Evaluation of Control Method of VRF (Variable Refrigerant Flow) System by Experimental Study and Simulation Analysis

Kuniyasu MATSUMOTO*† Keisuke OHNO** Seiichi YAMAGUCHI** Kiyoshi SAITO**

*Research and Development Department of R&D Center, The Kansai Electric Power Co., Inc. (11-20-3-Chome, Nakoji, Amagasaki, Hyogo 661-0974)
** Interdisciplinary institute for thermal energy conversion engineering and mathematics, WASEDA University (3-4-1 Oliikubo, Shinjyuku-ku, Tokyo, 169-8555)

Summary

Recently, the installation of VRF (Variable Refrigerant Flow) heat pump systems in offices – regardless of their size and shape – has become popular in Japan. This system consists of a packaged outdoor unit and multiple indoor units connected by a refrigerant pipe. It has the advantage of fitting in easily with the any building plans because of its standardized system. Moreover, this system is energy saving and enhances user comfort, as it can be easily operated as an indoor unit. On the other hand, as there are infinite combination of indoor units of VRF systems available for the users to be chosen freely within the range of outdoor capacity, and since the indoor units can be turned on and off independently, operation conditions are not predictable. So it is very difficult to find adequate control parameters under wider load conditions. For this reason, the purpose of this paper is set to organize the control characteristics systematically. In order to evaluate VRF system, we develop a numerical simulation model based on the laws of physics. This model can easily add and delete indoor unit's elements. Therefore, we hope that this model is adequate for VRF system’s analysis. In this report we reproduce machine's operation conditions precisely; for example, for unstable condition, we reproduce the hunting phenomenon of expansion valve and evaluate the effects of different control constants under different loads.

Keywords: VRF, Heat pump, Expansion valve, Simulation, Hunting

1. Introduction

Recently in Asia, and especially in Japan, the installation of compression type heat pump units in commercial and industrial buildings has become popular. The VRF (variable refrigerant flow) system, which consists of one outdoor unit and multiple indoor units which can be operated independently, has been particularly popular. Because many Japanese regard energy saving as a virtue, they turn off their rooms’ indoor units when not in use. The ability to operate each indoor unit independently to adjust the refrigerant flow rate, gives this system a high energy saving performance. But, as said earlier, as the users of VRF system can choose infinite combination of indoor units freely within the range of outdoor capacity, and since they can turn their indoor units on and off independently, operation conditions are not predictable; so it is too difficult to find adequate control parameters under wider load conditions. It is very difficult to design the control system in a way that it meets both the stability and high energy saving criteria. From the point view of actual operation condition, VRF system is used by partial load condition in most periods, so it is said that VRF system sometimes occurs decreasing performance of COP under light load condition by effects of intermittent driving condition. Previous studies1-3) show the possibility of unstable condition, known as the hunting phenomenon of the expansion valve. Hence, they proposed keeping the boundary condition stable. Moreover Orhan et al4) compared three kinds of control ways for a single indoor unit air-conditioner, which are, PID, Fuzzy and ANN. They proposed that ANN is superior among these, owing to its rapidity and energy saving characteristics, using step response analysis. However, no paper has properly evaluated the complex VRF system for its different control methods under different loads.

With this background, this study organizes the control characteristics of the VRF system systematically and reproduces the machine’s operating conditions using our simulation model precisely. Then, we make sure that the problem with VRF systems, which is that, it is too complex to tune the optimum control parameters under wide load conditions, is solved. Interestingly, single unit air-conditioners used in residential area do not have this problem. The machine used for testing in this study is controlled by PI method. Since PI method is the most popular5) and an easier method, we use it in this research, to study the effect of control parameters of VRF systems. Further, in this report, we evaluate the VRF system both experimentally and through simulation analyses, and reproduce the unstable hunting phenomenon of the electrical expansion valve.

Nomenclature

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2. System Overview

In order to evaluate the VRF system experimentally, we focus on the actual product, which is popularly installed in Japan. Fig.1 shows the system overview and the measuring points. Table 1 shows the specifications of this system. This system can manipulate a wide range of refrigerant flow rates by changing the number of compressor’s units and their rotational speeds. The refrigerant used in system is R 410A. All four indoor units are of the same capacity, and each indoor unit has both a fan and an expansion valve, which is manipulated depending on the load condition.

Table 1 Specification of the VRF system

<table>
<thead>
<tr>
<th></th>
<th>Outdoor</th>
<th>Indoor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capacity</td>
<td>28.0 kW</td>
<td>7.1 kW</td>
</tr>
<tr>
<td>Unit</td>
<td>1 unit</td>
<td>4 units</td>
</tr>
<tr>
<td>Refrigerant</td>
<td>R 410A</td>
<td></td>
</tr>
</tbody>
</table>

3. Evaluating Method

3.1 Experimental Study

We installed the machine as shown in Fig.1 in a test room, whose humidity and temperature can be controlled. The accuracy of the model was determined by comparing the simulation results with the experimental ones. Table 2 outlines the specifications of the experiment room and Fig.2 shows an overview of the experiment room.

