CHAPTER 39

PRINCIPLES OF VENTILATION

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INTRODUCTION

Ventilation is one of the most important engineering control techniques available to the industrial hygienist for improving or maintaining the quality of the air in the occupational work environment. Broadly defined, ventilation is a method of controlling the environment with air flow. In industrial ventilation this air flow may be used for one or a combination of the following reasons:

1. Heating or cooling;
2. Removing a contaminant;
3. Diluting the concentration of a contaminant;
4. Supplying make-up air.

These basic uses of industrial ventilation can be divided into three major applications:

1. The prevention of fire and explosions;
2. The control of atmospheric contamination to healthful levels;
3. The control of heat and humidity for comfort.

All of these applications are important to the industrial hygienist, and each must be understood thoroughly in order to provide safe, healthful and comfortable working conditions. The control of heat and humidity is covered in Chapter 38. This chapter, "Principles of Ventilation," together with Chapters 40, 41 and 42, deals primarily with the control of atmospheric contamination for assuring a healthful work environment.

CLASSIFICATION OF VENTILATING SYSTEMS

The control of a potentially hazardous airborne contaminant by ventilation can be accomplished by either one or both of two methods: diluting the concentration of the contaminant before it reaches the worker's breathing zone by mixing with uncontaminated air, or capturing and removing the contaminant at or near its source or point of generation, thus preventing the release of the contaminant into the workroom. The first of these methods is termed "general ventilation" or "dilution ventilation"; the second is called "local exhaust ventilation." Dilution ventilation does not reduce or eliminate the total amount of hazardous material released into the workroom air; local exhaust ventilation prevents the release of the contaminant within the workroom. Normally, local exhaust ventilation is the preferred and more economical method for contaminant control compared with dilution ventilation.

The differences between dilution and local exhaust ventilation are not always clearly defined. Nevertheless, the following criterion is used in classifying a ventilation system as one type or the other:[1]

> A ventilation system is a dilution ventilation system if the concentration of contaminant in the exhaust air stream is not significantly higher than in the general room air; it is a local exhaust system if the concentration of material in the exhaust air stream is significantly higher than that in the general room air.

General Ventilation

The term "general ventilation" suggests that a room or an entire building is flushed by supplying and exhausting large volumes of air throughout the area. Properly used, general ventilation can be very effective for the removal of large volumes of heated air or for the removal of low concentrations of non-toxic or low toxicity contaminants from minor and decentralized sources. General or dilution ventilation is achieved by either natural or mechanical means. Often the best overall result is obtained with a combination of mechanical and natural air supply with mechanical and natural exhausters.

Natural General Ventilation. The natural means by which buildings or enclosures can be ventilated include wind and thermal convection. These two effects, usually in combination, result from natural pressure differences and air density differences respectively, causing natural displacement and infiltration of air through windows, doors, walls, floors and other openings. Obviously, if it were sufficient, natural ventilation would be much cheaper than mechanical ventilation, but wind currents and thermal convection are erratic and sometimes hard to predict. Therefore, natural ventilation is unreliable as a primary control method. Erratic wind direction alone makes this aspect of natural ventilation undependable as a primary method of solution to any critical dilution ventilation problem.

When the wind is blowing, a pressure is exerted on the upwind side and a suction is exerted on the downwind side of the building. Wind forces can be accurately predicted for a flat terrain, but the determination of wind forces within a cluster of industrial buildings defies the inherent simplicity which design parameters must exhibit to be useful and applicable to ventilation engineering problems.

The amount of air that enters a building under a natural ventilation scheme depends both upon the wind and upon thermal effects occurring within the building. Warmer air inside a building rises and leaks out of openings, cracks, and vents in the upper areas; colder air leaks into the building by the same process in the lower areas, assuming the same degree of tightness throughout.

Thermal (air density) effects are more predictable than wind forces, and these effects can be reduced by calculation to useful engineering parameters.[2,3] Air density differences are often significant in hot, dry, industrial areas such as foundries and steel mills. The combined effect of wind and temperature differences can be significant under certain conditions, and can be characterized quantitatively in some applications.

The design of modern industrial buildings has increased the problem of controlling man's working conditions. Older buildings often provided a significant amount of natural ventilation because they were tall and narrower in width than length. Heated air rose to the roof and was expelled at the top of the building, while replacement air entered the building at the lower perimeter. This type of design is still used in many hot industries such as foundries but obviously this arrangement cannot provide acceptable working conditions under all circumstances.

Mechanical General Ventilation. The modern large-area, low-height industrial plant and most multi-story buildings of masonry and glass construction, present entirely different ventilation problems. In these cases, natural ventilation forces are practically nil, and mechanical ventilation must be relied on almost completely. To this end, mechanical exhaust of contaminated air is required and mechanical air supply must be provided all year round to reach interior areas, provide adequate air distribution and prevent creation of negative pressures in the building.

In large open industrial buildings, general ventilation can be achieved by roof fans used with or without gravity ventilators. Where little or no heat is available to furnish natural ventilation or where roof head-room is low, roof fans should be used in place of gravity ventilators to provide a measure of general exhaust ventilation.

The best method of providing general ventilation in a closed building is to supply air through duct work and distribute it into the work areas in a manner that will provide both humidity and temperature control.

Local Exhaust Ventilation

A local exhaust system is one in which the contaminant being controlled is captured at or near the place where it is created or dispersed. In contrast to dilution or general ventilation, local ventilation places much more reliance on mechanical methods of controlling air flow. A local exhaust system usually includes the use of hoods or enclosures, ductwork leading to an exhaust fan, an air cleaning device for air pollution abatement and finally, discharge to the outside air. Local exhaust systems usually contain more mechanical components than general exhaust systems, offer more operational parameters to be controlled within acceptable ranges, and therefore require more maintenance.

