Volatile Organic Compounds Emission from Chinese Wood Furniture Coating Industry: Activity-based Emission Factor, Speciation Profiles, and Provincial Emission Inventory

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ABSTRACT

Volatile organic compounds (VOCs) have been identified as the most crucial precursors of tropospheric photochemical O₃ formation and secondary organic aerosols. In this study, field measurement was conducted to develop VOCs emission factors and source profiles of the wood furniture coating industry in China. An activity-based database was established, involving coat consumption-based, coating area-based, furniture production-based, and output value-based VOCs emission factors. Combining the results of field tests and literature surveys, emission factors were calculated by enterprise scale, coating type, spraying technology, and emission control device. The uncertainties were quantified by using Monte Carlo simulations. VOCs emission factors were estimated: 0.22 (0.10–0.34, 95% CI) kg kg⁻¹ for coat consumption-based; 21.97 (10.10–29.38) g m⁻² for coating area-based; 0.69 (0.34–1.00) kg piece⁻¹ for furniture production-based; and 6.95 (3.42–10.21) kg 10⁻⁴ yuan for output value-based calculation, respectively. Aromatics and oxygenated VOCs (OVOCs) were predominant species of solvent borne paint emission, with the proportion of 71.1% and 22.9% of totals, respectively. VOCs emissions from the wood furniture coating industry were estimated at 179.76 × 10³ (88.58 × 10³–260.52 × 10³, 95% CI) t in 2016. Due to the huge production output and intensive distribution of enterprises, VOCs emissions mainly concentrated in Guangdong, Zhejiang, Shandong, Fujian, Jiangxi, and Sichuan province, with the combined contribution of 43.8% of the national totals.

Keywords: Wood furniture coating industry; VOCs; Activity-based emission factor; Source profile; Emission inventory.

INTRODUCTION

With the rapid growth of industrialization and urbanization in China, the annual average concentrations of fine particulate matter (PM₂.₅) and ozone (O₃) in the ambient atmosphere have increased dramatically, especially in economically developed eastern areas (Zhang et al., 2015; Guo et al., 2017; Xu et al., 2017). Volatile organic compounds (VOCs) have been identified as the most crucial precursors of tropospheric photochemical O₃ formation and secondary organic aerosols (Ling et al., 2011; Jenkin et al., 2017; Wu et al., 2016; Zheng et al., 2017a, b; Zhang et al., 2017). In the past few years, paint production and utilization have seen significant increases; hence, solvent utilization has become expected to increase continuously in China, the Chinese government has listed VOCs pollution control as the next major focus of its air pollution prevention and control endeavors, and included VOCs emission control as an indicator in its Thirteenth Five-Year Plan (2016–2020) (NPC, 2016; Zhang et al., 2018).

Compared with the foundation for controlling atmospheric pollutants such as SO₂, NOₓ, and particulate matter, the foundation for controlling VOCs remains markedly weak. In addition, unlike SO₂ and NOₓ emissions, VOCs involve fugitive emissions. Therefore, mandating that fixed organized pollution sources meet emission standards does not produce immediate results for controlling VOCs emissions. Among all emission sources, solvent utilization (e.g., printing and dyeing, asphalt pavements, and surface coating) is regarded as the key source of anthropogenic VOCs emissions and the largest contributor to ambient VOCs in certain areas (Klimont et al., 2002; Guo et al., 2011; Wu et al., 2016; Zheng et al., 2017a, b; Zhang et al., 2017).
the fastest-growing sector, and will become the largest contributor of VOCs by 2020, rising to 36–37% (Klimont et al., 2002; Wei et al., 2011; Zheng et al., 2017a, b).

Surface coating is a crucial subsector of solvent utilization that includes building painting, furniture manufacturing, vehicle coating and maintenance, and artware surface coating. Studies have suggested that furniture coating is the largest contributor to VOCs emissions among the sources of industrial solvent use (Wu et al., 2015). In addition, an analysis of source reactivities indicated that the potential for ozone formation is the highest for furniture coating, requiring priority control (Li et al., 2018). China is the world’s largest furniture manufacturer, accounting for 25% of the world’s output. During China’s Twelfth Five-Year Plan (2011–2015), furniture enterprises gradually transitioned from small-scale enterprises into medium- or large-scale enterprises; nevertheless, in 2015, small-scale furniture enterprises still accounted for 82.3% of all furniture enterprises in China (CNFA, 2016). Most of these small-scale enterprises mixed paint onsite, and paint was rarely gathered with appropriate methods even if it was prepared in a paint-mixing room, resulting in fugitive VOCs emissions.

