# FLUCTUATION OF INDOOR TEMPERATURE CAUSED BY INSUFFICIENT COOLING SUPPLY: COMPUTER SIMULATION AND EXPERIMENTAL STUDY

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## ABSTRACT

Energy recovery ventilator (ERV) is generally installed in an air-conditioning system to recycle the cooling load of exhaust air. However, air conditioning systems with the single ERV can not meet with outdoor air load and indoor cooling load in summer, which will cause fluctuation of indoor temperature. The goal of this study is to analyze such a fuctuating scenario of the indoor temperature. CFD and subjective evaluation are used in this study. The resuls of CFD confirm the improvement of the air-conditioning system before and after adding direct-expansion blast heater with heat pump in the primary air system and designing reasonable fresh air distribution. A computer room is chosen as the experimental case. The results demonstrate that the initial fluctuation of indoor air temperature has been reduced effectively before and after its rebuilding. New primary air system with ERV and direct-expansion blast heater with heat pump can improve indoor air quality and stabilize indoor temperature.

## KEYWORDS

Fluctuation of temperature, Cooling load, CFD, Subjective evaluation

## INTRODUCTION

Sick Building Syndrome (SBS) can be eliminated through supplying enough fresh air (WHO 1983, WHO 1990, Bjarne 1997). In China, Heating, Ventilation and Air Conditioning (HVAC) Design Code stipulated the minimum fresh air requirement for Variable Refrigerant Volume (VRV) systems (MC 2003). The primary air system for VRV could install the Energy Recovery Ventilator (ERV) to recovery the cooling/heat of exhaust air. Nevertheless, ERV usually works in sensible heat exchange model and had relatively low efficiency for cooling/heat exchange (Xu 2005). The strategy of the VRV with single ERV could not meet the indoor cooling/heat load and may result in fluctuation of the indoor temperature and condensing on the surface of the outlet of Variable Refrigerant Volume (VRV) systems. Basing on Computational Fluid Dynamics (CFD) and subjective evaluation (SE), this paper proposed that adding direct-expansion blast heater with heat pump (DBHHP) and ERV in new primary air system and designing reasonable fresh air distribution (FAD) may be a good measure.

## SIMULATION AND EXPERIMENT

### Fluctuation of temperature

ERV of VRV system works in two models, which are sensible heat exchange model (SHE) and total heat exchange model. Generally, the recovery efficiency of SHE is lower than 70%. As to SHE, the efficiency can be expressed as following (ASHRAE 1991, MC 2005):

$$\eta_t = \frac{t_w - t_j}{t_w - t_p} \qquad (1)$$

Where $\eta_t$ is the efficiency of SHE, $t_w$ (K) is the outdoor air temperature (used dry bulb hereafter), $t_j$ (K) is temperature of the fresh air, $t_p$ (K) is temperature of the exhaust air.

The study assumes that the assigned outdoor air requirement be equal to the assigned exhaust air volume. Basing on ASHRAE 62-1989R (ASHRAE 1996), $G$ can be calculated from the sum of minimum outdoor air requirement in one hour of per person and that in one hour of per square meter of available area, which defined as $R_P$ ($m^3 \cdot h^{-1} \cdot p^{-1}$) and $R_b$ ($m^3 \cdot h^{-1} \cdot m^{-2}$) respectively. So the insufficient cooling/heat loads from outdoor air, $\Delta Q$, can be developed as Equation 2:

$$\Delta Q = \rho \cdot (R_P \cdot P_D \cdot D + R_b \cdot A_b) \cdot [(1-\eta_t)(t_w - t_p)] \qquad (2)$$

Where $\Delta Q$ ($kJ \cdot h^{-1}$) is the value of the insufficient cooling/heat load, $G$ ($kg \cdot h^{-1}$) is the assigned outdoor air requirement and $c$ ($kJ \cdot kg^{-1} \cdot K^{-1}$) is the constant pressure specific heat, which approximates to 1.0 here, $\rho$ ($kg \cdot m^{-3}$) is density of outdoor air (approximating to 1.2 for engineering use), the $P_D$ is the number of subjects in room, $D$ is variable coefficient of $P_D$ (specified as 1.0 in the test) and $A_b$ ($m^2$) is the area of available space.

Generally, the insufficient cooling/heat loads from outdoor air may make the indoor temperature fluctuating. Unexpectedly, the outlet of VRV systems is also condensing because ERV did not dehumidificate enough and the vapor in the passing fresh air with relatively high humidity is condensed. The study uses CFD methodology and subjective evaluation to analyze the reasons of temperature fluctuation and condensing on the outlet. Moreover, this study tries to add DBHHP in such a HAVC system and design reasonable fresh air distribution to deal with the problems.

