

Impact of Early Stage Incomplete Mixing on Estimating VOC Emissions in Small Test Chambers

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Abstract Most of the existing emission models developed from small-scale chamber tests assume complete mixing in the chamber throughout the test period. This paper examined this assumption using a Computational Fluid Dynamics (CFD) model. The model simulated the three-dimensional air velocity profiles and Volatile Organic Compound (VOC) concentration distributions from wood stain in a well-designed mixing chamber of $1.0 \times 0.8 \times 0.5 \text{ m}^3$. The model used measured data to determine the time-dependent VOC surface concentrations of wood stain. The CFD results show that the VOC concentrations in the test chamber were not uniform in the early stage (about 18 minutes). The first-order decay model using the complete mixing assumption will underestimate the Total VOC (TVOC) emission rates by 65% and 59% in the first 3 minutes and next 15 minutes, respectively. Since wood stain emitted about one third of the VOCs in the first 18 minutes, the impact of incomplete mixing in the early period is significant for calculating the material emissions. Furthermore, the mass transfer coefficient of TVOC calculated by CFD is also compared with that calculated by analogue theory and that calculated by experimental correlation.

Key words VOC; CFD; Building material emissions; Incomplete mixing; Small chamber test; Emission modeling.

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Introduction

Small-scale test chambers (ASTM, 1990), which are less expensive than full-scale ones, are usually used to study Volatile Organic Compound (VOC) emissions from building materials. The crucial factors influencing material emissions, such as air temperature, humidity, velocity, air exchange rate, and product loading, can be accurately controlled in the chambers. Since direct measurements of the VOC emission rates from a material in a small-scale test chamber are difficult, they are usually

estimated from the time-dependent VOC concentrations measured at the chamber exhaust. At present the estimation is done by either empirical or physical modeling (Colombo et al., 1992; Chang and Guo, 1992).

The empirical models of building material emissions are derived from the chamber testing results via curve fitting. The first-order decay model, one of the commonly used empirical models, uses a lumped parameter method for the VOC sources and assumes that the VOC concentration is uniform in the test chamber. The model calculates the VOC emission rate by:

$$R(t) = R_0 e^{-Kt}$$

where:

$R(t)$ = material emission rate at time t , $\text{mg}/\text{m}^2\text{h}$
 R_0 = initial emission rate of the material, $\text{mg}/\text{m}^2\text{h}$
 K = emission decay constant, h^{-1}
 t = time, h

The R_0 and K are unknown and are determined by fitting the following equation with measured time-dependent VOC data:

$$C(t) = L_0 R_0 (e^{-Kt} - e^{-Nt}) / (N - K)$$

where:

$C(t)$ = VOC concentration in the test chamber at time t , mg/m^3
 L_0 = loading ratio of the material, m^2/m^3
 N = air exchange rate of the chamber, ACH

The physical models are based on the mass transfer mechanisms of VOC species. Typical physical models

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are the Vapor pressure and Boundary layer (VB) model (Tichenor et al., 1993), and diffusion models (Hanna et al., 1993; Christianson et al., 1993). The VB model determines the VOC emission rate, $R(t)$ ($\text{mg}/\text{m}^2\text{h}$), as follows:

$$R(t) = K_m [C_s(0) \Delta m_{\text{left}} / \Delta m - C(t)] \quad (3)$$

where:

- K_m = gas phase mass transfer coefficient, m/h
 $C_s(0)$ = initial surface concentration of the material, mg/m^3
 Δm_{left} = amount of VOC remained in the material at time t , mg
 Δm = total (initial) amount of VOC in the material, mg

Similar to the empirical models, physical models also assume complete mixing when using chamber data to obtain the unknown parameters.

Since most of the existing emission models use the complete mixing assumption, it is necessary to examine this assumption. By definition, the complete mixing assumption implies that VOCs, emitted from a substrate, have uniform concentrations throughout a test chamber. Common sense tells us that, for a period of time following the start of the test, this cannot be true. Initially there will be concentration gradients in the chamber. This period, however, depends largely on the chamber and its operating conditions. For most small chamber tests the air exchange rates are usually very low. Therefore, extra measures, such as a mixing fan or multi-port inlets are usually used to enhance the mixing (Tichenor, 1989). Even for such well-designed chambers, it still takes time to reach a perfect mixing. In fact, Haghghat et al. (1994) have computed the non-uniform VOC distributions in a partitioned room. By using the first-order decay models to match chamber test data, Bluysen et al. (1996) reported that the omission of the first measurement (when t is small) gave very different values of R_0 and K . This may be attributed to the incomplete mixing in the chamber. Although the findings from both studies were concluded from full-scale rooms, the same may happen in a small-scale test chamber. Quantitative analysis of the mixing and its possible impact on estimating emissions in a small test chamber has not been reported.

The empirical and physical models have been applied to various Indoor Air Quality (IAQ) programs to study IAQ in buildings. For example, Sparks et al. (1991) used the first-order decay model in their IAQ

program, EXPOSURE. Haghghat et al. (1994) incorporated the VB model into another IAQ program. Obviously, to obtain reliable results from those programs, the complete mixing assumption used in the empirical or physical models must be verified.

