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A Three-Dimensional Simulation of Temperature and Water Vapor Distributions between a Heat Source and a Ventilating Hood

C.P. Tso[1], S.C.M. Yu[1], P.C. Chia[2] and K. Sundaravadivelu[1]

[1]School of Mechanical and Production Engineering
Nanyang Technological University, Post Code 639798, SINGAPORE

[2] Ministry of the Environment, 40 Scotts Road, Post Code 228231, SINGAPORE

Abstract

Numerical simulation of air motion inside a kitchen is carried out in the presence of heat generation associated with the cooking process. A preliminary analysis on the heat removal capability is conducted under different capture velocities of the ventilating hood. A critical hood capture velocity is determined to provide a minimum requirement for efficient removal of heat and thus provide thermal comfort in the kitchen. A detailed investigation of the make-up air arrangements, radiation effects, effluent transport is under progress and will be discussed during the presentation.

Introduction

The working environment in commercial kitchens is often unsatisfactory due to uncomfortable indoor air quality and poor indoor climate. This in turn affects the worker's productivity and the thermal comfort in the refreshment area. Thermal comfort is the condition of the mind that expresses satisfaction with the thermal environment [2]. Though the regional climate conditions, living conditions, and cultures may differ throughout the world, the preferred temperature that people choose for comfort is almost similar. ASHRAE Standard 55 [1] provides the guideline for the environmental parameters for human occupancy, in which the effective temperature is found to be between 22.8°C and 26°C with a relative humidity (RH) between 30% and 60%. Of course during the cooking process, the chemical and physical characteristics of the food are changed, with impurities such as grease, smoke and small solid and liquid particles being produced and dispersed into the ambient air. Therefore it is important to design and implement a suitable ventilation system to remove the impurities and a part of the heat generated by the cooking equipment so as to provide a comfortable and hygienic environment. But in order to provide effective ventilation a complete understanding of the air motion around and into exhaust devices is necessary, before designing a suitable system. Therefore in this work a preliminary study is conducted to investigate the air motion in a real kitchen model that is been widely used in the hawker centres of Singapore. Moreover, as the most important component of the kitchen is the exhaust (ventilating) hood, we here carry out an optimal analysis of the hood capture velocity to provide efficient removal of heat and effluent.

Model and Solution Method

The kitchen model considered here is based on the typical size of cells in the hawkers' centres in Singapore [7]. The three-dimensional model of the kitchen measures 4.5 m long, 2.8 m wide and 3 m high and is sketched in figure 1.

