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Emissions of total volatile organic compounds from pressed wood products in an environmental chamber

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Abstract

An environmental chamber was used to characterise the emissions of total volatile organic compounds (TVOCs) from pressed wood products. One type of plywood, three types of hardboards and one type of particleboard were investigated. To compare the emissions of TVOCs with pressed wood products, a PVC board, often used as floor covering, was also measured. The temporal change of TVOCs concentrations was tested. The quantity of TVOCs emissions was measured by a Gas Chromatography/Flame Ionisation Detector (GC-FID). A double-exponential equation was used to evaluate the characteristics of TVOCs emissions from these pressed wood products. With this double-exponential model, the initial emission rates (E_{10} and E_{20}) and emission decay constants (k_1 and k_2) in evaporation-dominated and diffusion-dominated phases were simulated. These emission parameters could be used in estimation of TVOCs concentrations in an indoor environment. Model evaluation studies indicate that the hardboard I has the smallest model accuracy while the plywood and PVC board have the largest model accuracy. © 2002 Elsevier Science Ltd. All rights reserved.

Keywords: Pressed wood products; Environmental chamber; TVOCs; Modelling

1. Introduction

Over the last few decades, since the introduction of plywood, the construction industry has developed new and innovative methods to manufacture composite wood materials using glues and resins in order to bond wood fibres together into a panel. Composite wood products are used in all aspects of house construction, and are used in everything from furniture to cabinets to shelving. In modern housing, a majority of indoor surfaces are made from composite wood materials. Wood products such as furniture, cabinets and building materials may emit a variety of VOCs into the indoor air environment. Tichenor [1] identified the major VOCs emitted from a particleboard as formaldehyde, acetone, hexanal, propanol, butanone, benzene and benzaldehyde. Van der Wal et al. [2] investigated the VOCs emissions from plywood and particle cupboards and found that formaldehyde, terpenes, aromatic hydrocarbons and aliphatic hydrocarbons were the main VOCs emitted. The sources of these VOCs emissions include wood fibres and resins used to manufacture the composite wood, adhesives used to bond the fibres together, and coatings and other types of surface finishes EPA [3].

The wood fibres in composite materials pose little threat to health, it is the glues and resins used to bond the fibres together which can off-gas and pollute indoor air [4]. The effects of these chemicals include: headaches, dizziness, eye, nose and throat irritation, vomiting and breathing difficulties [4].

The wood products industries generate $180 billion in sales annually in the US from manufactured products such as plywood, flakeboard, particleboard, hardboard, oriented strand board, papers, and fabricated wood products [5]. In Australia, the composite wood production in 1994–1995 was 15.31 million cubic meters of railway sleepers, veneers, plywood, particleboard, hardboard, medium density fibreboard, softboard and other fibreboards [6]. There is an increasing tendency to use larger amounts of pressed wood products in new house constructions, and a trend towards the increasing use of pressed wood products in home renovations and new additions [7].

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Studies indicate that formaldehyde is a component of pressed wood products [1,8–12]. Formaldehyde is contained in resins that are used in the manufacture of pressed wood products such as plywood, particleboard, and medium density fibreboard. These wood products gained widespread use after World War II because of their low cost and durability [13]. They are used extensively in the construction of houses and are found in cabinets, roof, floor and furnishings [14,15].

Emissions tests by US EPA [16] indicated that overall emission rates from wood products with veneered substrates were significantly higher than overall emission rates from wood products with melamine and vinyl substrates because veneer was finished with sealer and acid catalysed topcoat. Formaldehyde emission rates from the veneered substrates were also higher than formaldehyde emission rates from the melamine and vinyl substrates. A decay study of the veneered substrates indicated that emission rates of certain compounds, including formaldehyde, were still greater than emission rates measured from the vinyl and melamine substrates after 31 days [16].

Regulations limiting emissions from certain building materials were developed as a result of numerous health complaints from people living in mobile homes. In 1984 the US Department of Housing and Urban Development (USHUD) imposed limits on formaldehyde concentrations in some types of particle board and interior plywood at 0.3 and 0.2 ppm (test chamber concentrations), respectively, to attain indoor air concentrations of not more than 0.4 ppm in manufactured housing (mobile homes) [12]. The National Particleboard Associations in the US approved a voluntary industry standard which limited emissions from medium density fibreboard to 0.3 ppm (test chamber concentration) [17]. Germany prohibited the import of wood products (or furniture containing wood products) that emitted more than 100 ppb formaldehyde in a test chamber [18]. Manufacturers in Australia have been reducing formaldehyde emission from pressed wood products for several years, so that 85–90% of current products meets European low-emission limit that is 500 ppb [19].

Traditional approaches for maintaining acceptable indoor air quality have focused on control strategies such as increased or improved ventilation. Research Triangle Institute (RTI), working in cooperation with the US EPA's Office of Research and Development (ORD), conducted research in 1996 to identify and demonstrate pollution prevention approaches to reduce indoor air pollution from composite wood products [3]. These approaches aimed to reduce or eliminate VOCs emissions in different manufacturing stages.