Since conventional approaches are inadequate to study the impact of incomplete mixing on material emissions, this investigation challenges the problem by using a Computation Fluid Dynamics (CFD) approach. This paper demonstrates the approach by applying it to calculate the VOC emissions from a commercially available wood stain in a well-designed, small-scale test chamber. The CFD model uses the VOC emission data from the chamber to determine the unknown boundary conditions of the model.

The CFD Model

The conservation equations of mass, momentum, and species concentrations, such as VOCs, govern the VOC transport in a test chamber. Since most of the chamber tests are conducted under isothermal conditions, the energy equation is not required. The CFD approach numerically solves these equations together with the corresponding boundary conditions for airflows and VOC concentrations in the chamber.

Governing Equations

Most airflows in test chambers and buildings are turbulent. With an eddy-viscosity turbulence model, the airflows and VOC transport can be described by the following time-averaged Navier-Stokes equations:

$$\frac{\partial}{\partial t} (\rho \Phi) + \text{div} (\rho V \Phi - \Gamma_{\phi, \text{eff}} \text{grad} \Phi) = S_{\phi} \quad (4)$$

where

- ρ = air density, kg/m^3
 Φ = C_i for VOC concentrations;
 = V_j ($j=1,2,3$) for three components of momentum;
 = 1 for mass continuity
 V = velocity vector
 $\Gamma_{\phi, \text{eff}}$ = effective diffusion coefficient
 S_{ϕ} = source term

The effective diffusion coefficient and source term for different Φ are listed in Table 1.

The effective viscosity, μ_{eff} , is the sum of molecular viscosity, μ , and turbulent viscosity, μ_t :

$$\mu_{\text{eff}} = \mu + \mu_t \quad (5)$$

Table 1 Values of Φ , $\Gamma_{\phi,eff}$ and S_{ϕ}

	Φ	$\Gamma_{\phi,eff}$	S_{ϕ}
Species (VOC)	C_i	D_{eff}	0
x-momentum	V_1	μ_{eff}	$-\partial\rho/\partial x$
y-momentum	V_2	μ_{eff}	$-\partial\rho/\partial y$
z-momentum	V_3	μ_{eff}	$-\partial\rho/\partial z$
Continuity	1	0	0

The μ is a fluid property while μ_t depends on flow conditions. Our previous investigation suggested a single algebraic equation to express the μ_t as a function of local mean velocity, V , and a length scale, l_{μ} (Chen and Xu, 1998):

$$\mu_t = 0.03874\rho V l_{\mu} \quad (6)$$

where l_{μ} is the distance from the numerical grid to the nearest wall.

Here we have estimated the effective diffusivity for VOC as:

$$D_{eff} = \mu / (\rho Sc) + \mu_t / (\rho Sc_t) \quad (7)$$

where Sc and Sc_t are the molecular and turbulent Schmidt numbers of VOC, respectively. The Sc for most VOCs in buildings is 1.5 to 3.0 (Sparks et al., 1996). Kays and Cranford (1980) suggested 0.9 for Sc_t . With $Sc_t = 1.0$, we can predict better VOC transport. Thus, the value of 1.0 is used for the present study.

Boundary Conditions

The governing equations can be closed with appropriate boundary conditions, such as the friction and VOC concentrations at a solid wall or material surface. Chen and Xu (1998) give detailed boundary conditions for friction. The VOC emission rate from the emission source, R , is determined by Fick's first law:

$$R = D_{eff}(C_s - C_1) / \Delta x_1 \quad (8)$$

where

C_s = VOC concentration at the material surface, mg/m³

C_1 = VOC concentration at the first grid, mg/m³

Δx_1 = the distance between the material surface and the first grid, m

The VOC concentration at material surface is difficult to determine, because it varies with material type, age, etc. For a wet material, surface concentration decreases with time while VOCs are emitted from the material.

We estimated the time-dependent surface concentration in the following method:

(1) Estimate an initial surface concentration, $C_s(0)$ at time $t=0$. The $C_s(0)$ depends only on the material type and can be estimated by regressing the dynamic data (Zhang et al., 1996) or static chamber test data (Sparks et al., 1996).

(2) Estimate the surface concentration $C_s(t)$ at time t using the VB model:

$$C_s(t) = C_s(0)(1 - \Delta m_{emitted} / \Delta m)$$

where $\Delta m_{emitted}$ is the VOC emitted from $t=0$ to t , and Δm is the total amount of VOC in the material. The Δm can be determined by integrating the time-dependent VOC curve from $t=0$ to $t=\infty$:

$$\Delta m = \int_0^{\infty} NV_c [C_{out}(t) - C_{in}] dt$$

where

N = air exchange rate of the chamber, ACH

V_c = volume of the test chamber, m³

$C_{out}(t)$ = VOC concentration at the outlet, mg/m³

C_{in} = VOC concentration at the inlet (≈ 0)

(3) Use $C_s(0)$ and $C_s(t)$ to compute the time-dependent surface concentration at the chamber outlet by the VB model. Then adjust $C_s(0)$ and $C_s(t)$ until the VOC concentration of the CFD computation is nearly the same as the experimental data. The purpose of this step is to compensate for factors that are not considered in the VB model, such as the sink effect of the substrate.

Numerical Procedure

A CFD program, PHOENICS (CHAM, 1996), was used to solve the time-dependent conservation equations together with the corresponding boundary conditions. The program discretized the space of the test chamber into non-uniform computational cells, and the discretized equations were solved with the SIMPLE algorithm (Patankar, 1980). The convergence criteria at each time step were to ensure the total normalized residual to be less than 1% for flow and 3% for VOC concentration.