The term "local exhaust" does not necessarily imply that the system is small. For example, the hood over a basic oxygen furnace in a steel mill is a local exhaust hood even though it may exhaust a million cubic feet per minute of air. A local exhaust system is usually superior to general ventilation if the main purpose of the ventilation is contaminant control. These advantages include the following:[2,4]

1. If the system is properly designed, the capture and control of a contaminant can be complete. Consequently, the exposure to workmen from the sources exhausted can be prevented. With general ventilation the contaminant has been diluted when the exposure occurs, and at any given workplace this dilution may be highly variable and therefore inadequate at certain times.
2. The volume rate of required exhaust is less with local ventilation; as a result, the volume of make-up air required is less. Local ventilation saves in both capital investment and heating costs.
3. The contaminant is contained in a smaller exhausted volume of air; therefore, if air pollution control is needed, it is less costly. As a first approximation, the cost of air pollution control is proportional to the volume of air handled.
4. Many local exhaust systems can be designed to capture large settleable particles or at least confine them within the hood and thus greatly reduce the labor required for good housekeeping.
5. Auxiliary equipment in the workroom is better protected from the deleterious effects of the contaminant, such as corrosion and abrasion.
6. Local exhaust systems usually require a fan of fairly high pressure characteristics to overcome pressure losses in the system. Therefore, the performance of the fan system is not likely to be adversely affected by wind direction or velocity, or inadequate make-up air, etc. This is in contrast to general ventilation which can be greatly affected by seasonal factors.

Glossary of Terms in Industrial Ventilation

The following list of terms have a special meaning within the field of industrial ventilation:[2,4,5]

Blast gate. A device for restricting airflow in a duct, usually consisting of a flat sliding plate which moves perpendicularly to the duct center line.

Capture velocity. The air velocity at a point within or in front of an exhaust hood necessary to overcome opposing air currents and particle inertia, causing the contaminated air to flow into the hood.

Coefficient of entry. The ratio of the actual rate of air flowing into an exhaust opening to the theoretical rate, calculated by assuming that the negative static pressure in the exhaust opening is completely converted to velocity pressure.

Control velocity. The air velocity required at the face of an enclosing hood to retain the contaminant within the hood.

Damper. A device for restricting the airflow in a duct, usually consisting of a flat disc mounted on a shaft which is perpendicular to the direction of airflow.

Entry loss. Loss in static pressure caused by air flowing into a duct or hood opening.

Entry loss factor. A factor derived from the coefficient of entry which, when multiplied by the velocity pressure at the hood, yields the entry loss in inches of water gauge.

Exhaust rate. The volumetric rate at which air is removed.

Grain. A unit of weight equal to 1/7000 of a pound.

Micron. A unit of length equal to 0.001 millimeter or 0.0000394 inches.

Plenum. A receiving enclosure for gases in which the static pressure at all points is relatively uniform.

Reynolds number. A dimensionless parameter computed by dividing the product of pipe diameter, average velocity and fluid density by the fluid viscosity.

Slot velocity. Linear flowrate of air through a slot.

Standard air. Dry air at 29.92 inches of mercury absolute pressure and 70°F, weighing 0.075 pound per cubic foot.

Static pressure. The pressure of a fluid exerted in all directions equal and opposite to the pressure tending to compress the fluid. In ventilation applications, static pressure is usually the difference between the absolute pressure in an exhaust system and atmospheric pressure, such that static pressure less than atmospheric pressure is termed "negative static pressure."

Still air. Air with a velocity of 25 feet per minute or less. Under practical circumstances there is always random air motion of 10 to 20 feet per minute even in rooms regarded as tightly constructed. This non-zero convection results from thermal circulation due to temperature differences, leakage in the building due to wind pressure and thermal head, and the ordinary movement of people.

Tempered air. Supply air which has been heated sufficiently to prevent cold drafts.

Total pressure. The algebraic sum of static pressure and velocity pressure.

Transition. A change in the cross-sectional shape or area of a duct or hood.

Transport (conveying) velocity. That velocity required to prevent the settling of a contaminant from an air stream, usually related to the flow of air in a duct.

Velocity pressure. The kinetic pressure due to flow, equal to that required to bring a fluid at rest to flow at a given velocity. Velocity pressure is always positive and in the direction of air flow.

FUNDAMENTALS OF VENTILATION AIR FLOW

The basic laws describing the complete motion of a fluid are complex and largely unknown. In the simple case of laminar flow the motion of the fluid may be computed analytically. However, for turbulent flow only a partial analysis can be made using the principles of fluid mechanics. The air flow in a local exhaust system is always turbulent to some degree; that is, the Reynolds number, an index of turbulence, is greater than 4,000. Therefore, the analytical solution to motion of air in exhaust systems is largely empirical and depends on experimental data.

Conservation of Mass

A basic consideration in the principles of air flow is the continuity equation or conservation of mass. This equation states that the mass rate of flow remains constant along the path taken by a fluid. Therefore, for any two points in a fluid stream:

$$A_1 v_1 \delta_1 = A_2 v_2 \delta_2$$

where A = cross sectional area, ft^2

v = velocity, ft/min.

δ = specific weight, lb/ft^3

In most applications in industrial ventilation, δ is relatively constant because the absolute pressure within a ventilation system usually varies over a very narrow range and the air remains relatively incompressible. Therefore,

$$A_1 v_1 = A_2 v_2$$

and $$Q_1 = Q_2$$

where $Q = Av$, the volumetric rate of air flow, ft^3/min.