There are comprehensive data on the emissions of VOCs from wood products in some European and Scandinavian countries and the US. However, the effects of VOCs emissions from pressed wood products on indoor air quality in Australia or in countries with a Mediterranean climate, where the weather is warm and the ventilation rate in a house is high, have not been conducted. Therefore, one of the aims of this study is to investigate the VOCs emissions from different types of pressed wood products and to prepare emissions inventory, which could be used to predict indoor air quality.

A double-exponential model was used in order to acquire emission parameters from pressed wood products. These parameters, associated with environmental parameters such as ventilation rate and material loading, are used to predict the total VOCs (TVOCs) concentrations indoors. With this empirical mathematical model, the TVOCs emissions from pressed wood products may also be examined.

2. Materials and methods

2.1. Materials

There are three specific types of pressed wood products on the market: particleboard, plywood panelling and medium density fibreboard (MDF) [9]. After investigation of product information and the use of pressed wood products indoors, five different composite wood products were selected. One was plywood, one was particleboard and three were hardboards. Characteristics of the five pressed wood products are described as follows:

Plywood: Phenolic glue is used to bond the plies of plywood together. The plywood is commonly used as decorative wall panelling, and both decoratively and structurally in joinery.

Particleboard: The particleboard product is a combination of fine wood particles (approximately 1 mm in diameter) and 6–8% by weight urea–formaldehyde-resin (UF-resin) pressed into panels. The particleboard is decoratively surfaced on both sides with low-pressure melamine-impregnated paper. The particleboard substrate is manufactured to comply with the requirements for Standard Grade Particleboard in AS/NZS 1859.1. The particleboard is suitable for interior use in a wide variety of furniture and joinery assemblies and particularly as shelving, in cupboards, wardrobes and wall units.

Hardboards: Since their prevalence on Australian market and their difference in appearance and manufacturing process, three different types of hardboards were chosen. These three hardboards have fine, densely bonded, wood fibre structure. They are bonded with phenolic resins. The smooth face surfaces provide an ideal base for paint finishing. The back surfaces of hardboards are characterised by a fine, wire-screen texture. The hardboard I has a layer of coating on the surface. The hardboard III has many small holes. They are used extensively in the building, packaging, furniture and general industrial manufacturing industries.

To compare the emissions of TVOCs with pressed wood products, a PVC board, often used as floor covering, was also measured. All samples, freshly delivered by the manufacturers to a local building material retailer, were purchased

Table 1
The selected pressed wood products

Product	Material loading (m^2/m^3)	Main chemical composition[a]
Plywood	2.01	Formaldehyde
Particleboard	2.37	Aromatic hydrocarbons
Hardboard I	1.80	Aliphatic hydrocarbons
Hardboard II	1.87	Terpenes
Hardboard III	1.87	
PVC board	1.79	

[a]Acquired from literature.

and stored in air-tight, unused Tedlar bags. Table 1 lists the samples tested.

Due to differences in edge thickness, the material loading for each product was a bit different.

2.2. Methods

2.2.1. The environmental chamber test

Experiments were designed to generate TVOCs concentration data from newly applied pressed wood products under controlled experimental conditions in an environmental chamber. Characterisation of the environmental chamber e.g. air mixing and leakage was detailed in our previous publication [20].

To avoid sink effects on interior surfaces, the material used to construct the chamber must be non-adsorbent, chemically inert and with a smooth surface. In this project, glass was used. Therefore, it is justified to neglect sinks. Detailed information on this point is in report No.8 of the ECA [21].

All pressed wood products were tested in the glass chamber (volume: 13.56 L) with one inlet and two outlets. The cleaned chamber was placed in the temperature controlled box. The relative humidity of the chamber air was controlled by bubbling a portion of the air stream through deionised water at a controlled temperature (in a water bath). A purified airflow of 200 ml/min was passed through the chamber. The atmosphere in the chamber was mixed by a small fan, which was suspended from the ceiling of the chamber.

Before testing each sample in environmental chamber, one chamber blank sample was analysed to ensure TVOCs concentration in the chamber below 5 $\mu g/m^3$. Otherwise, the chamber was cleaned again until it was qualified. The wood sample was prepared by cutting a piece with an area of about 15×15 cm^2 and then placing it in the chamber immediately. This operation was done under positive pressure from the clean air system to keep intrusion of room air to a minimum. The temperature in the chamber was set as $23^\circ C \pm 1^\circ C$; relative humidity $50\% \pm 5\%$ and air exchange rate 0.885 h.

During the experimental period, air sample volumes of 2.0 l at a sampling rate of 200 ml/min were collected at the outlet of the chamber using Tenax-GR adsorption tube. Immediately after sampling the tubes were tightly sealed and analysed within a few hours. Samples were collected at progressively increasing intervals. GC-FID (Varian Model 3700) was equipped with a modified thermal desorption cold trap injector. The samples were thermodesorbed into the GC-FID instrument for TVOCs quantitation. A film capillary (Alltech ECONO-CAP SE-54, 30 m $\times$ 0.53 mm I.D. $\times$ 1.2 μm) was employed for the separation of VOCs. The adsorbed sample was cryotrapped at $-80^\circ C$ and injected in the GC. The GC temperature program was $40^\circ C$ for 5 min $\rightarrow$ $5^\circ C/min \rightarrow 200^\circ C$ for 3 min. The injection temperature was $200^\circ C$; the temperature of detector was $230^\circ C$. Concentration of TVOCs was calculated from the total area of the FID chromatogram using toluene response factor.

