Improving Thermal Comfort in Aircraft Cockpit Based on Optimization of Supply Air Grille

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Abstract. Pilot’s thermal comfort and performance are directly affected by air flow field and temperature field in cockpit. A three-dimensional cockpit model of a certain civil aircraft is established, and the distribution of air velocity and temperature is obtained with the method of computational fluid dynamics (CFD). Aiming at the problems of high local air speed and uneven temperature distribution in the cockpit, two new supply air grilles are proposed. The results show that one of the grilles can obviously optimize air flow field and temperature in the cockpit and improve the thermal comfort of the pilots.

Keywords: Cockpit environment, Thermal comfort, Supply air grille, Air flow field, Temperature field.

1. Introduction
The environment in the cockpit, such as air velocity and temperature, is closely related to the thermal comfort of the pilots. If the comfort in the cockpit is not good, the work efficiency of the pilots will be reduced, and even the flight safety will be affected.

Nevertheless, researches show that the comfort of the environment in aircraft cabin is not satisfactory [1, 2]. For civil aircraft cockpit, the problem of thermal discomfort is even more seriously. For one thing, the internal space of cockpit is small, and there are many kinds of electronic equipment and instruments, so the size and position of air supply inlets are subject to various restrictions. For another, pilots have higher requirements for fresh air, and considering the thermal load of various electronic equipment in the cockpit, the demand for ventilation flow in the cockpit is larger. The above reasons lead to the problems of high local wind speed and uneven temperature distribution in the cockpit of civil aircraft, which leads to the poor thermal comfort of the cockpit environment.

In recent years, large amounts of researches have tried to improve thermal comfort in aircraft cabin. Liu et al [3] studied passengers’ thermal sensation in a newly designed aircraft cabin at 39,800 ft (12,131 m) cruise height in summer conditions, Lei [4] et al proposed a combined inverse-forward model to determine the total underfloor heating rates and the air-supply temperature in an aircraft cabin, Hu and You [5] searched the optimal air supply parameters of a MD82 first-class cabin by a multi-objective particle swarm optimization (MOPSO), and they further determined the optimal range of air supply parameters. However, most of the research focus on passengers’ comfort in cabin, few public studies on the improvement of cockpit comfort are found.
In order to solve the problem of poor thermal comfort in the cockpit, this paper analyzes the distribution of flow field and temperature field of a certain civil aircraft cockpit. On this basis, the scheme having the least impact on the cockpit configuration is put forward, that is, the change of the cockpit air supply grille. In this paper, two kinds of new grille are put forward to improve the distribution of flow field and temperature field. The simulation results show that both the two kinds of new grille are helpful to make the flow field and temperature field more uniform, and one of the new grilles is promising to improve the thermal comfort significantly.

2. Description of the design scenario

2.1. Design objectives

The objective of this paper is to improve the thermal comfort in cockpit at the minimum cost. The evaluating parameters of thermal comfort include local air speed, zone temperature and temperature spatial variations. According to ASHRAE standards [6], the acceptable thermal comfort evaluation indexes are as shown in Table 1, some description is adjusted to apply to actual state of the cockpit.

Table 1. The acceptable thermal comfort evaluation indexes

| Parameter                  | Acceptable Condition                                                                 |
|----------------------------|--------------------------------------------------------------------------------------|
| Zone Temperature           | Target operative temperature range, in-flight and ground operations: 65°F to 75°F (18.3°C to 23.9°C) |
| Local Air Speed            | Seated persons: <70 ft/min (<0.36m/s) Draft sensitive bare body areas: <60 ft/min (<0.3 m/s) |
| Temperature Spatial        | Horizontal operative temperature variation: <8°F (4.4°C)                               |
| Variations                 | Vertical operative temperature variation within a seat: <5°F (2.8°C)                   |
|                            | variation in temperatures measured at 4 in., 24 in., and 43 in. (100 mm, 610 mm, and 1090 mm). |

2.2. Design scenario

The options to improve the thermal comfort in cockpit usually include: increasing the size and number of air supply inlets, optimizing the layout of air supply inlets, changing the direction of air supply, etc. In engineering practice, the cockpit inlet is subject to too many restrictions, which often makes it difficult to implement most of the above schemes. For example, the change of inlet layout will inevitably lead to the change of cockpit inner structure, indirectly affect the layout of other equipment.

In comparison, it is a practical and effective method to optimize the air supply direction by changing the air supply grille in the cockpit, so as to improve the layout of the flow field and temperature field in the cockpit.

