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Calibration of the Welding Advanced REACH Tool (weldART)

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A B S T R A C T

Objectives: This paper reports a study to develop and calibrate a deterministic model of welding fume exposure based on a four-compartment mass-balance model - The Welding Advanced REACH Tool (weldART). To achieve this aim, measurements of welding fume exposure were collected along with data on exposure determinants needed in the modelling.

Methods: The welding fume exposure data was obtained from workers in a structural steel fabrication plant. Welders were engaged in three processes: flux-cored arc welding (FCAW), shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). Aerosol concentration was measured using 13 mm diameter Swinnex sampling heads and MicroPEM direct-reading aerosol monitors. The model was initially developed with three spatial compartments (near-field (NF), far-field (FF), and welding plume (WP)). However, in the welding scenario investigated the FF had a very large volume and it was necessary to subdivide the room volume into an intermediate zone representing the FF along with the remaining room zone (RM). We fitted linear equations forced through the origin to the gravimetric concentrations measured inside the welders' visor and the weldART model estimates. The flowrates between the model compartments were adjusted by trial and error to obtain proportionate concentrations in each compartment.

Results: The FCAW process generated higher welding fume particulate concentrations than SMAW and GTAW. The MicroPEM monitors considerably underestimated and were poorly correlated with the corresponding data from the Swinnex samplers. It was concluded that the MicroPEM data were unreliable. The model calibration showed a strong association between the personal exposure measurement and the weldART model values (R^2 = 0.94), with the average estimated value 1.3 times the measurements. The NF and the FF model estimates were poorly correlated with the corresponding compartment measurements (R^2 = 0.37 and 0.35, respectively), although on average the model estimates were close to the measurement data (ratio of modelled to measured 0.9, and 1.0, respectively).

Conclusions: The calibration shows that the weldART model is able to predict the exposure of welding fume particulate.

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A R T I C L E I N F O

Keywords: Welding, Fume, weldART, Advanced REACH tool, Exposure modelling, Calibration

Introduction

Welding is a basic manufacturing process carried out in many industries, including in maintenance of existing equipment and fabrication of new equipment or structures. The hazardous substances emitted from welding comprise metal oxide particles formed by evaporation, condensation and oxidation during the welding (fume) and gas phase contaminants such as carbon dioxide (CO_2), carbon monoxide (CO), nitrogen oxides (NO_x), sulphur dioxide (SO_2) and ozone (O_3) (Pires et al., 2006; Popović et al., 2014). Welding generates a considerable amount of heat, which results in the contaminants dispersing in a turbulent buoyant plume (Olander, 1985). The plume released from the welding fume emission source and has the general form of an inverted cone where the upward air velocity and the contaminant concentrations decrease with the height in the plume (Slater, 2004). Welders may inhale these contaminants.

The standard method for assessing human exposure to welding fume relies on the collection of air samples that are analysed gravimetrically or chemically to determine the concentration. This approach is relatively expensive and time-consuming, and the data is not generally available for some time after the sample collection. A mathematical model could provide a reliable prediction of the fume exposure levels, although to date there are no widely accepted models that can be used to assess welding fume exposure. There are a few models for airborne contaminant exposure assessment, such as the European Centre for Ecotoxicology and Toxicology of Chemicals' Targeted Risk Assessment (ECETOC TRA), Stoffenmanager®, and Advanced REACH Tool (ART) (Riedmann et al., 2015) but they are not tailored to estimate welding fume exposure.

The Near-Field/Far-Field model, also known as the two-zone model, has been used to evaluate exposure to airborne contaminants, including welding fumes (Boelter et al., 2009; Ganser and Hewett, 2017; Nicas, 1996). The room is modelled as two compartments, the near-field (NF) that surrounds the worker and the source and the far-field (FF) the remainder of the room space. This simplified model has been shown to encompass the essence of contaminant transport and dispersion in indoor spaces. The Advanced REACH Tool (ART) is based around the NF/FF model (Fransman et al., 2011; LeBlanc et al., 2018; Tielemans et al., 2011). ART is a probabilistic model, based on a multiplicative combination of identified modifying factors (MFs), that can be used to estimate exposure to a wide range of hazardous chemicals. It is not suitable to estimate fume concentration, although Sailabaht et al. (2018) reviewed the model structure to identify how it could be adapted to include welding. The review indicated that the key MFs contributing to the model should include welding process type, electrical input power, shield gas composition, and welding electrode type. The review also recommends the extension of the model framework to include three spatial compartments: NF, FF and the welding plume (WP), which was also recommended by Nicas et al. (2009).

The objectives of the present study were to develop and calibrate a deterministic model of welding fume exposure based on a four-compartment mass-balance model (The Welding Advanced REACH Tool or weldART) by using welding fume exposure data.

Materials and methods

Measurements of welding fume exposure was obtained from 17 workers in a structural steel fabrication plant making pipes, pressure vessels, heat exchangers and silos. Welders were engaged in three processes: flux-cored arc welding (FCAW), shielded metal arc welding (SMAW) and gas tungsten arc welding (GTAW). The majority of the welding tasks involved GTAW, with SMAW and FCAW only being used occasionally. They worked in a building with volume around 35,200 m^3 (20 m wide, 160 m long and 11 m high) that was open at both ends. There was no fresh air distribution system nor local air exhaust ventilation system at the welding workstations. Welders wore gloves and a welding visor. The environmental air temperature during the data collection ranged from 32 to 42 °C, over 17 monitoring points.

