Simulation optimization and experiment evaluation of air distribution mode for special cabin

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Abstract

The design of air distribution system in a submarine submerged for long periods often faces many constraint conditions. In order to optimize its cabin airflow field, a full-scale experimental bedroom cabin with three three-layer beds was built, and a Flow Visualization with Green Laser (FVGL) method was used to evaluate two types of air distribution mode. Experimental results show that Mode 2 with six individual air vents for lower beds could improve the air quality and heat sensation at lower beds. However, its strong sensation of draft at upper beds could not be avoided. In order to solve this problem, a multi-objective optimal method was built to search the optimal positions of top diffusors. Air age and Predicted Mean Vote (PMV) were chosen as the objective functions. The Micro-Genetic Algorithm (Micro-GA) was used in the presented optimization method to obtain the Pareto-Optimal Front (POF). Finally, the preferred positions of top diffusors can be determined from the POF.

Keywords

Air distribution system; Underwater cabin; Thermal comfort; FVGL; Micro-GA; Optimization.

1. Introduction

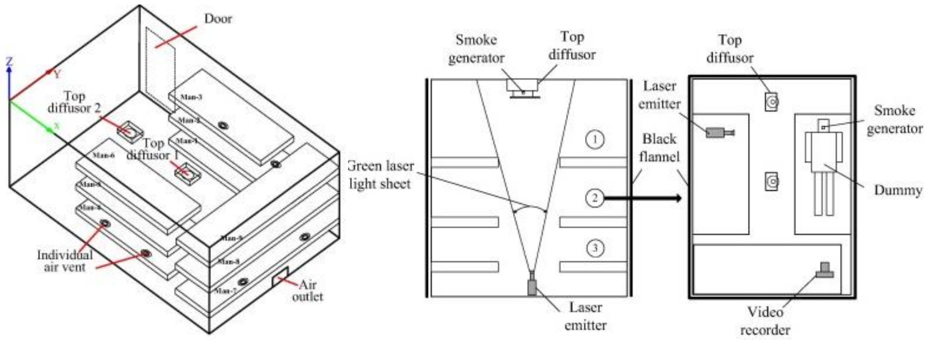
It is impossible for submarine to get fresh air from the outside atmosphere, so its has to totally recirculate its cabin air by purification, refrigeration and regeneration treatments [1]. Compared with some civilian spaces, the cabin environment in submarine submerged for long period often faces the following problems [2] [3] [4]: high crew density, low refrigeration capability and insufficient amount of fresh air. It is necessary to reasonably design its air distribution system, and form a good airflow field to satisfy the requirements of air speed, temperature and air quality.

Many scholars researched the air distribution modes [5] [6] [7]. Liu conducted a field questionnaire survey about the cabin thermal comfort. Zhang compared three types of air distribution modes. Chen evaluated the influence of supply angles using simulation method. Few researches conducted optimization study on the positions of air diffusors, although they impact the cabin air distribution greatly.

The traditional top-in-side bottom-out air distribution mode is widely used for high crew density spaces. Many scholars used experimental and simulation methods to investigate air distribution performance in these spaces [8 [9] [10] [11] [12]. They attempted to improve the traditional displacement and mixing ventilation system. Kabanshi introduced an intermittent air supply system to save energy and simulate airflow which had some similar characteristics to natural wind [13]. Results showed that the intermittent air supply system could save energy, increase ventilation efficiency and still satisfy thermal comfort. Lobentanz et al. focused on the air distribution in the sleeping space in bedrooms to evaluate the thermal comfort and air quality around occupants [14] [15] [16] [17]. Some new air distribution modes have been proposed in these years. Chen et al. researched the individual air vent in the airplane cabin [18] [19] [20] and hoped to increase the utilization of the fresh air around occupants.