By running a series of toluene standard solutions with different concentrations (50 μg/ml $\sim$ 500 μg/ml) in GC/FID, the toluene calibration curve was obtained ($R^2 = 0.99$). Consequently the total area of the chromatogram was converted into an equivalence of toluene. Replicate analysis of samples and standards were regularly conducted. To determine the recovery of toluene, 0.1 μl of toluene was injected into the absorption tubes before thermal desorption as a quality control measure. Duplicate samples were taken to confirm sampling reproducibility.

2.2.2. Modelling of TVOCs emissions in an environmental chamber

The emission rates of TVOCs from the pressed wood products are calculated by using a double-exponential model [21–23]

$$E(t) = E_1 + E_2 = E_{10}e^{-k_1 t} + E_{20}e^{-k_2 t}, \tag{1}$$

where

$E(t)$ = Emission rate of TVOCs (mg/m^2 h),
E_1 = Phase 1 (evaporation-dominated) emission rate (mg/m^2 h),
E_2 = Phase 2 (diffusion-dominated) emission rate (mg/m^2 h),
E_{10} = Phase 1 initial emission rate (mg/m^2 h),
k_1 = Phase 1 emission rate decay constant (h^{-1}),
E_{20} = Phase 2 initial emission rate (mg/m^2 h),
k_2 = Phase 2 emission rate decay constant (h^{-1}).

The mass balance for the chamber over a small time increment dt is

Change in mass = Mass emitted − Mass leaving chamber

This can be expressed as

$$V\,dc = AE(t)\,dt - Qc\,dt, \tag{2}$$

where

V = Chamber volume (m^3).
A = Sample area (m^2).
Q = Flow rate through chamber (m^3/h).
c = Chamber concentration (mg/m^3).

Integrating the chamber mass balance equation (Eq. 2) with the source term defined by Eq. (1) and assuming an initial concentration of zero gives the equation:

$$c = LE_{10}(e^{-k_1 t} - e^{-Nt})/(N - k_1) + LE_{20}(e^{-k_2 t} - e^{-Nt})/(N - k_2), \quad (3)$$

where

L = Material loading (m^2/m^3),
$N = Q/V$ = air exchange rate (h^{-1}).

The double exponential model is used to analyse the chamber data using a non-linear least squares best fit routine (MacCurveFit program). The four emission parameters E_{10}, E_{20}, k_1 and k_2 are then obtained. The quality of the least-squares fit and the uncertainties in the coefficients are assessed automatically by the MacCurveFit program [24].

The MacCurveFit program uses an exponential peeling procedure to calculate the best estimates of the emission parameters [24–26].

With known emission parameters from indoor sources, the TVOCs concentrations under specific material loading (L) and air exchange rate (N) can be simulated.

2.2.3. Model evaluation

The correlation between chamber measurements and emission *modelling* results was statistically evaluated by using techniques outlined by Stunder and Sethu Raman [27] and Hanna [28]. These techniques included both residual analysis which allows a quantitative estimate of $(\bar{C}_p - \bar{C}_m)$ and correlation which allows a measure of agreement between measured TVOCs concentration (C_m) and predicted concentration (C_p). Here, $\bar{C}_p$ is the mean of predicted concentrations, and $\bar{C}_m$ is the mean of measured concentrations.

This study used correlation coefficient (R or R^2), an index of agreement (d) and the mean square error (MSE) to interpret model accuracy. The index of agreement can be interpreted as a measure of how error-freely a model predicts a variable. MSE is composed of systematic MSEs and unsystematic MSEu. Difference measures provide the most rigorous and useful information regarding overall model performance. However, models contain both systematic and unsystematic errors. Systematic errors result from causes, which occur consistently. Unsystematic errors consist of a number of small effects such as the imprecision of a constant. The best model therefore has a systematic difference of zero since it should explain most of the systematic variation in observed values C_m, while the unsystematic difference should approach the MSE. The value of MSE should be minimised so that the model is predicting at peak accuracy. A large value of MSEu may indicate that the model is as good as possible under the present conditions [27].

Therefore, the statistical descriptive relative error measure which indicates the degree to which C_p approaches C_m can then be expressed as

$$d = 1 - [\Sigma(C_{pi} - C_{mi})^2/\Sigma(|C'_{pi}| + |C'_{mi}|)^2], \quad (4)$$

$$0 \leqslant d \leqslant 1; i = 1, 2, \ldots, n,$$

where $C'_{pi} = C_{pi} - \bar{C}_m$ and $C_{mi} = C_{mi} - \bar{C}_m$.

The index d therefore allows for sensitivity toward differences in C_m and C_p as well as proportionality changes. A value of 1.0 indicates perfect agreement between C_m and C_p values.