Conservation of Energy

The basic energy equation of a frictionless, incompressible fluid for steady flow along a single stream line is given by Bernoulli's Theorem:

$$H + \frac{P}{\delta} + \frac{v^2}{2g} = C$$

where H = the elevation above any arbitrary datum plane, ft

P = absolute pressure, lb/ft^2

δ = specific weight, lb/ft^3

v = velocity, ft/sec

g = gravitational acceleration, ft/sec^2

C = a constant, different for each streamline.

Each of the three variable terms in Bernoulli's equation has the units foot-pounds per pound of fluid, or feet of fluid, frequently referred to as elevation head, pressure head and velocity head, respectively.

When Bernoulli's equation is applied to industrial exhaust systems the elevation term, H, is usually omitted since only relatively small changes in elevation are involved. Since all streamlines originate from the atmosphere, a reservoir of nearly constant energy, the constant, C, is the same for all streamlines and the restriction of the equation to a single stream line can be removed. Furthermore, since the pressure changes in nearly all exhaust systems are at most only a few percent of the absolute pressure, the assumption of incompressibility may be made with negligible error.

Velocity Pressure

Air in motion exerts a pressure called velocity pressure. Velocity pressure maintains air velocity and is analogous to kinetic energy. It exists only when air is in motion, it acts in the direction of air flow, and it is always positive in sign. In Bernoulli's equation, the term $\frac{v^2}{2g}$ represents the velocity head. The relationship between the velocity of air and velocity pressure is:

$$v = \sqrt{2gh}$$

Where v = velocity, ft/sec
g = gravitational acceleration, ft/sec^2
h = head of air, ft

When $g = 32.17$ ft/sec^2 and the density of air is 0.075 pound per cubic foot, then:

$$V = 4005 \sqrt{VP} \quad \text{fpm}$$

where VP = velocity pressure, inches of water. Table 39-1 presents standard air velocity equivalents for velocity pressures between 0.01 and 14 inches of water.

Static Pressure

Static pressure produces initial air velocity, overcomes the resistance in a system caused by friction of the air against the duct walls, and overcomes turbulence and shock caused by a change in direction or velocity of air movement. Static pressure is analogous to potential energy and it exists even where there is no air motion. It acts equally in all directions and either tends to collapse the walls of the duct upstream from the fan or tends to expand the walls of the duct on the downstream side. Static pressure is usually negative in sign upstream from a fan and positive in sign downstream. It is measured as the difference between duct pressure and atmospheric pressure. The most common units of static pressure are inches of water.

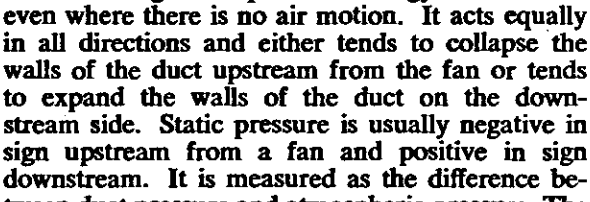
Total Pressure

The driving force for air flow is a pressure difference. Pressure is required to start and maintain flow. This pressure is called total pressure and has two components: velocity pressure and static pressure. Static pressure, velocity pressure and total pressure are all interrelated:

$$SP + VP = TP$$

Figure 39-1 shows the relationship between static, velocity and total pressure at different points in a duct system.

If gas flowing through a duct system undergoes an increase in velocity, a part of the available



American Conference of Governmental Industrial Hygienists — Committee on Industrial Ventilation: Industrial Ventilation — A Manual of Recommended Practice, 12th Edition. Lansing Michigan, 1972.

Figure 39-1. Relationship Between Static Pressure, Velocity Pressure, Total Pressure.

static pressure is used to create the additional velocity pressure necessary to accelerate the flowing gas. Conversely, if the velocity is reduced at some point in a duct system, a portion of the kinetic energy or velocity pressure at that point is converted into potential energy or static pressure. Static and velocity pressure are, therefore, mutually convertible. However this conversion is always accompanied by a net loss of total pressure due to turbulence and shock; i.e., the conversion is always less than 100% efficient.

Friction Losses

Air in motion encounters resistance along any surface confining the flowing volume. Consequently, some of the energy of the air is given up in overcoming this friction and is transformed into heat. The rougher the surface confining the flow or the higher the flow rate, the higher the frictional losses will be.

Frictional loss in a duct varies directly as the length, inversely as the diameter, and directly as the square of the velocity of air flowing through the duct. This loss can be calculated from charts[6] using the Fanning friction factor, which is an empirical function of Reynolds number, duct material and type of construction.

Dynamic Losses

Another type of energy loss encountered in air flow results from turbulence caused by a change in direction or velocity within a duct. The pressure drop in a duct system due to dynamic losses increases with the number of elbows or angles and the number of velocity changes within the system. The resulting pressure drop from these energy losses is expressed in units of "equivalent length." For example, an elbow of 12-inch diameter and 24-inch centerline radius is said to have an equivalent length of 17, meaning that the loss through the elbow will be the same as the loss through 17 feet of straight pipe with the same diameter operating under the same conditions (see *Industrial Ventilation*,[4] Fig. 6-11).

Another method of defining the losses due to turbulence and friction is to express the losses in terms of velocity pressure. For example, a loss of 0.28 VP in a transition or elbow means that the incremental pressure drop is equal to 0.28 of the velocity pressure of the air stream at that point (see *Industrial Ventilation*,[4] Figure 6-12, 6-13).

