VENTILATION EFFECTIVENESS - PAST AND FUTURE

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Abstract

During the last decade methods for evaluating the ventilation processes are being developed. The studies have for one thing unveiled the advantages of displacement ventilation. In fact displacement ventilation is not a new invention, and the results are in accordance with qualitatively based statements made hundred years ago. People at that time came to the right conclusions mainly by observing that warmed air rises and cooled air sinks in the surrounding air. The development during the last decade represent an important step forward.

By increased use of computers in the future studies of ventilation processes additional improvements of ventilation systems are to be expected.

1. The ventilation history is very long

Vitruvius, the famous roman architect, discussed ventilation of buildings two thousands years ago. Accordingly, one can imagine that people a long time have been concerned about efficient use of the ventilation air. However, the scientific approach to efficient ventilation belongs roughly speaking to the last 100 year.

With regard to discussing methods for characterizing the effectiveness of ventilation principles in retrospect and prospect, which is the purpose of this paper, it is natural to limit the discussion to this century.

2. Indoor air quality standards were developed 100 years ago

Pettenkofer had at the end of the last century developed the CO_2-criteria (0.7% CO_2). Hygenists in industrialized countries were very concerned about the health concequences of poor air quality in schools, dwellings, hospitals, barracks, theathers, etc., and CO_2-concentrations were measured in buildings in many countries and compared with Pettenkofers criteria.

Human beings produce also heat in addition to CO_2, and as illustrated by Shaw, the air temperature rise along a person was also used as a criteria to determine the demand for ventilation air (about 2^0C was regarded as acceptable).

The hygienists got by their field studies a very good insight into the world of realities. Some of them developed technical solutions for improving the ventilation process. One of those hygienists was Heymann in Stockholm.

With regard to effectiveness he observed that the air due to cold window and outside wall surfaces and warm surfaces of the tile stove was very well mixed. Heymann was, however, aware of the fact that ventilation by dilution is not the optimum ventilation principle. He used a cup of water with some dye as an illustration. By eliminating the dye by steady dilution he needed more water compared with emptiing the whole cup and filling it up with fresh water.

In short one may say that permissable limits of respirable impurities to keep up health conditions were developed. However, little attention was paid to physical laws of ventilation to ensure the fulfilment of the hygienists criteria. The demand for improved technical education was obvious, and in this connection it is interesting to notice that the first HVAC-institution on university level was established in Berlin about 100 years ago.

3. 50 years discussion about the location of supply and exhaust openings

Due to uncomplete quantitive physical knowledge about the ventilation processes, the years up to the second world war were filled with discussion about how to conduct air in ventilated rooms.

One school was supporting the idea that air should be supplied in the lower parts and exhausted from the upper parts of the room. The other school represented supporters of conducting the air in the opposite direction.

Shaw emphasized the demand for improved insight in physical laws to reduce the ventilation problem from mere qualitative suggestions to a numerical relationship.

According to Shaw, the dominating law in a ventilated room is the law of convection. Warmed air rises and cooled air sinks in the surrounding air. Air from our lungs and the heat loss from the body ensure a rising air flow such that we breath fresh air.

Accordingly, warmed air should be supplied from above and cooled air from below.

To secure efficient ventilation Rietschel's thoughts went along similar tracks as Shaw's, and he concluded that fresh air should be supplied at floor level with low velocity (0.3 m/s) and with a few degree below room air temperature and exhausted from the top of the room.

Obviously, separate heating was needed to take care of transmission losses.

The lecture hall at Rietschel's institution at University of Berlin was provided with a ventilation system according to that principle with good result.

Rietschel had pupils in many countries. The ventilation of the assembly hall at the Norwegian Institute of Technology finished in 1910 was based on the same principle.

Air may carry both heat and contaminants, and already at a very early stage air was used both for heating and ventilation. The supply air openings seemed in general to be located in the upper parts of the room and exhaust air openings at floor level.

However, by reduced heat load the supply of fresh air too had to be reduced which resulted in reduced air quality. Accordingly separate systems for ventilation and heating beeing seemingly in general recommended.

An English hygienist, living 150 years ago, expressed that heat is more important to the human frame than fresh air, and that one can not expect ventilation where food, clothing and fuel is in short supply.

