**Investigation on the Dynamic Response Property in a Big and High Air-conditioned Space**

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**Abstract**

This paper reports the investigation results of the dynamic response property in a big and high air-conditioned space using numerical simulation and experiment. The space is 30m × 30m × 20m (length × width × height), whose air temperature is kept constant. The best air distribution mode is obtained by steady state numerical analyses. The time lag, time constant and scale factor of the air-conditioned space of normal air supply and heat source variation are investigated by detailed 3-D transient state numerical analyses. Finally the results of the numerical analyses are verified by experiments with good agreement.

**Keywords**: Big and High Space; Constant Temperature Room; Control System; Numerical Analysis; Dynamic Response Property; Experiment Research

**Introduction**

With the development of advanced science and technology, there are requirements to construct big and high buildings with constant indoor temperature and humidity, and a high level of cleanliness, not only in the lower working area, but throughout the entire space. A new research problem exists, which is how to design and control the air distribution to meet these requirements. The object of the study is a constant temperature air conditioning system in a laboratory with a big and high space for laser nuclear fusion. The laboratory is 30 meters long, 30 meters wide, and 20 meters high. The required temperature of the entire space is 20°C, and the constant temperature zone, that is 10m aboveground is 20±0.5°C. There are a great number of non-uniformly distributed heat sources inside the building and the heat source strength varies randomly. Considering all the features of the interference and the controlled object, the zone control method is proposed as a general scheme, and the most reasonable air distribution mode is obtained by numerical analysis. Zone control means that the whole space is divided into a number of control zones, with an independent air supply/return system and a control point in each zone (Tan 1999). Based on the zone control, the air distribution mode of a non-wall-attachment ceiling diffuser with return air at the floor level is adopted (a square diffuser is used). The detailed arrangement of the inlet and outlet is shown in Figure 1. This mode is easy and can meet the design requirements of constant temperature control according to the results of analyses and calculations. The following numerical analysis is based on this configuration. First, according to the existing jet flow theory (Zhao et al. 1994), four better air distribution modes are proposed, which are shown in Table 1; then the best air supply temperature difference and velocity, the dimensions of the zone and air inlet and outlet are obtained through the steady state numerical analysis, as in scheme three shown in Table 1; finally the dynamic response property of the controlled object is gained according to transient state numerical analysis; and further, the neural fuzzy control method is adopted in each zone to carry out dynamic intelligence control.
Table 1. The Basic Data For Numerical Analysis Of Indoor Air Distribution

| Mode | Zone Area and Number | Air Supply Temperature Difference °C | Ventilating Rate 1/h | Air Volume of Each Diffuser m³/h | Dimension of Each Diffuser mm×mm | Air Supply Velocity m/s | Calculating Velocity m/s | Calculating Temperature Difference °C | Note |
|------|----------------------|--------------------------------------|----------------------|----------------------------------|---------------------------------|------------------------|------------------------|--------------------------------------|------|
| 1    | 5×5,36               | 3                                    | 9.9                  | 4950                             | 600×600                         | 3.82                   | 0.59                   | 0.34                   |      |
| 2    | 5×5,36               | 4                                    | 7.4                  | 3713                             | 600×600                         | 2.86                   | 0.44                   | 0.45                   | Best |
| 3    | 5×5,36               | 3                                    | 9.9                  | 4950                             | 800×800                         | 2.15                   | 0.44                   | 0.45                   | *Best|
| 4    | 5×5,36               | 4                                    | 7.4                  | 3713                             | 800×800                         | 1.61                   | 0.33                   | 0.59                   |      |

*In each mode, the supply and return air diffuser and heat source are placed in the center of each zone. The points for calculating velocity and temperature differences are located at positions 10m below the air supply diffuser. The details are shown in Figure 1.
The Governing Equation Set

The standard form of non-dimensional equation set for indoor air flow in an air conditioning field is shown in Table 2. The discrete equation set for numerical calculation is set up by using the control volume method. The next step is to carry out numerical calculations (Emmerich and McGrattan 1998, Partakar, 1984, Tao 1988).