2. Experimental

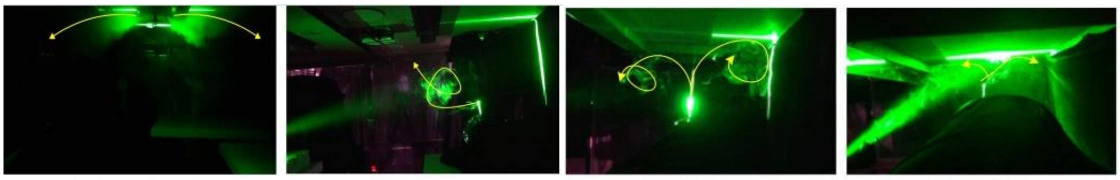
The experimental facility using FVGL method was set up to survey the airflow in the underwater bedroom cabin as shown in Fig. 1. Airflow field in two regions, Region 1 and Region 2, was observed and recorded carefully in the experiments. The FVGL method consists of three primary parts: a smoke generator, a video recorder and a laser emitter. The smoke generator releases white smoke by heating glycerol. The laser emitter produces a green laser sheet by cooperating with a cylindrical lens installed in front of the laser output mirror. The Sony video recorder records the entire process of airflow in the cabin.



(a) Cabin layout (b) Experimental layout for Region 1 (c) Experimental layout for Region 2

Fig. 1. Experimental layout for FVGL.

The experimental results in Mode 1 are shown in Fig. 2(a). White smoke, generated by smoke generator in the top diffusors, was taken away by the supply air and sprayed into the cabin directly. The supply air was blew out from the top diffusors, and then delivered to each bed. However, since the amount of supply air for the upper beds was much more than need, so the supply air still had a high kinetic energy at the upper beds after it reached the side wall. This absolutely leaded to a good clearance of CO2, but caused a high air velocity around the body and strong sensation of draft at the upper beds.



(a) airflow of top diffusor (b) upper bed (c) middle bed (d) lower bed

Fig. 2. Experimental results of airflow in Mode 1.

Fig. 3 shows the experimental result at lower bed in Mode 2. The motion of airflow was increased and the accumulation of CO2 was reduced greatly. At the same time, the sensation of draft at the lower beds can be acceptable.

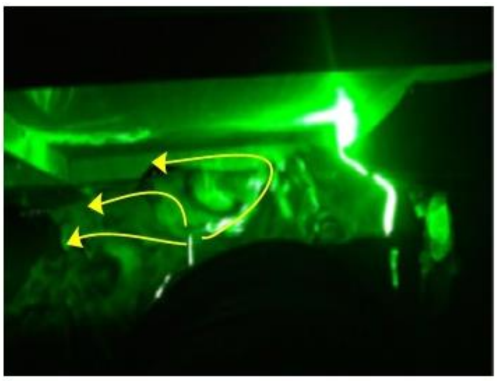


Fig. 3. Experimental result at lower bed in Mode 2.

In the following CFD optimization, the two top diffusors have the same boundary conditions. Constraint is built to avoid unexpected stop of CFD simulation, as shown in Fig. 4.

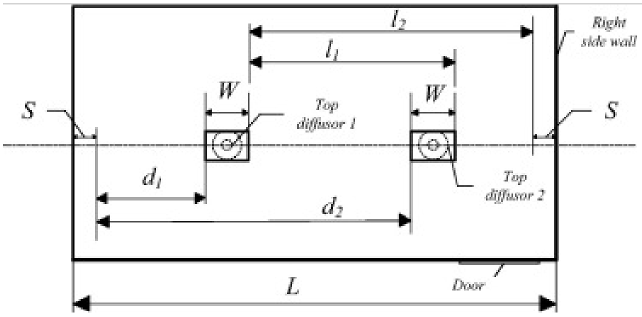


Fig. 4. Positions of top diffusors.

In this paper, the results of multi-objective function are different from the one of single objective function. The solution of multi-objective function is a solution set, which is named as POF. Since the mesh of the studied CFD model is huge, simulation calculation just for one model is already time consumption. While our study is to search the optimal results from multiple CFD calculations. Therefore, an optimization strategy, Micro-GA, is used to locate the POF. Micro-GA has high convergence efficiency [21] [22]. It realizes the optimal process by controlling the number of CFD calculations by Macro command. The whole procedure is shown in Fig. 5.

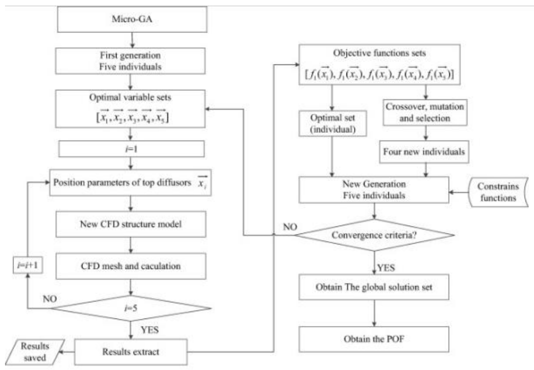


Fig. 5. Optimal procedure.

