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WELDING PLUME RISE IN A LARGE BUILDING WITH TEMPERATURE GRADIENT

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SUMMARY

Measurements were done for the plume rise from gas metal arc welding (GMAW) processes in a large laboratory chamber with positive temperature gradient.

Initial heat fluxes of welding plumes were calculated from the measured maximum heights of the welding plumes and the ambient temperature gradients. The upper and lower deflection heights were also measured and compared with experimental results from others. The ratio of the initial heat flux to the total power input was found to vary between 7 and 20% at a welding time of 2 minutes, increasing with higher melting rate of the electrode wire.

The formation and development of the welding plume were also studied by using a video camera. It was found that the maximum plume height and the stratified layer rose gradually due to the increasing heat input to the welding plume with welding time.

The study gives a better understanding of the welding plume characteristics. The measured welding plume heights and the calculated convective heat fluxes of the welding plumes may be used for designing more efficient ventilation systems in industrial workplaces.

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INTRODUCTION

Welding plumes are one of the most common contamination sources in industrial workplaces. During a welding process, gaseous and particulate contaminants are generated. These contaminants are brought into the workplace air by the plume generated from the welding process. The mechanism of the spread of contaminants depends on the characteristics of the welding plume. The characteristics of the plumes are thus important for designing efficient ventilation systems for industrial workplaces.

So far there is little literature available concerning the spread of turbulent welding plume. There are also few data on initial heat fluxes of the welding plumes. Measurements of welding plume rise from shielded metal arc welding (SMAW) processes have been reported in reference [1]. Gas metal arc welding (GMAW) is one of the most common welding processes in industries and has the greatest potential for growth in the near future, see reference [2]. The plume rise from a GMAW process was thus chosen for the study. The aim of this study was also to investigate the transient characteristics of the welding plume due to the increasing heat input to the welding plume with time.

PLUME RISE IN A STABLY STRATIFIED SURROUNDING

Positive air temperature gradients often exist in industrial workplaces. A plume rising in a stably stratified surrounding is shown in figure 1. The plume rises from the heat source due to the positive buoyancy force. Because of the positive vertical temperature gradient, the buoyancy force decreases with elevation. At the height of neutral buoyancy, the buoyancy force becomes zero and above this height the buoyancy force turns negative. The plume reaches a terminal height when the plume momentum is reduced to zero. The plume will then descend from the maximum height due to the negative buoyancy force and spread sideways around the neutral buoyancy height. This spread of the plume sideways will gradually form a layer. The heights of the upper and lower side of the layer are called respectively the upper deflection height, z_{ud}, and lower deflection height, z_{ld}. These two heights are proportional to the maximum plume height, z_m, according to experimental work, see references [1], [3] and [4].

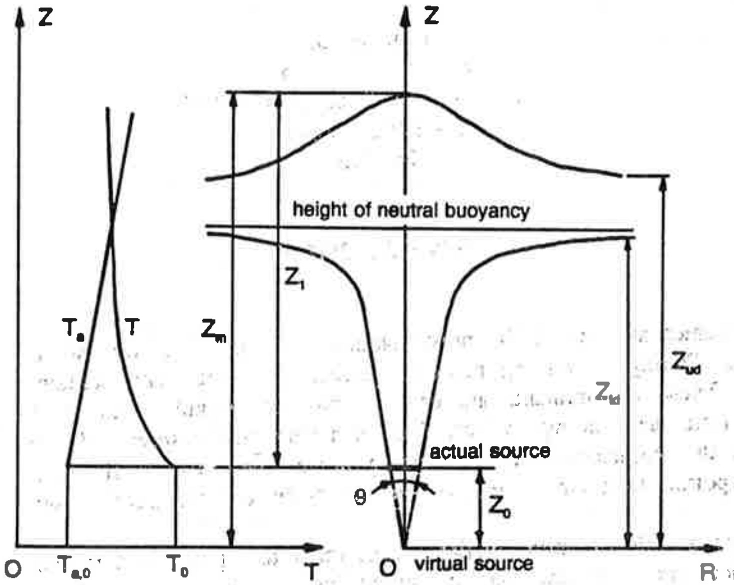

Fig. 1. Plume rise in a stably stratified surrounding.