In recent years, a series of studies have been conducted to investigate the characteristics of fugitive VOCs emitted by the furniture industry and establish emission inventory of the VOCs emitted by various countries or regions. (Yuan et al., 2010; Wei et al., 2011; Qiu et al., 2014; Wu et al., 2015; Mo et al., 2016; Wu et al., 2016; Liang et al., 2017; Zheng et al., 2017a, b; Zhong et al., 2017). However, current available studies have failed to adequately consider emission differences caused by activity-based differences. Presently, VOCs emission factors of wood furniture coating industry commonly are referred from the result of the United States Environmental Protection Agency and Taiwan’s Environmental Protection Administration, in which a single average emission factor is used to represent the emission factors of an industry (TEPA, 2009; Wei et al., 2009; US EPA, 2010; DEPG, 2013; EEA, 2016; Zhong et al., 2017). Of the few relevant test studies, most have involved conducting paint consumption-based experiments and calculating emission factors. While these studies have failed to consider that enterprise activity varies substantially between furniture enterprises, and that factors such as coating type, painting technology, enterprise management level, and operation methods employed by workers largely affect emission factors.

A comparison of VOCs source profiles for painting between Beijing and other parts of the world revealed significant region-specific discrepancies, probably caused by market demands and environmental standards (Yuan et al., 2010). As a result, the importance of updating localized emission factors and source profiles in a comprehensive and timely manner should be highlighted, especially for VOCs, because a specified VOCs emission inventory is fundamental for estimating ozone formation potentials (Zhong et al., 2017).

The calculation of VOCs emission factors is markedly laborious because of the following reasons: numerous types of furniture products are manufactured by the furniture industry, furniture sizes and shapes differ considerably between furniture types, and the types and the amount of paint and auxiliary materials used differ substantially between furniture types. In addition, to effectively control spraying efficiency in practice, enterprises are sometimes required to calculate the emission factors per unit coating area. For example, some spraying enterprises mandate that the VOCs emitted per unit area of spray meet the standard (US EPA, 2010). However, because calculating the surface areas of various products is remarkably difficult, identifying the emission factors per unit of surface area is a challenging task.

Because of the complexity and uniqueness of the furniture industry as well as differences in emission control technologies between enterprises, no single emission factor can effectively measure VOCs emissions. Data such as an enterprise’s actual activities, amount of raw and auxiliary materials used, furniture coating area, amount of furniture manufactured, and enterprise output value must be combined to develop an activity-based VOCs emission factor database that may be used by enterprises to calculate VOCs emissions. Accordingly, the purpose of this study was to acquire the furniture industry’s activity-based VOCs emission factors, and develop a specified profile to help the furniture industry construct a more accurate VOCs emission inventory. This emission inventory can be used to identify the effects of the furniture coating industry on the environment, formulate control standards and VOCs emission remediation programs for key industries, propose effective control measures, and provide technological support and data as evidence.

**MATERIALS AND METHODS**

**Sampling Methods**

As in shown in Table 1, a total of 132 valid VOCs source samples were collected from 15 wood furniture coating plants with mainstream technologies that were operated under normal conditions. The sample collection method adopted was based on that stipulated by the “Emission from Stationary Sources-Sampling of Volatile Organic Compounds-Bags Method” (HJ 732-2014), in which vacuum sampling bags (Tedlar bag, black, 10L) and vacuum sampling barrels were used to collect VOCs samples (MEP, 2014) (see Fig. S1 in the Supplementary Materials SI). During the sampling processes, flow-limiting valves were used to ensure that the samples were collected at a constant speed. The primary sampling equipment and materials used included vacuum sampling bags, vacuum sampling barrels, heating sampling tubes, glass filters, Teflon connection tubes, valves, activated carbon screening formulas, suction pumps (0.1–5.0 L min⁻¹), sample storage containers, and heating boxes. Images of the equipment and materials are displayed in Fig. 1. The sampling locations, frequencies, and collection times were determined based on relevant HJ/T397 operation provisions: the sampling locations included prime painting station, top coating painting station, drying room, and stack flues; the sampling collection time for each sample was 30 min; and three parallel samples were collected for each process.
Table 1. Operational parameters and numbers of samples collected for the tested coating enterprises.

<table>
<thead>
<tr>
<th>Plant size</th>
<th>Paint type</th>
<th>Application method</th>
<th>VOCs control technologies</th>
<th>Sampling location</th>
<th>No. of samples</th>
</tr>
</thead>
<tbody>
<tr>
<td>Small</td>
<td>NC, PE</td>
<td>Air atomized spray</td>
<td>ACA</td>
<td>Prime Coat</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>PE, PU</td>
<td>Air atomized spray</td>
<td>LTP</td>
<td>Top coat</td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>NC, PE PU</td>
<td>Air atomized spray</td>
<td>NA</td>
<td>Stack</td>
<td>12</td>
</tr>
<tr>
<td></td>
<td>AC, NC</td>
<td>Air atomized spray</td>
<td>NA</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td>Medium</td>
<td>NC, PU</td>
<td>Air atomized spray</td>
<td>LTP</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>PE, PU</td>
<td>Air atomized spray</td>
<td>NA</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>PU, PE</td>
<td>Air atomized spray</td>
<td>LTP</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>AC, NC</td>
<td>Air atomized spray</td>
<td>AM</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>WP</td>
<td>Air atomized spray</td>
<td>ACA</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td>Large</td>
<td>PE, PU</td>
<td>Air atomized spray</td>
<td>ACA</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>PU, PE</td>
<td>Air atomized spray</td>
<td>RTO</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>WP</td>
<td>Air atomized spray</td>
<td>PO</td>
<td></td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>PE, PU</td>
<td>Air atomized spray</td>
<td>ACA</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>PU, PU</td>
<td>Dip/flow coat</td>
<td>PO</td>
<td></td>
<td>9</td>
</tr>
<tr>
<td></td>
<td>WP, PE</td>
<td>Air atomized spray</td>
<td>PO</td>
<td></td>
<td>9</td>
</tr>
</tbody>
</table>