The CFD simulation will be used in our optimization, so it is compulsory to validate the models through experimental test before using for further evaluation. We measured more than one hundred of velocity points in Mode 2. The cabin air velocity was generally small, so their average values were used for comparison. The velocity measurement instrument was the Testo anemometer with about 5% error. In this paper, we only give the measured velocity data in three cross-sections along the Y-direction, as shown in Fig. 6(a).

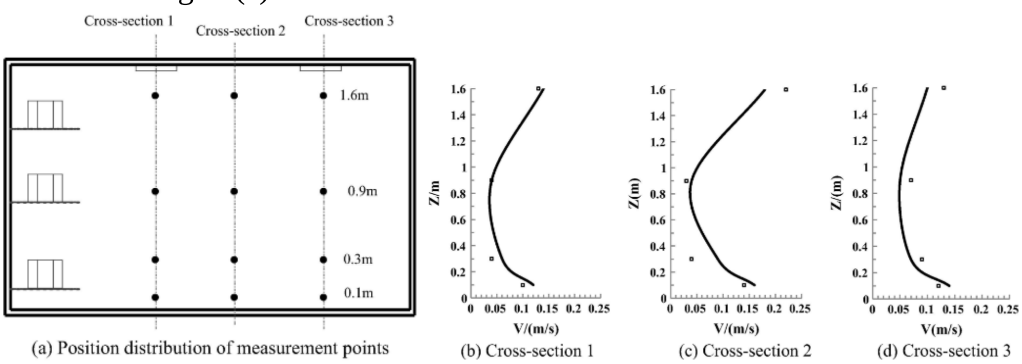


Fig. 6. Air velocity comparison between simulation and experiment results in three cross-sections.

Fig. 6(b)–(d) shows the comparison between simulation and measured data. The continuous curve represents the simulation data, and the square discrete points represent the measured data. Fig. 6 indicates the simulation results have good agreement degree with the experimental results, and the accuracy can be accepted.

3. Results and discussion

The optimization method obtains 41 CFD simulation results when it meets the convergence condition. A 2-D scatter figure of the optimization results is drawn in Fig. 7 for a clear observation. The point features, size and color, indicate which generation the point belongs to. For example, Generation 1 includes the points with the biggest size and white color. Meanwhile, Generation 10 includes the points with the smallest size and blue-black color.

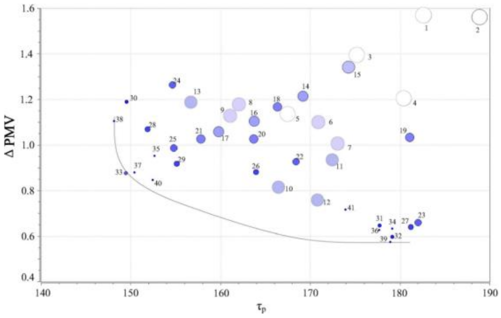
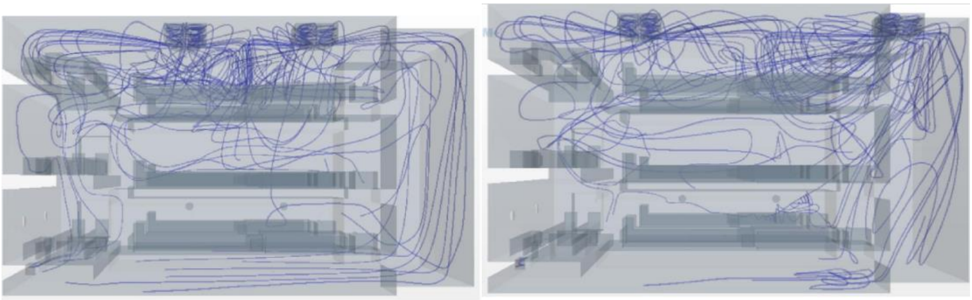


Fig. 7. 2-D scatter plot of optimization results.