Air sample collection and analysis

The air samples were collected during a number of single welding tasks not over the whole shift by two methods: 13 mm diameter Swinnex sampling heads (T18D58550 by Merck Millipore) were connected to personal sampling pumps using the BS EN ISO 10882-1:2011 method for airborne particulates in welding and allied processes (British Standards Institution (BSI), 2011) and a MicroPEM direct-reading aerosol monitor. For each task, three Swinnex samples were collected: one located inside the welding visor to evaluate fume exposure, one approximately 50 cm from the welding at a height of 1.5 m above ground to evaluate fume concentration in the NF and one about 200 cm distant at 1.5 m height to evaluate fume concentration in the FF. Each Swinnex holder contained a pre-weighed 13 mm glass fibre filters with a nominal pore size of 2 µm. The air was drawn through the sampling system at a flowrate 1 l/min. The airflow was checked before and after each sampling session using a primary standard meter (Model: Bios Defender 510, Serial no: 112114). The mean flowrate of each personal sampling pump was calculated by averaging the flowrates at the start and the end of the sampling period. After sampling the filters were reweighed using a Sartorius filter microbalance (Model: MSA6.6S000DF, Serial no: 33505850) to within 0.001 mg and the gravimetric concentration calculated. Samples were not analysed for component metals.

The version 3.2 MicroPEM developed by RTI International (https://www.rti.org/impact/micropem-sensor-measuring-exposure-air-pollution) is a light scattering instrument that measures $PM_{2.5}$ concentration; it was used after the manufacturer's calibration. The MicroPEM has a reported response time of 10 s (Williams et al., 2014). These devices were located on a belt worn by the welder and a sampling tube was used to draw air from inside the welding visor. According to the manufacturer, the flowrate through the instrument was set at 0.5 l/min and this was remeasured at the end of the sampling period.

As a control on the quality of the weighting, ten blank filters were prepared and exposed to the same conditions as the samples, but with no air drawn. The average change in mass found in the field blanks was subtracted from the corresponding mass found in the samples. The welders head position and welding time period were recorded using a video recorder during the monitoring (this was explicitly covered by the ethical approval). The sampling records indicated when and where the monitoring was carried out and the operations in progress at the time of the survey. The MicroPEM data was also used to identify the welding periods in conjunction with the video evidence. During the sampling, the exposure determinants were also collected, i.e. process type, sampling time, arc time, working room volume, and shielding gas.

Development of the weldART model

We initially suggested a multi-compartment mass-balance model of the welding process, as described in Sailabaht et al. (2018). The model comprised of three spatial compartments: NF, FF and WP. Fig. 1 shows a conceptual diagram of the weldART model. The

WP contains the welding fume emission source (E_{WP}). The breathing zone of the individual whose exposure is to be estimated is either the WP or NF compartment, depending on their head location (determine by the MicroPEM monitoring data and/or video record). During single welding tasks, however, most welders worked both in the WP and the NF, and the personal exposure concentrations (C_{exp}) were calculated as a time-weighted average concentration between those two compartments. The FF represents the remainder of the room. Airflow between compartments is represented by the β coefficients (m^3/s). The weldART model consists of three simultaneous differential equations as follows:

$$\frac{dC_{NF}}{dt} \cdot V_{NF} = (C_{WP} \cdot \beta_1) + (C_{FF} \cdot \beta_3') - (C_{NF} \cdot \beta_1') - (C_{NF} \cdot \beta_3) \quad (1)$$

$$\frac{dC_{FF}}{dt} \cdot V_{FF} = (C_{WP} \cdot \beta_2) + (C_{NF} \cdot \beta_3) - (C_{FF} \cdot \beta_2') - (C_{FF} \cdot \beta_3') - (C_{FF} \cdot Q_{FF}) \quad (2)$$

$$\frac{dC_{WP}}{dt} \cdot V_{WP} = E_{WP} + (C_{NF} \cdot \beta_1') - (C_{WP} \cdot \beta_1) + (C_{FF} \cdot \beta_2') - (C_{WP} \cdot \beta_2) \quad (3)$$

Where;
C_{WP}, C_{NF} and C_{FF} are the fume concentration in the WP, NF and FF, respectively (mg/m^3)
E_{WP} is a fume emission rate in the WP (mg/s)
V_{WP}, V_{NF} and V_{FF} are compartment volume in the WP, NF and FF, respectively (m^3)
β_x and β_x' are the airflow between compartments (m^3/s)
Q_{FF}' and Q_{FF} are volume airflow flowing in and out of the FF, respectively (m^3/s)

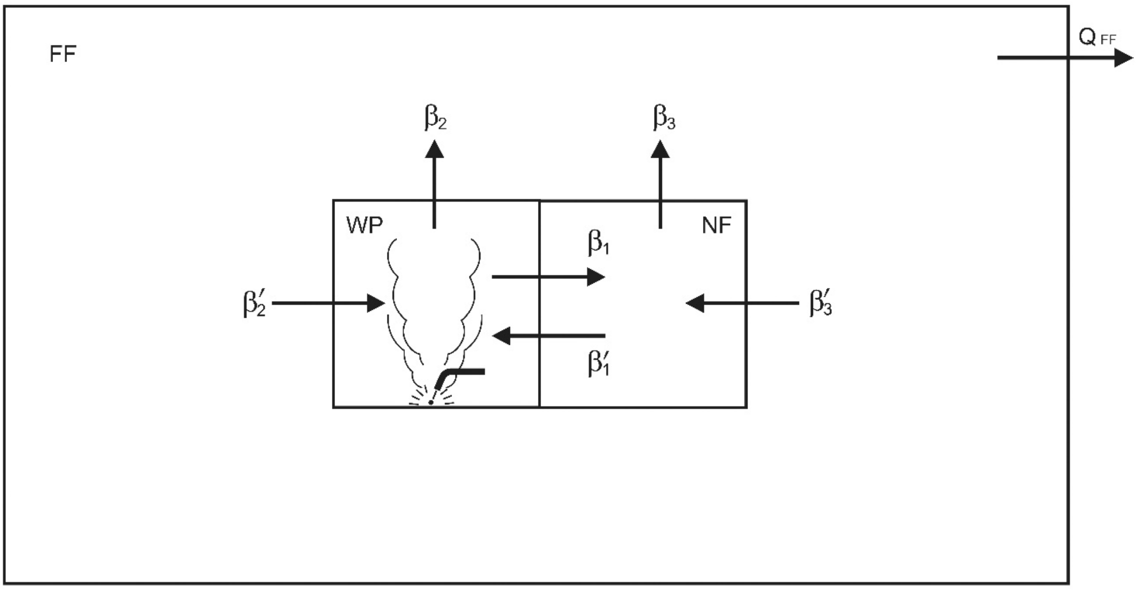

Fig. 1. A conceptual diagram of the weldART model with three compartments.