Concern about air quality and energy consumption is thus not restricted to our time.

Heymann who was very concerned about the hygiene in dwellings, discussed the conduction of the air both with regard to air quality and energy consumption. He emphasized that concerning contaminations owing to people and gas lighting, the exhaust should be located at ceiling level.

His observations unveiled that cold outside surfaces and warm stove surfaces resulted in a strong air circulation such that the CO_2 concentration was quite uniform in the room.

On the other hand there was a considerable temperature differance between air at ceiling and floor height, and Heymann concluded that due to energy saving air should be the exhausted from floor level. However, building constructed in the early parts of this century had exhaust openings located both in the upper and the lower part of the room, one for summer use and one for winter use.

The objections concerning air supply at floor level were transport of dust up into the breathing zone, and problems of finding sufficient space for the supply openings.

In the US Halls of Senate and Congress the ventilation principles was changed from upwards to downwards air supply when they discovered that the exhaust terminals in the ceiling were covered with a layer which according to the allegations consisted of dust and dried spitt and tobaccosauce.

According to the experience the air velocity should not exceed 0.3 m/s by suppliing air at floor level. The temperature difference between room air and supply air should additionly be less than 3°C. Evidently, it could be difficult to locate the substantial supply openings which such inlet conditions may lead to.

Higher air velocities and greater temperature-differences are possible when air is supplied in the upper part of the room. The location problem is, additionally, usually easier to solve and thus, it is regarded easier to handle great cooling loads that way.

Since the quantitative base for evaluating the systems was not (or insufficient) developed it changed in a way like fashion which of the opinions about how to conduct air through the room was predominant.

4. The first attempts to quantify the effectiveness

Heymann was aware of the fact that ventilation principles are not equal efficient, and he concluded that displacement ventilation was more efficient than dilution ventilation.

Rietschel and many with him, observed that by suppliing the air at floor level with low velicities and with temperature a few degrees below room temperature contaminants both from people and gas lighting in an efficient way were carried out of the room. Rietschel characterized suppliing air in in the upper part of the room as "a fashion" and opposed strongly using that principle in room with gaslighting and smoking. Additionally, local exhaust from gas-chandeliers was recommended both with regard to elimination of heat and particulate and gaseous contamination.

About the second world war Yaglou in US and Rydberg in Sweden studied the effectiveness of ventilation principles.

Rydberg used water models for his studies, and the ventilation effectiveness was expressed at the ratio between the colour concentration in the water discharge and the average concentration in the model.

Mathematically the effectiveness was expressed in this way:

$$\langle \varepsilon_v^c \rangle = \frac{C_E}{\langle C_i \rangle}$$

$\langle \varepsilon_v^c \rangle$ - ventilation effectiveness
C_E - concentration in exhaust opening
$\langle C_i \rangle$ - average room air concentration

The ventilation effectiveness is obviously equal to 1 when the air is completely mixed by short-circuiting the supply air is poorly utilized:

$$\langle \varepsilon_v^c \rangle < 1$$

If the exhaust opening is placed close to the source of contamination the ventilation effectiveness is greater than 1.

The relationship between supply of contaminants ($\dot{V}_m$), ventilation effectiveness ($\langle \varepsilon_v^c \rangle$), acceptable concentration in the room air ($\langle C_i \rangle$), and the supply air ($\dot{V}$) demand may be expressed this way:

$$\dot{V} = \frac{\dot{V}_m}{\langle \varepsilon_v^c \rangle \langle C_i \rangle}$$

Evidently the air supply demand and thus the cost of the system and the energy consumption decreace as the effectiveness improves.

As mentioned before air may carry both heat and pollutants, and a ventilation system may be used both for ventilation, cooling and heating.

The objective may thus be to provide the room both with acceptable air quality and thermal climate. Accordingly, parameters related to thermal climate are also used to characterize the ventilation system.

5. Providing acceptable thermal climate dominated the post war periode

A characteristic feature of the post war architectual design was greater glazed areas, lighter building construction, and reduced room heights. At the same the time lighting level was increased and more heat emitting equipment was taken into use.

Providing acceptable thermal comfort became the predominant objective, and uniform thermal climate throughout the zone of occupancy was required. Obviously, that requirement was best met by complete mixing, and the Americans seemed to design their ventilation systems accordingly.

