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Applied Occupational and Environmental Hygiene

ISSN: 1047-322X (Print) 1521-0898 (Online) Journal homepage: https://www.tandfonline.com/loi/uaoh20

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To cite this article: Robert T. Hughes (1990) An Overview of Push—Pull Ventilation Characteristics, Applied Occupational and Environmental Hygiene, 5:3, 156-161, DOI: 10.1080/1047322X.1990.10389612

To link to this article: https://doi.org/10.1080/1047322X.1990.10389612

Published online: 24 Feb 2011.

An Overview of Push–Pull Ventilation Characteristics

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Push–pull ventilation has been used as an engineering control technique for a number of years. It can provide efficient and cost effective control in conjunction with local exhaust. It is effective where control by local exhaust alone is not possible. However, its use has been limited due to a lack of design criteria and, in a large part, due to a lack of knowledge of the physical characteristics of the push–pull system components and their interaction with each other. Recent work by National Institute for Occupational Safety and Health (NIOSH) researchers has led to the development of design criteria for a number of processes including open surface vessels, foundry casting cleaning, roller mills used for rubber and plastics manufacture, and multiple opening presses used for laminating wood. In addition to providing the design criteria for these processes, the research has provided observations and data regarding the characteristics and limitations of the push–pull technique. For example, the belief that the push jet must have a high nozzle exit velocity can lead to a jet with excessive momentum and flow rate which can overpower the exhaust flow and spill contaminated air into the workplace. It also has been shown that low momentum push jets are very effective and are relatively insensitive to obstacles in the path of the jet. Many times push–pull has not been utilized due to the belief that it is effective only over short distances. However, a push jet can be used effectively over distances of 6 m (20 ft) or more. This article provides generic guidelines for the design of new push–pull ventilation systems and for the evaluation or correction of existing ones. Hughes, R.T.: An Overview of Push–Pull Ventilation Characteristics. Appl. Occup. Environ. Hyg. 5:156–161; 1990.

Introduction

Air flow into a local exhaust hood creates a flow field that intercepts and removes the contaminant, either particulate or gas. Local exhaust is effective where the process configuration is such that the hood can enclose the source (enclosing hood) or where the hood can be placed within 0.6–0.9 m (2–3 ft) of the emission source (exterior hood). In the case of the exterior hood, if greater distances are required, control effectiveness is usually compromised due to the rapidly decreasing air velocities.(1) Increasing the hood air flow may be of some benefit. However, the air flow necessary to achieve the required flow field beyond the 0.6–0.9-m (2–3-ft) range becomes rapidly large and prohibitive. In such cases, the use of push–pull ventilation or air curtains has been shown to be effective.(2)

Historically, the technique has been used primarily on plating tanks. Although its use is increasing, there are still misconceptions relating to the characteristics of the push jet and the jet–exhaust hood interaction. These misconceptions may preclude the use of the push–pull technique when it could be successfully applied or may cause problems where application is attempted.

This article discusses major characteristics of the push jet and the jet–exhaust hood interface based upon observations made during research projects and upon descriptions found in the literature. These observations are not presented as precise design criteria but rather to provide the designer and user with an overview which will assist them in the determination of applicability and in the design and operation of push–pull systems.

Jet Shape

Push–pull ventilation consists of a jet of air directed across a process emission location into an exhaust hood (Figure 1). The jet intercepts and carries the emission toward the hood. The hood receives the contaminant-laden jet and removes it through a conventional system of ducts, fan, and air cleaner.

