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Grinding booth for large castings

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The design of a grinding booth suitable for large castings and portable hand-held grinders is recommended. Systematically studied were the air velocities within the booth as functions of the geometry of the suction ports, recirculation jets, ventilation flow rate and recirculation flow rate. The rate at which grinding particles are injected into the air from the surface of the grinding wheel was studied and described in terms of a distribution function G(θ) and the metal removal rate.

Grinding booth for large castings

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introduction

After gray iron castings are removed from their molds, sprues, risers and gates are cut off and the castings ground to remove the remaining unwanted metal. Sand on the casting surface becomes airborne during grinding and unless steps are taken, the silica concentration in the workplace may exceed the threshold limit value (TLV).

Workers usually place large castings on low benches and lean over and around them to gain the leverage necessary to operate portable grinders. It is important to design a dust control system that preserves the workers freedom of movement. High velocity, low volume dust collectors attached to the grinder is the preferred control stratgegy. Unfortunately such systems are unattractive for small diameter, unguarded grinding wheels used to grind internal surfaces, small radius contours, etc. since they impede the worker's movement and vision. Under these conditions a grinding booth is the next most attractive control strategy, but unfortunately little guidance is given the designer concerning the booth's dimensions, exhaust volumetric flow rates, recirculation volumetric flow rates, or dimensions of the suction ports.

current design practices

The ACGIH "Industrial Ventilation - A Manual of Recommended Practice",[1] ASHRAE Handbook,[2] Hemeon,[3] DallaValle,[4] McDermott,[5] and Baturin,[6] contain no explicit recommendations for the design of grinding booths for large castings. Upon reviewing other grinding systems in these references, designers would be inclined to select air velocities at the booth inlet i.e. "face velocity" between 0.51-1.02 m/s (100-200 FPM). Hagopian and Bastress[7] recommend a grinding booth for large castings with face velocities between 0.51-2.03 m/s. All the booths are purely suction systems and no guidance is given to designers wishing to clean and recirculate air back into the booth.

The texts and handbooks contain a great deal of practical information but are deficient in the following respects:

concentration predictions

To insure that a proposed booth and ventilation flow rate keep concentrations below the TLV, designers must be able to predict the concentration at various points near the source. Furthermore, it will be necessary to make these predictions for a variety of work pieces and room air currents. These predictions cannot be made with the present design practices.

capture velocity

The capture velocity is defined as the "air velocity at any point in front of the hood necessary to overcome opposing air currents and to capture the contaminated air by causing it to flow into the exhaust hood".[1] The distance contaminants travel from a source depends on the velocity field through which they move. Contaminant concentrations and particle trajectories can be predicted, but it requires knowledge of the velocity field and the solution of the equations of motion. As a qualitative concept "capture velocity" may be a very useful metaphor to aid the designers intuition. As a quantitative concept, "capture velocity" is physically and fundamentally incorrect and should be abandoned. The concept suggests a physical independence between air and contaminant that does not exist. The concept impedes an understanding of the movement of contaminants and if extended beyond its limitations is misleading.

imprecision

Present design practices require designers to select volumetric flow rates, face velocities, and other parameters within ranges whose maxima and minima differ by factors of 2 or 4 (and sometimes more). Higher precision will be needed in the future as steps to conserve energy increase in importance.

inability to generalize

When an effective ventilation system is designed for a particular application, there is presently no way to generalize for other applications. When one wants to scale the design up or down, or run the system at different operating conditions, there is no way to predict the new performance.

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By means of numerical computation it should be possible to compute the velocities and concentrations in the vicinity of a source equipped with a ventilation system. The field of "computational fluid mechanics" is an accepted field of technology that has been applied to a variety of applications. There are several professional journals devoted to the subject and numerous books written on the subject. Large companies may have already applied these concepts to industrial ventilation. Since occupational health is a common concern and since little competitive edge is gained or lost by disclosing these techniques, it is hoped that these techniques will find their way into the technical literature.

objective

Research is in progress at Penn State to develop computer-aided design procedures to enable designers to predict air velocities and dust concentrations. The computer codes do not design a booth; designers retain their traditional role of selecting the booth shape and volumetric flow rate, the code is merely a predictive tool that will enable them to assess the effectiveness of the values that have been chosen. The analytical portion of this study has been published.[8] This paper describes the results of one set of experiments in which air velocities were measured for different volumetric flow rates and booth geometries, and another set of experiments in which particle concentrations and sizes were measured in the vicinity of a grinding wheel. The specific objectives of this paper are to

(a) describe air velocities in the booth,
(b) describe the particle generation rate and size distribution at different points on the periphery of the grinding wheel, and
(c) recommend a design of a grinding booth for large castings.

design criteria

The function of a booth is to prevent particles from traveling to other parts of the workplace and to produce a flow field within the booth that causes particles to travel to the suction ports. Thus the effectiveness of a booth can be assessed by its ability to enclose a region where,

1) the velocity if uniform, i.e. no eddy regions or regions of reverse flow.
2) the velocity toward the suction ports is large.

