Measurement of VOCs emission rates for evaporation-controlled materials by using an inner chamber

H. Tanaka*, S. Tanabe, R. Funaki, T. Nakagawa

Department of Architecture, Waseda University, Japan

ABSTRACT

In this paper, development of inner chamber for ADPAC to measure evaporation-controlled materials is reported. The inner chamber was made of stainless steel. A test piece is set at the bottom of the duct part. Air velocity and boundary layer in the main duct part are controlled by small DC fan, which is attached to the end of the duct. The air velocity inside the main duct was measured by an anemometer. The air velocity was to be controlled about 0.2 m/s in compliance with ENV13419-1. The mass transfer coefficient at the surface of test piece was calculated based on water vapor evaporation. The mass transfer coefficient was derived to be 10–11 m/h. In a typical room, the mass transfer coefficient is estimated to be in the range of 9–18 m/h. Emission rate for evaporation-controlled materials could be measured accurately by using the inner chamber for ADPAC.

INDEX TERMS

Emission rates; Evaporation-controlled materials; Boundary layer; Air velocity; Mass transfer coefficient

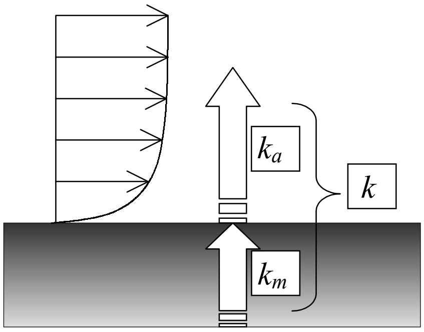
INTRODUCTION

Indoor air pollution by chemical contaminants from building materials has become a critical issue in Japan. To prevent indoor air pollution, it is required to obtain the emission rates from building materials. We developed a small-scale chamber ADPAC (ADvanced Pollution and Air quality Chamber) (Tanabe *et al.*, 2000) for emission test. ENV13419-1 (1999) specifies that air velocity in the chamber above test pieces should be in the range of 0.1–0.3 m/s. For internal-diffusion-controlled material like boards and most of the normal building materials, the effect of boundary layer above test pieces on emission is estimated to be minimal. On the other hand, air velocity is quite important for emission from evaporation-controlled materials like wet paint and liquid products. However, air velocity in ADPAC chamber without fan is too low to measure evaporation-controlled materials (Tanabe et al., 2002). In this paper, development of an inner chamber for ADPAC to measure evaporation-controlled materials is reported.

MASS TRANSFER FROM MATERIALS

Generally, there are two processes in emission of chemical substances. One is diffusion, and the other is evaporation. Emission characteristics take the process of either or both depending on the type and condition of materials. Figure 1 shows the scheme of mass transfer from a material to ambient air. Equation (1) describes the relation of mass transfer between material and ambient air. k is mass transfer coefficient, and k_a and k_m are mass transfer coefficient in ambient air and inside material, respectively. The smaller mass transfer coefficient becomes the dominant coefficient of its mass transfer. The mass transfer coefficient of internal-diffusion-controlled materials is described in Eqn (2). The mass transfer coefficient of evaporation-controlled materials is shown in Eqn (3).

* Corresponding author. E-mail: htanaka@tanabe.arch.waseda.ac.jp



$$\frac{1}{k}=\frac{1}{k_a}+\frac{1}{k_m} \quad \ldots(1)$$

Internal-diffusion-controlled materials

$k_a >> k_m \qquad \frac{1}{k}\approx\frac{1}{k_m} \quad \ldots(2)$

Evaporation-controlled materials

$k_a << k_m \qquad \frac{1}{k}\approx\frac{1}{k_a} \quad \ldots(3)$

Figure 1 Scheme of mass transfer from material to ambient air.