In Table 2, \( \tau \) (s) is time; \( \rho \) (kg/m\(^3\)) is air density; \( u \) (m/s) is velocity vector; \( u_i \) (m/s) is velocity component; \( T \) (°C) is air temperature; \( K \) is turbulent kinetic energy; \( \varepsilon \) is the dissipation rate of the turbulent kinetic energy; \( \varphi \) is a non-dimensional physical variable of 1, \( u_i \), \( T \), \( K \) and \( \varepsilon \) are all non-dimensional here; \( \Gamma_\varphi \) is the diffusion coefficient of \( \varphi \); \( S_\varphi \) is the general source item of \( \varphi \); \( \text{Re} \) is the Reynolds number; \( \text{Pr} \) is the Prandtl number; \( \text{Ar} \) is the Archimedes number; \( \text{Pr}_t \) is the turbulent Prandl number; \( p \) (Pa) is pressure; \( \nu \) (m\(^2\)/s) is kinematic viscosity; \( \nu_t \) (m\(^2\)/s) is turbulent kinematic viscosity; \( a \) (m\(^2\)/s) is thermal diffusivity; \( a_t \) (m\(^2\)/s) is turbulent thermal diffusivity; \( c_{e1}, c_{e2}, c_{e3}, c_{\mu} \) are all experimental constants.

### Table 2. Standard Form Of Control Equation Set Of Air Flow In Air Conditioning

| Standard Form | \( \frac{\partial}{\partial \tau} (\rho \varphi) + \text{div}(\rho u \varphi) = \text{div}(\Gamma_\varphi \text{grad}\varphi) + S_\varphi \) |
|---------------|-------------------------------------------------|
| \( \varphi \) | \( \Gamma_\varphi \) | \( S_\varphi \) |
| Continuity Equation | 1 | 0 | 0 |
| Momentum Equation | \( \frac{1}{\text{Re}} \left( \frac{1 + \nu_i}{\nu} \right) \) | \( -\frac{\partial p}{\partial x_i} - \frac{2}{3} \frac{\partial \delta}{\partial x_j} \frac{\partial K}{\partial x_j} - \text{Ar} T \delta_{ij} \) |
| Energy Equation | \( T \ | \( \frac{1}{\text{RePr}} \left( 1 + \frac{a_i}{a} \right) \) | 0 |
| \( K \) Equation | \( \frac{1}{\text{Re}} \left( 1 + \frac{\nu_i}{\nu} \frac{1}{\sigma_K} \right) \) | \( \frac{\partial u_i}{\partial x_j} \left[ \frac{1}{\text{RePr}} \frac{v_j}{\nu} \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} K \right] + \frac{\text{Ar} \delta_{ij}}{\text{RePr}} \frac{a_i}{a} \frac{\partial T}{\partial x_i} - \varepsilon \) |
| \( \varepsilon \) Equation | \( \frac{1}{\text{Re}} \left( 1 + \frac{\nu_i}{\nu} \frac{1}{\sigma_\varepsilon} \right) \) | \( c_{e1} \frac{\partial u_i}{\partial x_j} c_{\mu} K \left( \frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} \right) - \frac{2}{3} \delta_{ij} \varepsilon \) + \( c_{e3} \frac{c_{\mu}}{\text{Pr}_t} \text{Ar} \delta_{ij} K \frac{\partial T}{\partial x_i} - c_{e2} \frac{\varepsilon^2}{K} \) |
The Boundary Conditions

Based on the fact that the constant temperature room is a one order inertia system with pure time lag, the time lag $\tau$, time constant $T$, magnifying coefficient $K$ and characteristic scale $\tau/T$ of the air conditioning system can be obtained. In this paper, two instances are taken into account: the dynamic response properties of the constant temperature room under normal air supply and interference of heat source.

To study the influence of the controlled point’s location to the properties of the constant temperature room, two circumstances are considered: the controlled point is located at 8m above the central line of each zone (named as controlled point A) and is in the center of the return air inlet (named as controlled point B). The controlled point A is selected because the center point of hot and cold air flow interface of each control zone is at about the 8m level, and under a steady state, the temperature of this point is about 20°C, which is the exact balance temperature of the system; the controlled point B is the routine controlled point. The common property of the two controlled points is that when the system is operating under the steady state condition of the best Mode 3, no control action is required, which is the exact design requirement of the constant temperature air conditioning control system. Only under these conditions can the system be at its best operational state. It is unreasonable to randomly select other points as controlled points, so other space points are no longer studied as controlled points in this paper.