Air velocities at points upstream of a slot inlet are influenced by the slot geometry and volumetric flow rate. It is suggested that a desirable slot geometry is one in which for any flow rate this influence extends the furthest distance upstream of the slot. Air velocities, particle velocities and concentrations at specific points upstream of the slot have to be found before the designer can apply this rule in a quantitative manner.

From analytical studies,[8] the following is known.

1) Particles less than 15 μm travel very short distances (on

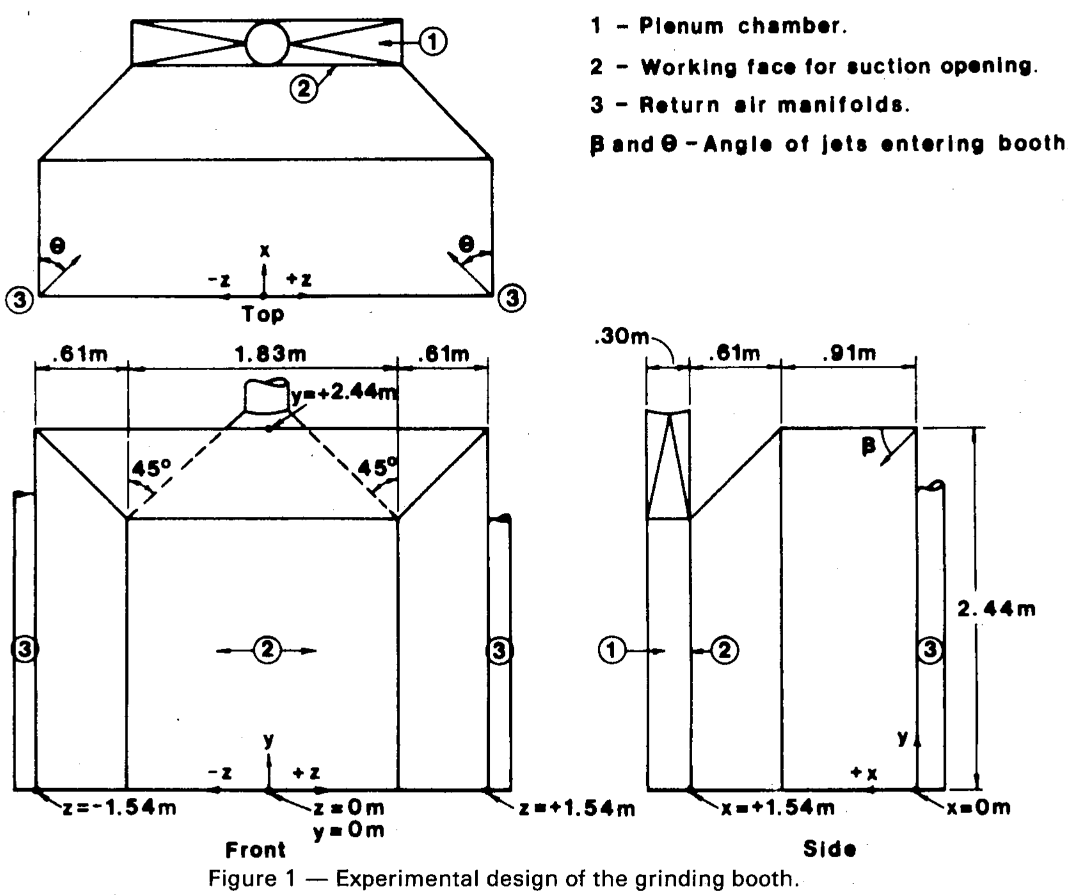

Figure 1 — Experimental design of the grinding booth.

TABLE I
Booth Configurations

Config.	Suction Ports			Recirculation Jets			
	number	opening (cm)	height of ports (cm)	number	opening (cm)	center of opening (cm)	direction of air jets (cm)
A	4	2,5x121,9	33.0 66.0, 99.0, 132.1	none	---	---	---
B	4	(same as A)	(same as A)	2	20.3x40.6	x=0, y=157.5, z= ±152.4	directed at x=152.4, y=91.4, z=0
C	1	35.6x121.9	78.7	none	---	---	---
D	1	(same as C)	(same as C)	2	(same as B)	(same as B)	(same as B)
E	4	(same as A)	(same as A)	20	6.4x6.4	uniformly distributed around 3 sides of booth inlet	directed at x=152.4, y=91.4, z= ±91.4
F	4	(same as A)	(same as A)	8	5.1x2.5	uniformly distributed across top of booth inlet	(same as E)

the order of centimeters) before they enter suction ports or are trapped in the aerodynamic boundary layer of the grinding wheel.

2) Particles capable of traveling distances of the order of meters are larger than 50 μm and pose a hazard to eyes but do not reach the lungs if inhaled.[9]

To prevent respirable partices from traveling to other parts of the building, grinding should be performed as close to the plane of the suction ports as possible and there must be no region of reverse flow at the entrance of the booth. The penetration distance of respirable particles is negligible and the particle velocity is essentially everywhere the same as the local gas velocity. Consequently the motion of respirable particles is essentially the same as the motion of the air in which they are contained. To minimize the worker's exposure to respirable particles, the flow field within the booth should not contain regions of low velocity, i.e. eddy regions or wake regions.

experiments

For large castings the booth shown in Figure 1 is recommended. The booth is 1.52 m (5 ft) deep and 3.05 m (10 ft) wide and 2.44 m (8 ft) high at the inlet. The booth converges and is 1.83 m by 1.83 m (6 ft by 6 ft) at the plane of the slots. Air is drawn into the booth from the room and leaves through the slots, a plenum chamber and exhaust fan. Makeup air or recirculated (but cleaned) air is injected into the booth at the inlet plane. Ducts carrying the makeup or recirculated air are located around three sides of the perimeter at the booth inlet. Openings in these ducts direct air toward the slot plane. Each opening is covered by an adjustable louver capable of controlling the direction of the jet.

