#115'24

THREE-DIMENSIONAL ANALYSIS OF AIRFLOW AND CONTAMINANT PARTICLE TRANSPORT IN A PARTITIONED ENCLOSURE

K. C. Chung[1] and C.M. Chiang[2]

[1]National Yunlin University of Science and Technology, Yunlin 640, Taiwan
[2]National Cheng Kung University, Tainan, Taiwan

ABSTRACT

Determination of the distribution of contaminant particles within zones becomes of great interest, with the increasing concern for indoor air quality. In order to improve the indoor air quality in a realistic building, the air movement and contaminant transport in a partitioned enclosure with ventilation have been studied numerically and experimentally. A three-dimensional analysis of air movement, temperature distribution and contaminant particle transport is made to investigate airflow patterns and deposition of contaminant particle in a partitioned enclosure. An experimental program was also performed to validate the airflow field and temperature distribution. However, the particle transport was not measured in the experiments. The experiment is carried out in a full-scale environmental control chamber. The agreement between the computed and the measured results of temperature and velocity fields are quite well. It is also shown that prediction results of contaminant particle's trajectory will give valuable information to be used for evaluating the indoor air quality in the design procedure.

KEYWORDS

Air flow pattern, partitioned enclosure, particles.

INTRODUCTION

Recently, indoor air quality and thermal comfort become important issues, as they are related to both energy conservation and building occupant health. Fanger and Pederson [1] have shown that the indoor air quality and thermal comfort in a room are not only affected by how uniform the air temperature and air velocity are in the occupied zone but also by the air motion and the dominant frequency of the flow fluctuations. These air environmental parameters which have profound influence on air quality and comfort, are controlled by a building's ventilation system. Consequently, the objective of a ventilation system in a building is usually to provide fresh air and remove contaminants from the ventilated space as quickly as possible, as well as meet the heating and/or cooling load of the building.

There are many configurations of ventilation air distribution systems and a wide range of potential conditions within a building. The prediction of thermal comfort and indoor air quality for any specific situation is difficult. The problems of air distribution and contaminant particle transport are most suitable for numerical solutions, by their nature, are good design optimization tools [2]. Since most air distribution methods are unique to a particular building, a rule of thumb approach is not often a good design practice. Therefore, numerical solutions are most suitable for studying the airflow pattern and contaminant particle transport inside a occupied zone as results can be readily obtained and modifications can be made as required within a short of time [3]. It seems that three-dimensional numerical simulation offers the ability to predict ventilation characteristics over a wide range of operation parameters and physical configurations. However, some specific experimental work are needed to support the accuracy of the numerical model.

It is well known that the indoor air quality in buildings is influenced by the ventilation and infiltration of ambient air. Airflow rates between zones in a building can alter the concentration of an air contaminant within any one zone. To predict air contaminant concentrations in any one zone, there is a need to quantify the air exchange rate between one zone and the adjacent zones. Solutions to the equations for the distribution of a contaminant in a multizone air movement model have been explored by Waters and Simons [4]. However, an assumption of well-mixed model was made in their macroscopic analysis. It is not able to obtain detail information of contaminant particle transport and deposition inside an occupied enclosure.

Recently, many investigators [5] have studied the behavior of airflow, and contaminant concentration using numerical technique. Kato and Murakami [6] used a 3-D solution for the velocity distribution and spread of contamination in downward flow clean rooms of different number of supply openings. Riffat et al. [7] used the age-of-air for trace gas and particle to determine the relative ventilation efficiency for different flow patterns. The effect of airflow patterns on the particle deposition rate on the surfaces of the chamber was also determined. Due to the complex boundary conditions of numerical analysis, a single occupied zone was used commonly. Some investigators [8] studied the relationship between ventilation efficiency and contaminant distribution by experimentally. However, the data for evaluating the dispersion and deposition of contaminant particle in a realistic partitioned building are limited. The purpose of this paper is to proposed a three-dimensional simulation model of contaminant particle transport as well as its experimental verification of temperature and velocity fields for a partitioned enclosure.

COMPUTATIONAL MODEL

The computational models for predicting the contaminant particle distribution in a building need two numerical parts. First, an airflow pattern must be known before calculating the distribution of the contaminant particle in a building. Then, substituting the already known velocity fields into the equation of particle motion, a complete particle trajectory can be obtained.