Case Study

The above CFD model was used to study the VOC emissions from a commercially available wood stair in a small-scale test chamber. The chamber test data were used for the CFD simulation to determine the time-dependent VOC surface concentrations. Figure 1 shows the configuration of the test chamber used

this investigation. The chamber consisted of an inner and outer chamber, both of which were made of electro-polished stainless steel. The outer chamber had a dimension of 1.0 m×0.8 m×0.5 m. The material was placed in the inner chamber, where the local velocity and turbulence level was controlled by a stainless tubular fan. The fan drew air through the inner chamber and discharged it through the holes into the outer chamber. Both the multi-port chamber inlet and the fan were used to enhance a complete mixing. The air velocity over the material was controlled by adjusting the voltage supplied to the DC motor. The perforated plate, screens, and buffer plate were used to control the air flow and turbulence level over the material. Conditioned air was supplied to the outer chamber to maintain a constant temperature and humidity (ASTM, 1990). A microcomputer was used to monitor and control the test conditions, including the airflow rate, temperature, humidity within the chamber, air velocity and turbulence above the material, and ambient air temperature and relative humidity.

Prior to the test, headspace analysis identified four major VOC components from the wood stain – nonane, decane, undecane, and dodecane. In the test, about 3 grams of wood stain was applied to study the VOC emissions. The time-dependent VOC concentrations at the exhaust of the outer chamber were monitored by tube sampling and Gas Chromatography and Mass Spectrometry (GC/MS) analysis. Dur-

ing the first hour, samples were taken every 15 minutes, then every 30 to 70 minutes for another three hours. As VOC concentrations became smaller and smaller, the sampling period was longer and longer (1.5 hours to 1 day). The air velocities in the boundary layer of the material were measured in the inner chamber using a fast response hot wire anemometer. The test conditions of the chamber were as follows (Zhang et al., 1996):

- Temperature: $24 \pm 0.5^\circ\text{C}$
- Relative humidity: $45 \pm 5\%$
- Air exchange rate: 0.5 ± 0.05 ACH
- Air velocity at the mid-height of the inner chamber: 0.167 m/s
- Inlet and outlet size: 0.0063 m in diameter
- Substrate of tested material: 0.25 m (long) by 0.5 m (wide) oak

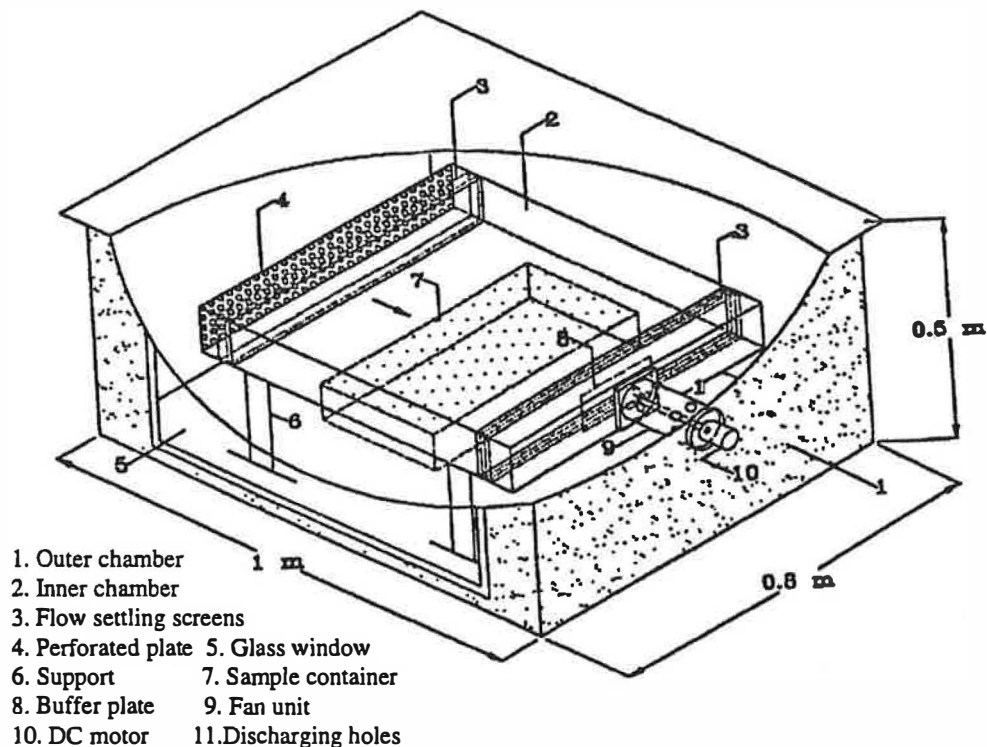
The Reynolds number of the flow, Re_h , in the inner chamber is:

$$Re_h = Vh\rho/\mu \quad (11)$$

where

- V = air velocity at the center of the inner chamber, m/s
 h = inner chamber height, m

Fig. 1 Configuration of the small-scale test chamber



1. Outer chamber
2. Inner chamber
3. Flow settling screens
4. Perforated plate
5. Glass window
6. Support
7. Sample container
8. Buffer plate
9. Fan unit
10. DC motor
11. Discharging holes

ρ =air density, kg/m^3
 μ =molecular viscosity of air, $\text{N}\cdot\text{s/m}^2$

In this case, $V=0.167\text{ m/s}$ and $h=0.08\text{ m}$. The Re_h was only 891, which means the flow was laminar. However, in the test, we used a perforated plate and flow settling screens (see Figure 1) to create turbulence over the material. Therefore, the flow in the inner chamber was turbulent although not strong. In the numerical simulation, an additional turbulent viscosity source was added at the entrance of the inner chamber to simulate the turbulence created by the perforated plate and flow settling screens.

