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USING LOW-VELOCITY AIR PATTERNS TO IMPROVE THE OPERATOR'S ENVIRONMENT AT INDUSTRIAL WORK STATIONS

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ABSTRACT

A supplied air system that provides additional control (SASPAC) for industrial operations that have existing local exhaust or general ventilation types of control is described. The system can also serve as a primary means for controlling exposure to contaminants and has the capability of producing significant control for physical hazards associated with hot work environments. Essential to the design of the system is the aerodynamic performance of the supply air distribution plenum, where uniform discharge velocities of 200 fpm or less provide dramatic improvements. This was accomplished without excessive pressure drop requirements or use of expensive high-pressure filter distribution techniques. The simplicity of the distribution plenum design and the uniformity of the performance attained make it possible to adapt the system to a wide range of work stations.

INTRODUCTION

Employers are required under the "General Duty" clause of the Occupational Safety and Health Act of 1970 to provide a place of employment free from recognized hazards (OSH Act of 1970, 29 USC 651-78). These potential occupational health hazards include exposures to both chemical and physical agents.

In industry, the use of general ventilation to dilute airborne concentrations of contaminants to acceptable levels and the use of local exhaust ventilation to capture potentially hazardous materials at their point of origin are two of the fundamental principles of industrial hygiene engineering.[1,2] Many texts and reference manuals are available that provide data on dilution ventilation, hood design exhaust quantities required, and capture velocities recommended for controlling work emissions for many typical industrial operations. There are, however, other factors besides these basic design criteria that influence the containment efficiency of a local exhaust system. These interferences include the disruption of control air patterns by the presence of the worker at the work station, variation in employee work practices, cross-drafts, and environmental stresses such as heat and humidity.[3,4,5] Many of these problems may be eliminated and/or minimized by designing closed systems; however, not all industrial processes lend themselves to this approach.

Many factors influence the achievement of optimum contaminant control and the minimization of employee exposures to toxic materials and physical hazards. These factors include normal variations in airflow associated with exhaust system operations, such as air volume changes due to increases in filter resistance; the worker's influence on the air patterns; variations in employee work practices; environmental factors (e.g., heat and humidity); or the use of disturbance sources, such as high-velocity pedestal fans.

It is the purpose of this paper to describe a technique using controlled low-velocity supply air patterns in the work zone to minimize the adverse effects of the interference factors mentioned above for work stations where remote control techniques or isolation of the worker cannot be implemented, the end result being an improved work environment that assures the worker optimum control of the potential hazards associated with his or her work. Typical work station applications could include weighing, mixing, loading, bag-filling, and spray-painting sites, as well as other material transfer points.

The ventilation system developed in this research addressed the gap that currently exists in the area of contaminant and/or climate control for the industrial operations that cannot be enclosed or isolated. It has been demonstrated that low-velocity controlled auxiliary air may be used to assist local exhaust or general ventilation systems, resulting in a minimization of exposure to a potentially hazardous substance. This system also optimizes the worker's environment by reducing the physical effects of heat and humidity. The system in this research is known as SASPAC (supply air system providing additional control).

RESEARCH METHODOLOGY

The development and design of SASPAC encompassed essentially six stages. First was the characterization of a typical work station so that a working model could be established. Parameters were set based on principles outlined in ergonomic work station design literature as well as personal observations of actual work sites. Second, it was necessary to design a supplied air dispensing system to distribute clean air in uniform, controlled, low-velocity patterns throughout the operator's breathing zone within the primary work station. The third stage involved a qualitative performance evaluation of the dispensing system using smoke tube and smoke candle tracer tests. During this stage, the velocity of air entering the SASPAC plenum was varied up to 2100 fpm and the SASPAC outlet velocity was varied from 50 to 300 fpm. Stage four looked at the effect of temperature variations between ambient and supply air on the vertical vector of air from SASPAC.

