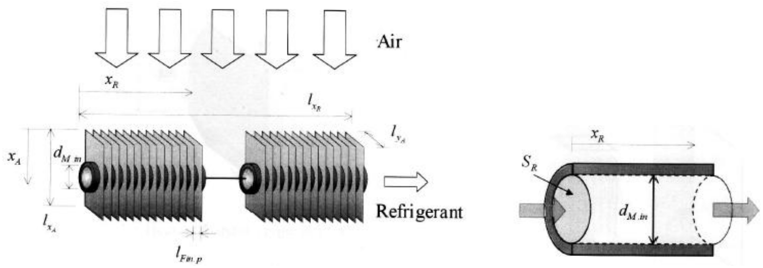

Figure 4: model of heat exchanger

$$\frac{\partial \rho_R}{\partial t} S_R = -\frac{\partial G_R}{\partial x} \tag{14}$$

$$\frac{\partial(\rho_R u_R)}{\partial t} S_R + \frac{\partial(\rho_R v_R h_R)}{\partial x_R} S_R = \pi d_{M\_in} q_{MR} \tag{15}$$

$$\frac{\partial P_R}{\partial x} = -f \frac{\rho_R v_R^2}{2D} \pi d_{M\_in} q_{MR} \tag{16}$$

$$\frac{\partial \rho_M u_M}{\partial t} S_M = -l_{A_{MR} x_R} q_{MR} + l_{A_{AM} x_R} q_{AM} \tag{17}$$

$$\frac{\partial \rho_A v_A}{\partial x_A} S_A = -l_{A_{AM} x_A} \dot{m}_{AM} \tag{18}$$

$$P_{AO} = P_{AI} \tag{19}$$

$$\frac{\partial(\rho_{DA} v_A h_A)}{\partial x_A} S_A = -l_{A_{AM} x_A} q_{AM} \tag{20}$$

$$q_{AM} = \alpha_{AM}(T_A - T_M) + \dot{m}_{AM} \Delta h_{phase} \tag{21}$$

$$q_{MR} = \alpha_{MR}(T_M - T_R) \tag{22}$$

$$\dot{m}_{AM} = \beta_{AM}(X_A - X_M) \tag{23}$$

2.4 Expansion valve

Expansion valve is the machine for decreasing the pressure from high pressure refrigerant to low pressure refrigerant, and it is role of changing condition from high pressure gas to low pressure liquid. When we create the mathematical model, we assume the two premises. Firstly when the refrigerant passes through the expansion valve, the refrigerant's enthalpy is stable. Secondly, the refrigerant flow volume ratio is constant according to the pressure. This element is restricted by equations (24)～(28).

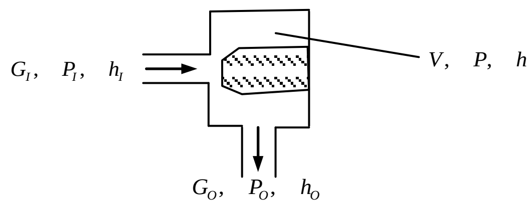

Figure 5: model of expansion valve

$$\frac{\partial \rho}{\partial t} V = G_I - G_o \tag{24}$$

$$\frac{d\rho u}{dt} V = G_I h_I - G_o h_o \tag{25}$$

$$G_I = \rho_I C_a \sqrt{2 \frac{(P_I - P_O)}{\rho_I}} \tag{26}$$

$$P_O = P \tag{27}$$

$$h_O = h \tag{28}$$

2.5 Accumulator

Accumulator is the machine for separating between gas and liquid, and it is role of prevention of invasion of liquid refrigerant to compressors, and absorbing refrigerant flow volume when the cooling output decrease. When we create the mathematical model, we assume the premise. The outlet of refrigerant is controlled by inside the accumulator's conditions. If in case of partial lord there is liquid refrigerant inside the accumulator, outlet is decided the saturated gas. If there is no liquid refrigerant in the accumulator, outlet is decided the superheated gas. This element is restricted by equations (29)～(31).

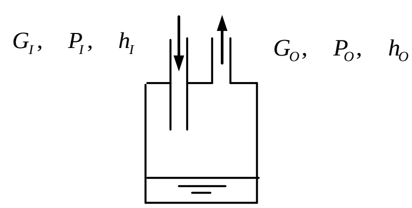

Figure 6: model of accumulator

$$\frac{\partial \rho}{\partial t} V = G_I - G_o \tag{29}$$

$$\frac{d\rho u}{dt} V = G_I h_I - G_o h_o \tag{30}$$

$$P_O = P = P_I \tag{31}$$

2.6 Reversing valve

Reversing valve is the machine for changing the route of refrigerant, and it is role of changing cooling cycle and heating cycle, because indoor unit's role changes between cooling cycle and heating cycle. When we create the mathematical model, we assume the premise. When the refrigerant passes through the reversing valve, the refrigerant's pressure is constant. This element is restricted by equations (32)～(37).