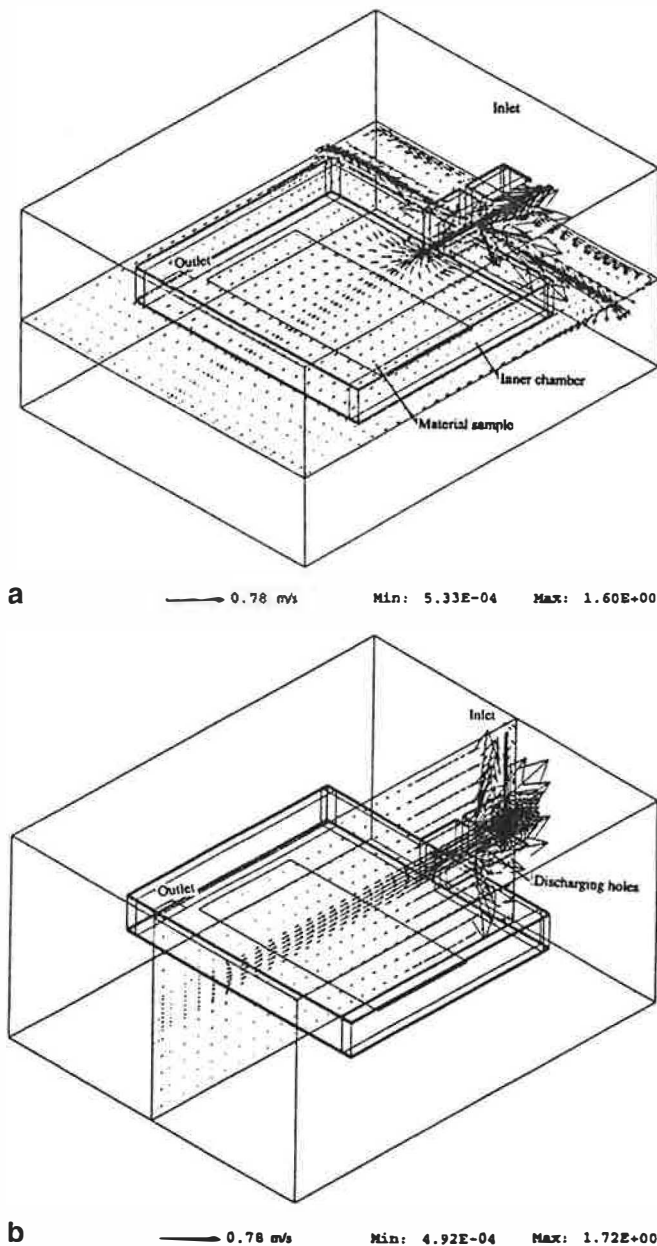


Fig. 2 Predicted velocity vectors in the chamber (a) In a section above the material (b) In a cross section

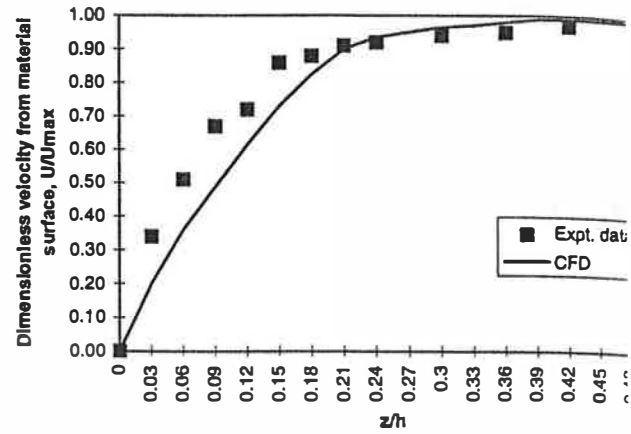


Fig. 3 Dimensionless velocity in the boundary layer of the material, $U_{max}=0.167\text{ m/s}$, $h=0.08\text{ m}$ (inner chamber height)

In the study, we used the Schmidt number, Sc , for single VOC and TVOC as follows (Sparks et al., 1996)

$Sc=2.63$ for nonane, decane, undecane, and TVOC.
 $Sc=3.06$ for dodecane

Results and Discussion

The chamber test lasted for a total of 125 hours. For wet materials like wood stain, most of the VOCs were emitted in the initial period. Therefore, the CFD computation was for the most important, initial period (about five hours).

Airflow Patterns

The airflow was steady though the VOC concentrations were time dependent. The computed airflow patterns in a section over the material and a cross section are shown in Figure 2. The air velocity at the center of the inner chamber was controlled to be 0.167 m/s in the experiment, which corresponded to 2000 changes per hour in the inner chamber. However, the air exchange rate in the whole chamber was only 0.5 ACH. The exhaust fan in the inner chamber exhausted the contaminated air to the outer chamber, resulting in a bulk velocity of about 0.01 m/s for the outer chamber. (The bulk velocity due to the net 0.5 ACH exchange rate for the whole chamber was negligible.)