Acceleration and Hood Entrance Losses

This type of dynamic loss, h_e, is a drop in pressure caused by turbulence when air is accelerated from rest to enter a duct or opening. Turbulence losses of this type vary with the type of opening and are defined for ducts and common types of hoods in Fig. 4-8, *Industrial Ventilation*[4].

This entry loss plus the acceleration energy required to move the air at a given velocity (one VP) comprise the hood static pressure, SP_h. SP_h is expressed algebraically as:

$$SP_h = h_e + VP.$$

SP_h can be measured directly at a short distance downstream from the hood entrance. The calculation of SP_h is the first step in the design or evaluation of a local exhaust system, discussed in Chapters 41 and 42.

TABLE 39-1

Velocity Pressures for Different Velocities — Standard Air[4]

FROM: $V = 4005\sqrt{VP}$ V = VELOCITY FPM
VP = VELOCITY PRESSURE, INCHES OF WATER

VP	V	VP	V	VP	V	VP	V	VP	V	VP	V
0.01	400	0.52	2888	1.03	4064	1.54	4970	2.05	5734	3.10	7051
0.02	556	0.53	2916	1.04	4084	1.55	4986	2.06	5748	3.20	7164
0.03	694	0.54	2943	1.05	4103	1.56	5002	2.07	5762	3.30	7275
0.04	801	0.55	2970	1.06	4123	1.57	5018	2.08	5776	3.40	7385
0.05	896	0.56	2997	1.07	4142	1.58	5034	2.09	5790	3.50	7492
0.06	981	0.57	3024	1.08	4162	1.59	5050	2.10	5804	3.60	7599
0.07	1060	0.58	3050	1.09	4181	1.60	5066	2.11	5817	3.70	7704
0.08	1133	0.59	3076	1.10	4200	1.61	5082	2.12	5831	3.80	7807
0.09	1201	0.60	3102	1.11	4219	1.62	5098	2.13	5845	3.90	7909
0.10	1266	0.61	3127	1.12	4238	1.63	5114	2.14	5859	4.00	8010
0.11	1328	0.62	3153	1.13	4257	1.64	5129	2.15	5872	4.10	8109
0.12	1387	0.63	3179	1.14	4276	1.65	5144	2.16	5886	4.20	8208
0.13	1444	0.64	3204	1.15	4295	1.66	5160	2.17	5899	4.30	8305
0.14	1498	0.65	3229	1.16	4314	1.67	5175	2.18	5913	4.40	8401
0.15	1551	0.66	3254	1.17	4332	1.68	5191	2.19	5927	4.50	8496
0.16	1602	0.67	3279	1.18	4350	1.69	5206	2.20	5940	4.60	8590
0.17	1651	0.68	3303	1.19	4368	1.70	5222	2.21	5954	4.70	8683
0.18	1699	0.69	3327	1.20	4386	1.71	5237	2.22	5967	4.80	8774
0.19	1746	0.70	3351	1.21	4405	1.72	5253	2.23	5981	4.90	8865
0.20	1791	0.71	3375	1.22	4423	1.73	5268	2.24	5994	5.00	8955
0.21	1835	0.72	3398	1.23	4442	1.74	5283	2.25	6008	5.10	9044
0.22	1879	0.73	3422	1.24	4460	1.75	5298	2.26	6021	5.20	9133
0.23	1921	0.74	3445	1.25	4478	1.76	5313	2.27	6034	5.30	9220
0.24	1962	0.75	3468	1.26	4495	1.77	5328	2.28	6047	5.40	9307
0.25	2003	0.76	3491	1.27	4513	1.78	5343	2.29	6061	5.50	9392
0.26	2042	0.77	3514	1.28	4531	1.79	5359	2.30	6074	5.60	9477
0.27	2081	0.78	3537	1.29	4549	1.80	5374	2.31	6087	5.70	9562
0.28	2119	0.79	3560	1.30	4566	1.81	5388	2.32	6100	5.80	9645
0.29	2157	0.80	3582	1.31	4583	1.82	5403	2.33	6113	5.90	9728
0.30	2193	0.81	3604	1.32	4601	1.83	5418	2.34	6128	6.00	9810
0.31	2230	0.82	3625	1.33	4619	1.84	5433	2.35	6140	6.10	9891
0.32	2260	0.83	3657	1.34	4636	1.85	5447	2.36	6153	6.20	9972
0.33	2301	0.84	3669	1.35	4653	1.86	5462	2.37	6166	6.30	10052
0.34	2335	0.85	3690	1.36	4671	1.87	5477	2.38	6179	6.40	10132
0.35	2369	0.86	3709	1.37	4688	1.88	5491	2.39	6192	6.50	10210
0.36	2403	0.87	3729	1.38	4705	1.89	5506	2.40	6205	6.60	10289
0.37	2436	0.88	3758	1.39	4722	1.90	5521	2.41	6217	6.70	10366
0.38	2469	0.89	3779	1.40	4739	1.91	5535	2.42	6230	6.80	10444
0.39	2501	0.90	3800	1.41	4756	1.92	5550	2.43	6243	6.90	10520
0.40	2533	0.91	3821	1.42	4773	1.93	5564	2.44	6256	7.00	10596
0.41	2563	0.92	3842	1.43	4790	1.94	5579	2.45	6269	7.50	10968
0.42	2595	0.93	3863	1.44	4806	1.95	5593	2.46	6282	8.00	11328
0.43	2626	0.94	3884	1.45	4823	1.96	5608	2.47	6294	8.50	11676
0.44	2656	0.95	3904	1.46	4840	1.97	5623	2.48	6307	9.00	12015
0.45	2687	0.96	3924	1.47	4856	1.98	5637	2.49	6320	9.50	12344
0.46	2716	0.97	3945	1.48	4873	1.99	5651	2.50	6332	10.00	12665
0.47	2746	0.98	3965	1.49	4889	2.00	5664	2.60	6458	11.00	13283
0.48	2775	0.99	3985	1.50	4905	2.01	5678	2.70	6581	12.00	13874
0.49	2804	1.00	4005	1.51	4921	2.02	5692	2.80	6702	13.00	14440
0.50	2832	1.01	4025	1.52	4938	2.03	5706	2.90	6820	13.61	14775
0.51	2860	1.02	4045	1.53	4954	2.04	5720	3.00	6937	14.00	14986