Note: waterborne paint (WP); activated carbon adsorption (ACA); photocatalytic oxidation (PO); regenerative thermal oxidizers (RTO); absorption method (AM); low temperature plasma technology (LTP); uncontrolled (NA).

Method Adopted for VOCs Emission Concentration and Source Profile Analysis

For the analysis of VOCs concentration and source profile, a proton-transfer-reaction mass spectrometer (PTR-MS; Ionicon, Innsbruck, Austria) was used. This device used a sampling system to convert test constituents into gas before transferring it to an ion source. Subsequently, the protons and molecules of the constituents were ionized to become charged ions. Next, a quality analyzer was used to separate the ions according to their mass-to-charge ratios (m/z), and the strength of the ions were measured and recorded using a detector, on the basis of which the mass spectrometry was calculated.

QA/QC

New vacuum sampling bags were used to collect the samples. If sampling bags had to be repeatedly used, they were required to undergo a blank experiment prior to the sampling process. Hydrocarbon-free air was injected into used air bags before they were sealed and placed in a room temperature environment for a duration longer than that used for monitoring actual samples. Subsequently, the same procedure employed for sample analysis was employed to measure the VOCs concentrations of the targets. If the concentrations were within or outside the limits, the sampling bags were retained (i.e., they could continue to be used) or discarded, respectively. For retained air bags, the gases were sucked out and the bags were stored.
Methods for Calculating VOCs Emission Factors and Establishing Emission Inventory

For furniture manufacturers, the key of developing VOCs emission inventory of the furniture coating industry involves identifying methods for acquiring accessible enterprise activity data, such as the amount of furniture fabricated, enterprise output value, amount of raw and auxiliary materials used during spraying, furniture spray area, and VOCs emission factors. Then, the amount of VOCs emissions can be estimated and a VOCs emission inventory can be acquired. Field surveys may be administered to obtain data that includes the amount of VOCs-containing raw and auxiliary materials used by enterprises; in addition, tests may be performed to analyze the VOCs content of various raw and auxiliary materials, on the basis of which a material balance algorithm may be utilized to calculate the enterprises’ VOCs emissions. This method is frequently adopted in “Bottom-Up” emission factor assessment methods to generate VOCs emission inventory from the furniture industry.

In practice, because numerous enterprises exist, accurately identifying the amount of raw and auxiliary materials used by each enterprise during spraying and the VOCs content of these materials is difficult. Therefore, statistical parameters such as the “amount of furniture manufactured” and “enterprise output value,” as well as “Up-Bottom” emission factor assessment methods, may be used to estimate the total VOCs emissions of the furniture industry.

The emission factors used in various calculation methods may be divided into two types: enterprise- and industry-based. For the enterprise-based factors, the amount of VOCs emitted per unit of raw and auxiliary material (kg kg\(^{-1}\) paint) and the amount of VOCs emitted per unit of spray area (kg m\(^{-2}\)) are first considered. Subsequently, the amount of VOCs-containing raw and auxiliary materials used by enterprises and the total spray areas of the furniture are determined to calculate the enterprises’ total VOCs emissions. For the industry-based factors, the amount of VOCs emitted per unit of product manufactured (g VOCs per unit of product manufactured) and the amount of VOCs emitted per unit of output (g VOCs 10\(^{-4}\) yuan) are used to calculate the industry’s total VOCs emissions. Calculation methods for the various activity–based VOCs emission factors are presented as follows:

By obtaining the amount of VOCs–containing raw and auxiliary materials (i.e., paint, paint thinners, hardeners, and adhesives) used by enterprises during the coating process, the VOCs contents of these materials, and the removal efficiencies of the VOCs control measures, the total VOCs emitted could be calculated. Subsequently, by subtracting the amount of recycled VOCs used, the VOCs emission factors per unit of paint consumed could be calculated using the following equation:

\[
EF_i = \frac{\sum_i M_i \times C_i \times (1 - \eta_i) - \sum_j R_j \times C_j}{\sum_i M_i} \tag{1}
\]

where \(EF_i\) is the VOCs emission factor per unit of paint consumed (measured in mg kg\(^{-1}\)); \(M_i\) is the amount of raw/auxiliary material \(i\) used (kg); \(C_i\) is the VOCs content of raw/auxiliary material \(i\) (\%); \(R_j\) is the amount of recycled VOCs material \(j\) used (kg); and \(C_j\) is the VOCs content of the recycled material \(j\) used (\%); \(\eta\) represents the removal efficiency of VOCs control technologies, and \(k\) is the type of control devices.