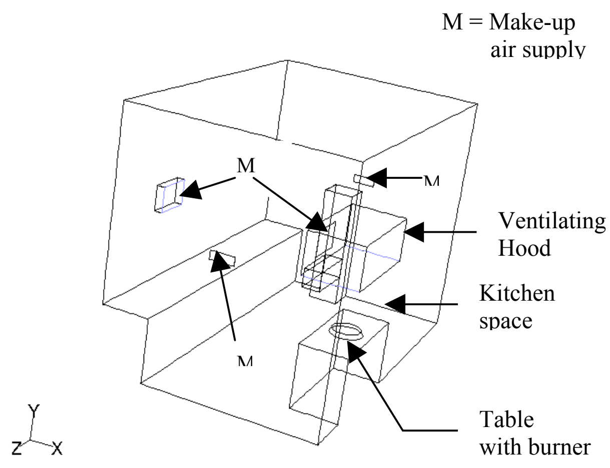

Figure 1. Schematic diagram of a real kitchen

A cooking table of dimensions 1.5 long, 0.6 m wide and 0.75 m high is placed inside the kitchen as shown in Fig. 1. An exhaust hood of 1.4 m long, 0.7 m wide and a height of .5 m is placed above the cooking table at height of 0.75 m. The ring burner, assumed to be at the centre of the cooking table, is of dimensions 0.2 m diameter and 0.025 m thickness. The top surface of the kitchen room is assumed to be closed. The cook's position is assumed to be at 0.4 m in front of the cooking table. In order to simulate the air motion during cooking process we have assumed that the water is boiling. Therefore the surface temperature of the pan is assumed to be 100^{o}C together with a 0.0025 kg/m^3 mass flux of water vapor . The top surface of the pan is assumed at a height of 0.2 m above the ring burner. Moreover a temperature of 220^{o}C is assumed to prevail around the outer edge pan. This form of temperature distribution is accounted in the form of thin ring (0.025 m thick) surrounding the pan. Such an assumption is due to the propagation of the flame around the pan. The walls of the kitchen are assumed to be at a constant temperature of 27^{o}C. A suction velocity boundary condition is specified at the bottom face of the hood in order to specify the capture velocity. The air inside the kitchen is treated as an incompressible liquid having laminar motion. Then the time dependent characteristics of the air motion inside the kitchen are governed by the 3-D laminar Navier-Stokes equations together with the conventional heat and species (water vapor) transport models. Further the radiation effects are assumed to negligible in the present analysis. Due to the complex geometry and the fluid flow phenomena, we use a commercial CFD software (Fluent 5.3) [5] based on the Simple algorithm of Finite Volume method to simulate the problem. The use of the software is well validated with classical results and a convergence analysis together with grid independence test has been carried out before implementing it to solve the present problem. The grid independence test suggested 20×20×20 as an optimum grid and the convergence criteria has been set as 10^{-3} in the present analysis for all variables.

Results and Discussions

The simulation is stopped once the calculation reaches the steady state and the results are stored. To discuss the results in brief here, we herewith provided only the temperature and water vapor distributions inside the kitchen for different hood capture velocity conditions. Before we proceed to discuss the results let us take a look at the health requirements in the kitchen. The most important criteria are the room temperature of the kitchen (28^{o}C), the upper limit of the air humidity at 16.5 g/kg dry air and a relative humidity (RH) of 70 % [3]. Now the aim of our investigation should be to optimize the physical parameters that govern the problem to meet the above requirements. The investigation is carried out, by varying the hood capture velocity from 0 to 0.5 m/s. From the temperature contours depicted in figures 2 and 3, it is found that the capture velocity affects the temperature distribution greatly.

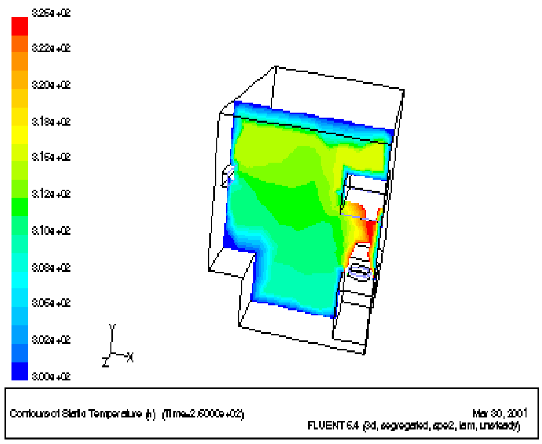

Figure 2. Temperature distribution for a hood capture velocity of 0.0 m/s.

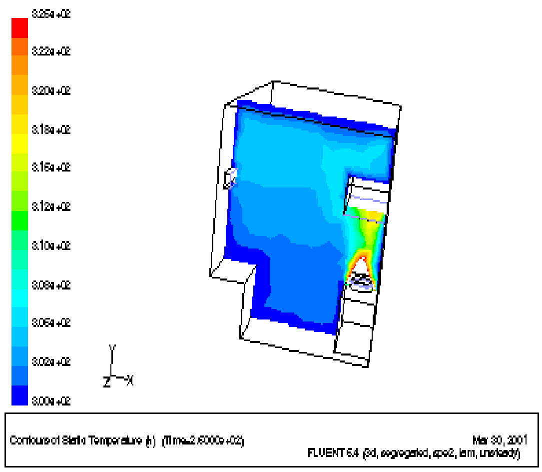

Figure 3. Temperature distribution for a hood capture velocity of 0.3 m/s.

