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Experimental measurements for gaseous transport within an aircraft cabin

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ABSTRACT

Given the vast route structures for aircraft operations and the diversity of people who fly on aircraft, the contamination of aircraft by dangerous pathogens is a concern. The research reported in this paper was part of a larger project to investigate the use of gaseous decontamination agents that may potentially be used to address such pathogens. Computational fluid dynamics (CFD) models are used to evaluate the distribution of such agents in an aircraft cabin under a variety of conditions. Such models required experimental data for validation and tuning. An 11-row wide-body aircraft cabin mockup with air distribution components from an actual aircraft was used to collect such data. Carbon dioxide was used as a tracer gas to simulate a gaseous decontamination agent. Detailed data for gaseous transport in the cabin were collected both with and without the use of supplementary fans. Geometric, thermal, and airflow boundary conditions were also measured or documented. Even though the cabin and boundary conditions are symmetrical, the gaseous transport in the cabin was shown to be non-symmetrical due to a horizontal circulation of air that naturally forms in the cabin. This horizontal circulation has a substantial impact on longitudinal gaseous transport. It also results in substantial left-to-right differences between normal-mode operation Environmental Control System (ECS) flows and the supplementary fans. The data collected captures the impact of this asymmetry both for normal-mode operation and supplementary fan operation and provide sets of data that should provide adequate challenges to CFD models needed for validation.

1. Introduction

The number of air travelers has grown continuously worldwide and, along with that growth, concern about the risk of airborne, food-borne, vector-borne, and zoonotic infectious diseases among airplane passengers has been increasing, too [1]. This issue has drawn the attention of a number of researchers studying the impact of different parameters and their effect on the transmission of infectious diseases from engineering, medicine, and multidisciplinary points of view [2–4]. The airliner cabin ventilation (airflow rates and patterns) plays an important role in the passengers' thermal comfort and transmission of infectious diseases [3,5]. The airflow pattern can be disturbed by various types of external means, such as personal air outlets, as well as passengers, crew, and service cart movement [4,6]. Several studies [1–6] have been carried out to determine the impact of each individual parameter on the main airflow pattern. Due to the turbulent and chaotic local airflow motions along with its unsteadiness [7], it is not an easy task to predict the cabin airflow pattern. Therefore, several different cases should be studied so that the impact and effectiveness of these parameters on the cabin airflow pattern can be determined. There are mainly two types of methods to do this. One is the experimental method which can simulate the cabin as closely as possible to a real case. However, it is costly and time consuming. The other one is the numerical simulation using computational fluid dynamics (CFD) models which is relatively an inexpensive and comparatively fast technique with the capability of handling more complex and complicated cases. However, CFD models require validation with experimental data to establish their reliability.

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The work reported in this publication is part of a larger study that investigated both the airborne transport of gaseous materials within an aircraft cabin through experimental measurements and computational fluid dynamics (CFD) model assessments. The overall study was intended to provide information for a variety of applications including environmental control system design, contaminant detection, and contaminate mitigation. One application included was the decontamination of aircraft cabins that may have been contaminated with disease pathogens using a gaseous decontamination agent that is distributed throughout the cabin. The CFD models were used to assess the distribution of the decontamination agent and estimate its effectiveness under various scenarios [2,5,8]. The primary purpose of the research reported in this paper was to collect a documented set of data that could be used for validation of these models.

Experimental measurements were conducted in a wide-body aircraft cabin mockup which used actual aircraft air distribution components to ensure accurate representation of a realistic aircraft cabin environment. Additionally, the cabin geometry was an accurate reproduction of a coach section of a B-767 aircraft. Carbon dioxide (CO_2) tracer gas was used to simulate a gaseous decontamination agent. Two sets of experimental data were collected. The first set was collected with the aircraft environmental control system operating in its normal mode with design airflows for the aircraft. To speed up the decontamination process and aid in thorough and uniform decontamination of a cabin, the addition of supplementary fans in the cabin likely would be employed in many decontamination scenarios. The question as to whether or not a CFD model developed and tuned for normal operation would accurately predict gaseous transport in this altered mode of operation naturally arises. Thus, the goal for the second data set was to collect data with supplementary fans added to the cabin and generate data that could be used to validate potential CFD models for this altered state. If enough supplementary fan power is added to the cabin, the airflows and velocities become quite high and the decontaminant agent would be quickly and uniformly mixed throughout the cabin by brute force and there is little value in CFD assessment and little challenge for a CFD model to accurately predict the result. To be of value for the intended purpose, the experimental conditions were selected so that the supplementary fans were large enough to generate a substantial disturbance to the normal operation mode airflows but not so large to totally overwhelm those airflows.

