History of the Changing Concepts in Ventilation Requirements

A.K. KLAUSS

R.H. TULL
Presidential Member ASHRAE

L.M. ROOTS

J.R. PFAFFLIN

MAN has been concerned with ventilation requirements for centuries, but it was not until the 18th century that attempts were made to investigate this subject in a scientific manner. During this period, ventilation was little understood as to its necessity, except that it was required to sustain a healthful human being. Diverse theories have been postulated as to its importance, but few have withstood the test of time.

The earliest theory pertaining to ventilation requirements probably evolved in the 17th or 18th century. It held that the accumulation and stagnation of the breath and perspiration of human beings crowded for a period in confined air were responsible for producing plague or fever. It was believed that these diseases could be communicated to healthy persons by contact or respiration. Little was understood about the true nature of diseases. The fact that the micro-organism was the primary agent of disease transmittance was yet to be discovered. Looking back, it would appear that rather than contaminated air, the overcrowded and unsanitary conditions were responsible for the unhealthful environment.

Oxygen depletion due to respiration by the inhabitants of a confined area was also believed by many to be a consequence of improper ventilation. This theory was refuted in experiments carried out by Lavoisier in about 1777. He postulated that instead of the oxygen content being depleted, it was the increase in carbon dioxide content that was responsible for the unhealthful atmospheres of confined places. Lavoisier maintained that as the carbon dioxide content increased, it interfered with the body's ability to absorb oxygen. Today we know that his theory was also incorrect. When the human body encounters higher levels of carbon dioxide than are present in normal air, it compensates by an increase in respiration rate. Still, Lavoisier's theory predominated in physiological circles for about 100 years.

One of the earliest texts which was an often-quoted source of ventilation theory is The Principles Of Warming And Ventilating – Public Buildings And Dwelling Houses by Tredgold,[1] published in 1836. The author expresses the belief that there are foul exhalations in the air, which are given off at each breath by individuals. It was concluded at this time already, in experiments by Priestly and Gay Lassac, that there was no chemically detectable difference between indoor (foul) air, and outdoor (healthful) air. Therefore some substance or substances which the analytical chemists could not detect were causing the air to become contaminated. This theory was commonly accepted because there was overwhelming empirical evidence that inhabitants of particular geographic districts showed "weak constitutions" and "pale visages," which were attributed to this foul air. Rather than a lack of ventilation it was, as mentioned earlier, overcrowding and rudimentary sanitary

A.K. Klauss is group leader, Materials & Process Laboratory, Grumman Aerospace Corp, Bethpage, N.Y.; R.H. Tull, retired, Lebanon, N.J.; Mrs. L.M. Roots is associate medical officer of health, City of Windsor, Ont., Canada; and J.R. Pfafflin, Electrical Engrg Dept, University of Windsor, Windsor, Ont., Canada.

facilities, providing an excellent environment for the spread of the numerous contagious diseases, which were responsible for the unhealthful condition. Nevertheless, believing that the human exhalations were the cause of the problem, an attempt was made to remedy the situation by supplying what was believed to be sufficient quantities of fresh air to preclude potentially toxic levels from developing. Using contemporary physiological knowledge and data, Tredgold proceeded as follows.

He reasoned that if 32 cu in. of oxygen were consumed each minute, then the oxygen was replaced by an equal volume of carbon dioxide. Believing that the total amount of carbon dioxide in the exhaled air must be purged to insure a healthful environment, it was a simple matter to calculate the gross amount of respired air which was contaminated by the carbon dioxide. This amount was calculated to be:

$$\frac{40 \text{ cu in. respired air}}{\text{respiration}} \times \frac{20 \text{ respirations}}{\text{min}} = \frac{800 \text{ cu in. respired air}}{\text{min}}$$

Therefore, if 800 cu in. of fresh air were supplied each minute, it would be sufficient to purge the vitiated 800 cu in. of respired air which contained the carbon dioxide.

