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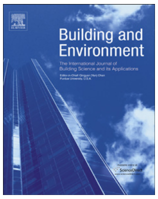

Investigating the impact of gaspers on cabin air quality in commercial airliners with a hybrid turbulence model

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ABSTRACT

It is not clear whether turning on the gaspers in the cabins of commercial airliners actually improves the air quality. To answer this question, this study first developed a hybrid turbulence model which was suitable for predicting the air distribution in an aircraft cabin with gaspers turned on. Next, the investigation validated the model using two sets of experimental data from a cabin mockup and an actual airplane. This study then used the validated model to systematically investigate the impact of gaspers on cabin air quality in a seven-row section of the fully-occupied, economy-class cabin of Boeing 767 and 737 airplanes. The CFD calculations formed a database consisting of 9660 data points that provide information about SARS infection risk. It was found that the distribution of opened gaspers can influence the infection risk for passengers. Even though the gasper supplies clean air, it is possible for it to have a negative impact on the passengers' health. Statistically speaking, the overall effect of turning on the gaspers on the mean infection risk for the general population was neutral.

1. Introduction

In commercial airliners, a strong association has been observed between cabin airflow patterns and the transmission of airborne infectious diseases [1]. These diseases include influenza [2], tuberculosis [3], and severe acute respiratory syndrome (SARS) [4]. With the rapid increase in air travel [5], improving cabin air quality has become crucial to public health. In commercial airplanes, personalized ventilation is typically provided by a system of gaspers, the small, circular, and adjustable vents above the seats passengers. When passengers turn on the gaspers, the air distribution in the cabin is altered [6,7]. Consequently, the transport of airborne infectious contaminants is affected [8]. It is important to investigate the impact of gaspers on cabin air quality in commercial airliners in order to evaluate the effectiveness of gasper-induced ventilation in reducing the risk of infection.

A number of studies have measured the airflow distribution of a jet from a gasper. For example, Dai et al. [9] used a high-precision hotwire anemometer to measure the velocity magnitude and turbulence intensity in the flow field of a gasper-induced isothermal flow. They found that the flow field was complex near the nozzle but could be simplified as a round jet when the flow was fully developed. You et al. [6] measured the airflow field in a full-scale, half-row, single-aisle aircraft cabin mockup with one gasper turned on, using a particle image velocimetry (PIV) technique. The measured data showed that the gasper-induced flow, the main flow in the cabin, and the thermal plume from a passenger interacted with each other and formed a complex flow field. Li et al. [8] measured the distributions of air velocity, temperature, and contaminant concentrations in the economy cabin of a functional MD-82 airplane with gaspers on and off. Although the gaspers directed clean air toward the passengers, the cabin air quality in this case was not improved.

In addition to experimental studies, several investigations have focused on the modeling of a gasper-induced jet with computational fluid dynamics (CFD). For instance, You et al. [6] evaluated the performance of the renormalization group (RNG) k-ε model and the shear stress transport (SST) k-ω model using their measured data. The SST k-ω model was found to be more accurate than the

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RNG k-ε model for predicting the air distribution of a gasper-induced jet. Shi et al. [10] calculated the entrainment ratio at different locations along a gasper-induced jet using a CFD model. They found that over 90% of the air in the breathing zone of a passenger was entrained from the surroundings when the gasper was turned on. Note that both of these studies used a detailed geometry with a large grid number to represent the actual gasper in the CFD simulations, which led to an unacceptably high computing cost. To overcome this problem, You et al. [7] developed a simplified gasper model to reduce the grid number for the gaspers without compromising the accuracy of the results.

Although the studies reviewed above have provided great insight into gasper-induced flow, there is a lack of systematic studies on the impact of gasper-induced ventilation on cabin air quality in commercial airliners. Namely, there is not a clear answer to the following question: will turning on the gaspers improve the cabin air quality in commercial airliners? To answer this question, this study first developed a hybrid turbulence model which was more suitable than previous models for predicting the air distribution in an aircraft cabin with gaspers turned on. The developed model was then validated using two sets of experimental data measured in a cabin mockup and an actual airplane. In addition, this investigation used the validated model to calculate the risk of infection by SARS in the seven-row section of economy-class cabin of two popular airplanes, Boeing 767 and 737, with different gasper on/off distributions. The database consisted of 9660 infection-risk data points, which were then used to explore the impact of gaspers on cabin air quality in the two airplanes.