As the development of the model progressed, it became clear that it was unrealistic to assume the emitted fume instantaneously mixed into the FF because it was a very large volume. The model was, therefore elaborated to comprise four compartments, with an intermediate zone as the FF along with the residual room zone (RM) (Fig. 2). This change resulted in an additional fourth differential equation as follows:

$$\frac{dC_{RM}}{dt} \cdot V_{RM} = (C_{FF} \cdot Q_{FF}) - (C_{RM} \cdot Q_{FF}') - (C_{RM} \cdot Q_{RM}) \quad (4)$$

Where;
C_{RM} is the air concentration in the RM (mg/m^3)
V_{RM} is compartment volume in the RM (m^3)
Q'_{RM} and Q_{RM} are volume airflow flowing in and out of the RM, respectively (m^3/s)

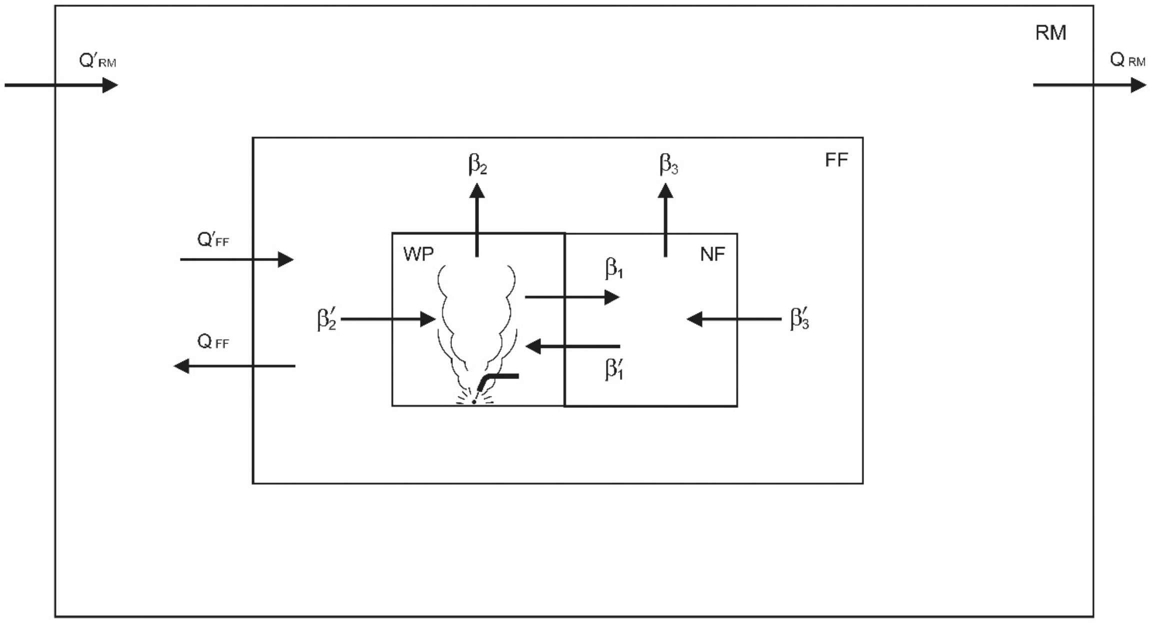

Fig. 2. A conceptual diagram of the weldART model with four compartments.

The equations were solved using R scripts (RStudio Team, 2016). The weldART model applies for only one source in WP although it could be extended to include other sources in the other compartments. The model assumes that air within each compartment is instantaneously well mixed and concentration starts at zero. Table 1 shows the weldART model parameters.

Table 1 The comparison of weldART model parameters between three compartments and four compartment models.

Parameters	Initial values (Three compartments)	Revised values (Four compartments)
Compartment volume (m^3)		
V_{NF} and V_{WP} (W x L x H)	0.2875 (0.5 m x 0.5 m x 1.15 m)	0.2875 (0.5 m x 0.5 m x 1.15 m)
V_{FF} (W x L x H)	35,200 (20 m x 160 m x 11 m)	300 (10 m x 10 m x 3 m)
V_{RM} (W x L x H)	-	35,200 (20 m x 160 m x 11 m)
Fume emission rate in the WP (E_{WP}) (mg/s)		
FCAW	2.6	2.6
SMAW	2.0	2.0
GTAW	1.6	1.6
Airflow between zones (m^3/s)		
β_1	0.0125	0.0125
β_1'	0.0288	0.0288
β_2	0.0738	0.0738
β_2'	0.0575	0.0575
β_3	0.0300	0.0300
β_3'	0.0463	0.0463
Volume airflow flowing in and out of the FF (m^3/s)		
Q_{FF}	22	0.25
Q_{FF}'	0	0.25
Volume airflow flowing in and out of the room (m^3/s)		
Q_{RM}	-	22
Q_{RM}'	-	22
Measured : Modelled ratio		
Personal	1.2	1.3
NF	1.1	0.9
FF	87.3	1.0

The fume emission rate information is necessary for the evaluation of contaminant dispersion and transport (Serageldin and Reeves, 2009). At present, there is no reliable information on fume emission rate, and the emission rate depends on many factors such as welding electrode type, electrode angle, electrode diameter, base metal, electrical input power, workpiece composition, shielding gas mixture and flow rate, arc length, polarity, and welding position, welding speed (Jilla, 2019; U.S. Environmental Protection Agency (EPA), 1994). Therefore, it is difficult to specify the emission rate in the model. However, Sailabaht et al. (2018) reported that the welding process is the key factor affecting the fume emission or formation rate (FFR). They suggested numeric values (multipliers) for the welding process factors decreased from FCAW (1.0) to SMAW (0.8), and GTAW (0.03). We tried to use these multipliers in the weldART model but the result showed the unrealistic concentrations. The emission rate values were then adjusted by trial and error, maintaining a decreasing emission rate from FCAW to SMAW and GTAW. Finally, the best emission rate values for the weldART model are 2.6 (FCAW), 2.0 (SMAW), and 1.6 (GTAW). The main change from Sailabaht et al. (2018) was the proportionate increase in emission from GTAW processes.

