International Symposium on Room Air Convection and Ventilation Effectiveness
University of Tokyo, July 22 – 24, 1992

EVALUATION OF VENTILATION EFFECTIVENESS AND WORKER EXPOSURE AT THE DESIGN STAGE

P. O. Tjelflaat
Associate Professor
The Norwegian Institute of
Technology
N7034 Trondheim-NTH
Norway

ABSTRACT

Measures for ventilation effectiveness and exposure assessment, to be used for evaluation at the design stage for industrial ventilation, have been reviewed, derived, and analyzed.
Measures, to be used along with CFD-simulations, are introdused for inhaled dose of contaminant and for worker concerning ventilation efficiency.

KEYWORDS Ventilation Effectiveness, Exposure Assessment, Industrial Workplace, Room Airflow, Design Evaluation

INTRODUCTION
VENTILATION EFFECTIVENESS AND EXPOSURE ASSESSMENT
Established Measures for Ventilation Effectiveness
Measures Considering Exposure Assessment
A Measure for Ventilation Effectiveness
CFD-SIMULATIONS FOR AN INDUSTRIAL HALL
Numerical Method
Building, Heat- and Contaminant Sources, Ventilation and Working Routines
RESULTS AND DISCUSSION
CONCLUSIONS
REFERENCES
NOMENCLATURE

1 INTRODUCTION

Industrial health practice attempts to limit worker exposure to injurious substances at levels that do not interfere with the work process and do not injure the workers' health. The elimination of all effects from contaminants is not attempted. Health effects from airborne contaminants are related to the inhaled rate of the injurious substance and to the time during which it is present. Regulations are mostly based on experience with worker health and are expressed as concentration limits for instantaneous and short- and long-term exposure.

In the process of designing for acceptable air quality for indoor work places, it is essential that relevant measures for evaluation of ventilation and for assessing exposure are used along with the best available tools for predictions. In that way, injure to workers health can be minimized and a ventilation with low ventilation rates can be achieved.

The main objective of this paper is to present a way of assessing exposure to airborne substances along with a new measure for efficiency of the general ventilation in a room. Expressions derived are based on accumulated exposure to inhaled airborne contaminants. The expressions are intended to be applied along with CFD-simulations for evaluating the ventilation design being suggested for new industrial halls or for retrofitting of existing ones.

It is also an objective to show the benefits of using such methods along with CFD-simulations in order to evaluate proposals for ventilation design for an industrial production hall.

2 VENTILATION EFFECTIVENESS AND EXPOSURE ASSESSMENT

2.1 Established Measures for Ventilation Effectiveness

The main objectives of ventilating are to supply fresh air at a sufficient rate to the breathing zone of occupants and to remove contaminated air.

The size and the location of the breathing zone in a room for indoor occupancy may vary with time and with the specific activities going on. If that is the case, most of the volume in the room must be considered as breathing zone and the use of average properties for the room are relevant for evaluation of ventilation effectiveness. Then the air change efficiency and the ventilation efficiency as derived by Sandberg (1984) and Skåret (1984) are very useful.

The *air change efficiency* ϵ_a is a measure of how effectively the air at every location in a room, at a average, is replaced by fresh air from the supply openings. ϵ_a Expresses a comparison of the average resident time for the molecules in the ventilation air in the room at the ideal "piston-flow ventilation" to the actual average resident time. Consequently, the air change efficiency for piston-flow ventilation is 1.0 while the air change efficiency for "complete mixing ventilation" is 0.5.

The *ventilation efficiency* ϵ_v is a measure of how quickly a contaminant is removed from the room. It can be expressed as the ratio between the concentration of the contaminant in the exhaust air and the average concentration in the room given a supply air free from the contaminant.

The first term is more relevant in rooms with uniformly distributed or many small and different or ill-defined contaminant sources while the latter is more relevant when there are few and specific contaminant sources. One good thing with ϵ_a is that it is easily measured with tracer gas technique.

Ventilation efficiency is generally considered to be the most appropriate measure for ventilation in processing industry where definite contaminant- and heat sources are present. However, the ventilation efficiency is only expressing how efficient the contaminant is transported by the airflows into the exhaust opening. It is not giving specific information about contaminant concentration in the breathing zone of the working area.