In the case of internal-diffusion-controlled materials, ambient conditions like air current and concentration above the material surface have little effect on emission, because emission rate is mainly controlled by the internal diffusion of the material. On the other hand, emission of evaporation-controlled materials is dominated by the evaporation on material surface. In order to measure VOC emission rates, ambient air current and air velocity need to be controlled. In a typical room, convective heart transfer coefficient is considered in the range of 3–6 $W/m^2/K$. The mass transfer coefficient is estimated to be 9–18 m/h by Lewis relationship. However, mass transfer coefficient inside ADPAC chamber was confirmed to be around 4 m/h, (Tanabe, S., et al., 2002) and it is lower than that of room. The inner chamber controlling air velocity is required for accurate measurement of VOCs emission rates for evaporation-controlled materials.

DEVELOPMENT OF AN INNER CHAMBER

Theory of Boundary Layer and CFD Analysis of Air Velocity

Contact of fluid and surface, such as gas and liquid, liquid and solid, results in transfer of heat and mass. When viscous fluid contacts a solid plane, the thin fluid layer is generated at the surface due to the drop in velocity. This layer is called the boundary layer. Flow inside boundary layer is a laminar flow at first, and it becomes a turbulent flow through an intergradation region. The minimum length of laminar flow region is estimated by Eqn (4). Air velocity inside boundary layer (u) declines smoothly from velocity of main flow (u_m) of outer edge. The thickness of boundary layer (δ_{99}), when u is $0.99u_m$, is estimated by Eqn (5).

$$\mathrm{Re_c} = u_m x_c / \nu = 3.2\times10^5 \qquad (4)$$

$$\delta_{99} = 5.0\sqrt{\nu x/u_m} \qquad (5)$$

where $\mathrm{Re_c}$ is the critical Reynolds number (–), x the length from leading edge (m), x_c the minimum length of laminar flow (m), and ν the kinematic viscosity (m^2/s) (= 1.46×10^{-5} for air.

The length of the laminar flow region and the thickness of the boundary layer were derived from Eqns (4) and (5), when u_m was 0.2, 0.3, 0.4 m/s, respectively. Because growth of boundary layer is enough when u is $0.95u_m$, δ_{95} was also considered. The calculation results are shown in Table 1. The value of x_c is high enough for the size of the inner chamber. Boundary layer becomes thick as air velocity of main flow becomes slow. When air velocity of main flow is 0.2 m/s, a thickness of at least 12 mm is required. Therefore, the distance of 15 mm is enough for the growth of the boundary layer. The distance from the sidewall of the duct to the edge of the test piece would be 15 mm. The height of the duct would be 30 mm because boundary layer is generated on both the ceiling and the bottom. The growth of boundary layer in duct was confirmed by STREAM, a commercially available CFD program.

Figure 2 shows the result of CFD analysis when exhaust air velocity at the end of duct is 0.2 m/s and height of duct is 30 mm. Sufficient growth of boundary layer was confirmed from the result.

Table 1 Length of laminar flow region ar boundary layer

u_m (m/s)	0.2	0.3	0.4
x_c (m)	23.4	15.6	11.7
δ_{95} (mm)	12.0	10.0	8.7

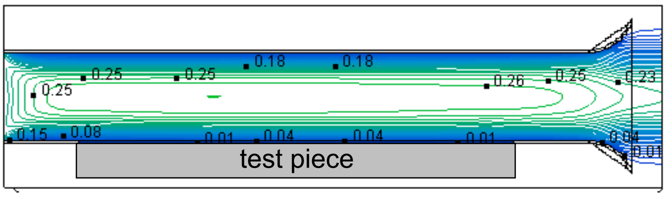


Figure 2 Result of CFD analysis

Inner Chamber

The inner chamber was produced based on the boundary layer theory and CFD analysis. Figure 3 shows the scheme and picture of the inner chamber, consisting of the main duct part and the fan duct part. The fan duct part is attached at the exit of the main duct part. They were made of stainless steel, which has no chemical emission and little sink effect. A test piece is set at the bottom of main duct part. Air velocity and current of boundary layer in main duct part is controlled by a small DC fan, which is attached to the fan duct part. When VOCs emissions are measured, it is necessary to take account of emission from the fan itself. This was not of a concern in this report, since mass transfer coefficient was measured with water.