Slater (2004) showed that at 1.15 m above the weld, the volumetric flowrate from the welding fume plume was 0.045 m^3/s. At this height the fume plume has lost most of its buoyancy and so stops rising and starts to spread laterally; this will occur at the top of the WP compartment assuming that the welding takes place at the bottom of the compartment. However, in addition to the convective airflow out of the WP compartment, there will be air movement latterly through the compartment from room draughts. Based on the study of

Baldwin and Maynard (1998), we assumed this airspeed was 0.05 m/s. Therefore, the total for β_2 (assuming the lateral airflow was 0.5 m x 1.15 m x 0.05 m/s) was set at 0.0738 m^3/s. We assumed β_2', the convective airflow from the welding plume compartment, was 0.0575 m^3/s (i.e. 0.5 m x 1.15 m x 2 sides x 0.05 m/s). Further we assumed there was one face of the WP and NF with 0.05 m/s airflow though and β_1' was 0.0288 m^3/s (0.5 m x 1.15 m x 0.05 m/s). β_1 is was then calculated to balance the airflow into and out of the WP ($\beta_1 = (\beta_1' + \beta_2') - \beta_2$). Therefore, β_1 was 0.0125 m^3/s. The airflows in the NF compartment were estimated in a similar way. The study of Mahyuddin et al. (2015) estimated that the upward airflow speed above the human head is 0.12 m/s. Therefore, we assumed β_3 was 0.03 m^3/s (i.e. 0.5 m x 0.5 m x 0.12 m/s). β_3' was calculated to balance ($\beta_3' = (\beta_1' + \beta_3) - \beta_1$), i.e. β_3' was set at 0.0463 m^3/s. Airflows into and out of the FF at rate Q (m^3/s) depend on the room size and general ventilation or air changes per hour (ACH). In this paper, Q_{FF} was set at 22 m^3/s based on an estimated air exchange of 2.25 ACH.

Calibration of the weldART model

We fitted linear equations forced through the origin to the filter concentrations corresponding to the weldART model estimates of personal exposure estimates (based on a time-weighted average of the WP and NF concentration), the NF and the FF concentrations. We did not adjust the emission rate values in the process of weldART model calibration. However, the flowrates between the model compartments were adjusted by trial and error to get the average modelled concentrations in the NF and FF close to the average measured value (Table 1).

Results

A total of 68 air samples were collected in the workshop building as shown in Table 2. There were three sample sets for FCAW, four for SMAW and ten for GTAW.

MicroPEM monitoring

The MicroPEMs were used to measure the real-time continuous $PM_{2.5}$ concentration. The data were downloaded and compared with the welding activities from the video record. We noted the times welding when the welder started and stopped welding and plotted these on a graph to compare with the MicroPEM concentrations. Subsequently, we summarised the welding times in each welding task. These times were used to estimate personal exposure. An example of the concentration and welding periods identified from the video record is illustrated in Fig. 3.

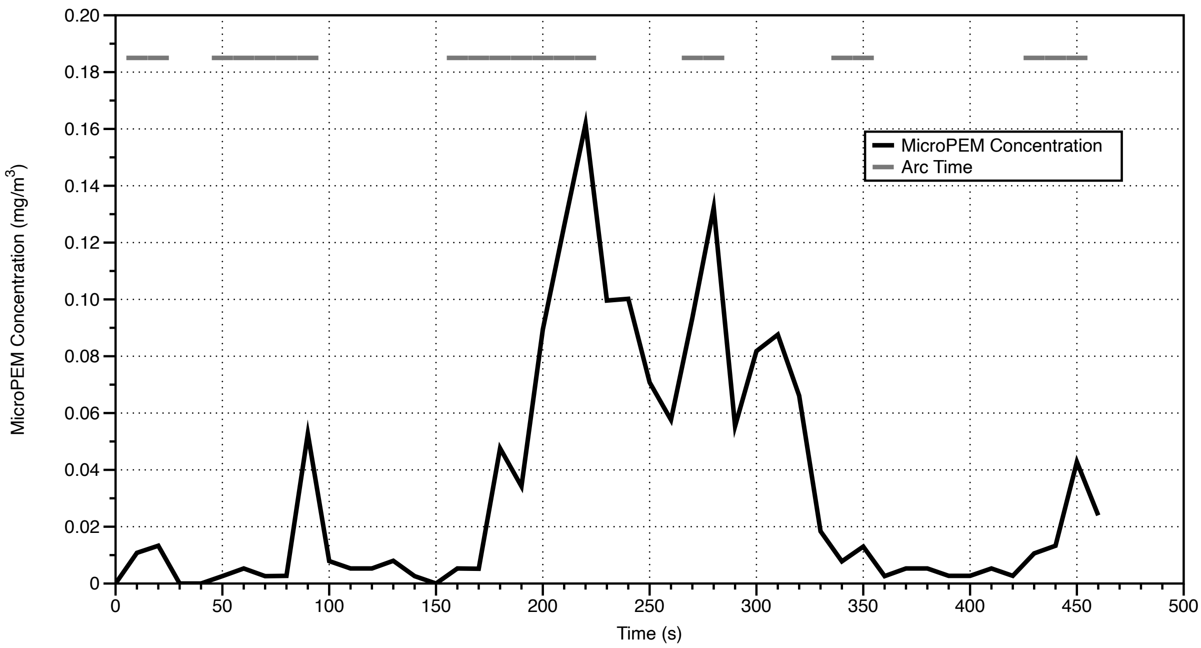

Fig. 3. The example (Sample ID 2) of the MicroPEM concentration and the arc welding period.

Air sampling results

Table 2 shows the results for total particulate (TP) gravimetric concentrations and average $PM_{2.5}$ concentrations during the sampling period from the MicroPEM. The FCAW process generated a higher concentration than SMAW and GTAW. In the subsequent analyses, we excluded data from Sample ID 1 because the personal concentration was an extreme outlier.