### CFD simulation

Single ERV of VRV system could not meet the indoor cooling/heat load and may result in fluctuation of the indoor temperature and condensing on the surface of the outlet of Variable Refrigerant Volume (VRV) systems. CFD methdology is used to compare the airflow scenarios before adding DBHHP and after adding DBHHP. In addition, the same analysis is conducted on the redesignation of reasonable fresh air distribution.

The basic conservation equation of CFD can be shown as Equation 3.

$$\frac{\partial(\rho T)}{\partial t}+\frac{\partial(\rho uT)}{\partial x}+\frac{\partial(\rho vT)}{\partial y}+\frac{\partial(\rho wT)}{\partial z} = \frac{\partial}{\partial x}\left(\Gamma\frac{\partial T}{\partial x}\right)+\frac{\partial}{\partial y}\left(\Gamma\frac{\partial T}{\partial y}\right)+\frac{\partial}{\partial z}\left(\Gamma\frac{\partial T}{\partial z}\right)+So \qquad (3)$$

Mass conservation form and momentum conservation form of Equation 3 are the control equations for the CFD simulation of the dynamics fields on the assumption that there is no energy impact. For convenience, it was also assumed that the leakage through the gaps of the door be zero. FLUENT 6.0 (Fluent Inc.) was used as the CFD tool for simulating the temperature field and velocity field before renovation and after renovation. RNG k-ε model was applied in the research and the boundary conditions had twenty velocity inlets and two velocity outlets. The inlets of fresh air and VRV units were designed as velocity inlets and outlets of exhaust air were adopted as velocity outlets. The wall of the computer room was assumed adiabatic. Moreover, there was an assumption that the indoor air have no particulate matter or other contaminants.

### Experiment

A computer room of communication building in Zhengzhou city is chosen as engineering case. The room is 3.2 meter high and has the available area in size of 900 square meters with the windtight building envelope. There are 90 computers in the room. The initial air conditioning systems are VRV system and primary air system with ERV. The designed indoor air temperature is 297K~300K in summer. A prior investigation on the staff shows that the bad IAQ and fluctuation of indoor temperature in the room (as Figure 1) have caused many SBS cases. During the initial systems working, $t_p$ and $t_w$ are logged in 2 meter high zone every 5 minutes by TSI ComuFlow™ model 8585 (TSI Inc., Shoreview, MN, USA). Then DBHHP is installed in new primary air system and new location of the outlet for FAD has also designed as Figure 2 and Figure 3 shown. When the new systems are operating, $t_p$ and $t_w$ are also investigated in 2 meter high zone every 5 minutes by TSI 8585. For each temperature TSI recorded the geometric mean value. At same regular interval, the surface of outlet of VRV system is inspected for condensing. The schematic of the test system can be illustrated in Figure 2.

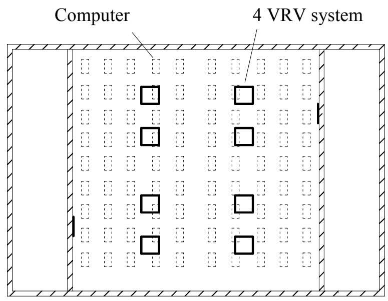


Figure 1 the Schematic for the VRV System before renovation

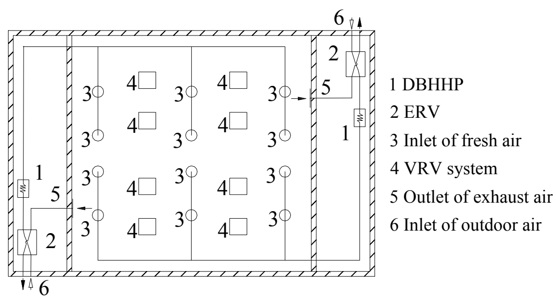


Figure 2 the Schematic for Restructured VRV System

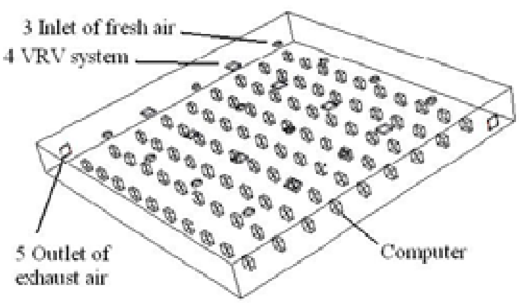


Figure 3 the 3D Schematic for Restructured VRV System

### Subjective Evaluation

World Health Organization (WHO) reported that the percentage of physiological syndrome being over 20% can result in SBS (WHO 1990). This test is carried out on base of subjective evaluation method proposed by ASHRAE who pointed out that the unacceptable percentage for IAQ should be lower than 20% (ASHRAE 1996). There are 50 test subjects for the test. All of them have no ill feeling before the test. Eighteen members of the group are female and the mean age of the group is 31 with the range from 21 to 58. After test system working well for five hours, all subjects use computer in the test room for one hour and then completed questionnaire. To ensure subjects making judgment correctly all subjects have detailed instructions under ASHRAE guide. The assessment indices for IAQ used in the test are listed in Table 1.

