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Factors Affecting the Capture Efficiency of a Fume Extraction Torch for Gas Metal Arc Welding

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ABSTRACT

Welding fumes are classified as Group 2B ‘possibly carcinogenic’ and this prompts to the implementation of local exhaust ventilation (LEV). The fume extraction torch with LEV integrated into the tool is the most attractive solution but its capture efficiency is often disappointing in practice. This study assesses the main parameters affecting fume capture efficiency namely the extraction flow rate, the positioning of the suction openings on the torch, the angle of inclination of the torch to the workpiece during welding, the metal transfer modes, and the welding deposition rate. The theoretical velocity induced by suction, estimated from the extraction flow rate and the position of the suction openings, is the main parameter affecting effectiveness of the device. This is the design parameter and its value should never be $<0.25\ \mathrm{m\ s^{-1}}$. The angle of the torch relative to the workpiece also has a great deal of influence. To improve efficiency, work station layouts need to favour positions where the torch is held with angles closer to perpendicular (<15°). Welding with high deposition rates ($>1.1\ \mathrm{g\ s^{-1}}$) and spray transfer leads to low capture efficiency if induced velocities are $<0.5\ \mathrm{m\ s^{-1}}$. The results of the study can be used in the design of integrated on-torch extraction systems and provide information for fixing system objectives.

KEYWORDS: capture efficiency; emission rate; fume extraction torch; GMAW; induced velocity; LEV; transfer modes; welding fume

INTRODUCTION

Semi-automatic welding is among the most commonly used welding methods. The high deposition rates and temperatures implemented render this technique particularly emissive. The welding fumes emitted have been classified Group 2B, ‘possibly carcinogenic,’ by the International Agency for Research on Cancer (IARC). They contain both particles and gases (CO, CO_2, O_3, NOx, phosgene, etc.), which may result from the decomposition of air, surface deposits, or even from the break-down of metal coatings (Lehnert *et al.*, 2012). The particle phase is of greatest concern as it contains an inhalable fraction that is mainly composed of metals (cadmium, beryllium, etc.), metal oxides (Chrome VI oxide, nickel oxides, diarsenic trioxide, etc.), and polycyclic aromatic hydrocarbons from greases, paints, and solvents that may be present on the surface (Jenkins and Eagar, 2005). Independently of the specific effects of such chemical agents, exposure to welding fumes may exceed the occupational limit value defined in most European countries (5 mg m^{-3}), even when a capture-type collective prevention system is in operation. Although co-exposures associated with welding (asbestos in particular) make epidemiological studies difficult, a figure of 30–50% more cases of bronchopulmonary cancer in welders than in the control population has been established (Ambroise *et al.*, 2006; Siew *et al.*, 2008). Occupational asthmas are caused by metal oxides, in particular.

The exposure levels can be curbed by reducing emissions and curtailing the hazardous nature of filler metal-related fumes. Filler metal classification in Standard EN ISO 15011-4 (British Standards Institution, 2006) allows substitution by products that are generally less emissive or hazardous to be envisaged. Changing the shielding gas is another option for reducing such emissions (Carpenter *et al.*, 2009; Costa, 2014). Moreover, the gradual integration of electronic components into welding power sources (pulsed, surface tension transfer, cold metal transfer, etc.) has enabled metals to fuse, while limiting supplied energies; this contributes to a decrease in emissions (Faes *et al.*, 2006; Rouly *et al.*, 2014). Nevertheless, the problems inherent in changing input materials or the process should not be minimized, since they require validation of the weld mechanical characteristics.

Welders are often equipped with personal respirators (powered and supplied air). While such systems greatly limit exposure, they do not prevent workshop pollution, exposing other employees or even welders themselves during multiple phases, in which they perform other tasks without masks (adjustment, tack welding, handling, etc.).

In this context, solutions based on fume capture at source remain essential for reducing exposure as long as these are efficient and suitable. The bibliographical review conducted by Flynn and Susi (2012) focuses on the performance of different solutions in various industrial sectors (mechanical engineering, shipbuilding, etc.). Three families of solutions are commonly used in the welding field—flexible arms, suction tables, or back boards and integrated suction torches.

Fume extraction torch

The ‘integrated suction tool’ is undoubtedly advantageous for use in the field of welding, particularly gas metal arc welding. This type of device is marketed under the name ‘fume extraction torch’ or ‘fume extraction gun’ (Fig. 1). This solution has a bad reputation, which currently curtails its wider use. Interviews carried out in French boiler-making and metal construction companies about the reasons behind the refusal to use fume extraction torches, or such torches being rejected after a few months of usage, highlight: the rigidity of the hose bundle; the size of the nozzle; the excessive weight of the torch that causes musculoskeletal disorders and loss of productivity; the suction of the shielding gas by the capture device causing weld porosities and insufficient capture efficiency.

