Stratification of Welding Fumes and Grinding Particles in a Large Factory Hall Equipped with Displacement Ventilation

RAIMO NIEMELÄ*, HANNU KOSKELA and KERSTIN ENGSTRÖM

Finnish Institute of Occupational Health, Laajaniittyntie 1, FIN-01620 Vantaa, Finland

The purpose of the study was to investigate the performance of displacement ventilation in a large factory hall where large components of stainless steel for paper, pulp and chemical industries were manufactured. The performance of displacement ventilation was evaluated in terms of concentration distributions of welding fumes and grinding particles, flow field of the supply air and temperature distributions. Large differences in vertical stratification patterns between hexavalent chromium (Cr(VI)) and other particulate contaminants were observed. The concentration of Cr(VI) was notably lower in the zone of occupancy than in the upper part of the factory hall, whereas the concentrations of total airborne particles and trivalent chromium (Cr(III)) were higher in the occupied zone than in the upper zone. The stratification of Cr(VI) had the same tendency as the air temperature stratification caused by the displacement flow field.

Keywords: chromium compounds; ventilation; air distribution; control; welding

INTRODUCTION

Exposure to welding fumes and other particles is a considerable hygiene problem in stainless steel welding and related operations (Hewitt, 1996; Karlsen et al., 1994). From the control point of view, investigation of fume formation mechanisms in different welding methods, particularly the generation of hexavalent chromium (Cr(VI)), is continuously of great interest (Dennis et al., 1996, 1997; Hewitt and Madden, 1989). In addition to process modification, control at the source is an effective way to eliminate or reduce welding fumes and grinding dust (BOHS, 1987; HSE, 1990). However, in many cases, source controls, such as local exhaust ventilation, are difficult to implement and use or they capture only part of the contaminants generated. Therefore, general ventilation airflows play an important role in the contaminant removal process, particularly in large industrial halls.

Displacement ventilation has become rather popular in industrial buildings owing to its notable benefits compared to the traditional dilution ventilation (Breum and Orhede, 1994). Although displacement ventilation has been used for more than twenty years, there is still a need for performance evaluation in different applications. Most performance evaluations based on tracer gas tests and temperature measurements have been carried out in laboratory conditions and office environments (Mundt, 1996; Skistad, 1994). Therefore, more information on dispersion of toxic contaminants in displacement flow conditions at industrial work rooms is needed.

The purpose of this study was to investigate the performance of the displacement ventilation in a large factory hall where big components for paper, pulp and chemical industries were manufactured. In particular, the field measurements were aimed at producing information on stratification patterns of welding fumes and other particles generated in stainless steel welding and related operations. Special attention was paid to the behaviour of chromium compounds.

METHODS

Description of the industrial process and the ventilation system

Process machines and components of stainless steel, with typical dimensions of 10x5x5 m were
manufactured in the factory hall (Fig. 1). Welding and abrasive grinding produced contaminants in the form of welding fumes and grinding particles. Manual flux cored arc welding on stainless steel was the main welding method but automatic welding machines were also used. Part of the welding was done inside cylindrical containers with two ends open, which is a difficult situation for contaminant control.

The air distribution system of the hall was based on displacement. Two air handling units controlled by a central system delivered inlet air through seven low impulse diffusers into the hall. As several parts of the furnaces and containers were under construction at the same time, they were transferred from one place to another in the hall. Some of them were placed close to inlet air diffusers, thus disturbing the supply airflow patterns. The air was exhausted with two roof fans. The ventilation system operated in three modes: night, warming up and normal daytime operation. During the night, the supply units used recirculation air only. The warming up operation was run in the morning, when the temperature in the hall was below the setpoint value. In this mode, the system uses recirculation air and the supply air heated at full power is blown through high impulse inlets located above the low impulse devices. When the set-point temperature is reached, the system shifts to the normal daytime operation in which the supply air is again introduced through the low impulse units and its temperature is maintained at the setpoint value.

Measuring conditions and methods

The measurements were carried out on three successive days under normal production conditions. The outdoor temperature ranged from 5 to 15°C in the daytime and from 0 to 5°C by night. The dust samples were taken in the afternoon, after the hall was heated up and the displacement flow was fully developed.

Sampling of particles. The concentrations of particles were determined by sampling at fixed sites and in the workers’ breathing zone (Table 1). The focus was laid on the fixed point sampling, because the tests were primarily aimed at documenting the dispersion of fumes and grinding particles. Filter samples (Millipore AAWP 025) for particles were taken at five fixed points at a height of 1.5 m according to the Finnish standard SFS 3860. The sampling sites were chosen to cover areas with major contaminant generating activities in the hall. In addition, in order to find out the stratification of particles, filter samples were taken above the working zone with two masts A and B, at which also temperature sensors and tracer gas sampling tubes were installed. The sampling time at the fixed points varied between 2 and 4 h. In addition, the personal sampling of six workers was carried out during work phases with intensive contaminant emissions in order to detect circumstances with high risk (Table 2). Personal sampling during welding was performed when workers were wearing normal welding masks or special helmets with a fan and filter. The sampling time of the personal sampling varied, depending on active working, time between 55 min and 2.5 h.