In the calculation there are more grids near the air inlet and outlet areas, heat sources and the wall areas than in other spaces. The grid interval of the former is 0.1m and that of the latter 0.4m. The boundary conditions used in the calculations are as follows:

- Air inlet: the real velocity and temperature of the air supply.
- Air outlet: the outlet pressure is considered as zero.
- Heat source and wall: all the wall surfaces are treated by the wall function method (Tao 1988). Temperature of the heat sources is constant at 55°C.
- Symmetrical boundary condition or approximate symmetrical boundary condition: the normal derivatives of all the physical variables in the boundary surface are set to zero.

In the transient numerical calculation, the time interval of the single iterative step and the corresponding ill-laxity factor should be selected reasonably. The initial time interval is 0.05s, and with the calculation result trending to constringency, the time interval is increased gradually to 0.075s and 0.1s, thus the convergence is accelerated and the calculation time is reduced.

Results and Discussions

1. Dynamic properties of the constant temperature room under normal air supply.

The scheme of numerical analysis: on the basis of steady state calculation condition in Mode 3, keeps the heat source unchanged, and increases the air supply temperature from 17°C to 21°C. When the calculation continues until a new steady state, the temperature is reduced to 17°C again. The variety of the controlled point temperature gained from numerical analysis is shown in Table 3, and the corresponding rising temperature curve is shown in Figure 2. The property parameters of the constant temperature room under normal air supply are gained from Table 3 and Figure 2, and shown in Table 4.
Table 3. Numerical Analysis Results of Dynamic Temperature Variety in the Constant Temperature Room

