Study on application of capillary plane radiation air conditioning system based on the slope roof

Y G Li1, T T Wang, X L Liu and X Z Dong

School of Thermal Energy Engineering, Shandong Jianzhu University, Jinan 250101, China

E mail: sdjglya@163.com

Abstract. In this paper, based on the principle of the capillary plane radiation air conditioning system, taking the slope roof as an example, the application of the capillary plane radiation air-conditioning system is studied and analysed. Then the numerical solution of differential equations is obtained by the technology of CFD. Finally, we analyze the distribution of indoor temperature of the slope roof and the predicted mean votes (PMV) using Airpak simulation software by establishing a physical model. The results show that the PMV of different sections ranges from 0 to 2.5, which meets the requirement of the comfort. These provide a theoretical basis for application and promotion of capillary plane in the slope roof.

1. Introduction

With the development of economy and people’s living conditions, air conditions has been widely applied in our daily life. Capillary air-conditioning system, supplying cooling and heating mainly by radiation, which can control temperature and humidity individually[1]. The sensible heat load and the latent heat load of the air conditioning are borne by the capillary network and the independent fresh air system respectively. Thus, the temperature of chilled water is raised from 7 °C to about 18°C in summer, so that the coefficient of function(COP) is improved by more than 40%, and energy-consumption of the air-conditioning system is reduced by more than 30% [2]. In winter, with “low temperature” (28-32 °C) water heating, the effect of energy-saving is remarkable. In addition, because of ease silence and no feelings of air draft, it enjoys more obvious advantages among assorted systems[3]. So it is no wonder that it becomes more high-grade building designers’ priority in the recent years.

Modern architects tend to introduce art and humanity into buildings, trying to highly reflect the local history background and cultural environment. Combining the large scale geometric figure with a large number of local materials makes the public feel friendly and encourages them to show their emotions and concerns. During the appreciating process, we realize the biomimetic and free concept from the exterior shape and transparent or translucent walls and roofs. They regard one construction as a creature, talking with her about the design thought. Seeing buildings in the light of their development, advocating the ideas of complexity and movement of the architectural space, and considering the requirement for multifunction architects manage to create brilliant architectures with simple geometric

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1 Address for correspondence: Y A Li, School of Thermal Energy Engineering, Shandong Jianzhu University, Jinan 250101, China. Email: sdjglya@163.com.
shapes. The city will be dressed in colorful styles of the buildings, meanwhile, it brings new topics for the design of capillary air-conditioning system. In the building of slope roof, sloving problems about layout of the capillary broadly, the effect of cooling in the summer and supplying heat in winter and the indoor comfort needs further research.

2. Establishment of model

2.1 System’s schematic diagram

Capillary plane radiation air-conditioning system mainly consists of cooling-heating sources, heat exchangers, circulating pumps, temperature control system, desiccant system and capillary network [4]. These are shown in figure 1.

![Schematic of capillary air-conditioning system](image)

Figure 1. Schematic of capillary air-conditioning system

It is shown in the Figure 1 capillary plane radiation air conditioning system consists of capillary net terminal and fresh air system, which are two independent systems. Capillary network is mainly responsible for the indoor sensible heat load, and fresh air system is in charge of indoor humidity control.

2.2 Physical models

In this paper, taking a common room in Ji'nan as an example, a physical model is established to simulate the real condition. Room size (length * width * height) is 4.5 m × 3 m × 2.8 m and the angle of the slope roof is 30° with a building area of 13.50 m². The main equipments of the room include three persons, fluorescent lamp×6, computer×3, desk×3, south ex-windows (2.5 × 1.8) and a gate (2 × 1.1). The device parameters are listed in the table below.

Table 1. The main equipment parameters in the model room

| Devices               | Quantity/Size | Remarks                                      |
|-----------------------|---------------|----------------------------------------------|
| Human bodies          | 3             | Quantity of body heat loss: 75W; Moisture scattering: 109g/h |
| Computers             | 3             | 100W                                         |
| Desks                 | 3             | 2×0.6m²                                      |
| fluorescent lamps     | 6             | 6×10W                                        |
| external window       | 2.5×1.8 m²    | Thickness: 18mm                              |
| Gates                 | 2×1.1 m²      | Thickness: 5cm                               |
We conduct this experiment based on the following assumptions:
(1) In order to simplify the model, humans, computers and desks are set into cube block;
(2) The temperature of capillary network radiation surface is well-distributed. Except for capillary network radiation surface, the external windows, exterior walls and doors the exterior protected construction are adiabatic;
(3) In the air outlet, the parameter of jet-flow is uniform, and the thermal parameters of indoor air are constant.