The CFD simulation results of the two modes are shown in Figs. 8–10. Compared with Mode 2, Mode 3 has two changes:

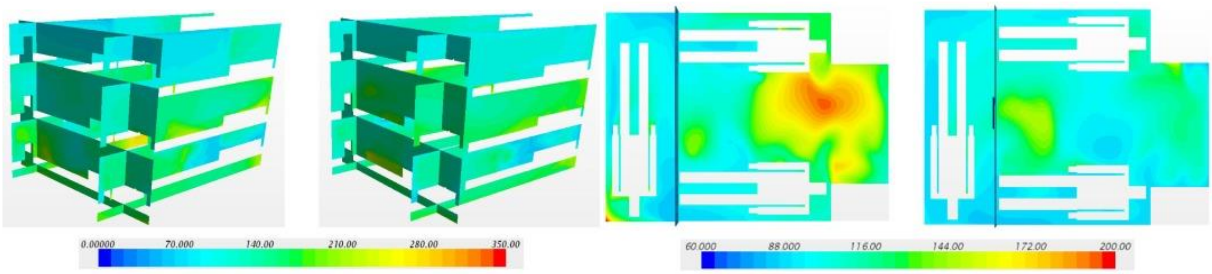
•Top diffusor 1 moves inside near to Man 9.

•Top diffusor 2 is no longer in the middle of cabin but moves 0.8 m toward the door.



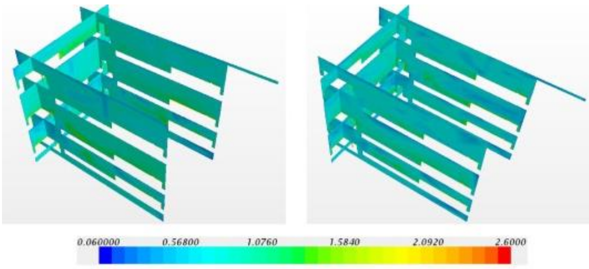
(a) Mode 2 (b) Mode 3

Fig. 8. Comparison of streamlines from top diffusors.



(a) Mode 2 (b) Mode 3 (c) Upper beds in Mode 2 (d) Upper beds in Mode 3

Fig. 9. Comparison of the distribution of air age.



(a) Mode 2 (b) Mode 3

Fig. 10. Comparison of PMV distribution.

Fig. 9 shows the distribution of air age in the two modes. The air age in Mode 3 is more uniform than in Mode 2. The chest parts of Man 3 and Man 6 in Mode 2 have low air age, but they suffer strong sensation of draft. However, this problem can be solved largely in Mode 3.

Fig. 10 shows the PMV distribution. Mode 2 has obvious cold boundary at upper beds because the incorrect positions of top diffusors. In Mode 3, the cold boundary disappears greatly at the upper beds, and relative uniform PMV distribution can be formed.

Specifically for the upper beds, Fig. 11 further presents the air velocity comparison at the monitored points. Compared with Mode 2, the air velocity values decline around Man 3 and Man 6, and slightly increase around Man 9 in Mode 3. This uniform distribution of air velocity around occupants can bring a comfort sensation for all the occupants at upper beds.

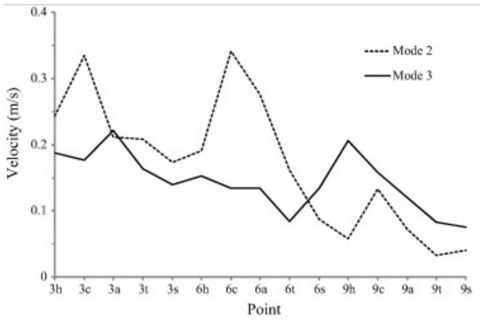


Fig. 11. Comparison of air velocity values at upper beds.

4. Conclution

In order to obtain the optimal positions for the top diffusors in Mode 2, a multi-objective optimal method combining Miro-GA and CFD simulation were further performed. The objective functions were specified as air age and PMV. Finally, the preferred air distribution mode, Mode 3, was selected from the POF of the multi-objective optimal solution set. The simulation results indicated that Mode 3 can effectively solve the problem of strong sensation of draft at upper beds, and increase the uniformity of air distribution.

