Optimal Supply Angle of Upside Air Supply in Manned Spacecraft Cabin-Based Air Age

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Abstract: The age of air in the workaround of a manned spacecraft cabin that contain astronauts, apparatus and simple living establishments was numerically simulated by use of commercial software and a standard *k-ε* turbulence model. An air inlet installed in the two top corners with a removed stagger mode supplied the air. Simulation results showed that the less the supply angle, the fresher the air, and the greater the air exchange efficiency. A 0° supply angle is advised if no block is in the ceiling.

Key words: manned spacecraft cabin; air age; supply angle; numerical simulation

With the farther development of manned spaceflight enterprise in China, and to achieve long-playing flight, a good environment in cabin must be created that may assure cosmonaut long-playing living healthily and assure apparatus long-playing working in gear. This is the function of Environmental Control and Life Support System (ECLSS) in manned spacecraft. As a subsystem of ECLSS, ventilation system has the function to achieve required velocity field, temperature field and concentration field. The microgravity environment occurs in cabin because of the balance between gravitation and centrifugal force caused periodic and circumterrestrial movement. To accomplish heat and matter exchange, mechanical ventilation must be adopted due to absence of natural convection caused by gravity effects. Age of air is an important parameter for estimation of the air exchange efficiency that is important for cosmonaut health. It is reasonable using air age to estimate air distribution stand or fall.

According to some study[1], removed stagger supply vent mode of upside air-supply is a better mode and was adopted in Lab-A module cabin in space station[2]. However, supply angle is still a question need to study. So, in this paper, supply angle would be optimized with removed stagger supply vent mode based air age simulation.

1 AIR AGE

Air age is the time τ for air to arrive at certain place from intake. After enter room from intake air was mixed with contamination and carbon dioxide continuously, thus cleanliness and greenness will decline gradually. The less is air age, the cleaner and greener is air. Air age is a more valid parameter to estimate ventilation effect than conventional parameters. We can't know the air age of a particle and only gain average age of particles exist in certain region. The frequency distribution function of all particles' age is supposed $f(\tau)$, thus

$$\tau_{\mathrm{p}} = \int_0^\infty \tau f(\tau) d\tau \qquad (1)$$

Another parameter which is correlative with air age and may be to describe the speed of entrance of flesh air and discharge of contamination quantitatively is average halt time of air before is discharged, τ_{r} The average time of entire room is equal to the doubleness of average air age of entire room, and is denoted $\overline{\tau_r}$. In theory, the best halt time τ_n equal to quotient dividing room volume by supply air capacity, namely reciprocal of exchange time. The ratio of τ_n and τ_r is called exchange efficiency η_a, and may be to estimate characteristic of air distribution and exchange effect.

Now, Main study ways on air age are tracer gas technique and numerical simulation. With tracer gas technique, people utilize the change of gas concentration to make certain local average air age. The main experiment means are pulse technique, ascend technique and descend technique. Each technique has different expression of concentration. With tracer gas technique, the relation between concentration of tracer gas and time need to be got and this will cost longer time and more money. The formula and solution method of air age adopted tracer gas technique in airplane cabin were studied by Zhuang Damin etc[3]. The decay curves of trace gas concentration and air age for eight mechanically ventilated cases in a chamber were obtained by Li Xianting etc[4].

In numerical simulation, the transport equation of tracer gas quantity concentration is gained by the equation of conservation of mass, and the transport equation of air age is got by tracer gas technique [5]:

$$\frac{\partial}{\partial x}(u\tau_p)+\frac{\partial}{\partial y}(v\tau_p)+\frac{\partial}{\partial z}(w\tau_p) = \frac{\partial}{\partial x}(\Gamma\frac{\partial\tau_p}{\partial x})+\frac{\partial}{\partial y}(\Gamma\frac{\partial\tau_p}{\partial y})+\frac{\partial}{\partial z}(\Gamma\frac{\partial\tau_p}{\partial z})+1 \quad (2)$$

Where, u, v and w is velocity, Γ is coefficient of diffusion. From equation, you can find the air age is relational with flow and coefficient of diffusion. The format of equation is the same as the equation of continuity, momentum and turbulence model. With transport equation of air age, air age would be gained through numerical simulation.

