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Influence of IMV on Space Station

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***Abstract*—**To study the impact of the inter-module ventilation (IMV) on the space station, the Computational Fluid Dynamic (CFD) model under the influence of IMV, the mathematical model, boundary conditions and calculation method are established and determined to analyze the influence of IMV on cabin air flow characteristics and velocity distribution firstly; and then an integrated overall thermal mathematical model of the space station is used to consider the impact of IMV on thermal management. The results show that: the IMV has a significant influence on the cabin air flow, the flowrate of IMV within a certain range can effectively improve the air velocity distribution in cabin, if too much may lead to its deterioration; IMV can affect the heat deployment of the different modules in space station, thus affecting its thermal management, the use of IMV can effectively maintain the temperature levels of the different modules and help the space station to dissipate the waste heat.

***Keywords*—**CFD, Environment control and life support, Space station, Thermal management, Thermal mathematical model.

I. INTRODUCTION

THE ventilation system plays an important role in the daily operation of the space station. As a component of the temperature and humidity control system, the ventilation system is to maintain crew comfort and the basic conditions for cooling equipment and to exclude contaminants. There are three major space station ventilation forms: the intra-module ventilation, the rack ventilation and the Inter-Module Ventilation (IMV), which refers to the ventilation between the different modules through the docking channel in space station. IMV can influence the space station in two aspects, on the one hand, the air flow characteristics inside the space station, such as the cabin air velocity distribution and the diffusion and distribution of pollutants; On the other hand, the thermal management of different modules. So IMV plays a great importance role in the process of thermal design, test and orbit operation of the space station.

The air flow analysis using CFD on the space station is very effective [1]. Werner (1990) [2], using PHOENICS, analyzed the flow field inside HERMES. Johannes A (1991) [3] and Andreas et al (1993) [4] analyzed the microgravity rack air flow using CFD software. Chang (1993, 1994) [5, 6] studied the air velocity distribution of US Lab on a variety of cases through experimental method. The cabin ventilation and rack ventilation were studied detailedly in their experiments, especially in [6], the results of experiments were compared with the numerical results using FLUENT obtained. Chang's results showed that the numerical method is very effective. Jorge (2002) [7] and Darrah (2005) [8] analyzed the ventilation of the International Space Station's Cupola and Node1 using CFD software. The air flows of the entire ISS (a total of 12 modules) after the assembly were simulated by Chang (2005) [9]. Fu (2006) [10] carried out the velocity distribution analysis to a pressure module in considering the layout of a variety of air diffusers and a variety of air flowrate, but took into account only the intra-module ventilation. Fu (2007) [11] suggested a flowrate margin (MFR) concept to directly reflect the impact of the air flowrate on the air velocity distribution in the ventilation design of space station. Can be seen that the current air flow in the space station is more comprehensive study, but few involve the influence of IMV on the thermal management of space station.

The influence of IMV on an experimental space station is analyzed in this paper. First of all, based on a simplified physical model, in the given conditions, the impacts of IMV on air velocity distribution are analyzed using CFD software; and then make use of the overall integrated thermal mathematical model (IOTMM) of this space station; the impact on thermal management is also considered.

II. SPACE STATION PHYSICAL MODEL AND ITS SIMPLIFICATION

This experimental space station operates on a nearly circular orbit, has an altitude of 350km and an inclination angle of about 42.0 °, its orbital period is 5390.0s. The total mass of this space station is about 8.5 tons and its largest diameter is 3.35m.

The space station has two major modules of the lab and the resource. The lab module can be divided into several zones of the crew activity and the electronic equipment. The crew activity zones include an aisle and two crew quarters. The crew quarters are used for the crewmembers to sleep during space station operation. The zones of electronic equipment are used to install the electronic equipment, to accomplish a variety of scientific experiments, and to store the goods. The Resource module, different from the lab module, is not a pressure module. There are various types of gas tanks, two ring-shaped plates and all kinds of equipment installed in the resource module. There are two large solar wings, orientating to the sun during running in-orbit, outside the Resources module. The internal and external general structure of this space station is shown in Fig.1.

In the manned mode of the space station, the air flows to the crew (and related equipment) and carries the heat and moisture to a condensing heat exchanger, which provides temperature and humidity control. The cooled and dehumidified air is sent back to the cabin of crew and formed a suitable residence

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atmospheric environment. In order to maintain the temperature level of the docking spaceship, the adequate warm air is supply from the lab module to the return module of the spaceship and the cooled air flow back through docking channel.