The turbulent plume rise from a point heat source in a stably linear stratified surrounding is governed by two parameters, the initial specific buoyancy flux, F_0, and the stratification parameter, S, see references [5] and [6]. The initial specific buoyancy flux, F_0, represents the initial energy in the plume

$$F_0 = \frac{Q_0 g}{\pi c_p \rho T_0} \tag{1}$$

where Q_0 is the initial heat flux of the plume, ρ is the plume density at the source and T_0 the plume temperature at the source.

The stratification parameter, S, is usually employed to represent the air temperature gradient in the ambient, which is:

$$S = \frac{g}{T_{a,0}} \frac{dT_a}{dz} \tag{2}$$

where $T_{a,0}$ is the ambient air temperature at the source level and dT_a/dz the ambient air temperature gradient.

Once these two parameters are determined, a semi-empirical formula can be used to calculate the maximum plume height, z_m,

$$z_m = 5.5F_0^{1/4}S^{-3/8} \qquad (3)$$

At room temperature and 1 atm (where $T_{a,0} = 293$ K and ρT_0 is approximately 353 for an ideal gas), equation (3) can be simplified to

$$z_m = 1.07Q_0^{1/4}(\frac{dT_a}{dz})^{-3/8} \qquad (4)$$

Equations (3) and (4) apply only for a turbulent plume from a point heat source where the buoyancy force is the dominant one in the plume rising, i.e. the initial momentum of the plume is negligible compared with the buoyancy in the plume rising.

HEAT TRANSFER DURING GMAW WELDING PROCESS

Figure 2 shows schematically a GMAW process. During the welding, a solid wire of filler material is fed continuously to the welding gun. An arc is generated between the wire tip and the workpiece (base metal) and the wire is molten by the heat generated from the arc. The arc is shielded from the air by the shielding gas .

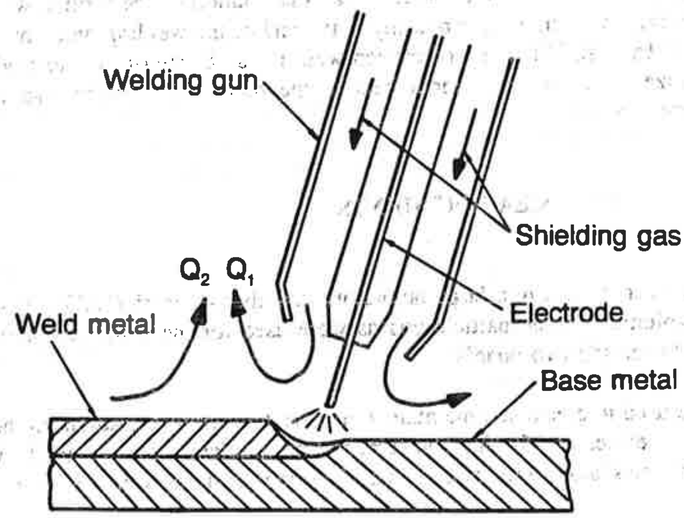

Fig. 2. Gas metal arc welding (GMAW) process.

The total power input by the arc is E, which depends on the welding current, I, and arc voltage, V,

$$E = I \times V \qquad (5)$$

The heat input is dissipated in three ways, by conduction, convection and radiation either to the workpiece and to the ambient. The actual mechanism how the heat is dissipated to the ambient and workpiece in not fully understood. Experimental work has been done to determine the ratio of the heat transferred to the workpiece and the total power input (defined as the arc efficiency) for different welding processes, see reference [2]. For GMAW process, the arc efficiency varies between 0.66 and 0.85, depending on the total power input. These data may hardly be used to determine e.g. the convective or radiant heat losses from the welding process.

