

# Model experiment on stratified air-conditioning in winter condition in High ceiling industrial plants

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**Abstract:** Engineering practices indicate that stratified air-conditioning used in high industrial plants has been proved to be good and energy-saving, but its application to winter heating condition is restricted due to the buoyant warm jet. By using model experiment, the temperature and velocity diffusion within the model when heating with transversal warm air curtain have been measured and analyzed. By measuring the temperature and velocity diffusion within the space in winter condition, whether the temperature at work area could be maintained above 14°C has been shown; By measuring the temperature gradient in whole space, whether the buoyant warm jet has been effectively controlled has been observed; By sealing or unsealing the exhaust outlet on the roof, the influence of air leak on air diffusion performance in occupied area has been observed; thus providing some experiences to other projects.

**Keywords:** high ceiling industrial plants; stratified air-conditioning; winter heating condition; model experiment

## 1. Introduction

With the development of modern industry, some industrial plants huge in size and different in function are constantly emerging. The height of these plants is usually up to several tens of meters, and the requirement for its thermal environment is often confined to the occupied space, so it is unreasonable to adopt traditional project of whole space cooling. If "Stratified air conditioning" is adopted, the cooling load may decrease by a big margin, thus produce significant savings in energy consumption, running cost and construction cost.

The study on application of stratified air conditioning to high ceiling industrial plants in summer cooling condition has showed that the benefit has been significant and the technology is gradually tend to be ripe. But its application in winter heating condition wants study. If the stratified air conditioning system designed for summer cooling condition is used for winter heating condition, the key "stratified" effect

may probably be broken by the buoyant warm jet, and the application value of this technology may be influenced.

Through investigation a typical span of a high ceiling machining plant has been chosen. The size of it is 12.18 m×11.06 m×12.32 m.

## 2. Determination of similarity scale

The geometric scale of model ( $C_l$ ) is the first must be made. The greater the value of  $C_l$ , the easier simulating prototype truly. But the value of  $C_l$  involves the construction cost of model, the ground area the model occupies, power capacity and the difficulty of the measurement and control of some relevant parameters. 1/3.5 has been chosen for  $C_l$  of the model through comprehensive consideration, and the size of the model (length × width × height) can be determined as 3.48 m × 3.16 m × 3.52 m. Finally, all similarity scales demanded for designing the model are showed in Table 1.

Table1. Similarity scale of model

| Geometric | Temperature | Temperature variation | Velocity | Air rate | Density | Gravity-acceleration |
|-----------|-------------|-----------------------|----------|----------|---------|----------------------|
| $C_l$     | $C_T$       | $C_{\Delta T}$        | $C_v$    | $C_L$    | $C_p$   | $C_g$                |
| 1/3.5     | 1           | 1                     | 1/1.87   | 1/22.89  | 1       | 1                    |

## 3. Experiment devices and measuring method

### 3.1 Introduction of model experiment devices

The experiment devices include nozzles, fans, air

conditioner, plenum chamber, variable transformer, thermal anemometer and intelligent digital temperature recorder. The temperature of jet can be regulated by the air conditioner, and the supply air rate of fans can be

changed by the variable transformer.

### 3.2 Layout of points for measurement

The positions of 37 points for measurement within the model are as following: Ten points on the plane 0.3m above the ground; Five points on the plane 0.6m above the ground; Seven arranged on the central vertical line from 0.3m to 2.5m above the ground for measuring the central temperature gradient; Five on the vertical line far away from outlets for measuring the shielding effect of jet; Two at the nozzles; two at the return air inlets and another two at the air outlets.

## 4. Experiments and analyses of stratified air conditioning in winter condition

According to the designing method [1,2] for stratified air conditioning in summer condition, five round nozzles with 210mm in diameter and 2400mm in space have been installed 4m above ground, and the total supply air rate is  $5 \times 750 \text{ m}^3/\text{h}$ . Air supply from single sidewall accompanying with the same sidewall return air at lower level (complemented with upper and lower level exhaust) is its air distribution mode, thus can produce a number of parallel jet to obtain good "stratified" effect. The temperature in work area in prototype is required to be maintained at  $14^\circ\text{C}$  or above in winter condition, and the velocity in it within  $0.4 \text{ m/s}$ .