Because furniture shape varies considerably, obtaining the surface area of each and every piece of furniture is difficult. However, for enterprises that manufacture furniture of similar shapes, statistical or empirical inference methods may be utilized to estimate the furniture spray area per year for enterprises of varying sizes. On the basis of these estimations, the VOCs emission factors for spray area per furniture item per unit of time may be calculated, as shown in the following equation:

\[
EF_{v} = \frac{A \times T \times C \times D}{(H_{dry} / H_{wet}) \times E} \times (1 - \eta) \tag{2}
\]

where \(EF_{v}\) is the VOCs emission factor for each unit of coating area (measured in kg m\(^{-2}\)); \(A\) is the coating area, m\(^2\); \(T\) is the paint spray thickness (µm); \(C\) is the VOCs content of paint (measured as a fraction of volume); \(D\) is the paint density (g L\(^{-1}\)); \(H_{dry}\) represents the dry film thickness, µm; \(H_{wet}\) represents the wet film thickness, µm; \(H_{dry}/H_{wet}\) is the solid content of coating (measured as a fraction of volume); and \(E\) is the spraying efficiency (\%).

Because enterprises can easily obtain activity-related data such as the amount of products manufactured and total output value (VOCs emissions per unit of furniture manufactured or per output value) when estimating VOCs emissions during the production processes. Therefore, the actual tests performed and statistical inferences drawn (on the basis of material measurements) to obtain the emission factors (per unit output or per output value) of enterprises of varying sizes, application method and coating types may be used to develop VOCs emission factors. An equation was formulated as follows:

\[
EF_{p} = \frac{E_{L}}{P} \times (1 - \eta) \tag{3}
\]

\[
EF_{v} = \frac{E_{L}}{V} \times (1 - \eta) \tag{4}
\]

where \(EF_{p}\) and \(EF_{v}\) are the VOCs emission factors per unit output or per output value, respectively; \(E_{L}\) is the total amount of VOCs emitted by an enterprise; and \(P\) and \(V\) are the amount of furniture produced and output value of an enterprise, respectively.

By using the wood furniture production-based emission factors as an example, available activity data including wood furniture production and VOCs removal efficiency, etc., were compiled to calculate provincial VOCs emissions as follow equation, and the spatial distribution was demonstrated by the ArcGIS software.
\[ E_m = A_t \times EF_p \times \eta \]  

where \( E_m \) is the VOCs emission of \( m \) province, \( t \); \( A \) represents the wood furniture production, piece.

**Methods for Quantifying Uncertainty**

Uncertainties related to emission factors were analyzed using Monte Carlo simulations. The probability distribution of the field tests was fitted using the Oracle Crystal Ball software, and the Kolmogorov-Smirnov test was conducted for goodness-of-fit. The parameters and corresponding statistical distributions for determining the various activity-based emission factors were placed in the mode of Monte Carlo, and 10,000 simulations were performed to analyze the uncertainties. In addition, sensitivity analysis was conducted to quantify the contribution of the parameters to the uncertainties.

**RESULTS AND DISCUSSION**

**Overview of the Wood Furniture Industry in China**

Production volume and the number of wood furniture manufacturing enterprises in China are shown in Fig. 2. In 2016, the output of wood furniture was reported to be 261 million pieces in China, accounting for 32.8% of all furniture production and ranked first in the world. The production mainly concentrated in the southeast and east region of China. According to the statistics of China National Furniture Association (CNFA), the total number of wood furniture manufacturing enterprises is approximately \( 4.34 \times 10^4 \). Guangdong province ranked first at more than 7000 enterprises, with the proportion of nearly 16.2% of the totals. Historical trends of the development in number of wood furniture manufacturing enterprises during the Twelfth Five-Year Plan period can be seen in SI Fig. S2.