The most commonly encountered jet shape in industrial push–pull systems is a plane jet. It can be generated by using a long, thin slot; a linear array of nozzles; or properly sized and spaced orifices. There are two general types of plane jets: a free plane jet and a half jet. A free plane jet is one that has no bounding planes and can expand freely on both sides of the jet centerline. The expansion angle varies according to the physical construction of the nozzle but will be in the range of 20° to 30° included angle. The jet cross section becomes elliptical in shape with the major axis horizontal as it leaves the nozzle. If the jet path is long enough, the cross section will become circular and then

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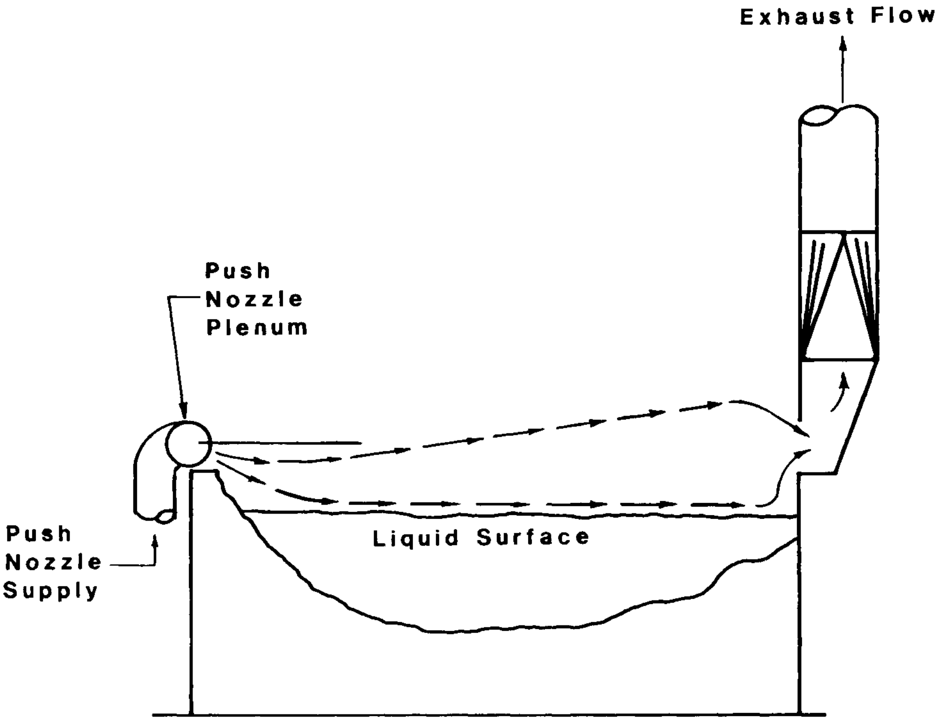

FIGURE 1. Plating tank push–pull.

back to elliptical, but with the major axis vertical.[3] This will result in a slight contraction of the jet width over its effective length (Figure 2).

A half jet is one that is bounded on one side by a plane surface. The expansion perpendicular to the nozzle length is approximately one-half that of a free plane jet. It will, however, expand slightly in the parallel direction unless restricted by a bounding surface. An example of a bounding surface is the free board edges of a plating or cleaning tank (Figure 3). This is significant when applying the push–pull technique to plating and cleaning tanks in that the push jet will be contained within the tank length, thereby precluding any spillage over the sides or beyond the edges of the exhaust hood.

Nozzles

A plane jet can be formed by air blown through a long, thin slot or a number of other nozzle configurations. Individual jets from a line of closely spaced nozzles or holes

