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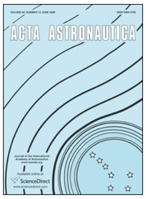

Numerical investigation of air stability in space capsule under low gravity conditions

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ABSTRACT

To obtain reasonable air distribution in space capsule, the indoor air stabilities under two basic gravity conditions – weightlessness and lunar gravity conditions – are studied in this paper. The influences of the indoor air stability on the characteristics of pollutant transport (CO_2) are discussed, by means of computational fluid dynamics (CFD) method under three different air stability conditions: stable condition, neutral condition and unstable condition. Two preliminary three-dimensional physical models were established and used to compare the influence of different arrangements of outlets and positions of pollutant source on the contaminant distributions. The results show that the air stability under the weightless conditions has no impact on the pollutant diffusion. However, the air stability under low gravity conditions significantly affects the pollutant spread and diffusion in the space capsule. Under lunar gravity conditions, the pollutant under unstable conditions has an obvious tendency of deviating from the mainstream direction and approaching the two flanks. On the contrary, the pollutant under stable condition moves faster in the mainstream direction and arrives at outlets more easily. It is possible that the air stability exists under low gravity conditions and affects the characteristics of pollutant transport.

1. Introduction

Space capsule is narrow and airtight, so the problem of foul air may be very serious. Therefore, providing clean air for astronauts is one of the important objectives of a spac e capsule design. More than twenty kinds of air pollutants have been detected in the spacecraft cabin, which mainly come from the metabolism of the astronauts. And the CO_2 from the respiratory metabolism of the astronauts accounts for the largest proportion. Generally, a person inhales about 576 l of O_2 (standard state), and exhales about 490 l of CO_2 (standard state) per day [1]. If no effective measures are taken to purify the capsule air and refresh it timely, CO_2 partial pressure would continue to rise in the capsule and probably will reach the allowed upper limit rapidly, which might affect the astronauts' health and working efficiency [2–4]. Therefore, it is of great importance to study the factors affecting pollutant transport in space capsule. This paper focuses on investigating the influence of air stability on pollutant spreading and diffusion in the space capsule.

In order to realize a healthy indoor air environment in space capsule, many studies have been accomplished by researchers. The air distribution system controls the flow of air in the open space of a space capsule. In order to meet crew comfort criteria, the local velocities for cabin air are required to be distributed within a specified range with upper and lower limits [5,6]. Achieving this desired velocity distribution depends on the (1) design of the cabin air

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Nomenclature

a	acceleration
g	weight acceleration
T	gas temperature
γ_d	dry air adiabatic vertical lapse rate
γ	indoor air vertical lapse rate
z	vertical height

supply equipment and cabin air return equipment, (2) total flow rate of air supplied to and subsequently returned from the cabin, and (3) interactive effects of any other additional air flow streams that enter and exit the cabin [6].

Additionally, many studies on the issue of indoor air quality have been carried out. The applicability of the cleaning methods to the different types of total volume of air distribution used at present indoors, i.e. mixing, displacement and under floor ventilation, as well as advanced air distribution techniques (such as personalized ventilation) is discussed [7]. Besides, the importance of indoor air characteristics, such as temperature, relative humidity and velocity, for the efficiency of different ventilation methods is analyzed, taking into consideration the nature of the pathogens themselves [7,8]. The effects of the ventilation system and moisture-buffering properties of the building fabrics on the stability of the indoor temperature and humidity are analyzed by means of long-term field measurements. In general, it may be concluded that ventilation has a greater effect on the indoor climate than the properties of the building fabric [9].

Under low gravity conditions, the natural convection caused by density difference is weak and sometime negligible [10,11]. To realize reasonable design of air velocity field and flow rate, organized and forced convection should be implemented [12–14]. Liu [15] and Ren [16] used numerical analysis and a model test to study the air flow distribution and heat transfer in a space station, by means of three-dimensional convection–radiation heat and mass transfer modeling, and the possible ventilation configuration was proposed to meet the requirement of the comfort and the homogeneity of temperature, humidity and velocity. Wu et al. [17] established a simplified model of a two-dimensional square space, to simulate the mode of ventilation and heat exchange in the chamber, and the air distribution affected by wind angle was studied. Zheng et al. [18] found that ventilation methods satisfying the requirement of indoor thermal comfort under earth gravity condition cannot meet the requirements under low gravity condition. Fu et al. [19] used the $k-\varepsilon$ model to simulate the different impacts of flow rate, diffuser arrangement and the wind inlet direction on air flow field. The 45º wind inlet angle has been chosen as the superior settings in a previous research [20].

In fact, a certain temperature gradient distribution or thermal stratification in a room or finite space must occur, because there are various kinds of heat and humidity sources, besides employing varieties of heating, cooling, and ventilation approaches in the space capsule. Gong et al. [21] reported that correlation analyses between thermal stratification and air stability strongly corroborate that under the two absolutely opposite circumstances: normal distribution with positive temperature gradient and inverse distribution with negative temperature gradient, pollutant transport property will differ drastically accordingly. Their work explained that the dynamics of the vertical temperature gradient and stability structure are prevalent in indoor thermal environment.

Computational fluid dynamics (CFD) has been used to determine the airflow, heat transfer, and chemical species transport in the analysis of indoor environmental conditions as well as a wide range of other HVAC&R applications; the decision to use CFD must be firmly based on realistic expectations of its performance, cost, and effort required [22]. The CFD model can effectively capture the characteristic flow features and contaminant transport observed in the small-scale model [23]. Since it is difficult to perform experimental study on the low gravity environment in a laboratory, numerical simulations by means of CFD can be an alternative choice.

As no research has demonstrated the indoor air stability under low gravity conditions, this paper focuses on the effects of air stability or the temperature gradients on indoor contaminant transport properties. Additionally, the different arrangements of outlets and positions of pollutant source are compared in order to find more effective methods to control pollutant transport in a space capsule.

2. Model description

2.1. Basic model

In this study, the Shenzhou VI spacecraft's orbital module is used as the prototype. The main activity zone of the astronauts is taken into account [24,25]. A three-dimensional physical model of the space capsule under weightless conditions is established, as shown in Fig. 1. The physical dimension of this model is 2.4 m (length) × 2 m (height) × 2 m (width). The origin of the coordinates is located at the center of the chamber. Six inlet openings with the same size of 0.1 m × 0.1 m are distributed on the top. Three outlets (0.2 m × 0.1 m) are in the bottom.

Hexahedral cells are used with a mesh of 76,800 cells. The simulation is performed based on the b standard $k-\varepsilon$ model. The velocity–pressure coupling is solved by the SIMPLE scheme. Finally, the transient flow of 100 s is simulated using a time step of 1 s.

2.2. Modified model

In order to compare the influence of the positions of the outlets on the characteristics of pollutant transport, a modified model is established which is presented in Fig. 2. The only differences between the basic model and the modified one are the locations and the sizes of the