Fume extraction torch development began in the 1970s. Research undertaken from 1985 to 1990 using a tracer gas concluded that a flow rate of the order of 100 $m^3 h^{-1}$ would efficiently capture fumes (Cornu *et al.*, 1991). Torch inclination was found to have a strong influence on capture performance during these studies. Experiments conducted by Yapp *et al.* (2001) represented the first overall approaches (ergonomics and capture efficiency) to address this problem. The Econweld project (Marconi and Bravaccini, 2010), which was co-financed by the European Union, included a facet with similar aims to those of Yapp, i.e. to design a lightweight, efficient, ergonomic torch, which would curtail exposure to welding fumes.

Field observations are currently being carried out in France on the use of fume extraction torches and their capture performance characteristics but these remain unsatisfactory. Apart from the ‘ergonomic’ and ‘weld quality’ aspects, knowledge of the parameters affecting capture efficiency remains limited. The wide variety of torch models on the market, their

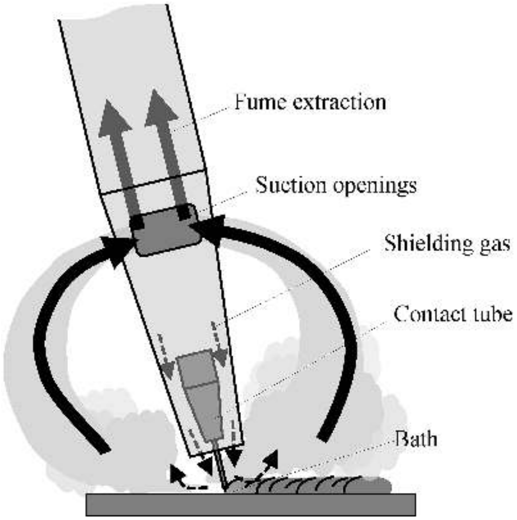


Figure 1 Outline diagram of fume extraction torch.

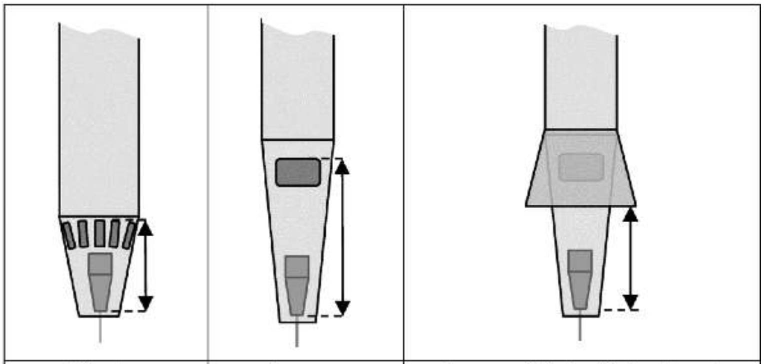
related capture flow rates, and, above all, the welding configurations (part geometry, transfer mode, wire distance, shielding gas flow rate and type, etc.) dictate a multifactor approach and lead to complex findings which are not necessarily easy to understand. Moreover, observing welders' gestures reveals that they rarely work with the torch in a position that is perpendicular to the welding surface (90° for flat welds, 45° for angle welds) as is used in most experimental studies. Torch inclination favours bath viewing by removing the torch tip; the inclination angles are then often >20° with respect to the perpendicular to the surface. In the case of angle welding, the use of large torch inclinations by some welders has been noted. They place their torch-holding hand on the horizontal metal sheet to relieve the efforts exerted on the wrist. The very fact of placing their hands on the sheet actually causes the large inclinations.

These observations, combined with the fact that a fume extraction torch is frequently the only solution when the part dimensions exceed 1 m, prompted the INRS to undertake research with a view to providing data that will ensure the long-term improvement of this capture system.

EQUIPMENT AND METHODS

A laboratory test bench was set up to measure the main parameters affecting capture efficiency (Table 1). A preliminary study was conducted on other parameters, such as shielding gas flow rate, but their limited influence meant they were not considered a priority. The tests were limited to the most commonly encountered welding

Table 1. Parameters tested

Parameter	Conditions
Torch models	Four models were retained. The main selection criterion was to cover the distances separating the suction openings from the contact tube. The capture opening upper limit was taken as reference for calculating the distance. Two of the models were fitted with a removable capture shroud and six geometries were therefore finally tested. The *opening – contact tube* distances were 35, 45, 53, 67, 68, and 77 mm. The three examples below show that the models chosen offer variety in the shape of air intake.  Shorter (35 mm) Longer (77 mm) Longer fitted with its shroud (53 mm)
Transfer modes	Voltage current settings were selected to cover 'short circuit (SC)', 'globular (G)', and 'spray (S)' transfer modes (Kou, 2002).
Wire diameters	Three solid wire diameters (0.8, 1.0, and 1.2 mm) were tested.
Position	Welding on horizontal surfaces only (position PA: Standard ISO 6947).
Torch inclination angle	Angles of 0°, 15°, 30°, and 45° were tested. The torch inclination was varied while the *stick-out* was kept constant.

configuration, namely solid wire G3Si1 on unalloyed steel with M21 shielding gas (82% argon – 18% CO_2).