A full-scale model of the booth was built and tested in the laboratory. Various slot configurations and recirculation jets were studied and are summarized in Table I. Configuration A is purely a suction system using four narrow slots. Configuration C is also a purely suction system but used a single wide slot. Configurations B, D, E and F used the same type of suction slots as configuration A and C but employed four different arrangements of recirculation jets. The right hand column "direction of jet" shows the point(s) on the slot plane to which the jet is pointed. The operator simply adjusts the louvers covering each recirculation jet until it "points" to the specified points on the plane of the suction ports. The description is admittedly crude technically, but will be retained because it is operationally uncomplicated. Note also the coordinate system. The origin of the coordinate system is in the lower center of the inlet plane of the booth. The distance x is the direction of flow and increases as the air approaches the slot plane. The distance y is the vertical height above the floor and the distance z is in the transverse direction.

Each booth configuration listed in Table I was tested using isothermal, clean air at various volumetric flow rates Q_v and Q_r. No grinding was performed during these tests. Velocities were measured with a Sierra, Model 441 hot wire anemometer. An anomemeter was used to record the air speed and smoke traces were used to determine direction. The volumetric flow rates Q_v and Q_r were computed from measurements of the velocity profile at selected points in the ductwork downstream of the plenum chamber. The booth will shortly be installed in a commercial foundry where full-scale measurements of velocity and particle concentration will be conducted under normal grinding conditions.

no recirculation

With no recirculation ($Q_r = 0$) the velocity v_x was found to be uniform and directly proportional to the ventilation flow rate Q_v except within a small distance of the slot plane, i.e. $121.9 \text{ cm} \leq x \leq 152.4$ cm. Figure 2 shows the average centerline velocity at various distances directly in front of the suction port for the two slot configurations used in enclosures A - F and experimental data from Baturin.[6] So long as the ratio of the upstream distance to the hydraulic radius exceeds 2, the data in Figure 2 correlates with an expression given by Baturin,[6]

$$v_x = 0.3\, v_s\, [(152.4 - x)/b]^{-1} \quad (1)$$

where

$(152.4 - x)/r_h > 2$

r_h (hydraulic radius) = slot cross sectional area/slot perimeter

$(152.4 - x)$ = distance upstream of the slot, x in cm

b = slot width in cm.

Figure 2 and equation (1) show that the larger the slot width, the longer the region directly in front of the slot in which the air velocity is influenced. The length of the region directly in front of the slot in which the air velocity component perpendicular to the slot is large, will be called "reach". The phrase is a metaphor just as its counterpart "throw" is a metaphor in HVAC technology. Both phrases are qualitative but may aid the designers' intuition. For a particular slot velocity, designers should choose a single slot instead of multiple slots of the same total cross sectional area. The only virtue to multiple slots of the same cross sectional area is that for a particular ventilation flow rate, the region in which the air flow is influenced is more uniformly distributed over the plane of the slots.

At distances 137.2 cm $\geq x \geq$ 121.9 cm, the air velocity is only mildly dependent on the slot geometry, and at $0 \leq x \leq$ 121.9 cm, the velocities are independent of the slot geometry and depend only on the ventilation flow rate Q_v.

It is obvious that the higher the ventilation flow rate, the better the control of particles. Less obvious is knowledge of which slot configuration achieves the best control for any given flow rate. Figure 2 and equation (1) suggest, and later calculations by Bennett et al.[8] confirm, that the optimum slot configuration is one which produces a large localized region of high velocity into which the bulk of the swarf passes. Viscous forces quickly damp the relative velocity between particle and air, and once reduced even low air velocities elsewhere in the booth will remove particles from the booth. A large "reach" exposes particles to a localized region of high air velocity. By locating a single, wide slot near the swarf, the bulk of the particles will be slowed. A large "reach" also implies the existence of regions elsewhere in an enclosure (of constant cross sectional area) in which the velocity components perpendicular to the slot plane are small. These regions do not impede particle control because the velocity components in the other directions may be large to damp particle motion or secondly, these low velocity regions may be far from the operators breathing zone. To minimize the existence of low velocity regions, the grinding booth should converge near the slot plane as shown in Figure 1.

booths with recirculation

The recirculation of cleaned air is inherently attractive. In addition to conserving energy, recirculated air stream can act as a jet pump (of low efficiency) that aids the exhaust fan drawing air through the suction ports. The designers task is to choose the proper value of the recirculated flow rate (Q_r) for the booth configuration and ventilation flow rate (Q_v) that have been selected. Figure 3 shows the velocity profile at