Stage five involved the selection of a gas tracer and concentration measurement techniques for quantitative evaluation of control provided by plenum design. The sixth and final phase of the project used the chosen quantitative techniques to look at the effect of the supply air distribution by the plenum on simulated industrial operations. These included one with a local exhaust enclosure, another with generation of tracer from a point source with only general room ventilation, and, last, one

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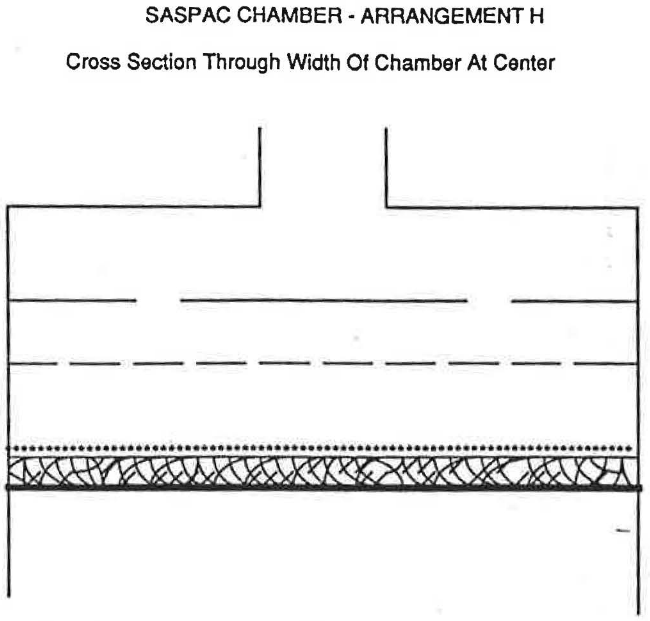

Overall Chamber 40"long x 19.5" wide x 16 "high

Inlet diameter: 10 inches

First Slot plate has two 2" slots

Second slot plate has nine 1/2" slots

One perforated panel with 1/4" holes on 1/2" centers

Two inch layer of glass fiber filter material
supported by an egg crate with 1/2" square openings

NOTE: Sketch is not to scale

Figure 1 *Schematic representation of SASPAC air dispensing system*

from a non-point (general room) contamination source with only general room ventilation.

Work Station Size

In designing a work station, it is vital to have knowledge of the range of human movement for all operations performed. This is necessary because in the field of ergonomics, the work area must be designed for near, intermediate, and far accessibility, and the station must be organized so that the most common tasks are performed close to the operator and the less frequent tasks are further away.[6] Another concern for a person designing work stations is that most of the anthropometric data used are derived from young, healthy, male Caucasians, commonly in the military services, and tend therefore to be specific to a selected group.[6]

Since there is so much variability in the potential size for a work station, a generally sized system was chosen based on personal observations made during industrial hygiene field experiences. Operators at mixing stations were observed to move in approximately a 5 to 8 square foot area while performing their usual tasks. The ventilation system prototype was designed to fall within this range and allow variations to provide the average discharge velocities desired using the air-handling system available. Since the discharge velocity parameters required uniform distribution, it was believed that the design would be adaptable for any size of operation once the proper air distribution system had been developed and disturbances from other sources controlled or eliminated.

Prototype Design

The actual prototype consisted of a plenum 40 in. long by 19.5 in. wide by 16 in. high. Various plate designs that distributed the air across the length and width of the plenum along with a perforated plate that provided a uniform distribution from the plenum discharge were evaluated. Figure 1 is a schematic of the final plenum design.

The design criterion of most importance is the need for uniform air distribution throughout the length and width of the supply air plenum. With a 10-in. duct and a maximum incoming air velocity of approximately 2000 fpm (for control of air noise and friction loss), the maximum volume of air for this prototype is 1100 cfm.

In an attempt to achieve the longitudinal distribution, the initial slot plate was designed to reduce the 2000 fpm inlet velocity to 1000 fpm. For the 40-in.-long plenum, a total slot width of 4 in. is required. Plate designs evaluated were therefore limited to total slot widths that varied from less than 4 in. to not more than 4.5 in. while maintaining a 40 in. slot length for all slots.

Although many configurations were tried, detailed evaluations were made on configurations of four equally spaced 1 in. slots, nine equally spaced ½-in. slots, two equally spaced 2-in. slots, a single 2-in. slot along the center of the plate, and a combination of these plates in series. In addition to the slot plates, a perforated plate (¼-in. fiberboard) and a fiberglass filter were used to attain more uniform distribution of air discharging from the plenum. Table 1 lists the eight different slot plate, perforated plate, and filter combinations examined.