| Group No. | Time (s) | Temperature variety under normal air supply, °C | Temperature variety under heat source interference, °C |
|-----------|----------|-----------------------------------------------|-----------------------------------------------------|
|           |          | Air supply temperature | Controlled point A | Controlled point B | Temperature of heat source | Controlled point A | Controlled point B |
| 1         | 0        | 17.00 | 20.27 | 20.02 | 17.00 | 19.75 | 20.02 |
|           | 120      | 17.00 | 20.27 | 20.02 | 17.00 | 19.75 | 20.02 |
|           | 120      | 21.00 | 20.27 | 20.02 | 17.00 | 19.75 | 20.02 |
|           | 140      | 21.00 | 20.27 | 20.02 | 17.00 | 19.76 | 20.02 |
|           | 150      | 21.00 | 20.27 | 20.02 | 17.00 | 19.75 | 20.02 |
|           | 160      | 21.00 | 20.27 | 20.02 | 17.00 | 19.75 | 20.03 |
|           | 170      | 21.00 | 20.35 | 20.00 | 17.00 | 19.56 | 20.06 |
|           | 180      | 21.00 | 20.62 | 19.96 | 17.00 | 19.29 | 20.08 |
|           | 190      | 21.00 | 20.59 | 19.93 | 17.00 | 19.05 | 19.86 |
|           | 200      | 21.00 | 20.71 | 19.94 | 17.00 | 18.79 | 19.23 |
|           | 210      | 21.00 | 20.92 | 20.01 | 17.00 | 18.59 | 18.92 |
|           | 220      | 21.00 | 21.14 | 20.11 | 17.00 | 18.41 | 18.77 |
|           | 240      | 21.00 | 21.45 | 20.35 | 17.00 | 18.25 | 18.63 |
|           | 270      | 21.00 | 21.84 | 20.73 | 17.00 | 18.00 | 18.47 |
|           | 300      | 21.00 | 22.19 | 21.08 | 17.00 | 17.91 | 18.35 |
|           | 330      | 21.00 | 22.34 | 21.38 | 17.00 | 17.82 | 18.24 |
|           | 360      | 21.00 | 22.60 | 21.67 | 17.00 | 17.75 | 18.13 |
|           | 420      | 21.00 | 22.95 | 22.16 | 17.00 | 17.61 | 17.93 |
|           | 480      | 21.00 | 23.23 | 22.55 | 17.00 | 17.50 | 17.77 |
|           | 540      | 21.00 | 23.46 | 22.86 | 17.00 | 17.41 | 17.64 |
|           | 600      | 21.00 | 23.62 | 23.09 | 17.00 | 17.34 | 17.53 |
|           | 660      | 21.00 | 23.74 | 23.28 | 17.00 | 17.27 | 17.44 |
|           | 780      | 21.00 | 23.92 | 23.55 | 17.00 | 17.18 | 17.30 |
|           | 900      | 21.00 | 24.03 | 23.71 | 17.00 | 17.12 | 17.20 |
|           | 1020     | 21.00 | 24.10 | 23.82 | 17.00 | 17.08 | 17.14 |
|           | 1140     | 21.00 | 24.15 | 23.88 | 17.00 | 17.05 | 17.09 |
|           | 1380     | 21.00 | 24.19 | 23.95 | 17.00 | 17.02 | 17.04 |
|           | 1533     | 21.00 | 24.21 | 23.97 | 17.00 | 17.01 | 17.02 |
|           | 1533     | 17.00 | 24.21 | 23.97 | 55.00 | 17.01 | 17.02 |
|           | 1553     | 17.00 | 24.25 | 23.97 | 55.00 | 17.01 | 17.04 |
|           | 1563     | 17.00 | 24.25 | 23.97 | 55.00 | 17.01 | 17.05 |
|           | 1573     | 17.00 | 24.20 | 23.98 | 55.00 | 17.02 | 17.08 |
|           | 1583     | 17.00 | 24.26 | 24.00 | 55.00 | 17.39 | 17.16 |
|           | 1593     | 17.00 | 23.98 | 24.00 | 55.00 | 17.79 | 17.30 |
|           | 1603     | 17.00 | 23.84 | 23.95 | 55.00 | 18.03 | 17.37 |
|           | 1613     | 17.00 | 23.48 | 23.80 | 55.00 | 18.25 | 17.44 |
|           | 1623     | 17.00 | 23.07 | 23.64 | 55.00 | 18.43 | 17.55 |
|           | 1633     | 17.00 | 22.81 | 23.51 | 55.00 | 18.63 | 17.67 |
|           | 1653     | 17.00 | 22.59 | 23.36 | 55.00 | 18.76 | 17.96 |
|           | 1683     | 17.00 | 22.19 | 23.10 | 55.00 | 18.81 | 18.29 |
|           | 1713     | 17.00 | 22.06 | 22.79 | 55.00 | 18.84 | 18.52 |
|           | 1743     | 17.00 | 22.06 | 22.54 | 55.00 | 19.04 | 18.69 |
|           | 1773     | 17.00 | 21.79 | 22.28 | 55.00 | 19.24 | 18.85 |
|           | 1833     | 17.00 | 21.51 | 21.84 | 55.00 | 19.41 | 19.08 |
|           | 1893     | 17.00 | 21.27 | 21.47 | 55.00 | 19.49 | 19.26 |
|           | 1953     | 17.00 | 21.08 | 21.18 | 55.00 | 19.55 | 19.39 |
|           | 2013     | 17.00 | 20.91 | 20.95 | 55.00 | 19.51 | 19.51 |
|           | 2073     | 17.00 | 20.78 | 20.76 | 55.00 | 19.60 | 19.59 |
|           | 2193     | 17.00 | 20.59 | 20.49 | 55.00 | 19.64 | 19.73 |
|           | 2313     | 17.00 | 20.47 | 20.31 | 55.00 | 19.70 | 19.82 |
|           | 2433     | 17.00 | 20.39 | 20.20 | 55.00 | 19.71 | 19.88 |
|           | 2553     | 17.00 | 20.34 | 20.13 | 55.00 | 19.73 | 19.92 |
|           | 2793     | 17.00 | 20.29 | 20.05 | 55.00 | 19.76 | 19.96 |
| 3         | 2946     | 17.00 | 20.28 | 20.03 | 55.00 | 19.76 | 19.98 |
Fig. 2. Dynamic Response Temperature of the Constant Temperature Room Under Normal Air Supply

Fig. 3. Dynamic Response Temperature of the Constant Temperature Room under Heat Source Interference
Table 4. Property Parameters of the Constant Temperature Room Under Normal Air Supply

| Property Parameters | Time Lag $\tau$ (s) | Time Constant $T$ (s) | Magnifying Coefficient $K$ ($^\circ C/^\circ C$) | Characteristics Scale $\tau/T$ |
|---------------------|---------------------|----------------------|-----------------------------------------------|---------------------------|
| Controlled point A  | 50                  | 250                  | 0.983                                         | 0.200                     |
| Controlled point B  | 80                  | 280                  | 0.985                                         | 0.286                     |

