Numerical Simulation and Analysis of Air Supply Mode in Luxury Cruise Air-conditioning System

Shaoshu Zhang\textsuperscript{1,*}, Haibo Gao\textsuperscript{1,\textsuperscript{b}}, Zhiguo Lin\textsuperscript{1,\textsuperscript{c}}, Yunrui Zhao\textsuperscript{1,\textsuperscript{d}}, Yunhua Guo\textsuperscript{1,\textsuperscript{e}}, Yi Hu\textsuperscript{1,\textsuperscript{f}}

\textsuperscript{1}School of Energy and Power Engineering, Wuhan University of Technology, Wuhan, China

\textsuperscript{a}sszhang@whut.edu.cn

\textsuperscript{*}Corresponding author: \textsuperscript{b}hbgao@whut.edu.cn

\textsuperscript{c}zglin@139.com

\textsuperscript{d}yrzhao@whut.edu.cn

\textsuperscript{e}wtugyh@163.com

\textsuperscript{f}huiwhut@163.com

Abstract—Passengers’ comfort was strongly affected by the indoor thermal environment in luxury cruise cabins. Based on the installation position of the fan coil unit (FCU), two different air supply modes were proposed. The indoor thermal environment of air-conditioning cabin in luxury cruise summer condition was simulated under Airpak environment with two different air supply modes. The temperature and velocity nephograms of two modes are discussed. The results show that up-supply up-return mode has excellent comfort and is suitable for cruise practical application.

1. INTRODUCTION
As a "mobile city on the sea" with high technology, high added value and high comfort, the luxury cruise provide passengers with high-end entertainment facilities and luxurious living environment. The passenger cabins of luxury cruise are required to provide accurate temperature control and comfortable air distribution. Therefore, the fan coil unit (FCU) and fresh air system is widely used. Passenger cabins are the main place for passengers to rest. And the living comfort of passengers is directly affected by cabins’ air distributions [1]. Air temperature field and velocity field are two main factors affecting passengers’ comfort. Classification society regulations require air temperature and velocity to be controlled within a certain range to ensure cabins comfort.

The improvement of air distribution efficiency plays an important role in improving cabins comfort. Li (2010) used Airpak software to simulate the indoor thermal environment of a small room. The results show that the displacement ventilation will supply better air quality and efficient utilization of energy as well as air supplying and returning from the top-side [2]. Liu (2011) simulated the indoor thermal environment of the ship’s crew air-conditioning cabins with three different air outlet positions. The results show that up-supply air conditioning system has good performance with little eddies and can contribute to energy saving [3]. Volintiru (2018) made analysis and modeling to optimize the air conditioning system load calculations of special ships [4]. Su (2020) studied the airflow characteristics
of the ro-ro ship passenger cabins based on Airpak software. The results show that the air supply from the radiant air conditioning system was fully utilized in a good economic effect [5].

The purpose of this paper is to study indoor thermal environment of luxury cruise air-conditioning cabins based on Airpak software. Based on the installation position of the FCU, the air supply modes of up-supply up-return and up-supply down-return were analyzed. In order to demonstrate the advantages and disadvantages of two kinds of air supply modes, a simulation model of a luxury cruise passenger air-conditioning cabin was established for numerical simulation and analysis.

2. Basic Theory of Numerical Simulation of Cabin Air Supply

It includes several steps in numerical simulation of indoor air flow, such as building mathematical and physical models; deriving control differential equations; discretizing flow control differential equations; organizing the discrete results into a system of algebraic equations; solving Algebraic Equations; obtaining air flow distribution data.

In this paper, the following assumptions are made on the air flow in the passenger cabin:

- Indoor air flow complies with Boussinesq hypothesis: Density changes do not significantly change fluid properties. The influence of density changes on the inertial force term, pressure difference term and viscous force term is negligible, and only the influence on the mass force term is considered. Indoor air physical properties can be treated as normal physical properties.

- The viscosity of indoor air cannot be ignored and is studied by the theory of viscous fluid dynamics. That is, indoor air flow is usually turbulent flow, so turbulence theory is used to simulate.

- The indoor air flow is mixed convection where natural convection and forced convection coexist, or natural convection affected by radiation heat transfer, and there is also isothermal forced flow during ventilation.

- The air conditioning system of luxury cruise passenger cabin is a closed hydrodynamic problem, which obeys three conservation laws: mass conservation law, momentum conservation law and energy conservation law.

3. Simulation Model

3.1. Research object

In this paper, a typical passenger cabin of a certain 8035 gross tonnage luxury cruise is taken as the research object, as shown in Fig. 1. Actual size of passenger cabin: 5975mm×2998mm×2100mm (length × width × net height), The size of the window: 1900mm×2058mm (width × height). The passenger cabin also includes some static items including wardrobes, bed, TV, light and two standing mannequins.