2.3 Mathematical models
The indoor air flow is relatively complex, unsteady and irregular vortex. Each physical parameter of fluid keeps randomly changing along with the temporal and spatial conditions. It is a typical kind of turbulent flows, corresponding to turbulence models. The model of the 0 equation is used in this study. The model of the 0 equation does not require the solution of differential equation. However, a link between turbulent viscosity coefficient and average physical quantity is established by the algebraic relationship. The 0 equation do not need the solution of the K equation and the $\varepsilon$ equation \[^5\]. So this model is timesaving and the calculating speed is also much faster compared with one equation model and the standard model (K- $\varepsilon$ model). Its formula is very simple, consisting of velocity $V$ and the nearest distance ($l$) being away from the wall:

$$\mu = 0.03874 \rho vl$$

According to the law of conservation of energy, the general form of governing equations is like Equation (2).

$$\frac{\partial (\rho \phi)}{\partial t} + \text{div} (\rho U \phi) = \text{div} (\Gamma_\phi \text{grad} \phi) + S_\phi$$

In Equation (2), $\frac{\partial (\rho \phi)}{\partial t}$ is non-steady state term; $\text{div} (\rho U \phi)$ is convection term; $\text{div} (\Gamma_\phi \text{grad} \phi)$ is diffusion term; $\Gamma_\phi$ is generalized diffusion coefficient; $S_\phi$ is generalized source term; $\phi$ is expressed general variable, which can be represented u, V, W, T waiting for the variable.

By reference to general form of the governing equation (2), the Reynolds Stress are assumed as a kind of algebraic function of average physical quantity according to the 0 equation model. The
parameter Φ represents the velocity and the temperature of fluid flow. The corresponding air flow controlling equation is different due to representing different physical quantities, which are listed in Table 2.

**Table 2.** Indoor air flow control equation of zero equation turbulent model

| $S_e$ | $\phi$ | $\Gamma_e$ |
|-------|-------|---------|
| 1     | 0     | 0       |
| $u$   | $\mu_e$ | $\frac{\partial p}{\partial x} + \frac{\partial}{\partial x} \left( \mu_e \frac{\partial u}{\partial x} \right) + \frac{\partial}{\partial y} \left( \mu_e \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu_e \frac{\partial w}{\partial z} \right) + g_x \left( \rho - \rho_{ref} \right)$ |
| $v$   | $\mu_e$ | $\frac{\partial p}{\partial y} + \frac{\partial}{\partial x} \left( \mu_e \frac{\partial u}{\partial y} \right) + \frac{\partial}{\partial y} \left( \mu_e \frac{\partial v}{\partial y} \right) + \frac{\partial}{\partial z} \left( \mu_e \frac{\partial w}{\partial y} \right) + g_y \left( \rho - \rho_{ref} \right)$ |
| $w$   | $\mu_e$ | $\frac{\partial p}{\partial z} + \frac{\partial}{\partial x} \left( \mu_e \frac{\partial u}{\partial z} \right) + \frac{\partial}{\partial y} \left( \mu_e \frac{\partial v}{\partial z} \right) + \frac{\partial}{\partial z} \left( \mu_e \frac{\partial w}{\partial z} \right) + g_z \left( \rho - \rho_{ref} \right)$ |
| $h$   | $\frac{\mu_e}{\sigma_h}$ | $S_h$ |

In the formula $\mu_e = \mu_l + \mu_t$, $\mu_l$ is the dynamic viscosity of laminar air flow; $\mu_t$ is calculated by the Equation (1); $u$, $v$, $w$ represent the velocity of x axis, y axis and z axis respectively; $h$ and $P$ represent the air enthalpy and pressure respectively; $g_x$, $g_y$, $g_z$ refer to the acceleration of gravity in three dimensional directions; $\rho_{ref}$ is the referenced air density; $\mu_e$, $\mu_t$, $\mu_l$ represent the effective viscosity coefficient, turbulent viscosity coefficient and laminar viscous coefficient, respectively; $\sigma_h$ is equivalent Prandtl number; $S_h$ is calorific power of unit volume [6].

3. The numerical solution of mathematical model

3.1 Set the boundary condition

It is crucial to set the boundary conditions in the numerical simulation. The boundary conditions are related to the proximity level of the simulation results and the actual situation. The temperature of water in capillary plane radiation system increased by 1℃ compared with traditional comfortable air conditioning [7]. In this paper, room temperature is 26℃ and the relative humidity is 50% [8].

(1) Outdoor calculating parameters

The air temperature curve in Ji'nan in some years is shown in Figure 3. The design parameters of outdoor air conditioning in summer in Ji'nan is: the temperature of dry bulb is 34.4℃, wet bulb is 26.7℃ and the average wind speed is 2.8m/s.
Figure 3. A curve of annual temperature change in Ji'nan

(2) Boundary conditions of retaining structure
Western and southern walls are all exterior wall in this model. Western Wall is 4.5\times 2.8\text{m}^2 and the south wall is 3\times 2.8\text{m}^2. There is a external window on the southern wall. In order to simplify the calculation, heat transfer of the exterior wall can be regarded as a boundary condition of constant heat flux with conduct heat density of 19.5\text{W/m}^2 and heat transfer coefficient of 0.49\text{W/(m}^2\text{K)}. Southern exterior window is 2.5 \times 1.8\text{m}^2 with thickness of 18\text{mm}, heat transfer coefficient of 3.38\text{W/(m}^2\text{K)}, solar radiation heat load of 59.05\text{W/m}^2 and heat flux density of 81.23\text{W/m}^2. Other retaining structure is adiabatic boundary without difference in temperature, and heat flow density is 0\text{W/m}^2.