Table 5. Property Parameters of the Constant Temperature Room Under Interference of Heat Source

| Property Parameters | Time Lag $\tau$ (s) | Time Constant $T$ (s) | Magnifying Coefficient $K$ ($^\circ C/^\circ C$) | Characteristics Scale $\tau/T$ |
|---------------------|---------------------|----------------------|-----------------------------------------------|---------------------------|
| Controlled point A  | 40                  | 110                  | 0.072                                         | 0.364                     |
| Controlled point B  | 60                  | 180                  | 0.040                                         | 0.333                     |

2. Dynamic properties of the constant temperature room under interference of heat source

The scheme of numerical analysis is made on the basis of the steady state calculation condition in Mode 3 to keep air supply temperature invariable, and reduce the heat source temperature from 55$^\circ C$ to 17$^\circ C$ (equivalent to lack of heat source). When the calculation continues until the new steady state the heat source temperature is increased to 55$^\circ C$ again, and then continues calculating until another steady state is reached. The variety of the controlled point temperature from numerical analysis is shown in Table 3, and the corresponding rising temperature curve is shown in Figure 3. The property parameters of the constant temperature room under the interference of heat source are obtained from Table 3 and Figure 3, and shown in Table 5.

3. The optimal location of the controlled point

According to the result of Tables 4 and 5, and considering other factors, the characteristics of the controlled point A and B are obtained as follows:

- The time lag and time constant of the controlled point A are shorter than those of the controlled point B. Therefore the dynamic response property of the controlled point A is better than that of the controlled point B. If the controlled point A is selected, the system can respond more quickly and sensitively.

- When intensity of the heat source is kept steady, and its location change in the control zone negligible, the temperature of the controlled point B will not be changed upon the balance of heat in the control zone. This means that the control system doesn’t respond, but is in a steady state. Whereas the temperature of the controlled point A is variable and the control system will respond, which is unreasonable and will result in excess-adjustment and unsteadiness of the system.

- Since the controlled point B is located in the return air inlet, and the controlled point A is
in the constant temperature room, the temperature sensor of the controlled point B is generally easier to install than that of the controlled point A as it is not affected by indoor facilities. It is however possible to install the temperature sensor at the controlled point A.

According to the above characteristics of the two controlled points, when the heat source location remains basically unchanged and it is convenient to install the controlled point sensor, the controlled point A should be selected in this kind of control zone. In other kinds of control zone, the controlled point B should be selected. Therefore, selection of the controlled point in each zone of the actual system may vary. Detailed location of the controlled point depends on the arrangement and function characteristic of the facilities in the big and high space.

Experimental Validation

To compare the validity of the numerical analysis results, the dynamic response property of the controlled point A under normal air supply in Mode 3 are experimentally studied, in which the model experiment method is adopted. The dynamic response property parameters of the controlled point A in the constant temperature room obtained from experiments, as well as from numerical analysis and from the literature (Shi 1983) are shown in Table 6. The time constant, the most important property parameter in the constant temperature room, of the results of numerical analysis is closer to that of the experiment with a difference of 91s. The relative difference is 36.4 percent; the time constant in the literature (Shi 1983) is too great. Obviously, the calculation formula of time constant in the literature (Shi 1983) is unsuitable for the big and high space studied in the paper. On the other hand, the time lag from numerical analysis agrees fairly well with the literature (Shi 1983) so that the time lag obtained from the experiment has a bigger error. Based on the above, it is believed that the numerical analysis result is more reliable. Thus it is selected as the dynamic response property parameter of the constant temperature room.

Conclusions

In the paper, the dynamic response property of two controlled points in a constant temperature room are obtained by the transient numerical analysis of air flow in the optimal air distribution mode. The corresponding property parameters are shown in Tables 4 and 5. These calculation results provide a reliable basis for a temperature control scheme of the constant temperature room. The method is feasible to obtain the dynamic response property of the constant temperature room, and the calculation result can reflect the property of the actual system well.

Table 6. Comparisons of Property Parameters of the Constant Temperature Room Under Normal Air Supply Obtained by Different Methods

| Property Parameters | Time Lag $\tau$ (s) | Time Constant $T$ (s) | Magnifying Coefficient $K$ (°C/℃) | Characteristics Scale $\frac{\tau}{T}$ |
|---------------------|---------------------|----------------------|-----------------------------------|-------------------------------------|
| Numerical Analysis  | 50                  | 250                  | 0.983                             | 0.200                               |
| Experiment          | 23                  | 341                  | 0.45                              | 0.067                               |
| Literature (Shi 1983)| 55                  | 545                  | 0.62                              | 0.1                                 |
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