The *local air change index* ϵ_p is similar to the air change efficiency ϵ_a. The only difference is that the value for the average resident time for every location in the room is exchanged with the value for one point which could be the breathing zone of a stationary worker. The breathing zone of a worker operating along a production line could be represented by the average value for resident time for air molecules in that volume. Thus, the local air change index can be used to evaluate if the breathing zones for workers are supplied with fresh air.

The *local ventilation index* ϵ_{vp} is defined similarly to the ventilation efficiency ϵ_v. The only difference is that the value for the average concentration of the contaminant in the room is exchanged with the value for one point or a volume that is representing the breathing zone. When the general ventilation in a processing hall is evaluated and the local ventilation index is found to have high values in the breathing zone, the ventilation is characterized as efficient.

Even though the expressions for air change efficiency and index and ventilation efficiency and index can be used to evaluate the ventilation effectiveness, a relevant quantitative measure, which estimates the exposure to the contaminant, is missing. Thus, there is a need for a measure that can quantitatively express the exposure and be compared to limits given in regulations for indoor workplaces.

2.2 Measures Considering Exposure Assessment

The most cost-effective solution for general ventilation in a room is accomplished when sufficient air quality is provided at a lowest possible cost. The cost, and also the energy-consumption, of mechanical ventilation is strongly related to the supply air volume rate. Thus, it is a question of keeping the exposure of a worker to airborne injurious substances below legal limits at a lowest possible volume rate.

In regulations, the exposure dose of an injurious substance is expressed as a *time weighted average concentration* (TWA), a *short-term exposure limit* (STEL), and a *threshold limit value* (TLV), ASHRAE (1989). The TWA is based on a 40-hour work week with 8 to 10-hour days. The STEL is based on time periods up to 15 minutes during which the TWA can be allowed exceeded, The Labour Inspectorate (1990). The TLV is a concentration level that shall not be exceeded even instantaneously.

The health-risk is not only related to factors like level of concentration and time-period of exposure; the dose of injurious substance actually being inhaled is likely to be very important. The breathing rate of the worker along with the level of concentration of the contaminant in the breathing zone and the time-period of exposure is the basic information needed in order to estimate the amount of substance inhaled by the worker. That amount can be related to the concentration limits given in regulations.

The TLV corresponds directly to the concentration of the contaminant in the breathing zone. That value will be independent of the behaviour of the worker being exposed.

The health hazard is often related to the dose of injurious substance inhaled. In the case of instantaneous exposure it would be natural to use an expression for dose rate. The *inhaled dose rate* is expressed in terms of kg substance per hour as:

$$\dot{m}_c(t) = \dot{m}_{vp} C(x_l, t) \qquad (1)$$

where $\dot{m}_{vp}$ is the mean pulmonary ventilation rate. Based on the work by Fanger (1970), it can be written as:

$$\dot{m}_{vp} = 0.0070 M(t) \qquad (2)$$

where the metabolic rate M(t) is directly related to the activity level of the worker. Metabolic rate for different types of activities is listed in Fanger (1970) and in ISO Standard 7730 (1990). For an adult male, the metabolic rate varies from about 125 W for standing, relaxed to about 300 W for standing, heavy work.

A worker having metabolic rate within these limits has a pulmonary ventilation rate typically varying between 0.9 and 2.1 kg air per hour. Consequently, also the inhalation rate of the injurious substance would vary 1:2.3 at the two different levels of activity, assuming the concentration in the breathing zone being the same. The inhalation rate of the substance, i.e. the dose rate, would be a more relevant measure for the instantaneous exposure than the TLV. However, specifying a value for metabolic rate along with the TLV in the regulations is the only action needed to be taken to calculate the dose rate.

A measure to be compared with the short term exposure limit STL can be found by integrating the dose rate over short time periods during a work-day. Though, a specification for metabolic rate is also here needed to make the comparison.

The *dose of a contaminant a worker is exposed to during a work-day* can be found by integrating the instantaneously dose rate from the start to the end of the work-day:

$$m_{cd} = \int_{t_s}^{t_e} \dot{m}_{vp} C(x_l, t) dt \qquad (3)$$

This measure should be relevant for evaluation of long term exposure to the contaminant. Also with the use of this measure, there is a need for the metabolic rate to be specified in the regulations along with the time weighted average concentration TWA.