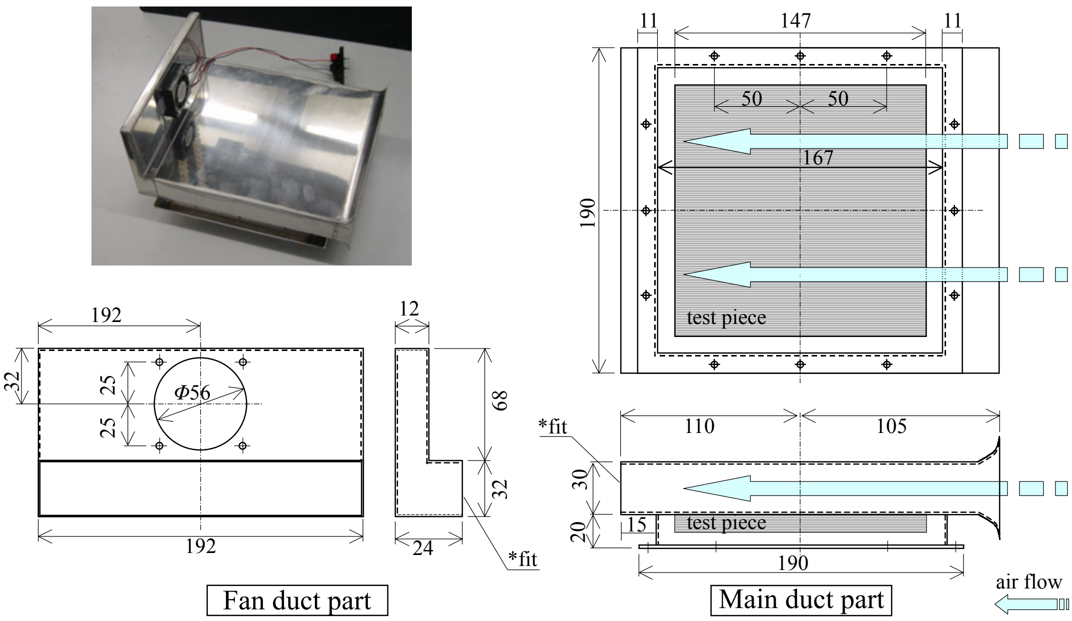


Figure 3 Scheme and picture of inner chamber.

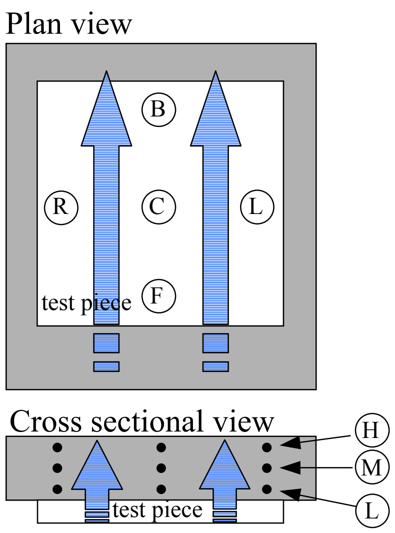
MEASUREMENT OF AIR VELOCITY

Methods

Air velocity inside the main duct was measured for 1 min at intervals of 1 s by a heated anemometer (KANOMAX1560). Two types of DC fans, L (ORIX MD625BM-12) and S (ORIX MDS410-12), were used, and four conditions of drive voltage, 3, 4, 5 and 7 V, were supplied by a DC power supply. The points of measurement were 15 points, five points on plane and three points perpendicularly, and these are depicted in Figure 4.