**Table 1 the Assessment Indices for IAQ**

| | temperature | humidity | Odor feeling | Air velocity feeling |
|---|---|---|---|---|
| Unacceptable | Bad (cooling in winter or hot in summer) | Dry feeling or wet feeling | Yes | Yes |
| Acceptable | Normal | Normal | No | No |
| Comfort | Good (comfort) | Moderate feeling | No | No |

## RESULT ANALYSIS AND DISCUSSION

As Figure 4 shown, $\Delta Q$ varied inversely as $t_p$ and directly as $t_w$ respectively. In the test $R_P$ and $R_b$ were adopted as 10.8 $m^3 \cdot h^{-1} \cdot p^{-1}$ and 1.3 $m^3 \cdot h^{-1} \cdot m^{-2}$ respectively for office category. With 50 subjects and 90 square meters available area in the room and $\eta_t$ defined as product labeled value (70%), $\Delta Q$ could be calculated from Equation 2 and ranged from 615.0 $kJ \cdot h^{-1}$ (170.8W) to 1088.1 $kJ \cdot h^{-1}$ (302.3W). As Figure 4 illustrated, the paper draw a comparison between the initial data of $t_p$ and $t_w$ and data logged after rebuilding for VRV system. In addition, the plus geometric standard deviation for each data of temperature was demonstrated in Figure 4.

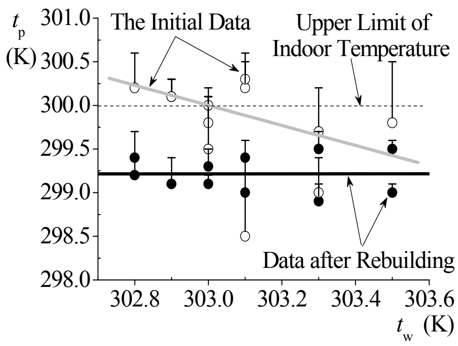


**Figure 4 the comparison between the initial $t_p$ and $t_w$ and logged data after rebuilding**

The results of CFD analysis for indoor temperature before rebuilding and after rebuilding can be shown in Figure 5 and in Figure 6, respectively. In addition, the results of CFD analysis for velocity before rebuilding and after rebuilding can be shown in Figure 7 and in Figure 8, respectively.

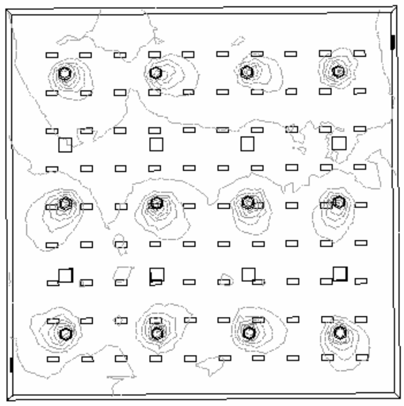

**Figure 5 Contours of indoor temperature before rebuilding**

Currently, air conditioning system in the building was preferred to be designed for reasonably low fresh air volume for energy saving (ASHRAE 1996, EPA 2000).

