EXPERIMENTAL SURFACE MASS TRANSFER COEFFICIENTS IN A STANDARD FLEC

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ABSTRACT
FLEC (field and laboratory emission chamber) is becoming a standard method to characterize pollutant emissions from building materials. Up until now, only the emission rate profiles are obtained, which are useful for the comparison and ranking of emission strength from different materials. However, to use the chamber emission test data to model pollutant concentrations in real buildings, and also to evaluate the effects of various control strategies, mass transfer model is required. As the first step, surface convective mass transfer coefficients are essential. In this study, a first series of direct measurements of surface mass transfer coefficients using distilled water at 5 air flow conditions ranging from 186ml/min to 509ml/min in a standard FLEC is conducted. Mass transfer data inside the FLEC is correlated by a dimensionless equation.

INDEX TERMS
FLEC, Mass transfer, Emission, Model

INTRODUCTION
There is an increasing awareness regarding the potential impact of indoor air pollution on health and comfort, in particular, the emission of volatile organic compounds (VOCs) from building materials and products. This has resulted in various technical guides for emission testing. The current state-of-the-art involves two types of devices: emission test chamber and emission cell. The emission test chamber is defined as an enclosure with operational parameters for the determination of VOCs emitted from building products. Typical chamber volumes cover a range from 20 L to 1m³ (Spiker, et al., 1992). In case of the emission cell, the surface of the test specimen itself becomes the integral part of the cell and it has a high sensitivity due to large loading ratio (surface area/volume). To-day, the best described and most frequently used tool is the so-called Field and Laboratory Emission Cell-FLEC (Wolkoff, 1996). The emission cell is portable and user-friendly, therefore, FLEC has become a standard for emission testing in Europe (CEC, 1998; Uhde, Borgschulte and Salthammer, 1998).

There have been many tests with FLEC involving various building materials. Clenφ and co-workers (Clenφ, Clausen, and Weschler et al., 2001) measured the ozone removal rates by selected building products. Wolkoff and Nielsen (Wolkoff and Nielsen, 1996) obtained the diffusion profiles of trans-2-nonenal with FLEC data from carpet and hexane from sealing material, to name but a few. In these researches, emission rate profiles are obtained for a given air volumetric flow rate. These results are test-specific. However, to use these emission test data to model pollutant concentrations in real buildings, and also to evaluate the effects of

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various control strategies, more detailed mass transfer model is needed. A complete emission model should include three mechanisms: convective mass transfer on surfaces, diffusion in solids, and sorption-desorption with building materials. As the first step, in this study, the surface convective mass transfer coefficients in a standard FLEC are obtained experimentally. Such work has not been found in the open literature. Correlations are summarized to estimate the average and local Sherwood numbers using dimensionless parameters governing the transfer and flow properties.

**EXPERIMENTAL PROCEDURE**
The FLEC cell is circular and made of stainless steel with a diameter of 150mm and a maximum height of 18mm. The flow geometry is shown in Fig.1. The cell in our experiment is composed of two parts: cap and lower cavity. The deepness of the lower cavity is 10mm. When testing, the material is placed on the bottom surface of the lower cavity and becomes an integral part of the emission cell. The air is supplied through the cap. It is introduced through two diametrically positioned inlets (symmetrically placed) into a circular-shaped channel at the perimeter from where the air is distributed over the test surface through the circular air slit. The flow geometry of the cell is shown in Fig.1 and the pictures of the cap and lower cavity are shown in Fig.2. The cell is supplied with clean and humidified air from air supply unit. After mass transfer, the air leaves the cell at the top of its center. A more detailed description of the structure and parameters of the cell can be found in [3,6]. The complete test rig is shown in Fig.3. The supply air flows from a compressed air bottle and is divided into two streams. One of them is humidified through a bubbler immersed in a bottle of water and subsequently it is mixed with the other dry air stream. The humidity of the mixed air stream is controlled to the set points by adjusting the proportions of air mixing. The air-flow rates are controlled by two air pumps/controllers at the inlet and outlet of the Flec. To prevent outside air from infiltrating into the Flec, a manometer is installed to monitor the pressure inside the FLEC and ensure the inside pressure positive. The humidities and temperatures in and out the FLEC are measured by the built-in RH and temperature sensors in the pumps/controllers. The measuring accuracies are respectively 2% for relative humidity and 0.2°C for temperature and 2.5% for air flow rate.

![Figure 1](image-url)  
*Figure 1.* A schematic showing the flow geometry of the FLEC.
(a) The cap

(b) The lower chamber

Figure 2. Pictures of the FLEC, showing the cap (a) and lower cavity (b).

Figure 3. The set-up of the test apparatus.
In this experiment, distilled water is used as the loading material. Rather than directly measuring emission rate profiles of VOCs from building materials, convective surface mass transfer coefficients are calculated by measuring the humidity differences between the inlet and outlet of an air stream, which flows through the FLEC and exchanges moisture with water on the lower surface. To investigate the mean and local mass transfer coefficients at different FLEC radius, five glass discs with thickness of 10mm and diameters ranging from 130 to 148mm are prepared. In each test, a disc is placed onto the bottom surface and distilled water is filled in the space between the cell wall and the disc. Special care is given to ensure the water has the same height with the disc and doesn’t wet the disc’s upper surface. When the air is pumped, it exchanges moisture with the water and is humidified. Since the RH of water on water surface is 100%, by calculating the humidity differences, the mean convective mass transfer coefficients across the water surface can be calculated. Different discs provide the mean mass transfer coefficients at various FLEC radius. To investigate the influences of different gases, both air and N2 are used in the experiment.