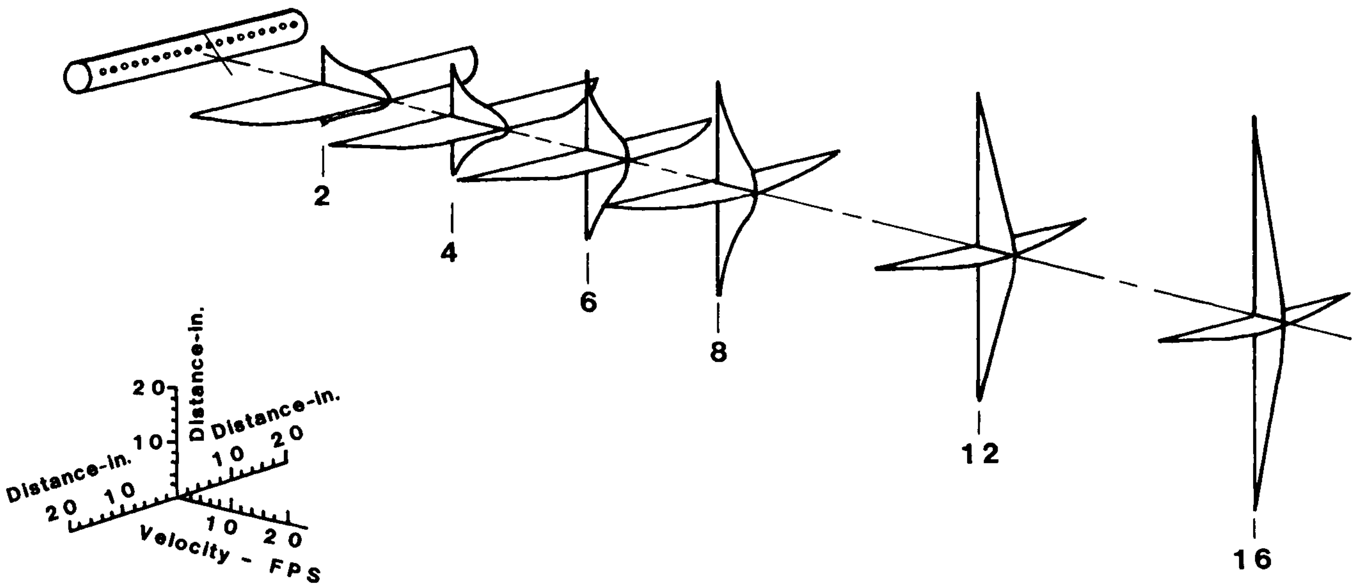

FIGURE 2. Free plane jet velocity profile versus distance from nozzle.

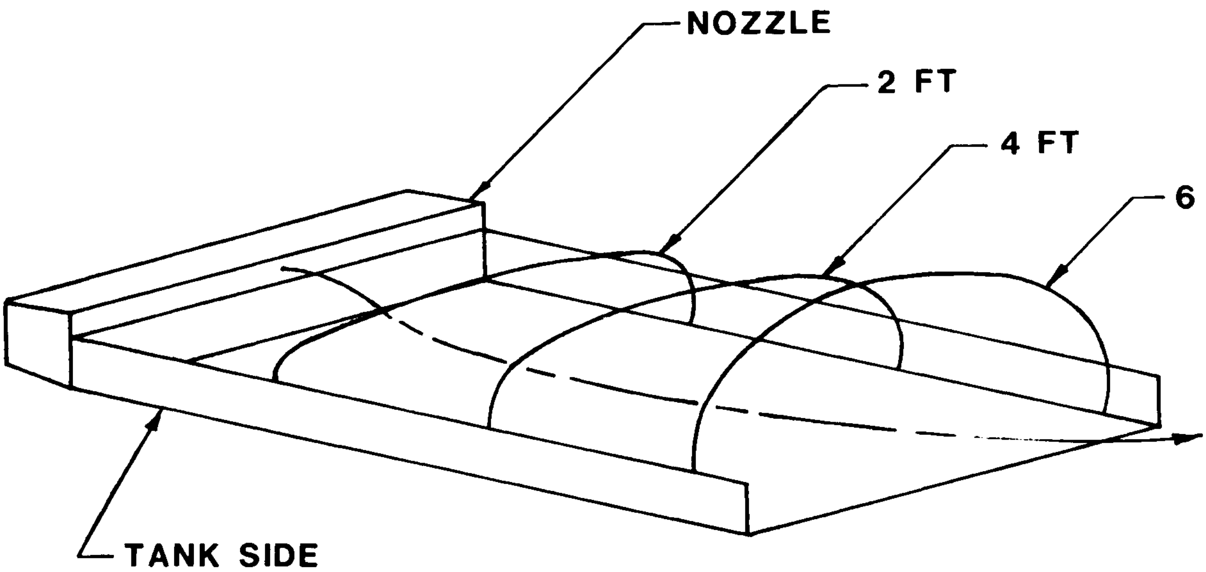

FIGURE 3. Half plane jet boundary versus distance from nozzle.