The original air supply grille style of a certain civil aircraft cockpit is shown in Figure 1 (a). In the early design, the angle of the grille has been optimized. Due to the requirement of minimum fresh air amount and the limitation of cockpit space, the air supply grille cannot be designed as an adjustable form. So, the focus of this paper is not to optimize the angle of the grille, but to put forward two new type grille form. The two new grilles aim at solving the two prominent discomfort problems, that is the uneven distribution of flow as well as temperature field, and the high local air speed. The two new grilles are shown in Fig. 1 (b) and (c). It should be noted that grille b) has two air supply directions, which avoids the cockpit air supply too concentrated in one direction, and is conducive to even distribution of the flow field and temperature field. Grille c) not only has two air supply directions, but also has side air supply, which increases the effective air supply area and further reduces the local air speed.
3. Simulation model

3.1. Geometric model
In order to facilitate the computational fluid dynamics (CFD) simulation, the general three-dimensional model of the aircraft cockpit is simplified as shown in Figure 2. In addition, three manikin models are added to represent two pilots (captain and co-pilot) and one observer in cockpit.

Figure 1. The original air supply grille and two new grills.

Figure 2. The simplified geometric model of a certain civil aircraft cockpit

For a certain civil aircraft cockpit, almost all the air to adjust the cockpit temperature and air speed is from the main air supply inlet. There are two main air supply inlets, locating on the top ceiling of the cockpit, as is shown in Figure 2.

3.2. Governing equations and parameter setting
The field distributions of air velocity and temperature are obtained by computational fluid dynamics (CFD) calculation. The basis of CFD can be summarized as the following equations:

$$\frac{\partial}{\partial t}(\rho \phi) + \sum_{j=1}^{3} \frac{\partial}{\partial x_j}(\rho u_j \phi) = \sum_{j=1}^{3} \left( \Gamma_{\phi} \frac{\partial \phi}{\partial x_j} \right) + S_{\phi}$$

(1)

Where $\rho$, $t$, $\Gamma_{\phi}$, $S_{\phi}$ are air density, time, diffusion coefficient and source term respectively, $u_j$ is velocity component in three directions ($x_j$, $j = 1, 2, 3$). When $\phi$ stand for different values, equation (1) can represent continuity, momentum and energy equations.
In this study, the numerical simulations are conducted by using the CFD software Star-CCM+. The air in the cockpit is assumed to be incompressible Newton viscous gas, and the fluid is steady turbulence. The main physical model settings are shown in Table 2.

### Table 2. The CFD parameter setting

| Parameter | Physics Model |
|-----------|---------------|
| Enabled Models | Three Dimensional |
| Time | Steady |
| Material | Gas |
| Flow | Segregated Flow Gradient |
| Equation of State | Constant Density |
| Viscous Regime | Turbulent Reynolds-Averaged Navier-Stokes |
| | | K-Epsilon Turbulence |
| | | Realizable K-Epsilon Two-Layer |
| | | Exact Wall Distance |
| | | Two-Layer All y+ Wall Treatment |
| Optional Models | Segregated Fluid Temperature |
| | Gravity |
| | Boussinesq Model |
| | Gray Thermal Radiation |

#### 3.3. Mesh generation

In this paper, all the simulation meshes are generated by the CFD software Star-CCM+. The main meshing strategies include Surface Remesher, Automatic Surface Repair, Polyhedral Mesher, Prism Layer Mesher, and so on. The basic mesh size is 0.01m, and more denser and smaller meshes are generated near particular zones, such as zones near the air supply inlet or pilots. The final generated meshes are shown in Figure 3.

![a) Overview of the cockpit meshes](image1)

![b) Meshes on the manikin model](image2)

**Figure 3.** Meshes of the CFD model

#### 4. Results and discussion

In order to quantitatively compare the performance of the three air supply grilles, three cross section are selected. As shown in Fig. 4, the three cross sections include two vertical sections and one horizontal section, respectively representing the vertical and horizontal distribution of air flow or temperature in cockpit.
4.1. Air flow field

Fig. 5 presents the air flow distribution near captain and co-pilot on the air supply condition of different grilles.

Fig. 5(a) shows the air flow field on the condition of original air supply grille, it can be seen that the local air speed reaches about 0.3 m/s to 0.4 m/s in the area near two pilots’ head, which is a little high compared to the acceptable condition (draft sensitive bare body areas <0.3 m/s). Besides, the local air speed around and below the two pilots’ waist is about 0.4 m/s to 0.6 m/s, which is also above the acceptable condition (<0.36 m/s). Therefore, on the condition of original air supply grille, the captain and co-pilot are likely to feel the draft sensation, which can result thermal discomfort.
Fig. 5(b) shows the air flow field on the condition of grille b). Compared with Fig. 5(a), the local air speed around and below the two pilots’ waist is decreased. However, the local air speed increased near two pilots’ head, which could lead to more strong draft sensation.