Table 2 Specification of experiment room

<table>
<thead>
<tr>
<th></th>
<th>2 rooms (Independently)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room</td>
<td></td>
</tr>
<tr>
<td>Scale</td>
<td>7.9(W)×6.8(D)×6.3(H) (m)</td>
</tr>
<tr>
<td>Range</td>
<td>Temperature: -10~40 (℃)</td>
</tr>
<tr>
<td></td>
<td>Humidity: 40~90 (%)</td>
</tr>
<tr>
<td>Accuracy</td>
<td>Temperature: ±0.1 (℃)</td>
</tr>
<tr>
<td></td>
<td>Humidity: ±2 (%)</td>
</tr>
<tr>
<td>Method</td>
<td>Air enthalpy method</td>
</tr>
</tbody>
</table>

Fig.1 VRF system overview

Fig.2 Experiment room overview
3.2 Simulation analysis

We build the simulation model using the modular analysis algorithm and regard all the elements such as the control volume and mass, and the volume of the flowing refrigerant, as standardized modules.

To begin with, we derived differential equations for all the modules based on the laws of physics, such as the mass conservation law and the energy conservation law. Then, we reiterate the calculations using the Newton-Raphson method so that every connected module’s refrigerant condition has the same value. The details of this algorithm have been extensively investigated in previous studies 6-7). In this report, we introduce the expansion valve module. Fig. 3 shows the overview of an electric expansion valve. We assumed that the expansion valve follows the lumped parameter model, because the speed of change in the refrigeration condition is so fast and the volume of element is so small, that the refrigerant never stays in this module. Moreover, the change in the refrigeration condition between the inlet and the outlet is not isentropic, but isenthalpic. Eqs. (1)-(6) show the refrigerant conditions in the expansion valve.

\[
\begin{align*}
\rho_{R,0}v_{R,0}S_{R,0} - \rho_{R,1}v_{R,1}S_{R,1} &= 0 \\
\rho_{R,1}v_{R,1}S_{R,1} &= C_vS\sqrt{2\rho_{R,1}(P_{R,1} - P_{R,0})} \\
\rho_{R,0} &= \frac{\rho_{R,1}}{f(P_{R,1}, h_{R,0})} \\
\rho_{R,0} &= \frac{\rho_{R,1}}{f(P_{R,1}, h_{R,0})} \\
m_R &= 0
\end{align*}
\]

In this study, we focus only on the expansion valve in indoor units and evaluate them using the PI control method. Fig. 4 shows the block diagram of the control method.

![Fig.4 Block diagram of the electric expansion valve](image)

### Table 3

<table>
<thead>
<tr>
<th>Actuator</th>
<th>Manipulated variable</th>
<th>Controlled variable</th>
</tr>
</thead>
<tbody>
<tr>
<td>Compressor</td>
<td>Rotational speed and the number of active units</td>
<td>Evaporating pressure</td>
</tr>
<tr>
<td>Expansion valve (indoor unit)</td>
<td>Open pulse rate</td>
<td>Degree of super-heating at evaporator outlet</td>
</tr>
<tr>
<td>Fan (outdoor unit)</td>
<td>Rotational speed</td>
<td>Degree of air flow outlet</td>
</tr>
</tbody>
</table>

In this system, there are certain elements that can be manipulated, such as the rotational speeds of the compressor and fans, and the open pulse of the expansion valves. Moreover, as each indoor unit is equipped with both a fan and an expansion valve, we have to consider infinite combinations of control logic. In order to keep the operation stable while saving energy, it is important to adjust the refrigerant flow rate depending on the dynamic load change. Hence, in this report, we focus on three types of actuators and we decide on the controlled variable responding to each actuator. Table 3 shows the connection between the manipulated and the controlled variables.

#### 4. Control Logic and Problem

4.1 Control logic

In this system, there are certain elements that can be manipulated, such as the rotational speeds of the compressor and fans, and the open pulse of the expansion valves. Moreover, as each indoor unit is equipped with both a fan and an expansion valve, we have to consider infinite combinations of control logic. In order to keep the operation stable while saving energy, it is important to adjust the refrigerant flow rate depending on the dynamic load change. Hence, in this report, we focus on three types of actuators and we decide on the controlled variable responding to each actuator. Table 3 shows the connection between the manipulated and the controlled variables.
variables, which are compressor speed and fan speed, are constant under rated condition.

![Graph showing EEV pulse and Temperature](image)

**Fig. 5 Results of the static characteristics**
(Upper: Manipulated only IND1 Lower: Manipulated both IND1 and 2)

**Fig. 6 Results of dynamic characteristics**
(Medium: Manipulated only IND1 Lower: Manipulated both IND1 and 2)

### 4.3 Experiment results (Problem of the hunting condition)

In this section, we show the two test results. Fig. 7 shows the expansion valve’s open pulse and Table 4 shows the test conditions. Fig. 7 shows the expansion valve’s open pulse and the temperature at the evaporator’s inlet and outlet.