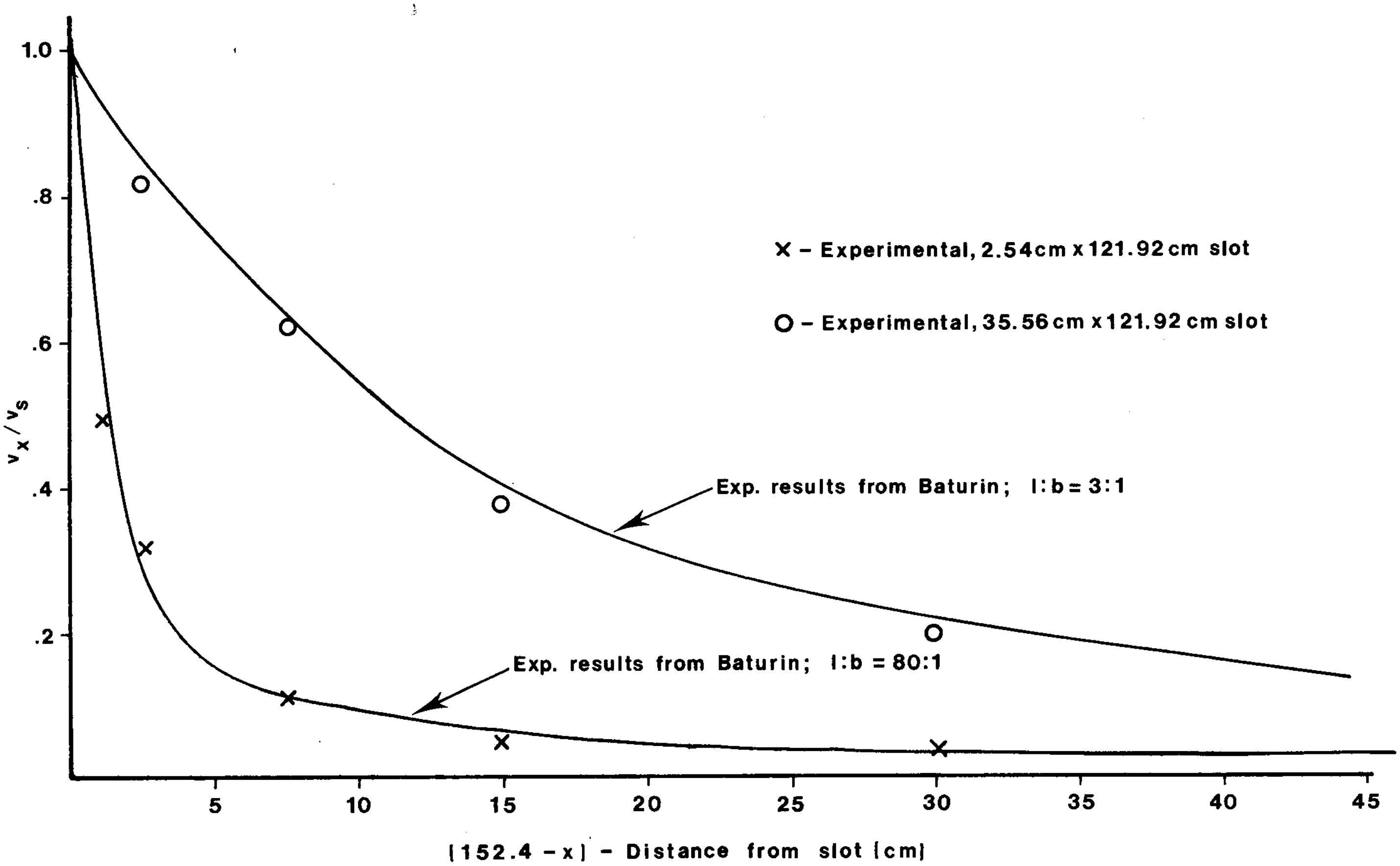

Figure 2 — Center line velocity upstream of slot.

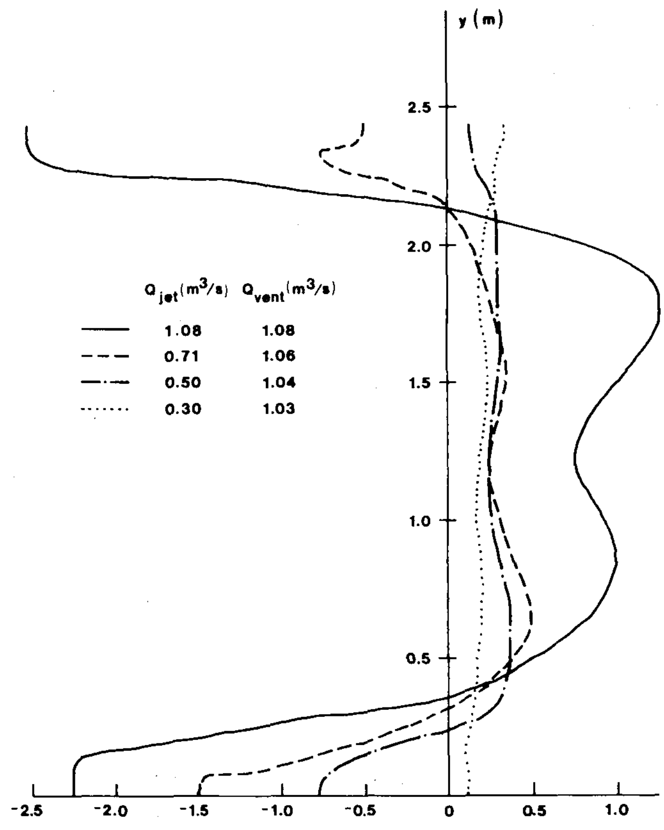

Figure 3 — Velocity profile at booth inlet (x = 0 m, z = 0.305 m) for configuration B at various jet volumetric flowrates.