Along with CFD-simulation, the described measures for exposure assessment are valuable to check whether worker exposures are likely to be in accordance with regulations or not when a new production hall is being designed or an existing one is being retrofitted.

2.3 A Measure for Ventilation Effectiveness

A commonly applied method for design of general ventilation in industrial production halls is to assume the amount of the contaminant submitted to the air being diluted and completely mixed with the air in the room. The supply air flow rate is often dimensioned to give a resulting concentration everywhere equal to 1/3 of the TWA. That concentration value is chosen in order to have a safety factor covering uncertainties with contaminant and heat emittance rate from processes, air distribution in the room and working routines.

A design as above may be used as a first coarse estimate for the air flow rate being needed for ventilating the room. Especially in cases with high release of heat and contaminants, complete mixing is rarely achieved unless resulting air speeds being too high in the zones of occupancy. In such cases, especially where there are common sources for release of heat and contaminants, displacement ventilation can be used with good results. For displacement ventilation, simple relations for vertical air flow rates from heat sources can be used to estimate the ventilation air flow rate required to bring the contaminated upper layer of the indoor air above the zone of occupancy.

However, recirculating airflows caused by high momentum air flows from thermal plumes and by downdraughts from poorly insulated windows are often present and are not easy to estimate with simple methods. And the use of physical models or CFD-simulations is then required in order to ensure the best available evaluation of the suggested ventilation design. A typical case of industrial ventilation is presented in Figure 1 which shows the effect of resirculating flows. Results are taken from the CFD-simulations described below.

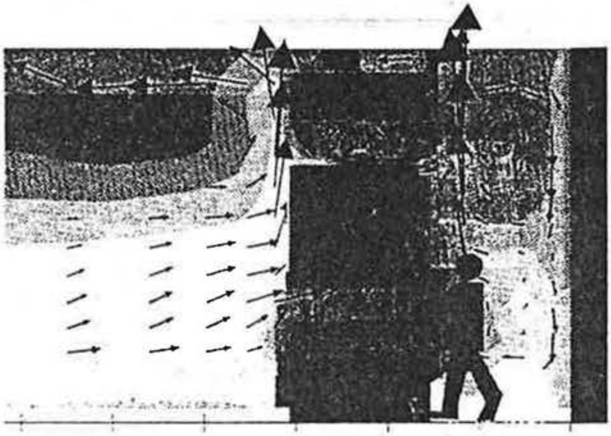

Fig. 1 The effect of resirculating flows. Shading is illustrating increasing concentration of the contaminant. From Isaksen (1991).

The established measures for ventilation effectiveness described above can be used along with CFD-simulations to check the ventilation effectiveness. But, as discussed above, these measures cannot be used to check the exposure to contaminants. As measures for ventilation effectiveness in the design process, the expressions for air change efficiency and ventilation efficiency are best suited for analyzes of industrial halls where access to data is scarce and the task of achieving the optimum effectiveness not has a high priority.

In order to evaluate the ventilation effectiveness for a room, the resulting ventilation for the actual case has to be compared to a commonly known case. In the case of ventilation efficiency, the actual average concentration in the room is compared to the concentration in the room in the case of complete mixing ventilation i.e. the concentration in the room is identical to the concentration in the exhaust air.

In an evaluation procedure, the check for exposure being within regulations should be carried out anyway. Then the idea naturally suggests itself that exposure dose also being used in expressions for ventilation effectiveness. It is logic to suggest the following expression called the *worker concerning ventilation efficiency* (WCVE):

$$\epsilon_W = \frac{\int_{t_s}^{t_e} \dot{m}_{vp}(t)\, C_e(t)\, dt}{\int_{t_s}^{t_e} \dot{m}_{vp}(t)\, C(x_i, t)\, dt} \qquad (4)$$

Here, the actual inhaled dose of the contaminant, accumulated during a work-day, is compared to the inhaled dose of the same worker in the case of full mixing ventilation in the room. The worker being focused on has a specific schedule for location of breathing zone and for metabolic rate.