TABLE 1
Plate Configurations for Various Plenum Designs

CONFIGURATION	SLOT PLATE	PERFORATED PLATE
A	(4) 1-in. slots	1/8-in holes on 1-in. centers
B	(4) 1-in. slots	¼-in. holes on ½-in. centers
C	(9) ½-in. slots	¼-in. holes on ½-in. centers
D	(2) 2-in. slots	¼-in. holes on ½-in. centers
E	(1) 2-in. slot	¼-in. holes on ½-in. centers
F	(1) 2-in. slot (9) ½-in. slots	¼-in. holes on ½-in. centers
G	(2) 2-in. slots (9) ½-in. slots	¼-in. holes on ½-in. centers
H	(2) 2-in. slots (9) ½-in. slots	¼-in. holes on ½-in. centers 2-in. low-resistance glass fiber filter

Supply Air Calibration System

In order to characterize the performance of the SASPAC plenum, a calibrated airflow system was used. This system included a fan, a straight run of 9 in. duct, and a calibrated sharp-edged orifice (see Figure 2). The orifice was calibrated using a standard pitot tube through a range of air volumes from 400 cfm to 1100 cfm. A calibration curve was developed illustrating the relationship between the pressure drop across the orifice and a corresponding air volume flowing through the system.

Qualitative Evaluation

Smoke tubes were used to visually evaluate the vertical vector air pattern observed beneath the SASPAC plenum. Next, a face velocity profile of the discharge from the plenum was taken via a 56-point traverse using a hot wire anemometer. After an acceptable air pattern was found, the system was then visually evaluated using a smoke candle technique. The smoke candle was placed at the inlet of the SASPAC system and the vertical throw from the plenum, while maintaining a well-defined column of smoke, was noted.

Quantitative Evaluation

The SASPAC plenum's ability to provide control was quantified using a tracer gas technique based on the methods suggested by Fuller and Etchells,[4] Caplan and Knutson,[7] as well

TABLE 2
Aerodynamic Performance for Various Plenum Designs

Plenum Design	Air Volume (cfm)	Discharge Velocity ± Std. Dev. (fpm)	Pressure Drop Across Plenum, in. H_2O	Comments
A	580	—	2.5	Pressure drop excessive, Design not acceptable.
B	1100	261 ±92	0.57	Poor distribution.
	1020	240 ±87	0.56	Smoke stick very erratic.
	580	—	0.17	
	400	—	0.08	
C	1060	218 ±94	0.45	Distribution still erratic.
	1050	188 ±79	0.42	No significant improvement.
	705	177 ±58	—	
D	965	211 ±120	0.35	Low pressure but poor distribution.
	705	153 ±97	0.19	
E	985	165 ±120	0.67	Distribution lengthwise better;
	690	126 ±99	0.40	not uniform; static high.
F	990	175 ±60	0.78	Good distribution; not uniform;
	700	133 ±52	0.45	static high.
G	1050	182 ±75	0.36	Good distribution; not uniform;
	700	133 ±49	0.29	low static.
H	1000	168 ±22	0.57	Best overall performance; uniform and
	700	121 ±15	0.32	smooth. Accept as design.

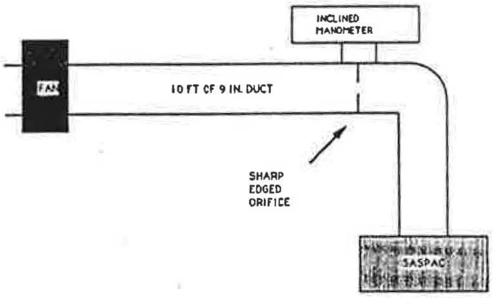

Figure 2 *Supply air system*

as ASHRAE,[8] for the performance evaluation of laboratory hoods. The tracer gas used was dichlorodifluoromethane (R-12). The R-12 was piped to an ejector as described by Caplan and Knutson.[7] The ejector is equipped with a valve and pressure gauge. The tracer gas passes through an orifice that maintains a constant flow at a given upstream pressure. Air entrains through holes in the side of the ejector tube and is distributed through a wire mesh outlet diffuser (R-12 ejector).

The flow rate of the tracer gas is dependent upon the pressure in the system and the orifice size. The orifice used has a diameter of 0.33 mm with an upstream pressure of 50 psi; the R-12 flow rate was 1 liter per minute (L/min). This was verified using a soap bubble flowmeter. Fuller and Etchells report that this release rate results in an R-12 concentration of 12,000 ± 500 ppm at the ejector head.