Acknowledgements

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References

[1] Zhi-jie Zhou, Ren-yi DongThermal management of submarine cabins Chin. J. Ship Res. (Feb) (2010)

[2] L.Y. He, S.N. JingAnalysis and control of the common disease during the submarine voyage J. Navy Med., 23 (3) (2002), pp. 216-217

[3] X.H. Le, G.G. Chen, D.C. Wang, et al.Effects of 60-day navigation on a new-type diesel submarine on physical tolerance and psychological ergonomics of submarines J. Prev. Med. Chin. People's Liberation Army, 17 (4) (1999), pp. 246-250

[4] Yidong Lu, et al.Cabin ventilation system on offshore working tug J. Ship Des. (2) (2005)

[5] Hongmin Liu, Jiujian Ni, et al.An investigation and analysis of indoor environment in air-conditioned Chinese ship vessel cabins Indoor Built Environ., 20 (3) (2011), pp. 377-385

[6] Weidong Zhang, Shichong Wang, et al.The technology of air-conditioning and ventilation optimization in ship chambers Ship Sci. Technol., 33 (2) (2011)

[7] Jianbo Chen, Wei Wang, et al.Study on hot air distribution of ship cabin air-conditioning Procedia Eng., 121 (2015), pp. 1420-1427

[8] ChangWei Yang, XiWen Zhang, et al.Numerical study of the instantaneous flow fields by large eddy simulation and stability analysis in a single aisle cabin model Build. Environ., 96 (2016), pp. 1-11
[9] Yang Wang, Jens Kuckelkorn, et al.Evaluation on classroom thermal comfort and energy performance of passive school building by optimizing HVAC control systems Build. Environ., 89 (2015), pp. 86-106
[10] Daniel Risberg, Mattias Vesterlund, Lars Westerlund, Jan DahlCFD simulation and evaluation of different heating systems installed in low energy building located in sub-arctic climate Build. Environ., 89 (2015), pp. 160-169
[11] Mohammad Hassan Fathollahzadeh, Ghassem Heidarinejad, Hadi PasdarshahriPrediction of thermal comfort, IAQ, and energy consumption in a dense occupancy environment with the under floor air distribution system Build. Environ., 90 (2015), pp. 96-104
[12] Weiqin Wu, Zhang LinAn experimental study of the fluence of a walking occupant on three air distribution methods Build. Environ., 85 (2015), pp. 211-219
[13] Alan Kabanshi, Hans Wigo, Mats SandbergExperimental evaluation of an intermittent air supply system – Part : thermal comfort and ventilation efficiency measurements Build. Environ., 95 (2016), pp. 240-250
[14] I.S. Lobentanz, S. Asenbaum, K. Vass, C. Sauter, G. Klosch, H. Kollegger, W. Kristoferitsch, J.ZeitlhoferFactors influencing quality of life in multiple sclerosis patients: disability, depressive mood, fatigue and sleep quality Acta Neurol. Scand., 110 (1) (2004), pp. 6-13
[15] K. Tsuzuki, K. Okamoto-Mizuno, K. Mizuno, T. IwakiEffects of airflow on body temperatures and sleep stages in a warm humid climate Int. J. Biometeorol., 52 (4) (2008), pp. 261-270
[16] M. MiyazawaSeasonal changes of sleep environment at bedtime and on arising Proceedings of the 18th Symposium on Human-Environment System, Tokyo, Japan (1994), pp. 187-189
[17] D. Pan, S. Deng, Z. Lin, M.Y. ChanAir-conditioning for sleeping environments in tropics and/or sub-tropics – a review Energy, 51 (2013), pp. 18-26
[18] T. Zhang, Q. ChenNovel air distribution systems for commercial aircraft cabins Build. Environ., 42 (4) (2007), pp. 1675-1684
[19] T. Zhang, P. Li, S. WangA personal air distribution system with air terminals embedded in chair armrests on commercial airplanes Build. Environ., 47 (1) (2012), pp. 89-99
[20] T. Zhang, S. Yin, S. WangAn under-aisle air distribution system facilitating humidification of commercial aircraft cabins Build. Environ., 45 (2010), pp. 907-915
[21] D.E. GoldbergGenetic Algorithm in Search Optimization, and Machine Learning Addison Wesley Publishing Company (1988)
[22] S.W. ParkOptimization of combustion chamber geometry for stoichiometric diesel combustion using a micro genetic algorithm Fuel Process. Technol., 91 (2010), pp. 1742-1752