The GMAW welding plume is generated by two mechanisms, one is the direct heating of the shielding gas by the arc and the other is the convective flow caused by the high temperature weld metal as shown in figure 2. Thus the initial heat flux of the welding plume, Q_0, is

$$Q_0 = Q_1 + Q_2 \qquad (6)$$

where Q_1 is the heat directly transferred to the welding plume by the arc and Q_2 is the heat transferred to the welding plume from the molten weld metal.

The heat obtained directly from the arc, Q_1, depends mainly on the arc temperature, and the volume flow rate of the shielding gas. The secondary heat transfer, Q_2, depends on the volume and temperature of the molten weld metal, distribution of the molten weld metal etc. Q_2 is often the dominant one, especially at the end of the welding when most of the heat is released from solidification of molten weld metal. Some of the electrode is evaporate or oxidized and they also input heat to the plume. This effect can be neglected as the amount is small.

MEASUREMENTS

The experiments were carried out in a large laboratory chamber - 8×6×5 (L×W×H) in size and 240 m^3 in volume. Double particle boards were used for the walls and there was a 8 cm space between the two boards.

Four convectors were used to create and maintain a positive temperature gradient in the chamber, each with an effect of 750 W. The temperature gradient was measured by placing 11 thermal couples along the room height. The temperatures were measured twice a minute.

As the smoke generated from the welding was too weak to be seen, an extra smoke source was used for visualization of the shape of the rising plume. The smoke was released just above the welding gun. Two lamps were placed at opposite corners of the chamber to illuminate the plume. The light was passed through a shield to illuminate just one vertical plane through the center of the welding plume. The chamber had a plexiglas window. A video camera was placed outside the chamber to record the shape of the rising plume during the welding.

The welding machine used was a semi-automatic GMAW welding machine of type Power Compact 200 from ESAB, Sweden. The steel electrode wires used were ESAB OK 12:51. Three sizes of electrode wires were available for the welding machine and the diameters were 0.6 mm, 0.8 mm and 1.0 mm.

The shielding gas is a mixture of argon (80%) and carbon dioxide (20%) and the flow rate was set to 14 l/min.

Steel plates were used as base metals for the welding. The plate had an area of 5×15 cm^2 and a thickness of 5 mm. The steel plate was placed 5 cm above the floor. The plate was weighed before and after the welding to get the weight of the molten electrode wire deposited on workpiece. Some of the electrode wire was spattered to the ambient or evaporated. As the spattered electrode wire contributes little to the plume generation and the amount of evaporated metal is little, the amount of molten electrode wire was used for correlating the data of heat input to the welding plume. The welding path was not a straight line but in zigzag to allow longer welding time. The welding time varied from 2 to 4 minutes during the measurements.

The arc voltage and welding current data were sampled continuously by a computer. As the welding current was oscillating at a very high frequency, an interface with an integrating A/D converter was used to ensure a stable value.

RESULTS AND ANALYSIS

A typical measured vertical temperature profile in the ambient before and after the welding is shown as an example in figure 3. The linear temperature gradient was calculated from the mean values under the maximum plume height.

The whole welding process was video filmed for later studying the formation and development of the welding plume. As the welding starts, the initial plume is usually so weak that it was heavily disturbed by the spread of shielding gas flow in horizontal direction. The initial plume has a relatively large initial radius. As more electrode wire is molten, the convection becomes more intense and a buoyant flow forms and rises. The buoyant flow continues to rise to a terminal height and then starts spreading sideways. A mushroom shape is then formed and the flow keeps spreading horizontally as a stratified layer. Figure 4 shows the formation of a welding plume during the first 60 seconds of the welding.