For a case with steady state conditions with respect to outdoor environment, room envelope tightness, heat- and contaminant release and ventilation flow rate WCVE is written as:

$$\epsilon_W = \frac{\int_{t_s}^{t_e} \dot{m}_{vp}(t)\, C_e\, dt}{\int_{t_s}^{t_e} \dot{m}_{vp}(t)\, C(x_i)\, dt} \qquad (5)$$

The interpretation of the numerical values being calculated for the WCVE is as follows: When $\epsilon_w < 1$ the ventilation is less efficient than with complete mixing ventilation. The goal should be to achieve $\epsilon_w > 1$ and as high as possible. Then the applied ventilation air flow rate is utilized to the highest degree.

The greatest benefit with worker concerning ventilation efficiency compared to the established measures emerges when the ventilation efficiency is not satisfying and redesign is carried out.

In industrial ventilation, problems with high exposure of contaminants to workers are first tried solved by eliminating the contaminant emittance to the workplace environment. Then, considerations with automation of the production process, the working routines and the air distribution and volume rate should be carried out. In that process, suggestions for redesign must be evaluated in a relevant way; with respect to exposure assessment as well as with respect to ventilation effectiveness.

The value for WCVE is being influenced by alterations in working procedures including changes in working area, changes in activity level and changes in time period for different working operations.

Of the established measures for ventilation efficiency, only the local air change index and the local ventilation index are influenced by such alterations - and the change in working area is the only alteration taken into account.

For evaluation of ventilation effectiveness in an industrial production hall with more than one worker, an average value based on the WCVE found for each worker should be applied. The following expression for $\overline{WCVE}$ is suggested:

$$\bar{\epsilon}_W = \frac{1}{n}\sum_{i=1}^{n} \epsilon_{Wi} \qquad (6)$$

where n is the number of workers.

3 SIMULATIONS FOR AN INDUSTRIAL HALL

3.1 Numerical Method

The simulation program being applied is KAMELEON. The code has been developed at NTH-SINTEF Division of Thermodynamics, The Norwegian Institute of Technology. A description of the program is given by Holen and Magnussen (1989). The program is capable of solving two- or three-dimensional steady state or transient time-averaged equations for conservation of mass, momentum, energy, turbulent energy and dissipation of turbulent energy based on finite-volume considerations. A low-Reynolds number $k - \epsilon$ model of turbulence is used.

The equations are solved on a staggered grid by using one of several options for differencing. A pressure correction method called SIMPLEC and under-relaxation is used to iterate towards a converged solution. The solution method is basically as described by Patankar (1970). The simulation program code is vectorized to run efficiently on the CRAY XMP-2 computer.

The results from CFD-simulations presented here are from Isaksen (1991).

In the numerical model, the room was represented with a total of 22,512 grid points. Ventilation supplies and extracts, heat supply from production processes, and heat loss through the building envelope were modelled. The real contaminants were modelled by a method similar to the tracer step-up method in tracer gas technique to find the air change efficiency and index.

Numerical solutions, with satisfying convergence for all variables, were typically achieved after 600 iterations and by using 1300 CPU-seconds on the CRAY computer.

3.2 Building, Heat- and Contaminant Sources, Ventilation and Working Routines

Simulations are carried out for an industrial hall. The main dimensions of the hall considered are length L=48 m, width W=20 m and height H=4.5 m.

Winter conditions at outdoor temperature $-10°C$ are assumed. The total heat loss by transmission through the building envelope is estimated to 38 kW.

The power released from the production processes to the air in the room is estimated to a total of 115 kW.

The supply air flow rate is $30{,}000 m^3/h$. Displacement ventilation with a total of 6 supply units at floor level is used. The outlet velocity of supply air is 0.13 m/s while the supply air temperature is $18°C$. A horizontal cross-section, indicating the production lines L6 and L7 and the supply unit, of the industrial hall is shown in Figure 2. The shaded areas are enclosures separated from the hall.