Also when the capture velocity is set to 0.3 m/s or above, the temperature field around the cook's position is found to be acceptable. As the velocity is further increased, to 0.5 m/s, say, no significant improvement in the temperature distribution in the vicinity of the cook is observed, except in the region directly above the cooking surface. These results infer that the compatible thermal environment can be achieved by operating the ventilating hood at a capture velocity of 0.3 m/s or higher. The humidity removal ability of the hood is also studied by generating a high rate of evaporation from the cooking surface and observing the effect of the capture velocity on the humidity. The simulation results show (Figs. 4 & 5) that, when the hood is not operating, or when the hood velocity is lower than the escape velocity of the water vapor, the water vapor rapidly disperses into the room and

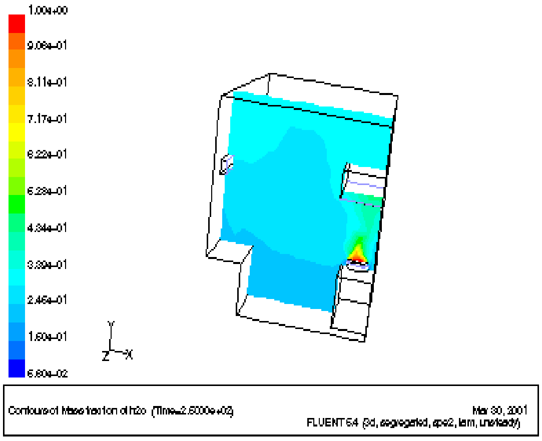

Figure 4. Water Vapor distribution for a hood capture velocity of 0.0 m/s.

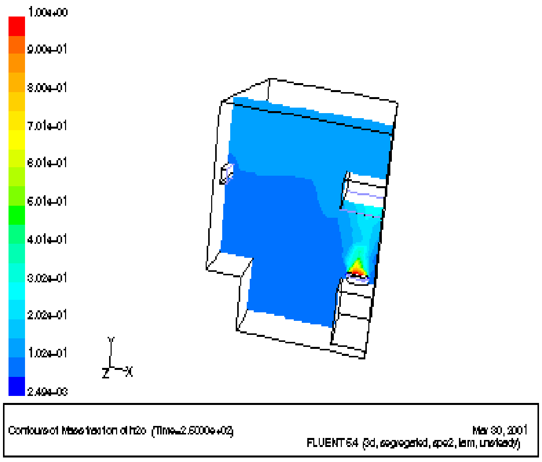

Figure 5. Water Vapor distribution for a hood capture velocity of 0.3 m/s.

therefore affects the thermal comfort of the cook. But if the capture velocity is maintained above the escape velocity of the vapor, the vapor transport around the cook can be effectively controlled (Fig. 5). Also by placing the hood at different heights above the cooking surface the heat removal process is analyzed. It is observed from the analysis that with the hood placed approximately 1.4 m above the cooking surface the rate of removal of the heat and vapor generated inside the kitchen is maximised. This observation agrees with the recommendations of Australian Standard 1668 [4]. In an earlier two-dimensional analysis [6], the effect of angle at which rate of make-up air is injected into the kitchen by fixing the hood capture velocity at 0.2 m/s was investigated. It is observed from the results obtained that when the angle of incoming make-up air varies between 30^{o} and 45^{o} (angles here refer with respect to x-y surface), optimal control of heat and vapor transport inside the kitchen is achieved.

Conclusions

Varying the performance parameters and location of the ventilating hood has a significant effect on the temperature and vapor distribution in the kitchen. By operating the hood at a velocity of 0.3 m/s or higher it is found that an acceptable thermal environment can be achieved inside the kitchen. The two-dimensional analysis shows that the optimum capture velocity may be further influenced by optimising the make-up air arrangement. A critical height for locating the ventilating hood above the cooking surface has been determined to provide effective removal of the heat and water vapor generated during the cooking process.

References

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