the inlet of booth B for various values of Q_r/Q_v. Above a value of Q_r/Q_v equal to 0.29 there is reverse flow at the inlet and air travels outward from the booth. Similar curves were obtained for Configuration D. Based on these data, it is concluded that Q_r/Q_v should be approximately 0.25 in order to satisfy the first design criterion for Configuration B and D.

To satisfy the second design criterion it is necessary to determine if there are eddy regions within the booth. Unless a three dimensional hot wire anemometer is used, the simple measurement of the average velocity will be misleading. Even if such equipment is used, the reduction of data is a formidable task. A quick and useful way to acquire information for design purpose is to use smoke traces. Air bubbled through an NH_4OH solution and then passed over an HCl solution produces a steady stream of white NH_4Cl that can be seen easily. Such studies showed that along a horizontal xz plane, 121.9 cm above the booth base (the approximate height of a worker's head while grinding) that a large eddy region existed in the center of the booth for Configurations B and D at Q_r/Q_v = 0.25. It was also determined that the best way to recirculate air was to introduce it uniformly at the booth inlet. What remained unknown was whether it was better to introduce it from numerous jets around the full perimeter of the booth entrance or merely from the top.

Velocity profiles were measured at the booth inlet for various Q_r/Q_v and graphs similar to Figure 3 were obtained for Configurations E and F. In both cases reverse flow did not occur at $Q_r/Q_v \leq 0.25$. Observations of smoke traces showed that both Configurations E and F produced smaller eddy regions than B and D at the same Q_r/Q_v but that the

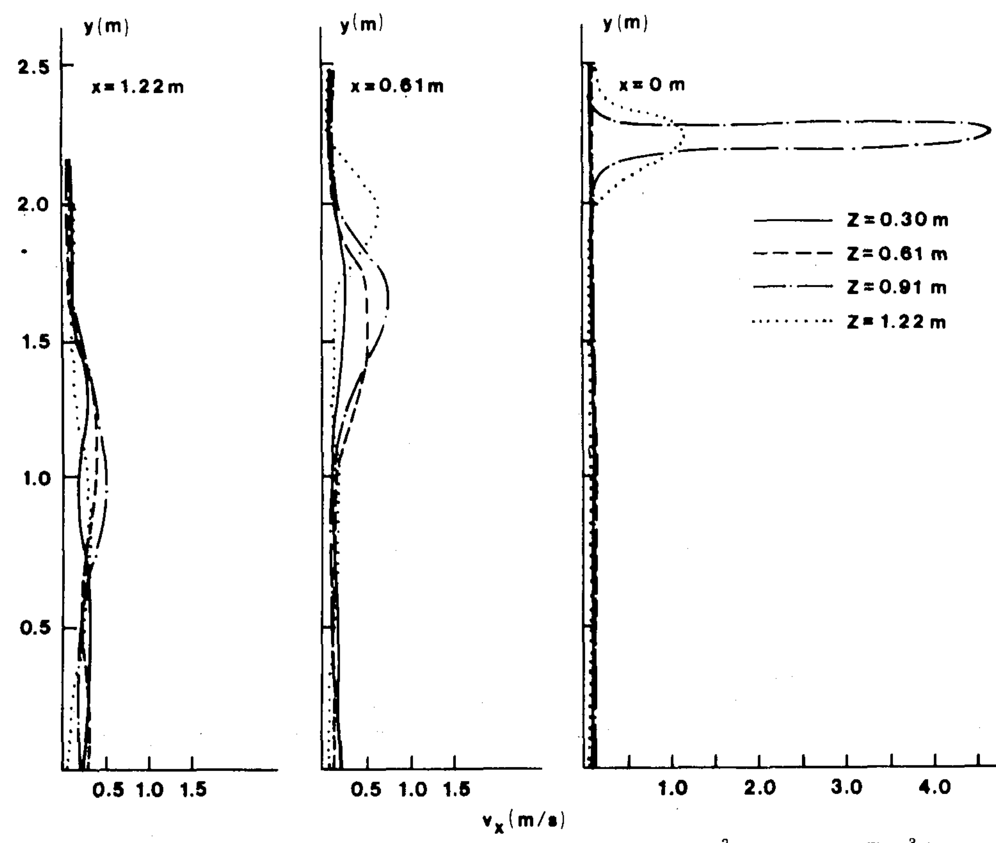

Figure 4 — Velocity profile configuration F, Q_r = 0.07 m³/s, Q_v = 1.07 m³/s.