Measuring capture efficiency

Capture efficiency is the ratio of captured pollutant flow (q_p) to emitted pollutant flow (Q_p). The method involves performing two identical welding operations in succession, one with the extraction system in operation and the other with it switched off. All fumes that were not captured were drawn into an extraction hood under air flow Q_a. Particle concentrations C_{ref} and C were measured in the extraction hood outlet duct for the above two configurations:

1. C_{ref} without extraction: the pollutant rate $Q_p = Q_a{\cdot}C_{\text{ref}}$ since 100% of the emitted flow enters the hood.
2. C with extraction: the captured pollutant rate $q_p = Q_a{\cdot}C_{\text{ref}} - Q_a{\cdot}C$ since $Q_a{\cdot}C$ is the fraction not drawn into the torch device.

The capture efficiency can be re-expressed as $\eta = \dfrac{Q_a.C_{\text{ref}} - Q_a.C}{Q_a.C_{\text{ref}}} = 1 - \dfrac{C}{C_{\text{ref}}}$.

In its final formulation, the method is similar to that used to evaluate the decontamination index described in StandardEN 1093-11 (British Standards Institution, 2001). This method of determining capture efficiency could form the basis of future Standard ISO 15012-3 (International Standard Organization, 2015) to determine the capture efficiency of on-gun welding fume extraction.

Measurements were taken with a MicroDust Pro—first-generation (Casella brand) photometer, with its sensor positioned directly in the hood extraction duct. The formula for η includes a concentration ratio (C/C_{ref}). Thus, an uncalibrated but linear response instrument can be used. Calibration was nevertheless performed by comparing readings with isokinetic filter samples to derive fume emission rates (mg min^{-1}).

The hood extraction flow rate was adjusted to the minimum that would enable all fumes to be drawn in (200 $\text{m}^3\,\text{h}^{-1}$). The air velocity induced in the welding zone was <0.1 m s^{-1} to ensure no capture disturbance.

Welding system

The welding power source was a Digiwave (Air Liquide Welding) incorporating the 'Synergie' function. This function uses pre-set models to optimize voltage and current combinations according to the filler metal, shielding gas, wire feed rate, etc. Most of the welds were performed using this automatic mode. The welding power source has a USB interface for the collection of 'voltage,' 'current' and 'wire feed rate' data.

A 2D movement system ensured the displacement of the work piece and torch. The system was installed in an enclosure whose lower section was fitted with mesh to allow incoming air to compensate for air extracted within the top section of the enclosure (Fig. 2). The 1 × 0.5 × 1 m enclosure was selected in preference to 'bell'-type test benches designed to measure emission rates (ISO 15011-4, British Standards Institution, 2006). In this study, the torch welding test conditions were much closer to those of a real usage situation, therefore avoiding certain areas of questioning (interaction between capture and the fume hood air flow; fume plume development, etc.). The whole system was installed in premises where the air is renewed (a supply of coarsely pre-filtered temperature-regulated outside air). The ambient dust concentration levels are stable and low given the concentrations acquired without extraction.

Air flow extracted by torch

The extraction air flow was estimated in the torch network by inserting a Venturi-type measuring device at the hose bundle connecting tee. This air flow was measured again at the tip of the torch by channelling air in a pipe. The flow rates obtained on a torch that was totally sealed using plastic film were included in the comparison to ensure consistency between the two measuring methods and the difference between the two mass flow rates of air was found to be <1%.

Induced velocity

The velocity induced by capture at the pollutant emission point is usually the factor which conditions efficiency. The velocity was evaluated in a free field at a distance from the torch tip equivalent to the length of wire which is usually unwound (the *stick-out*). Velocities were measured with a multidirectional thermal anemometer (Fig. 3).

RESULTS

Capture flow rate

Preliminary tests were conducted to estimate extraction flow rates of nine torches in their original unused

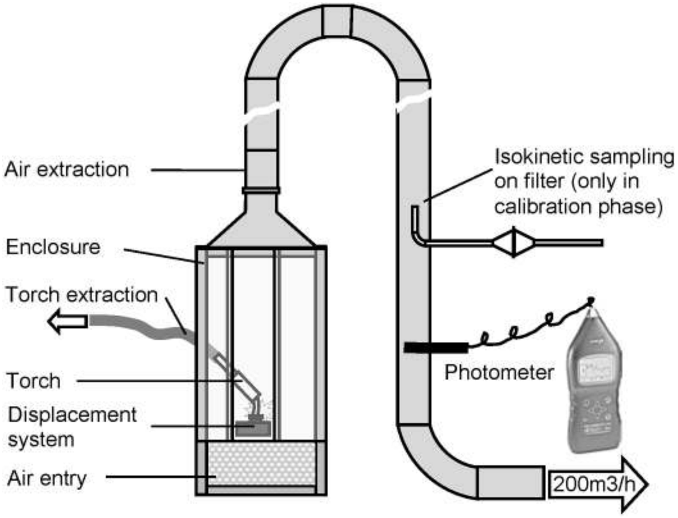


Figure 2 Experimental setup.