Results

Figure 5 shows the average air velocities and standard deviations of middle level and lower level for 1 min on each condition and at each point. Air velocity on the same level was uniform. The air velocity near the surface of test piece became lower than that of the middle level because of the developed boundary layer. Although the air velocity near the ceiling became lower like near the surface, variation of velocity was large. Air velocity increased in proportion to the drive voltage of the DC fans. Consequently, air velocity inside the main duct was uniform and stable, and it was confirmed that the unit could control the airflow required for measurement of evaporation-controlled materials. When a voltage of 3 V was supplied to fan L and 4 V was supplied to fan S, the air velocity of around 0.2 m/s required in ENV13419-1 was acquired in the middle level. DC fan S supplied with voltage of 4 V was applied in this report, because both of the fans would not operate normally under the voltage of 3 V.



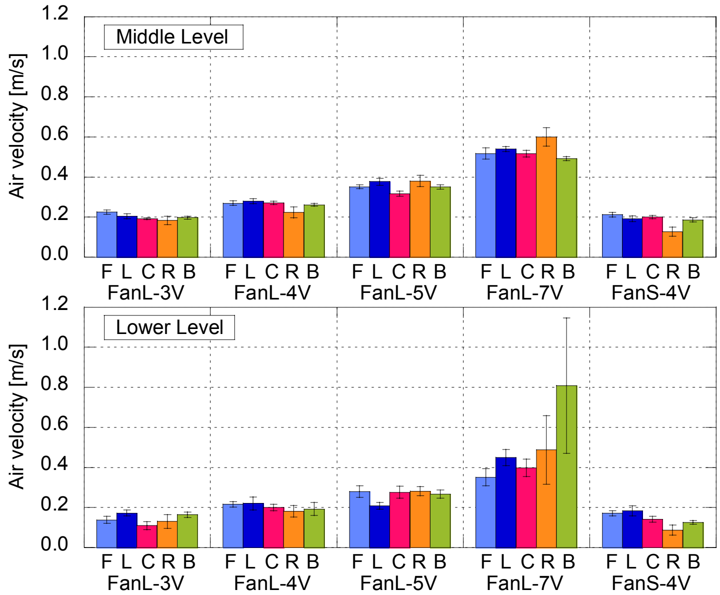


Figure 4 The points of measurement. **Figure 5** The result of measurement of air velocity.

MEASUREMENT OF MASS TRANSFER COEFFICIENT

Purpose and Methods

It was confirmed from the experimental results presented above that the inner chamber could control air velocity to be around 0.2 m/s. The mass transfer coefficient of water was measured as a representative of evaporation-controlled materials. It was examined whether the mass transfer coefficient was controlled in the range of 9–18 m/h, when the air velocity above test pieces was around 0.2 m/s.

A pile of filter papers with the size of 14.7 cm × 14.7 cm was installed in the inner chamber. The inner chamber was set on an electronic balance, and the balance was placed in a room. The weight was monitored every 5 s. The amount of reduction in 1 h was assumed to be the evaporation amount of water vapor. Temperature and relative humidity of ambient air were measured by thermo recorder, and surface temperature of the saturated filter paper was measured by thermocouples. Averaged values of 1 h were used for ambient air temperature, humidity and surface temperature. Equation (6) shows the mass transfer of water, and the mass transfer coefficient based on concentration (k_c) was calculated by Eqns (7) and (8) (Kimura, 1970). Absolute humidity was derived from the temperature and relative humidity. Relative humidity of surface paper was 100%RH.

$$L = k_x A\left(x_w - x_a\right) \tag{6}$$

$$k_x = k_c \gamma \tag{7}$$

$$\gamma = \frac{1.293}{(1+0.003660\theta)} \times \frac{f_a}{760} \quad (8)$$

where A: contact area of boundary layer (m^2) = 0.022 m^2
L: evaporation amount of water vapour (kg/h)
f_a: pressure of dry air (mmHg) = 760 mmHg in this paper
k_c: mass transfer coefficient based on concentration (m/h)
k_x: mass transfer coefficient based on humidity ratio (kg/m^2 h(kg/kg′))
x_a: humidity ratio of ambient air (kg/kg′)
x_w: humidity ratio at paper surface (kg/kg′)
γ: weight volume ratio (kg′/m^3), and θ: temperature of ambient air (°C).

