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To cite this article: H. Li *et al* 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **238** 012053

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Dynamic simulation of a VAV system based on dynamic PMV control

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Abstract. The predicted mean vote (PMV) index is taken as the control target in an air-conditioning system is in line with the requirements of the indoor thermal environment. In addition, with the emergence of "air conditioning disease", people began to pay more attention to the study on the dynamic thermal comfort of indoor thermal environment. Firstly, the dynamic PMV is proposed, and the amplitude and period of the dynamic PMV are confirmed by experiments and questionnaire surveys. Then, a simulation model of variable air volume (VAV) air-conditioning system based on dynamic PMV control is built by Transient System Simulation Program (TRNSYS). Simultaneously, the simulation models of the VAV air-conditioning system based on constant temperature control and static PMV control are also built by TRNSYS. The simulation results show that the comfort and energy saving of the VAV air-conditioning system based on dynamic PMV control are more prominent.

1. Introduction

The variable air volume (VAV) system usually takes the indoor temperature as the control target. The damper to that space will gradually close to decrease the inflow of cold air if the indoor temperature is lower than its set value. During the closing of the damper, the pressure of supply duct will rise that will signal the supply fan frequency decreased. The power of supply fan is cut down, and the operating energy consumption of fan is reduced. The control strategies of a VAV system mainly include damper control of VAV box [1], duct constant static pressure control and duct variable static pressure control [2-4] and supply air temperature reset control [5,6]. The main control method of indoor thermal environment is temperature control. The indoor temperature keeps constant by adjusting the damper in VAV box. Because the thermal comfort of human body is also related to the indoor relative humidity,



the wind speed, the radiation temperature, the body clothing and the personnel metabolic rate, some researchers studied the static Predicted Mean Vote (PMV) control [7,8]. In order to approximate to the natural environment and reduce the operating energy consumption of fan, the dynamic PMV control was proposed by authors [9]. For analyzing the operational performance of a VAV system based on dynamical PMV, a simulation model of VAV system based on dynamical PMV control is built by Transient System Simulation Program (TRNSYS) software in this paper.

2. Method

2.1. Dynamic PMV index

The dynamic PMV index means that the PMV index changes periodically over a certain range. The amplitude ($PMV_{max} - PMV_{min}$) and the period of the dynamic PMV index are determined by experiments and questionnaire surveys. The experimenters vote on the thermal comfort of the indoor environment under different PMV values that are measured by SWEMA PMV instrument. Through comparison and analysis, the PMV_{max} is 0.75 and the PMV_{min} is 0.5. According to the PMV response curve of the experiment room and the thermal environment adaptation of human body, the period T of dynamic PMV index is 1 hour.

The operating time of the VAV system is from 8:00 to 18:00. Figure 1 is the regulation rules of dynamic PMV index for the VAV system within one day. The PMV value is set to 0.75 at 8:00 considering the adaptation process of human body from outdoor environment to indoor environment in the morning. With the gradual adaptation of human body to the indoor thermal environment, the PMV value is set to 0.6 at 9:00, the indoor temperature is slightly reduced, and the comfort level of staffs is increased. The PMV is set to 0.5 at 10:00, and the comfort level of staffs is increased furtherly. The staffs begin to go out for lunch during 11:00-12:00. Because the outdoor temperature is much higher than the indoor temperature, and the human body needs an adaptive process, the PMV value is increased to 0.6 at 11:00. The number of staffs indoor generally is small and most of the staffs need lunch break during 12:00-13:00, the PMV value is set to 0.75 at 12:00 for energy conservation. The number of staffs indoor gradually increases and the staffs begin to work from 13:00, the PMV value is set to 0.6 at 13:00. The PMV value is set to 0.5 at 14:00 and 15:00. The staffs work in a comfortable office environment, which helps them to improve the work efficiency. The number of staffs indoor gradually decreases from 16:00 and the human body needs an adaptive process, the PMV value is set to 0.6. The PMV is set to 0.75 at 17:00 until the air conditioning system is closed at 18:00.

2.2. building load model

An office building is taken as the example, which is located in Jinan City, Shandong Province. A standard floor of the office is selected to build the load model. Figure 2 shows the three-dimensional model of the standard floor drawn by SketchUP. Table 1 shows the heat transfer coefficient and structural description of the office building. Table 2 shows the window-wall ratios of each direction in the office building.