Table 2 The results of total particulate concentrations from the Swinnex samplers and average $PM_{2.5}$ concentrations from the MicroPEMs during the sampling period.

Sample ID	Process type	Sample time (min)	Arc time (min)	% Arc time	Concentrations (mg/m^3)			
					Swinnex sampler			MicroPEM
					Personal	NF	FF	
1	FCAW	21	11	52.4	75.0	5.2	1.8	5.25
2	FCAW	8	4	50.0	14.6	3.0	0.6	0.04
3	FCAW	19	7	36.8	13.5	4.6	1.5	2.43
4	SMAW	11	11	100.0	8.8	0.7	0.2	0.02
5	SMAW	21	19	90.5	5.5	0.5	0.2	0.01
6	SMAW	21	21	100.0	3.2	0.5	0.2	0.02
7	SMAW	12	10	83.3	7.1	0.7	0.2	0.02
8	GTAW	21	20	95.2	5.5	0.3	0.1	0.02
9	GTAW	19	9	47.4	5.0	1.7	0.5	0.01
10	GTAW	31	31	100.0	4.4	0.5	0.1	0.16
11	GTAW	41	39	95.1	4.0	0.3	0.1	0.03
12	GTAW	21	20	95.2	4.0	0.3	0.1	0.02
13	GTAW	31	31	100.0	3.9	0.3	0.1	0.02
14	GTAW	71	69	97.2	3.9	0.2	0.1	0.02
15	GTAW	41	38	92.7	2.8	0.3	0.1	0.05
16	GTAW	41	38	92.7	2.7	0.3	0.1	0.02

Sample ID	Process type	Sample time (min)	Arc time (min)	% Arc time	Concentrations (mg/m³)			
					Swinnex sampler			MicroPEM
					Personal	NF	FF	
17	GTAW	54	50	92.6	1.5	0.3	0.1	0.04

Sampling time was positively correlated with arc time (r^2 = 0.96) and made up about 90% of the sampling time on each occasion. Arc time was negatively correlated with measured personal exposure (r^2 = 0.45) but was less clearly associated with the NF and FF concentrations. There was a weak correlation between the personal gravimetric concentrations from Swinnex sampler and MicroPEM data (r^2 = 0.29), both of which were sampling inside the welders' visor, with the latter being around a factor of 20 lower. The relationship between Swinnex sampler and MicroPEM data is presented in Supplemental Fig. S1. In the calibration of weldART, the MicroPEM data were only used to identify the welding periods.

weldART model development and calibration

Sixteen sets of fume exposure measurements were used to calibrate the weldART model. Each dataset comprised of four concentrations: personal exposure level measured inside the welding visor, the weldART model estimates, along with the NF and FF concentration measurements. Fig. 4 shows the data from the final model estimates following adjustment of the compartment flowrates in relation to the measured data.

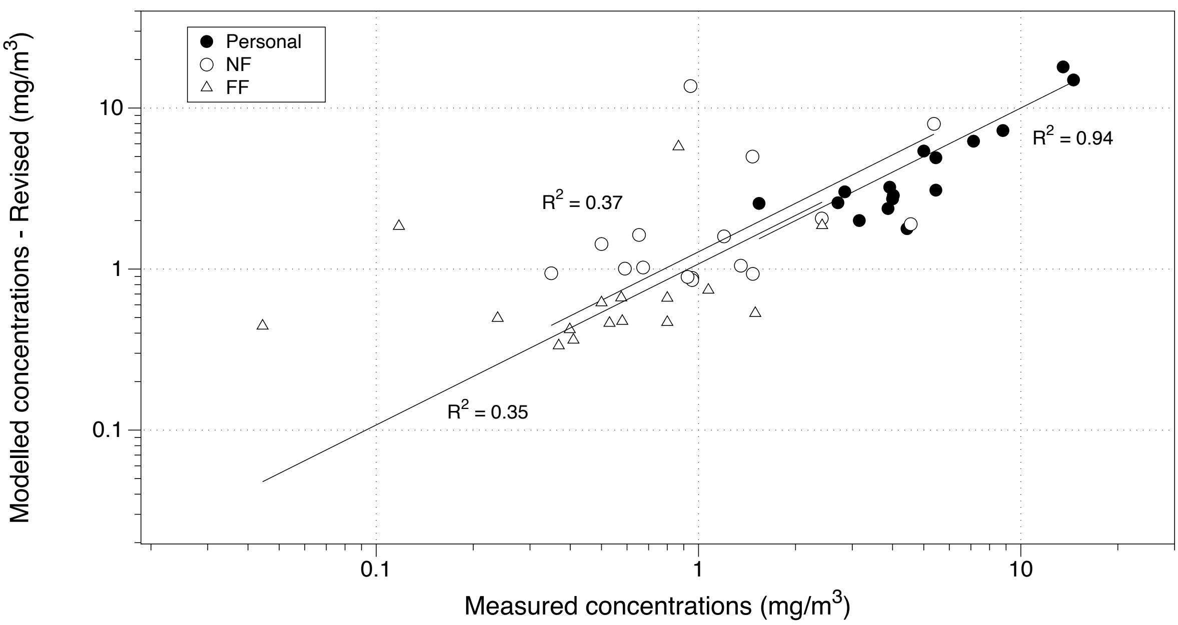

Fig. 4. Scatterplot with R-square between measured and weldART (4-compartment) model concentration.

The initial model comprised of three compartments, i.e. NF, FF, and WP, and the RM was included in the final model. In this model, the FF volume (V_{FF}) was set at 300 m³, and the V_{RM} was therefore 35,200 m³, are shown in Table 1.

The personal exposure estimates show a high correlation with the measured values (r^2 = 0.94), with the average estimated value 1.3 times the measurements. The NF and FF model estimates were low correlated with the corresponding compartment measurements (R^2 = 0.37 and 0.35, respectively), although on average they were close to the data (ratio of modelled to measured 0.9, and 1.0, respectively).