Dimensionless numbers, Schmidt, Sherwood and Reynolds numbers, were derived from Eqns (9)–(12). Air velocity inside main duct part was predicted from Eqn (13) (JSME, 1986).

$$Sc = v/D \quad (9)$$

$$Sh = \upsilon k_x l/D \quad (10)$$

$$\upsilon = 0.00455 \times (0.622 + x_a) \times (273.15 + \theta) \quad (11)$$

$$Sh = 0.664\, Re^{1/2}\, Sc^{1/3} \quad (12)$$

$$Re = ul/(v3600) \quad (13)$$

where, D: diffusion coefficient (m^2/h) = 0.92 m^2/h at 25°C and 1 atm (JSME, 1986)
Re: Reynolds number [–] Sc: Schmidt number [–]
Sh: Sherwood number [–]
l: representative length = 0.74 m, which is half the length of the test piece
u: air velocity (m/s)
v: kinematic viscosity (m^2/h) = 1.397 m^2/h at 25°C and 1 atm for vapour (JSME, 1986)
υ: specific volume (m^3/kg).

Results

Table 2 shows the measurement results and calculations of mass transfer coefficient and predicted air velocity. Measurements were performed twice. The values of k_c were 9.9 and 9.8 m/h, respectively, and it was within the range of general residential room, 9–18 m/h. The predicted air velocities of 0.13 m/s, coincided closely with the setting air velocity of 0.2 m/s. It was considered that the air current inside inner chamber was agreeable for measurement of evaporation-controlled materials.

Table 2 The measurement results and calculations of mass transfer coefficient and predicted air velocity

	Ambient air			Surface of paper		L	k_c	u
	Temp. (°C)	RH (%RH)	x_a (g/kg′)	Temp. (°C)	x_w (g/kg′)	(g/h)	(m/h)	(m/s)
1st	24.1	30	5.60	17.5	12.52	1.83	9.9	0.13
2nd	22.1	33	5.41	18.4	13.25	2.05	9.8	0.13

Discussion

When the inner chamber is set in a room as the experiment above, evaporation from filter paper has little influence on humidity of ambient air. However, when papers are installed in a small chamber like ADPAC-20L, the humidity inside the chamber would increase due to evaporation from the filter paper. Since the difference of potential between surface and ambient air will become small when the humidity of ambient air rises to some extent, it is expected that the evaporation from the filter paper would be suppressed. This would apply not only to evaporation of water but also to VOCs emissions. The loading factor of the examined paper size of 14.7 mm × 14.7 mm would be equal to 1.1 m^2/m^3 for ADPAC-20L chamber. This would be too large for measurement of evaporation-controlled materials at ventilation rate of 0.5 h^{-1}, which is the normal measurement condition for ADPAC (Murakami *et al.*, 2001). In case evaporation-controlled materials are installed in a small chamber, the loading factor should be decreased.

CONCLUSIONS

In this paper, development of inner chamber for ADPAC to measure evaporation-controlled materials is reported. The inner chamber made of stainless steel was developed based on the boundary layer theory, and the growth of boundary layer in main duct was confirmed by CFD. A test piece is set at the bottom of the main duct part. Air velocity and current of boundary layer in main duct part is controlled by small DC fan, which is attached to the fan duct part. The air velocity in the duct was measured by an anemometer. The air velocity inside main duct was uniform and stable, and it was confirmed that the unit could control air velocity and current required for measurement of evaporation-controlled materials. The mass transfer coefficient of water, which is representative of evaporation-controlled materials, was measured based on the water vapour evaporation. The mass transfer coefficients were 9.9, 9.8 m/h, and they were within the range of a typical room, 9–18 m/h. The air current inside the inner chamber was considered to be agreeable for measurement of evaporation-controlled materials by using the inner chamber for ADPAC.

ACKNOWLEDGEMENTS

A part of this study was financially supported by Advanced Research Institute for Science and Engineering, Waseda University. The authors would like to express sincere gratitude to Mr. Ikuo Kihara for his cooperation on this study.

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