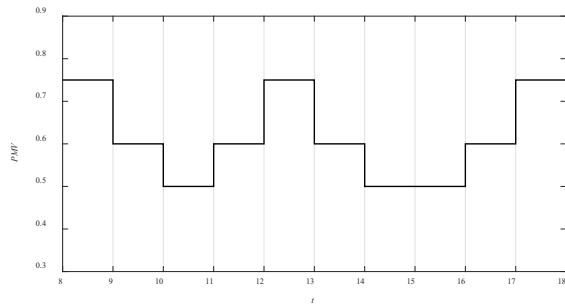


Figure 1. Dynamic PMV index
Regulation rules within one day

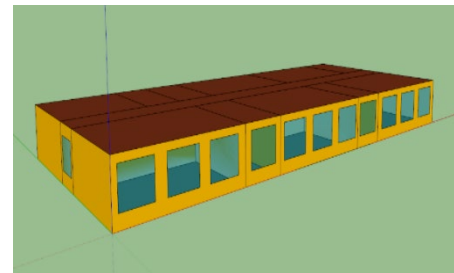


Figure 2. Three-dimensional graph
of the standard floor

Table 1. Parameters of the office building

Building envelope	Heat Transfer Coefficient (W/(m ² ·K))
Exterior Wall	0.434
Roof	0.387
Outside Window	1.61
Interior wall	0.358

Table 2. Window-wall ratios of each direction

Orientation	East	South	West	North
window-wall ratio	0.23	0.27	0.17	0.27

The cooling time of the air conditioning system in Ji'nan is from May 2nd to September 24th. The daily running time of the air conditioning system is 8:00~18:00. Figure 3 shows the hourly load dynamic curve of the standard floor in summer.

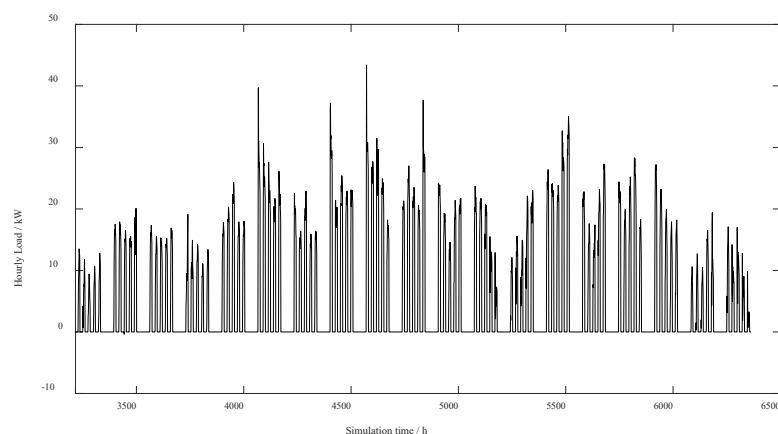


Figure 3. Hourly load curve of the standard floor in summer

2.3. Simulation model of VAV air-conditioning system

2.3.1. Mathematical model of variable frequency fan. One of the most important components in the VAV system is the variable frequency fan. In the TRNSYS simulation software, there is a module Type111 of the variable frequency fan. Because the Type111 module cannot modify the performance parameters of the variable frequency fan according to its sample characteristic curve, a new mathematical model of variable frequency fan with constant static pressure control is established, and the module Type275 is developed based on TRNSYS. The characteristic curve equation of variable frequency fan can be expressed as formula (1) according to the sample data provided by fan manufacturers and the similarity rate of the fan [10].

$$H = a_1 G^2 + a_2 G I + a_3 I^2 \quad (1)$$

Where, H is the head of fan, Pa; G is the air flow rate, m³/s; a_1 , a_2 , a_3 are the polynomial fitting coefficients; I is the speed ratio of the fan.

$$f = 50I \quad (2)$$

Where, f is the supply power frequency of fan, Hz.

The input power of variable frequency fan can be expressed as

$$P = \frac{H_m G}{10^3 \eta} \quad (3)$$

Where, P is the input power of fan, kW; H_m is the total head of the fan, Pa, assuming the internal resistance H_n of the air treatment unit is 290Pa, then $H_m = H + H_n$; η is total operating efficiency of variable frequency fan.

The module Type275 is developed by C++ programming. The input parameters of Type275 include the inlet temperature T_{in} , the supply air flow rate G required by load side and the minimum operating frequency H_{zmin} . The output parameters of Type275 include the outlet temperature T_{out} of variable frequency fan, the supply air flow rate G of variable frequency fan, the output frequency H_z of frequency converter, the power P and the total efficiency η of variable frequency fan.