In addition to the above quantity of fresh air required to purge carbon dioxide, additional air is needed to remove the body moisture constantly given off at the rate of approximately 18 grains per min. At 60 F, Tredgold calculated it would require 3 cfm of fresh air to accomplish moisture removal. This 3 cu ft figure appears to be low since saturated air at 60 F contains approximately 6 grains of water per cu ft. Calculating:

$$\frac{\frac{18 \text{ grains}}{\text{min}} \text{ (Body moisture given off per min)}}{\frac{6 \text{ grains}}{\text{cu ft}} \text{ (Absorbed by ventilating air)}} = \frac{3 \text{ cu ft ventilation air}}{\text{min}}$$

But this assumes the ventilating air can absorb 6 grains of moisture per cu ft which implies that the ventilating air contained little or no moisture on entering, an unrealistic situation at best.

Finally, he concludes that 1/4 cu ft of air is required to supply oxygen for candles and/or lamps which might be present. Summing up to get the total fresh air requirement yields:

Carbon dioxide dilution	=	800 cu in./min
Body moisture removal at 3 cfm	=	5184 cu in./min
Oxygen demand of candles and lamps at ¼ cfm	=	432 cu in./min
		6416 3 cu in./min
		(Equals approx. 4 cu ft.)

Thus, a 4 cu ft quantity is the minimum ventilation requirement for closed spaces according to Tredgold and his contemporaries of 1836.

Another work which was published a few years after the above reference also presents some interesting points when examining the rationale behind the minimum requirements for ventilation. This work was entitled The History And Art Of Warming And Ventilating by Meikleham,[2] which appeared in 1845 and, therefore, espoused the carbon dioxide contamination theory of Lavoisier. This author proceeded as follows. Inhaled air contains about 20% oxygen and the exhaled air only 11 to 12%. These values differ significantly from the information which we have today relating to the quantities of oxygen taken up in the bloodstream. Only about one-fifth of inhaled oxygen is sent through the bloodstream. Nevertheless, let us proceed with Meikleham's reasoning. If the maximum amount of carbon dioxide gas permissible is 3.5%, then 8 to 9% exceeds the permissible amount by approximately 2.4 times. The average person breathes in about 600 cu in. per min and, therefore, renders unfit for breathing 2.4 times this amount, or 1440 cu in. each min. In addition to this, he takes into account that the human body gives off about 23 grains of water per min. Each cu ft of air at 64 F with 50% rh could carry off at most 2.48 grains of water. Therefore it would require 9.25 cfm of air to remove the body moisture. The sum of 9.25 cu ft for moisture dissipation and approximately 1 cu ft (1440 cu in.) for carbon dioxide dissipation totals 10.25 cu ft which would then be the minimum ventilation requirement per min.

It was not until 1862 that Max Von Pettenkofer,[3] in Germany, first expressed the theory that carbon dioxide was no more responsible for making air unfit to breathe than was the depletion of the oxygen content. He stated that under normal conditions the carbon dioxide concentration will never reach levels where it will have any harmful physiological effects. Subsequent experience has shown that in well-constructed dwellings, oxygen content may fall from 21 to 20% and carbon dioxide may rise from .03 to .5%. Greater changes than these are not observed even in the most crowded and poorly ventilated rooms. Practical limits on construction techniques preclude elimination of all leaks to outdoor air; therefore, only a hermetically sealed structure can be said to be leak-free and, consequently, totally ventilation-free. A ventilation-free structure would be the only type of enclosure in which oxygen depletion and carbon dioxide build-up would be cause for concern. A decrease in oxygen concentration of 1 or 2% has no harmful physiological effects as witnessed by the fact that the body has no problem adapting to reduced oxygen partial pressures encountered at the higher elevations. In fact, many health resorts (e.g., the Tuberculosis Sanatorium at Tupper Lake, N.Y.) are located at higher elevations and are known to provide extremely healthful climates. Limited carbon dioxide content increases (up to .5%) have also been shown to produce no harmful effects. Only at carbon dioxide concentrations higher than those levels which could normally be expected to be caused by inadequate ventilation would physiological symptoms be observed. Von Pettenkofer did postulate that carbon dioxide concentration could be used as a guide to determine the levels present of the organic substances which are given off by the lungs and body surfaces. He believed these organic substances to be the actual contaminants that caused vitiation of the air. That Von Pettenkofer's theory gained wide acceptance is witnessed by the following two American publications on the subject of ventilation.

In the work Acoustics and Ventilation by Saeltzer,[4] published in 1872, the emphasis is placed on the organic impurities as being the actual "poison." He, too, believed that carbon dioxide exhaled at each breath could be used as a measure of the amount of these organic contaminants.