The systematic mean square error is the error caused by model additive or proportional problems and can be expressed as

$$\text{MSEs} = [\Sigma(\hat{C}_{pi} - C_{mi})^2/n]^{1/2}, \quad i = 1, 2, \ldots, n, \quad (5)$$

where $\hat{C}_{pi} = a + bC_{mi}$, and a and b are regression coefficients.

The unsystematic mean square error is

$$\text{MSEu} = [\Sigma(C_{pi} - \hat{C}_{pi})^2/n]^{1/2}. \quad (6)$$

The total MSE is written as: $\text{MSE} = (\text{MSEs}^2 + \text{MSEu}^2)^{1/2}$.

In addition to MSEs, MSEu and d, calculation of summary measures such as $\bar{C}_m$, $\bar{C}_p$, S^2_m and S^2_p along with simple linear regression will be of use [29]. Here, S^2_m and S^2_p are squared standard deviations for measured values and for predicted values, respectively.

Hanna [28] stated that the total model error or uncertainty can be defined as $\overline{(C_p - C_m)^2}$, where the bar indicated an average over a certain number of pairs of C_p and C_m observed at various points and/or times. Therefore, this study also evaluates the uncertainty of models by using $\overline{(C_p - C_m)^2}$.

3. Results

3.1. Chamber testing

The following figures represented the time dependence of the concentration of TVOCs from pressed wood products. Besides the experimental data points, the figures include fitted curves described below in more detail.

The TVOCs concentration from the plywood product passed through a maximum value after approximately 1 day and declined toward 17% of the maximum within 9 days (Fig. 1). The maximum TVOCs concentration was only 28.5 $\mu g/m^3$. The emission rate started at the maximum of 64.6 $\mu g/m^2$ h and reduced to 18.5% of the maximum within 1 day and to 3.6% within 9 days.

The TVOCs concentration from the particleboard increased to a maximum value within 21 h and decreased rapidly to 4.9% after 165 h exposure (Fig. 2). The maximum TVOCs concentration was 154 $\mu g/m^3$. The emission rate started at the maximum of 87.6 $\mu g/m^2$ h and decreased to 3% of the maximum within 1 week.

For the hardboard I, the TVOCs concentration increased to the maximum value of 408 $\mu g/m^3$ within 24 h and decreased to only 2.5% of the maximum within 1 week

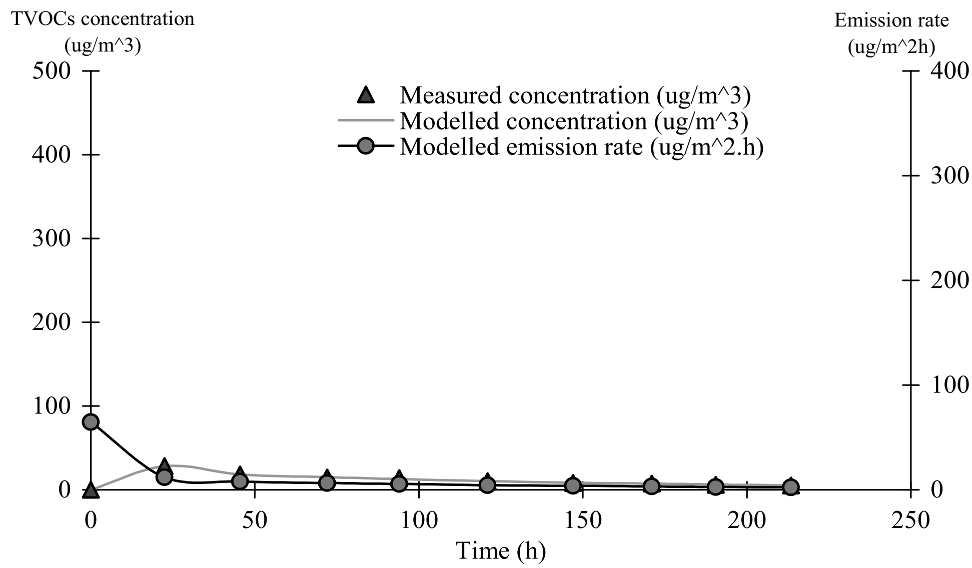

Fig. 1. The TVOCs concentration and emission rate from plywood.