The coefficient of entry, C_e, is a measure of how efficiently a hood entry is able to convert static pressure to velocity pressure. The coefficient of entry is defined as the ratio of rate of flow by the hood static pressure to the theoretical flow if the hood static pressure were completely converted to velocity pressure. This term is computed as follows:

$$C_e = \frac{4005A\sqrt{VP}}{4005A\sqrt{SP_h}} = \frac{\sqrt{VP}}{\sqrt{SP_h}}$$

Pressure Drop through Ductwork

The result of the friction and dynamic losses to air flowing through ductwork is a pressure drop in the system. Bernoulli's Theorem can be restated in a simplified expression of conservation of energy as follows:[4]

$$SP_1 + VP_1 = SP_2 + VP_2 + \text{losses}.$$

Static pressure plus velocity pressure at a point upstream in direction of air flow equals the static pressure plus velocity pressure at a point downstream in direction of air flow plus friction and dynamic losses.

PROPERTIES OF AIRBORNE MATERIALS

Dusts

Dusts are solid particles generated by handling, crushing, grinding, and detonation of organic and inorganic materials such as rock, metal, coal, wood, and many other materials. Dust particles do not diffuse in air in the classical sense, but the finer particles of diameters <20 microns are carried with air currents because the settling rate is so low as to be of no practical significance. Dust particles must be about 5 microns or smaller to reach the lungs; larger particles are filtered out in the nasal passages or other parts of the breathing apparatus.

Fumes

Fumes are small, solid particles created by condensation from the gaseous state, generally after volatilization or by chemical reaction such as oxidation. Fumes are usually submicronic in size.

The outstanding characteristic of most fumes is their tendency to flocculate and coalesce. Very small spherical fume particles tend to attach themselves together in long chains or clumps of particles due to Brownian diffusion and electrostatic attraction.

Mists

Mists are suspended liquid droplets generated by condensation from the gaseous to the liquid state or by breaking up a liquid into a dispersion such as by splashing, foaming and atomizing. Fogs are similar to mists but the term is usually reserved for high concentrations of very fine droplets that are more frequently airborne.

Smoke

Smoke is the aerosol mixture which results from the incomplete combustion of carbonaceous material such as coal, oil, tar and tobacco.

Vapors

Vapors are the gaseous forms of substances which are normally in the liquid or solid state and which can be changed to these states either by increasing the pressure or decreasing the temperature alone.

Gases

Gases are normally compressible, formless fluids which occupy the space of an enclosure and which can be changed to the liquid or solid state only by the effect of increased pressure and decreased temperature or both.

Effective Specific Gravity

Frequently, the location of exhaust hoods is mistakenly based on a supposition that the contaminant is "heavier than air" or "lighter than air." In most health hazard applications this criterion is of little value; hazardous dusts, fumes, vapors and gases are truly airborne, following air currents and are not subject to appreciable motion, either upward or downward, because of their own density.

APPLICATIONS OF DILUTION VENTILATION

When considering whether dilution or local exhaust is better, it should be remembered that dilution ventilation has four limiting factors:[4]

1. The quantity of contaminant generated must not be excessive or else the air volume necessary for dilution will be impractical.
2. Workers must be far enough away from contaminant evolution or else the contaminant must be in sufficiently low concentrations so that workers will not have an exposure above acceptable concentrations.
3. The toxicity of the contaminant must be low.
4. The evolution or generation of contaminants must be reasonably uniform.

On the basis of these factors, dilution ventilation is usually not recommended for fumes and dust because: (1) the high toxicities often encountered require excessively large quantities of dilution air; and (2) the velocity and rate of evolution are usually very high, resulting in locally high concentrations.

Dilution Ventilation for Comfort

Ventilation for heat relief includes certain aspects of air conditioning or treating of air to control simultaneously its temperature, humidity, cleanliness and distribution to meet the requirements of the conditioned space. In most residential, office and commercial ventilation the requirements are comfort for the occupants. In many industrial situations, however, comfort conditions are impractical to maintain; and the function of ventilation and air conditioning along with other control methods is to prevent acute discomfort and adverse physiological effects.

Exhaust ventilation may be used to remove heat and humidity if a source of cooler air is available. If it is possible to enclose the heat source, such as in the case of ovens or certain furnaces, a gravity or forced air stack may be all that is necessary to prevent excessive heat from entering the workroom.

Dilution Ventilation for Preventing Fires and Explosions

One function of dilution ventilation is to reduce the concentration of vapors within an enclosure to below the lower explosive limit. However, this concept must not be applied in cases where workers are exposed to the vapor. In such instances, dilution rates for health hazard control must always be applied. The reason for this distinction is fundamental and must be thoroughly understood.