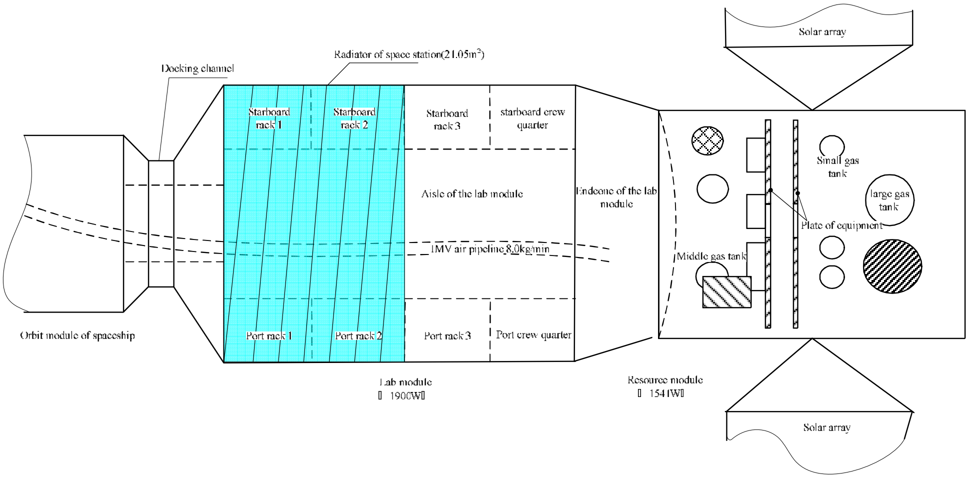

Fig. 1 Sketch of the space station

A. Geometry model

The endcones of the lab module are generally used to store goods. When space station operates in manned mode, people usually work in aisle and sleep in the crew quarters, and less to the docked spaceship. Therefore, the influence of IMV on the air flow of the space station only involves the aisle and the two quarters in this paper. As shown in Fig.2, the simplified geometry model contains three constituents: two crew quarters and an aisle. Because the crew quarters are used for the crewmembers to sleep during space station operation, the accumulation of CO_2 in these quarters will cause possible medical hazards especially when crews are sleeping, so there must be air supply and return registers in the quarters. The different arrangement schemes of diffusers are mainly applied in the aisle. The x-axis points to the flight direction, the y-axis points to the zenith and the z-axis points to the port in Fig.2. The IMV can be supplied through the hatch between the spaceship and the space station.

B. Interface between the space station and the spaceship

The warm air is provided from the aisle to the spaceship through the Ø0.12m air pipeline, and the cooled air returns directly through docking channel, as shown in Fig.3. This paper focuses on the IMV impact, the handling of the interface of the space station and the spaceship as follows:

a) because the cooled air flows back through the docking channel, the hatch of the channel will be simplified to hydraulic diameter of 0.8 meters (about 2 times the cross-line length), as shown in Fig.2;

b) the outlet of the warm air for delivery in the end of aisle is simplified to a square surface of 0.2m×0.4m, as shown in Fig. 2. The end of the aisle is the interface of the lab module and the resource module. The air outlet arranged there, providing air to the spaceship, can be formed in "suction" effect.

C. Diffusers and return registers

The effective outlet area of each diffuser is $0.04 \times 0.1 m^2$. Six diffusers are arranged symmetrically near the ceiling board and subsequently six return registers are arranged symmetrically near the floor. This arrangement is shown in Fig.2. Many computational results have proved that the influence of the outlet velocity direction is small and the inlet velocity direction with 45-degree angle to the ceiling board is appropriate for this space station.

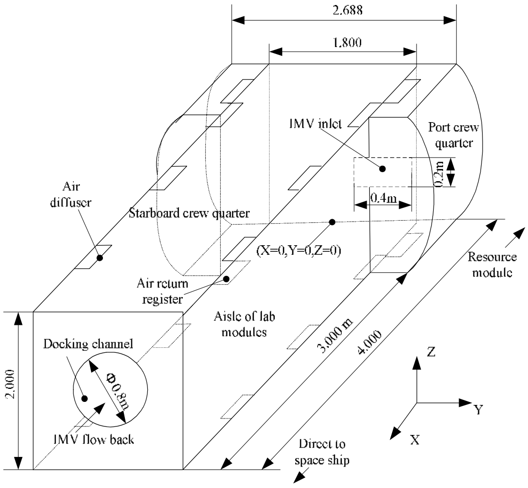

Fig. 2 Schematic of the analytical model

D. Consideration of the rack ventilation

In the daily operation of the space station, the rack ventilation is independent and its few affect is not taken into account in this article.