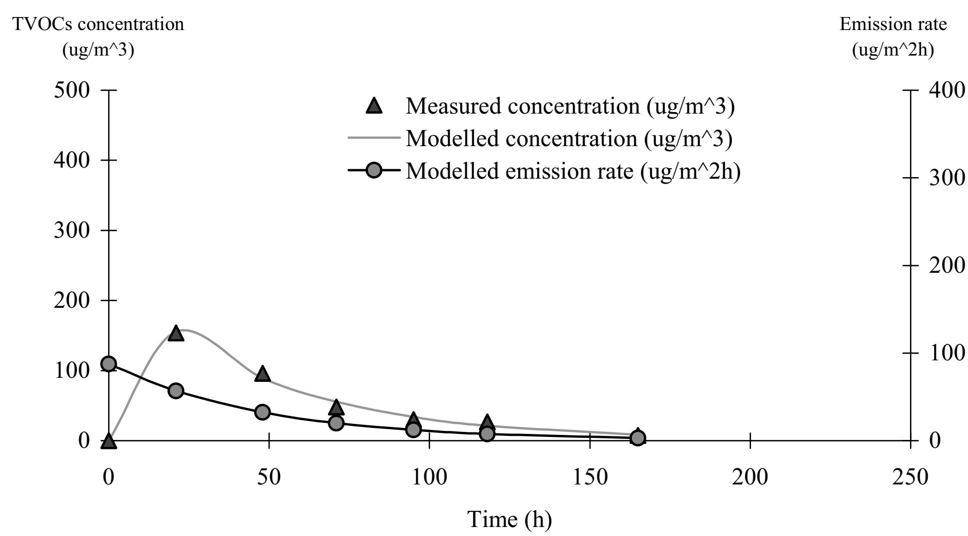

Fig. 2. The TVOCs concentration and emission rate from particleboard.

(Fig. 3). The emission rate declined to 16.3 μg/m^2 h in 1 week after reaching the highest value 350 μg/m^2 h at 47 h.

The TVOCs concentration from hardboard II increased with time passing through a maximum at about 24 h and it then reduced to 15.22 μg/m^3 within 5 days (Fig. 4). The maximum TVOCs concentration was 108 μg/m^3. The emission rate started at the maximum value of 308 μg/m^2 h and decreased to 2.7% of the maximum within 6 days.

The TVOCs concentration produced from emissions from hardboard III reached an equilibrium value about 45 μg/m^3 within 24 h and maintained this value for about 4 days, then started to decrease (Fig. 5). The emission rate started at the maximum value of 35 μg/m^2 h and then decreased slowly to 14 μg/m^2 h within 7 days.

For the PVC building material, the TVOCs concentration reached a maximum value within 23.5 h and then reduced to 9.4% of the maximum value within 9 days (Fig. 6). The maximum TVOCs concentration was 63.5 μg/m^3. The emission rate started at the maximum of 76.5 μg/m^2 h and decreased to 3% of the maximum within 9 days.

3.2. Modelling

The amount of TVOCs released from 1 m^2 pressed wood products ranged from 1.9 to 21.5 mg (Table 2). The emission mass of TVOCs from hardboard II and III in the first week testing period was similar to that from particleboard. The plywood released the smallest amount of TVOCs

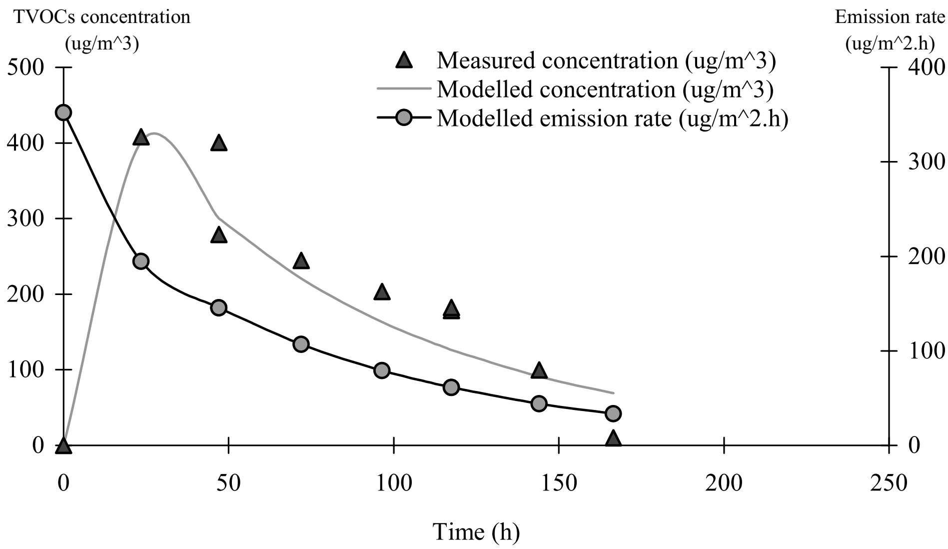

Fig. 3. The TVOCs concentration and emission rate from hardboard I.

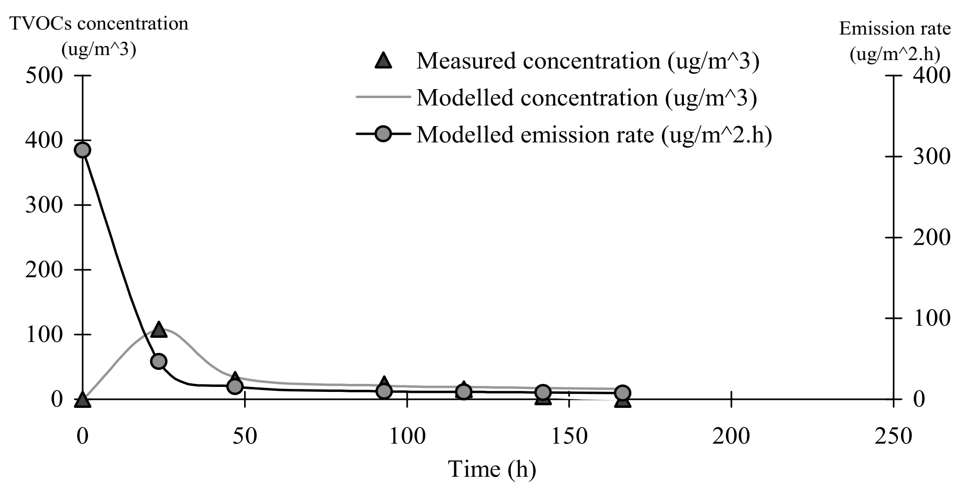

Fig. 4. The TVOCs concentration and emission rate from hardboard II.