An infrared gas analyzer was used to obtain instantaneous measurement of R-12 concentrations at all sampling points employed. Calibration of the instrument was achieved using the closed-loop calibration system (CLCS) as recommended by the manufacturer. In this method, known amounts of the tracer gas are injected into the closed system via an injection septum to give known concentrations of the R-12 in the CLCS. The observed light absorbance values were then plotted vs. the corresponding concentrations to develop a standard curve.

The tracer gas technique was used in three separate ways. First, it was used to determine the effect that SASPAC had on the mannequin's breathing zone concentration of R-12 at a simulated industrial operation with local exhaust ventilation. Next, it was used to determine the effectiveness of SASPAC when a point source of R-12 existed and only general room ventilation was available for control and, finally, to determine the effect of SASPAC on the reduction of ambient air contaminant concentrations (from such operations as fabric coating) when only general room ventilation was available for control.

RESULTS

Having set the dimensions (length, width, and height) of the distribution chamber, the size of the inlet duct opening, and the maximum volume of air that was attainable with the equipment available, attempts were made to distribute the air evenly. It was desired to have a uniform and smooth discharge of all air leaving the chamber and to maintain the performance at all flows up to the design maximum.

The distribution along the length and width of the chamber was achieved by use of slot plates, perforated plates, and combinations of both. As each combination was tested, multi-point (56) air velocity readings were obtained in the horizontal plane at the chamber discharge. These readings were taken using a hot wire anemometer, and the mean and standard deviations were used to characterize uniformity. Smoke tubes were also used to identify the air vectors and smoothness of air flow. The static pressure was also measured across the chamber (including inlet) as it was desired to achieve performance with reasonable system losses. Based on losses noted by laboratory furniture manufacturers for operation of their supply air laboratory hoods, which ranged up to 0.75 in. wg at design flows, it was deemed acceptable to use this figure as the upper limit.

In Table 2, the results of the tests made on the eight major plenum configurations have been compiled along with comments on the aerodynamic performance attained. With configurations E and F, which use a single 2-in. slot plate, the distribution lengthwise required unacceptable static pressure losses. However, when combinations were employed using arrangements of multi-slot plates, an acceptable performance could be obtained within the static limitations proposed. Design G, which incorporated a plate with two 2-in. slots coupled with the nine ½-in. slot plates and a perforated plate with the ¼-in. holes on ½-in. centers, provided very good distribution and the static pressures were well within design limitations. The final design, H, added a 2-in. layer of low-resistance glass fiber filter, which provided a very uniform, smooth airflow over the entire range of air volumes used (see Table 2).

The operation and performance attained were qualitatively evaluated using smoke sticks and smoke candles. The smoke stick identified the "column" of clean air that was maintained under the SASPAC plenum. The smoke candle tests showed the smooth uniformity of air as it was discharged and how this was maintained for 5 or more feet below the discharge point.

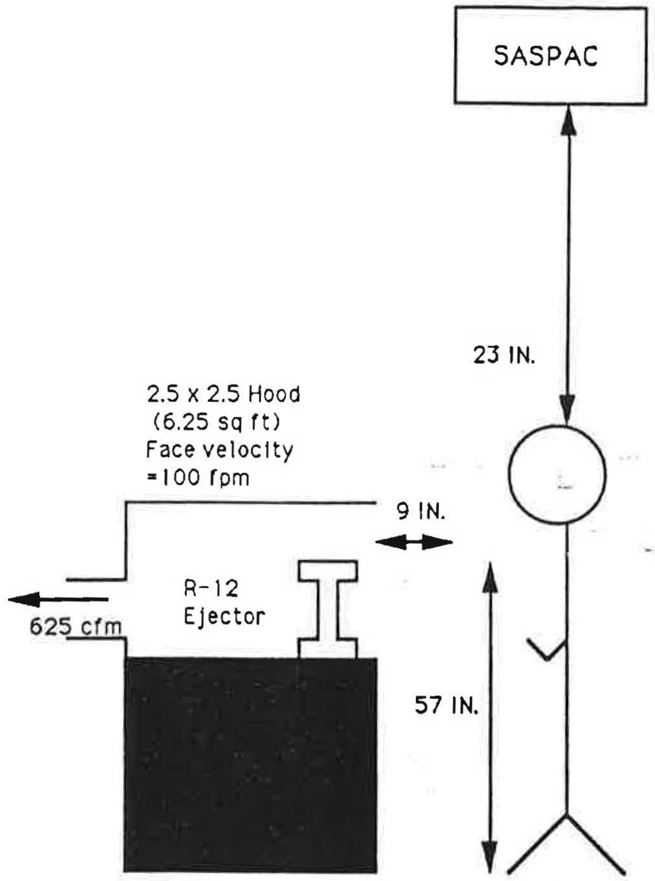

Figure 3 *Local exhaust hood setup*

Effect on Local Exhaust

The prototype of the distribution chamber was tested in a simulated industrial situation, where a contaminant source is enclosed and ventilated but the operator is required to work at the hood and other minor acceptable interferences occur, such as co-worker traffic, that might affect control.