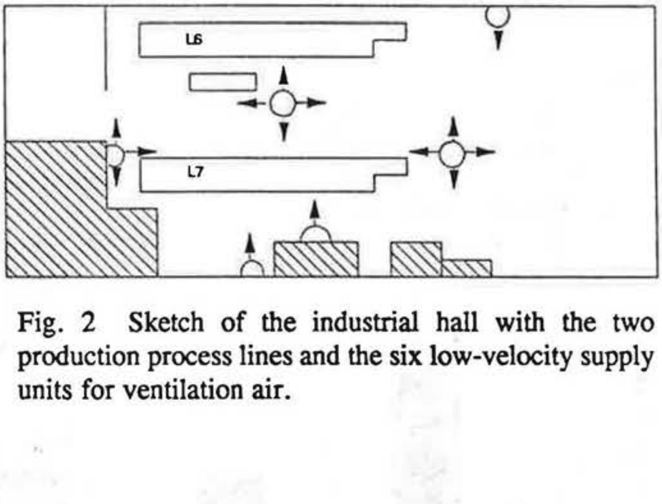

Fig. 2 Sketch of the industrial hall with the two production process lines and the six low-velocity supply units for ventilation air.

4 RESULTS AND DISCUSSION

The computed results for temperature- and velocity-distribution and distribution of turbulent kinetic energy were processed along with information on metabolic rate and position for the breathing zone as a function of time during the work-day.

Consider a worker occupied with keeping the production line L6 running. The production line, shown in Figure 2, has several positions where a contaminating substance is being released. The worker is most of the day working in the area between that production line and the outer wall of the building which has poorly insulated windows causing downdraughts. A typical position for this worker is shown in Figure 1. The workers activity is partly heavy work. His typical work day is broken down to half-hour periods and schedules for metabolic rate and position for breathing zone are made.

There are many ways of improving an exposure situation for a worker and/or the ventilation effectiveness for a ventilated room. In this presentation, the effect of process automation to give metabolic relief and the effect of transfer of working area to avoid the most contaminated zones are analyzed.

The accumulated inhaled dose of contaminant for the typical work-day is shown in Figure 4 for the same four cases. The effects of reduction of metabolism and transfer of work area are similar but even stronger than for the inhaled dose rate.

In a real case, the calculated results for inhaled dose rate have to be related to the TLV-value and the inhaled dose of contaminant for a work day has to be related to the TWA-value.

But as discussed in Chapter 2.2, reference values for metabolic rate have to be given in regulations. The maximum value of inhaled dose rate of the contaminant for the worker during a work-day is shown in Figure 3. The original situation is the one marked WA1, M2. Lower metabolic rate in the same working area WA1, M1 is seen to more than halving the inhaled dose rate. The position of breathing zone as a function of time is the same for both cases. The transfer of the working area from the original position WA1 to a position on the opposite side of production line L6 is seen to reduce the inhaled dose of contaminant with about 30%.

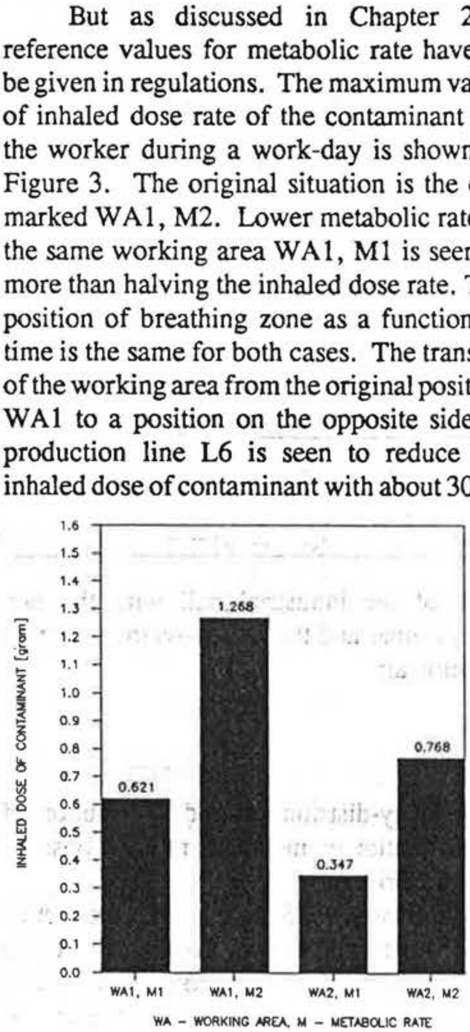

Fig. 4 The accumulated inhaled dose of contaminant over a work-day for 4 combinations of worker area and worker metabolism.