Threshold Limit Values or Acceptable Concentrations for health hazard control are typically 1-3 orders of magnitude below the lower explosive limit for a given material. A table of comparative values is shown below.[4, 7]

Material	TLV ppm	LEL %	LEL ppm
Acetone	1000	2.55	25,500
Ethanol	1000	3.28	32,800
Isopropanol	400	2.02	20,200
Toluene	100	1.27	12,700
Xylene	100	1.00	10,000

Exposure to atmospheres controlled to concentrations "below" the lower explosive limit (or some fraction thereof) could cause narcosis, severe illness or death. Therefore it is extremely important not to confuse dilution ventilation requirements for health hazard control with fire and explosion prevention.

Dilution Ventilation for Health

In general, dilution ventilation is not as satisfactory as local exhaust ventilation for primary control of health hazards. However, there are occasional circumstances in which dilution ventilation must be used because the operation or process prohibits local exhaust. Circumstances may occasionally be found in which dilution ventilation provides an adequate amount of control more economically than a local exhaust system. However, this is the exception. One should be careful, moreover, not to base economical considerations entirely upon the initial cost of the system because dilution ventilation invariably exhausts large volumes of heated air from a building. This can easily result in huge operating costs in the form of conditioned make-up air which will make the general ventilation scheme much more expensive over a period of time.

Dilution ventilation for the control of health hazards is used to best advantage in controlling the concentration of vapors from organic solvents of low toxicity. In order to successfully apply the principles of dilution to such a problem, data must be available on the rate of vapor generation or on the rate of liquid evaporation. Usually such data can be obtained from the plant if it keeps any type of adequate records on material consumption.

Rate of Air Change

The volume of a room to be ventilated and the ventilation rate are frequently related to one another by taking the ratio of the ventilation rate to the room volume to yield a "number of air changes per minute" or "number of air changes per hour." These are terms that are used quite frequently in discussions of ventilation requirements. Unfortunately, through widespread use over the years, they are more often employed incorrectly than properly.

It must be understood that ventilation requirements based on room volume alone have no validity. Calculations of the required rate of air change can only be made on the basis of a material balance for the contaminant under question. Similar calculations can be made for the rate of concentration increase or decrease; however, they require not only the air change rate but also the rate of generation of contaminant. In the design of industrial ventilation, "X number of air changes" has valid application only very rarely. The term is useful when applied to meeting rooms, offices, schools and similar spaces where the purpose of ventilation is simply the control of odor, temperature, or humidity and the only contamination of the air is from the activity of people.

Dilution ventilation requirements should always be expressed in cubic feet per minute or some other absolute unit of air flow, not in "Air Changes per Minute."

Calculating Dilution Ventilation

The concentration of a gas or vapor at any time can be expressed by a differential material balance, which, when integrated provides a rational basis for relating ventilation to the generation and removal rates of a contaminant.

Let C = concentration of gas or vapor at time t

G = rate of generation of contaminant

Q = rate of ventilation

K = design distribution constant, allowing for incomplete mixing

$Q' = Q/K$ = effective rate of ventilation, corrected for incomplete mixing

V = volume of room or enclosure

Starting with a fundamental material balance, assuming no contaminant is in the supply air,

Rate of Accumulation = Rate of Generation − Rate of Removal

$$VdC = Gdt - Q'Cdt$$

Consider the following applications:

1. *Concentration Buildup*

Rearranging the differential material balance,

$$\int_{C_1}^{C_2} \frac{dC}{G - Q'C} = \frac{1}{V}\int_{t_1}^{t_2} dt$$

$$\ln\left(\frac{G - Q'C_2}{G - Q'C_1}\right) = -\frac{Q'}{V}(t_2 - t_1)$$

if $C_1 = 0$ at t_1,

$$\ln\left(\frac{G - Q'C}{G}\right) = -\frac{Q'}{V}\, t$$

or,

$$\frac{G - Q'C}{G} = e^{-Q't/V}$$

Example A

$V = 100{,}000\ ft^3$

$C_1 = 0$

$Q = 6000$ cfm

$K = 3$

$Q' = 2000$ cfm

$G = 1.2$ cfm

How long before the concentration of the contaminant reaches 200 ppm?

Solution:

$$t = -\frac{V}{Q'}\left[\ln\left(\frac{G - Q'C}{G}\right)\right] = 20.3 \text{ minutes}$$

Example B

Using the same values as in the preceding example, what will the concentration of the contaminant be after one hour?

Solution:

$$C = \frac{G - G_e^{-\left(\frac{Q't}{V}\right)}}{Q'} = 419 \text{ ppm}$$

2. *Rate of Purging*

In the case where a volume of air is contaminated, but where further contamination or generation has ceased, the rate of decrease of concentration over a period of time is as follows:

$$VdC = -Q'Cdt$$

$$\int_{C_1}^{C_2} \frac{dC}{C} = \frac{-Q'}{V}\int_{t_1}^{t_2} dt$$

$$\ln\left(\frac{C_2}{C_1}\right) = \frac{-Q'}{V}(t_2 - t_1)$$

Example:

In the room of the examples above, assume that ventilation continues at the same rate ($Q' = 2000$ cfm), but that the contaminating process is interrupted. How much time is required to reduce the concentration from 100 to 25 ppm?