2. Model development

To obtain the air distribution in an aircraft cabin with gaspers turned on, it is important to identify an accurate and robust turbulence model. According to a number of comparative studies, the RNG k-ε model is the most robust Reynolds-averaged Navier-Stokes (RANS) model for predicting air distribution in the bulk air regions in enclosed environments [11–14]. However, the RNG k-ε model fails to accurately predict the complex airflow in the near wall regions, because it uses a wall function instead of resolving the near wall airflow. In aircraft cabins, the airflow near a human body, where the gasper-induced jet encounters the thermal plume, could be very important in terms of thermal comfort and contaminant transport [6]. Several comparative studies found that the SST k-ω model was superior in predicting airflow in the near wall regions [6,10]. This is because the SST k-ω model uses the standard k-ω model in the near wall regions, which resolves the near wall airflow. In the bulk air regions, however, the SST k-ω model utilizes the standard k-ε model, which is less robust than the RNG k-ε model. Therefore, it is worthwhile to develop a hybrid turbulence model for cabin airflow simulations, one which will not only be robust in the bulk air regions but also accurate in the near wall regions. This hybrid turbulence model will use the standard k-ω model in the near wall regions and a transformed RNG k-ε model in the bulk air regions. A blending function will be employed to gradually switch the two models on and off. This section details the development of the model.

2.1. Standard k-ω model in near wall regions

The hybrid turbulence model uses the standard k-ω formula in the near wall regions. The standard k-ω model solves two transport equations for turbulence kinetic energy (k) and specific dissipation rate (ω). The turbulence kinetic energy, k, is calculated by:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k U_i)=\frac{\partial}{\partial x_j}\left(\Gamma_{k1}\frac{\partial k}{\partial x_j}\right)+G_{k1}-Y_{k1} \tag{1}$$

where t is the time, ρ the air density, U the Reynolds-averaged air velocity, x the coordinate, μ the air viscosity, μ_t the eddy viscosity, Γ_{k1} the effective diffusivity of k, G_{k1} the generation of k due to mean velocity gradients, and Y_{k1} the dissipation of k due to turbulence. The specific dissipation rate, ω_1, is calculated by:

$$\frac{\partial}{\partial t}(\rho \omega)+\frac{\partial}{\partial x_i}(\rho \omega U_i)=\frac{\partial}{\partial x_j}\left(\Gamma_{\omega 1}\frac{\partial \omega}{\partial x_j}\right)+G_{\omega 1}-Y_{\omega 1} \tag{2}$$

where $\Gamma_{\omega 1}$ is the effective diffusivity of ω, $G_{\omega 1}$ the generation of ω, and Y_{k1} the dissipation of ω due to turbulence. The detailed formulation of Γ_{k1}, G_{k1}, Y_{k1}, $\Gamma_{\omega 1}$, $G_{\omega 1}$, Y_{k1}, and the constants can be found in Wilcox [15].

2.2. Transformed RNG k-ε model in bulk air regions

The hybrid turbulence model utilizes the RNG k-ε formula in the bulk air regions. In the RNG k-ε model, a transport equation for the turbulence dissipation rate (ε) is used instead of ω. The RNG k-ε model calculates the turbulence kinetic energy, k, as follows:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k U_i)=\frac{\partial}{\partial x_j}\left(\Gamma_{k2}\frac{\partial k}{\partial x_j}\right)+G_{k2}+G_b-\rho\varepsilon-Y_M \tag{3}$$

where Γ_{k2} is the effective diffusivity of k; G_{k2} and G_b the generation of k due to mean velocity gradients and buoyancy, respectively; and Y_M the contribution of the fluctuating dilatation in compressible turbulence to the overall dissipation rate. The dissipation rate, ε, is calculated by:

$$\frac{\partial}{\partial t}(\rho \varepsilon)+\frac{\partial}{\partial x_i}(\rho \varepsilon U_i)=\frac{\partial}{\partial x_j}\left(\Gamma_{\varepsilon 2}\frac{\partial \varepsilon}{\partial x_j}\right)+C_{1\varepsilon}\frac{\varepsilon}{k}(G_{k2}+C_{3\varepsilon}G_b)-C^{*}_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \tag{4}$$

where $\Gamma_{\varepsilon 2}$ is the effective diffusivity of ε, and $C_{1\varepsilon}$, $C^{*}_{2\varepsilon}$, and $C_{3\varepsilon}$ are constants. The detailed formulation of Γ_{k2}, G_{k2}, G_b, $\Gamma_{\varepsilon 2}$, Y_M, and the constants can be found in Yakhot and Orszag [16].

To consolidate the standard k-ω model and the RNG k-ε model, one should transform the original RNG k-ε model into the same format as that of the standard k-ω model. The relationship between ε and ω can be expressed by:

$$\varepsilon=\beta^{*}\omega k \tag{5}$$

where β^* is a constant. When Eq. (5) is inserted into Eq. (3), the k equation becomes:

$$\frac{\partial}{\partial t}(\rho k)+\frac{\partial}{\partial x_i}(\rho k U_i)=\frac{\partial}{\partial x_j}\left(\Gamma_{k2}\frac{\partial k}{\partial x_j}\right)+G_{k2}+G_b-\rho\beta^{*}\omega k-Y_M \tag{6}$$

Next inserting Eq. (5) into Eq. (4) and performing a long derivation transforms the ε equation, Eq. (4), into the following: