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Predicting Contaminant Particle Distributions to Evaluate the Environment of Lavatories with Floor Exhaust Ventilation

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The upgrading of contamination control and air quality in the lavatory environment with floor exhaust ventilation systems is studied. Using this new ventilation design, the distributions of airflow and polluted odors (contaminant aerosol particles) in normal lavatories are explored in order to improve comfort conditions. Considering the turbulent and unstable behavior of the airflow, residence time theory is applied to describe the characteristics of aerosol particles in terms of probability distribution functions. A complete numerical simulation of airflow and contaminant particles (odors from excreta) is undertaken and the results of a typical men's room and a typical women's room are presented. © 1997 Elsevier Science Ltd. All rights reserved.

NOMENCLATURE

$F(t)$	cumulative distribution function
g	gravitational acceleration constant
P	pressure
p	probability
T	air temperature
t	residence time
V	mean velocity
ρ	density
α	thermal diffusivity
ν	kinematic viscosity
τ	all possible values of residence time
ω	vorticity

INTRODUCTION

IN modern society, more and more people spend most of their time indoors. Therefore, indoor air quality in residences, offices and other non-industrial indoor environments has become an issue of increasing concern, as an important aspect of indoor environment. Dols *et al.* [1] and Chung and Wang [2] have shown that indoor air quality has considerable influence on the productivity and health of human inhabitants. Sandberg and Blomqvist [3] and ASHRAE [4] also show that indoor air pollutants are normally at higher concentrations than their outdoor counterparts. Ventilation is usually considered to be the engineering solution to improve indoor air quality. An understanding of the characteristics of airflow is a major concern for a ventilation system designer. One difficulty when attempting to predict in detail indoor airflow is that there are many factors which influence the flow, such as air distribution design, building construction, outdoor environment, and human beings themselves. When designing and analyzing ventilation systems, engineers and scientists generally have three tools with which to study indoor airflow patterns: analytical method, model experiment, and numerical investigation. Analytical methods are restricted by the need for simplifying assumptions and simplistic configurations. Full-scale measurements can provide the most reliable data, but are more expensive and difficult to perform. Numerical studies seem to be the most general and accessible methods. This is evident from the fact that, over the last 20 years, prediction methods for indoor airflow have increased, based mostly on finite difference and finite element solution of Navier–Stokes equations with the addition of some turbulence models [5–7].

In recent years numerical simulation of airflow and temperature fields has often been used in the design of indoor air-conditioning. It is used to predict air velocity and temperature distributions within the designed indoor environments and to see whether or not velocity and temperature fall within tolerable levels [8, 9]. So far, the research on contaminant particle distributions within the indoor environment is still limited. Understanding the behavior of aerosol particles and gaseous contaminants in rooms or chambers, in which the contaminant particles are generated or into which the contaminants are introduced, is of practical importance. The knowledge of the

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distribution of polluted particles within an indoor environment is very helpful in contamination control technology.

Nevertheless, polluted air problems caused by contaminants are frequently found in many situations, such as smoke in a room, particle dispersion in clean rooms, and air polluting particles in kitchens. Little concern has arisen with regard to the internal pollution of lavatories. The polluted air stream from lavatories might not cause any harm to people, but increases the uncomfortable sensation of the people who use the lavatories. The inappropriate ventilation design of lavatories will result in the odors from excreta flowing to other nearby spaces.

THEORETICAL MODELS

The two-equation k–ϵ model is widely used in industrial applications due to its simplicity and the relative ease of use. This model could be incorporated in Navier–Stokes equation solver codes [10, 11]. However, it is also well known that the standard k–ϵ model suffers from several serious limitations. These restrictions have not been addressed by previous users. At lower velocities, convergence problems are likely to arise due to the ϵ/k and ϵ^2/k terms in the kinetic energy dissipation equation. These terms may become unbounded near the boundaries where k goes to 0 but not ϵ. Therefore, a time-dependent, two-dimensional room airflow vortex model is used in this study to calculate the vorticity formulation in the Navier–Stokes equations. A major feature of the vortex model is that it alleviates the need for a statistical steady-state model of turbulence. The energy conservation equation is solved simultaneously, for the temperature and velocity fields are coupled via the buoyancy term.

For an incompressible fluid, the equations of continuity, balance of momentum and energy conservation are given as follows by Boussinesq approximation [12].

$$\nabla \cdot V = 0 \tag{1}$$

$$\frac{DV}{DT} = g - \frac{1}{\rho}P + \upsilon\nabla^2 V \tag{2}$$

$$\frac{DT}{Dt} = \alpha\nabla^2 T. \tag{3}$$

From the momentum equation (2), the dynamic vorticity is derived as

$$\frac{D\omega}{Dt} = (\omega \cdot \nabla)V + \upsilon\nabla^2\omega + \frac{1}{\rho^2}\nabla\rho \times \nabla P - \nabla \times (\rho g), \tag{4}$$

where

$$\omega = \nabla \times V. \tag{5}$$

The velocity components of the flow field may be obtained by integrating the vorticity values from the solution of equation (4) [13]. The above equations are subjected to the following boundary conditions: (1) the velocities are zero along the walls, (2) the inlet velocity is assumed to be known, (3) the velocities at the outlet should satisfy the overall mass balance, and (4) the velocity and temperature gradients are equal to zero across the outlet.

The purpose of ventilation is to provide clean air in the parts of the room where it is required. The efficie of a ventilation system can be viewed in terms o capacity to remove or dilute airborne pollutants. Bes ventilation, there are other control measures for ind air quality: for example, some sources can be isol from the air by use of paints or coatings; product activities generating contaminants can be excluded f the building (smoking). However, ventilation, whe natural or mechanical, is the only available means removing human odors, and providing the perceptio fresh acceptable air quality.

The aesthetics of body odor in occupied spaces h remained the main object of concern in the field of v tilation for the last 40 years [14, 15]. Cain [16] has p lished literature reviews of the field of ventilation odor control. Experimental evidence on body odor c firmed the conclusion of the commission on ventila and, until the 1970s, ventilation rates of 5–20 cfm v prevalent from ASHRAE [17]. Age of aerosol parti is a very important variable for air contaminant cont It is measured between the initial release of an airbo contaminant in the environment and its final exit fr this environment. By definition, the age of a particl zero when it first enters the environment. The age the particle when it leaves for the last time is called residence time. Residence time theory has been s cessfully applied to chemical reactor design problems over 25 years [18]. Its main purpose is to predict yield chemical reactions taking place in complex systems fr a macroscopic point of view. This means that the the does not need a detailed knowledge of all the field p ameters, such as velocity, temperature, pressure, microscopic level of mixing, when predicted the react rates at every location within the environment [19]. general, and most particularly for room airflows, r dence time is a stochastic variable and is characteri by a probability distribution function. The fundame function is the cumulative distribution function an defined as

$$F(t) = p(\tau \leq t),$$

where p denotes probability. t, the residence time, is random variable, and τ represents all possible values residence time [20]. Thus $F(t)$ gives the fraction of p ticles which have residence time smaller than t. $F(t$ defined over the interval $\{0, \infty\}$, is non-decreasing its value ranges between 0 and 1. The situation for wh $F(\infty) < 1$ indicates a dead volume. The residence the assumes that the boundaries of the system are redefi so that $F(\infty) = 1$. The most obvious means of de mining residence time consists in the releasing of a la number of tracer particles at the inlet with age t_o = The cumulative distribution function of residence ti is simply the proportion of particles which have left system expressed as a function of particle age t_o. Num cal simulation may be achieved very easily by markin sample of Lagranian particles at the inlet. A time cour is attached to each particle so that particles may released either at the same time, or at a given rate. T residence time of each particle is, by definition, the va of its time counter when it exits the system. The histogr of particle ages for a large number of particles constitu the cumulative distribution of residence times. Theref

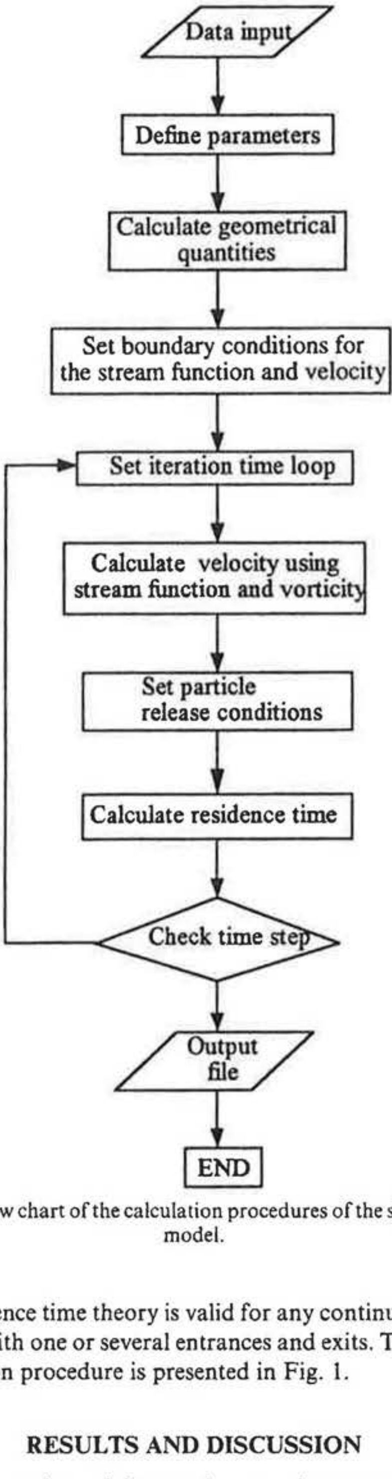


Fig. 1. Flow chart of the calculation procedures of the simulation model.

the residence time theory is valid for any continuous flow system with one or several entrances and exits. The entire simulation procedure is presented in Fig. 1.

RESULTS AND DISCUSSION

In this section, airflow and contaminant particle distributions are described using a transient model in which contaminant particles are continuously released at a constant rate to simulate the excreta odors from a contaminant source. Two-dimensional numerical simulations of the lavatory flow fields as well as the aerosol particle distribution are conducted by using the vortex model. Although the complete temperature fields are able to be obtained by this study, the results of temperature effects on the environment of lavatories are not presented in this paper. It is assumed that the average occupied time for each user is short and no significant heat source/sink exists inside the lavatories. The region in the analysis is divided into about 792 (33×24) cells using the rectangular mesh system. A time step of 0.25 seconds insures that the displacement for a very large proportion of discrete vortices is bounded by the cell size.

Simulation of the lavatory for men

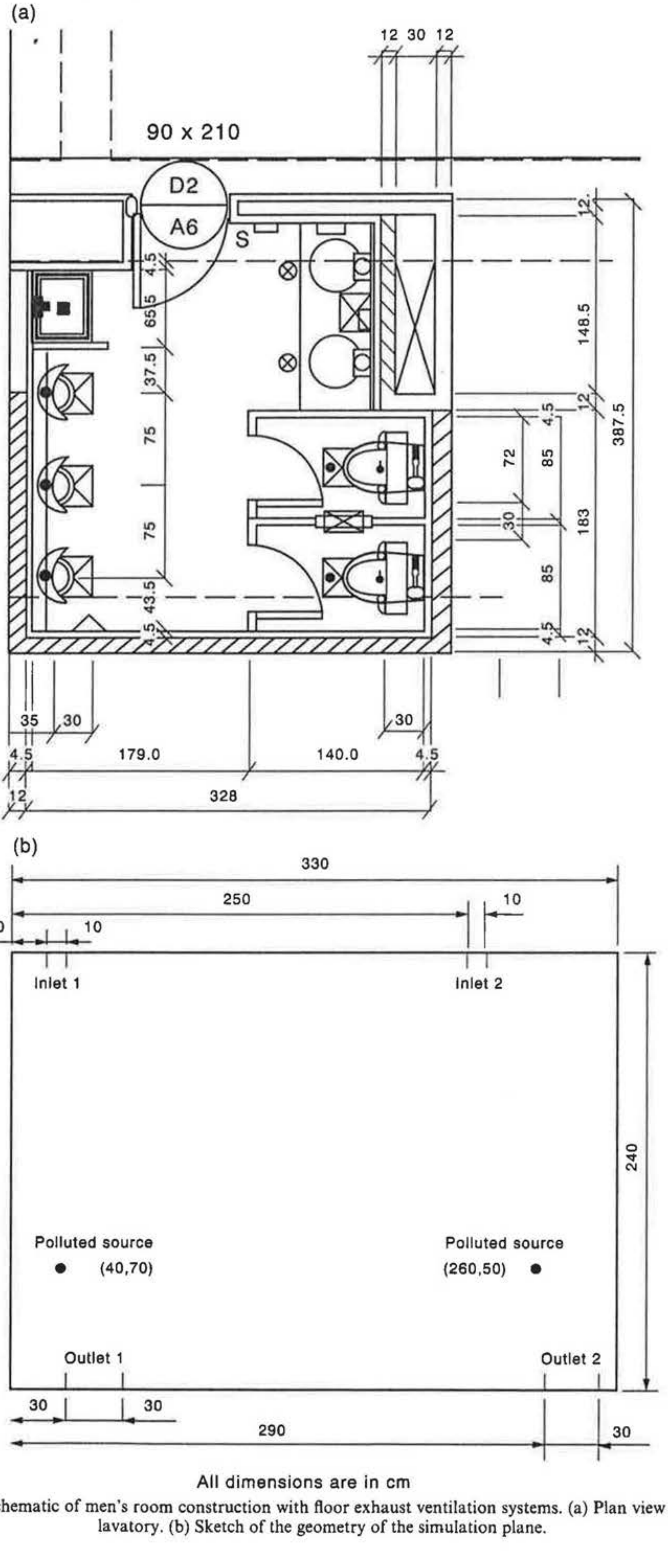
Figure 2 shows the characteristics of the men's rooms used for the two-dimensional numerical simulation. A floor exhaust ventilation system rather than traditional ceiling mounted ventilation outlets was supplied to improve the air quality of the lavatories' environment. The men's room is 3.3 m long and 2.4 m high. Two inlets to the ventilated space are located in the ceiling (top boundary) at 0.25 and 2.55 m from the top left corner, respectively. These inlets consist of two 0.1 m wide slits perpendicular to the plane of the simulation.

The two innovative designs of floor exhaust outlets are located on the floor (bottom boundary) at 0.45 and 3.25 m from the bottom left corner, respectively. Each outlet consists of a 0.3 m wide opening. The flow rates of inlet 1 and inlet 2 are 0.17 and 0.22 m^3/s, respectively. The contaminant aerosol particles are released from the urine pot at the locations of (0.4, 0.7 m) and from the closestool at (2.6, 0.5 m), respectively. It is rather difficult to simulate the odor characteristics in a real lavatory environment. However, it is reasonable to use a small sized particle (diameter less than 1 μm) to represent the gaseous odor behavior. The strength of the odors was simulated by 40 contaminant aerosol particles dispersed continuously per second from polluted sources and lasting for 5 minutes.

The complete simulation results for the men's room including distribution of velocity vectors and the trajectory of aerosol particles are shown in Fig. 3. The air from the supply inlets at the ceiling flows to the floor exhaust outlets through the occupied area. In order to overcome the problems of odors from excreta, different air volume designs for inlets and outlets are specified. Between the two air streams directly under the inlets, two recirculating flows are formed due to two different exhaust air volumes. The left outlet (outlet 1) has triple the flow rate of the right one (outlet 2). Since the air from inlet 2 exhausts partly through outlet 1, it might cause a recirculating flow near the floor area.

Figure 3 also shows the contaminant particle (simulating the odors from excreta) trajectories for the men's room from the beginning to 6 minutes. It is evident that the contaminant particles were constricted under the bottom area by the floor exhaust ventilation design within the period of lavatory occupancy. Although the contaminant particles are delivered continuously from the polluted sources (excreta), the smell of the odors cannot reach the height of the breathing area of people. When the user left the lavatory after 5 minutes (300 seconds), the odors from excreta (contaminant particles) were almost exhausted by the floor ventilation system within 60 seconds. This phenomenon can be observed from the simulation results shown in Fig. 3k and l.

The main objective of ventilation is to supply sufficient fresh air to the breathing zone of occupants and to remove contaminated air. The size and the location of the breathing zone in a room may vary with time and with the specific activities going on. In order to evaluate



All dimensions are in cm

Fig. 2. Schematic of men's room construction with floor exhaust ventilation systems. (a) Plan view of the lavatory. (b) Sketch of the geometry of the simulation plane.

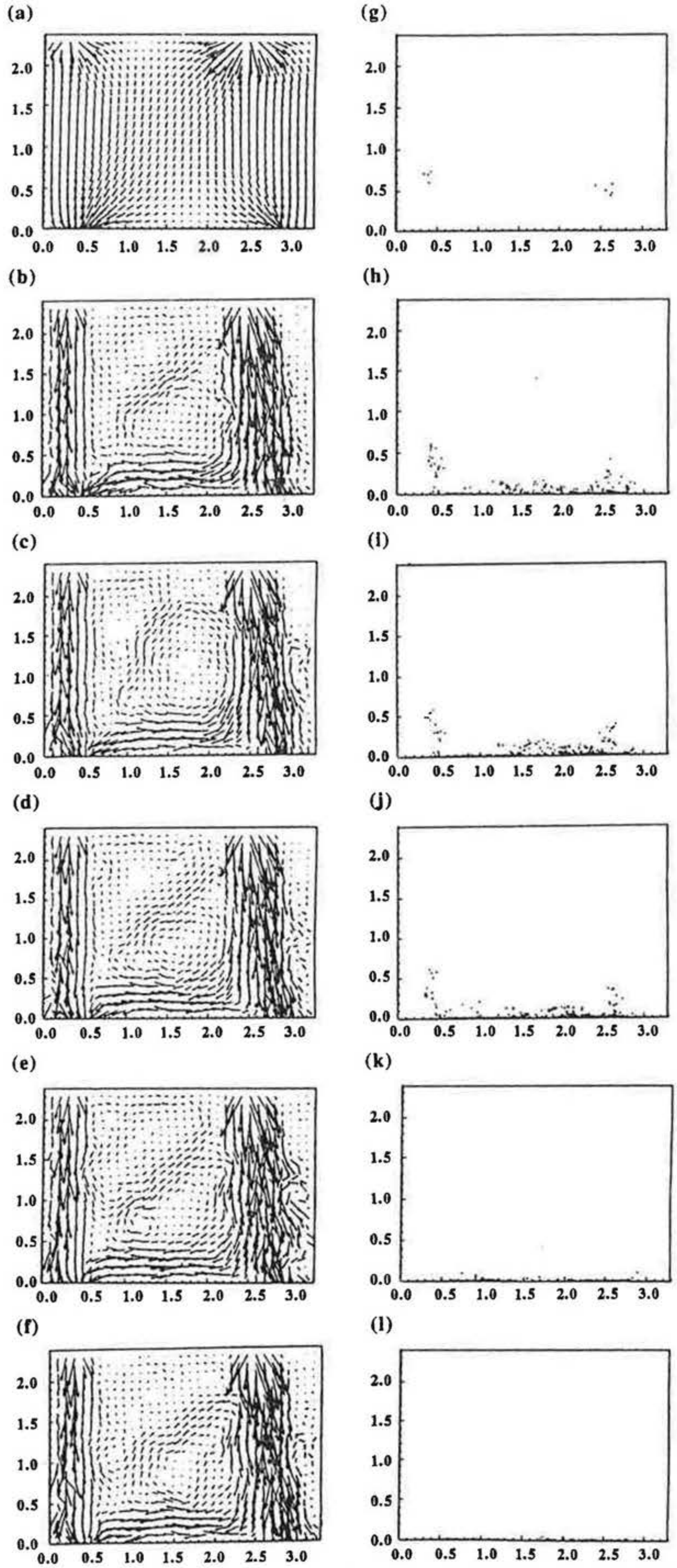


Fig. 3. Transient flow patterns and contaminate particle paths at (a) and (g) 1, (b) and (h) 60, (c) and (i) 180, (d) and (j) 300, (e) and (k) 330, and (f) and (l) 360 seconds for the men's room.

the effectiveness of the floor exhaust ventilation system, the time history of removed contaminant particles is illustrated in Fig. 4. Owing to the people using the lavatories during the first 5 minutes, the amount of contaminant particles increased, as shown in Fig. 4. At the sixth minute, the amount of contaminant particles remains constant because of the vacuum condition of lavatories, whereas the amount of exhausted contaminant particles increases due to operation of the floor exhaust ventilation system. After the user leaves the lavatory, the amount of contaminant particles in the air drops dramatically between 300 and 360 seconds. Only 1.2% of contaminant particles remain at the end of the simulation. It is believed that the floor exhaust ventilation system can work successfully in odor control in the lavatory environment.

Simulation of the lavatory for women

The configuration of the women's room used for numerical simulation is shown in Fig. 5. Similar to the design of the men's room, a floor exhaust ventilation outlet was arranged at the location of 0.65 m from the left bottom corner. Only one exhaustive diffuser was considered because the closestools for the women's room are located at the same line in the lavatory. However, two inlets were mounted at 1.05 and 2.55 m from the top left corner of the ceiling. Each inlet had a 0.1 m wide open perpendicular to the plane. The flow rates of inlet 1 and inlet 2 were 0.17 and 0.11 m^3/s, respectively. The contaminant particles from excreta were delivered at the locations 0.7, 0.5 m, which are just above the closestool. The strength of the odors was simulated as for the men's room case. Forty contaminant particles were dispersed continuously per second and lasted for 5 minutes. The entire simulation results for the women's room are plotted in Fig. 6. The general flow pattern from the ceiling inlets to the floor outlet through the occupied area is rather different from the men's room results. Due to the design of two inlets–one outlet, most draft flowed to the outlet diffuser close to the left side and caused a recirculating flow in the center part of the women's room as well as a stagnant area near the top left corner. The

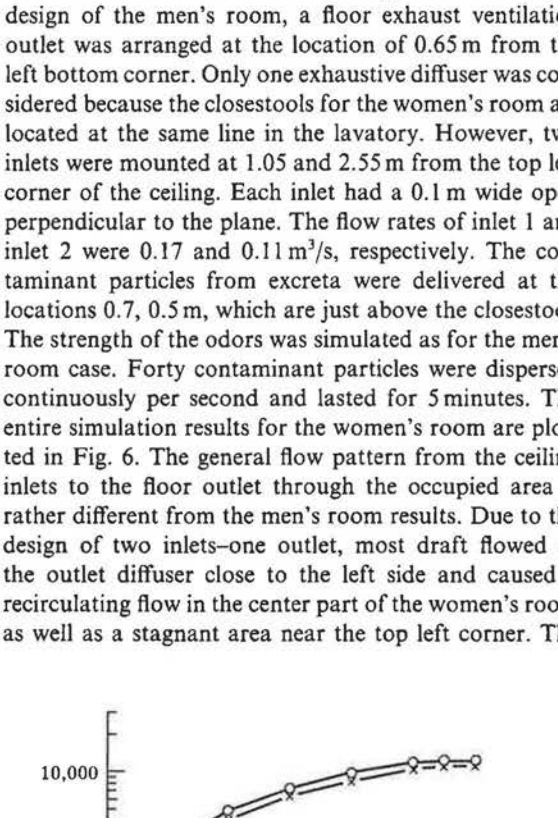


Fig. 4. The relationship between the amount of particles and operation time of floor exhaust ventilation systems for the men's room.

complete contaminant particle trajectories are illustra in Fig. 6 for the time from the beginning of the simulat to 6 minutes. During the period of the people's sta the lavatory (from 0 to 300 seconds), most of the c taminant particles were exhausted by the floor ventila system. However, some contaminant particles accu lated at the left part along the wall. After the user left lavatory, no more contaminant particles were produ and the particles near the floor were exhausted by floor ventilation system within another 60 seconds (fr 300 to 360 seconds). By looking at the velocity fields the contaminant particle trajectories, the contamin control of the lavatory environment can be successf predicted through the model presented in this pa Nevertheless, we can still observe a few contaminant p ticles close to the left side wall even under the operat of the floor ventilation system.

The results presented in Fig. 7 show the age of c taminant particles during the 6 minutes. As for the c of the men's room, a total of 12 000 aerosol particles w produced by the user when she stayed in the lavat for 5 minutes (40 particles/second). The sixth minut mainly for clearing the contaminant particles which w made by the former user. The results in Fig. 7 sh that the curve of the amount of particles remains rat similar to the case of the men's room but no signific decline in the amount of remaining contaminant partic was observed at 330 seconds. This is due to the sup draft being greater than the exhaust draft and causi part of the air flow to rise along the left side wall. The fore, some contaminant particles will flow up along air stream. After the complete evaluation time (360 seconds) for the lavatory environment, only 1.5 contaminant particles were still suspended in the under operation of the floor ventilation system.

Simulation of an individual space

Usually, when people occupy the closestool, an isolat environment is encountered. Therefore, the numeri simulation of an individual space was performed to inv tigate the effect of the floor exhaust ventilation syste on improving the contaminant control technology of t lavatory environment. The individual room was 1.5 long and 2.5 m high, with a louver at the lower part the door. The louver is 40 cm high, 50 cm wide and 30 above the floor. A 10 cm wide inlet was mounted at t ceiling and a 30 cm wide outlet was installed at the flo A complete construction and the stream function of t individual room are presented in Fig. 8. The pollut source was located at (0.5, 0.5 m) and released eight ae sol particles per minute. The occupied time is assumed 5 minutes for each user and the total simulation period 6 minutes. The inlet and outlet airflow rate are 0.055 a 0.079 m^3/s, respectively.

The velocity vectors and the distribution of co taminant aerosol particles are illustrated in Fig. 9. T single inlet–single outlet flow stream divided the spa into two parts. Due to the louver effect, the air circulati loop at the door side is larger than that at the wall si The average diameter of the recirculating flow, whi occurs near the floor, is restricted under 1.2 m from t ceiling. As can be seen from Fig. 9, most odors fr excreta (simulated by aerosol particles) were confin

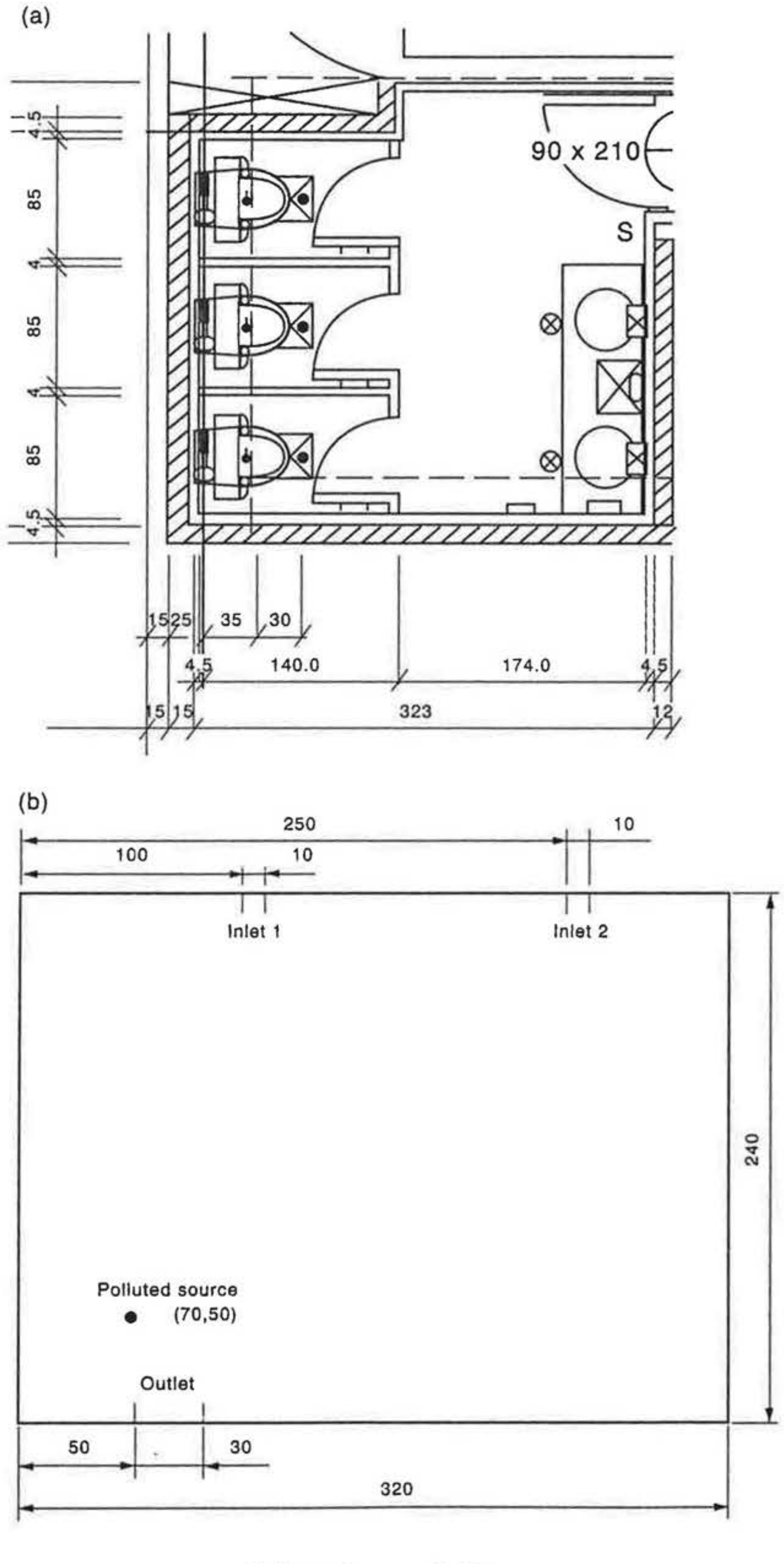


Fig. 5. Schematic of women's room construction with floor exhaust ventilation systems. (a) Plan view of the lavatory. (b) Sketch of the geometry of the simulation plane.

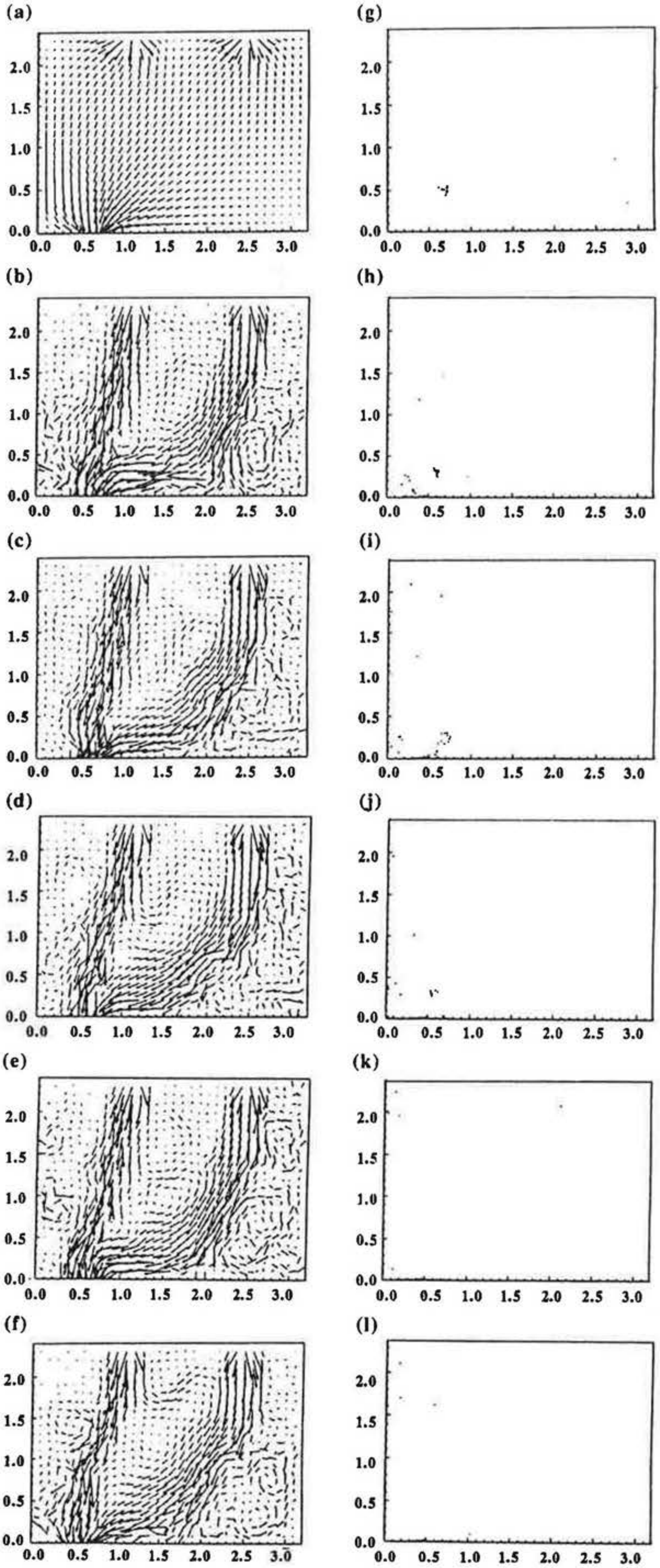


Fig. 6. Transient flow patterns and contaminate particle paths at (a) and (g) 1, (b) and (h) 60, (c) and (i) 180, (d) and (j) 300, (e) and (k) 330, and (f) and (l) 360 seconds for the women's room.

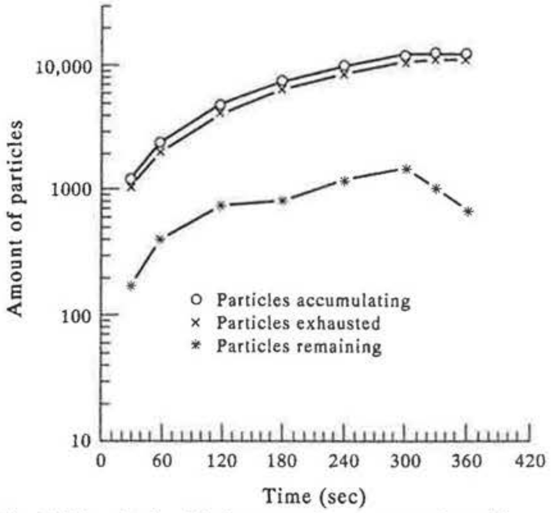


Fig. 7. The relationship between the amount of particles and operation time of floor exhaust ventilation systems for the women's room.

around the bottom left corner because of the floor exhaust ventilation system. One minute after the user leaves the lavatory, the floor exhaust ventilation can efficiently clear out the contaminant particles, as shown in Fig. 9j–l.

CONCLUSIONS

In this work, a numerical simulation successfully predicted the characteristics of airflow velocities and the transport of airborne aerosol particles as an aid to improving air quality in lavatories. Using residence time variables coupled with a vortex fluid model, the results of both men's and women's rooms have been presented. In addition, an individual space inside the lavatory was simulated by a single inlet–single outlet ventilation system with a louver at the door side. In order to simulate the real pollutant source in lavatories, 40 contaminant particles per second from excreta were delivered continuously. The design of floor exhaust ventilation system has been proved to efficiently purge the odor from the polluted sources. According to the simulation results, only 1.2 and 1.5% particles remain in the men's and women's rooms, respectively. This means that, with the assistance of the floor exhaust ventilation operation, after the first user has left the lavatories for 60 seconds, the environment of the lavatories is comfortable for the next user to enter.

Although the strength of the odors from lavatories is difficult to simulate precisely, the simulation technology described in this paper is a good tool for predicting the trend of the "odor flow". It is clear that the model presented in this paper can provide enough data for evaluating the environment of lavatories before actual construction. All of the fundamental parameters used for evaluation of the indoor environment, such as location of diffuser, air velocity, strength of pollution source, contaminant particle trajectory, and location of contaminant particle, can be provided through the technology described in this paper. Also, from the results of the numerical simulation, the aerosol particle trajectories relating to airflow formulation are predicted well through the contamination control model described in this paper. It should be noted that the pollutant sources studied in

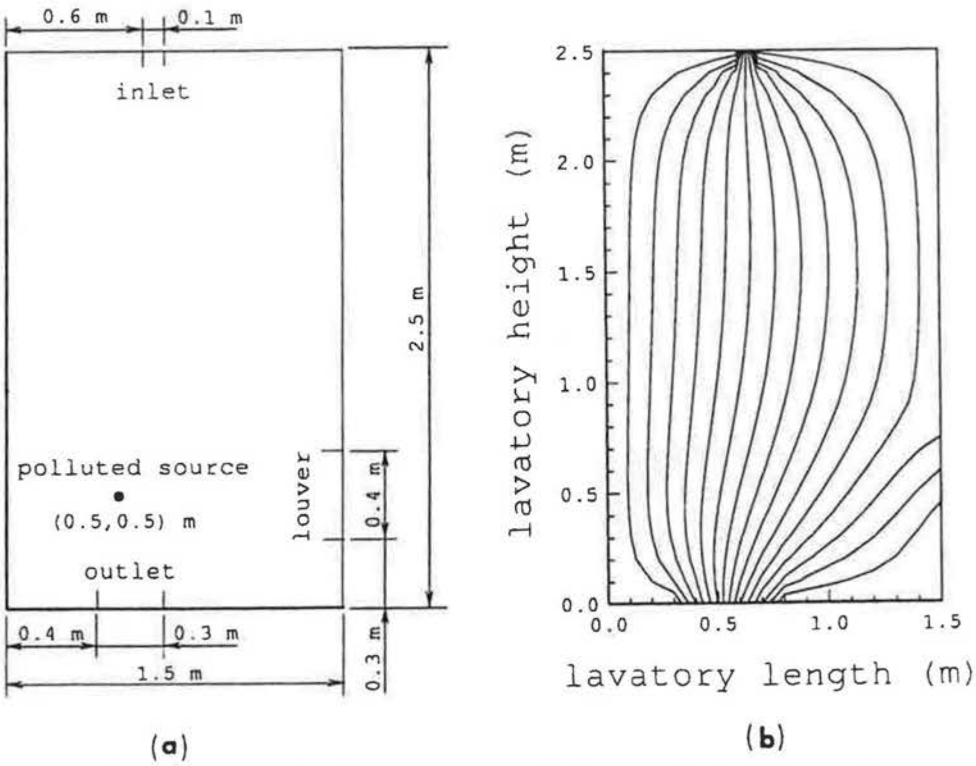


Fig. 8. (a) The simulated geometry of an individual space. (b) The stream function of an individual space.

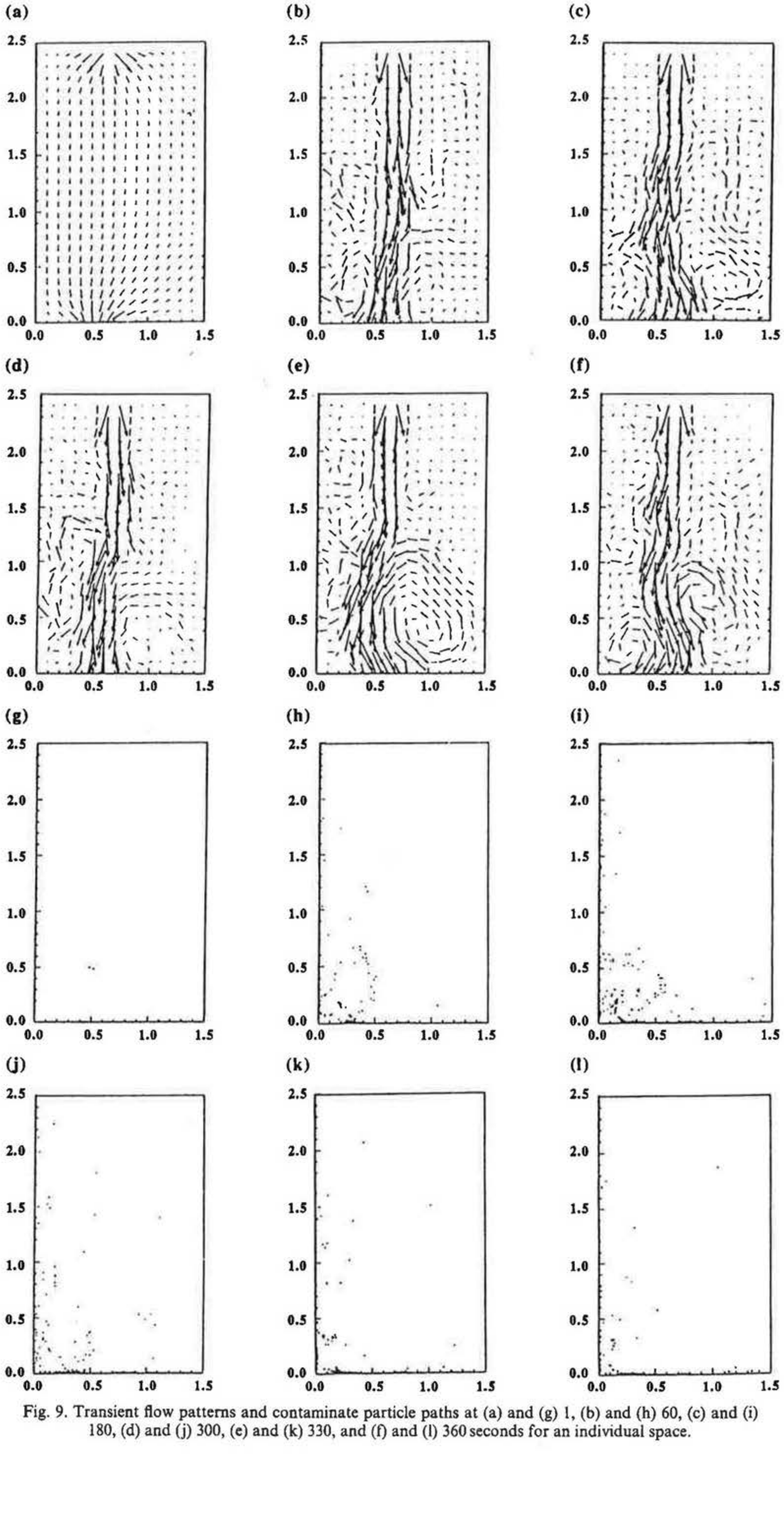


Fig. 9. Transient flow patterns and contaminate particle paths at (a) and (g) 1, (b) and (h) 60, (c) and (i) 180, (d) and (j) 300, (e) and (k) 330, and (f) and (l) 360 seconds for an individual space.

this paper are odors from lavatories, but could be any type of contaminants found inside buildings. This technology can not only predict the lavatory environment but also be applied to general indoor environments for predicting the velocity, temperature, and particle distribution under any specific conditions. However, the testing and validation of the simulation results and determination of the optimum range of the model parameters constitute obvious work for further research.

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