The governing equation of the flow field

The computer program EXACT3 is an airflow program developed by Kurabuchi et al. [9]. EXACT3 is a three-dimensional finite-difference computer program for simulating buoyant airflow within buildings. The buoyancy effect is accounted for by Boussinesq approximation. The program solves the conservation equations for continuity, momentum, and energy as well as the equations for turbulent kinetic energy and its dissipate rate. The two-equation κ-ε turbulent model is used in EXACT3 in conjunction with empirical wall functions. The κ-ε turbulent model is relative efficient and stable computationally compared with the more complicated Reynolds stress models. It is also reasonably accurate for a wide range of turbulent flow. The governing equations can be written in the general elliptic form for an incompressible fluid as

$$\frac{\partial \phi}{\partial t} + \nabla \cdot [\overline{v}\,\phi - \Gamma_{\phi}\,\nabla\phi] = S_{\phi} \qquad (1)$$

where ϕ stands for any one of the following: 1, u, v, w, θ, κ and ε. When $\phi = 1$, the equation changes into the continuity equation. A complete description of the theoretical basis and definitions of the coefficients Γ_ϕ and S_ϕ corresponding to each of these can be found in refs. [10]. A pressure relaxation method is used to satisfy the Poisson equation for mass conservation. The governing equations are solved by an explicit time-marching technique using the marker-and-cell method . A staggered grid and a hybrid upwind/central differencing combination scheme are used in EXACT3.

Formulation of the contaminant particle transport equation

In order to study the Brownian motion effect on small size particle, the numerical integration scheme developed by Busnaina and Abuzeid [11] was used to solve the contaminant particle transport. The particle equation of motion includes the Brownian and lift forces in addition to the turbulent dispersion effect and gravity. The governing equations for the small contaminant particles transport can be express as follows:

$$\frac{du_i^p}{dt} = \frac{3}{2d(2R+1)}\frac{C_d}{C_c}W_r(u_i-u_i^p) + F_i + \left(1-\frac{1}{R}\right)g_i + n_i(t) + \frac{F_{ei}}{m} \qquad (2)$$

and

$$\frac{dx_i}{dt} = u_i^p \qquad (3)$$

Here, u_i^p is the velocity of the particle and x_i is its position. W_r is the relative velocity defined as

$$W_r = \sqrt{\sum_{i=1}^{3}(u_i-u_i^p)^2} \qquad (4)$$

u_i is the instantaneous fluid velocity with $u_i = \bar{u}_i + u_i'$, where $\bar{u}_i$ is the mean velocity of the fluid, and u_i' is the fluctuation component of fluid velocity.

EXPERIMENTAL PROGRAM

Measurements were carried out in a full-scale environment control chamber which is 4 m long, 3.2 m wide and 2.5 m high. The chamber was equipped with one inlet diffuser at the ceiling and two outlet diffusers on the opposite wall. the size of all diffusers is 0.525 m x 0.525 m. Three individual zones (zone A, zone B, zone C) were formed by wood-framed wall with glass fiber mat insulation as shown in Figure 1. The detail dimensional data are also shown in Figure 1. For understanding the flow pattern of a partitioned space, two interior doors (openings) were installed inside the chamber. Both the size of the interior doors are 1.575 m x 0.7 m. The area of the three individual zones are 4.41 m^2, 4.41 m^2, and 3.31 m^2, for zone A, zone B, and zone C, respectively. The physical configurations of test chamber were identical to the data which used in the computer simulation. In order to evaluate the results from the model analysis, all experiments were carried out under steady-state conditions. To achieve constant initial indoor temperature, a 150 W electrical heat source was used to warm up the enclosure until the expected average indoor temperature (29.5 C) for the upcoming experiment was reached. After completing the warmup, the supply air volume and temperature were adjusted to their selected setpoints, and conditions in the test chamber were allowed to further stabilize. Typical control of the supply air temperature entering the enclosure was 28 C over the test period.

A data logger which can measure temperature and velocity instantaneously was used to record the data from each measured point. Measurements of air velocity fields were taken using omnidirectional hot-wire anemometers reading the scalar velocities. At each measurement in the test chamber, air velocity and temperature were measured at four, six, and four points along x, y, and z direction, respectively. The local primary airflow direction was determined by visual observation using a smoke tester. The measurement uncertainty of the velocity and temperature measurements for this study were estimated to be within ± 0.1 m/s and ± 0.1 C of the measured values, respectively.