$$\ln\left(\frac{C_2}{C_1}\right)=\frac{-Q'}{V}(t_2-t_1)$$

$$\Delta t = 69.3 \text{ minutes}$$

3. *Maintaining Acceptable Concentrations at Steady State*

At steady state, $dC=0$

$$Gdt = Q'Cdt$$

$$\int_{t_1}^{t_2} Gdt = \int_{t_1}^{t_2} Q'Cdt$$

at a constant concentration C, and uniform generation rate, G,

$$G(t_2-t_1)=Q'C(t_2-t_1)$$

$$Q'=\frac{G}{C}$$

$$Q=\frac{KG}{C}$$

Therefore, the rate of flow of uncontaminated dilution air required to reduce the atmospheric concentration of a hazardous material to an acceptable level can be easily calculated, if the generation rate can be determined. Usually the acceptable concentration is considered to be the Threshold Limit Value or Acceptable Eight-Hour Time Weighted Average Concentration. For liquid solvents the steady-state dilution ventilation requirement can be conveniently expressed as:

$$Q=\frac{(6.71)(10^6)(SG)(ER)(K)}{(MW)(TLV)}$$

Where: Q = actual ventilation rate, cfm
SG = specific gravity of volatile liquid
ER = evaporation rate of liquid, pints/hr
MW = molecular weight of liquid
K = design safety factor for incomplete mixing
TLV = Threshold Limit Value, ppm.

Example:
Methylene chloride is lost by evaporation from a tank at the rate of 1.5 pints per hour. How much dilution air is required to maintain the concentration below the TLV?

For methylene chloride,
TLV = 500 ppm
SG = 1.336
MW = 84.94

Assuming K = 5,

$$Q=\frac{(6.71)(10^6)(1.336)(1.5)(5)}{(84.94)(500)}$$

$$Q = 1583 \text{ cfm}$$

Specifying Dilution Ventilation

The foregoing discussion introduced the concept of a "design safety factor" (K) for calculating dilution ventilation requirements. This K factor is based upon several considerations:[5]

1. The efficiency of mixing and distribution of make-up air introduced into the room or space being ventilated.
2. The toxicity of the solvent. Although TLV and toxicity are not synonymous the following guidelines have been suggested for choosing the appropriate K value:
   Slightly toxic material: TLV >500 ppm
   Moderately toxic material: TLV 100-500 ppm
   Highly toxic material: TLV <100 ppm
3. A judgment of any other circumstances which the industrial hygienist determines to be of importance, based upon experience and the individual problem. Included in these criteria are such considerations as:
   a. Seasonal changes in the amount of natural ventilation.
   b. Reduction in operation efficiency of mechanical air moving devices.
   c. Duration of the process, operational cycle and normal location of workers relative to sources of contamination.
   d. Location and number of points of generation of the contaminant in the workroom or area and,
   e. Other circumstances which may affect the concentration of hazardous material in the breathing zone of the workers.

The K value selected will usually vary from 3 to 10 depending on the above considerations.

Industrial Ventilation[4] (Table 2-1) lists the air volumes required to dilute the vapors of twenty-nine common organic solvents to the TLV level based upon the liquid volume solvent evaporated per unit time. These values must be multiplied by a K factor to allow for variations in uniformity of air distribution, and other considerations. Hemeon[6] includes a table of recommended dilution rates for fifty-three organic solvents. The "Ventilation Design Concentrations" in this table are not based on threshold limit values alone, but are based also on odor. All of the concentrations in this table are lower than the threshold limits, but those substances which are especially toxic or which have a very disagreeable odor have the greatest safety factors.

It must be emphasized that Threshold Limit Values are subject to revision, and the use of tables to estimate dilution values may become obsolete if the Threshold Limit Values are lowered; therefore, such a table should be used with caution, and with reference to the *latest* TLV list.

MAKE-UP AIR

All local and general exhaust ventilation systems must have air to exhaust, and by the basic consideration of conservation of mass, that air must be supplied pound for pound by a make-up air system. The supply and distribution of make-up air is often over-looked or neglected in the design of ventilation but remains fundamental to its successful operation.

Principles for Supplying Make-Up Air

1. The fresh air intake should be located away from any contaminating sources such as exhaust stacks or furnace exhausts. It is advisable to filter the fresh air to protect

the equipment and provide maximum heat exchange efficiency.

2. The air supply system must be provided with a fan, otherwise the room or building will be under a negative pressure.
3. Make-up air sources should be located to provide cross ventilation. In this way, the air can be "used twice." First, it will provide general dilution and secondly it will provide make-up air for the exhaust systems. This does not apply for spot-cooling applications where the air will be introduced directly at the work station and may vary significantly from room temperature. The air distribution pattern must be engineered carefully to provide effective area coverage without excessive cross drafts which will interfere with the workers or the existing systems.
4. Make-up air should be introduced into the "living zone" of the plant, that is, below the 8-10 foot level. In this manner, the air is used first by the people and the best results of general or dilution ventilation are obtained. This distribution also provides closer control of the ambient working temperature.
5. Make-up air temperature is usually heated or cooled to approximately the same as desired in the room being supplied. Since the air is being used for ventilation and for replacement purposes, the usual temperature range will be 65-80°F.

Recirculation of Air from Industrial Exhaust Systems

Plant Circulation. It should be apparent that if large amounts of air are exhausted from a room or building in order to remove obnoxious dusts, gases, fumes or vapors an equivalent amount of fresh, tempered air should be supplied to the room. This supplied air must be heated in cold weather, and heating costs may be large if sizable amounts of air are handled. Therefore, attempts are sometimes made to eliminate such heating costs by appropriate cleaning of the exhausted air and subsequent recirculation of the air into the room. The acceptability of such recirculation depends on the degree of health hazard associated with the particular contaminant being exhausted as well as on other factors.