Once the humidity differences are measured, the mean mass transfer coefficient is calculated by

\[
Sh_m = \frac{2k_m \delta}{D_v} = \frac{V \Delta \omega}{A_t \left( \omega_s - \bar{\omega} \right)}
\]

(1)

where \(V\) is the volumetric air flow rate to the FLEC (m³/s), \(\Delta \omega\) is the humidity ratio differences between air inlet and outlet (kg/kg), \(A_t\) is the transfer area between air and water surface (m²), \(\omega_s\) is humidity ratio on the water surface (kg/kg), and \(\bar{\omega}\) is the mean humidity ratio of air in FLEC (kg/kg), \(D_v\) is vapor diffusivity in air mixture (m²/s), \(Sh\) is Sherwood number and \(k_m\) is the mean mass transfer coefficient (m/s). The Reynolds number used to characterize the airflow rate is based on the height of the air inlet slit, \(\delta\), and given by

\[
Re = \frac{2u_m \delta}{\nu}
\]

(2)

where \(\nu\) is the kinematic viscosity (m²/s) and \(u_m\) is the mean air velocity at the slit, and it is calculated by

\[
u_m = \frac{V}{2\pi r_0 \delta}
\]

(3)

where \(r_0\) is the maximum radius of the emission surface (m).

**RESULTS AND DISCUSSION**

Table 1 lists the experimentally obtained mean Sherwood numbers with different radius glass discs. Two types of gases, air and nitrogen, are available. Seven diameter discs are used. A correlation has been summarized to calculate the mean Sherwood numbers from the experimental data with regression techniques as following:
\[ S\!h_m = 0.8171 \text{Re}^{0.8578} \text{Sc}^{0.6790} \left( \frac{r_0 - r}{2\delta} \right)^{-0.6761} \] (4)

where \( \text{Sc} \) is the Schmidt number.

**Table 1.** Experimentally obtained Sherwood numbers.

<table>
<thead>
<tr>
<th>( r_0 ) (mm)</th>
<th>( V ) (ml/min)</th>
<th>( V' ) (ml/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>74</td>
<td>0.81391</td>
<td>1.03057</td>
</tr>
<tr>
<td>72</td>
<td>0.43780</td>
<td>0.56455</td>
</tr>
<tr>
<td>70</td>
<td>0.28898</td>
<td>0.37821</td>
</tr>
<tr>
<td>67.5</td>
<td>0.19596</td>
<td>0.26686</td>
</tr>
<tr>
<td>65</td>
<td>0.15243</td>
<td>0.20342</td>
</tr>
<tr>
<td>60</td>
<td>0.10811</td>
<td>0.14691</td>
</tr>
<tr>
<td>55</td>
<td>0.08623</td>
<td>0.11304</td>
</tr>
<tr>
<td>( r_0 ) (mm)</td>
<td>( V ) (ml/min)</td>
<td>( V' ) (ml/min)</td>
</tr>
<tr>
<td>186</td>
<td>245</td>
<td>316</td>
</tr>
<tr>
<td>74</td>
<td>0.91957</td>
<td>1.03340</td>
</tr>
<tr>
<td>72</td>
<td>0.47904</td>
<td>0.57112</td>
</tr>
<tr>
<td>70</td>
<td>0.31088</td>
<td>0.40202</td>
</tr>
<tr>
<td>67.5</td>
<td>0.22056</td>
<td>0.27714</td>
</tr>
<tr>
<td>65</td>
<td>0.17872</td>
<td>0.23797</td>
</tr>
<tr>
<td>60</td>
<td>0.13079</td>
<td>0.17036</td>
</tr>
<tr>
<td>55</td>
<td>0.10244</td>
<td>0.13481</td>
</tr>
</tbody>
</table>

The comparisons between the experimentally obtained and the calculated \( S\!h \) numbers are plotted in Fig. 4. It is seen that the correlation fits the experimental data well. The largest deviation happens when the \( S\!h \) is very large, namely, in the position near air slit. This phenomenon may result from the influences of inlet flow conditions. Generally speaking, the
correlation can be used to represent the mean Sherwood numbers. The calculated mean Sh numbers from the above equation in relation to FLEC radius are shown in Fig.5 for air. It is disclosed that the Sherwood numbers decrease with the flow progressing. The higher the air flow rates, the larger the Sh numbers. For air flow rate ranging from 186 to 509ml/min, the mean Sherwood numbers on the whole FLEC emission surface change from 0.05 to 0.2.

CONCLUSIONS
In this experiment, the mean mass transfer coefficients in a standard FLEC cell are measured. A correlation is summarized to calculate the Sherwood numbers along the chamber radius. The results indicate that the mean Sherwood numbers on the whole emission surface change from 0.05 to 0.2, depending on the air volumetric flow rates. Locally, the mean Sh numbers decrease with radius decreasing. This correlation will be used for the development of mass-transfer based emission models.

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REFERENCES