Paint is the primary material used in wood furniture coating processes, accounting for over 50% of all materials used globally. In China, the amount of paint produced for wood furniture coating increased from 0.87 million tons in 2011 to 1.09 million tons in 2016, equating to an annual growth rate of approximately 6%. Guangdong, Jiangsu, Shanghai, Zhejiang, Shandong, Beijing, and Tianjin ranked in the forefront of provinces in production of paint for wood furniture coating. In China, solvent borne paint remains the main paint type used in wood furniture coating, including PE, PU, NC, and AC. In 2016, the proportion of solvent borne paint still remained high at over 93% of all paint used (CNFA, 2017). During the Twelfth Five-Year Plan period, environmentally friendly paint began to be favored by local policies, laws, and regulations and thus the amount of waterborne paint used increased. However, after roughly 10 years of development, waterborne paint still represented only 7% of the total consumption of solvent borne paint. The main reasons why waterborne paint was less popular than solvent borne paint among consumers were consumer habits, coating effects, and emulsion prices. However, new coating types with lower VOCs emissions will enjoyed increasing popularity in the market because the environmental protection laws and regulations have become increasingly comprehensive and the consumers’ environmental protection awareness has continued to increase. Thus, the use of waterborne paints is expected to grow in the near future.

**VOCs Content of Paint and VOCs Emission Concentrations during the Spraying Processes**

VOCs contents of the various raw and auxiliary materials used by enterprises during the furniture coating processes are presented in SI Table S1. According to the table, all paints had higher VOCs contents than adhesives. Paints with the VOCs content of 20% or above accounted for 70% of all paint, and was exclusively solvent borne paint. Solvent borne paint (NC, PE, PU, and AC) had an average VOCs content of approximately 42.5%; NC paint displayed the highest VOCs content at 71.0%. By contrast, waterborne paint showed an average VOCs content of approximately 10.0% at 7.0%. Further, the VOCs emissions from the spraying processes of wood furniture manufacturing enterprises in China were calculated.

![Fig. 2. Wood furniture production and number of wood furniture manufacturing enterprises in China, 2016.](image-url)
1.1%. Paint thinners and hardeners both possessed high VOCs contents at 95.5% and 45.3%, respectively, whereas adhesives (primarily containing urea-formaldehyde resins and white latexes) possessed lower VOCs contents (i.e., 20% or lower). Paint thinners and hardeners are generally added when using solvent borne paint and become important sources of VOCs when manufacturing wood furniture.

Fig. 3 shows the VOCs concentration distributions of the samples during the various stages of the furniture coating process. VOCs concentrations were higher for the solvent borne paints NC, AC, and PU, for which the average VOCs concentrations were 569.19 (399.02–781.21, 95% CI), 467.51 (385.62–531.22, 95% CI) and 385.92 (299.62–462.13, 95% CI) mg m$^{-3}$, respectively. The reason for these paints displaying higher VOCs concentrations was because they mainly used lipids to form films. Between identical coating types, the prime coating process emitted fewer VOCs than the top coating process. Because the VOCs contents of paint of top coating processes are founded typically higher than those of prime coating. It is reported that VOCs emission concentrations of most furniture enterprises that use solvent borne paint exceeded the emission limit, which was mainly because most small scale furniture coating enterprises had no effective VOCs control measure in place, or the control measure could not be successfully implemented. For enterprises that installed activated carbon devices and had an effective control measure in place, their average VOCs concentration was 8.56 mg m$^{-3}$. For furniture enterprises that used waterborne paint, their average VOCs emission concentration was 2.53 (0.98–4.85, 95% CI) mg m$^{-3}$, which was substantially lower than the emission standard. Thus, using waterborne paint is the solution to decreasing VOCs emissions.

**Source Profiles of VOCs Emitted by the Furniture Coating Industry**

Fig. 4 lists the major VOCs species and their proportions in the source profiles of stack emissions for wood furniture with solvent borne coating operations. According to the figure, of the VOCs emitted by solvent borne paint, aromatics accounted for 71.1%, followed by oxygenated VOCs (OVOCs) at 22.9%, whereas alkanes, alkenes, and halocarbons accounted for only 3.0%, 1.0%, and 1.9% of the VOCs emitted, respectively. Of all aromatics components, ethylbenzene, 1,2,4-trimethylbenzene, o-xylene, and toluene were the primary components and contributed to approximately 35.3% of VOCs emissions. Similarly, of all OVOCs components, ethyl acetate was the primary component and contributed to approximately 15.9% of total VOCs emissions. Solvent borne paint created sizeable VOCs emissions because it contained a high ratio of benzene series, styrenes, alcohols, and esters. Comparisons of the VOCs emissions between enterprises revealed that for some coating types, the source profiles of the emitted VOCs varied. Whether an enterprise installed a VOCs control device had a considerable effect on the source profiles of the VOCs emissions. In addition, various VOCs control devices exhibited varying effects on removing VOCs emissions. For example, adsorbent materials such as activated carbon exhibited a strong removal effect on molecules with high molecular weights, such as benzene series, toluene, and xylene, resulting in a reduction in the ratio of benzene emitted from chimneys. These treatment facilities may alter the proportions of VOCs species because of their varying physical and chemical properties, such as their polarity or volatility.