The second publication was probably the most authoritative American work at its time on ventilation design. J.

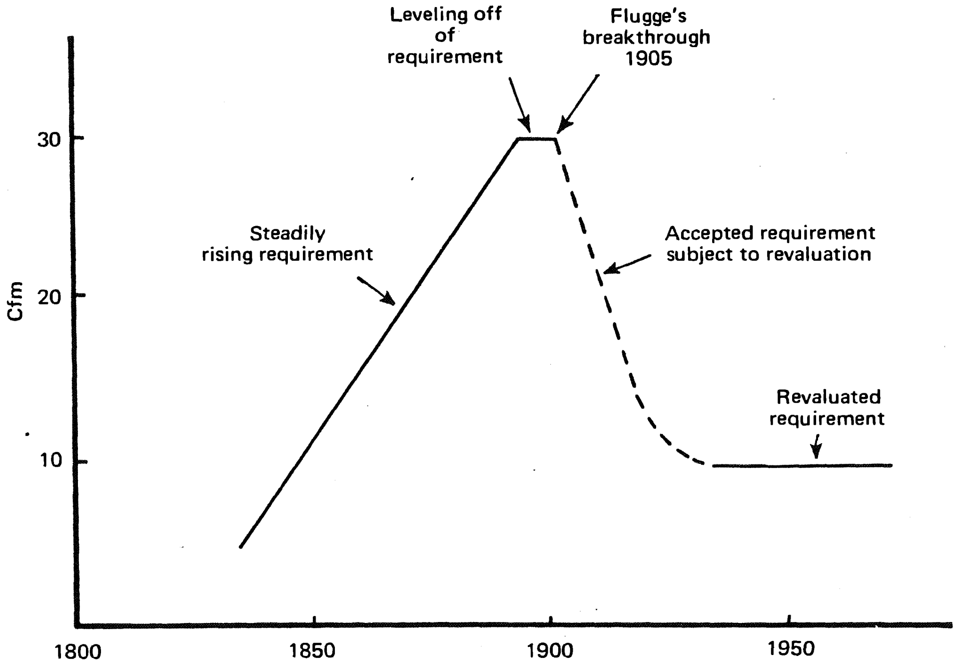

Fig. 1 Typical minimum outdoor air requirement

Billings' Ventilation and Heating[5] was written in the last decade of the 19th century and, therefore, it too reflected the widely held human organic exhalation contamination theory. The author points out the "accepted" connection between inadequate ventilation and the prevalence of phthesis (pulmonary tuberculosis). It was Billings' opinion that 30 cu ft of air is not sufficient for good ventilation if rooms are continuously occupied. Under such circumstances he believed air would become foul and exercise a very deleterious influence upon the health of the occupants. The occupants would be prone to tuberculosis and unnamed allied diseases if they remained in this environment for any length of time. He also stated that even though some sources may believe that 10 cfm is sufficient ventilation for most applications, he, Billings, disagreed. If areas are to be occupied continuously, 30 cfm is a minimum and 45 cfm, with the possibility of an increase to 60 cfm, is desirable. The rationale behind the higher quantities was arrived at as follows. As previously stated, it was believed that there was a direct relationship between carbon dioxide concentration and organic impurity concentration. Tests showed that if carbon dioxide concentration due to respiration were kept below 200 ppm then the organic impurity concentration, as measured by body odor produced, would remain at a tolerable level. Using 0.6 cfh of carbon dioxide production per person, it would then be a simple matter to determine the fresh air required to maintain a maximum level of 200 ppm carbon dioxide.

$$\frac{.6 \text{ cfh } CO_2 \text{ exhaled}}{(A) \text{ cfh fresh air required}} = \frac{200}{10^6}$$