US is the leading country in the field of air conditioning, and the US-systems were copied around the world. The American way of thinking thus influenced the development in other countries considerably.

Fresh air for some people is draught for other people. A critical aspect of ventilation is draught, and draughts criterias were taken into use for evaluating ventilation systems.

Rydberg developed in the 60'thies design guidelines for supply air terminals. Basis for the development, along with fluid dynamics for jets was Rydberg/Houghtons draught criteria - the effective draught temperature:

$$\theta = (\theta_x - \theta_o) - 8(w_x - 0.15)\ {}^0\mathrm{C}$$

θ_x - local temperature ^{0}C
θ_o - average roomtemperature ^{0}C
w_x - local air velocity m/s

Nevins and Miller used the same criteria as basis for their air diffusion performance index (ADPI).

According to Rydberg/Houghton 20% or less of a population would be dissatisfied due to draught if:

$$-1.7^0\mathrm{C} < \theta < 1.1^0\mathrm{C}$$

As upper limit for the air velocity Nevin and Miller used $w = 0.35$ m/s.

ADPI is defined as the relationship between the number of measuring points with results within the comfort zone defined above and the total number of measuring points.

The ADPI is always less than 1 and ADPI represents a kind of efficiency.

In 1970 Fanger presented an operativ method for the evaluation of thermal climate, and new terms like predicted mean vote (PMV) percentage dissatisfied people (PDP) were introduced.

Fangers index such as other thermal comfort indices give the highest score for a uniform climate, and accordingly one may conclude that complete mixing is the ideal ventilation process. But, is it really so with regard to the air quality?

During the postwar periode seemingly people did not bother about air quality. The time made, however, a new turn and operative methods for characterizing the efficiency of the ventilation processes with regard to air quality were obviously needed in addition to the thermal climate.

6. Evaluation of the ventilation processes by the air exchange efficiency and the ventilation effectiveness

During the last decade the ventilation processes have been studied by Scandinavian scientists, first of all by Sandberg and Skåret. The main results of their studies were firstly that they unveiled that effectiveness/efficiency could be expressed by time-constants which easily could be determined by tracergas-measurements. Secondly, the introduction of the two-zone model made it possible to analyse ventilation processes in fairly simple, but reasonable accurate way. Thirdly, their studies and analyses resulted in development of displacement ventilation systems not only for assembly halls, industrial buildings etc., but also for ordinary buildings such as offices. In that way the development represent a renaissance of displacement ventilation and a confirmation of qualitative validations and practical conclusions by Rietschel, Shaw and many others.

By considering some simple flow situations it is possible to explain the main ideas quite easily.

First of all we want a ventilation system that provide every part of the room with fresh air. We want to eliminate stagnant zones where pollutants may be locked in.

By letting the air flow uniformly through the room (plug flow) one get the most efficient air change. Plug flow is thus used as a reference flow.

We then study a hypotetical situation where the room volum is devided into small volume elements. Each of these elements are provided with a local source of contamination by entering the room.

If there is no exchange of pollutants between the elements it is easy to see that the concentration in each element is proportional to the time it has spent in the room (the age of the element).

The transit time which is independent of the flow principles is:

$$\bar{\tau}_n = \frac{V}{\dot{V}}$$

V - room air volume m^3

In stationary conditions the concentration in the exhaust opening will always be proportional to the transit-time for the room.

By plugflow the average concentration or the average age is then:

$$\frac{\bar{\tau}_n}{2}$$

In the general case the average age will be: $\langle \bar{\tau}_i \rangle$

The air exchange efficiency is defined as the relationship between the average age for the ideal flow and the average age for the real flow through the room.

$$\langle \eta_a \rangle = \frac{\tau_n}{2\langle \bar{\tau}_i \rangle}$$

By using tracergas the time-constants τ_n and $\langle \bar{\tau}_i \rangle$ are quite easily determined as responses of unit functions. For common ventilation principles the air exchange efficiency will be:

Plug flow	$\langle \eta_a \rangle = 1$
Displacement ventilation	$0.5 < \langle \eta_a \rangle < 1$
Complete mixing	$\langle \eta_a \rangle = 0.5$
Short-circuiting	$\langle \eta_a \rangle < 0.5$

So far we have used the contamination as a tracer. The next step is to consider it as it really is.