2.3.2. Simulation model of VAV air-conditioning system. In general, the static pressure sensor is installed at the 2/3 of the main supply air duct. The range of static pressure set value is between 250 to 375 Pa. In this paper, the static pressure sett value of the VAV air conditioning system is 250Pa. Type 14h is used to set the variation of the dairy PMV setting value. Type 648 is an air mixer, which is used to mix the fresh air and return air. Type 22 Iterative Feedback Controller is selected as the dynamical PMV controller of VAV-BOX. Figure 4 is the dynamical PMV control block diagram of VAV-BOX. The output signal of the iterative feedback controller is between 0 to 1, which means the open degree of damper in the VAV Box is 0~100%. The flow characteristic of the damper is linear, then the actual supply air flow of VAV-BOX can be calculated by formula (4).

$$G_B = G_{B,100} \times \varphi \quad (4)$$

Where, G_B is the actual supply air flow of VAV-BOX, m³/s; $G_{B,100}$ is the supply air flow of VAV-BOX with 100% opening degree of damper, m³/s; ϕ is the opening degree of damper, %.

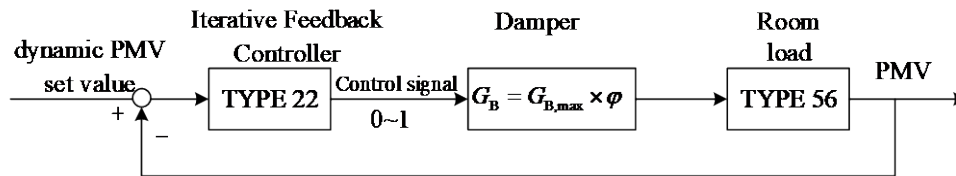


Figure 4. PMV control Schematic diagram of VAV-BOX

Ultimately, the simulation model of VAV system based on dynamical PMV is build, as shown in Figure 5.