$$A = \frac{.6 \times 10^6}{200} = 3000 \text{ cfh fresh air required}$$

Billings, a physician, believed when dealing with matters of air supply, engineers should endeavor to secure maximum and not minimum quantities. The American Society of Heating and Ventilating Engineers (ASH&VE), one of ASHRAE's predecessors organized in 1895, adopted the view that engineers were ready to accept the ideas of hygienists and physiologists. The hygienic and physiological communities had adopted the 30 cfm minimum as being required for adequate ventilation. This necessitated mechanical means, and therefore ventilation was essentially an engineering problem. Consequently, it was the engineers who were held responsible in future years for wasting large sums of money on over-designed ventilating systems. The prevalent thought in hygienic circles at Billings' time is perhaps best illustrated by his definition of perfect ventilation. He states, "Perfect ventilation can be said to have been secured in an inhabited room only when any and every person in that room takes into his lungs at each respiration air of the same composition as that surrounding the building and no part of which has recently been in his own lungs or of those of his neighbors." Such a definition is certainly out of step with later discovered facts pertaining to the properties required of ventilation air. It was during the last two decades of the 19th century that the relatively high quantities of fresh air requirements were developed and then found their way into certain statutes. These statutes were in effect for many years and, needless to say, large sums of money were wasted on unnecessary ventilation facilities.

The turning point in ventilation study began in 1883 when Hermans, in Amsterdam, presented a completely new theory.[3] He suggested that it was actually interference with the heat loss process which produced the adverse physiological effects on a human body confined in poorly ventilated quarters. Over 20 years elapsed before the theory was proved in 1905 by Flugge and his pupils Heymann, Paul and Ercklentz at the Institute of Hygiene in Breslau, Germany, and later confirmed by Hill and Haldane in England. Through a series of systematic experiments, these researchers showed conclusively that the mechanism of air vitiation was a physical rather than a chemical phenomenon.[6] In these experiments a subject was confined in a small chamber which had two separate air supply systems. One system provided air to the chamber itself and the other supplied air directly to the subject. By varying the parameters of both air supply systems, i.e. odor, temperature, moisture and carbon dioxide level, the influence of each could be determined. The effects of these variations, gauged by a team of subjects and observers, showed that excessive temperature was the "contaminant" which caused the body to react adversely. Odor played a subordinate role in that it adversely affected the appetites of the subjects. With these findings substantiated, researchers began to ask certain questions pertaining to previously accepted standards. As mentioned earlier, during the latter portion of the 19th century 30 cfm or more of fresh air was in most cases accepted as required for good ventilation. Why 30 cfm? Would lower quantities of supply air which would be temperature and humidity controlled provide adequate ventilation? The 30 cfm came into acceptance because, in the judgment of the boards of health in the 1880's, it was thought to be required. It was written into the law in Massachusetts, and it was easy for other states to follow the Massachusetts example. That this standard had gained wide acceptance was exemplified by a model law, proposed by the ASH&VE in 1914, which stated that a positive outdoor supply of fresh air should be equal to or greater than 30 cfm. Gravity supply of fresh air for small schools, not more than eight classrooms, was permitted as long as 30 cfm was supplied.

The need for answers to the questions which now arose led researchers to probe deeper into the subject. In 1910, at the urging of the Chicago Dept of Health, a commission was appointed representing ASH&VE, the Chicago Public School System and the Chicago Health Dept to study the subject of ventilation. In a report issued by the commission in 1914, it was stated that carbon dioxide was not the harmful agent of major importance in expired air but that temperature and humidity were the two most important considerations.[7] On the subject of air change requirements, the commission concluded that not less than 30 cfm was required for schoolrooms although there was no evidence produced to substantiate this conclusion. Summing up, the Chicago Commission's report produced no radical changes in air requirements, but it initiated further exploration on this subject.

The newly discovered physiological aspect of ventilation prompted still further questioning, such as: Was it plausible to use recirculated air? Could air which was drawn from exhaust ducts and then washed and conditioned be sent back into rooms? Professors A.B. Affleck, D.D. Kimball and F. Bass, in independent experiments conducted in 1913, produced results which on the whole were favorable toward the practice of recirculation of air.

Although significant progress had been made, there still were many unanswered questions. Providing the answers led to the appointment of the New York State Ventilation Commission of 1913. This body carried out extensive experimentation with respect to school and public building ventilation. The commission issued its findings in a report, published in 1923. The first part of the report presented the physiological significance of the various factors – heat, moisture and temperature in ventilation; and the second part presented the results achieved by employing various methods for schoolroom ventilation.[3] At its publication, this work was the most authoritative and extensive treatise on ventilation produced in the United States.