2 DESCRIPTION OF THE PROBLEM

2.1 Description of Physics Model

The study object is the workaround that size is 8.7×2.2×2.2m in manned spacecraft cabin, , as showed in figure 1. In workaround, there are one table, one medicine equipment, two desks, and three cosmonauts. Within three cosmonauts, one is taking exercise on medicine equipment, who's heat and moisture emanation is considered as heavy labor's, another two is working at desk who's heat and moisture emanation is considered as light labor's. Apparatus are disposed near left and right cabin wall, and emit 1000w heat. Lamp emits 400w heat. Living establishment's moisture emanation is supposed 1.8kg/h including wash equipment and drying equipment

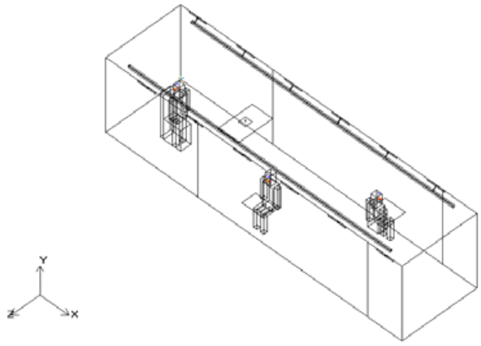

Fig. 1 Plane & section plane of cabin

The design temperature in cabin is 25℃, and relative humidity is 50%. Constant volume air conditioning system is adopted and the air volume is $960m^3/h$. After simulation, we find the air exchange efficiency is the best and the vent quantity is lightest when outlet air velocity was 1.1m/s in the condition mentioned above, that is to lay six supply vents that size is 500×40mm on either side. In paper, flight state is supposed and the gravity is $1e^{-6}m/s^2$.

2.2 Mathematics Equation:

The mass conservation Equation:

$$\frac{\partial u_i}{\partial x_i}=0 \quad (3)$$

Momentum equations:

$$\frac{\partial}{\partial t}(\rho u_i)+\frac{\partial}{\partial x_j}(\rho u_i u_j)=-\frac{\partial p}{\partial x_i}+\frac{\partial \tau_{ij}}{\partial x_j}+\rho g_i+F_i \quad (4)$$

Energy conservation equation:

$$\frac{\partial}{\partial t}(\rho h)+\frac{\partial}{\partial x_i}(\rho u_i h)=-\frac{\partial}{\partial x_i}(\lambda+\frac{c_p\mu_t}{\Pr_t})\frac{\partial T}{\partial x_i}+S_h \quad (5)$$

In conducting solid regions, Airpak solves a simple conduction equation that includes the flux due to conduction and volumetric heat sources within the solid:

$$\frac{\partial}{\partial t}(\rho h) = \frac{\partial}{\partial x_i}(\lambda \frac{\partial T}{\partial x_i}) + q \qquad (6)$$

Species transport Equations:

$$\frac{\partial}{\partial t}(\rho m) + \frac{\partial}{\partial x_i}(\rho u_i m) = -\frac{\partial}{\partial x_i} J_i + S \qquad (7)$$

Where u is velocity, ρ is density, p is the static pressure, τ_{ij} is the stress tensor, ρg_i is the gravitational body-force in the i direction, F_i contains other source terms that may arise from resistances, sources, etc, h is sensible enthalpy, λ is conduction coefficient, c_p is specific heat, μ_t is turbulent viscosity, Pr_t is the turbulent Prandtl number for energy, S_h includes any volumetric heat sources, T is temperature, q is the volumetric heat source, S is the rate of creation by addition from user-defined sources, and J_i is the diffusion flux of species i.

3 VALIDATIONS OF SIMULATION TOOL UNDER MICROGRAVITY CONDITION

Simulation tool adopted in the paper is software Airpak which is specialty software for room ventilation authorized by American Fluent Inc. The standard k-ε turbulence model was used in the paper, and the model constants $C_{1\varepsilon}$, $C_{2\varepsilon}$, C_μ, δ_k, δ_ε have the follow values:

$C_{1\varepsilon}$=1.44，$C_{2\varepsilon}$=1.92，C_μ=0.09，δ_k=1.0，δ_ε=1.3

It is very difficult to experiment under microgravity condition; hence it is hard to find comparable experiment data. According to thermal scale ration technique based on similitude theory, “temperature- humidity- material-Nu-Sh” [7] conservation technique was adopted. Though changing heat flux across wall and keep 1:5 model rations, we gained Validation data.