SIMULATION CHARACTERISTICS

Numerical simulation is done using the identical geometry of the partitioned enclosure for experiment as shown in Figure 1. it has one inlet diffuser at the ceiling center of symmetry line between zone A and zone B. One outlet diffuser located at the wall of zone B and the other one at the wall of zone C. The air inlet and outlet conditions that are specified were quite simple. Sixteen sells (4 x 4) are specified in the doors. Nondimensional values of 0.2114 for κ and 0.022194 for ε were used for all the computations presented in this paper. The inlet velocity was specified as uniform across the opening, as was the temperature, κ and ε. The inlet average velocity is 1.5 m/s and the inlet average temperature is 28 C. The average indoor temperature is 29.5 C inside the enclosure. The total calculated grid points is 9177 (21 x 23 x 19). For evaluating the partition effect on contaminant particle transport, three different contaminant source locations have been chosen with three different particle diameters (0.1, 0.5, and 1.0 μm) in the computations.

RESULTS AND DISCUSSION

The computation of the temperature and velocity fields within a partitioned enclosure was done first, as they are independent of the contamination level. Then, the contaminant particle trajectory was predicted by particle transport equation.

Figure 2 demonstrates that the velocity simulation results of the partitioned enclosure is a complex three-dimensional flow field. Three-dimensional plane of velocity fields were presented at three different planes, y-z plane (at x =5, 12 and 16 grid point), z-x plane (at y = 9, 14, and 20 grid point), and x-y plane (at z = 4, 9, and 12 grid point). A significant recirculated flow was found in the zone B near the outlet diffuser area as shown in Figure 2.

The comparison of numerical and experimental results of velocity field at three different directional planes are illustrated quantitatively in Figure 3. In order to match the same locations measured points, the simulation results of y-z plane at x = 0.7 m, z-x plane at y = 0.53 m, and x-y plane at z = 1.9 m were taken for comparisons as shown in Figure 3. The subfigures (a) to (c) are presented the results that three different constant z-directional points were taken for comparing the y-directional velocities. As shown in subfigures (a) to (c), the comparison between predicted and experimental results are quite well. The average discrepancy is about 8 % and the maximum one is about 20 %.

In Figure 4, the temperature distributions of the partitioned enclosure were demonstrated by three different directional planes at x = 2.28, y = 1.75, and z = 1.75 m for y-z, z-x and x-y planes, respectively. Due to the isothermal condition and no heat source inside, the temperature distribution is relatively uniform within the partitioned enclosure.

Representative graphs of numerical and experimental results of temperature distribution at y-z plane are presented in Figures 5. The temperature comparison locations are same as velocity one used in Figure 3.

Figure 5 shows the comparison between the temperature measurements in y-z plane at x = 0.7 m with three different z-directional points and that in the computer simulation. Notice the agreement cover most data points. The simulated temperature fields are quite stable due to isothermal boundary condition. The average discrepancy is under 3 % approximately for all test points. It was found that the air temperatures in Figure 5 are very uniform with little temperature stratification in z direction.

Persily [12] indicated that indoor pollutant concentration (i.e. carbon dioxide) and occupancy patterns in many buildings will never approach equilibrium. Thus, a transient simulation was done to determine the contaminant trajectory and deposition effect in the partitioned zones using the equation of particle motion. It was necessary to note that the precise prediction results of contaminant trajectory and deposition depend on that a correct velocity field and be obtained from numerical simulation first. In order to understand particle transport and deposition inside s partitioned enclosure, several simulations for different point sources of particle with various size are performed. From the simulation results, it is observed that the particle spreading patterns are quite similar at same releasing locations of contaminant particle sources, no matter whether the particle size is 0.1, 0.5, or 1.0 μm. Therefore, only the predicted trajectories of 1.0 μm contaminant particle diameter are reported with three different releasing source points. Figure 6 shows the trajectory of the contaminant particle release from source (0.7 m, 1.93 m, 1.4 m) in zone B and pass through the outlet diffuser (at $y = 0$ m) within 53.3 seconds of calculation time. It is observed that no particles deposit on the internal zones because of the direction of the incoming flow from inlet diffuser.