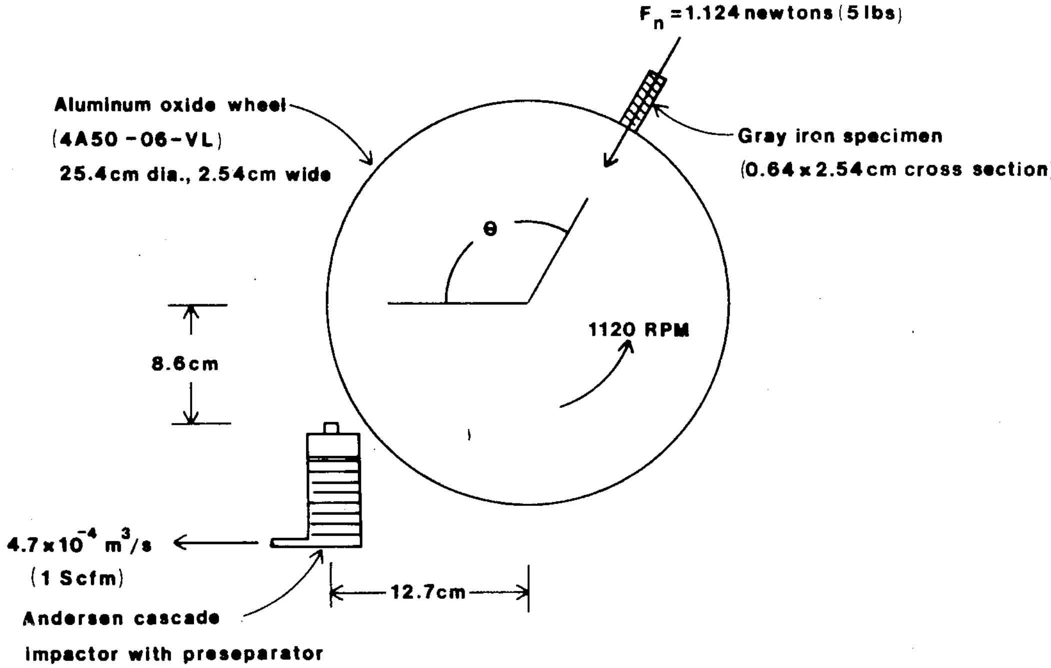

Figure 5 — Swarf experiments.

eddy region was smallest for Configuration F. Figure 4 shows the velocities throughout the booth. For distances closer to the slot face, velocities shown in Figure 2 apply.

swarf experiments

In addition to the swarf (principal stream of particles from grinding wheel), Innes[10] found that particles leave the grinding wheel over its entire surface. Thus the wheel can be considered analytically as a generator from which different size particles, in varying amounts enter the air with the wheel's tangentially velocity. Computer-aided design codes require expressions for,

(a) local particle generation rate ($\dot{m}_g$) as a function of location (θ) on the wheel's periphery,
(b) particle size distribution at these locations.

Without this information, particle trajectories and concentrations cannot be computed. A series of duplicate experiments were conducted in quiescent air in which particles in the wheel's boundary layer were sampled with an Andersen cascade impactor at locations θ degrees from the work piece. Figure 5 gives the details of the experiments.

local generation rate

Figure 6 shows that the rate at which particles are collected decreases rapidly with increasing values of θ.

The collection rate at $\theta = 45°$ is only 1/6 the value in the swarf itself ($\theta = 0$).

It is suggested that the local particle generation rate can be expressed as

$$\dot{m}_g(\theta) = G(\theta)\,\dot{m}_r \quad \textbf{(2)}$$

where $\dot{m}_r$ is the overall metal removal rate of metal and $G(\theta)$ is a distribution function that describes what fraction can be expected to enter the air at a position on the wheel θ degrees displaced from the point of contact between wheel and metal. Based on Figure 6 it is furthermore suggested that a good approximation of $G(\theta)$ can be obtained from

$$G(\theta) = \dot{m}_i \Big/ \int_0^{2\pi} \dot{m}_i \, d\theta \quad \textbf{(3)}$$

where $\dot{m}_i$ is the rate at which mass was collected from the wheel boundary layer at location θ. Using the data of Figure 6 and equation (3), the distribution function $G(\theta)$ can be expressed as

$$G(\theta) = 0.169932 - 3.53\text{x}10^{-3}\theta + 0.2279\text{x}10^{-4}\theta^2 - 0.398\text{x}10^{-7}\theta^3 \quad \textbf{(4)}$$

for θ from 0 to 90 degrees.

It was not possible to sample isokinetically, and in addition the impactor did not remove the entire boundary layer. In spite of this, a value of 0.762 g/min was obtained for the denominator of equation (3) which was 67% of the measured specimen metal removal rate ($\dot{m}_r$) of 1.134 g/min. Consequently the expression for $G(\theta)$ is believed to be a good first approximation, it will be weakest for $\theta \leq 15$ degrees.