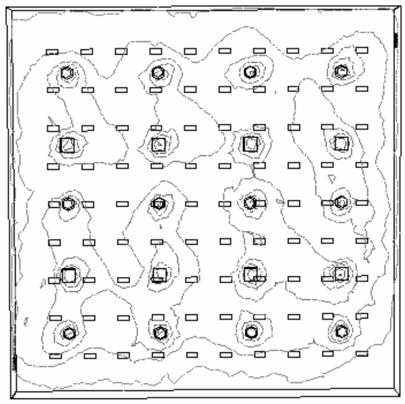

**Figure 6 Contours of indoor temperature after rebuilding**

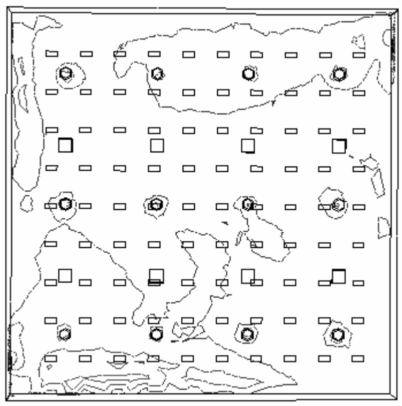

**Figure 7 Contours of velocity before rebuilding**

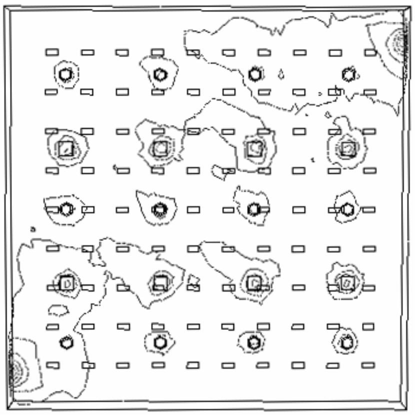

**Figure 8 Contours of velocity after rebuilding**

For the reason of high insufficient load as $\Delta Q$, the indoor temperature could not be controlled in designed range and fluctuated. After technical rebuilding for the air conditioning system, the indoor temperature relatively stabilized in a small range as demonstrated in Figure 4. In addition, the reasonable fresh air distribution had avoided the fresh air airflow directly mixing with return air airflow and eliminated the condensing on the outlet of VRV system, which is as shown from Figure 5 to Figure 8. Before rebuilding, the contours of indoor temperature clustered close to the inlets of fresh air. This distribution can be improved after rebuilding of the system as Figure 6 shown. The velocity can also be illustrated a similar scenario in Figure 7 and Figure 8. The results of Subjective Evaluation had shown the improvement of IAQ, which was shown in Figure 9.

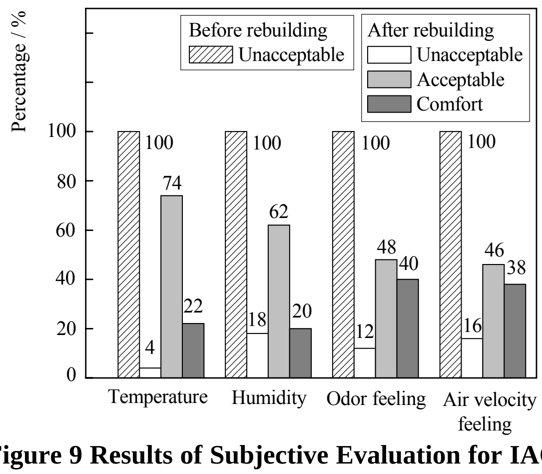


**Figure 9 Results of Subjective Evaluation for IAQ before and after Adopting the New Method**

In comparison with initial air conditioning system, new primary air system with ERV and DBHHP could improve IAQ and stabilized indoor air temperature in a small range. As Figure 4 demonstrated, logged data of indoor air temperature after rebuilding (black line in Figure 4) did not fluctuate more than the initial data of $t_p$ (gray line in Figure 4) and all of the previous data had a lower deviation from 300K (dash line in Figure 4) than the latter. In addition, a reasonable FAD had decreased condensing on the outlet of VRV system. All of those improvements can also be proved by the results of CFD simulation from Figure 5 to Figure 8.

As Figure 9 demonstrated, the percentages of unaccepted subjects for temperature and humidity were 4% and 18% respectively. The feeling for odor and air velocity brought the unaccepted percent of 12% and 16% respectively. All of the results from subjective evaluation had lower unaccepted percentage than 20%. So the results of Subjective Evaluation for IAQ showed that the technical rebuilding for the air conditioning system in the test engineering case had succeeded.

## CONCLUSION

The technical rebuilding, which included adding DBHHP for primary air system and designing reasonable FAD, had shown many advantages in the experiment. Firstly, DBHHP could partially supplement the insufficient load caused by ERV with low recovery efficiency in primary air system. To a great extent, fluctuation of indoor temperature could be eliminated. Secondly, the reasonable fresh air distribution could decrease condensing. This did also attribute to the fact that the temperature of fresh air was approximate to that of indoor air. As a result, the fresh air velocity could vary in a large stipulated range. The well designed supply method of fresh air may be a good measurement for eliminating condensing. Moreover, the reasonable fresh air distribution could also improve the IAQ in the respiratory zone (ASHRAE 1999). Furthermore, new independent outdoor air system with DBHHP and ERV had made the control of percentage of return air easier than single direct-expansion fan-coil unit in air conditioning system.

In China, many VRV systems had no primary air system. Although the fresh air requirement had stipulated in the design code, the above problems caused by fresh air load appeared far and wide. This paper proposed the technical improvement in order to make the researchers and organizations pay more attention to these problems.

## ACKNOWLEDGMENTS

The research in supported by Science and Technology Department of Henan Provincial Government, No. 072102350033. The authors want to thank the professors from Zhongyuan University of Technology and the organizers of Building Simulation 2007.

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