CONCLUSIONS

A computation model concerning contaminant particle transport and deposition in turbulent flows in a complex geometry partitioned enclosure was described. The trajectory and deposition of contaminant particle were successfully predicted by an equation of particle motion coupled with precise velocity field obtained by a three-dimensional turbulence model and validated through a full-scale experimental chamber. The maximum discrepancy of the velocity distribution between experiment and analysis is 32 % approximately. However, the average overall discrepancy is under 9 % approximately between measured and predicted velocity field in a partitioned enclosure.

The investigated results show that path of particle and its residence time depend greatly on the region of zone where it originate. It is also noted that contaminant particles in the range of 0.1 to 1.0 μm were nor affected by their different diameters, although a particle of hundreds μm did exhibit a significantly different movement pattern. For the contaminant particle diameter less the 1 μm, the drag force due to the relative motion between particle and fluid is generally a dominating force for particle motion. However, when the particle approach a surface (i. e., floor, ceiling, and wall), the Brownian and gravitational forces become significant one in monitoring the contaminant particle motion.

The results presented in this paper indicated that contaminant particle trajectory could be a effective tool for evaluating the indoor air quality and ventilation performance of a room. Also, the computational model may find applications in analyzing contaminant particle transport in a realistic building and understanding the possible contaminant areas in a occupied partitioned enclosure.

REFERENCES

[1]. Fanger, P.O. and Pedersen, C.J.K. (1977) Discomfort due to air velocities in spaces. *Proceedings of the Meeting of Commission E1 of the International Institute of Refrigeration.* Belgrade 307-313.

[2]. Awbi, H.B. (1989) Application of computational fluid dynamics in room ventilation. *Building and Environment*, 24 (1), 73-84.

[3]. Xu, J., Liang, H. and Kuehn, T.H. (1994) Comparison of numerical predictions and experimental measurements of ventilation in a room. *Proceedings of Room Vent '94: Air Distribution in Rooms, Fourth International Conference*, Krakow, Poland, 2, 214-227.

[4]. Waters, J.R. and Simons, M.W. (1987) The evaluation of contaminant concentrations and air flows in a multizone model of a building. *Building and Environment*, 22 (4), 305-315.

[5]. Chung, K.C. and Lee, C.Y. (1995) Using particle trajectories to evaluate indoor air quality. *Indoor Environment*, 4, 170-176.

[6]. Kato, S., Murakami, S. (1988) New ventilation efficiency scales based on spatial distribution of contaminant aided by numerical simulation. *ASHRAE Transactions*, 94, 309-330.

[7]. Riffat, S.B., Cheong, K.W., Adam, N. and Shao, L. (1995) Measurements and computational fluid dynamics modelling of aerosol particles in buildings. *Indoor Environment*, 4, 289-296.

[8]. Heiselberg, P. and Bergsoe, N.C. (1992) Measurements of contaminant dispersion in ventilated rooms by a passive tracer gas technique. *1992 International Symposium on Room Air Convection and Ventilation Effectiveness*, Tokyo, 427-431.

[9]. Kurabuchi, T., Fang, J.B. and Grot, R.A. (1989) A numerical method for calculating indoor airflow using a turbulence model. NISTIR 89-4211, Gaithersburg, MD: National Institute of Standards and Technology.

[10]. Yaghoubi, M.A., Knappmiller, K.D. and Kirkpatrick, A. T. (1995) Three-dimensional numerical simulation of air contamination dispersal in a room. *ASHRAE Transactions*, 101, 1031-1040.

[11]. Busnaina, A.A. and Abuzeid, S. (1989) Accuracy of numerical modeling of fluid flow in clean rooms. *Proceedings-Institute of Environmental Science*, 245-250.

[12]. Persily, A.K. (1993) Ventilation, carbon dioxide and ASHRAE Standard 62-1989. *ASHRAE Journal*, 40-44.