In the model experiment on stratified air conditioning in Three-gorges hydropower station, we have compared the impacts of different supply air patterns on air distribution characteristics in work area, and verified that supplying air at an angle downwards could restrain buoyant warm air more effectively than supplying air horizontal [3,4], and the temperature of jet should be less than  $40\sim 45^\circ\text{C}$  in winter condition avoiding insufficient air changes [5], therefore air is supplied at an angle of  $15^\circ$  downwards, and the range of temperature of jet is  $28\sim 35^\circ\text{C}$ .

### 4.1 Exploring several sets of parameters under the conditions of identical Ar number

So long as Ar number is the same, the axial locus of jet and the attenuation of axial velocity of jet are totally identical [2]. Thus, on the basis of ensuring the effect of "stratified" and energy-saving, several sets of parameters have been obtained by the aid of smoke generator, thermal anemometer and other means. Table 2 shows that if  $d_0$  (diameter of nozzle) is reduced to 51 mm, i.e. L (supply air rate) is only 70 % of that in

summer conditions,  $T$  (the temperature at work area) could be satisfied when to (supply air temperature) is  $30^\circ\text{C}$ , and the energy consumption could be reduced notably.

Table2. Four sets of parameters under the same Ar

| Condition | $d_0$<br>/mm | L<br>/( $\text{m}^3/\text{h}$ ) | $t_0$<br>/ $^\circ\text{C}$ | Ar<br>/ $10^3$ | T<br>/ $^\circ\text{C}$ |
|-----------|--------------|---------------------------------|-----------------------------|----------------|-------------------------|
| One       | 60           | 750                             | 32.0                        | 2.559          | 19.0                    |
| Two       | 57           | 600                             | 28.1                        | 2.557          | 17.6                    |
| Three     | 51           | 600                             | 35.0                        | 2.520          | 17.1                    |
| Four      | 51           | 525                             | 30.0                        | 2.545          | 15.0                    |

### 4.2 Experiment and analysis of characteristics of air diffusion performance in work area

The temperature and velocity diffusion at work area measured under the condition of four sets of parameters is shown in Tables 3, 4, 5 and 6. Because decreasing supply air rate does little influence on the "stratified" effect and the uniform of temperature and velocity at work area under the same Ar number, the air conditioning effect could be ensured. In a word, the reduction of supply air rate could be used as a method for energy saving in winter conditions. We use temperature (velocity) standard deviation  $\sigma T$  ( $\sigma v$ ), temperature (velocity) uneven coefficient  $kT$  ( $kv$ ) to evaluate the evenness of air diffusion.

$$\sigma T = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (T_i - T)^2} \quad (1)$$

where  $n$  is the number of points;  $T_i$  is the temperature for each point,  $^\circ\text{C}$ ;  $T$  is the mean temperature in work area,  $^\circ\text{C}$ .

$$\sigma v = \sqrt{\frac{1}{n-1} \sum_{i=1}^n (v_i - v)^2} \quad (2)$$

where  $v_i$  is the velocity for each point,  $\text{m/s}$ ;  $v$  is the mean velocity in work area,  $\text{m/s}$ .

$$kT = \frac{\sigma T}{T} \quad (3)$$

$$kv = \frac{\sigma v}{v} \quad (4)$$

Table3. Horizontal temperature distribution of work area

| Condition | $d_0(\text{mm})$ | $v_0(\text{m/s})$ | $T/^\circ\text{C}$ | $\sigma_T$ | $k_T$  |
|-----------|------------------|-------------------|--------------------|------------|--------|
| One       | 60               | 3.2               | 19.0               | 0.235      | 0.0124 |
| Two       | 57               | 2.8               | 17.6               | 0.230      | 0.0131 |
| Three     | 51               | 3.5               | 17.1               | 0.167      | 0.0098 |
| Four      | 51               | 3.2               | 15.0               | 0.247      | 0.0165 |

Table4. Temperature/°C of work area at 2m above the ground

| Condition | Mean | Maximum | Minimum |
|-----------|------|---------|---------|
| One       | 18.9 | 19.1    | 18.8    |
| Two       | 17.5 | 17.8    | 17.2    |
| Three     | 17.1 | 17.2    | 16.9    |
| Four      | 14.9 | 15.1    | 14.7    |

Table5. Temperature/°C of work area at 2m above the ground

| Condition | Mean | Maximum | Minimum |
|-----------|------|---------|---------|
| One       | 19.3 | 19.4    | 19.2    |
| Two       | 17.8 | 18.0    | 17.6    |
| Three     | 17.3 | 17.4    | 17.1    |
| Four      | 15.3 | 15.5    | 15.2    |