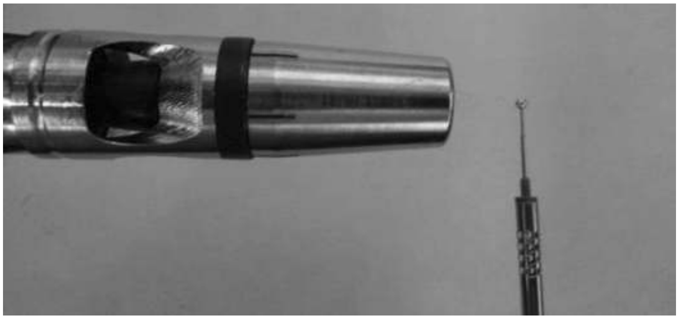


Figure 3 Measuring capture-induced velocity.

condition. The torches were connected to a suction network to obtain a 15 kPa negative pressure at the hose bundle connecting tee. In this sample, the average air flow rate at the tip represents 81% of flow rate at the tee and a value of 69% was found for one of the torches. By successively leak-proofing the different sections using plastic film, the main leaks were pinpointed to the torch casing assembly, the control trigger, and the casing-hose bundle connection. The capture effective flow is the one at the tip of the torch. Only this flow is considered in the remainder of this study.

Induced velocity

For the six geometries of torches tested on the bench, the induced velocities were evaluated at different capture flow rates. As a first approximation, we considered that the torch suction created an isovelocity sphere centred on the capture openings (Fig. 4). The extract flow was proportional down to the sphere surface area ($4\pi L^2$) and this enabled us to estimate the theoretical capture velocity at distance L.

The results illustrated in Fig. 5 show that the induced velocity can be estimated from the torch air flow and geometry, even for torches in which the openings are close to the tip of the nozzle. Distance L is composed of the *opening-contact tube* distance + the *stick-out* length (20 mm in this case).

Mass emission rate

The emission rate coefficient of variation was very often <10%, but for some configurations it may be as high as 40%. Low levels of repeatability appeared in the transition zone between globular and spray transfer (transfer modes detailed below) and also for high deposition rates ($>1.8\ \mathrm{g\ s^{-1}}$). The torch inclination is a

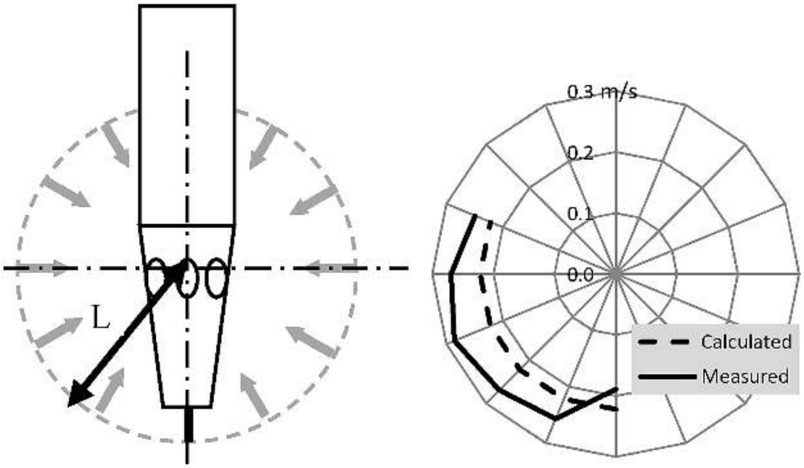


Figure 4 Example of a suction-generated isovelocity curve.

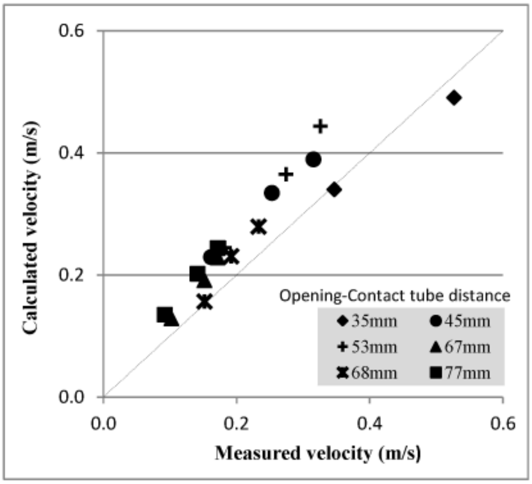


Figure 5 Comparison of measured and calculated induced velocities.

factor that was found to lower the level of repeatability. These poor repeatability levels were complemented by problems of reproducibility mainly due to uncertainties concerning torch repositioning during back and forth movements between configurations (inclination angle, stick-out). Metal sheet batches and their preparation also cause measurement dispersion. Based on this observation, the two measurements required for estimating capture efficiency were very often taken consecutively.