3.2. Air supply mode

The luxury cruise adopts fan coil unit and fresh air system, and the layout of the passenger cabin air outlets are restricted by the FCU. Two air supply modes were proposed according to the installation position of the FCU. In Mode 1, the FCU was installed horizontally on the top of the passenger cabin. The FCU air supply outlet was arranged in the center and top of the passenger cabin. The FCU’s air
return outlet was arranged on the top of the cabin entrance, which was a form of up-supply up-return mode, as shown in Fig. 2. In Mode 2, the FCU was installed vertically in the triangle area between the toilet unit and the corridor. The air supply outlet was arranged on the upper part of the toilet unit wall toward the side, and the air return outlet was arranged on the lower part of the toilet unit wall toward the side, which was a form of up-supply down-return mode, as shown in Fig. 3. The passenger cabin ventilation in both modes was taken through the grille at the bottom of the toilet unit door, and exhausted through the air outlet on the top of the toilet unit.

Figure 2 The 3D Model 1 of passenger cabin air supply.

Figure 3 The 3D Model 2 of passenger cabin air supply.

According to the above two air supply modes, the models are appropriately simplified, and the simulation models are built in the Airpak environment, as shown in Fig. 4.

Figure 4 Simulation models of different air supply modes in the passenger cabin.
3.3. Boundary condition setting

3.3.1. Physical boundary conditions
- Luxury cruises have high requirements for comfort, and the passenger cabins require personalized temperature adjustment. The working condition in summer requires a minimum temperature of 22°C. This paper takes the working conditions in summer as an example to set the boundary conditions as follows:
  - The right side is bulkhead exposed to sun’s, and the outdoor air temperature is set to 35°C, as shown in Fig. 1. All other bulkheads are adjacent to the air-conditioning area and set up as a heat-insulating surface. The large area of bulkhead exposed to sun’s adopt glass sliding doors with shading effect. The solar heat gain coefficient (SHGC) value of the glass sliding doors is 0.4, and the heat transmission coefficient of the glass sliding doors is 140W/m2.
  - The air outlet temperature of FCU is 13°C, and the air outlet velocity of FCU is 2m/s. The return air outlet temperature of FCU is 22°C, and the return air outlet velocity of the FCU is 0.55m/s. The fresh air volume is 30 m3/p/h.
  - The ventilation of the toilet unit is the natural return air under the conditions of the ambient pressure and temperature of the passenger cabin.
  - Room lighting is provided by a fluorescent lamp with a calorific value of 8W/m2. There are two human body models with heat load of 120W/p and a TV model with a heat load of 60W.

3.3.2. Mathematical boundary conditions
- Airpak software commonly used turbulence models such as zero equation model, Indoor zero equation model, Two equation model, RNG model, Spalart-Allmaras model. The luxury cruise cabins belong to indoor air flow, and the indoor air flow field changes smoothly. Therefore, this paper adopted the indoor zero equation model to simulate.
  - A hexahedral coarse grid is adopted as the computational grid.
  - The finite volume method is adopted to discrete the control equations, and the discrete format is a first-order upwind scheme. The mesh refinement was carried out for the positions of air supply outlet, air return outlet and heat source. The number of grids in Model 1 and 2 was 644593 and 869971 respectively.
  - The number of iterations was 500 times.
  - Steady-state calculation was adopted.

4. COMPARATIVE ANALYSIS OF THE TWO MODES
Det Norske Veritas (DNV) regulations have related requirements for the indoor thermal environment of passenger ship cabin, including temperature, air velocity, minimum fresh air volume, and vertical temperature difference, as shown in Table 1. The type of cabins listed as shown in Table 2. In this paper, the models of two air supply modes were simulated and calculated. The temperature, vertical temperature difference, and air velocity in the X, Y, and Z directions of both modes were compared and analyzed. The typical planes in the three directions of X/Y/Z (YZ plane at X=2m, XZ plane at Y=1.5m, XY plane at Z=1.5m) were used to analyze and explain the problem.

| Designated cabin type | Comfort rating number | Minimum air temperature control span* | Maximum air velocity | Minimum fresh air supply quantity per person | Vertical air temperature difference |
|-----------------------|-----------------------|---------------------------------------|----------------------|---------------------------------------------|-----------------------------------|
|                       | crn                   | 15°C and below(outside) 40°C and above(outside) | Min./Max. limit (°C) | Min./Max. limit (°C) | m/s | m3/h | °C |

Table I Air properties and quality at different localities and comfort standard[6].
**Table II Classification of accommodation spaces[6].**

| Type | Classification |
|------|----------------|
| A    | Cabins         |
| B    | Hospital and Ward rooms |
| C    | Wheel house, Control rooms, Office areas and public spaces intended for low physical activity such as Conference rooms, Libraries, Card rooms, Seating areas, etc. |
| D    | Public spaces intended for high physical activity such as Show lounges, Dining areas, Atriums, Casinos, Shopping areas, Bars, Dance lounges, Discos, Gymnasiums, etc. |