For grinding applications where the metal removal rate ($\dot{m}_r$) is not measured or otherwise known, it is recommended that a theoretical value can be used. Hahn and Lindsay[11-13] recommended an expression.

$$\dot{m}_r = \Lambda\, F_n \quad \textbf{(5)}$$

The term (F_n) is the normal force between work piece and wheel and Λ is the metal removal parameter that can be either measured or computed from empirical expressions that depend on wheel RPM and the physical properties of wheel and metal. It is not possible to generalize Λ, Hahn and Lindsay[11-13] give values for cast iron from 0.001 to 0.020 in^3/min when F_n is measured in pounds and $\dot{m}_r$ in in^3/min. A value of 0.002 in^3/ min was obtained in experiments (Figure 6) with a clean specimen of gray cast iron.

Both wheel and metal abrade during grinding. Measurements by Hahn and Lindsay[13] show that for cast iron, only 2% of the particles are wheel fragments. In the case of foundry sand clinging to a casting's surface, it is known that a significant number of the airborne particles are sand. In this case the value of Λ will have to be amended.

Experiments were not repeated for different values of (F_n), wheel speed and physical properties of wheel and metal. It is suspected that the function $G(\theta)$ is not terribly sensitive to these variables. For design, it is recommended that equation 3 and Figure 6 be used for all grinding conditions since the uncertainty in (F_n) and Λ is larger than the uncertainity of $G(\theta)$.

size distribution

The inability to sample isokinetically prevented an analysis of the size distribution. The majority of the particles were captured in the preseparator. At $\theta = 15°$, 90% of the particles were collected in the preseparator and at $\theta = 120°$, 71% of the mass was collected in the preseparator. Since the tested specimen was clean, it is not possible to speculate about the size distribution of particles obtained by grinding gray iron castings containing foundry sand on their surface.

other factors affecting booth performance

plenum

The sole function of the plenum chamber is to create a uniform velocity across the face of the suction ports. The design is not critical so long as this function is fulfilled. Multiple slots require a thinner (dimension perpendicular to the slot face) than a single slot of the same cross sectional area. A slot wider than 4 inches will require either a plenum chamber thicker than 1 foot or the installation of internal turning vanes. The velocities across the slot face should be checked experimentally to insure uniformity .

wakes

On the lee side of the worker, workpiece, tools, etc. there will be a region of low velocity, i.e. wake. Respirable particles which travel to the wake will remain there for quite some time. If the wake is in the operators breathing zone, the health hazard is large. Wakes will have to be treated on an individual basis either experimentally or analytically.

It is believed that the best remedy for wakes is to continue the use of an air purifying helmet with face shield. A well designed booth lessens the function present helmets are asked to perform. Helmets have other important features that are often overlooked;

