Introduction

Motivation and outline of the thesis.

The present work is motivated by the problem of ventilation and its influence on the distribution of oxygen, carbon dioxide and temperature etc. inside a manned spacecraft cabin. In space, because of the microgravity environment, the natural convection due to the buoyancy of warm or cold air in a gravity field is eliminated or greatly reduced, many heat and mass transfer processes such as the mixing of the atmosphere constituents (O_2, N_2, CO_2, water vapour etc.) and the cooling of electric equipment etc. by natural convection which happen naturally on Earth must be accomplished by forced convection (ventilation), therefore an appropriate ventilation system is very important because forced ventilation is the primary means to promote the well mixing of atmosphere constituents and to remove the excessive heat produced by onboard equipment and the crew — both of the processes are very important to assure a comfortable thermal condition and a good air quality inside the cabin for the well-being of the crew and to promote their productivity.

The environmental condition inside a manned spacecraft cabin is maintained by the Environmental Control and Life Support System (ECLSS) which is a very complicated system consisting of many subsystems such as atmosphere control and supply (ACS) subsystem, temperature and humidity control (THC) subsystem, air revitalization (AR) subsystem etc. Its environmental control part is responsible for the control of the cabin total pressure, cabin air temperature and humidity, cabin ventilation, and also for the control of the concentrations of oxygen, carbon dioxide, and many other trace contaminants emitted by the crew and by various onboard equipment and construction materials. The main task of the cabin ventilation system is to distribute the freshly supplied oxygen to the cabin, to dissipate the heat produced by the onboard electric equipment and to diffuse the carbon dioxide exhaled by the crew to the cabin air by forced convection. The aim is to maintain a uniform distribution of oxygen, carbon dioxide, humidity and temperature in the cabin air to provide comfortable and productive living conditions for the crew. For this purpose, air ventilation and circulation has to be carefully optimized to allow the maximum mixing of oxygen with cabin air, efficient removal of carbon dioxide and other trace contaminants and for heat and humidity control. Unfortunately it is almost impossible to optimize the ventilation system design by means of experiments conducted on Earth because the influence of natural convection cannot be eliminated which may be responsible for an important part of the heat and mass transferred in the experiments. It is thus decided to investigate this problem with the help of Computational Fluid Dynamics (CFD) which, due to the ever-increasing availability of high-performance computation facilities and the rapid development of numerical techniques, is now increasingly employed to investigate building ventilation problems and has become one of the most generally used methods to study air flow pattern and air distribution in buildings.

Due to the presence of turbulence in ventilation flows and uncertainties in turbulence modelling and in specifying appropriate boundary conditions for air supply diffusers, ventilation fans, internal heat and mass sources etc., the numerical models and modelling methods used in CFD simulations must be validated against experimental data before they can be trusted to use for practical purposes, which is an important and necessary step of the simulation process.

In order to validate modelling and simulation methods for such airflow problems, it is necessary to compare simulation results with experimental data from carefully designed and well instrumented experiments. Up to now, such experiment data are only available for ground-based systems in open literature, and they are mainly for the room airflow problems in buildings. It was thus decided to limit the objectives of the present thesis to study some basic ventilation problems and the associated heat and mass transfer processes, which allow us to investigate separately the main classes of environmental problems encountered in a spacecraft cabin. Namely, we consider the following problems:

- ventilation under isothermal and homogeneous condition;

- ventilation with internal mass sources (heterogeneous, isothermal) or heat sources (homogeneous, non-isothermal);
- ventilation with internal heat and mass sources (heterogeneous and non-isothermal).

The last two problems involve a strong coupling between natural and forced convections. In fact the forced convection (ventilation) in an indoor environment or in a spacecraft cabin cannot be too strong due to the consideration of thermal comfort and energy saving, thus the airflow in such an environment is often of the character of turbulent mixed convection which is at present still a very challenging problem to solve by numerical simulations, and in some sense the problem is more difficult to solve for ground-based condition than for microgravity condition because in the latter case the influence of gravity and thus the influence of natural convection is greatly reduced. Once the solution method is validated for ground-based condition, we can expect that it can be safely used for microgravity condition.

The perspective of this study is: through such a study, we should eventually be able to answer the following important questions:

- For a given ventilation configuration, what will be the air flow pattern and air distribution in the cabin?
- For a desired air flow pattern, how and where the air supply diffusers and return openings should be placed and how many of them should be used?
- How well the ventilation experiments conducted on Earth represent the real cases in space?

The thesis' manuscript is organized as follows:

A brief introduction to the basic concepts of Environmental Control and Life Support System (ECLSS) and its functions is first given in Chapter 1 which is the background of the present study.

A general review on ventilation methods and their numerical simulations is presented in Chapter 2. The main issues and problems related to the modeling and simulation of ventilation flows are highlighted and analyzed.

The basic concepts of turbulence modeling and some commonly used turbulence models are introduced in Chapter 3. Some turbulence modeling problems pertaining to ventilation flow simulation are highlighted.

Chapter 4 presents the results of validation studies on isothermal 2D/3D ventilation flow simulation: validation of simulations on a 2D baseline test case (IEA Annex 20 benchmark Test Case 2D), ventilation in a 3D partitioned room featuring jet impingement, strong recirculation and flow separation and 3D ventilation with complicated boundary conditions (IEA Annex 20 Test Case B).

Validation studies on 3D ventilation flow with heat or mass transfer are presented in Chapter 5. Two test cases were considered: IEA Annex 20 Test Case E (Mixed convection, summer cooling) and IEA Annex 20 Test Case F (Forced convection, isothermal with contaminants).

Chapter 6 presents the results of validation studies on two test cases with complicated flow configuration and simultaneous heat and mass transfer: displacement ventilation (buoyancy-driven) in a complicated 3D room (PCs, human simulators, cabinets and lamps) with pollutant transport (SF_6) and forced ventilation with ceiling slot diffuser under the same configuration. For the latter case which is similar to the ventilation system in a spacecraft cabin (forced convection), simulations were carried out under normal g and zero g conditions. The results are compared in terms of velocity, temperature, SF_6 distribution and also thermal comfort to show the differences of heat and mass transfer processes under these two conditions and their influences on the thermal comfort.

Finally the general conclusions and the perspective for future study are presented in Chapter 7.