Although numerous studies have analyzed the material compositions of VOCs emitted during the spraying process with solvent borne paint, those analyzing the source profile of VOCs with waterborne paint remain scant (Yuan et al., 2010; Zheng et al., 2013; Ou et al., 2015; Mo et al., 2016). The tested profiles of VOCs species of waterborne coating of this study are shown in Fig. 5. Waterborne coat is the mixture of water, natural or artificial synthetic polymer
Fig. 4. Source profile of VOCs species in solvent borne coating processes.
materials, and various pigment fillers and additives. VOCs content of waterborne coat samples is approximately only 8.1% (3.1%–11.4%, 95% CI), which is much less than that of solvent borne paint. For the species profile, test results indicated that the waterborne prime and topcoat only had approximately 4.0% benzene series emissions, respectively, and an average of 1.7% and 1.1% toluene and xylene, respectively.

The comparison of the source profiles between the results of this study with available literatures can be seen in Fig. 6. It can be found that the profiles showed similar trend for the species of benzene, toluene, m-ethyltoluene, isomers of xylene, and ethylacetate. While for the species of styrene, ethylbenzene, butyl acetate, and 1,2-Dichloroethane, there were obvious diversity during different studies.

Analysis of Activity-based Emission Factors and Uncertainties

The mean values and data distribution of the parameters when determining emission factors were recalculated using Monte Carlo simulations with normal, lognormal, and triangular probability distributions, respectively. The simulation results are presented in SI Fig. S3. The emission factors with 95% CI based on various activity data related to the wood furniture coating industry are summarized in Table 2. For emission factors based on the amount of paint used, the industry had an average emission factor of 0.22 (0.10–0.34) kg kg\(^{-1}\) coat for sloven borne coating, while the average value only 0.08 (0.03–0.14) kg kg\(^{-1}\) coat for waterborne coating. Because large enterprises that adopt the spraying method generally used waterborne paint and equip high efficiency VOCs control technologies, their average VOCs emission factor was merely 0.11 (0.05–0.18) kg kg\(^{-1}\) coat. Differing from large-scale enterprises, the application ratio of solvent borne coat is relatively higher for medium-scale enterprises, and the proportion of enterprises equip relatively fewer high removal efficiency control devices. According to the investigation result, the average VOCs removal efficiency of the medium-scale is approximately 60%. Therefore, the emission factors of these scale of enterprises is calculated at 0.26 (0.11–0.40) kg kg\(^{-1}\) coat. All the coating paint are solvent borne for small-scale coating enterprises. Most enterprises have no effective control measurements, and average VOCs removal efficiency is only nearly 15%. The average VOCs emission factor is calculated at 0.54 (0.26–0.81) kg kg\(^{-1}\) coat.

The idea of an emission factor based on the spray area was proposed mainly to quantify enterprises’ spraying efficiency and formulate enterprise emission standards. In 1999 and 2004, the European Union (EU) issued and revised the VOCs Directives 1999/13/EC and 2004/42/EC, respectively. The directives specified that permissible emission level for the furniture coating industry is 30 g m\(^{-2}\) coating area. Currently, China is yet to propose the permissible VOCs emissions per unit of coating area. On average, for the furniture industry, the emission factor based on spray area is 21.97 (10.10–29.38) g m\(^{-2}\); solvent borne and waterborne paints have average emission factors of 32.35 (16.17–41.10) g m\(^{-2}\) and 9.88 (3.02–15.70) g m\(^{-2}\), respectively. Both coating type and painting skills have an effect on the emission factors of the coating areas, and the effect of painting skills is greater. When the coating areas

Fig. 5. Source profile of VOCs species in waterborne coating processes.

Fig. 6. Comparison of the source profiles between this study and available literatures.
Table 2. Activity-based VOCs emission factors from wood furniture coating industry.