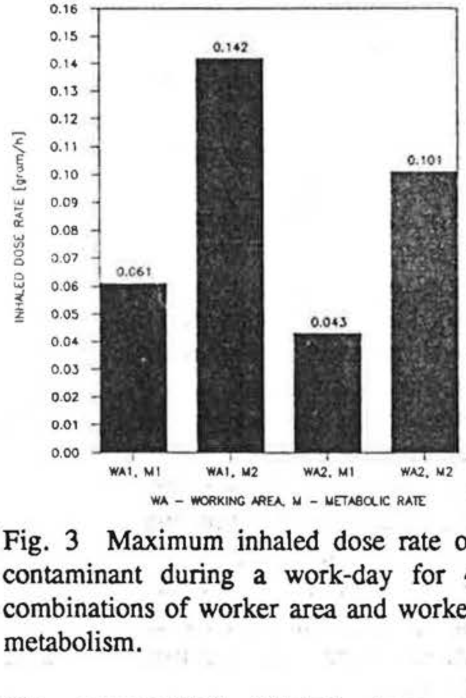

Fig. 3 Maximum inhaled dose rate of contaminant during a work-day for 4 combinations of worker area and worker metabolism.

The accumulated inhaled dose of contaminant for the typical work-day is shown in Figure 4 for the same four cases. The effects of reduction of metabolism and of transfer of work area are similar but even stronger than for the inhaled dose rate.

In a real case , the calculated results for inhaled dose rate have to be related to the TLV-value and the inhaled dose of contaminant for a work-day has to be related to the TWA-value. But as discussed in Chapter 2.2, reference values for metabolic rate have to be given in regulations.

The evaluation of ventilation effectiveness can be carried out in several ways as discussed in Chapter 2.

For the present simulations, the ventilation efficiency is found to be $\epsilon_v = 1.2$. This is somewhat better than for complete mixing. The air change efficiency is calculated to be $\epsilon_a = 0.51$ which is the same as for complete mixing. Those two efficiency measures are average values for the room and are not influenced by worker behaviour in the premises considered. The local air change index as an average for the breathing zone related to the working zone WA1 is found to be $\epsilon_p = 0.86$ which is better than for complete mixing.

The worker concerning ventilation efficiency WCVE has been calculated. Results are shown in Figure 5. With respect to ventilation effectiveness, it is obvious that air in the breathing zone of the original working area WA1 is contaminated. That is also seen on Figure 1; resirculating flows are transporting contaminants from the ceiling level and into the breathing zone. In addition, horizontal draughts forces the contaminated plume from the production line towards the breathing zone. A major improvement in WCVE is seen when the working area is transferred to the opposite side of the production line. Here the air is less contaminated than it would be with complete mixing. This is also indicated in Figure 1 even if that figure only is showing one cross-section.

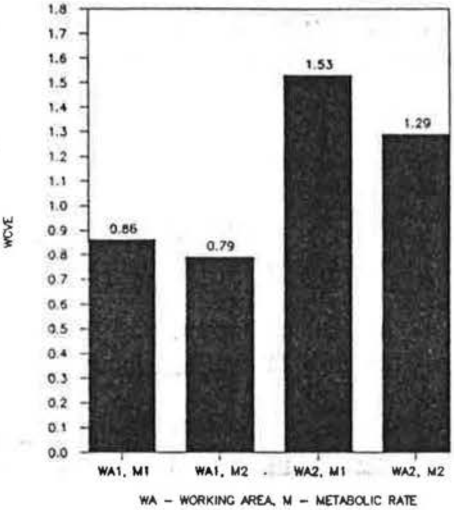

Fig. 5 Worker Concerning Ventilation Efficiency WCVE for 4 combinations of worker area and worker metabolism.

WCVE is probably a better measure to use along with detailed CFD-simulations than the established measures air change efficiency and -index and ventilation efficiency and -index. However, air change efficiency and ventilation efficiency should be calculated as for the case described here. The reason is that while the dose rate and the accumulated dose may be hard to measure realistically with todays equipment, the air change efficiency and the ventilation efficiency are easily measured with tracer gas methods. If measurement results for these efficiencies in the completed industrial hall are in agreement with calculations made at the design stage, then it is likely that the planned indoor air quality is being achieved.