(1.9 mg/m^2), which was close to the TVOCs amount emitted from the PVC building board. The hardboard I, however, emitted the highest amount of TVOCs, which was 3 times those from the other two hardboards and the particleboard, and 10 times the amount released from the plywood.

Table 3 listed the model derived emission parameters from five pressed wood products and a PVC board.

The squared correlation coefficients (R^2), a measure of the degree to which the empirical model (2) fitted the measured TVOCs concentration-time profiles, were from 0.833 to 0.995. The sum of squared error (SSE) between the observed and predicted values ranged from 2.73 to 829.5. A value of zero for SSE indicates a perfect fit. Plywood has a value close to zero. The hardboard I has the largest SSE value.

To better understand about the degree of error, a listing of the various summary measures, regression coefficients and difference measures are presented in Table 4. The $\bar{C}_m$ vs. $\bar{C}_p$ summary measures indicate that on the average, the hardboard I under-predicts concentration values, and hardboard II over-predicts. The plywood, particleboard, hardboard III and PVC board predictions fit the experimental values very well. A comparison of S_m and S_p gives a relative indication of how well a model is producing the observed variance. From Table 4, therefore, it seems that the plywood, particleboard and PVC board are best at fitting the observed variability.

The analysis of MSE from Table 4 indicates that the hardboards I and II have the highest overall MSE with almost the same value for MSEs and MSEu, implying that they do not fit the criteria of the systematic error. The plywood has the smallest SSE and small systematic error.

The index of agreement (d) suggests that the percentage of the potential for error in predicting concentrations

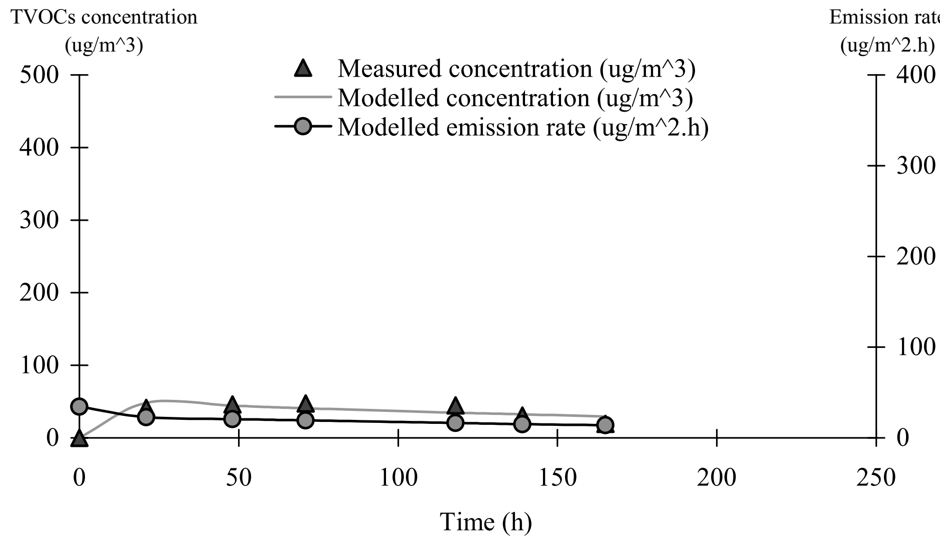

Fig. 5. The TVOCs concentration and emission rate from hardboard III.

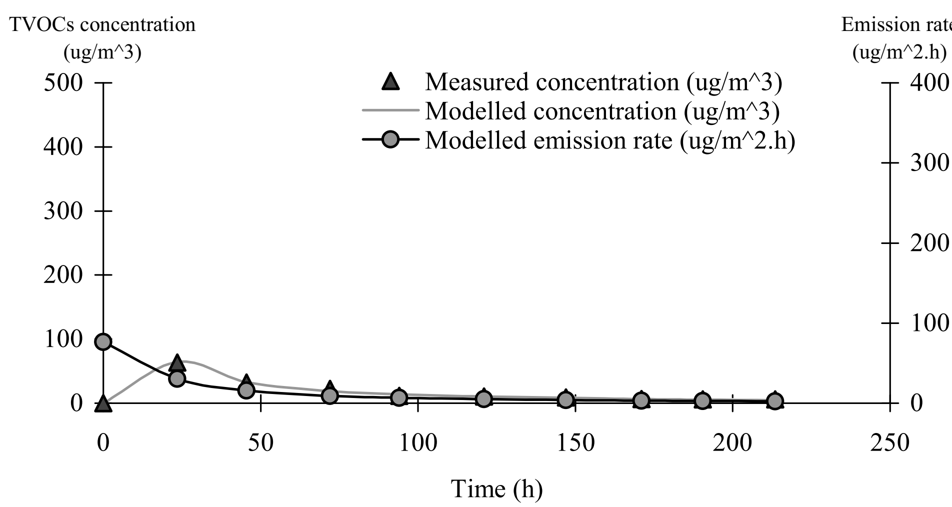

Fig. 6. The TVOCs concentration and emission rate from PVC board.