The method retained for estimating the capture efficiency provides a value of the emission flow rate for each configuration tested. While not central to the work carried out, this by-product provides usable data in an approach aimed at reducing exposure.

The transfer mode conditions the way in which the metal detaches from the wire and is deposited on the work piece (Kou, 2002). In 'short-circuit' mode (SC), the wire comes into contact with the work piece to create a short-circuit that will heat it until it breaks off. A section of wire detaches, triggering an arc until the advancing wire closes the circuit and initiates a new cycle. Conversely, in 'spray' mode (S), there is no contact between the wire and the work piece; a steady arc is created, in which the end of the wire melts continuously; the electrical and magnetic forces cause droplets of metal to be projected into the melt bath. The intermediate mode, 'globular' or 'big drops' (G) generates metal drops of a diameter equivalent to several wire diameters. Non-uniform detachment of these drops causes metal projections.

The transfer mode is governed by the [voltage *U*, current *I*] pair and by the shielding gas (Pires *et al.*, 2007). The filler wire feed rate and diameter partly impose the [*U*, *I*] operating point through the effective melting power. Fume production is strongly influenced by the transfer mode. Figure 6 illustrates an example of emission variation with the mass rate of wire consumed for a 1.0 mm diameter wire (emission is expressed as the ratio of the fume mass rate to the wire mass consumption rate). Data shown in this figure reflect the reproducibility of emission rate as measurements were taken throughout the study for one torch. Emission–transfer mode correlation has been widely described (Quimby and Ulrich, 1999). Few tests have been conducted beyond a wire feed rate of 1.8 g s^{-1} due to measurement scatter and also to protect the torches and displacement system from high temperatures. The test piece used in such experiments was small ($5 \times 50 \times 500$ mm) and its support was not cooled. The rare tests conducted beyond 1.8 g s^{-1} revealed a rapid rise in emission rate as the wire feed rate increases.

The inclination angle of the torch influences the emission rate, whatever the transfer mode. Changing the angle from 0° to 15° produced an average increase of a factor of 1.2; changing the angle from 0° to 30° produced an average increase of a factor of 2.8. Our bibliographical search did not provide an explanation for the origin of this phenomenon. A number of hypotheses associated with torch inclination may be put forward. These include a larger bath surface area, poorer bath protection due to air induced by the shielding gas, or less arc stability in space due to a skewed wire feed.

Capture efficiencies

Figure 7 shows the aggregate results of the six torch geometries tested. Capture efficiency is displayed with respect to the induced velocity for different torch inclinations. The points resulting from the same inclination angle are consistently placed, supporting the theory that the ‘torch model’ can be reduced to only the *opening-contact tube* distance parameter. In the remainder of this paper, the capture efficiency results are quoted

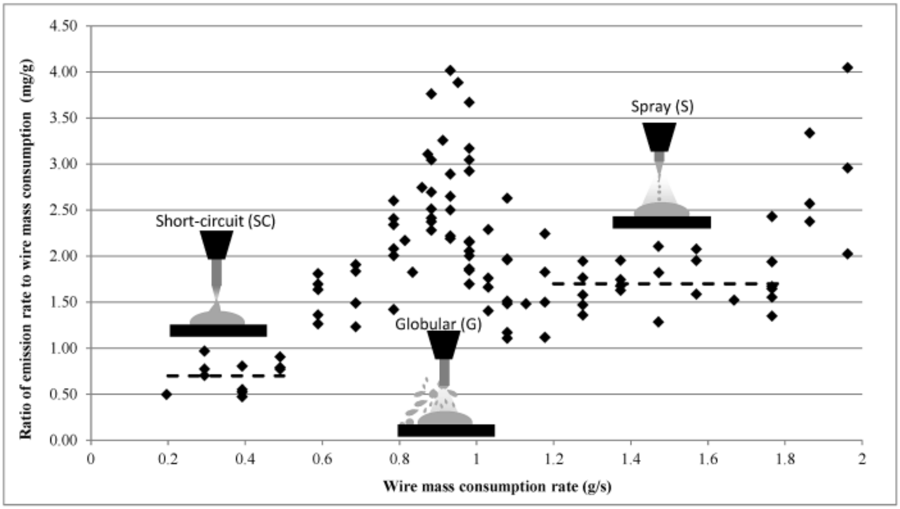


Figure 6 Fume production with respect to wire mass consumed (angle 0°, 1.0 mm wire).