The test arrangement had the R-12 ejector and R-12 tank enclosed in a small bench-type hood (2½ ft wide by 2½ ft high by 2½ ft deep) that vents to the outside atmosphere, and, when the exhaust system is "on," a face velocity of 100 fpm is maintained at the hood opening (see Figure 3).

The mannequin was stationed in front of the hood, and, using a smoke stick in the breathing zone, the air movements were demonstrated under various conditions. The first set of conditions had the SASPAC chamber located 23 in. above the mannequin but not operational, local exhaust ventilation off, and no R-12 generation. The air currents indicated by the smoke stick revealed no set direction to the air currents in the breathing zone (essentially still-air conditions).

The local exhaust was then turned on and one "walk by" was made behind the mannequin. Using a single smoke stick, fair control was demonstrated as indicated by the smoke trails into the hood, but there was also some minor turbulence and kickback observed at the breathing zone level.

For test three, all conditions of the operation noted above were maintained but SASPAC was also turned "on" at a low flow rate (560 cfm). An improved vector at the breathing zone and control vector toward the hood were evident. The smoke trails from the stick were conveyed directly into the exhaust hood and no kickbacks or turbulence were noted.

The added control achieved in these qualitative tests was evaluated quantitatively using the R-12 diffusion system and infrared gas analyzer procedures mentioned earlier. These results are compiled in Table 3. For all of these tests, an average face velocity of 100 fpm was maintained for the local exhaust hood, the R-12 ejector flow was 1 L/min, and the reduced concentrations were achieved within one minute after the SASPAC was turned on.

TABLE 3
SASPAC—Effect on Local Exhaust Hood Performance

SASPAC Plenum Discharge Velocity fpm	Breathing Zone Concentrations *LEV On SASPAC Off ppm	LEV On SASPAC On ppm	Percent Reduction
180	60	<0.01	>99
130	30	1	97
104	60	7	88

* LEV: Local Exhaust Ventilation

The initial tests resulted in even lower breathing zone concentrations (i.e., better control) than the averages reported here for all SASPAC airflows. The gradual increase may be the result of re-entrainment of R-12, because the exhaust system outlet and the supply air system inlet were less than 10 ft apart.

The results in Table 3 do, however, indicate that the use of SASPAC to control air vectors at the work station does dramatically improve the overall protection provided in all cases.

Effect on Breathing Zone Concentrations from a "Point" Source

The use of the SASPAC plenum for worker environment control was also evaluated when a point source of contamination existed and only general room ventilation was available for control. To evaluate this potential, the technique of Fuller and Etchells noted earlier for the testing of laboratory hoods was used. The mannequin was positioned so that it was 9 in. away from the diffuser, and all samples were taken at the breathing zone level, which was 57 in. above the floor level. The ejector flow was maintained at 1 L/min and no local exhaust was provided. The discharge of the SASPAC plenum was 23 in. above the mannequin for all tests (see Figure 4). Refrigerant concentrations in the breathing zone were measured, then the SASPAC chamber was turned on. The R-12 concentrations were measured one minute after the system was turned on, and measurements were taken for 10-minute periods. The "source" was maintained for the entire period.

The results have been compiled in Table 4 and indicate that significant improvement can be achieved for operations in this category. Examples would be brazing, printing press operations, some machining, coating, degreasing, etc.

Effect of SASPAC and Plenum Height on Breathing Zone Concentrations from "Non-Point" Source

The use of SASPAC to reduce potential exposures when there is general area contamination from a non-point source was evaluated by generating a high tracer gas concentration throughout the entire test room, turning on SASPAC, and then measuring the breathing zone concentrations over time while maintaining the source of general contamination. An attempt was also made to determine how the distance between the outlet of the chamber and the mannequin influenced the control achieved. It was observed that the concentrations in the breathing zone after SASPAC was turned on showed a significant reduction and that exposure levels stabilized in approximately five minutes. The results in Table 5 are the levels maintained after five minutes of operation.