Bland-Altman plots of the data for each zone are shown in Supplementary Fig. S2-S4; the 95% limits of agreement are shown as two dotted lines in these plots. These results confirm there is a good agreement between the model and measured concentrations.

Discussion

We originally set out to produce a model structured in the same style as the ART tool, i.e. a multiplicative deterministic model with weighting factors (multipliers) related to specific model determinants. However, because welding comprises a narrowly defined set of similar processes, it was possible to develop a more elaborate multi-compartment mass balance model. Elsewhere we argue that this approach is not appropriate for the broad range of scenarios that the ART tool has to encompass because of lack of knowledge about emission strengths, compartment airflow rates and other factors (Cherrie et al., 2020), but it is more realistic in the restricted context of welding.

The MicroPEM monitors used in our field investigation were poorly correlated with and underestimated the gravimetric measurements. The cause of this underestimate might be because the MicroPEM measures $PM_{2.5}$, but welding fume has particle sizes ranging from a few nanometres to 20 µm and the Swinex samplers will collect larger particles than the MicroPEMs (Jenkins and Eagar, 2005; Yang et al., 2018). However, it is also possible that particles were lost in the sampling tube before the aerosol sensor because of the electrostatic deposition (Jankovic et al., 2010). Overall, it was judged that it was not possible to use these data in the calibration, other than to help identify welding periods.

The initial weldART model comprised three spatial compartments. However, it was found that the modelled concentrations in the FF were much higher than the measured values (mean ratio of model to measurements was 87.3; r^2 = 0.34), while the personal and NF concentrations were much closer to the measured data (exposure ratio 1.2; r^2 = 0.97, and NF 1.1; r^2 = 0.45). Adding a fourth compartment and adjusting the airflows allowed the model to better predict FF concentrations in the large space where the welding was carried out while maintaining a good prediction of personal exposure (ratio of the modelled exposure to the measured values was 1.3; r^2 = 0.94). The poorer correlation between modelled and measured concentrations in the NF and FF may partly be due to the low concentrations and the short sampling times resulting in poor sensitivity for the gravimetric samples.

WeldART provides estimates of total welding fume, although in some countries it is considered more appropriate to regulate exposure using the concentration of individual metal components in the fume. However, the International Agency for Research on Cancer (IARC) evaluation of the carcinogenicity of welding fume implies that it is the fume and not the toxic metal components that are important in determining cancer risk (Cherrie and Levy, 2019). Pesch et al. (2018) studied welding exposure in chromate production and found Spearman's correlation coefficients (r_S) indicated that the concentration of Cr (r_S = 0.33, 95% CI 0.25-0.42) and Cr(VI) (r_S = 0.38, 95% CI 0.29-0.46) were weakly correlated with the overall fume concentrations; Ni (r_S = 0.44, 95% CI 0.35-0.52) concentrations were moderately correlated with welding fume concentrations. While the weldART model could be adapted to use the percentage of individual metals in the fume to estimate the exposure level it would add to the overall uncertainty of the assessment and we do not recommend that this is an appropriate strategy to estimate the metal components in the fume.

In the situation where the weldART model was calibrated there were no local ventilation controls, but to be credible the model should allow exposure estimation in this situation. Local controls are included in the ART model as one of the MFs (from 0.5 for a canopy hood or moveable captor hood to 0.01 for ventilated enclosures like fume cabinets) (Fransman et al., 2013). While we do not have specific data for welding ventilation controls it is recommended that the MFs from ART would be appropriate for the weldART model.

To apply the weldART model to other welding scenarios it is necessary to have relevant fume emission rates and airflow data, which is not usually reported in exposure measurement studies. However, Boelter et al. (2009) reported a welding fume exposure assessment amongst welders who used SMAW on carbon steel pipes in a boiler room and breezeway. These authors estimated a fume emission rate (0.65 mg/s for boiler room and 0.67 mg/s for breezeway, which were about a third of the values used in the weldART) during the welding activities and applied these data to a two-zone mass-balance model. We compared our model with their measurements and model estimates, as shown in Table 3.

Table 3 The comparison of welding fume concentrations between the Boelter et al.' study and the weldART model in the boiler room and the breezeway

	Boiler Room		Breezeway	
	C_{exp}	FF	C_{exp}	FF
Boelter et al.'s measurement (mg/m^3)	4.73	1.37	2.89	0.57
Boelter et al.'s model (mg/m^3)	5.36	1.25	4.04	0.57
weldART model (mg/m^3)	5.68	1.38	8.32	2.02

The Boelter et al. (2009) model and the weldART showed the C_{exp} and the FF were much the same in the boiler room. However, both the weldART and Boelter et al. models had higher estimates of C_{exp} than the measurement data (although this was based on just two measurements). These differences may occur because of the nature of the airflow in a breezeway, which is a semi-outdoor space, giving rise to uncertainty about the airflow rate between model compartments.

The model also demonstrates the importance of knowing about the times when welding is taking place during sampling in interpreting the final result. For example, Fig. 5 reproduces the pattern of welding fume concentrations and exposure through work activity. Personal exposure is the average over the sampling period. It is the cumulative sum between WP and NF concentrations that they are multiplied by the time when welder's head is inside WP and NF.