Table 2
Estimated total quantities of VOCs emitted from pressed wood products

Product	E_{10}/k_1 (mg/m^2)	E_{20}/k_2 (mg/m^2)
Plywood	0.40	1.50
Particleboard	0.13	4.16
Hardboard I	0.38	21.09
Hardboard II	3.2	3.78
Hardboard III	0.009	7.14
PVC board	1.24	1.63

has been explained by the model [27]. For the six products noted in Tables 2 and 3, the d values range from 0.952 to 0.999. However, interpretation of the index d should not be given too much weight since d becomes unstable when the denominator is small.

The values of $\overline{(C_p - C_m)^2}$ in Table 4 indicate that the hardboard I has the smallest model accuracy while the plywood and PVC board have the largest model accuracy.

The maximum TVOCs emission rate from wood products indicated that emissions from hardboard I and hardboard II > particleboard > hardboard III and plywood. The maximum TVOCs concentration from the PVC board was less than those from wood products, except for the plywood product.

4. Discussion

The chamber experiments showed that the hardboard I had the highest emission rate of TVOCs. Next, were the particleboard and the hardboard II. The plywood and the hard-

Table 3
Modelled emission parameters from wood products and PVC board

Product	E_{10} (μg/m^2 h)	k_1 (h^{-1})	E_{20} (μg/m^2 h)	k_2 (h^{-1})	Correlation coefficient (R^2)	Sum of squared error (SSE)
Plywood	53.51 ± 1.72[a]	0.135 ± 0.159	11.11 ± 0.86	0.0074 ± 0.0006	0.995	2.73
Hardboard I	259.5 ± 30.79	0.0123 ± 0.015	92.81 ± 30.57	0.246 ± 0.186	0.942	829.5
Particleboard	86.89 ± 74.7	0.0209 ± 0.051	0.751 ± 7.22	0.0056 ± 0.0046	0.992	153.7
Hardboard II	293.9 ± 57.5	0.092 ± 0.32	13.92 ± 22.9	0.0037 ± 0.019	0.995	100.8
Hardboard III	10.0 ± 40.4	1.068 ± 1.29	24.56 ± 7.04	0.0034 ± 0.0028	0.833	311.8
PVC board	62.76 ± 122.4	0.0504 ± 0.063	13.76 ± 12.6	0.0084 ± 0.0055	0.972	22.03

[a]The mean ± the standard error of the mean.

Table 4
Quantitative measures of model performance for pressed wood products

Product	Summary measures				Model uncertainty	Linear regression		Difference measures			
	$\bar{C}_m$	$\bar{C}_p$	S_m	S_p	$\overline{(C_p - C_m)^2}$	a	b	MSE	MSEs	MSEu	d
Plywood	11.2	11.23	8.09	7.99	0.273	0.193	0.986	0.515	0.096	0.506	0.999
Particleboard	51.8	51.9	54.9	54.7	21.96	0.509	0.992	4.686	0.418	4.668	0.998
Hardboard I	200.7	179.8	140.9	124	2224.95	11.84	0.837	47.18	30.18	36.27	0.964
Hardboard II	24.76	29.32	35.49	32.88	59.73	6.744	0.912	7.729	5.420	5.510	0.985
Hardboard III	32.78	32.86	17.66	15.96	44.54	5.806	0.825	6.676	2.862	6.031	0.952
PVC board	16.69	16.53	18.9	19.11	2.256	−0.289	1.007	1.502	0.213	1.487	0.998

board III had the lowest emission rates. These conclusions are consistent with the results obtained by other studies. Engström [29] tested melamine laminates and PVC panelling. Formaldehyde was the compound most often found. However, formaldehyde cannot be measured with Tenax-GR. It is not a component of TVOCs concentration. The emission rates of VOCs from different pressed wood products have not been reported. Larsen and Funch [30] reported that formaldehyde was the predominant single compound emitted from urea-glued boards. The emissions from wood-based boards vary considerably dependent on the glue system used. The pressed wood products tested in this study are bonded with synthetic resin adhesives. For plywood and hardboards, phenolic resins were used. For the particleboard, UF-resin was used as an adhesive. These synthetic resin adhesives in the wood products are the main sources of VOC emissions. Godish [9] reported that wood products are the major sources of indoor formaldehyde contamination. These products are bonded or finished with UF-resins, which are responsible for free formaldehyde liberation into indoor air [9,31]. Godish [9] outlined emission potentials for a variety of wood products found in the indoor environment (Table 5).