will merge to form a single jet. For example, jets from holes with centerlines spaced at 3 times the hole diameter will have merged into a fully formed plane jet at a distance from the nozzle equal to 20 times the hole spacing.[4]

While arrays of individual nozzles have been used, the more common approach is the use of a pipe or plenum with slots or holes. These have the advantage of being durable and inexpensive to construct. Slot widths of 6.4–13 mm (0.125–0.250 in.) or a pipe with 13-mm (0.250-in.) holes on 3- to 8-hole diameter spacing have been recommended.[5]

It is important that even flow be maintained across the entire nozzle length. This can be accomplished by assuring that the cross-sectional area of the nozzle plenum is equal to or greater than 3 to 4 times the total nozzle exit flow area.[5]

Jet Flow and Velocity

The flow and velocity characteristics of a jet are somewhat dependent on nozzle configuration but can be estimated rather well by Baturin's equations:[6]

$$\frac{V_x}{V_o} = \frac{1.2}{\sqrt{\frac{ax}{b_o} + 0.41}} \quad (1)$$

$$\frac{Q_x}{Q_o} = 1.2\sqrt{\frac{ax}{b_o} + 0.41} \quad (2)$$

where: V_o = nozzle exit velocity, m/sec (fpm)
V_x = jet peak velocity at distance x, m/sec (fpm)
x = distance from nozzle, m (ft)
Q_o = supply flow to nozzle manifold, m^3/sec (cfm)
Q_x = jet flow at distance x, m^3/sec (cfm)
a = a dimensionless factor describing the nozzle (= 0.13 for the nozzle discussed herein)
b_o = free jet slot nozzle width or equivalent slot width for a nonslot nozzle. For a half jet, the slot or equivalent slot width is $2b_o$

Hemeon[3] also provided equations which are useful in determining push-pull characteristics. For a free plane jet:

$$\frac{V_x}{V_o} = \sqrt{\frac{1}{N}} \quad (3)$$

$$\frac{Q_x}{Q_o} = \sqrt{N} \quad (4)$$

For a half plane jet:

$$\frac{V_x}{V_o} = 120\left(\frac{w}{x}\right)^{0.36} \quad (5)$$

$$\frac{Q_x}{Q_o} = 0.8N^{0.36} \quad (6)$$

where: V_o = nozzle exit velocity, m/sec (fpm)

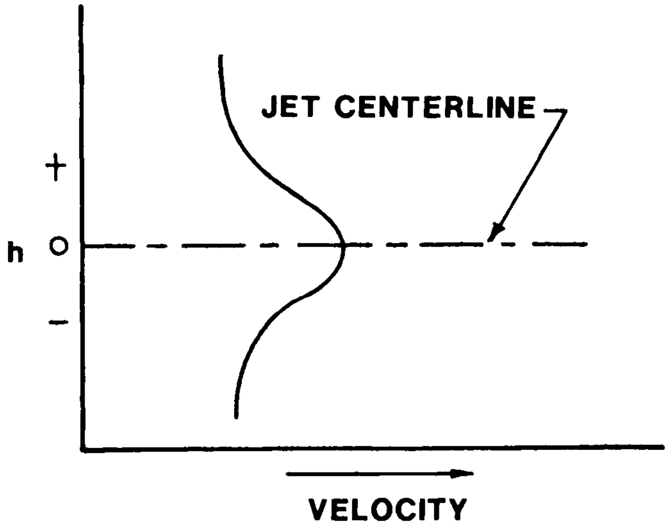

FIGURE 4. Free plane jet velocity versus height above and below jet centerline.