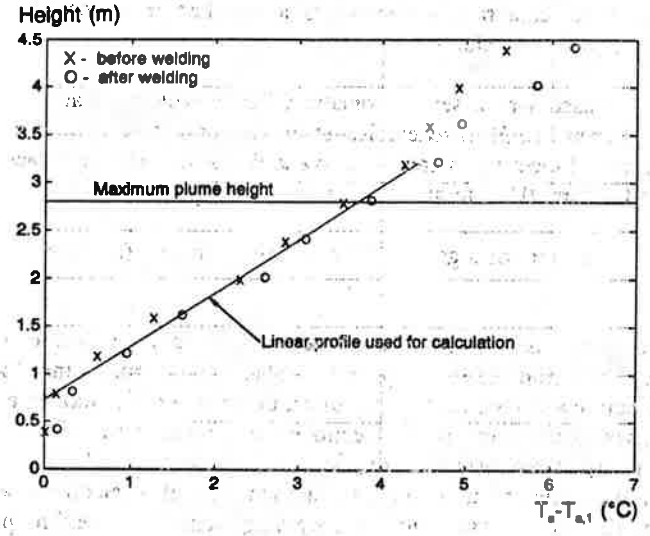

Fig. 3. Measured vertical temperature gradient. $T_{a,1}$ is the temperature at z = 0.4 m before the welding.

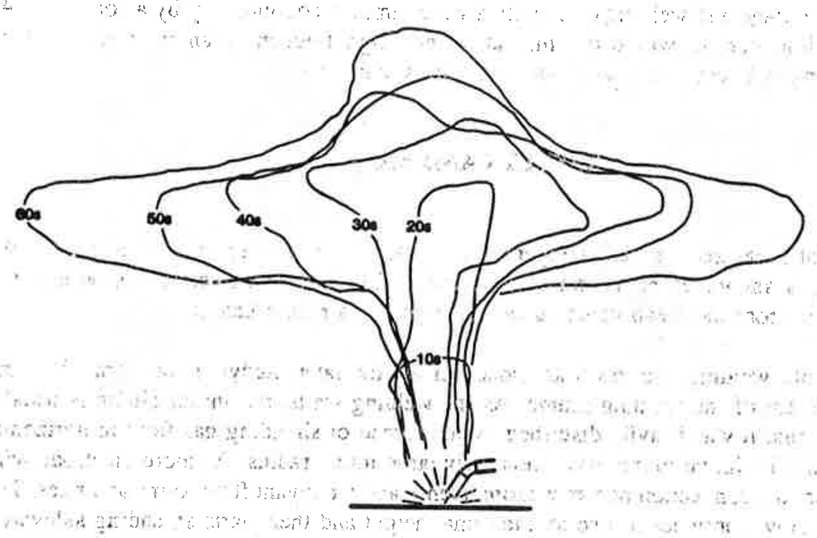

Fig. 4. Formation and development of a welding plume.

As the welding continues and the buoyant flow becomes even stronger, the whole stratified layer rises gradually. The rising of the stratified layer continues until the end of the welding. Figures 5(a), 5(b) and 5(c) show the shapes of a welding plume 40, 80 and 120 seconds after the welding start.