Therefore, this design should provide the largest challenge for the CFD models and validation with these data would also be expected to be accurate with both more and less fan power in the cabin. This set of experimental data would provide a tool for validation of CFD models which are intended to simulate the impact of any secondary air motion, such as those mentioned above, as well as normal cabin operation.

2. Experimental protocol

2.1. Description of the mockup aircraft cabin

All of the tests were conducted in an 11-row mockup Boeing 767 aircraft. The geometric shape and the dimensions of the mockup cabin are the same as an actual Boeing 767 aircraft cabin. The mockup cabin seats, the air supply ducts, and the diffusers are parts from a salvaged Boeing 767 aircraft. This mockup cabin is 31 ft (9.4 m) long and 15.5 ft (4.7 m) wide. The mockup cabin contains 11 rows with each row consisting of 7 seats as shown in Fig. 1. Each seat in the cabin is occupied by a thermal manikin. The manikins are wrapped in resistance wire, which is connected to AC power causing each of them to produce approximately 341.2 Btu/h (100 W) of heat. This heat generation is a little higher than the sensible heat expected from a sedentary adult and the extra heat generation is intended to compensate for additional non-people thermal loads, such as lighting, laptops, in-flight entertainment systems, etc., in an actual cabin, ASHRAE [9].

There are two outboard and two center simulated stowage bins installed along the length of the cabin. The air diffusers are located between the two center stowage bins. The remaining space between the upper parts of the inside and the outside of the mockup aircraft cabin is occupied by the air conditioning and the lightening systems components. The chamber consists of a crawl space under the cabin and a hallway on either side to allow access to the cabin from any direction. Two access doors to the cabin are provided at the rear of the cabin. Shehadi [10] provides detailed dimensions of the cabin, its furnishings, air supply diffusers, and the air supply ducting to the diffusers.

Air is supplied from an air-conditioning system that provides 1400 cfm (660 l/s) of conditioned and filtered air at 60 °F (15.5 °C). This quantity of air and its temperature are based on the information provided by Hunt et al. [11]. The air is 100% outside air; after conditioning, it passes through a set of HEPA filters before it enters the cabin ductwork.

The flow rate of the supply air provides about 18 cfm (8.5 l/s) for each of the 77 seats in the cabin which is appropriate for this aircraft Hunt et al. [11]. The humidity of the air supplied was not controlled for these experiments and was typically higher than the 15%–20% relative humidity commonly observed on commercial aircraft, ASHRAE [12]. The air exits the cabin through a 5 in (127 mm) wide slot that traverses the length of the cabin along the base of both exterior walls. The uniformity of airflow along the full length of the cabin's inlet and the balance of the airflow between both sides of the cabin are important considerations. The aircraft components used are designed to provide this uniformity and balance. However, detailed traverses of the inlet jet using a hot-wire anemometer were conducted along the full length of the cabin for both sides, confirming the inlet uniformity Mazumdar et al. [13]. Balance of the cabin exhaust airflow is not forced in this arrangement, but the exhaust area is uniform along the full length of the cabin and opens into a large plenum common to the whole cabin with negligible pressure gradients. This configuration is intended to represent the actual aircraft, where exhaust vents are uniformly spaced along the length of the cabin and empty into the open plenum formed by the knee area of the aircraft.

2.2. Description of the tracer gas

Carbon dioxide (CO_2) is used as the tracer gas to simulate contamination or decontamination agent dispersion inside the aircraft cabin. The CO_2 gas is balanced with helium to provide neutral buoyancy prior to its injection into the cabin airflow. That is, sufficient helium is added to the CO_2 to give the mixture a molecular weight equal to that of air.

Three non-dispersive infrared absorbance (NDIR) sensors were used to measure CO_2 concentration levels inside the mockup cabin, as shown in Fig. 2. Two of them are used to measure the CO_2 level of the inlet and exhaust cabin airflows while the other one is used for analyzing the CO_2 concentrations inside cabin at the selected locations. The latter is connected to a gas sampling tree. This sampling tree is equipped with a set of solenoid valves which select the port on the sampling tree to be measured. It can be moved along and across the cabin to take sample in different location inside the cabin. A data acquisition system (DAS) controls the solenoid values and the signals from all the CO_2 analyzers are recorded by the DAS.