Rydberg defined the ventilation effectiveness as the ratio between the concentration in the exhaust opening and the average room concentration.

$$\langle \varepsilon_v{}^c \rangle = \frac{c_E}{\langle c_i \rangle}$$

In the hypothetical situation with plug flow the ventilation effectiveness will thus be:

$$\langle \varepsilon_v^c \rangle = \frac{\tau_n}{\tau_n/2} = 2$$

We then change the hypothetical situation a bit. The volum elements are provided with contamination sources but nothing happens before we turn all sources on at once. The concentration measured in the exhaust opening will then increase linearly from 0 to the stationary value C_E during the time τ_n.

The transit time for the contamination will in this case be:

$$\tau_t^c = \frac{\tau_n}{2}$$

In the general case the ventilation effectiveness is:

$$\langle \varepsilon_v^c \rangle = \frac{C_E}{\langle C_i \rangle} = \frac{\bar{\tau}_n}{\bar{\tau}_t^c}$$

By complete mixing $\langle \varepsilon_v^c \rangle = 1$ and by shortcircuiting-stagnation zone - $\langle \varepsilon_v^c \rangle < 1$. With the source of contamination in the exhaust opening $\langle \varepsilon_v^c \rangle \rightarrow \infty$.

Evidently the transit-time for the contamination should be as short as possible. That means that we should strive for low average room air concentrations and shortcircuiting of the contaminants.

In real rooms the conditions may be quite complicated. There may be warm surfaces, and cold surfaces, and the heat sources may be unevenly distributed. Additionally, heat is transfered both by convection and radiation. There may be jet flows, and the sources of pollutants may be unevenly distributed with regard both to space and time. However, this rather complicated situation may in general be simulated by a two zone-model with reasonable good result. Dividing the room into two zones represents a considerable simplification of the problem. Within each zone the air is regarded as completely mixed, and between each zone there may be a certain air exchange.

With both the supply and exhaust terminal located in the upper zone and with evenly distributed contamination sources in the room, it is necessary to improve the air exchange between the upper and lower zone, as best as possible, for instant by increased impact of jets. The best possible result in this case is complete mixing, and therefore:

$$\langle \eta_a \rangle < 0.5 \quad \text{and} \quad \langle \varepsilon_v^c \rangle < 1$$

By displacement ventilation all the ventilation air is passing from one zone to the other. In this case additional mixing between the zones will deteoriate the result. Complete mixing is in this case the worst situation. Thus:

$$0.5 < \langle \eta_a \rangle < 1.0 \quad \text{and} \quad \langle \varepsilon_v^c \rangle > 1$$

Contaminants released by human beings, office machines etc., are warmer than the surrounding air. The contaminated air ascends upwards into the upper zone and may in fact be regarded as produced there. In such cases the effectiveness will be improved significantly. Obviously, displacement ventilation has certain advantages, and during the last decade the system is taken into use in offices, restaurants, hospitals etc. in the Scandinavian countries.

A Norwegian text book on ventilation and heating from 1886 states that there ought to be one system for heating and one for ventilation. By using displacements ventilation we are back to that situation again.

Since the air has to be supplied with a few degrees below the room temperature, a separate heating system is needed.

Displacement ventilation has also unveiled the advantages of appliing separate systems for each of the three functions ventilation, cooling, and heating.

Displacement ventilation is well suited for variable air volume flow. It represents a considerable cooling effect. In office buildings with high cooling load the additional cooling capacity is covered with cooling panels in the ceiling with good result.

7. Smoke control, demand controlled ventilation and minimum ventilation rates.

Among other aspects of ventilating systems, smoke control, demand controlled ventilation and minimum ventilation rates have also to be considered here.

Fire starts very often as smouldering fire. The smoke rises direct to the ceiling by displacement ventilation, and thus the fire is detected sooner then by dilution ventilation.

Usually the death caused by fire is due to smoke. For nursing homes, hospitals, hotels etc., a few minutes earlier detection may mean death or life for the occupants. Additionally, the displacements ventilation keeps a zone along the floor free from smoke for a certain time such that people lying on the floor easier survive or easier are rescued by the fire brigade.