On the subject of air requirements, the New York State Commission concluded as follows: Recirculated air exerts no appreciable harmful influence and the practice of recirculation need not be considered to involve any danger to health or any hindrance to mental progress. Of equal significance, it was concluded that dependable air quantity standards (e.g., 30 cfm) are non-existent. The reason for the latter conclusion is that air quantity by itself is not a reliable gauge of the adequacy of the ventilation. The other variable, air quality, must also be taken into consideration.

Despite the conclusions of the New York State Ventilation Commission, in 1925 the laws of 22 states still called for a minimum of 30 cfm of outdoor air or, in other words, mechanical ventilation.

During the period following the work carried out by the New York State Ventilation Commission, it became increasingly clear that a new approach should be adopted. C.-E.A. Winslow clearly stated this when he cautioned against any dogmatic approach to ventilation requirements. He, too, reasoned that air quality standards were the important consideration, not mechanical standards of air quantity which were assumed would satisfy the necessary air quality standards. Thus, it would appear that each ventilation application would have to be examined for its own particular requirements and then designs tailored to meet these requirements should be provided.

This new approach to solve ventilation problems evolved into the "Effective Air Supply Concept." Briefly stated, this concept required that air supply be tailored to meet each specific application and, as a rule of thumb, provide for 30 cfm with provisions to recirculate up to two-thirds of this supply.[8]

By the year 1926, no revision had yet been made and most statutes called for a 30 cfm outdoor air requirement. In 1931 a bill to repeal the 30 cfm requirement in New York Statutes was passed by both houses of the State legislature, but the Governor vetoed it.

In 1931, School Ventilation Principles and Practices was published.[9] This work summarized all the research carried out by the New York State Ventilation Commission from 1913 to 1923 and supplementary research carried out by this body from 1923 through 1931. Included in the recommendations of this work were the following:

1. The legal standard of 30 cfm was not justified and the law should be amended.
2. For schoolrooms, 10 to 15 cfm fresh air was adequate ventilation and this quantity could be supplied by window gravity ventilation.
3. Any new law should express the desired hygienic results to be obtained or specify engineering devices to be used in their attainment.

As more information was gathered through extensive laboratory research and experimentation, the quantities of fresh air which were thought to be required were reduced. But, experimentation also determined that as the quantity of fresh air was decreased, the intensity of odor produced by the subjects increased. This was shown in such tests as those carried out by Lehmberg, Brandt and Morse and detailed in their work, A Laboratory Study of Minimum Ventilation Requirements: Ventilation Box Experiments.[10] It was determined that 5 cfm or less generally gave a disagreeable odor to judges (located outside the test chamber) and subjects (located inside the chamber). The subjects were not as conscious of odor except for staleness, flatness and a lack of freshness. A nominal range of outside air required to dilute body odor was between 13 and 27 cfm, depending on body surfaces. Also of significance, odors could not be eliminated with ventilation rates up to 50 cfm. The volume of enclosure/occupant ratio was considerably lower than for the average inhabited room; therefore, the ventilation rates above cannot be applied without suitable adjustment. What these rates do point out is that body odor intensity in an occupied room can be taken as a satisfactory index of minimum requirements, since body odor appears to be the most difficult to control of all the objectionable parameters.

Further work was carried out by Yaglou, Riley and Coggins[11] on the subject of correlating odor intensity production to ventilation flow rates. Among the more significant conclusions arrived at by these researchers were the following:

1. Outdoor air requirements can be determined by gauging the odor produced.
2. Individuals give off varying amounts of odor.
3. The recirculation of untreated air had no effect on the odor intensity or air quality.
4. Recirculated air can be rendered relatively odor-free by the process of washing, humidifying, cooling and dehumidifying.
5. Under comfortable conditions of temperature and relative humidity, the air quality was found to be related closely to the intensity of the odor.
6. The body odor perceived varied inversely with the logarithm of the flow rate of outdoor air supplied and the logarithm of the air space allowed per person.
7. A healthy, clean person who is freshly bathed requires 15 to 18 cfm to dilute body odors.
8. Children require slightly higher ventilation rates than adults.
9. Carbon dioxide concentration is an unreliable index of adequate ventilation because its concentration is not proportional to the odor intensity produced.