V_x = jet peak velocity at distance x, m/sec (fpm)

Q_o = supply flow to nozzle manifold, m³/sec (cfm)
Q_x = jet flow at distance x, m³/sec (cfm)
x = distance from nozzle, m (ft)
w = nozzle slot width or an equivalent slot width for a nonslot nozzle, m(ft)
N = x/w

In a typical free plane jet, the maximum or peak velocity occurs at the jet centerline and decreases rapidly away from the centerline (Figure 4). The peak velocity for a half jet occurs very near the boundary surface and, as with the free jet, decreases rapidly away from the boundary surface (Figure 5).

A convenient starting point for use of Equations 1 through 6 is the average velocity at the exhaust hood face. Evaluation of a plating tank push–pull system[2] has shown that a velocity range of 0.76–1.25 m/sec (150–250 fpm) for tank widths of 2.4–1.2 m (8–4 ft), respectively, to be appropriate.

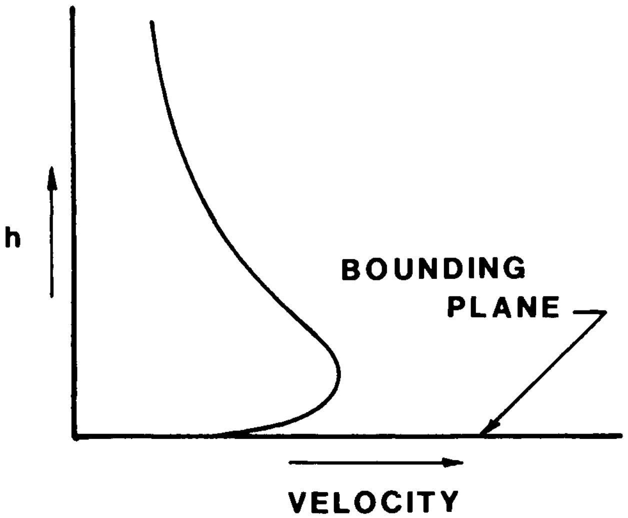

FIGURE 5. Half plane jet velocity versus height above bounding plane.

Jet Momentum

The jet is essentially a constant momentum process. Air leaves the nozzle at a relatively high velocity and low flow rate. Along the path of the jet, the total air flow increases as a result of entrainment of room air into the jet. In order to conserve momentum, the increase in air flow must be accompanied by a decrease in velocity (Figure 6). The result is the jet expansion discussed previously.

Improper jet momentum is a common problem with push–pull systems. To be effective, the jet momentum must be sufficient to overcome cross drafts and to capture and carry the contaminants of concern into the exhaust hood. If too high, the contaminant will be captured, but the exhaust may be overpowered and the contaminant may escape into the workplace. If too low, the jet may not be captured by the exhaust.

The jet nozzle exit flow times the nozzle exit velocity, Q_oV_o, is directly related to nozzle exit momentum. It can be seen that to maintain a correct momentum value, both Q_o and V_o can vary but not independently. If a higher velocity is desired, flow must be decreased and vice versa. Specific momentum values have not been specified for many potential push–pull applications. However, it has been shown that a Q_oV_o value of 0.456 m⁴/sec²/m (58,800 ft⁴/min²/ft) of nozzle length provides satisfactory results for jet path lengths of 1.2–2.4 m (4–8 ft).[5] The nozzle supply flow to achieve this Q_oV_o value can be determined from

$$Q_o = 0.675\sqrt{A_o} \quad (243\sqrt{A_o}) \tag{7}$$

where: Q_o = nozzle supply flow (nozzle exit flow), m³/sec/m (cfm/ft) nozzle length
A_o = nozzle exit areas, m³/m (ft²/ft) nozzle length

This expression will provide a Q_oV_o value of 0.456 m⁴/sec²/m (58,800 ft⁴/min²/ft) for push nozzles of various flow areas. For example, the 0.456 m⁴/sec²/m (58,800 ft⁴/min²/ft) value can be achieved with 0.054 m³/sec/m (35 cfm/ft) from a 6.4-mm (0.25-in.) wide slot nozzle and also with 0.02 m³/sec/m (13 cfm/ft) from a nozzle with 6.4-mm (0.25-in.) holes on 19-mm (0.75-in.) centers.