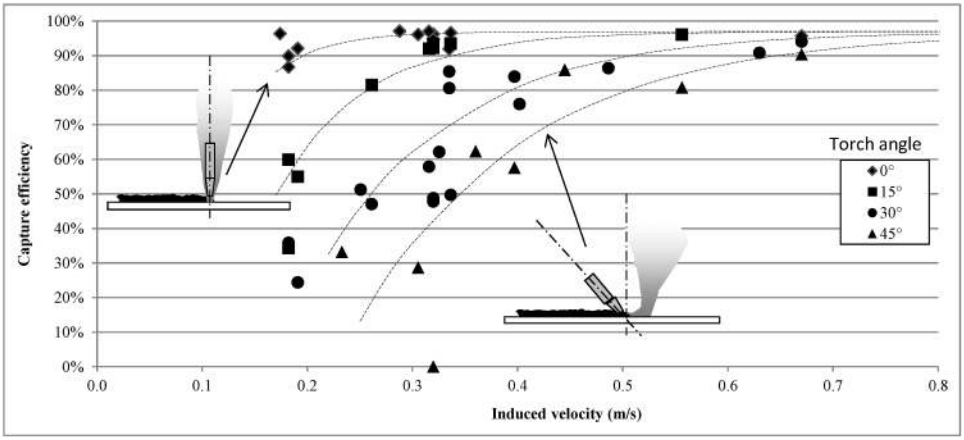


Figure 7 Capture efficiencies with respect to induced velocity for different torch inclinations (deposit rate 0.85 g s^{-1}).

with respect to the induced velocity calculated from the *opening-contact tube* distance + *stick-out* distance and the extracted flow. Curves have been added to make the graph easier to read. These curves were plotted based on a classic efficiency decay shape with induced velocity V: $\eta = 100\% - ae^{-v/b}$. In this case, because of both sparks and residual emissions of fumes after moving the torch, the efficiency value never reached 100%. A 97% basis was retained as an asymptote. We noted that, for a torch inclination angle of 0° (torch perpendicular to the welding surface), the efficiency exceeded 90% even at low induced velocities (<0.2 m s^{-1}). The efficiency then decreased as the torch inclination increased. To reach an efficiency of 90%, we needed 0.33, 0.50, and 0.65 m s^{-1} induced velocities at 15°, 30°, and 45° inclination angles, respectively. There are two different explanations for the curve shape. Firstly, as the torch is inclined, the suction openings move away from the vertical and thus away from the natural path of fumes under convection. Secondly, as the torch is inclined, the shielding gas injected at the nozzle generates a velocity in the fumes that is initially tangential.

To compare the levels of induced velocities with the values usually found on site, a sample of 97 torches was tested in a company context. This provides a rather optimistic view insofar as the installations were checked before measurement. The median was 0.26 m s^{-1}, only 17% of the values exceed 0.33 m s^{-1} and 8% exceed 0.50 m s^{-1}. 17% are <0.20 m s^{-1}.

Deposition rates are likely to affect capture efficiency through different mechanisms acting on fume production conditions—convection effects, fume volumetric flow rate, and transfer mode. The transfer mode will cause gas acceleration in the plasma zone under the action of electrical and magnetic forces (magnetohydrodynamics) (Dreher *et al.*, 2010). The velocities induced along the wire axis, which may reach 300 m s^{-1} locally in S mode, also contribute to fume dispersion. Figure 8 shows capture efficiencies by deposition rate which were acquired with different torches for 30° inclination and 1.0 mm diameter wire. Efficiencies were found to be high for low deposition rates (SC mode) and low for deposition rates exceeding 1.3 g s^{-1} (S mode).

Figure 9 illustrates the variation in emission rates and capture efficiency for an induced velocity of 0.33 m s^{-1}. This value represents a high velocity for the torches encountered on site. The capture efficiency was found to be >85% for deposition rates <1.4 g s^{-1}; for deposition rates >1.4 g s^{-1} (S mode), the drop in efficiency was rapid.

DISCUSSION

The main advantage of the method used is that it does not require us to measure the concentration in the high negative pressure network (−15 kPa). Measurement in the torch-related network may prove difficult for several reasons—in total filter collections, there is a risk of torch-extracted flow reduction due to clogging; the torch tends to suck up large non-airborne particles that distort the measurement; concentration determinations in the high negative pressure network are subject to implementation difficulties of a technical