CO_2-controlled ventilation is today regarded as an cost-effective measure for energy conservation. However, studies on sites unveil that the result to a large extend depend upon the ventilation effectiveness.

When the fresh air is short cicuiting the room, the CO_2-concentration in the exhaust duct is lower than in the zone of occupancy.

Obviously, it is possible to save quite a lot of energy. But the quality of the air breathed by the occupants is below the acceptable level.

To ensure that the air quality in the zone of occupancy is on the safe side of the quality measured in the exhaust duct, displacement ventilation should be used.

The term "Minimum Ventilation Rates" are questionable, in particular by displacement ventilation.

Plumes rising from people, lighting etc. are entrained by air from the surrounding. Above a certain height the supply air is not sufficient to feed the plumes, and the plume then start feeding itself by recirculation. Obviously, the room should be provided with a rate of supply air such that the zone of the reciculation is above the breathing zone.

The demand for supply air has thus to be adjusted to the particular case.

Recirculating of air in the ventilation system is not to be recommended, and heat recovery is a natural part to make the system both energy and cost effective.

8. Summary

During the last decade scientists in many countries, in particular in Scandinavia, have been concerned about efficient ventilation, and methods for evaluating the ventilation prosesses are developed. The Scandinavian approach is characterized by the use of time-constants and by use of two zone models. The time constants are easily determined by tracergas.

The studies unveiled for one thing the advantages of displacement ventilation, and as a result displacement ventilation is used in industrial buildings, assembly halls, restaurants, hospitals, offices etc. In Scandinavia today the advantage of displacement ventilation by smoke control and CO_2-controlled ventilation is emphasized too.

The results confirm statements made already by the end of the last century by Rietschel in Germany, Shaw in England, Heymann in Sweden etc.

They came to the right conclusions by applying, mainly qualitatively, the law of convection which is the dominating law of ventilated rooms. It simply learn that warmed air rises and cooled air sinks in the surroundings air.

The development in the last decade represent an important step forward. The future lies first of all in the application of computers, which scientists are already using for analyses of air distribution, air temperature, concentrations of pollutants, air velocities etc. in ventilated rooms and buildings.

It is also easy to see a future combination of computer programs simulating the ventilation processes with programs simulating the outdoor climate the building construction and the thermal environmental systems such that both the indoor air quality, the thermal indoor climate, the energy consumptions etc. may be analyzed on a yearly basis.

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AIRBORNE BACTERIA AND THE INDOOR CLIMATE

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Abstract

Since the 1940's there has been an increase in the awareness and appreciation of the importance of airborne infection. The importance of particle size (<5 μm) and the concept of droplet nuclei which remain suspended in air for considerable periods have been seen as important determinants of infectivity. The appearance of humidifier fever caused by thermophilic actinomycetes and amoebae and the recognition of Legionnaires' disease has lead to an appreciation of the microbiological dangers posed to individuals in modern buildings. These microorganisms like the legionellaceae are aquatic in nature and are able to colonise building water services probably gaining access via the public water supply. Proliferation of these organisms within building water systems, humidifiers and air conditioning equipment is associated with inadequate maintenance or infrequent usage. These factors provide the ideal conditions for settlement and growth of organisms in water handling equipment. The survival of these organisms or their toxins in aerosols produced by water handling equipment can lead to the establishment of disease in susceptible individuals who inhail them.

Introduction

As building technology has advanced together with improvements in standards of living, the ability to control the indoor climate in new buildings has become a necessity. These advances, however, have thrown up unforeseen problems. The colonisation of cooling towers by microorganisms has lead to impairments in their heat rejection abilities. This in turn has caused the development of the modern industry of water treatment using chemicals to inhibit the growth of these "fouling" organisms.

The storage of water within buildings to provide water for showers, baths and general washing is now commonplace. Often regarded as potable, this stored water may be subject to deterioriation in chemical and bacteriological quality and hence is not potable. The degree of microbial growth in treated water systems depends on water temperature, pH, redox potential, the residence time of the water within the system, the concentration and persistence of any residual disinfectant, the type of water treatment process applied, the availability of organic or inorganic substrates and the presence of sediments or corrosive products.(6)