(3) Boundary conditions of capillary network radiation
Capillary net radiation air-conditioning system supplies cooling in summer. The temperature of the medium usually is 18\text{\Celsius} and the return water temperature is set up to 20\text{\Celsius} considering influence of difference in temperature. We assume that the temperature of radiation surface is uniform, and the radiation surface can be regarded as a steady-state boundary condition of constant temperature [9].

(4) Boundary conditions of air port
In this model, air diffuser is at the bottom. The guiding diffuser is simplified to rectangle diffuser, the temperature and velocity of the fresh air is 20\text{ \Celsius}, 0.5\text{m/s}, respectively [10]. Return air inlet is arranged on the top, and boundary conditions of air inlet are set for entrance velocity.

3.2 Comfort conditions and simulation results
Professor Fanger, who is a famous scholar in Denmark Industrial University has started to research on the comfort conditions of indoor thermal environment since 1960s.[11] He provided the PMV-PPD index system of thermal comfort to predict the PMV(predicted PMV mean vote) index according to the thermal comfort equation and ASHRAE 7-point scales (the PMV index of cold, cool, slightly cool, neutral, slightly warm and warm heat are -3, -2, -1, 0, +1, +2 and +3, respectively). This index has been widely used in Europe. The range of the PMV index is from -3 to +3 corresponding to the degree of human feeling from cold to hot. PMV index represents the feeling of most people in the same environment, so it can be used to predict the human’s response to thermal environment. However, even if most people are satisfied with the thermal environment, there will be still some people are not comfortable due to physiological differences among humans. In order to illustrate this relationship, Fanger provided a standard of PPD (predicted percentage of dissatisfied), which measured the number of people being not satisfied with the thermal environment. In fact, when the value of PMV is 0, that is the feeling of human body to the environment is best, there are still 5% people being dissatisfied with the environment. Therefore, the PPD index affirms the most people's perception and retains the dissatisfaction of the few people with the environment. It is an index that most people can accept. The PMV-PPD index is based on thermal comfort equation. It is an environmental evaluation index, which is developed through the analysis of thermal sensation of 1396 American and Dane. It has been accepted by the world due to a big experimental data. In ISO Standard 7730 and ASHRAE Standard 55-2004, PMV and PPD index were used to evaluate the thermal environment respectively [12].

The PMV of indoor capillary network air-conditioning system of slope roof is simulated and analyzed The vertical section across the human and the computer is x=1.7m; the vertical section of the respiratory system corresponding to seating human body is y=1.2m and the vertical sections of human body at the position of z=0.2m, z=2.8m. Figure 4~9 describe the simulating results of capillary plane radiation air-conditioning system of slope roof.
From Figure 4 and Figure 5, it can be seen that the application of capillary radiation air-conditioning system in slope roof make the indoor temperature distribution uniform, which is maintained 24 ℃. This is because cooling load from heat and the radiation area of retaining structure is proportional to the temperature difference of supplying and returning water. The larger radiation area is conducive to supply cooling. Figure 6–9 show that the values of PMV are generally from 0 to 0.25, satisfying requirements of indoor comfort. Although the values of PMV surrounding human and computer are slightly higher, it does not affect the overall comfort.
4. Conclusions
In order to enrich the landscape of city and realize the goal of "better city, better life", new architectural shapes is emerging in an endless stream, which requires air-conditioning system keep pace with the times. The capillary plane radiant air conditioning system has outstanding performance in comfort, energy saving and so on. However, due to the various aspects of the comprehensive reasons, China's capillary plane radiation air-conditioning system has not been widely used.
In this paper, the application of the capillary plane radiation air conditioning system is studied based on the slope roof, so built a physical model by using a sloping roof construction in Ji'nan. Then by using Airpak software, our simulation experiment proves that it is feasible to apply capillary plane radiation air-conditioning system in the building of slope roof, for the value of PMV (predicted mean vote) of indoor in different sections is from 0 to 0.25, meeting the requirements of comfort. At the same time, the slope of the roof laying indoor temperature about 24 degrees, cooling capacity has been improved, as long as the layout of capillary plane radiation air-conditioning system is reasonable in the building of slope roof, the gradient of indoor temperature is not more than 1°C. It is conform to the requirement that the gradient of the temperature is not more than 3°C. so it is feasible to apply the capillary plane radiation air conditioning system in the building of slope roof. This provides a theoretical basis for the application and popularization of the capillary plane radiation air conditioning system in the slope roof construction. This is of great significance.

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