It was also evident that with the higher velocities and the plenum closer to the operator, the control achieved was greater. Since the column of air under the plenum in this test arrangement is subjected to the contaminant on all sides, there is measurable penetration within the column, but potential exposure at breathing zone levels are significantly reduced in all cases. The term "protection factor" may be defined here as the decrease in the amount of contaminant concentration in the worker's breathing zone when SASPAC is in use. The range

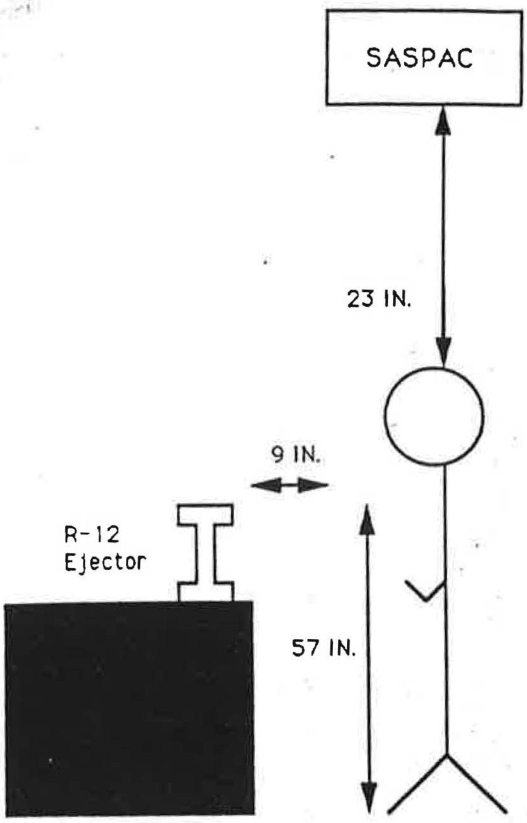

Figure 4 *Point source with general exhaust only*

TABLE 4
SASPAC—Effect on Breathing Zone Concentration from a Point Source with Only General Room Ventilation

SASPAC Plenum Discharge Velocity fpm	Breathing Zone Concentrations SASPAC OFF ppm	SASPAC ON ppm	Reduction Factor
180	>300	<0.01*	30,000
100	>300	<0.01*	30,000

* None Detected

of protection factors went from a low of 7- to a high of a 50-fold reduction.

The penetration becomes fairly uniform throughout the air column after extended operating times. This was confirmed by centerline measurements along the length and width of the air column at bench level after 20 minutes of operation with the plenum set 18 in. above the mannequin and with the flow at 180 fpm. The concentrations in this plane ranged from 10 to 22 ppm.

Centerline Velocity Measurements for Various Temperature Differentials

One of the proposed uses of the SASPAC chamber has been for improved worker comfort in hot environments. Since both air temperature and air velocity are two of the main aspects in determining "effective temperature," some data were collected on the "throw" or maintenance of air velocity as air is discharged from the SASPAC plenum. A complete range of temperature differentials between SASPAC-supplied air and room air could not be conducted, as heating and cooling equipment was not available. The evaluations, therefore, were limited to two conditions: (1) where SASPAC air and room air temperatures were the same and (2) where SASPAC air was 25°F below room air temperature. This was achieved by using all room air or all outside air for SASPAC operation. The centerline velocity was measured at 6-in. intervals downward from the outlet edge of the chamber. The final measurement was made 5 ft from the outlet edge (2 ft from the floor). These measurements were recorded for three different airflows and for both temperature conditions. The results have been compiled in Table 6.

It is interesting to note that when there is no differential in temperatures, the velocities are essentially uniform over the entire 5 ft distance. However, when the incoming air was 25°F lower than the room air temperature, the actual velocity measured showed an increase over the 5 ft measurement interval. The incoming air, in this case being denser, "fell" faster. This indicates that introduction of cooler air into a high-temperature environment could prove to be an attractive application for the SASPAC plenum.

SUMMARY AND RECOMMENDATIONS

A supplied air system has been developed that provides additional control for industrial operations that have existing local exhaust or general ventilation types of control. The system is also adaptable as a prime contaminant control technique for special operations where local exhaust cannot be provided and has the capability of producing significant control for physical hazards associated with hot work environments.