Fig. 5(c) shows the air flow field on the condition of grille c). Compared with Fig. 5(c), the local air speed is decreased to about 0.3 m/s or less in the area near two pilots’ head, and the local air speed is also obviously decreased around and below the two pilots’ waist, barely meet the acceptable condition.

Fig. 6 presents the air flow distribution near the observer on the air supply condition of different grilles. Similar to the above analysis, it can be seen in Fig. 6(a) that the local air speed near observer is about 0.5 m/s to 0.8 m/s, which means strong draft sensation to the observer on the condition of original air supply grille. Compared with Fig. 6(a), the local air speed in Fig. 6(b) and Fig. 6(c) is about 0 to 0.3 m/s, both meeting the acceptable thermal comfort condition, which means grille b) and grille c) can improve the thermal comfort of observer from the point view of draft sensation.

Figure 6. Air flow distribution near the observer

Combing the above two points, on the air supply condition of original air supply grille, the local air speed near three pilots is too high, and thus leads to discomfort. On the air supply condition of grille b), the air flow field near captain and co-pilot is not improved, but local air speed near observer is decreased. On the air supply condition of grille c), the local air speed near three pilots decreased obviously and barely meet the acceptable condition.

4.2. Temperature field

Fig. 7 presents the temperature distribution near captain and co-pilot on the air supply condition of different grilles.

Fig. 7(a) shows the temperature field on the condition of original air supply grille, it can be seen that the temperature is mainly distributed in the range of 19 ℃ to 23 ℃, except limited areas clinging to the pilots. This limited local high temperature is mainly caused by heat dissipation of pilots, and thermal comfort should be evaluated by the temperature beyond the boundary layer. Therefore, the temperature range is accepted. Besides, the temperature in the height near pilots’ head, waist, and ankle is about in the range of 21 ℃ to 23 ℃, which means the vertical temperature variation is in acceptable range (vertical operative temperature variation within a seat <2.8 ℃).

Similarly, in Fig. 7(b) and Fig. 7(c), the temperature range and vertical temperature variation is also in acceptable range. However, temperature in Fig. 7(b) and Fig. 7(c) seems to more uniform than in Fig. 7(a). Therefore, on the air supply condition of grille b) and grille b), the vertical temperature range and temperature variation are in thermal comfort range, and even better than that using original air supply grille.
Fig. 8 presents the temperature distribution near the observer on the air supply condition of different grilles. Similar to the above analysis, the vertical temperature range and temperature variation are in thermal comfort range on the air supply condition of any of three grilles. However, the temperature variation in Fig. 8(b) is larger than in Fig. 8(a) and Fig. 8(c), and temperature variation in Fig. 8(b) is less than in Fig. 8(a). Therefore, the grille c) is the most likely to make the observer feel thermal comfort.
Fig. 9 presents the temperature distribution in horizontal cross section in cockpit on the air supply condition of different grilles. In Fig. 9(a), on the condition of original air supply grille, some local high temperature areas exist, but the area is small and not close to pilots. And the temperature in the front side (near captain and co-pilot) is higher than that in the behind side (near the observer). This is because almost all kinds of the electronic equipment are placed in the front side of cockpit, such as electronic display screen. In addition, the front side is the mainly solar area, so the front side tends to be more high temperature. However, the temperature variation is in acceptable range (horizontal temperature variation $<4.4\, ^\circ C$). Similarly, in Fig. 9(b) and Fig. 9(c), the temperature range and horizontal temperature variation is also barely in acceptable range.

However, temperature in Fig. 9(b) seems to more uniform than in Fig. 9(a), and temperature in Fig. 9(c) is the most uniform. Therefore, on the air supply condition of grille b) and grille b), the horizontal temperature range and temperature variation are in thermal comfort range, and grille c) is the most likely to make the pilots feel thermal comfort.

**Figure 9.** Temperature distribution in the horizontal cross section

5. Conclusions

In this study, two kinds of new grille are put forward to improve the thermal comfort in the cockpit, and air flow temperature distribution on the air supply condition of different grilles are obtained with CFD simulations.
The results confirmed the problems of local high air speed and temperature variation in cockpit on the condition of original air supply grille. It should be noted that air speed near the observer is about 0.5 m/s to 0.8 m/s, which could lead to strong draft sensation.

Both the two kinds of new grille are helpful to make the flow field and temperature field more uniform, and the local air speed near pilots can be decreased to acceptable range on the air supply condition grille c), which means the thermal comfort can be improved significantly in cockpit.

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