The results indicate that the formaldehyde emission rates of medium-density fibreboard were higher than those of particleboard and plywood. The softwood plywood had the lowest formaldehyde emission rates.

The emission rates presented in Table 5 are for formaldehyde, as it has been reported to be the predominant single compound emitted from UF-resins [9,30,31]. Compared to the TVOCs results obtained in this study, the formaldehyde emission rates in Table 5 are generally higher for the same type of product. For example, the emission rates from particleboard ranged from 83 to 1042 μg/m^2 h in Table 5, while in this study the maximum emission rate was only 88 μg/m^2 h for TVOCs. The differences in emission rates observed may be due to differences in formaldehyde capture. The data in Table 5 were determined from formaldehyde specific sampling and analytical methods and formaldehyde adsorption and retention on Tenax is poor.

Table 5
Formaldehyde emission potential for selected wood products [9]

Material	Range of formaldehyde emission rates (μg/m^2 h)
Medium-density fibreboard	733–2,292
Hardwood plywood panelling	62.5–1,417
Particleboard	83–1,042
Softwood plywood	10–30

In this study, three hardboards were investigated and the results showed that the hardboard I had a higher emission rate (352 μg/m^2 h) than the other two hardboards (34–308 μg/m^2 h). This may be due to the fact that different types of wood, glues and resins were used in these three hardboards. The coatings on the surface of the hardboard I and the glues used are probably one of the reasons why that it had a high emission rate.

The theoretical evaluation of potential VOCs emission sources was based on the knowledge of the materials forming part of the product such as wood, glues, oils and lacquers [32]. The differences in TVOCs emissions among the products tested resulted from the use of different types of wood (e.g. oak had low VOCs emissions while pine and spruce had high VOCs emissions) [16,32], the different glues and resins used to bond the fibres together, and coatings and other types of surface finishes. In this study, the pressed wood products tested used urea–formaldehyde resin or phenolic resins to bond the fibres together. The resins used can off-gas a variety of VOCs especially formaldehyde. To clarify the source of the VOCs in these products, further experimentation is needed to determine the relative contributions of the various materials used in product manufacture, e.g. raw composite board, veneer, glue, and wet finishes.

A high degree of reproducibility was found between the duplicated samples for the wood products tested. The reproducibility, expressed as the difference between duplicates divided by the mean, ranged from 5.0% to 7.4% for total chromatographed organics. In addition, recovery of the toluene ranged from 92% to 97% with a mean value of 94% (S.D. = 7%).

This study found that the TVOCs concentrations and emission rates from pressed wood products in an environmental chamber changed double-exponentially with time. Model evaluation studies suggest that the data input error is often a major contributor to total uncertainty. The impact of the model input data on the concentrations calculated using the model is normally examined by the sensitivity analysis of the model. In this study, the source emission parameters (E_{10}, E_{20}, k_1 and k_2) for the six products are modelled from chamber measurements. The uncertainties in the four parameters for the six products are quite large (Table 3). The large uncertainties in the source emission parameters may result from the insufficient sampling data.

This study found that the TVOCs emission rates from hardboards ranged from 34 to 352 μg/m^2 h; emissions from particleboard were 88 μg/m^2 h and plywood emissions were 65 μg/m^2 h. The TVOCs emission values in this study were lower than those of most other studies, possibly because the sensitivity varies with different compounds. A sample containing a small amount of hydrocarbons can give a larger response than a sample containing a large amount of more toxic aldehydes, chlorinated hydrocarbons, and amines. For non-speciated TVOCs using a FID detector in this study, the assumption that equal amounts (weight or moles) of all compounds elicit the same detector response as the single reference compound can lead to some apparently anomalous results, as demonstrated by Otson and Fellin [33]. The FID-TVOC (non-speciated) values obtained were much lower than the summation of the 26 VOCs determined by GC-MSD, and that determined by speciated GC-FID.

A review of TVOCs measurements [34] found that the mean indoor TVOCs concentrations were 1130 μg/m^3 in established residences and approximately 4000 μg/m^3 in new buildings, indicating the major source was new indoor materials and products. Aikivuori et al. [35] measured the TVOCs concentrations in a room in a refurbished building and found the TVOCs concentration was 19565 μg/m^3 after 1520 h and 11 μg/m^3 after 2550 h. In this study the measured maximum TVOCs concentrations from wood products were from 18 to 408 μg/m^3. These values were much lower than indoor concentrations in residences and buildings. In fact, Indoor concentrations of TVOCs are the outcome of TVOCs emissions from many other materials and household products.

5. Conclusion

Environmental chamber tests showed differences in rates and patterns of TVOCs emissions from pressed wood products. The temporal change of TVOCs concentrations and emission rates in the test chamber presented a good fit with the results from a double-exponential model. The double-exponential model provided reliable estimates of the initial emission rate, maximum TVOCs concentration, mass of TVOCs released, and other emission parameters. Model evaluation studies indicate that the hardboard I has the smallest model accuracy while the plywood and PVC board have the largest model accuracy.

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