What then are the accepted standards of today. From the research carried out in the 1920's and 1930's, it is now commonly accepted that the desired objective is to provide for an odor-free environment. It has definitely been shown that where conditions of excessive temperature and body odor are encountered, attention should be directed to the latter since it is the more difficult parameter to control. In other words, if odor is reduced to an acceptable level, it will preclude the occurrence of excessive temperature. The important considerations which must be taken into account when attempts are made to provide an odor-free environment are: dietary and hygienic habits of the occupants, the air space allowed per person, the odor removal capacity of any air-conditioning processes, and the temperature and relative humidity of the room.

The importance of air space per person is illustrated by the fact that ASHRAE requires a mere 7 cfm when the air space is 500 cu ft per person, but requires an increase to 25 cfm when the air space is 100 cu ft per person.[12] These design parameters are based on work carried out by Yaglou, Riley and Coggins in 1936.

Smoking can increase the fresh air quantity requirement to as high as 50 cfm where extreme conditions are encountered.

We have examined the changing concepts of ventilation requirements of the last two centuries and have shown that, while it was a subject of great concern, only relatively recently has its fundamental importance been understood. The concepts of ventilation practice have changed as research provided more knowledge. We may still see changes in the future, but they will most likely be confined to improved engineering techniques rather than any fundamental changes in basic theory.

REFERENCES

1. T. Tredgold, The Principles of Warming and Ventilation – Public Buildings, M. Taylor, London, 1836.
2. R.S. Meikleham, History and Art of Warming and Ventilation, Bell, London, Vol, II, p. 316, 1845.
3. Ventilation – Report of the New York State Commission on Ventilation, E.P. Dutton & Co, New York, 1923.
4. A. Saeltzer, Acoustics and Ventilation, D. Van Nostrand, New York, 1872.
5. J.S. Billings, Ventilation and Heating, The Engineering Record, New York, pp. 120-130, 1893.
6. E.B. Phelps, Public Health Engineering, Wiley, New York, 1948.
7. Report of the Chicago Commission on Ventilation, Chicago, 1914.
8. P. West, Modern Trend in the Science of Ventilation, ASH&VE TRANSACTIONS, Vol. 30, p. 377, 1924.
9. New York State Commission on Ventilation, School Ventilation Principles and Practices, Bureau of Publications, Teachers College, Columbia University, New York, 1931.
10. W.H. Lehmberg, A.D. Brandt and K. Morse, A Laboratory Study of Minimum Ventilation Requirements: Ventilation Box Experiments, ASH&VE TRANSACTIONS, Vol. 41, p. 157, 1935.
11. C.P. Yaglou, E.C. Riley and D.I. Coggins, Ventilation Requirements, ASH&VE TRANSACTIONS, Vol. 42, p. 133, 1936.
12. ASHRAE GUIDE AND DATA BOOK, 1965 and 1966.

BIBLIOGRAPHY

1. Boyle, R., The Ventilation of Public Buildings, Robert Boyle & Sons, London, 1923.
2. Crowder, T.R., On the Reinspiration of Expired Air, American Assn, Chicago, 1913.
3. DIN, 1946, Blatt 1, Lueftungstechnische Anlagen; DIN, 1946, Blatt 2, Lueftung Von Versammlungsraumen.
4. Gauge, H.A., New Systems of Ventilation, D. Van Nostrand, New York, 1881.
5. Hill, L.E., M. Flack, J. McIntosh, R.A. Rowlands and H.B. Walker, The Influence of the Atmosphere on Health, Washington Smithsonian Institute, 1913.
6. Keith, J., Evolution in Ventilation Hygienics, The Naval Architects Number of the SYREN and Shipping Illustrated, April 19, 1916.
7. Manual of Planning Standards for School Buildings, Second Edition, The University of the State of New York, State Education Dept, Div of Facilities Planning, Albany, 1967.
8. NASA SP-3006, Bioastronautics Data Book, National Aeronautics & Space Administration, Scientific & Technical Information Div, 1964.
9. Palmer, G.T., Modern Tendencies of Ventilation Practices, ASH&VE TRANSACTIONS, Vol. 29, p. 19, 1923.
10. Snow, W.G., Ventilation in Its Relation to Health, Webster, Camden, N.J., 1910.
11. Ventilation Laws in U.S.A., Heating & Ventilating Magazine Co, New York, 1912.
12. Winslow, C.-E.A., New Art of Ventilation, Medical Review, 1912.