Table6. Velocity/ (m/s) distribution of work area

| Condition | Mean  | Maximum | Minimum | $\sigma_v$ | $k_v$ | $v$   |
|-----------|-------|---------|---------|------------|-------|-------|
| One       | 0.110 | 0.20    | 0.08    | 0.0358     | 0.325 | 0.206 |
| Two       | 0.076 | 0.11    | 0.06    | 0.0179     | 0.236 | 0.142 |
| Three     | 0.081 | 0.13    | 0.06    | 0.0137     | 0.169 | 0.151 |
| Four      | 0.076 | 0.11    | 0.06    | 0.0179     | 0.236 | 0.184 |

#### 4.3 Experiment and analysis of vertical temperature distribution performance in whole space

To observe whether buoyant warm air can be controlled by the transversal warm air curtain in winter conditions, the data measured at seven points for analyzing the temperature gradient in whole space are listed in Table 7.

Table7. Vertical temperature/°C distribution in different height

| Height/m | Temperature/°C |        |        |        |
|----------|----------------|--------|--------|--------|
|          | Test 1         | Test 2 | Test 3 | Test 4 |
| 1.05     | 18.9           | 17.5   | 17.0   | 15.0   |
| 2.10     | 19.2           | 17.8   | 17.3   | 15.3   |
| 3.15     | 19.3           | 17.8   | 17.5   | 15.4   |
| 4.20     | 19.4           | 17.8   | 17.5   | 15.6   |
| 5.25     | 19.4           | 17.7   | 17.5   | 15.6   |
| 7.00     | 19.3           | 17.6   | 17.3   | 15.4   |
| 8.75     | 19.2           | 17.4   | 17.2   | 15.3   |

The temperature of middle part is a little higher than that of both ends in vertical direction. The maximum difference is only 0.6°C below 8.75m, and it indicates that the temperature is well-distributed in vertical direction. The conclusion could be made that the transversal warm air curtain can offer the “stratified” effect and control the buoyant warm air.

The main reason that the mean temperature of unconditioned zone is a little higher than that of

conditioned zone is low outdoor temperature and weak solar radiation intensity. The temperature of internal surface on the roof is lower than that of work area, i.e. the air within the space is cold at upper level and warm at lower level. Therefore the air is under a condition of thermal instability and lead to strong thermal convection within the space.

#### 4.4 Experiment and analysis of influence of air leak on the roof on air distribution performance in work area

To remove a considerable portion of the roof heat gain and sensible heat from lights, an exhaust fan has been installed on the roof in summer condition. Considering that the buoyant warm air flow may exhaust disorganizedly from the leak and take parts of heat out of the model, the experiment is carried in two groups: the leak sealed and unsealed. The parameters are:  $t_o$  is 35.4°C,  $d_o$  is 51mm and  $v_o$  is 3.4m/s. The results are shown in Table 8 and 9.

The temperature of work area is identical under the same experiment condition. Therefore, it may be concluded that small leak on the roof has little impact on the air distribution performance in work area

Table8. Temperature/°C distribution of work area

| Condition     | Mean | Maximum | Minimum | $\sigma_T$ |
|---------------|------|---------|---------|------------|
| Leak sealed   | 17.1 | 17.5    | 16.8    | 0.163      |
| Leak unsealed | 17.1 | 17.4    | 16.8    | 0.175      |

Table9. Velocity /(m/s) distribution of work area

| Condition     | Mean  | Maximum | Minimum | $\sigma_v$ |
|---------------|-------|---------|---------|------------|
| Leak sealed   | 0.075 | 0.10    | 0.07    | 0.01       |
| Leak unsealed | 0.079 | 0.12    | 0.06    | 0.02       |

### 5. Concluding remarks

Model experiment has been a very important and effective method for studying stratified air conditioning in high ceiling space up to now. With the aid of it, this paper measures and analyzes the air distribution performance in whole space in high ceiling industrial plants in winter conditions, and reaches some conclusions for reference.

- 1) Temperature is well-distributed in whole space in winter conditions, and the temperature of unconditioned zone is slightly higher than that of conditioned zone. This indicates that the transversal warm air curtain can fulfill the stratified heating.
- 2) The air should be supplied at a downward gradient, and the supply air rate in winter may be less than that in summer, thus can produce extraordinary energy saving.
- 3) The leak of ventilation opening on the roof does

little impact on air distribution performance at work area.

- 4) It is a common sense that adopting stratified air conditioning in high ceiling plants can produce significant savings in several aspects. The results of this model experiment show that transversal warm air curtain can also produce "stratified" effect, thereby save energy greatly.

### References

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