After the above analysis, the simplified CFD model is formed as Fig.2.

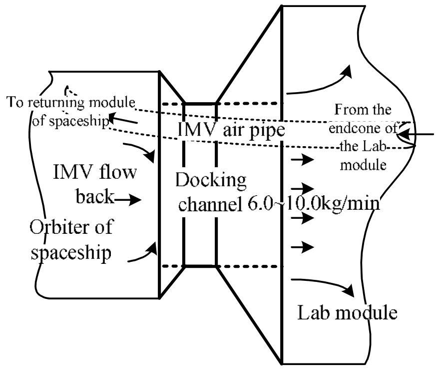

Fig. 3 Schematic of the hatch and the IMV air pipe

III. IMV INFLUENCE ON THE AIR VELOCITY DISTRIBUTION

The main purpose of ventilation design is to make the air velocity distribution in the appropriate range. The velocity distribution of the International Space Station (ISS) requires that two-thirds of the local velocity measurements are within the range of 0.051m/s~0.203m/s, with a minimum velocity of 0.036m/s and a maximum velocity of 1.02 m/s. The atmospheric velocities within 0.15m of the cabin interior surface are not considered in this requirement.

Achieving desired velocity distribution is dependent on: 1) design of the cabin air supply and return equipments, 2) flowrate of air supplied to and subsequently returned from the cabin, and 3) interactive effects of other additional air flow streams, such as the stream of IMV, which enter and exit the cabin. The 1) and 2) factors are discussed in [10] and [11], and the last one will be considered in this paper.

A. Mathematical Model and Its Solution

The realizable k-ε turbulence model was used for computations, the governing equations as follows:

$$\frac{\partial}{\partial x_i}(\rho u_i) = 0 \tag{1}$$

$$\frac{\partial}{\partial x_j}(\rho u_i u_j) = -\frac{\partial p}{\partial x_i} + \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\tau_{ij} = \eta\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i} - \frac{2}{3}\delta_{ij}\frac{\partial u_l}{\partial x_l}\right) \tag{2}$$

$$\rho u_l \frac{\partial \varepsilon}{\partial x_l} = \frac{\partial}{\partial x_l}\left[\left(\eta + \frac{\eta_t}{\sigma_\varepsilon}\right)\frac{\partial \varepsilon}{\partial x_l}\right] + \frac{c_1 \varepsilon}{k}\eta_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - c_2 \rho \frac{\varepsilon^2}{k} \tag{3}$$

$$\rho u_j \frac{\partial k}{\partial x_j} = \frac{\partial}{\partial x_j}\left[\left(\eta + \frac{\eta_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + \eta_t \frac{\partial u_i}{\partial x_j}\left(\frac{\partial u_i}{\partial x_j} + \frac{\partial u_j}{\partial x_i}\right) - \rho\varepsilon, \eta_t = \frac{c_\mu \rho k^2}{\varepsilon} \tag{4}$$

Where ρ is the air density, x is the position coordinates, u is the velocity, p is the pressure, τ_{ij} is the stress tensor, η is the dynamic viscosity, η_t is the turbulence viscosity, δ_{ij} is the Kronecker delta(δ =1, when $i = j$,or δ =0), k is the turbulence kinetic energy and ε is its rate of dissipation, the constants of σ_ε , σ_k c_1 , c_2 and c_μ are 1.3, 1.0, 1.44, 1.92 and 0.09 respectively.

The governing equations were solved using a segregated solver. A standard interpolation scheme was used for pressure. The Pressure Implicit with Splitting of Operators (PISO) was chosen as the pressure-velocity coupling scheme, and the second-order upwind discretization scheme was used for both the momentum and the k-ε model governing equations.

In order to save computing resources and to protect the accuracy, the non-uniform grid was chosen and compacted appropriately near the diffusers and the return registers.