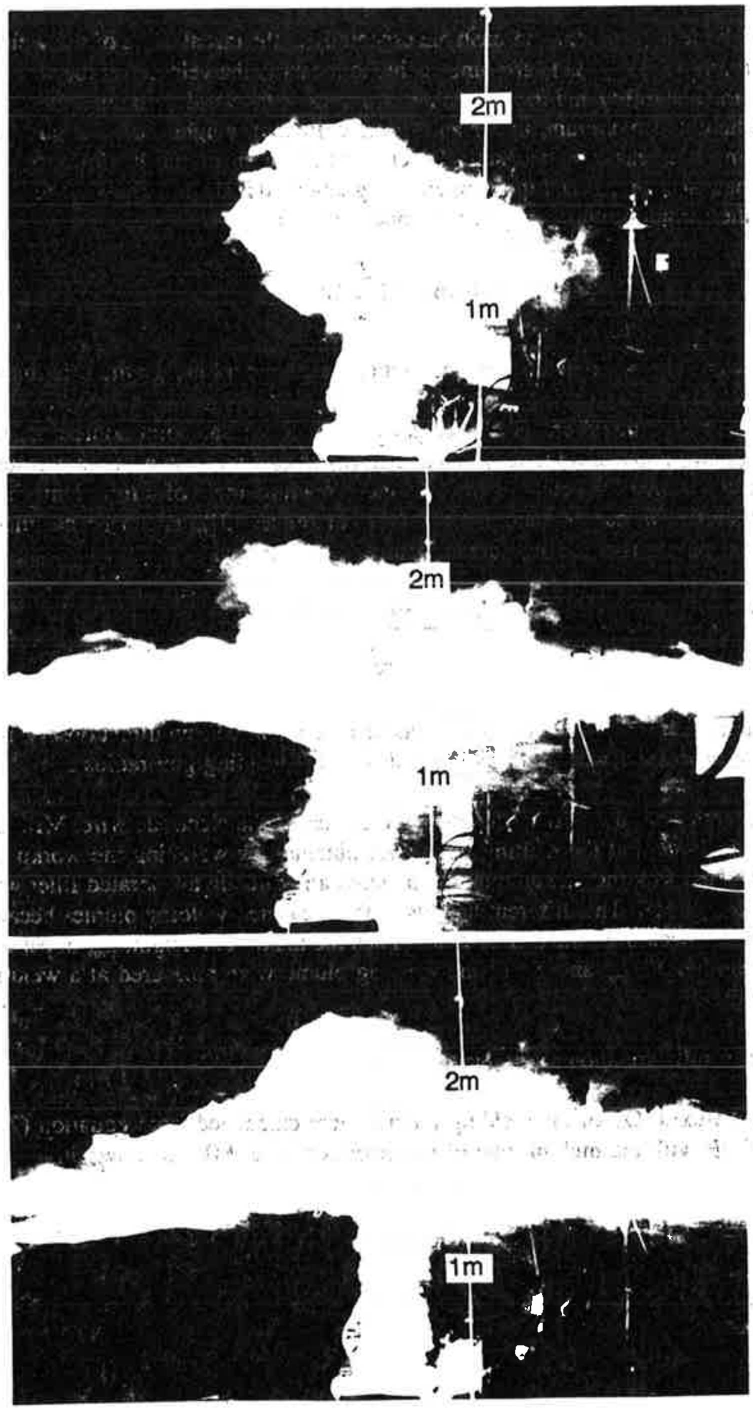

Fig. 5. Welding plume 40, 80 and 120 seconds after the welding start.

The welding plume is turbulent and unstable especially at the initial stage of the welding process, see reference [1]. It is nearly impossible to measure the velocity in the welding plume due to the instability and transient characteristics of the welding plume. However, the different heights (maximum, upper and lower deflection heights) of the plume are more stable and thus easier to measure. When the maximum plume height above the virtual point heat source, z_m, and the temperature gradient, dT_a/dz, are known, the initial heat flux of the turbulent plume, Q_0, can be obtained from

$$Q_0 = 0.762\ z_m^4 (\frac{dT_a}{dz})^{3/2} \tag{7}$$

Equation (7) can only be applied when the ambient air temperature gradient is linear.

In order to know the maximum plume height above the virtual point source, z_m, the actual source height above the virtual point source, z_0, should be known as the measured plume height was above the actual source. As the spreading angle of a turbulent plume from a point source, θ, can be taken as 18° (see references [3]), z_0 can be calculated when the initial plume radius at the actual source, R_0, is known

$$z_0 = \frac{R_0}{\tan(\frac{\theta}{2})} \tag{8}$$

The initial plume radius, R_0, is difficult to measure or calculate. From direct observation of the welding process, it was taken as twice that of the welding gun radius .

The measurements were done for different melting rates of the electrode wire, MR, and power inputs, E. Note that the melting rates were obtained by weighing the workpiece before and after the welding, the amount of spattered and directly evaporated filler wire was not included in MR. The different heights of the measured welding plumes became quite stable after a welding time of 2 minutes. Thus the maximum height, z_m, upper and lower deflection height, z_{ud} and z_{ld}, of the welding plume were measured at a welding time of 2 minutes.

The measured results are shown in table 1.

The initial heat fluxes, Q_0, of the welding plumes were calculated from equation (7). Variation of Q_0/E with the melting rate of the electrode wire, MR, is shown in figure 6.