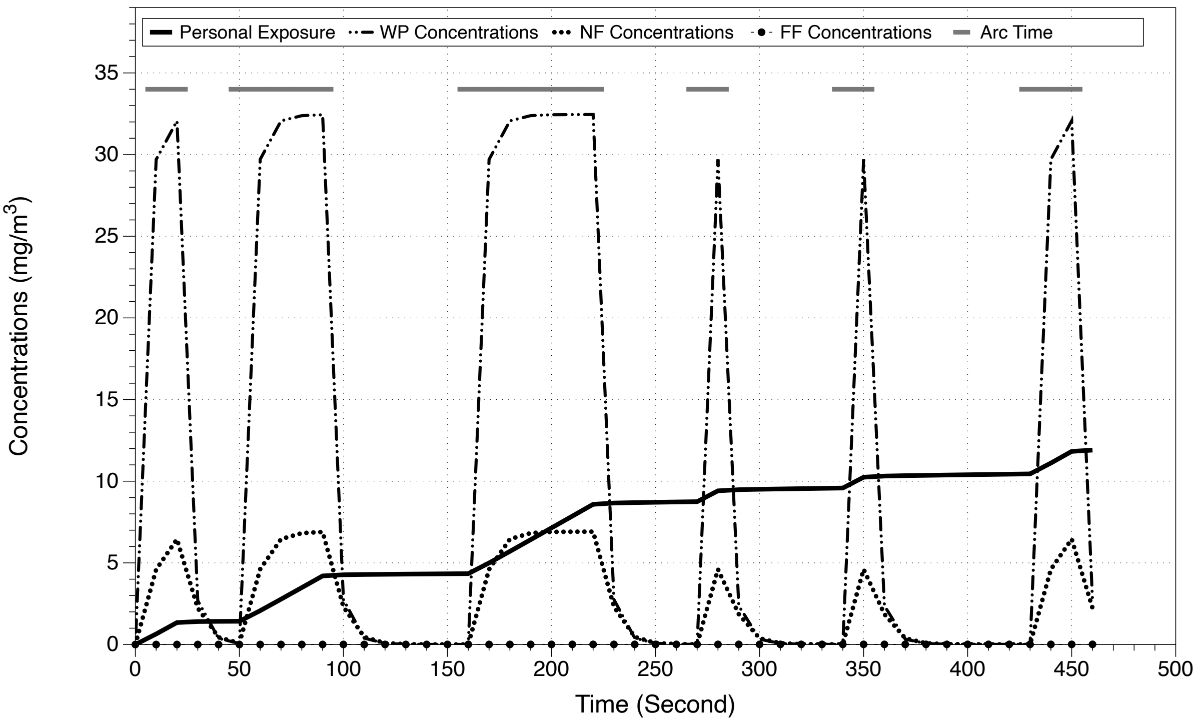

Fig. 5. The example (Sample ID 2) of the pattern of welding fume concentrations in the different compartments.

The average arc time in Fig. 5 was about 50% of the measurement time. Using the arc time to estimate the exposure data, i.e. assuming one continuous welding period instead of the actual welding times, the average personal exposure concentration in this example was 17.3 mg/m^3 rather than 11.9 mg/m^3. We suggest that it is important to realistically model the pattern of welding and not just assume a simple measure of arc time. In our dataset (Table 2) welding took place during most of the sampling time, which we consider atypical.

The time that the welders head is in the WP will also affect the exposure concentration. In this study almost all welders had their head in the welding plume through the welding. Training the welders to avoid the WP could reduce their exposure. For example, in the above example if the welder completely avoided the welding plume his exposure would have been estimated to be 3.0 mg/m^3, i.e. the concentration in the NF. If the welder had only had his head in the WP for half the time his exposure would have been 7.45 mg/m^3 (rather than 11.9 mg/m^3). It is clear that knowledge of the time the welder spends with their head in the welding plume is an important exposure determinant and something that should be recorded when exposure measurements are made.

The results of the model calibration show that weldART could have good potential to estimate the exposure of welders based on data on welding process (emission rate), welding parameters - which modify emission rate (e.g. current and voltage), arc time or more detailed data on times welding, time welder spends with head in plume, local ventilation, room size and ventilation rate, interzone flow rates. However, the model must be validated by comparing estimated exposure with a wider set of available measurement data from a wide range of other workplaces with differing welding conditions. As much of the currently available data lacks specific data on the weldART exposure determinants it will be necessary to adapt the model into a probabilistic form to take account of the uncertainty from the lack of knowledge of the circumstances where the measurements were obtained. WeldART is currently implement as a R script (RStudio Team, 2016), and can easily be adapted vary the input values for each parameter in a Monte Carlo simulation, e.g. to account for uncertainty in parameters such as the arc time or the intermittency of welding during the work shift.

In the future when occupational hygienists make exposure measurements from welding activities, they should collect all relevant exposure determinant information needed for weldART to better describe the circumstances of the measurements and make the data more useful for model development. A suitable welding data collection spreadsheet is available as an online supplement to this paper.

Conclusions

We developed and calibrated a model to estimate welding fume exposure. The results of the weldART model calibration demonstrate that a four-compartment mass-balance model can predict welding fume exposure. However, the next step is to extend the weldART model into a probabilistic form and undertake further validation testing using a wide variety of measurement datasets. This will ensure it is a reliable tool to predict welding fume exposure.

Conflicts of interest

The authors declare no conflict of interest.

Ethical approval

Ethical approval for this study was received from the Ethics Committee of the School of Engineering and Physical Sciences, Heriot-Watt University, Edinburgh, UK. The approval reference number is 19/EA/JC/2.

Informed consent

Informed consent was obtained from all study participants.

Author contributions

Aduldatch Sailabaht and John Cherrie conceived and designed the study and interpreted the results. All authors prepared and revised the manuscript. Aduldatch Sailabaht coordinated the fieldwork and analysed the data. All authors read and approved the final manuscript.

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References

Baldwin, P.E.J., Maynard, A.D., 1998. A Survey of Wind Speeds in Indoor Workplaces. Ann. Occup. Hyg. 42, 303–313. https://doi.org/10.1093/annhyg/42.5.303

Boelter, F.W., Simmons, C.E., Berman, L., Scheff, P., 2009. Two-zone model application to breathing zone and area welding fume concentration data. J. Occup. Environ. Hyg. 6, 289–297. https://doi.org/10.1080/15459620902809895

British Standards Institution (BSI), 2011. Health and safety in welding and allied processes -