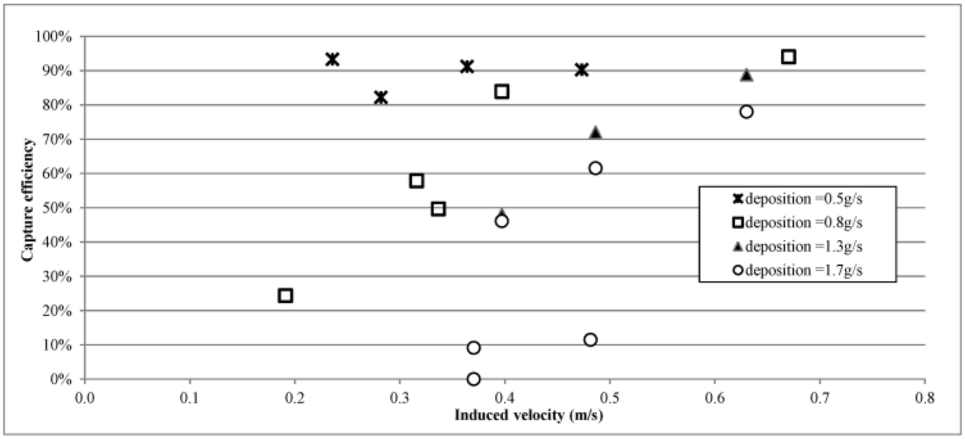


Figure 8 Capture efficiencies with respect to induced velocity for different deposition rates (30° inclination, 1.0 mm wire).

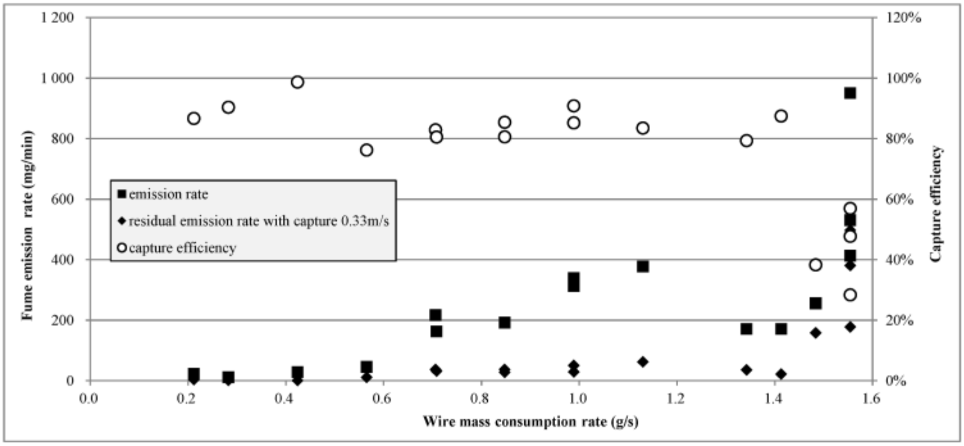


Figure 9 Total and residual emission rate combined with capture efficiency (30° inclination angle, wire diameter 1.2 mm).

nature. Furthermore, the method does not require a balance involving air flows in the extraction hood and in the torch network line.

On the other hand, the underlying principle of the method retained requires the same level of fume generation to be reproducible in the two welding operations which make up a test. However, its formulation attenuates the impact of possible emission rate variation for high efficiencies. Table 2 shows the impact of a 30% emission flow variation between the two stages of a test (with and without extraction). The errors mainly affect the low efficiencies, with a limited impact for efficiencies >80% that are at the heart of our interests.

The simplicity of the experimental setup enables it to be used in a transportable format to run efficiency measurement tests on site.

Table 2. Example of impact of emission rate variation

Theoretical η	η recalculated for an emission flow rate variation between 'with' and 'without' capture stages	
	−30%	+30%
100%	100%	100%
90%	93%	87%
80%	86%	74%
50%	65%	35%
30%	51%	9%

CONCLUSION AND PERSPECTIVES

The methodology used to measure efficiency, based on a direct reading of concentration by a photometer, allowed us to evaluate a large number of welding configurations (496 sets), thus increasing the likelihood of finding the right key parameters. As the methodology enabling us to retrieve the emission rate, the influence of certain of these parameters on emission levels was determined.

Torch inclination is a factor with a double influence: it induces an increase in fume emissions and, in parallel, a reduction in capture efficiency. As far as possible, the welding station should be laid out to encourage welding positions in which the torch is held perpendicular to the work piece surface.

The velocity induced by suction at the fume emission point is one of the variables that explain capture efficiency. If we consider 30° maximum torch inclinations, this velocity should not be <0.25 m s^{-1} to ensure capture system effectiveness (50% efficiency).

Although their respective contributions are not clearly identified, the electrical power and transfer mode affect capture efficiency. In simple terms, we can consider that welding configurations allowing deposition rates >1.1 g s^{-1} make capture difficult and demand induced velocities >0.5 m s^{-1}; beyond 1.6 g s^{-1}, capture efficiency is low.

Examining torches available on the European market reveals that 50% do not reach 0.25 m s^{-1}, even when connected to individual 4 kW vacuum cleaners/ extraction units. Some of these torches achieve this induced velocity by means of an additional removable capture shroud, which decreases the *opening-contact tube* distance. However, we have found that these capture devices are quickly dismantled in workshops because they hamper torch handling in narrow spaces.