Where distances are greater than the 1.2–2.4 m (4–8 ft) range or where process emissions are very strong, a higher Q_oV_o value may be required. For example, control of air carbon arc gouging required a Q_oV_o value of 2.78 m⁴/sec²/m (360,000 ft⁴/min²/ft).[7] Determinations of the appropriate value usually will require experimentation unless information on a similar application is available.

Jet Distances

The effective distance of a plane jet can vary; however, lengths up to six slot (or nozzle manifold) lengths are commonly accepted as satisfactory.[3] Successful application of a 7.3-m (24-ft) jet from a 3-m (10-ft) long slot nozzle has been demonstrated.[8] There are, however, potential problems that must be recognized. The velocity in

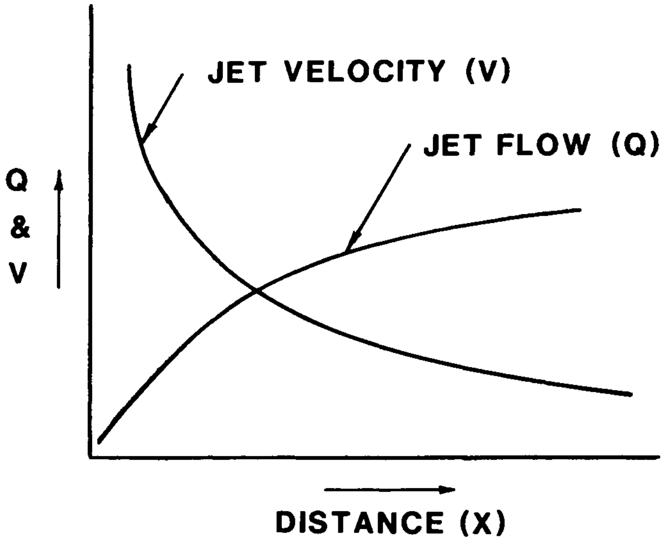

FIGURE 6. Jet flow and velocity versus distance from nozzle.

the outer portion of the jet is relatively low. The longer the jet path, the larger the low velocity areas become and the greater the susceptibility to cross drafts. Figure 6 compares the low velocity area for a 1.8-m (6-ft) and a 3.6-m (12-ft) jet path. Up to 1.8 m (6 ft), cross draft effects may not be severe, but at longer distances, care must be taken to minimize the cross draft or its effects.

Obstructions

A major misconception regarding push–pull relates to the effects of an obstruction in the jet path. It is true that if an obstruction is large relative to the jet cross section, deflection may occur and cause spillage into the workplace. However, if the obstruction is contained within the jet cross section, flow around it may occur without any spillage problems. Wherever possible, the obstruction should be located in the last two-thirds of the jet length where the jet is wider and has lower velocities.

Small cross section objects (e.g., plating or cleaning tank parts hangers), parts, or parts containers usually will not cause problems. Parts being removed from or placed into a plating or cleaning tank may cause temporary spillage. The spillage usually will be quickly recaptured by the jet air entrainment flow. Very large parts such as sheets of metal can completely block the jet flow with resultant deflection of the jet into the workplace. In such cases, shutting the jet off during part removal may be necessary. If the contaminant is very toxic, push–pull may not be appropriate if the spillage cannot be controlled.

Exhaust Hood

The purpose of the exhaust hood is primarily to receive and to remove the push jet. To do so, the hood must have a flow rate of 1.5 to 2.0 times the jet flow delivered to the hood to account for the turbulent nature of the jet.[2] If the hood flow rate is less than the 1.5 ratio, the jet may not be completely captured. Flow ratios greater than 2.0 will capture the jet but may waste energy. For plating tanks and other open surface vessels, an exhaust flow of 0.38 $m^3/sec/m^2$ (75 cfm/ft^2) of surface area, in conjunction with the nozzle supply flow determined by Equation 7, will be adequate. These values will also suffice for push–pull over a flat table.