Essential to the design of the air system is the aerodynamic performance of the distribution plenum. This required accepting inlet air velocities of up to 2000 fpm and converting it to uniform, smooth, nonturbulent discharge velocities over the range of 50 to 200 fpm. This was accomplished without excessive pressure drop requirements or use of expensive high-pressure filter distribution techniques.

The evaluations conducted indicated that approximately 200 cfm/ft^2 of work station area was the maximum flow requirement for control of anticipated applications and that 80 to 100 cfm/ft^2 of work station area provided significant reductions in hazard potential. The controlled environments extended to 5 ft below the chamber, even at the lower flows.

The simplicity of the plenum design and the uniformity of the performance attained make it possible to adapt the system to a wide range of work station situations. The distribution system

TABLE 5
Effect of SASPAC and Plenum Height on Breathing Zone Concentrations from Non-Point Source with Only General Room Ventilation

SASPAC Plenum Height* in.	SASPAC Plenum Discharge Velocity fpm	Breathing Zone Concentration SASPAC Off ppm	SASPAC On ppm	"Protection Factors"
23	180	600	90	7
18	180	500	20	25
	100	700	100	7
12	180	610	45	13
	100	440	35	12
6	180	600	12	50
	100	410	30	13

* Distance above mannequin

TABLE 6
Centerline Velocity Measurements vs. Distance from Plenum for Various Temperature Differentials

Airflow cfm	Temperature Differentials °F	Velocity at Discharge fpm	Velocity at 60 in. fpm	Range fpm
550	0	80	84	80-92
	25	105	200	105-210
715	0	110	105	100-110
	25	135	200	130-200
980	0	145	140	130-150
	25	180	245	160-245

could also be expanded to include air-cleaning or air-purifying devices if such an application was required for recirculating air systems. The air could also be conditioned and used as a source of make-up air in plants that are lacking sufficient make-up air. In these cases, the "add ons" would be placed on the inlet side of the fan system so that only "clean" air would enter the pressure side of the system including the SASPAC plenum.

Although considerable additional study is needed, there appears to be great potential for use in hot environments, especially those where provision of air conditioning has not been economically feasible. The ability to provide a column of cool air for a work station located in a large, wide open area of high temperature creates many potential applications. Using "throw away" conditioned air from other plant locations, actually providing limited air conditioning, or use of outside sources of cooler air could be incorporated to improve work conditions in many industries.

Additional work that should be conducted would include the testing of other work station parameters, looking at the economics associated with installation of such systems including comparisons with more costly techniques, and detailed evaluations of the performance associated with variation in temperature both below and above ambient temperature. Additional studies should also determine the effect of other interferences, such as cross-currents. If applications were envisioned that required supplying heated air to cooler work stations, then performance of the chamber at higher discharge velocities would be necessary if air was still to be supplied from overhead. The need for increased "throw" would be anticipated to overcome the inclination for the warmer air to rise rather than fall. This also indicates that, for such applications, introducing SASPAC air horizontally or from floor levels may need to be studied.

The SASPAC prototype developed in this work was designed to improve air patterns at the work station by minimizing interferences from normal variations in airflow associated with exhaust system operation: the worker's influence on the air patterns in the work zone, variations in work practices among operators, other health-related factors such as heat and humidity, and use of disturbance sources such as high-velocity pedestal fans. At air velocities less than one-half that reported by other supply air island systems (375 fpm), a significant reduction in contaminant breathing zone concentrations was achieved.[9]

These results indicated that SASPAC has potential applications for work stations with contaminant exposures greater than the allowable time-weighted averages as well as at operations where high-velocity air currents may interfere with performance of local exhaust control systems. This use of low-velocity control air patterns to improve operator environment at industrial work stations will result in the realization of the lowest possible worker exposures to potentially hazardous materials and physical stresses.

ACKNOWLEDGMENT

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DISCUSSION

Charles Costantinou, Senior Mechanical Engineer, Metcalf & Eddy, Manchester, NH: How was the effect of the higher weight of R-12 tracer gas over air compensated for in the experiments–by mixing ahead of supply air discharge, or what?

L.A. Chamberlin: The weight of R-12 was not a factor in these studies. The actual ambient concentration rather than absolute distribution was the main parameter. The special mixing provided by the diffuser, along with the natural air currents, resulted in a gas concentration that was so low that the air vs. gas/air density was not significantly different.