*For outside temperatures between 15°C and 40°C, the control span is to comply with the graphs shown in Fig. 5.*

**Figure 5 Temperature control span, designated space type A and B.**

### 4.1. Temperature nephogram analysis

The simulation results are shown in Fig. 6. The vertical temperature difference is relatively gentle, the temperature in the cabin is approximately in the range of 21°C–23°C, and the temperature gradient is small as shown in Fig. c) and Fig. c). The temperature in the personnel activity area is uniform as shown in Fig. a). The Mode 1 meets the regulations and design requirements. The temperature rises vertically upwards, and the temperature distribution is evenly within the vertical distance of 0m to 1.2m in the range of 21.5°C to 22.5°C as shown in Fig. d) and Fig. f). However, the temperature above 1.5m shows a gradual upward trend, and the temperature reaches 25–26°C in the range of 1.8m–2.1m. The temperature in the area near the bulkhead exposed to sun’s is higher, ranging from 25°C to 26°C as shown in Fig. b) and Fig. d). The temperature distribution in the personnel activity area is uneven, the horizontal temperature gradient is about 3°C, and the horizontal and vertical temperature gradients in the Mode 2 are both large as shown in Fig. b).
a) Mode 1 (XZ plane at Y=1.5m).

b) Mode 2 (XZ plane at Y=1.5m).

c) Mode 1 (XY plane at Z=1.5m).

d) Mode 2 (XY plane at Z=1.5m).

e) Mode 1 (YZ plane at X=2m).
4.2. Velocity nephogram analysis

The simulation results are shown in Fig. 7. The air velocity of the air supply Mode 1 at the air outlet is higher, and then gradually decreases as shown in Fig. a), Fig. c), and Fig. e). In the main area of personnel activities, the air velocity is 0.1 m/s ~ 0.2 m/s, which will not produce a blowing sensation to the human body. The Mode 1 meets the requirements of the regulations. The air velocity of the air supply Mode 2 at the air outlet is higher, and then gradually decreases as shown in Fig. b), Fig. d), and Fig. f). However, the air velocity is relatively high in the local area of personnel activities, the air velocity is as high as 0.5~0.6 m/s and it has a blowing sensation to human body. The velocity gradient air supply Mode 2 is larger than the air supply Mode 1.
5. CONCLUSION

Different air supply modes have their own advantages and disadvantages. The Mode 2 is convenient for maintenance and management, and can shorten the length of the air duct to save costs. The FCU of the Mode 2 is far away from the passengers. The indoor noise level of the Mode 2 is better than air supply the Mode 1. The Mode 1 can also prevent the leakage of condensate from the FCU and damage the room decoration. However, the Mode 1 has better control effects on the temperature and air velocity in the passenger cabin, and the vertical temperature difference, temperature gradient and velocity gradient in the personnel activity area are smaller. Although the economy and noise level of the Mode 2 are better than that of the Mode 1, comprehensive economy and comfort of the Mode 1 is more recommended as the practical application of luxury cruise.

ACKNOWLEDGMENT

High Technology Ship Scientific Research Funded by the Ministry of Industry and Information Technology in 2018 (MC-201918-C10)—(Research of the Key Technology of Design and Construction of Polar Small Cruise Ship).

REFERENCES

[1] H. Q. Qi, Z. Y. Li, L. H. Zhou, “Numerical analysis of air environment comfort in ship accommodation cabin”, Chinese Journal of Ship Research, vol.13, pp.93-98, 2018.
[2] Y. L. Li, H. L. Tian, J. C. Gao, “Numerical research on indoor airflow organization and air quality”, Building Energy Efficiency, vol.38, pp.17-22, 2010.
[3] H. M. Liu, “Simulation and Optimization of Indoor Thermal Environment in a Ship Air-
conditioning System”, Proceedings of 2011 2nd International Conference on Challenges in Environmental Science and Computer Engineering (CESCE 2011 Part C), Intelligent Information Technology Application Association: Society for the Application of Intelligent Information Technology, vol.11, pp.1055-1063, 2011.

[4] O. N. Volintiru, I. C. Scurtu, T. M. Stefănescu, “Modeling and optimization of HVAC system for special ships”, Journal of physics. Conference series, vol.1122, 2018.

[5] S. C. Su, J. M. Chen, Y. T. Zou, Z. G. Gao, J. Y. Wang, H. Shi, “Numerical simulation on cabin airflow distribution of Ro-ro passenger ship”, Science Technology and Engineering, vol.20, pp.4141-4148, 2020.

[6] DNV, “DNV Rules for Classification of Ships”, DNV, 2014.