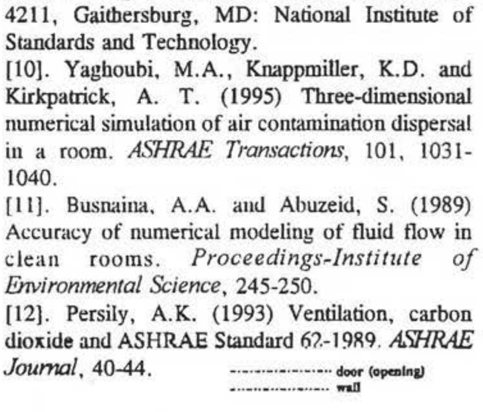


Figure 1. A schematic of the geometry of the partitioned enclosure

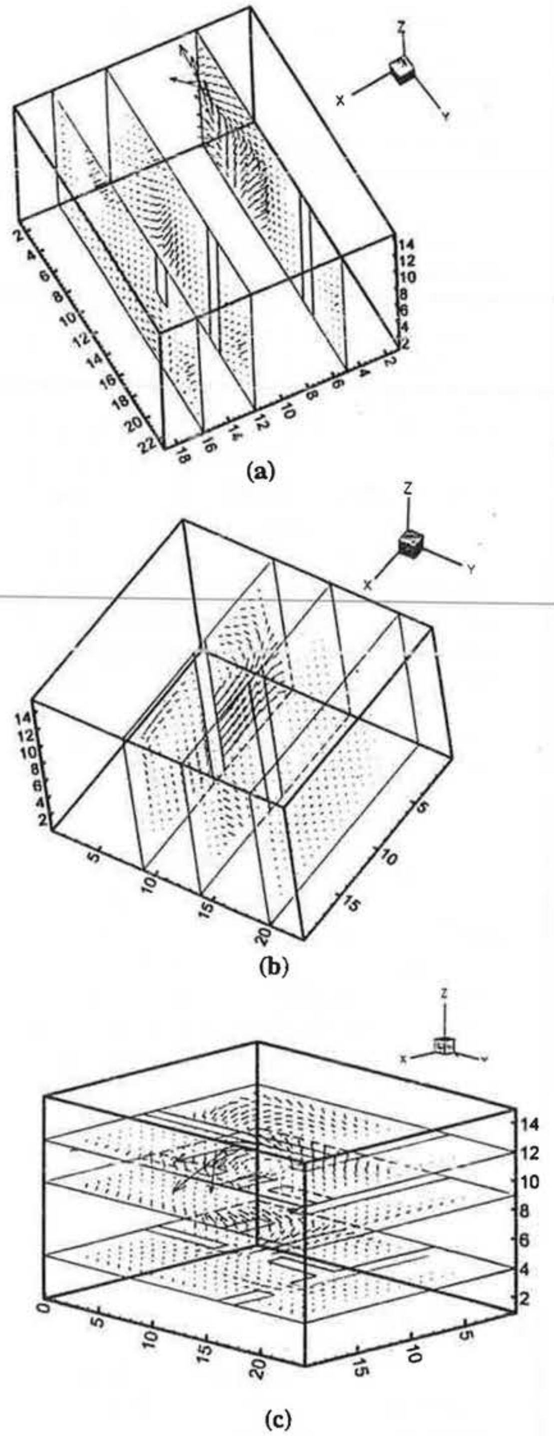


Figure 2. Three-dimensional computed airflow patterns of the partitioned enclosure at three different directional sections (a) y-z plane (b) z-x plane and (c) x-y plane