The dimensionless velocity distribution above the material in the inner chamber is shown in Figure 3. The CFD results agree reasonably with the test data (Zhang et al, 1996). The computed air velocity profile is consistent with the well-known log-law for turbulent flow.

Concentration Profiles

Figure 4 illustrates the time-dependent concentration profiles of TVOC and four individual VOCs (nonane, decane,

undecane, and dodecane) at the chamber outlet, respectively. The agreement of the CFD computation with the data was actually achieved by adjusting the surface concentrations at different times to fit the data. As a comparison, the TVOC concentrations predicted by the first-order decay model using the complete mixing assumption are also shown in Figure 4(a). The first-order decay model could not perfectly match the test data as did the CFD model. Discrepancies can be found especially within the first hour.

The time-dependent TVOC surface concentrations calculated by CFD are shown in Figure 5. The initial surface concentration was 4300 mg/m^3 , but dropped rapidly to 3650 and 2180 mg/m^3 in the first 18 and 30 minutes, respectively. The concentration decay was slow afterwards. This presents typical emission characteristics of a wet material. The calculated surface concentrations by the VB model are also shown in Figure 5 for comparison. Note that the VB model predicted higher surface concentrations than CFD when $t > 30$ minutes. Since the VB model did not take the sink effect into account, this discrepancy may be attributed to the existence of the sink from the oak substrate and the chamber walls. As pointed out by many investigators

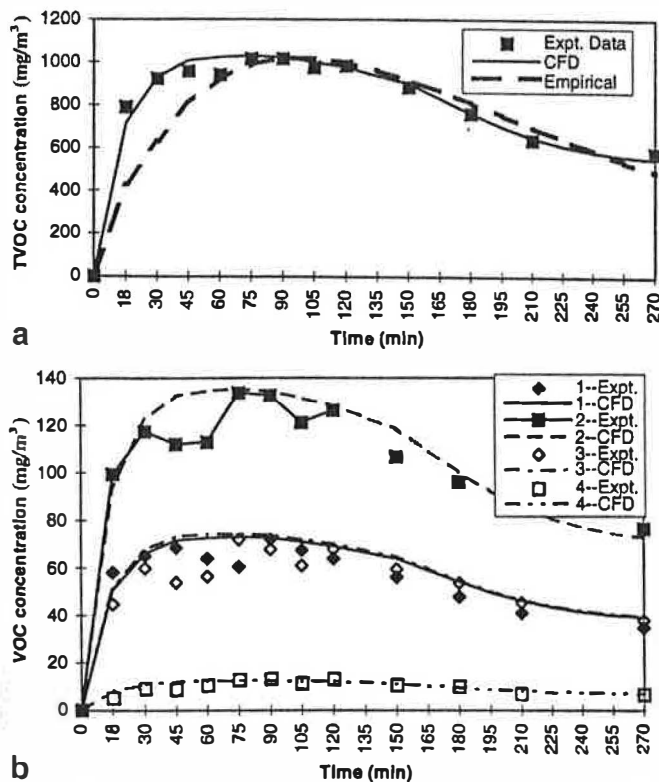


Fig. 4 Time-dependent VOC concentrations at the outlet. The agreement was achieved by adjusting the time-dependent surface concentrations until the VOC concentrations at the chamber outlet, as calculated by CFD, were nearly the same as those measured by the experiment. (a) TVOC profile (b) Individual VOC profiles (1=nonane; 2=decane; 3=undecane; 4=dodecane)

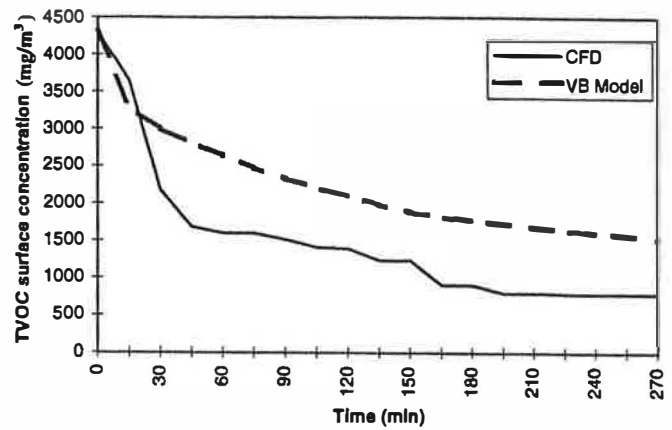


Fig. 5 Predicted TVOC surface concentration by different models

(Tichenor et al., 1991; Axley, 1991; Dunn et al., 1987), the sink effect can be important in the material emission process. The CFD results show that the substrate could have absorbed some VOCs in the first few hours.

Figure 6 shows the TVOC concentration distributions in a cross section at $t=6, 12, 18$ and 30 minutes, respectively. The figure depicts the evolution of the concentration profiles in the test chamber and show five different mixing zones in the chamber (Z1 to Z5, see Figure 6(a)):

- Zone 1: The inlet zone, including the clean air jet and the adjacent air entrained by the jet;
- Zone 2: The inner chamber zone;
- Zone 3: The upper zone, which is above the inner chamber;
- Zone 4: The lower zone, which is under the inner chamber; and
- Zone 5: The mixing zone, an area between the jet from the discharging holes and the upper and lower zones.