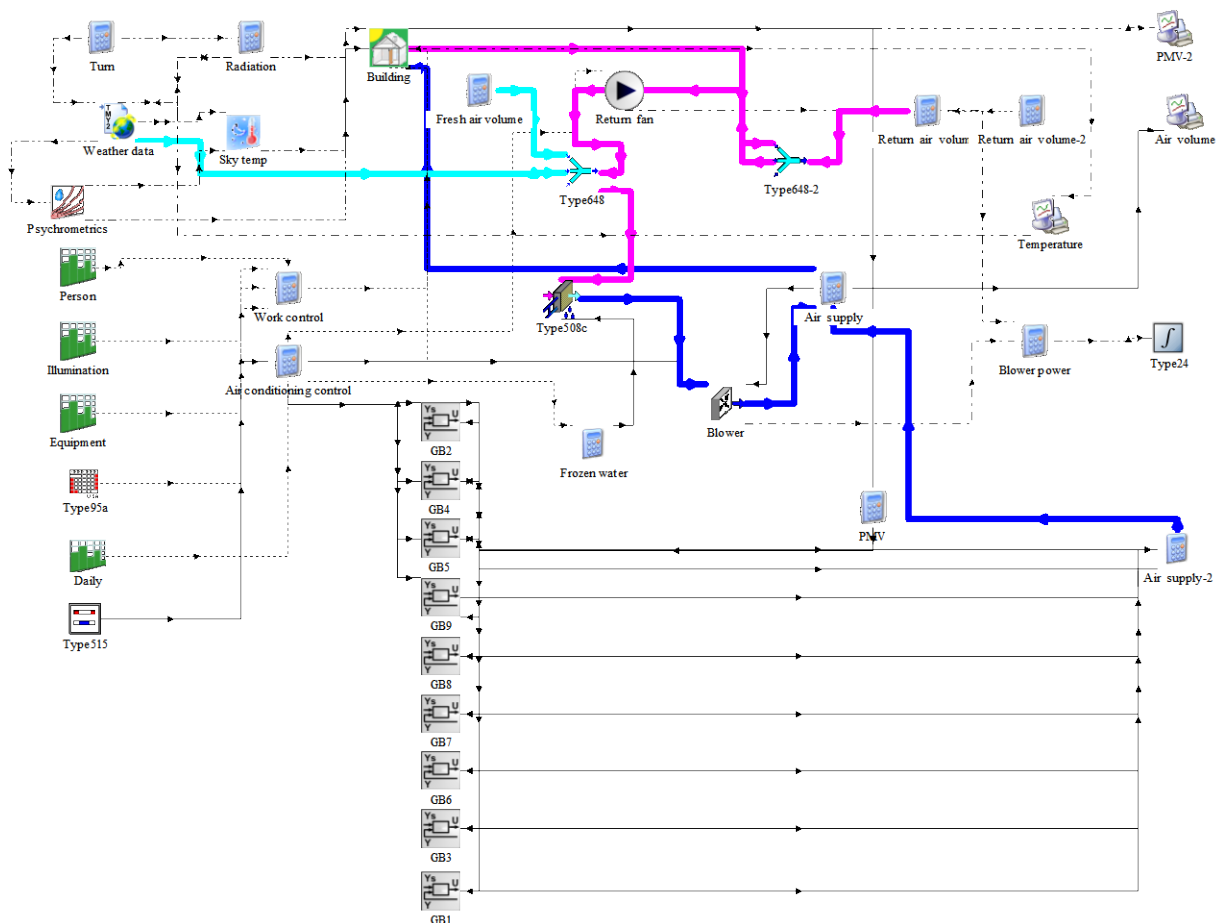


Figure 5. simulation model of VAV system based on dynamical PMV

3. Simulation and analysis

3.1. Dynamical PMV simulation and analysis

The simulation time is from May 2nd to September 24th. The daily running time of the air conditioning system is 8:00~18:00 during Monday to Friday. The air conditioning system is off at weekend. The PMV and temperature change curves of each room can be derived by simulation. The control principle of each room is the same, office 7 is selected to analyze the PMV and temperature changes. In order to express the change of PMV clearly, Figure 6 only shows the change curve of PMV value of office 7 during a week. It can be seen from the figure 6 that the indoor PMV value can meet the indoor dynamical PMV control requirements. The indoor PMV value has a little fluctuation with the dynamical PMV set value during the operating time. The maximum fluctuation is about 0.02, and the human body can hardly feel this change. However, the dynamical PMV is constantly changed, so the human body is in a dynamically changing indoor environment.