Sandberg and Sjberg adopted pulse, ascend and descend technique respectively to measure the air age of point 1, point 2, point 3, point 4 and exit in a room as showed in figure 2[8]. And the air age of these points were computed by Li Xianting though numerical simulation [5]. A room of 5 times size was simulated in this paper, and the results were compared with the results in references mentioned above as listed in table 1 to testify the validity of simulation tool adopted in this paper. Where τ_n is the ratio of volume of room and supply air capacity.

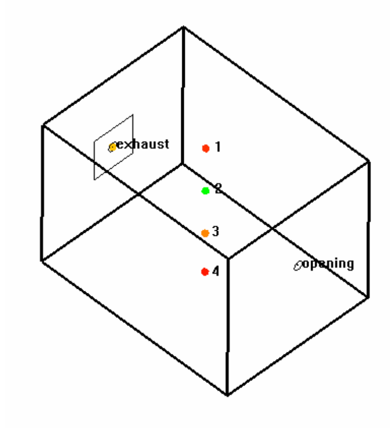

Fig. 2 Test chamber

Tab.1 Comparison of simulation result and references

Point	τ_p/τ_n Ref. [7]	Ref. [3]	text	Relative error Between[7]	Between [3]
1	1.08	1.137	1.25	15.7%	9.9%
2	0.85	1.051	0.96	12.9%	8.7%
3	1.15	1.146	1.13	1.7%	1.4%
4	1.16	1.146	1.13	2.6%	1.4%
Exit	1.00	1.023	1.05	5.0%	2.6%

From the data of table 1 you can find the simulation results of point 3, point 4 and exit in paper tally with the results of references. The results of point 1, point 2 is also consilient on the whole. The common characteristic is that the air age of point 2 is least whether with experiment or with simulation. The analysis above reveals the validity of the tools and methods in this paper.

4 ANALYSES OF SIMULATION RESULTS

After simulation, the air ages of three representative sections with different supply angle had been listed in table 2. Here, supply angle denotes the angle between the direction of air jet and ceiling. The supply angles include 0°, 15°, 30°, 45°, 60°, 75°, 90°, and the three sections denote the altitude of cosmonauts’ mouths and noses when they are sitting, are taking exercise, and are standing respectively. From the data in table 2, you can find that with larger supply angle, the air ages in the three sections are greater, that is air is staler.

In order to ulteriorly illuminate the relation between air exchange efficiency and supply angle, authors have given the variety of air exchange efficiency with the supply angle as showed in figure 3. The curve denotes the air exchange efficiency will decrease obviously with the increase of supply angle. It is obvious that with same supply mode but different supply angle the effect of ventilation will be different greatly. With the result in this paper, 0° supply angle was advised if no block is in ceiling.

Tab.2 Comparison of air age in different supply angle

τ_p (s) / Supply angle	y=1.28m	y=1.53m	y=1.70m
0°	137～152	129～149	116～149
15°	142～157	134～155	123～155
30°	160～176	150～174	138～173
45°	197～215	179～213	141～213
60°	281～302	246～301	150～300
75°	554～573	526～571	423～570
90°	5149～5182	5150～5250	5150～5184

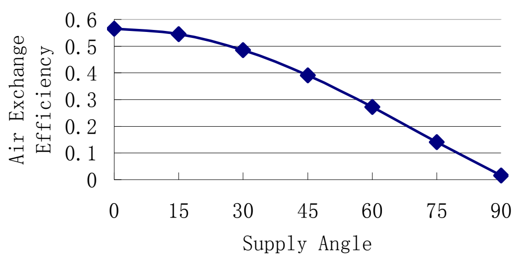

Fig.3 Relation between air exchange efficiency and supply angle

5 CONCLUSIONS

(1) Acting thermal scale ration technique as the bridge between microgravity and common gravity, authors have found the method validating the simulation results under microgravity condition.

(2) When removed stagger supply vent mode is adopted, the less is supply angle, the fresher is air, and greater is air exchange efficiency.

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