In the first 18 minutes, the VOC was accumulated in the chamber and the concentration was not uniform. The concentration gradient in the inner chamber (Zone 2) was large. For instance, at $t=6$ minutes, the TVOC concentration at the material surface was 3650 mg/m^3 . It dropped to 830 mg/m^3 at about 0.01 m away from the material surface and 248 mg/m^3 on top of the inner chamber (0.08 m away). The concentration in Zone 2 was several times higher than in Zone 3 and Zone 4. Because the upper zone had more clean air, the concentration at the outlet was lower than that in Zone 4. As time went on, the gradient in the inner chamber and the difference between Zone 3 and Zone 4 became smaller and smaller. A uniform concentration distribution was nearly reached when $t > 18$ minutes. The

above can also be observed by viewing the dimensionless TVOC distribution at a vertical line through the chamber outlet and at a vertical line above the material in the inner chamber as presented in Figure 7.

The VOC Emission Rates

The emission rates of TVOC versus time are shown in Figure 8. The emission rate at $t=3$ minutes was as high as $15,535 \text{ mg/m}^2\text{h}$. It dropped to $10,636$ and $4421 \text{ mg/m}^2\text{h}$ at $t=18$ and 30 minutes, respectively. As time went on, the rate of decrease became slower and slower. The TVOC emission rates predicted by the empirical first-order decay model are also illustrated in Figure 8. Compared with the CFD predictions, the empirical model underestimated the VOC emission rates by 65% and 59% in the first 3 minutes and next 15 minutes, respectively. The discrepancy became insignificant only after the uniform concentration in the chamber had been established. Since wood stain is a fast decay material, about one-third of the VOCs were emitted in the first 18 minutes.

Based on the CFD calculation, the first-order decay model is not accurate enough for calculating the material emissions in the initial period.

The complete mixing model performed poorly in the initial period because it could not take the non-uniform VOC distribution into account. Initially, the actual concentration at the chamber outlet was lower than the average in the test chamber. The difference was especially significant in the first few minutes. The mixing model considered the concentration at the outlet to be the same as the mean in the chamber. The emission rates thus tend to be smaller than the real values.

The predicted local transfer rates of TVOC from wood stain to the air are shown in Figure 9. The local VOC transfer coefficient, K (m/h), was calculated based on the local VOC emission rate R ($\text{mg/m}^2\text{h}$) and the overall VOC concentration difference between the material surface, C_s (mg/m^3), and the air in the flow, C_∞ (mg/m^3), via:

$$K=R/(C_s-C_\infty)$$

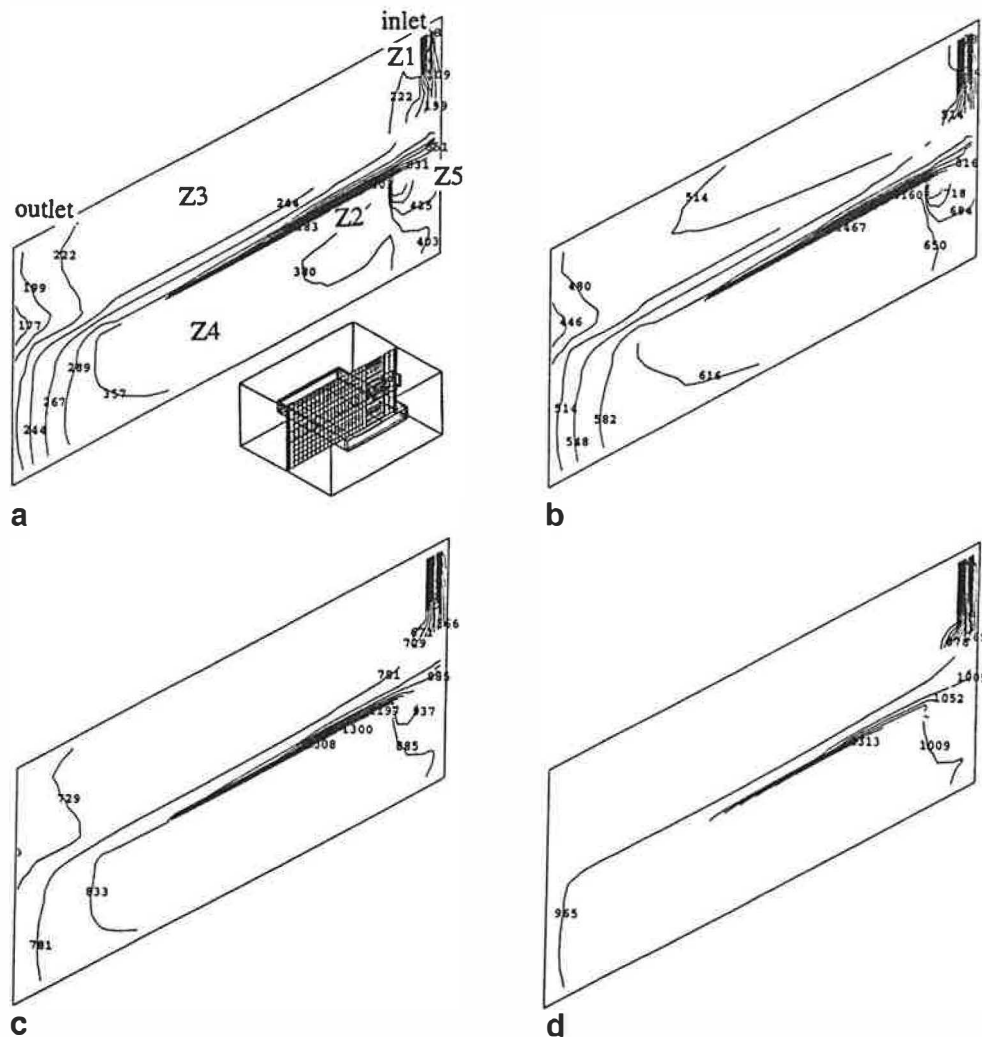


Fig. 6 TVOC concentration distributions in a cross section (m^3) (a) $t=6$ minutes (b) $t=12$ minutes (c) $t=18$ minutes (d) $t=30$ minutes

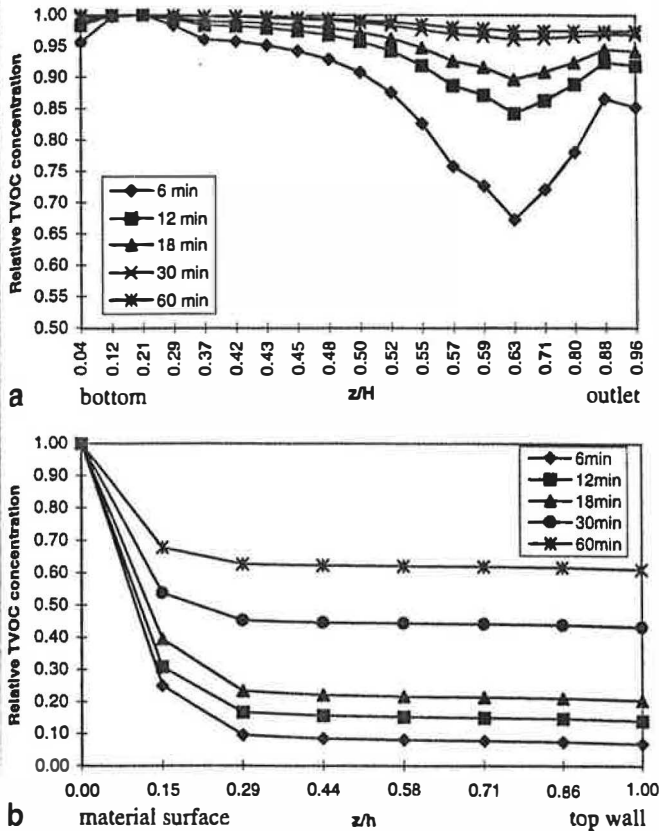


Fig. 7 TVOC distributions in a vertical line in the chamber (a) Outer chamber, H=0.5m (chamber height) (b) Inner chamber, h=0.08m (inner chamber height)

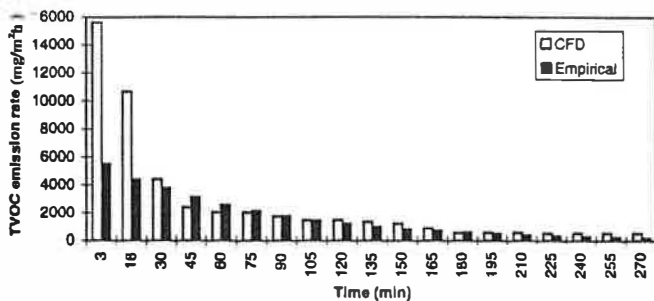


Fig. 8 Time-dependent TVOC emission rates

The results show that the local VOC transfer coefficients are close to constant. The local VOC transfer coefficients can also be expressed by a dimensionless Sherwood number, Sh:

$$Sh = KL / (3600D) \quad (13)$$

where L is the characteristic length of the source (m) and D the molecular diffusion coefficient of VOC (m²/s). Sparks et al. (1996) suggested the use of the square root of the source area as the characteristic length. Since the airflow is unidirectional in the inner chamber,

it is more appropriate to use the length of emission source in the present study.

Correlations are available to relate the Sherwood number, Sh, with the Reynolds number, Re_L, and the Schmidt number, Sc. For VOC species transfer over a flat plate, Sparks et al. (1996) obtained the following formula based on the data from chambers and a test house with constant synthetic stain and moth cakes:

$$Sh = 0.28 Re_L^{0.65} Sc^{0.333} \quad (14)$$

where L is used as the characteristic length for Re_L:

$$Re_L = VL\rho/\mu \quad (15)$$

Axley (1991) suggested the following correlations by using the heat and mass transfer analogy (White, 1988):

$$Sh = 0.664 Re_L^{0.5} Sc^{0.333} \text{ for } Re_L < 500,000 \quad (16)$$

$$Sh = 0.037 Re_L^{0.8} Sc^{0.333} \text{ for } Re_L > 500,000 \quad (17)$$

In the case studied, the Sh for TVOC calculated by Equations (14) and (16) were 67 and 48.3, respectively. The CFD obtained an average Sh of 44.2 (see Figure 9). This means that the local TVOC transfer coefficient obtained by CFD was very close to that of Equation