(a) provides eye and face protection,

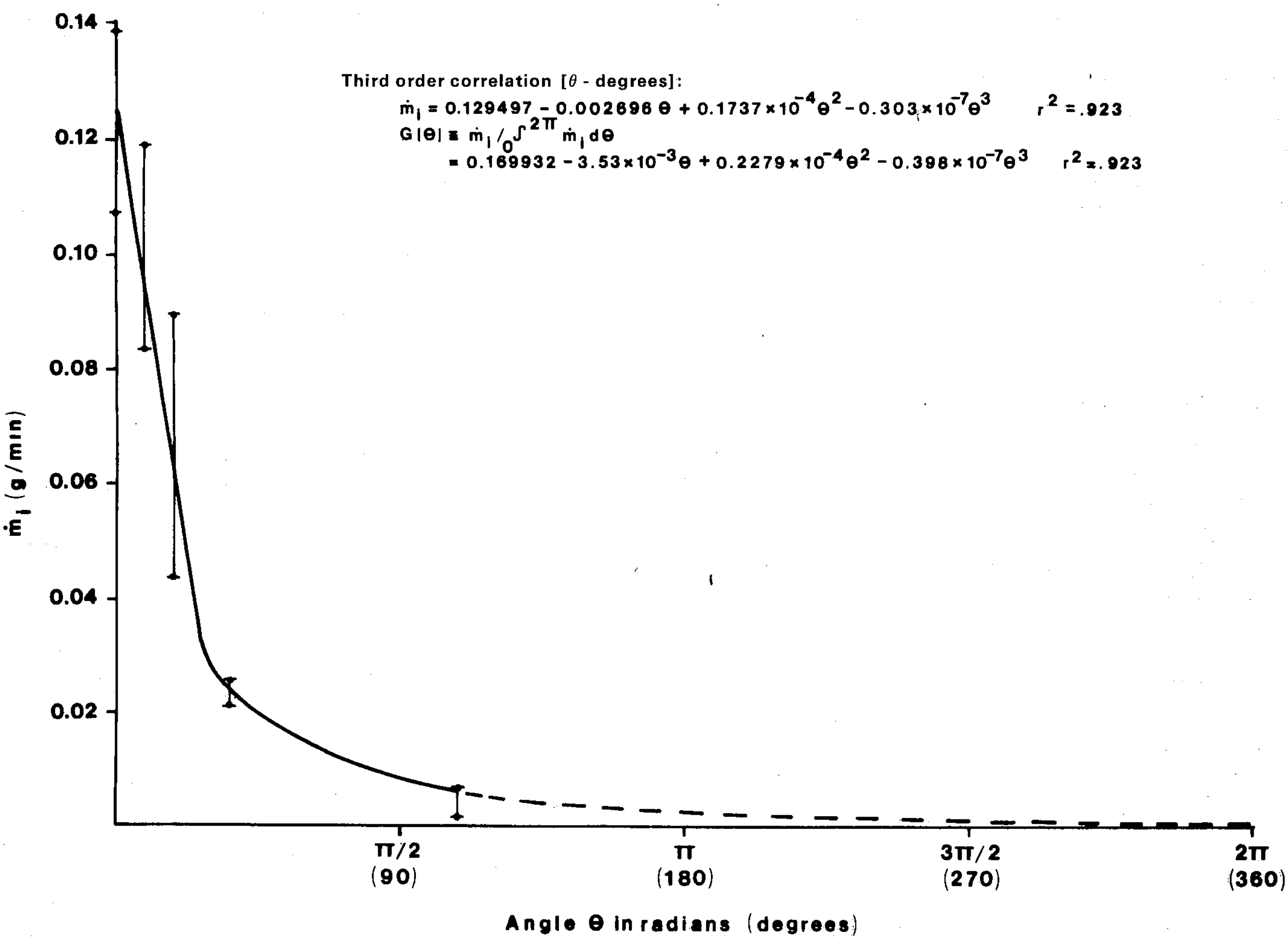

Figure 6 — Particle collection rate as a function of angle θ.

(b) reduces noise,
(c) provides a steady stream of cool, clean air for the worker's head,
(d) prevents dust from collecting in the worker's hair, ears, skin, etc., which could be inhaled or ingested later during rest periods and meals.

room air currents

A systematic study of how room air currents affect booth performance was not undertaken. Analytically it is easily studied since the designer can input a skewed velocity profile at the booth inlet and compute the new velocity field, particle trajectories and concentrations in the booth. If designers anticipate capricious air currents, the depth of the booth should be increased.

lighting and noise suppression

The inside surfaces of the booth should be faced with sound absorbing materials. A number of commercial products are available. Since face shields impede vision, it is very important that illumination be good. Shatterproof flourescent light panels should be installed flush with the three slanted walls of the booth as shown in Figure 1.

grinding benches

The choice of a grinding bench is left to the discretion of the user. A simple bench to support the casting may be enough or one may wish to use a down-draft grinding bench. A down-draft bench is purely a supplementary device and in no way replaces or reduces the function performed by the booth itself. The design and ventilation requirements of the booth should not be reduced to accommodate a bench. If a down-draft bench is used, the fan requirements of the overall system must be increased or a separate fan used for the bench. A down-draft bench will have a grated top to support the casting with a plenum beneath to collect large particles. The down-draft bench should have no vertical sides extending above the top surface in order to prevent wake regions from forming.

exhausts from pneumatic tools

Exhaust from pneumatic tools are noisy and resuspend particles adhering to surfaces. Such exhausts may be as serious a source of particle generation as grinding. It is recommended that exhausts from tools be ducted directly into the plenum.

housekeeping

The most overlooked method to control contaminants is good housekeeping. All surfaces within the booth should be cleaned regularly and systematically.

recirculated air

The exhausted air (Q_v) can either be cleaned by a fabric filter recirculated to the booth by blowing jets (Q_r), returned to the workplace as makeup air, or discharged to the atmosphere. It is not recommended practice to allow filtered air to be returned to the workplace. If the particles are toxic, recirculation to the workplace is not permissible.

conclusions and recommendations

To control particles generated by portable hand-held grinders and large castings, it is recommended that the grinding booth shown in Figure 1 be adopted and operated as follows:

Slot design:	single slot, 0.46 m (1.5 ft) high by 1.22 m (4 ft) wide, centered 0.84 m (33 inches) above the floor
Exhaust volumetric flow rate (Q_v):	3.78 m^3/s (8000 SCFM)
Recirculation flow rate (Q_r):	0.95 m^3/s (2000 SCFM)
Recirculation jet design:	Configuration F

The recommended design is basically Configuration F, but with a single large slot and exhaust flow rate that corresponds to a booth face velocity of 0.51 m/s (100 FPM). Exhaust flow rates less than this result in booth performance sensitive to room air currents. The recirculation flow rate should be no greater than 25% of the exhaust flow rate. Once installed smoke tracer tests should be performed and the recirculation flow rate adjusted to satisfy design criteria discussed earlier.

The local rate at which grinding particles are injected into the air varies with location on the wheel periphery as well as several operating variables and physical properties of grinding. The local rate of particle generation can be estimated from the metal removal rate and a distribution function $G(\theta)$ given by equation (4).

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nomenclature

b — slot width
F_n — normal force between workpiece and wheel
l — slot length
$\dot{m}_i$ — rate at which particles are collected by impactor
$\dot{m}_g$ — rate at which particles are generated on wheel surface
$\dot{m}_r$ — metal removal rate
Q_r — recirculation volumetric flow rate
Q_v — ventilation volumetric flow rate
r_h — hydraulic radius, cross sectional area/perimeter
t — time
v_x — velocity in x-direction
v_s — slot velocity
x,y,z — spatial coordinates (cm)
  x — distance in direction of flow
  y — vertical height above booth floor
  z — transverse distance
Λ — metal removal parameter
θ — angle (degrees)

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