Analytical procedure. Before sampling the filters were dried for two days in a desiccator with blue silica gel and subsequently weighed. After the sampling the same procedure was used for determination of total particle weight.

The filters were heated for 30 min at 80–85°C in 15 ml deionised water. The solutions were subsequently filtered and then diluted to 50 ml. To form a coloured complex with the hexavalent chromium, a 20 ml sample aliquot is mixed with 50 ml deionised water, 5 ml sulphuric acid (diluted 1:1) and 1 ml of 0.2% 1,5-diphenylcarbazide solution. The determinations were made with a spectrophotometer at wavelength 540 nm (Karlsen et al., 1994). The filters obtained from the filtering procedure described above were digested in a mixture of 10 ml dithizone-treated nitric acid and 5 ml suprapur hydrochloride acid for analysis of nickel.
Stratification of welding fumes and grinding particles

Table 1. Concentrations of air contaminants at the fixed sampling sites in the occupied zone

<table>
<thead>
<tr>
<th>Compound</th>
<th>Western part</th>
<th>Eastern part</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Mean</td>
<td>Range</td>
</tr>
<tr>
<td>Total airborne particles (mg/m³)</td>
<td>0.8</td>
<td>0.25–2.0</td>
</tr>
<tr>
<td>Chromium (VI) (µg/m³)</td>
<td>3.4</td>
<td>1.5–5.3</td>
</tr>
<tr>
<td>Chromium (III) compounds (µg/m³)</td>
<td>17</td>
<td>8–38</td>
</tr>
<tr>
<td>Nickel (µg/m³)</td>
<td>9</td>
<td>4–24</td>
</tr>
</tbody>
</table>

Table 2. Personal samples during heavy emissions

<table>
<thead>
<tr>
<th>Sample</th>
<th>Total particles (mg/m³)</th>
<th>Cr(VI) (µg/m³)</th>
<th>Cr(III) (µg/m³)</th>
<th>Ni (µg/m³)</th>
<th>Cr(VI) (%)</th>
<th>Cr (III) (%)</th>
<th>Ni (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Outside a container</td>
<td>2.2</td>
<td>8</td>
<td>50</td>
<td>29</td>
<td>0.4</td>
<td>2.3</td>
<td>1.3</td>
</tr>
<tr>
<td>2 Outside a container</td>
<td>7.7</td>
<td>12</td>
<td>152</td>
<td>57</td>
<td>0.2</td>
<td>2.0</td>
<td>0.7</td>
</tr>
<tr>
<td>3 Outside a container</td>
<td>2.3</td>
<td>4</td>
<td>58</td>
<td>39</td>
<td>0.2</td>
<td>2.5</td>
<td>1.7</td>
</tr>
<tr>
<td>4 Inside a container</td>
<td>2.8</td>
<td>22</td>
<td>67</td>
<td>34</td>
<td>0.8</td>
<td>2.4</td>
<td>1.2</td>
</tr>
<tr>
<td>5 Inside a container</td>
<td>11.8</td>
<td>340</td>
<td>42</td>
<td>42</td>
<td>2.9</td>
<td>0.4</td>
<td>0.4</td>
</tr>
<tr>
<td>6 Inside a conical cylinder</td>
<td>16.1</td>
<td>790</td>
<td>104</td>
<td>70</td>
<td>4.9</td>
<td>0.6</td>
<td>0.4</td>
</tr>
</tbody>
</table>

and trivalent chromium with flame atomic spectrometry.

Air flow patterns. The mixing patterns of the inlet air with the hall air mass were described by the local air change index based on the age of the supply air molecules obtained from tracer gas experiments (Sutcliffe, 1990). The local air change index is defined as a ratio \( \eta = \tau_i / \tau_n \) where \( \tau_i \) is the local mean age of air at point \( i \) and \( \tau_n \) is the nominal time constant of the system (V/Q). The step-down injection procedure was applied by using sulphur hexafluoride (SF6) as a tracer. The concentration of the tracer gas in the hall was monitored by two photo-acoustic infrared analysers at twelve sampling points (Fig. 1).