It shall not be concealed that unsatisfying thermal comfort may cause more complaints from workers than poor air quality does. But thermal comfort is not addressed in this work.

5 CONCLUSIONS

Measures for ventilation effectiveness and exposure assessment, to be used in the design process for industrial ventilation, have been reviewed, derived, and analyzed.

For the first coarse design, when detailed information are not available and plans are not final, ventilation efficiency ϵ_v and air change efficiency ϵ_a are sufficiently detailed measures for evaluation purposes.

At the final stage of the design process, detailed plans are available and the best possible tools and measures should be used to evaluate worker exposure and ventilation effectiveness. The use of measures for inhaled dose rate $\dot{m}_c$ and for the accumulated dose of contaminant inhaled during a work-day m_{cd} can be related to TLV-, STL-, and TWA-values in regulations. The ventilation effectiveness can be evaluated by using WCVE or ϵ_W that is the worker concerning ventilation efficiency. That measure expresses the accumulated dose of contaminants inhaled over a work-day at complete mixing ventilation related to the accumulated dose at the actual ventilation being designed.

The measures are to be used along with CFD-simulations and are advantageous to use when there are one or a few dominant contaminants to be considered and when conditions in the industrial hall can be estimated and are not varying too much.

REFERENCES

ASHRAE. 1989. ASHRAE STANDARD 62-1989. Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

The Labour Inspectorate. 1990. Concentration Limits for Working Environment. Publ. No. 361. Oslo: The Labour Inspectorate of Norway. (Direktoratet for arbeidstilsynet.)

Fanger, P. O. 1970. Thermal Comfort. Analysis and Applications in Environmental Engineering. New York: McGraw-Hill.

Holen, J. and Magnussen, B. F. 1989. KAMELEON-A general purpose program system for simulation of fluid flow, heat- and mass transfer. Trondheim: Dep. of Applied Thermodynamics, NTH.

Isaksen, T. 1991. Numerical Simulation of Exposure Assessment in Industrial Environment. Master Thesis 1991. (In Norwegian.) Trondheim: The Norwegian Institute of Technology.

ISO 7730-1984(E) 1990. Moderate thermal environments-Determination of the PMV and PPD indices and specifications of the conditions for thermal comfort. International Organization for Standardization. Modified version- October 5th, 1990.

Patankar, S. V. 1980. Numerical Heat Transfer and Fluid Flow. New York: McGraw-Hill.

Sandberg, M. 1984. Ventilation systems-connections between air flow pattern and pollution exposition. Stockholm: VVS & Energi, No. 4.

Skåret, E. 1984. Ventilation Efficiency-A survey of concepts of ventilation effectiveness. Trondheim: SINTEF, Report STF15 A84057.

NOMENCLATURE

$\dot{m}_{vp}$	pulmonary ventilation rate	$[kg/h]$
$\dot{m}_c$	inhaled dose rate of contaminant	$[kg/h]$
m_{cd}	dose of contaminant inhaled during a period	$[kg]$
M	metabolic rate	$[W]$
V	room volume	$[m^3]$
Q	airflow rate from supply duct	$[m^3/h]$
C_s	concentration of contaminant in supply duct	
$C_e(t)$	concentration of contaminant at exhaust at time t	
$<\bar{\tau}>$	room mean age (resident time) of air	$[s],[h]$
t	time, $t=\infty$indicate steady state	$[s],[h]$

Specific Flow

$n=\frac{Q}{V}$ $[1/s],[1/h]$

Nominal Time Constant:

$\tau_n=\frac{V}{Q}$ $[s],[h]$

Air Change time:

$\tau_r=2<\bar{\tau}>$ $[s],[h]$

Air Change Efficiency:

$$\epsilon_a=\frac{\tau_n}{\tau_r}=\frac{\tau_n}{2<\bar{\tau}>}$$

Local Air Change Efficiency:

$$\epsilon_p=\frac{\tau_n}{\bar{\tau}_p}$$

Ventilation efficiency:

$$\epsilon_v=\frac{C_e(\infty)-C_s(\infty)}{<C_p(\infty)>-C_s(\infty)}$$

Local ventilation index:

$$\epsilon_p=\frac{C_e(\infty)-C_s(\infty)}{C_p(\infty)-C_s(\infty)}$$