Sampling of airborne particles and gases in the operator's breathing zone Part 1: Sampling of airborne particles (ISO 10882-1:2011).
Cherrie, J.W., Fransman, W., Heussen, G.A.H., Koppisch, D., Jensen, K.A., 2020. Exposure Models for REACH and Occupational Safety and Health Regulations. Int. J. Environ. Res. Public Health 17, 383. https://doi.org/10.3390/ijerph17020383
Cherrie, J.W., Levy, L., 2019. Managing Occupational Exposure to Welding Fume: New Evidence Suggests a More Precautionary Approach is Needed. Ann. Work Expo. Heal. 64, 1–4. https://doi.org/10.1093/annweh/wxz079
Fransman, W., Cherrie, J., Tongeren, M. van, Schneider, T., Tischer, M., Schinkel, J., Marquart, H., Warren, N., Spankie, S., Kromhout, H., Tielemans, E., 2013. Development of a mechanistic model for the Advanced REACH Tool (ART) Version 1.5.
Fransman, W., Tongeren, M. Van, Cherrie, J.W., Tischer, M., Schneider, T., Schinkel, J., Kromhout, H., Warren, N., Goede, H., Tielemans, E., 2011. Advanced Reach Tool (ART): development of the mechanistic model. Ann. Occup. Hyg. 55, 957–979. https://doi.org/10.1093/annhyg/mer083
Ganser, G.H., Hewett, P., 2017. Models for nearly every occasion: Part II - Two box models. J. Occup. Environ. Hyg. 14, 58–71. https://doi.org/10.1080/15459624.2016.1213393
Jankovic, J.T., Hall, M.A., Zontek, T.L., Hollenbeck, S.M., Ogle, B.R., 2010. Particle Loss in a Scanning Mobility Particle Analyzer Sampling Extension Tube. Int. J. Occup. Environ. Health 16, 429–433. https://doi.org/10.1179/107735210799160002
Jenkins, N.T., Eagar, T.W., 2005. Chemical analysis of welding fume particles. Weld. Journal-New York 84, 87s-93s.
Jilla, A., 2019. Evaluation of Total Fume and Heavy Metal Emission Factors Applicable to Gas Metal Arc Welding. Univ. New Orleans Theses Diss. University of New Orleans.
LeBlanc, M., Allen, J.G., Herrick, R.F., Stewart, J.H., 2018. Comparison of the near field/far field model and the advanced reach tool (ART) model V1. 5: exposure estimates to benzene during parts washing with mineral spirits. Int. J. Hyg. Environ. Health 221, 231–238. https://doi.org/10.1016/j.ijheh.2017.10.016
Mahyuddin, N., Awbi, H.B., Essah, E.A., 2015. Computational fluid dynamics modelling of the air movement in an environmental test chamber with a respiring manikin. J. Build. Perform. Simul. 8, 359–374. https://doi.org/10.1080/19401493.2014.956672
Nicas, M., 1996. Estimating exposure intensity in an imperfectly mixed room. Am. Ind. Hyg. Assoc. J. 57, 542–550. https://doi.org/10.1080/15428119691014756
Nicas, M., Boelter, F.W., Simmons, C.E., Scheff, P., Berman, L., 2009. A three-zone model for welding fume concentrations. J. Occup. Environ. Hyg. 6, D69-71; author reply D71. https://doi.org/10.1080/15459620903139235
Olander, L., 1985. Welding fume buoyant plume. Aerosol Sci. Technol. 4, 351–358. https://doi.org/10.1080/02786828508959061
Pesch, B., Lehnert, M., Weiss, T., Kendzia, B., Menne, E., Lotz, A., Heinze, E., Behrens, T., Gabriel, S., Schneider, W., Brüning, T., 2018. Exposure to hexavalent chromium in welders: Results of the WELDOX II field study. Ann. Work Expo. Heal. 62, 351–361. https://doi.org/10.1093/annweh/wxy004
Pires, I., Quintino, L., Miranda, R.M., Gomes, J.F.P., 2006. Fume emissions during gas metal arc welding. Toxicol. Environ. Chem. 88, 385–394. https://doi.org/10.1080/02772240600720472
Popović, O., Prokić-Cvetković, R., Burzić, M., Lukić, U., Beljić, B., 2014. Fume and gas emission during arc welding: Hazards and recommendation. Renew. Sustain. Energy

Rev. 37, 509–516. https://doi.org/10.1016/j.rser.2014.05.076
Riedmann, R.A., Gasic, B., Vernez, D., 2015. Sensitivity analysis, dominant factors, and robustness of the ECETOC TRA v3, Stoffenmanager 4.5, and ART 1.5 occupational exposure models. Risk Anal. 35, 211–225. https://doi.org/10.1111/risa.12286
RStudio Team, 2016. RStudio: Integrated Development Environment for R.
Sailabaht, A., Wang, F., Cherrie, J., 2018. Extension of the advanced REACH tool (ART) to include welding fume exposure. Int. J. Environ. Res. Public Health 15. https://doi.org/10.3390/ijerph15102199
Serageldin, M., Reeves, D.W., 2009. Development of welding emission factors for Cr and Cr(VI) with a confidence level. J. Air Waste Manag. Assoc. 59, 619–626. https://doi.org/10.3155/1047-3289.59.5.619
Slater, G.R., 2004. Welding fume plume dispersion. University of Wollongong.
Tielemans, E., Warren, N., Fransman, W., Tongeren, M. Van, Mcnally, K., Tischer, M., Ritchie, P., Kromhout, H., Schinkel, J., Schneider, T., Cherrie, J.W., 2011. Advanced REACH Tool (ART): overview of version 1.0 and research needs. Ann. Occup. Hyg. 55, 949–956. https://doi.org/10.1093/annhyg/mer094
U.S. Environmental Protection Agency (EPA), 1994. Development of Particulate and Hazardous Emission Factors for Electric Arc Welding (AP-42, Section 12.19).
Williams, R., Kaufman, A., Hanley, T., Rice, J., Garvey, S., 2014. Evaluation of Field-deployed Low Cost PM Sensors. U.S. Environmental Protection Agency EPA/600/R-14/464 (NTIS PB 2015-102104), Washington, DC.
Yang, S.Y., Lin, J.M., Young, L.H., Chang, C.W., 2018. Mass-size distribution and concentration of metals from personal exposure to arc welding fume in pipeline construction: A case report. Ind. Health 56, 356–363. https://doi.org/10.2486/indhealth.2017-0197