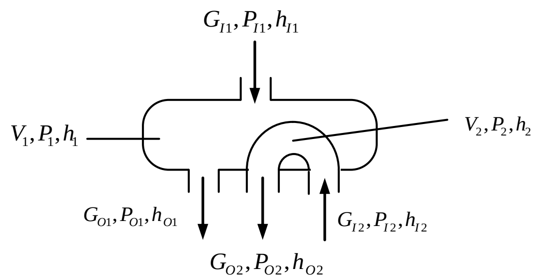

Figure 7: model of reversing valve

$$\frac{d\rho_1}{dt}V_1 = G_{I1} - G_{o1} \tag{32}$$

$$\frac{d\rho_1 u_1}{dt}V_1 = G_{I1}h_{I1} - G_{o1}G_{o1} \tag{33}$$

$$P_{I1} = P_{o1} \tag{34}$$

$$\frac{d\rho_2}{dt}V_2 = G_{I2} - G_{o2} \tag{35}$$

$$\frac{d\rho_2 u_2}{dt}V_2 = G_{I2}h_{I2} - G_{o2}G_{o2} \tag{36}$$

$$P_{I2} = P_{o2} \tag{37}$$

3. Facility of experimental room

We simulate the VRF system by using the modular analysis method using computers, and analyze an actual VRF system in our experimental rooms to verify the accuracy of the simulation results. The experimental rooms consist of two boxes, and the temperature and humidity can be controlled separately in each box. Table 1 shows the specifications of the rooms. Two different sizes of manometers are installed in the upper box: they take in air for the indoor units and outdoor unit, and measure physical conditions. Figure 4-1 shows the diagram of experimental rooms.

Table 1: Room conditions

Scale	**Two room (Same)**	7.9m(W)×6.8m(D)×6.3m(H)
Range	**Dry bulb**	-10～40℃ (minimum range : ±0.1℃)
	Humidity	40～90% (minimum range : ±2%)
Insulation		Main 100mm + air + Sub 40mm
Air flow	**For outdoor unit**	20～440m^3/min
	For indoor unit	15～185m^3/min
Ability	**Air-conditioners**	2.5HP～20HP

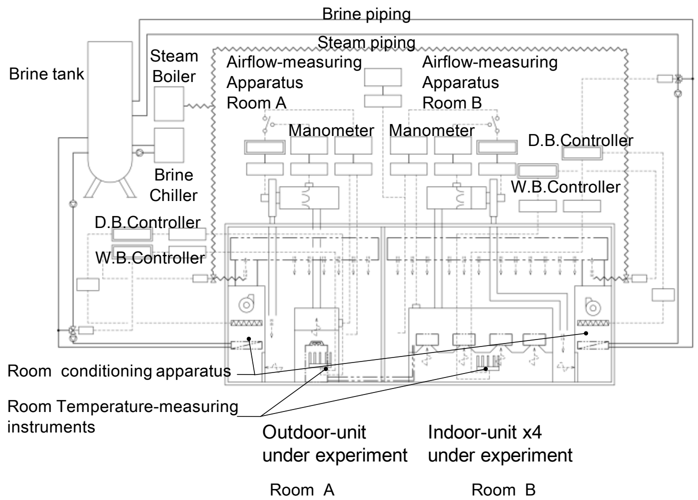

Figure 8: Experimental room

4. Results and simulation and experiment

We simulated the VRF system by using the modular analysis method for varying patterns of initial conditions. The test conditions were roughly classified into two groups: steady-state simulation under constant conditions, and unsteady-state simulation under varying conditions such as the number of active indoor units. The former was used to compare the results of simulation and measurement data in a stable environment, and the latter to test the response to changing situations. Ohno and Saito (2010) simulated evaluation of different capacity of VRF System using this model.
We conducted simulations of various conditions of cooling and heating, and reported the cooling conditions which the JIS standard proposes for measuring an air-conditioner's cooling capacity. Table 2 shows the temperature conditions of the indoor units and outdoor unit.