B. Set the boundary conditions

The solid surfaces meet the no-slip boundary condition and a wall-function is used near the wall. Inlet velocity boundary conditions are adopted for each inlet diffuser and the hatch (open mode), and the velocity magnitude is achieved by corresponding mass flowrate and the effective area. The pressure out boundary is adopted for each return registers and the IMV provided outlet using the user-defined function to set the target-mass-flowrate.

C. Computational results

1) Air flow characteristics under the impact of IMV

Figure 4 is the air velocity nephogram of the section Z=1.0m, and Figure 5 is the air velocity vectorgraph of the section Z=1.0m. It is clear from these figures to see the air flowing into the aisle from the hatch and flowing out to the air pipe. The cabin have a very even velocity distribution (mostly within the range of 0.05m/s ~ 0.20 m/s), and the air velocity near the wall is very low, which indicates the wall no-slip conditions take effect

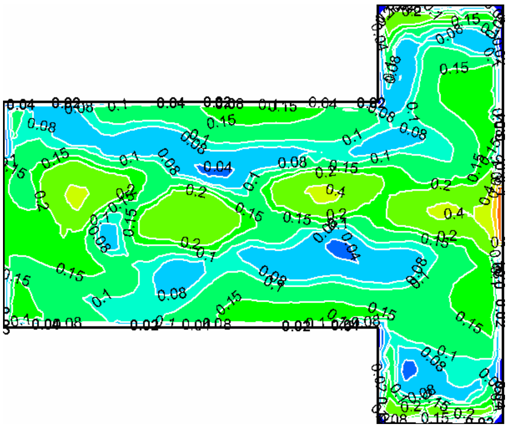

Fig.4 Velocity nephogram of the section Z=1.0m

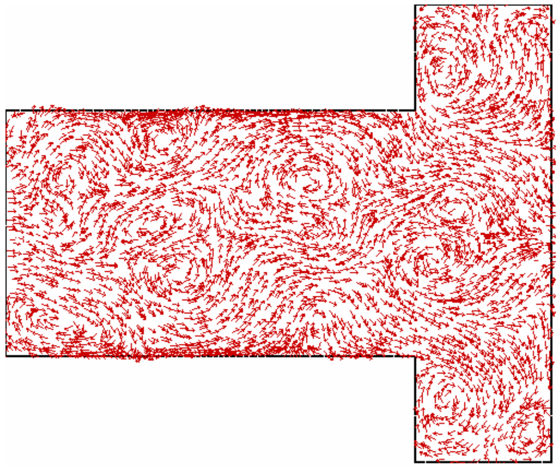

Fig. 5 Velocity vectorgraph of the section Z=1.0m

2) Influence of IMV on velocity distribution

The computational results are summarized in Table 1 with the varying air flowrate of IMV. The desired velocity range is R3 of 0.051m/s~0.203m/s. The flowrate of intra-module ventilation (cabin ventilation) is 8.0kg/min, and the flowrates of IMV are 4.0kg/min, 6.0kg/min, 8.0kg/min and 15.0kg/min respectively. When flowrate of IMV is 0.0kg/min, there is no IMV and the intra-module ventilation is the only ventilation form. The arrangement of the measuring point can be seen in [10].

As can be seen from Table 1, IMV with flowrate of 4.0kg/min, 6.0kg/min and 10.0kg/min can improve the air velocity distribution, but when the IMV flowrate is 15.0kg/min, IMV can deteriorate the air velocity distribution in cabin. The above results indicate: when the IMV flowrate is in a certain range, IMV can improve the cabin air flow, or IMV will lead it to deteriorate. This impact of IMV should be carefully considered in the ventilation system design of the space station, and must be verified in the ground test. When the flowrate of IMV is too great, it is necessary to install a curtain in the channel to limit the air speed.

TABLE 1 THE AIR VELOCITY DISTRIBUTION UNDER THE UNFLUENCE OF IMV

IMV flowrate (kg/min)	The velocity distribution of cabin air (%)				
	R1	R2	**R3**	R4	R5
0.0	3.75	7.50	**77.5**	11.25	0.00
4.0	1.875	6.25	**79.375**	12.5	0.00
6.0	2.50	5.625	**81.25**	10.625	0.00
10.0	1.875	3.125	**81.875**	13.125	0.00
15.0	2.5	1.875	**73.125**	22.5	0.00

Here R1 represents the velocity range of 0.0m/s-0.036m/s, R2: 0.036m/s-0.051m/s, R3: 0.051m/s-0.203m/s, R4: 0.203m/s-1.02m/s and R5: above 1.02m/s.