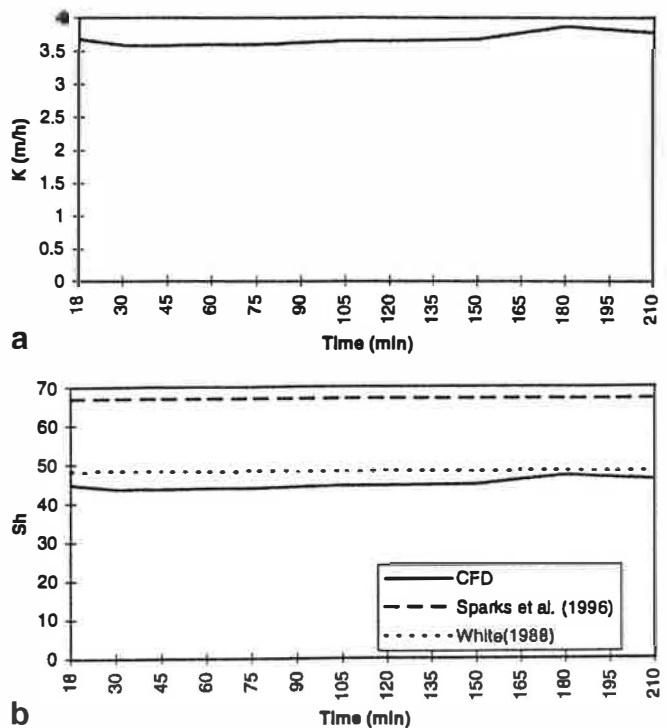


Fig. 9 Time-dependent local TVOC transfer coefficient (a) Local transfer coefficient (b) Sherwood number

(16), but was about 34% lower than Sparks's result by Equation 14. One possible reason is that Equation (14) was developed by using constant emission sources, whereas a decreasing source was used in the present investigation.

Implication of This Study to Small Chamber Test Method

According to the ASTM standard, complete mixing should be established in a test chamber. However, quantitative guidance on the mixing is unavailable. At times, the mixing is indirectly determined by injecting a given concentration of tracer gas (e.g., SF₆) at the chamber inlet and monitoring the time-dependent concentrations at the outlet. The deviation of the measured concentration with the theoretical, complete mixing curve indicates the extent of mixing. For emission testing, the compounds are usually from a surface or volume source in the chamber instead of from the inlet. The tracer gas test may not reflect the mixing in the actual test conditions. The use of CFD technique provides an alternative method to evaluate accurately the mixing and calculate the emission rates in a test chamber even when the complete mixing has not been established.

The mixing of a small chamber is usually determined by the operating conditions of the test chamber. In an attempt to obtain VOC concentration in the chamber similar to that of actual indoor environments, some small chamber tests use the same air exchange rate (e.g., 1.0 ACH) and material loading as that found in buildings. Girman (1993) indicated that, in this case, the air velocities in the small test chamber may be two or three orders of magnitude lower than they should be for realistic testing (0.1 m/s as recommended by Christianson et al. (1989)). This is undesirable because such low velocities may have significant consequences on material emissions especially for wet materials. In addition, if the air velocities in the test chamber are too small, it will also take a much longer time to reach a complete mixing. A mixing fan can be used to increase the air velocities and enhance the mixing, but that will cause uncontrolled airflow over the material. In order to control both the airflow and mixing, the small chamber needs to be carefully designed and operated. Girman (1993) suggested that a small chamber should either be operated with sufficiently high ventilation rates to obtain velocities close to those found indoors, or operated with recirculated air or with small, internal mixing fans. The chamber used in this study meets the requirements of both surface air velocity and internal mixing. Considering that the air velocity of 0.167 m/s used in this investigation is close to that normally

found indoors, the 18 minutes for a wet source material represent the typical length of time before the VOC concentration in the chamber can be reasonably approximated as uniform. Of course, the mixing time can be shorter if air velocity is higher and vice versa.

Scaling the Model to Buildings

The CFD model presented in this paper can be used to study material emissions in buildings, because the air and VOC transport can be described by the same equations whether in a small-scale chamber or in a real room. Therefore, there is no scaling problem in using the CFD model. Of course, since the flow and thermal conditions may be rather complicated in buildings, the CFD model should be further developed to address the combined effect of various environmental factors, such as air temperature, air velocity, relative humidity, and material loading, on material emissions. This will be reported in the future.

Conclusions

This paper reported the results of an investigation which used a Computational Fluid Dynamics (CFD) model to simulate the VOC emissions from wood stain in an emission test chamber of 1.0×0.8×0.5 m³. The CFD model gave three-dimensional air velocity profiles and VOC concentration distributions in the chamber without using the complete mixing assumption. The model used measured data to determine the time-dependent VOC surface concentrations of wood stain.

We have found that, in the initial period, the VOC concentrations from the wood stain in a well-designed mixing chamber were not uniform, based on the CFD simulation results. The first-order decay model using complete mixing assumption underestimated the TVOC emission rates by 65% and 59% in the first 15 minutes and the next 15 minutes, respectively. Since the wood stain emitted about one third of the VOC in the first 18 minutes, the impact of incomplete mixing in the early period is significant for calculating the material emissions. Furthermore, the mass transfer coefficient of TVOC calculated by CFD is close to that calculated by analogue theory, but 34% lower than that calculated by experimental correlation based on the data from chambers and a test house with constant synthetic stain and moth cakes.

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