Research into induced velocity measurements and extracted flow rates showed that a significant part of the air flow was lost in leaks between the hose bundle connecting tee and the torch tip with the flow rate often <85% of the initial rate. This problem becomes worse as the torch components age so it is preferable not to carry out periodic checks of capture performance levels by measuring the flow rate at the tee connector. This measurement is wrongly preferred because it is easy to implement at this site on the equipment. The measurement should instead be made at the torch tip by channelling air in an additional pipe.

The study presented in this paper should be completed by a study of weld defects caused by air extraction (disturbances to the gas shielding). Negative feedback from users mostly focuses on the in-corner weld configuration (intersection of three planes). A study has been started to determine the parameters which may cause problems (part geometries, extracted flow rate, position of suction openings, etc.). Ideally, these results should enable induced velocity values to be set, which should not be exceeded, to ensure optimum weld quality.

DECLARATION

The author designed and executed the study and has sole responsibility for the writing and content of the manuscript. No funding or sponsorship was received by the author or his employer for this research.

REFERENCES

Ambroise D, Wild P, Moulin JJ. (2006) Update of a meta-analysis on lung cancer and welding. *Scand J Work Environ Health*; 32: 22–31.

British Standards Institution. (2001). BS EN 1093-11:2001. *Safety of machinery. Evaluation of the emission of airborne hazardous substances. Decontamination index*. London: British Standards Institution.

British Standards Institution. (2006). BS EN ISO 15011-4:2006. *Health and safety in welding and allied processes - laboratory method for sampling fume and gases - Part 4: fume data sheets*. London: British Standards Institution.

Carpenter KR, Monaghan BJ, Norrish J. (2009) Analysis of fume formation rate and fume particle composition for gas metal arc welding (GMAW) of plain carbon steel using different shielding gas compositions. *ISI J Int*; 49: 416–20.

Cornu JC, Muller JP, Guelin JC. (1991) Torches aspirantes de soudage MIG/ MAG. Méthode de mesure de l'efficacité de captage. Etude de paramètres d'influence. *INRS, Note documentaire ND*; 145: 663–8

Costa L. (2014) Correlation between the welding process and the development of fumes: characterization, analysis and risk management. *Weld Int*; 28: 700–7.

Dreher M, Füssel U, Schnick M. (2010) Numerical optimization of gas metal arc welding torches using ANSYS CFX Proc. 63rd Annual Assembly and Int. Conf. of the Int. Istanbul, Turkey: Institute of Welding.

Faes K, Verstraeten B, Broeckx K. (2006) Un rendement accru grâce aux procédés de soudage novateurs. *Métallerie*; 95: 1–4. Available at http://www.bil-ibs.be/sites/default/files/publicaties/200611_95a05_soudage_a_haut_rendement_innolas.pdf. Accessed 8 april 2016.

Flynn MR, Susi P. (2012) Local exhaust ventilation for the control of welding fumes in the construction industry–a literature review. *Ann Occup Hyg*; 56: 764–76.

International Standard Organization. (2015). PR ISO 15012-3 Health and safety in welding and allied processes - equipment for capture and separation of welding fume - Part 3: determination of the capture efficiency of ongun welding fume extraction devices. Geneva: International Standard Organization.

Jenkins NT, Eagar TW. (2005) Chemical analysis of welding fume particles. *Welding J*; 87–93.

Kou S. (2002) *Welding metallurgy*. 2nd edn. New York: Wiley Interscience. pp. 263–95.

Lehnert M, Pesch B Lotz A *et al.* (2012) Exposure to inhalable, respirable, and ultrafine particles in welding fume. *Ann Occup Hyg*; 56: 557–67.

Marconi M, Bravaccini A. (2010) Capture efficiency of integral fume extraction torches for GMA welding–Part 2. Welding in the World 54:15–33.

Pires I, Quintino L, Miranda RM. (2007) Analysis of the influence of shielding gas mixtures on the gas metal arc welding metal transfer modes and fume formation rate. *Materials Design*; 28: 1623–31.

Quimby JB, Ulrich GD. (1999) Fume formation rates in gas-shielded metal arc welding. *Weld J* ; 78: 142–9.

Rouly G, Maltrud F, Jubin L. (2014) Réduire les poussières émises lors du soudage à l'arc. *Lavoisier S.A.S.* ISBN-10: 2854009940.

Siew SS, Kauppinen T, Kyyronen P *et al.* (2008) Iron and welding fume exposure and the risk of lung cancer. *Scand J Work Environ Health*; 34: 444–50.

Yapp D, Lawmon J, Castner H. (2001) *Development of lightweight fume extraction welding guns*. National Shipbuilding Research Program SP-7 Final repport. Edison Welding Inst. Available at http://www.dtic.mil/cgi-bin/GetTRDoc?Location=U2&doc=GetTRDoc.pdf&AD=ADA452250. Accessed 8 April 2016.