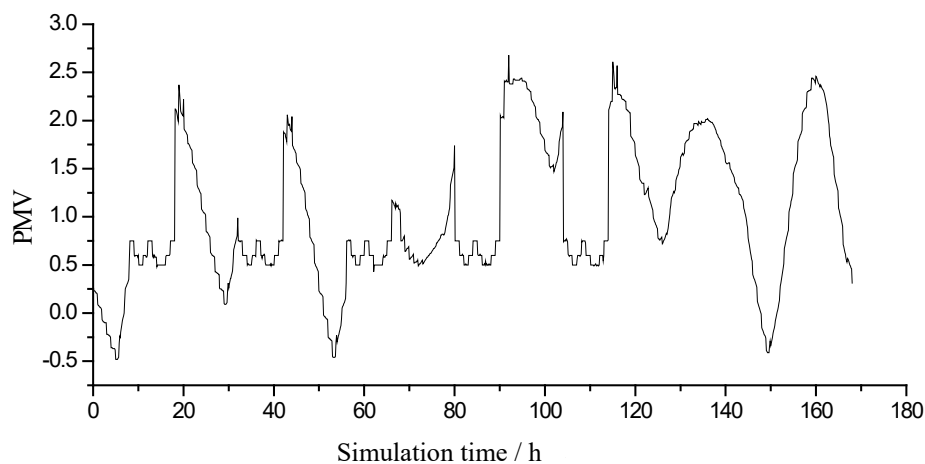


Figure 6. Change curve of PMV of office 7 in one week

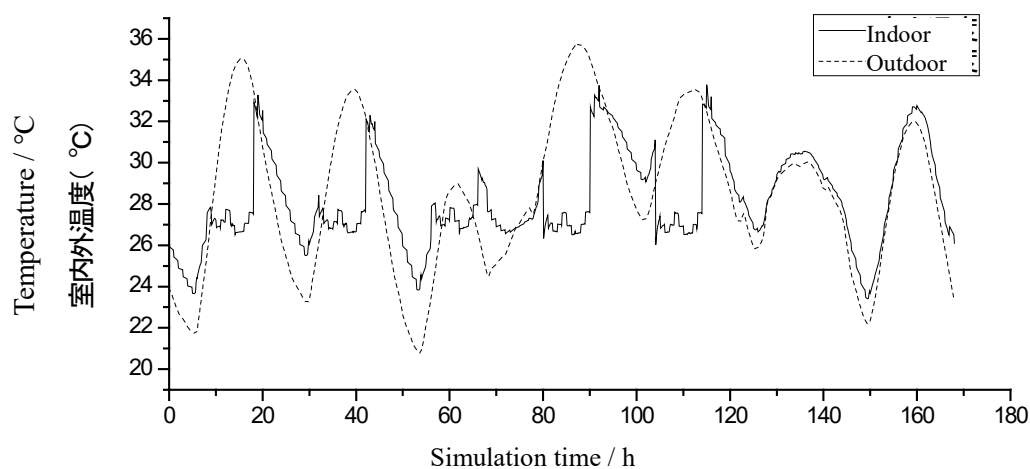


Figure 7. Outdoor temperature and indoor temperature of office 7

3.2. Energy consumption analysis

The temperature control simulation model and the static PMV control simulation model of the VAV air-conditioning system are also build with temperature set value 26°C and static PMV set value 0.5. The other parameters and settings of the simulation models of VAV air-conditioning system are consistent with the simulation model of dynamic PMV control. Figure 8 is the fan energy consumption curves of the VAV system with the three different control methods in whole summer. The specific cumulative energy consumptions of fans are shown in table 3. The results show that, compared with the VAV system based on temperature control, the fan energy saving of VAV system based on static PMV control is 10.35%, and the fan energy saving of VAV system based on dynamic PMV control is 20.59%. Obviously, the VAV system with dynamic PMV control is more energy efficient.

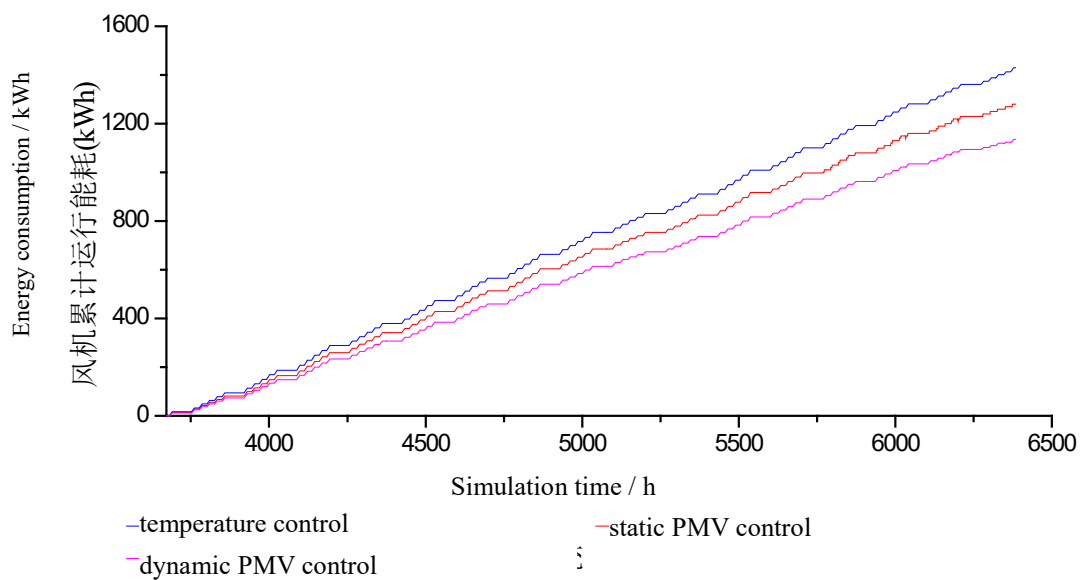


Figure 8. Cumulative energy consumption of fans in three control methods

Table 3. Total accumulative energy consumption in three control methods

Control method		temperature control	static PMV control	dynamic PMV control
Accumulative energy consumption (kWh)		1430	1282	1135.6

4. Conclusion

In this paper, a dynamical PMV model is proposed by experiments and questionnaire surveys. The amplitude of dynamical PMV is 0.25 with PMV_{max} 0.75 and PMV_{min} 0.5. The period of dynamic PMV is 1 hour. A simulation model of VAV system based on dynamic PMV is established by using TRNSYS software. The simulation results show that the fan energy saving of the VAV system based on dynamic

PMV control is 20.59% and 11.42% compared with the temperature control and static PMV control. In summary, the VAV system based on dynamical PMV is not only more in line with the needs of the human body healthy, but also has high energy efficiency, which is in line with the concept of green development at this stage.

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Acknowledgments

This work is supported by National Natural Science Foundation (NNSF) of China under Grant 61773246 and Major Program of Shandong Province Natural Science Foundation under ZR2018ZB0419.