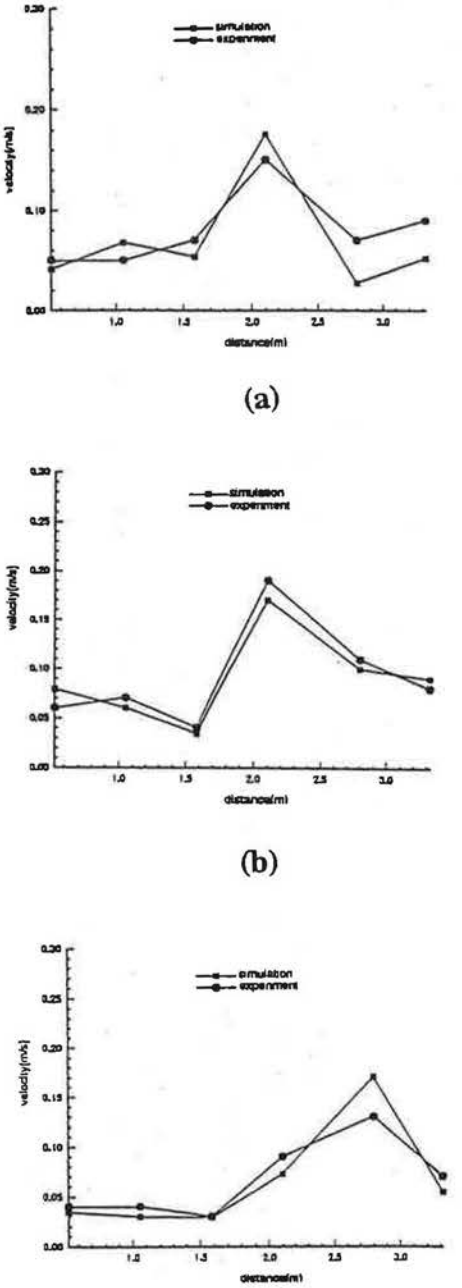


Figure 3 Comparison of measured and predicted velocities of the partitioned enclosure on y-z plane at x = 0.7 m for y-directional points (a) z = 1.0 m (b) z = 1.4 m and (c) z = 1.94 m

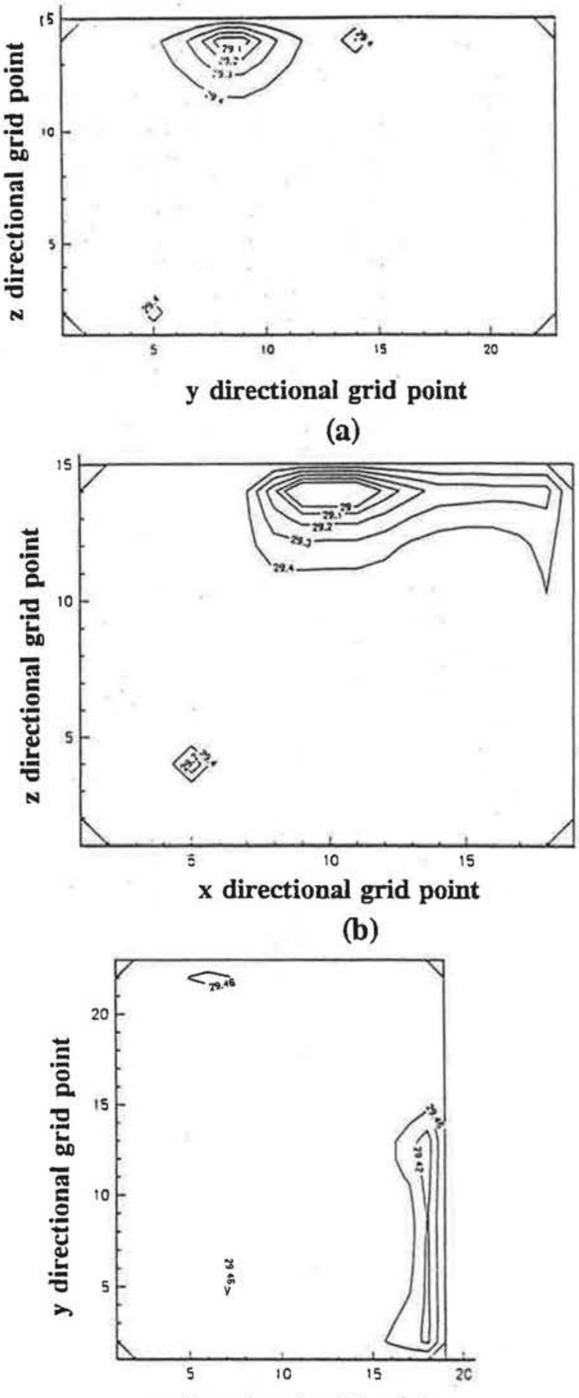
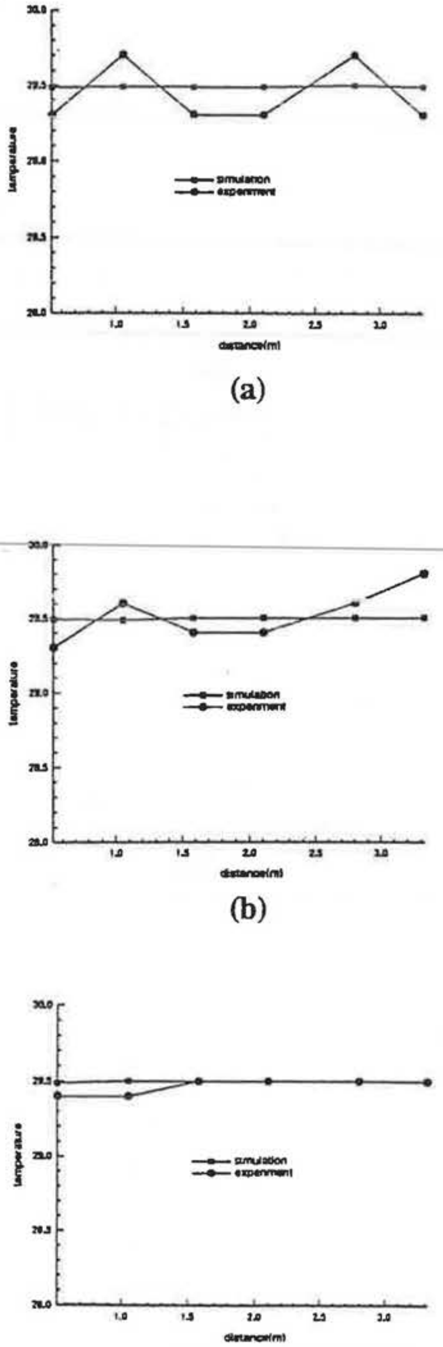