<table>
<thead>
<tr>
<th>Scale</th>
<th>Application Methods</th>
<th>Coat types</th>
<th>Treatment</th>
<th>Emission factors</th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Coat consumption-based</td>
<td>Coating area-based</td>
<td>Output value-based</td>
<td>Production-based</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>kg kg⁻¹ coat</td>
<td>kg VOCs m⁻²</td>
<td>kg VOCs 10⁻⁴ yuan</td>
<td>kg VOCs piece⁻¹</td>
<td></td>
</tr>
<tr>
<td>Large scale</td>
<td>Air atomized spray</td>
<td>Solvent borne</td>
<td>Controlled</td>
<td>0.06(0.03–0.09)</td>
<td>5.53(2.76–7.02)</td>
<td>1.93(0.96–2.90)</td>
<td>0.20(0.10–0.29)</td>
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<td></td>
<td></td>
<td>Waterborne</td>
<td>Controlled</td>
<td>0.02(0.01–0.03)</td>
<td>1.83(0.56–2.90)</td>
<td>0.35(0.16–0.43)</td>
<td>0.03(0.01–0.04)</td>
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<td>Uncontrolled</td>
<td>0.15(0.05–0.26)</td>
<td>18.25(5.57–29.01)</td>
<td>3.52(1.56–4.31)</td>
<td>0.26(0.11–0.33)</td>
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<td></td>
<td>Dip coat and flow coat</td>
<td>Solvent borne</td>
<td>Controlled</td>
<td>0.12(0.06–0.19)</td>
<td>11.79(5.89–14.98)</td>
<td>4.11(2.05–6.18)</td>
<td>0.42(0.21–0.62)</td>
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<td>Uncontrolled</td>
<td>0.31(0.15–0.46)</td>
<td>29.47(14.73–37.45)</td>
<td>10.27(5.13–15.45)</td>
<td>1.06(0.52–1.55)</td>
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<td>Waterborne</td>
<td>Controlled</td>
<td>0.03(0.01–0.06)</td>
<td>3.89(1.19–6.19)</td>
<td>0.75(0.33–0.92)</td>
<td>0.06(0.02–0.07)</td>
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<td>Uncontrolled</td>
<td>0.08(0.03–0.14)</td>
<td>9.73(2.97–15.47)</td>
<td>1.88(0.83–2.30)</td>
<td>0.14(0.06–0.18)</td>
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<td>Medium scale</td>
<td>Air atomized spray</td>
<td>Solvent borne</td>
<td>0.23(0.11–0.35)</td>
<td>22.11(11.05–28.09)</td>
<td>7.03(3.85–11.59)</td>
<td>0.79(0.39–1.16)</td>
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<td>Controlled</td>
<td>0.58(0.28–0.87)</td>
<td>55.27(27.63–70.23)</td>
<td>19.26(9.63–28.98)</td>
<td>1.98(0.98–2.91)</td>
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<td>Waterborne</td>
<td>Controlled</td>
<td>0.06(0.02–0.10)</td>
<td>7.30(2.23–11.60)</td>
<td>1.41(0.62–1.72)</td>
<td>0.10(0.04–0.13)</td>
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<td>Uncontrolled</td>
<td>0.15(0.05–0.26)</td>
<td>18.25(5.57–29.01)</td>
<td>3.52(1.56–4.31)</td>
<td>0.26(0.11–0.33)</td>
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<td>Dip coat and flow coat</td>
<td>Solvent borne</td>
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<td>Waterborne</td>
<td>Controlled</td>
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<td></td>
<td>Small scale</td>
<td>Air atomized spray</td>
<td>Solvent borne</td>
<td>0.49(0.24–0.74)</td>
<td>46.98(23.49–59.70)</td>
<td>16.37(8.19–24.63)</td>
<td>1.68(0.83–2.47)</td>
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<td></td>
<td>Controlled</td>
<td>0.58(0.28–0.87)</td>
<td>55.27(27.63–70.23)</td>
<td>19.26(9.63–28.98)</td>
<td>1.98(0.98–2.91)</td>
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<td>Waterborne</td>
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<td>Dip coat and flow coat</td>
<td>Solvent borne</td>
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are identical, the air spraying method yields the most VOCs, whereas the electrostatic spraying and brush coating methods yield the least. Studies have shown that among the spraying processes, air-assisted airless spray coating, airless spraying, and air spraying can achieve efficiencies of 75%, 60%, and 35%, respectively. In recent years, air-assisted airless spraying equipment has been applied in the furniture manufacturing industry, which has reduced emission factors by 53.3%. Although spraying efficiency is not a direct method for controlling VOCs emissions, VOCs emissions can nonetheless be effectively reduced.

Emission factors based on the amount of furniture manufactured and enterprise output value were 0.69 (0.34–1.00) kg piece\(^{-1}\) and 6.95 (3.42–10.21) kg 10\(^{-4}\) yuan, respectively. For enterprises that used solvent borne paint, the emission factors based on the amount of furniture manufactured and enterprise output value were 1.16 (0.57–1.70) kg piece\(^{-1}\) and 11.27 (5.63–16.96) kg 10\(^{-4}\) yuan, respectively. By contrast, for enterprises that used waterborne paint, emission factors were 0.14 (0.06–0.18) kg piece\(^{-1}\) and 1.90 (0.84–2.33) kg 10\(^{-4}\) yuan, respectively. For enterprises that used solvent borne paint, both the enterprises number and VOCs emissions were considerably higher than those that used waterborne paint. Although enterprises that used solvent borne paint only replaced some of this paint used with waterborne varieties, VOCs emissions were effectively diminished.

Of the many VOCs control technologies currently available, the water curtain absorption method, adsorption cotton absorption method, adsorption paper absorption method, and the increasing activated carbon absorption device method are the most commonly used by furniture manufacturers. According to the study results, large-scale furniture manufacturers are equipped with highly efficient VOCs control equipment. The control efficiency distribution diagram of these control technologies is shown in SI Fig. S4. Although water curtain absorption method (WCB) technology is the most widely used, it has poor control efficiency (i.e., an average control efficiency of approximately 15%). By contrast, RTO technology has high control efficiency (i.e., over 95%). PO and ACA technologies are the most widely used and have average control efficiencies of 90% and 80%, respectively. Enterprises may use the VOCs removal efficiency of their control technologies to estimate their final VOCs emission factors. Compared with medium- and large-scale enterprises, more small-scale furniture manufacturers use solvent borne paint, fewer small-scale furniture manufacturers are equipped with highly efficient VOCs control measures, and fewer small-scale furniture manufacturers implement control measures on their normal operation rates. Therefore, small-scale furniture manufacturers have higher VOCs emission factors.