As previously discussed, a half jet will expand at an angle approximately one-half that of a free plane jet, about 13° or about 43 cm (17 in.) in 1.8 m (6 ft). Laboratory tests have shown no measurable differences in overall system capture efficiency for hood plating tank openings ranging from 10–25 cm (4–10 in.) for a 1.8-m (6-ft) jet path.[5] While this suggests that the hood opening height is not critical, it is recommended that the opening be close to the jet height if possible, especially for long jet paths. As can be seen in Figure 7, the low velocity area of the jet becomes rather large for long paths making it more susceptible to cross drafts and escape due to turbulence. Narrower exhaust openings may not be capable of producing the flow field necessary to capture the jet at the outer edges.

The primary consideration in hood design is to achieve the required flow rate with even flow distributions. If the exhaust flow is 1.5 to 2.0 times the jet flow delivered to the hood, the resultant hood face velocity will be at least 1.5 times the average jet velocity, thereby assuring efficient jet capture. An interlock should be provided to shut off the jet in the event that the exhaust flow system malfunctions.

Application and Design

Specific criteria for the application of push–pull ventilation is available for a limited number of processes. These limited examples cover a wide range of applications and show the ability of push–pull as an effective contaminant control mechanism. Included are plating tanks,[2,5] air carbon arc gouging,[7] foundry torch cutting,[9] roller mills,[10] multiopening presses, and wood panel gluing.[11]

The advantages shown from these examples vary. Plating tanks up to 8 ft wide can be effectively controlled with exhaust flows less than 50 percent of that required for local exhaust only. Roller mill control is achieved with exhaust flows 30–50 percent less than for local exhaust only. Although exhaust flows required for air carbon arc gouging and torch cutting were large, ranging from 7.0–9.4 m^3/s (15,000–20,000 cfm), effective control was achieved. These operations were on large castings that generate excessive amounts of contaminants and could not be effectively controlled by local exhaust alone. Multiopening press emissions were reduced by over 90 percent by using an air curtain barrier between the press and the operator.

The criteria provided in the above referenced documents can be used for direct application of push–pull technique to the specific (or similar) process. For example, the criteria for plating tanks[5] covers a range of push nozzle configurations, giving the required exhaust flow and a simple equation (Equation 7) to determine push supply flow. These criteria will provide a push–pull system which will satisfactorily control plating and cleaning tank emissions.

To design a system where specific criteria or a similar operating system is not available, considerations should first be given to the general push–pull characteristics discussed herein. Secondly, the basic system configuration (i.e., push–pull flows, nozzle configuration, and exhaust hood) can then be determined from Equations 1 through 6.

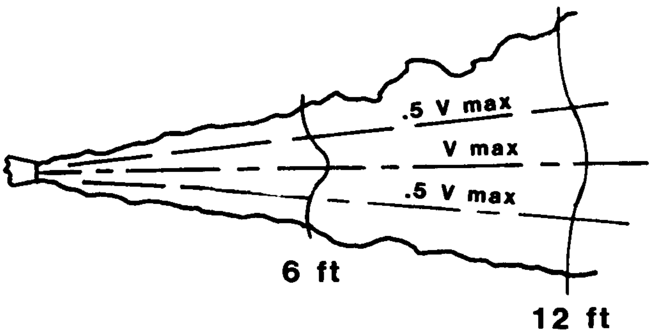

FIGURE 7. Free plane jet velocities versus distance from nozzle.

A mock-up of the system is strongly advised. The mock-up should simulate the nozzles, jet flow path including obstructions, and exhaust system. Use of a smoke machine, smoke candles, or smoke tubes will permit observations and adjustment of the nozzle and exhaust flows and will determine applicability of push–pull to the specific process and to optimize effectiveness.

Conclusions

Push–pull ventilation has been shown to be a viable and effective control method. Systems can be designed by using published criteria or by the equations of Baturin or Hemeon. Where specific criteria are not available, considerations of the push–pull characteristics and limitations discussed in this article will permit design, construction, and operation of effective systems.

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Received 12/9/88; review decision 2/16/89; revision 9/5/89; accepted 10/5/89