<table>
<thead>
<tr>
<th>Case 1</th>
<th>Case 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temperature (℃)*1</td>
<td>JIS standard (35/24 27/19)</td>
</tr>
<tr>
<td>Load ratio (%)</td>
<td>100%</td>
</tr>
<tr>
<td>(heating by test room)</td>
<td></td>
</tr>
<tr>
<td>Compressor (rps)</td>
<td>26(inverter)</td>
</tr>
<tr>
<td>(Automatic control)</td>
<td>+60(Fix)</td>
</tr>
</tbody>
</table>

*1: Outdoor temperature is constant. Indoor temperature is controlled by machine

**Fig. 7 Transition of EEV open pulse and temperature at evaporator inlet and outlet (test results)**

As may be seen in Fig. 7, Case 1 keeps the temperature close to 5°C or more, whereas Case 2 repeats unstable temperature conditions from 0 to 8°C.

**4.4 Fitting simulation results with experimental data**

As the actual PI control constants have not been estimated, the experimental and the simulation results are compared parametrically. In addition, the appropriate control constants are fit, which include the proportional gain and integral constants as defined in the digital control method given by Eqs. (7)-(8). In order to fit the value of the control constants, we reiterate the calculations while gradually changing two kinds of control constants. When the error, as is defined in Eq. (9) as the difference between the test results and the calculation results was minimum, we judged those to be the appropriate control constants of the test machine. Fig. 8 shows a comparison between the experimental data and the calculation results using the identified control constants. The change in trend of the open pulse in the experimental data is similar to that obtained by calculation.
4.5 Evaluate control constants

In this section, we evaluate the effect of control constants by the simulation method. First, we adopt the control constant under Case 1, and evaluate the effect of the control constants by a step response study. In order to obtain a unified interpretation, we define three evaluative functions. Eqs. (10)-(12) show three evaluative indexes, which are ‘rapidity’, ‘stability’, and ‘comfort’. Rapidity shows the index for rapidity with which the setting point is reached. Stability is the index for the stability of the expansion valve, because we assume that minimizing the number of the manipulated changes leads to a decrease in the burden of the manipulated element. Comfort shows the index for minimizing overshoot, because we assume that the higher degree of overshoot of super-heating leads to an increase in the temperature of the compressor input and affects the unstable temperature phenomenon at the evaporating airflow temperature. When the sum of all the three indices are compared for several cases, the one that produces the minimum sum is considered to have the optimum values for the control constants. Fig.9 shows the comparison of the three cases of control parameters. Table 5 shows the results of the calculations of the three indices.

1) Rapidity

\[ V_1 = \sum (T_{\text{set}} - T_{\text{sh,n}})^2 \]  

(10)

2) Stability

\[ V_2 = \sum (MV_{\text{st}} - MV_n)^2 \]  

(11)

At time 0, we increase the setting temperature from stable condition to 5°C, and the expansion valve open pulse was manipulated by the control logic shown in Fig. 4. The system response was then calculated using the simulation model. Fig. 9 shows a comparison of the three parameters of the control constants (Table 5).

Although the optimized control parameter change drastically under a wide range of operational condition, if the operation condition keeps constant, there is a possibility that it is uniquely determined. So, we perform the parameter study of control
constants in order to understand the nature of effect of control parameter. We evaluate by the index of both rapidity and stability given Eqs. (10)-(11). Fig.10 shows the simulation results. We evaluate the effect of only one control constants (proportional gain or integral constants), and fix the others. In this report, proportional gain has a negative value; in Fig.10, proportional gain is replaced to absolute value in order to easily compare the effect of control parameters. In Fig.10, the line that connects the simulation results is the “three-order spline curve”. Both rapidity and stability show downward convex function, so there is a possibility that the optimized control parameter is under stable load range.

Comparison of Case 1 and 2 shows that Case 2 is more sensitive than Case 1, especially in change of gain. In Case 1 the change in the amount of evaluation indices is smaller than Case 2. In both cases, when the gain has a small value or integral constant is large value, the index of rapidity also has a larger value. This is why does setting point called offset is not achieved. Moreover, when the gain is large or integral constant is small value, the indices of rapidity and stability are large. This is the why an increase and decrease over setting point called hunting occurs, as is shown in Fig.9.

**Fig.10 Evaluation of rapidity and stability changing control constants**

5. Conclusions and Future Studies

In this report, we built a simulation model, which we can control every element of the VRF system, and we evaluated the control constants of a test machine. Thus, we were able to reproduce many test conditions to evaluate the effect of the control actuator. When the load is low where one compressor stops and the refrigerant flow rate is slower than the rated condition, we recognized the possibility of instability of the expansion valve hunting. On the other hand, in case of the rated condition, in order to optimize the control constants, the proportional gain and the integral constants needed to be adjusted. But this led to a decrease in the stability of the low load condition. Thus, it is important to adjust the control constants appropriately, depending on the load condition. In future studies, we would like to assess the condition where stability is limited and would like to propose solutions to implement both stability and high performance for energy saving operation of the system. Finally, we would like to apply other ways of controlling VRF system to our developing simulation model.

References

5. Terashima, K., Recent overview and future development of system and control theory, Materials Transactions, 2000, 72, pp.47-56 (in Japanese)