**Comparisons with Other Studies**

The comparison between the emission factor results of this study and those of other studies is shown in Fig. 7. Overall, the four types of emission factor matched the data in the other studies, only parts of emission factors exceeded the data distribution of this study. The reasons...
contributing to this discrepancy were that the VOCs contents of paint used in earlier studies were higher than in more recent studies, and that the VOCs emission factors of furniture spraying enterprises varied substantially by time. For emissions factors per unit of spray area, those of this study exceeded the limit set by the European Union in 2004, indicating that spraying skills and spraying efficiency in China remain poor and must be substantially improved.

**VOCs Emission Estimation and Spatial Distribution Analysis**

VOCs emissions were estimated by compiling the statistics of provincial activity data of Chinese wood furniture manufacturing industry and the emission factors obtained in this study. Provincial activity data can be seen SI Table S2 and Figs. S5–S6. Total VOCs emissions were estimated at $179.76 \times 10^3$ (88.58 \times 10^3–260.52 \times 10^3, 95% CI) t for the year of 2016. Spatial distribution by province is shown in Fig. 8. VOCs emissions concentrate mainly in the provinces of Guangdong, Zhejiang, Shandong, Fujian, Jiangxi, and Sichuan, with the total contribution of 43.8% of the whole country. Annual VOCs emissions per enterprise of wood furniture production are demonstrated in SI Fig. S7. Total average VOCs emissions per enterprise were estimated at approximately 3.04 t a\(^{-1}\). Annual VOCs emissions of Fujian province were estimated at nearly 21.72 \times 10^3 t, with the emissions per enterprise at 11.35 t a\(^{-1}\). While for Guangdong province with the most VOCs emissions in China (36.30 \times 10^3 t), the emissions per enterprise were estimated at only 5.18 t a\(^{-1}\), less than half of that of Fujian province. That can be mainly attributed to the stricter emission standard of VOCs for wood furniture coating industry in Guangdong since 2010. Besides the implement of VOCs emission limitations, the development of industrial clusters of wood furnituring also plays an important role in emission control. The wood furniture manufacturing concentrates in three main industrial clusters, Dayong town and Sanxiang town of Zhongshan city, and Dajiang town of Taishan city in Guangdong province. To reduce VOCs emission and improve air quality, other provinces like Fujian, Shandong, and Sichuan have gradually issued local VOCs emission standards since the year of 2017. Those typical industrial clusters include Ningning county of Shandong, Chongzhou city of Sichuan, Yuhuan district of Zhejiang, Nankang district of Jiangxi, Xiayou county of Fujian, etc. By comparing with the total emissions from anthropogenic sources, wood furniture coating processes contribute nearly 10% of VOCs emissions of surface coating industry (Wu et al., 2017a). To achieve the goal of VOCs emission reduction of Thirteenth Five-Year plan, available proposals for wood furniture coating industry include the application of control technologies with high efficiency, the substitution of water-based coatings, and the development of industrial aggregation.

**CONCLUSIONS**

An integrated emission factor database for the wood furniture coating industry in China was developed based on field tests and thorough data surveys. Activity-based database including coat consumption-based, coating area-based, furniture production-based, and output value-based emission factors were developed for estimating the emissions of both enterprises and the industry as a whole. VOCs emission factors were estimated: 0.22 (0.10–0.34, 95% CI) kg kg\(^{-1}\) for coat consumption-based; 21.97 (10.10–29.38) g m\(^{-2}\) for coating area-based; 0.69 (0.34–1.00) kg piece\(^{-1}\) for furniture production-based; and 6.95 (3.42–10.21) kg 10\(^{-4}\) yuan for output value-based calculation, respectively. Provincial VOCs emission inventory was developed by compiling available activity of statistics and emission factors obtained in this study. VOCs emissions from the wood furniture coating industry were estimated at $179.76 \times 10^3$ (88.58 \times 10^3–260.52 \times 10^3, 95% CI) t in 2016. Although advanced VOCs emission control devices are increasingly being used, their actual performance varies significantly because specific policies and regulatory incentives remain lacking, particularly for small-scale
enterprises. Along with improving targeted policies and regulatory implementation, more field tests for these devices are recommended, and higher resolution emission inventory can be expected in the future.

ACKNOWLEDGMENTS

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SUPPLEMENTARY MATERIAL

Supplementary data associated with this article can be found in the online version at http://www.aaqr.org.

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