Figure 4. Computed temperature contours of the partitioned enclosure at three different directional sections (a) y-z plane at x = 2.28 m (b) z-x plane at y = 1.75 m and (c) x-y plane at z = 1.75 m

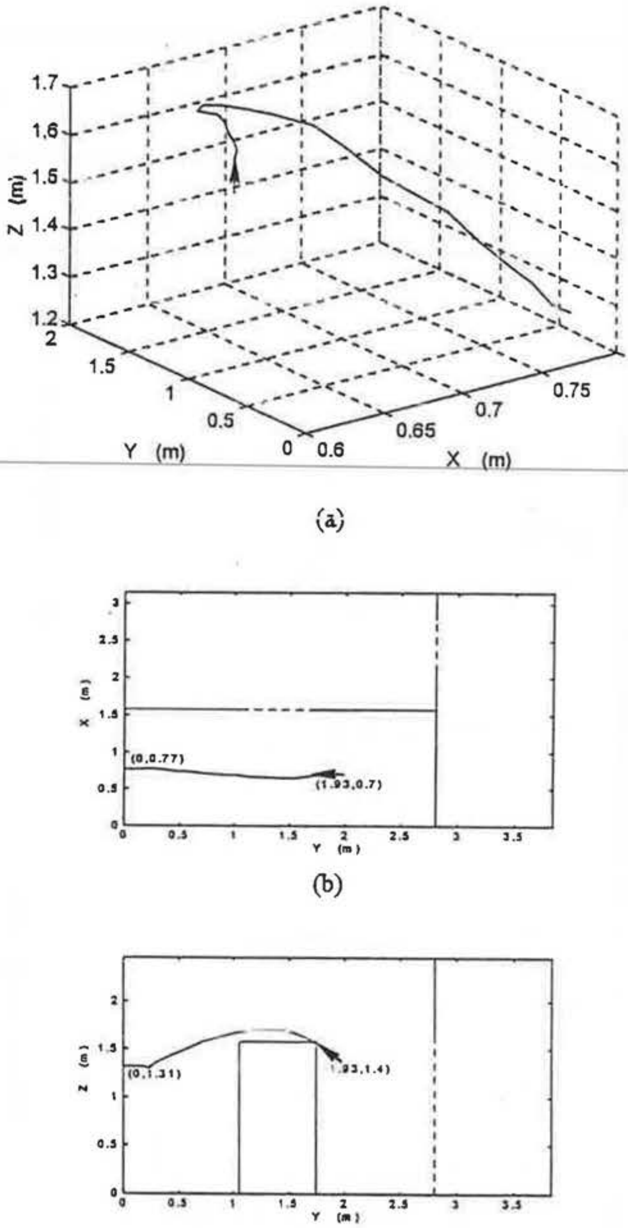


(a)

(b)

(c)

Figure 5. Comparison of measured and predicted temperatures of the partitioned enclosure on y-z plane at x = 0.7 m for y-directional points (a) z = 1.0 m (b) z = 1.4 m and (c) z = 1.94 m



(a)

(b)

(c)

Figure 6. The trajectory of 1.0 μm contaminant particle released from source located in zone B (0.7 m, 1.93 m, 1.4 m)