Table 2: Measurement Condition for cooling system (JISB8616)

Air temperature	Indoor unit	Outdoor unit
Dry bulb (℃)	27	35
Wet bulb (℃)	19	24
Electrical condition	60Hz / 200V	

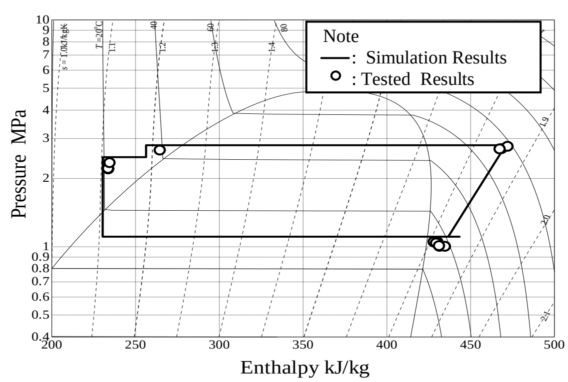

Figure 9: Ph diagram under cooling cycle

5. Evaluation of heat exchanger by simulation analysis

In this study we focus on the VRF system, it is used for both heating cycle and cooling cycle, and heat exchanger's role differ from both cycles. In the cooling cycle, indoor units are role for evaporators, and in the heating cycle, indoor units are role for condensers. Because of changing the operation, we think that the adequate heat exchangers facilities are different both cycles. Generally speaking, when the refrigerant flows into the heat exchanger, it passes through the distribution element, and refrigerant's route separates two more paths. Depending on the number of paths, refrigerant flow speed and heat transfer area change, and it effects heat transfer coefficient and the loss of pressure. So Then, we focus on the numbers of refrigerant paths which are important factor of designing of heat exchangers, and we evaluate by the simulation model by Modular analysis. Table 3 shows the facility of heat exchangers.

Table 3: Facility of heat exchanger

	Outdoor unit	Indoor unit (per one unit)
Tube Diameter (mm)	7.48/8.00	6.44/7.00
Tube Length (m)	226.5	42.5
The number of Paths (-)	18	5
Fin Pitch (mm)	1.3	1.25
Interval of Tube (mm)	25	20
Fin Thickness (mm)	0.095	0.105
Width of fin (mm)	17.25	12.5

We do the parameter study with simulation model by changing the initial conditions of the number of paths. Table 4 shows the input conditions of case. Figure 11 show the result of simulation.

Table 4: Parameter study of changing the number of paths of heat exchanger

	Case	the number of Paths			Case	the number of Paths	
		Outdoor unit	Indoor unit			Outdoor unit	Indoor unit
Cooling Cycle	1	24	5	Heating Cycle	1	24	5
	2	18	10		2	18	10
	3	24	3		3	18	3
	4	18	8		4	18	8
	5	18	15		5	15	5
	6	18	25		6	25	5
	7	18	35		7	18	15
	8	18	5		8	18	5
	9	15	5				

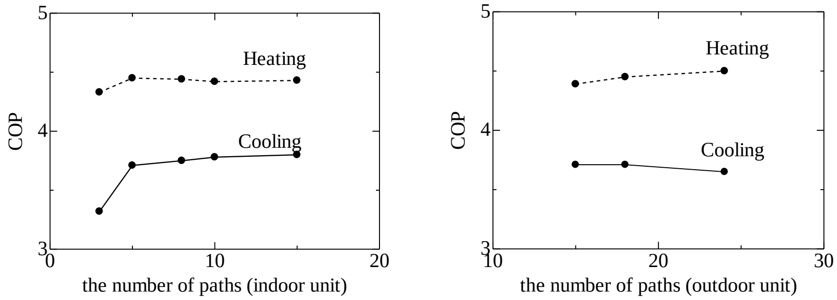

Figure 11: Results of simulation

6. CONCLUSIONS

We constructed a simulation model for analyzing the VRF system under the unsteady state. We show the results of the simulation and experimental data, the results were similar. We evaluated the influent of COP by changing the heat exchanger's number of paths. According to figure 11, in case of increasing evaporator's path (cooling cycle at indoor unit and heating cycle at outdoor unit) COP increase about 10%, but in case of increasing condenser's path, COP is almost stable. We consider the reason why COP increase at evaporator because of decreasing the loss of pressure. Increasing the number of path occurs decreasing refrigerant' flow per path, and the refrigerant flow speed decrease. But it has a peak because of heat transfer coefficient. On the other hand, At condenser, the refrigerant gas almost control the condition, changing the number of path effect subtly.
By the way, we recognize this simulation results are small different compared to experimental data, because we assume some kind of premises in order to finish the calculation. In the future, we will improve the accuracy of the model, and add a heat recycle model, and analyze other systems such as gas heat-pumps, to identify the most suitable VRF system.

NOMENCLATURE

G	Mass flow rate	(kg/s)		**Subscripts**
h	Specific enthalpy	(kJ/kg)	I	Inlet
ρ	Density	(kg/m^3)	O	Outlet
V	Volume	(m^3)	Iad	Compressed gas adiabatically
P	Pressure	(kPa)	A	Air
u	Specific internal energy	(kJ/kg)	M	Tube
s	Entropy	(J/K)	R	Refrigerant
n	Rotational speed	(rpm)		
W	Work	(kW)		
S	Area	(m^2)		
q	Specific heat flux	(kW/m^2)		
l	Length	(m)		
α	Heat transfer coefficient	($kW/m^2 \cdot K$)		
T	Temperature	(K)		

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