IV. IMV INFLUENCE ON THE THERMAL MANAGEMENT

A. IMV air loop

The Integrated Overall Thermal Mathematical Model (IOTMM) includes the thermal node network models and the fluid loop models. IOTMM can represent the integrated thermal performance of the space station and depict its all thermal action when the space station operates in space. As one of the main fluid loops, the IMV air loop can impact the heat allocation among different modules.

This paper uses the IOTMM established in [13] and [14] to analyze the impact of IMV on the temperature of the docking spaceship and the lab module of the space station. The normal flowrate of IMV is 6.0kg/min. The heat will be transported to the spaceship from the lab module of the space station through IMV. Based on the feedback temperature of the inspecting point in the spaceship, the IMV flowrate can be regulated automatically to maintain the spaceship at the appropriate temperature range.

B. Simulation results

1) IMV influence on spaceship temperature

Figure 6 is a contrast of the IMV flowrate and the spaceship temperature. As a result of the temperature control aim is maintain the air temperature in the returning module of the spaceship between 18.7□ and 23.6 □, the IMV flowrate has been maintained at 0.1kg / s because the temperature throughout the process are controlled within the required scope.

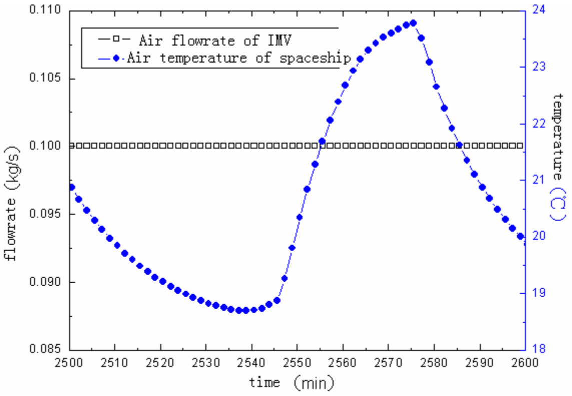

Fig. 6 The influence of IMV on the spaceship

2) IMV influence on the heat dissipation of space station

Figure 7 shows the quantity of heat provided by space station through IMV air loop, which is also on behalf of the heat dissipation of the space station through IMV. The transient heating load subjected to the lab module is also showed in Fig.7.

We can see from Fig.7, when the heating load of the lab module increases (the air temperature of IMV increases synchronously), the heat provided to spaceship will quickly increase (from 90W up to 200W). The temperature of the spaceship increases and more heat will be dissipated into space. This reduces the fluctuation of the cabin air temperature and helps to dissipate more waste heat.

From the above analysis we can see, IMV can effectively distribute the heat among different modules of the space station, for maintaining the temperature of the module in different levels and benefiting the waste heat dissipation.

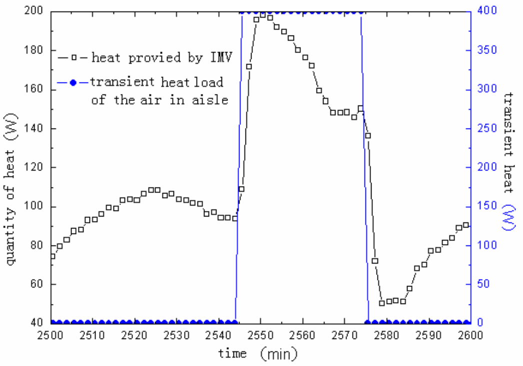

Fig. 7 The heat provided by IMV

V. CONCLUSION

IMV should be an important consideration in the thermal management system design of the space station; IMV can effectively affect the performance of the space station in orbit. The results of this paper show that: IMV of the appropriate flowrate can improve the air velocity distribution in cabin, but too much flowrate will lead to its deterioration; IMV can be effective on allocating the heat among different modules, thus affect the station's thermal management. The use of IMV can maintain the modules temperature of different levels and benefit the heat dissipation of the space station. These numerical results provided here have been mostly applied to the real design and will be validated in the future ground tests.

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