RESULTS

The total dust concentration in the general air of the occupied zone was lower than 1 mg/m³ (10% of 8h OEL in Finland), except in three samples. The concentrations of particles in the eastern part were 30–50% of those in the western part (Table 1). This was to be expected because the main activities took place in the western part where also automated welding machines were used. In all but two samples, the hexavalent chromium levels collected at the fixed sites in the occupied zone were less than 5 µg/m³ (10% of OEL in Finland). The concentrations of trivalent chromium and nickel were usually a few percent of the corresponding OEL.

The personal samples collected during periods of heavy emissions show that the concentration levels of particles may be ten times higher than in the general plant air in the occupied zone (Table 2). When welding was performed inside a conical cylinder, the concentration of hexavalent chromium may rise to even 100-fold higher than corresponding concentrations in the general air. The vertical stratification of particle concentration, air temperature and local air change index are shown in Figs 2 and 3.

DISCUSSION

The performance of the displacement ventilation of the large factory hall was evaluated in terms of concentration distributions of welding fumes and grinding particles, the flow field of supply air and temperature distributions.

Surprisingly, there were great differences in vertical distribution between hexavalent chromium and other particulate contaminants (Fig. 2). The concentration of hexavalent chromium was notably lower in the zone of occupancy than in the upper part of the factory hall. In contrast, the concentrations of total airborne particles and Cr(III) were higher in the occupied zone than in the upper zone. The stratification of Cr(VI) has the same tendency as the air temperature stratification (Fig. 3) of the displacement flow field.

The different stratification patterns between hexavalent chromium and other particles may be due to differences in the generation mechanisms and particle sizes. Because hexavalent chromium is formed during welding only, the thermal welding fume plumes containing Cr(VI)-enriched small-sized particles create favourable conditions for displacement ventilation. On the other hand, larger particles are generated parti-
cally in grinding and polishing processes which do not generate thermal buoyancy flows or hexavalent chromium. Because larger particles have a tendency to settle down by gravity, trivalent chromium compounds and other metal particles are enriched in the occupied zone. The particle size distributions were not analysed in the present study. The detailed investigation of fume and other particle formation mechanisms was also outside this study. It is evident that the stratification phenomena in the displacement flow field need further investigation in the future.

From the health perspective, the stratification of Cr(VI) in the upper part of the factory hall is a desirable phenomenon, because Cr(VI) containing compounds have carcinogenic and allergic potential.

The personal samples were in line with exposure levels reported previously in corresponding work (Karlsen et al., 1994; van der Wal, 1990). Welding inside containers and conical cylinders spaces yielded high hexavalent chromium levels as expected. In these samples, the portion of hexavalent chromium of the sample total mass was clearly higher than in the samples taken in the open space. The breathing zone data indicate that in order to attain proper protection, the use of respirators is needed during welding in stagnant regions, for instance, inside cylinders or behind large flow obstacles. The assembly hall was also equipped with high-pressure local exhaust ducts, but the system was not used obviously due to its interference with the work process. Although control at the source is the effective way to reduce occupants’ exposure to fumes, well functioning general ventilation also plays an important role. In addition to welders, there were other persons such as supervisors and cleaners who were not exposed to the near field of welding fumes. It is also worth noting that the welders wearing fan and filter equipped helmets performed welding only 10–20% of the active working time. Therefore, the purity of the general atmosphere has a considerable influence on the contaminant dose of the workers. In this respect, the importance of the flow patterns of the general ventilation must not be ignored.

The local air change index values in the occupied zone (Fig. 3) confirmed that the supply air distribution system worked in the intended way, when the supply air temperature was lower than the ambient air temperature. There were, however, problems in achieving the displacement flow pattern in the morning due to slow heating of the hall after the cold night. In ideal
Stratification of welding fumes and grinding particles

thermal displacement, the supply air temperature has to be slightly lower than the air temperature in the occupied zone. A further reason for difficulties in maintaining the displacement flow pattern was the marked infiltration. According to the tracer gas tests and air flow rate measurements, it can be estimated that infiltration through the building envelope, doors and windows was responsible for about 30% of total incoming air flow, whereas 70% was introduced by the ventilation system.

CONCLUSIONS

- The vertical stratification patterns of hexavalent chromium differed from those of other particulate contaminants due to different generation mechanisms.
- When the displacement flow pattern was established in the factory hall, the concentration of Cr(VI), which is the most critical substance from the health perspective, was significantly lower in the occupied zone than in the upper part of the hall. This meets the original requirements set by good ventilation practice.
- The creation and maintaining of displacement flow patterns presupposes a well-functioning temperature control system as well as a balance between the supply and exhaust flow rates.

Acknowledgements—The financial support of the Technical Development Centre Finland and the co-operation with Sunda Defibrator are gratefully acknowledged.

REFERENCES

HSE - Health and Safety Executive. The control of exposure to fume from welding, brazing and similar processes, EH55. London: Health and Safety Executive.