It is generally accepted as good practice not to recirculate exhaust air if the contaminants therein can have an effect on the health of the worker. The reasons are:

a. Many types of air cleaners do not collect toxic contaminants efficiently enough to eliminate the health hazard. This is especially true for gases and vapors.
b. Poor maintenance of the air cleaner would result in the return of highly contaminated air to the breathing zones of the workers. One of the facts of life is that air cleaners are not generally production equipment, and are too often poorly maintained or not maintained at all.
c. Improper operation of the air cleaner through mechanical failure or through ignorance or neglect on the part of the operators can also result in the return of highly contaminated air.

In general, recirculation should be avoided unless the reasons indicating its use are truly compelling. Its use will always require an understanding of the hazardous nature of the contaminant, the knowledge of the performance of the specific air cleaner, the general ventilation scheme, and the judgment of experience.

Unplanned Recirculation. Unplanned recirculation of exhausted air can be a serious problem. This usually results from inadequately separated exhaust stacks and air inlets or insufficient discharge height, either from short stacks relative to the roof line or low "effective" stack height resulting from poorly designed weather caps on stack heads. This subject is treated in more detail in Chapter 42.

AIR MOVING DEVICES

The term "air moving device" is an inclusive one which denotes machines more commonly known as fans, blowers, exhausters, turbo compressors and ejectors. By definition, an air moving device (AMD) is a power-driven machine causing a continuous flow of air. In more practical terms, the air moving device manufacturer, to gain acceptance for his product, must earn membership to the "Air Moving and Conditioning Association" by subjecting his product to its test code for air movers. In addition, air moving devices manufacturers must furnish a prospective buyer of his product, certain data relative to the product and its applications. This subject is covered in more detail in Chapter 42.

Because fans are the most commonly used exhausters in ventilation for industrial hygiene purposes, they alone are considered in this discussion.

In the field of industrial ventilation, two major types of fans are used: axial flow types, where the air flow is parallel to the fan shaft, and centrifugal type, where air flow is perpendicular to the fan shaft. These two major fan types can be further defined by listing the various units that comprise each type. The components of an air moving device which influence its performance most are the wheel and the air inlet. This will be apparent in the list below which shows comparative components for the two major types of air moving devices.

Axial Flow Fans

1. Propeller: This is an AMD with a propeller or disc wheel within a mounting ring or plate through which the air flow is predominantly parallel to the axis of rotation. This unit is used to move large volumes of air at relatively low velocity against a low static pressure (0-½"W.G.) and low temperature. This fan is commonly used for general ventilation.

2. Duct Fan: This is a step up in the evolution of fans from the propeller fan, in that it constitutes a propeller mounted inside a section of duct. The improvements gained in this configuration are elevated temperature applications (to 600°F in belt-drive units), and higher static pressures (from 0-2" W.G.)
3. Tube-Axial: This is an axial fan without guide vanes. It is used for medium to large volumes against static pressures up to 4" W.G. and temperatures up to 600°F in belt-driven units. This fan is best suited for moving an air stream containing materials that will not collect on fan blades.
4. Vane-Axial: This is an axial fan with either inlet or discharge vanes or both, which impart greater efficiency in delivering medium to high volumes against static pressures up to 8" W.G. Higher pressures are attainable in some units with variable pitch impellers. Temperature applications up to 600°F are attainable in belt-driven units. This type of fan is commonly used for mine ventilation or industrial systems whose characteristics vary widely.
5. Axial-Centrifugal: This is an axial fan with a centrifugal wheel. The wheel is available in both backwardly inclined and airfoil design. This fan is the latest improvement in axial flow air moving devices in that it combines the high efficiency of the axial unit with the quiet operation and high static pressure level of the centrifugal fan. Although temperatures of operation are relatively low (under 200°F), static pressures up to 20" W.G. are attainable. In addition, the non-overloading feature of the backwardly inclined and airfoil design wheels is an important advantage of this fan.

Centrifugal Fans

1. Radial Wheel: This fan is the workhorse of the dust control industry. It is the least efficient centrifugal fan type, but is quite suitable for rough service, including material handling applications. Generally it it is used to handle volumes to about 100,000 CFM at static pressures to 20" W.G., and temperatures up to 1000°F.
2. Forward-Curved Blade: This fan delivers high volumes at low static pressure with relatively low noise levels. However, it is not very efficient, and therefore, has lost much of its favor to other type units.
3. Backward-Inclined Blade: Sometimes known as "power limiting" or "non-overloading," this type wheel is used more and more for general air handling. It is an efficient fan, with high top speeds and is a good choice for handling large volumes of clean air.
4. Airfoil Design: This unit is the latest development in centrifugal fan wheels. The airfoil wheel was developed to reduce noise levels; however it is also backwardly inclined and has the non-overloading feature. It, too, can deliver large volumes against high static pressures.

Fan Selection

In order to select the proper fan for a given application, the following information is required:[4]

1. Air volume to be moved;
2. Fan static pressure;
3. Nature and extent of airborne particulate (a radial-bladed centrifugal fan would be needed if the air stream contains a high concentration of particulates);
4. Direct or belt-drive (belt-drive can be changed for variation in air volume handled; direct drive is inflexible, but occupies less space and requires less maintenance);
5. Noise Level — (a function of tip speed, it is usually a limiting factor in industrial applications);
6. Special considerations such as high operating temperature, corrosiveness, flammable or explosive materials, and space limitations.

The application of specific fan types in the design of exhaust systems is described in Chapter 42, after a more thorough discussion of local exhaust ventilation in Chapter 41.

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