MR (mm³/s)	Z_m (m)	dT_a/dz (°C/m)	Q_0 (W)	E (W)	Q_0/E
23.9	2.55	1.80	77	1057	0.073
23.9	2.85	1.74	115	950	0.121
27.4	2.70	1.82	99	1113	0.089
23.2	2.50	1.79	71	780	0.091
23.1	2.70	1.67	87	989	0.088
40.9	2.75	1.91	115	1286	0.089
40.9	3.40	1.72	229	1307	0.175
37.3	3.55	1.57	238	1477	0.161
35.4	3.15	1.95	204	1315	0.155
35.4	2.75	1.88	112	1160	0.097
53.6	3.65	1.66	289	1575	0.183
53.6	3.65	1.69	297	1595	0.186
42.8	2.95	1.80	139	1368	0.101
42.8	3.40	1.60	206	1324	0.156
65.8	3.80	1.84	396	1981	0.200
65.8	3.50	1.90	299	1954	0.153
78.1	3.85	1.95	456	2495	0.183

Table 1. Measured results of the plumes from GMAW process.

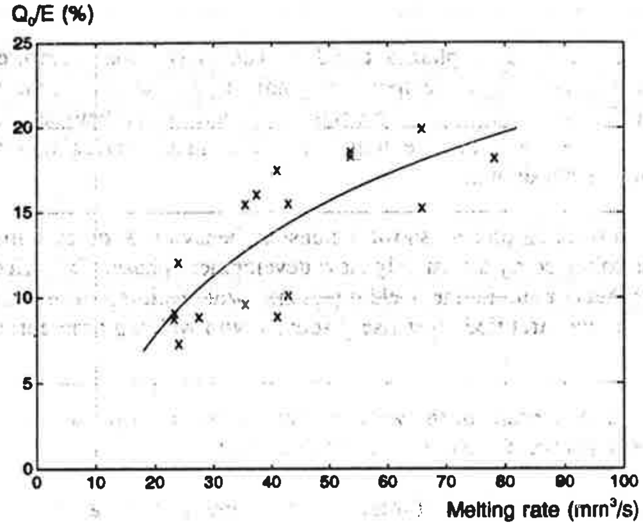

Fig. 6. Variation of the ratio of initial heat flux to the total power input, Q_0/E, with the melting rate, MR.

Figure 6 shows that ratio of the initial heat flux of the welding plume to the total power input, Q_0/E, increases with increasing melting rates of the electrode wire. The curve in the figure which fits best the data points can be expressed as

$$\frac{Q_0}{E} = -0.1787 + 0.0857 \ln(MR) \qquad (9)$$

For SMAW process, Q_0/E was found to vary between 0.05 to 0.07 at a welding time of 1 minute [1].

The upper and lower deflection heights, z_{ud} and z_{ld} were also measured. Comparisons of measured upper and lower deflection heights of the welding plume are listed in table 2.

Author	z_{ud}/z_m	z_{ld}/z_m
Reference [1]	0.79 ± 0.05	0.54 ± 0.06
Present study	0.74 ± 0.05	0.52 ± 0.08

Table 2. Measured upper and lower deflection heights of the welding plume

Good agreements were found with the previous study for both z_{ud}/z_m and z_{ld}/z_m.

CONCLUSIONS

The initial heat fluxes of the welding plumes could be calculated from measured maximum plume heights and ambient air temperature gradients in a large laboratory chamber. The initial heat fluxes of the welding plumes were found to be between 7.3 and 20 percent of the total power input at a welding time of 2 minutes, increasing with higher melting rates of the electrode wire.

The buoyant plume from a welding process shows a transient behavior. A quick initial plume formation phase is followed by a relatively slow development phase. This effect is due to the increasing heat input to the welding plume with welding time. The maximum plume height and the stratified layer rise gradually with welding time during the development phase.

The upper and lower deflection heights of the welding plume stratified layer were also measured and good agreements were found with a previous study.

The obtained initial heat flux as a function of total heat input and melting rate may be used to estimate the volume flow rate of the welding plume, which is of vital importance for designing efficient ventilation systems for industrial workplaces.

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