Strojniški vestnik - Journal of Mechanical Engineering 54(2008)9, 579-587
UDC 697

Paper received: 19.02.2008
Paper accepted: 07.07.2008

Relative Decrease of Tracer Gas Concentration as a Measure of the Ventilation Effectiveness

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An analysis of the ventilation effectiveness measured on a prototype system for local air-conditioning named PERMICS (Personal Microclimate System) was made based on simultaneous measurements of velocity field and of tracer gas concentration using the decay method. A new parameter based on a relative decrease of tracer gas concentration in the first minute of system operation dC(1) was introduced. The newly defined parameter has been verified by simulation results from commercial computational fluid dynamics (CFD) software. The usefulness of the parameter is the possibility to make quick measurements of the local efficiency of personalized ventilation systems.

Keywords: air distribution, air conditioning, ventilation, efficiency

0 INTRODUCTION

Heating, ventilation and air-conditioning (HVAC) systems are mainly designed to provide a healthy and comfortable indoor environment for the occupants of closed spaces. In recent time indoor air quality and thermal comfort of the occupants have been drawing more and more attention [1]. People have also become more aware of their satisfaction with the thermal environment and perception of the air-quality as well as of the sick building syndrome (SBS) [2] and different building related health complaints, such as allergies, headaches and fatigue. Poorly ventilated spaces are the main cause of SBS [3], which depends on different influencing parameters, such as the type of ventilation and HVAC system, the hygienic quality of the inlet air and classical physical factors in environment. These parameters interact to influence people's health conditions and feeling.

Decreased volume flow rates of fresh air into the building consequents much worse indoor air quality. This was coinciding with the appearance of more and more interior pollutants from numerous sources that represent potential health risk, such as new building materials, furniture, laser printers, photocopiers, detergents, as well as people themselves and their activities. After the last energy crisis it was found that indoor air quality also has an economic impact. There were savings in spite of increased ventilation rates which entailed the increased energy use. Namely, buildings with SBS are more expensive because of decreased productivity, absence of work and consequently higher health care costs of employees, as there is a strong connection between these and indoor environment [4] to [6].

Different studies carried out in Slovenia show dissatisfaction of people with the indoor environment mainly in mechanically ventilated buildings [7] to [10] and also the significance of psychological factors in the evaluation of indoor environment parameters [7], [10] to [12]. Further studies show that displacement ventilation is very useful in achieving good air quality, especially when heated sources of contaminants are present [13]. However, this type of ventilation could be at the same time problematic due to the draught and a large vertical temperature gradient [14] and [15]. Furthermore it has also been shown with analysis that up to 50% of occupants may still be dissatisfied with the thermal environment from displacement ventilation [16]. The gained conclusions from these studies indicate the need for new, more qualitative ventilation and air-conditioning systems for indoor environments. Considering the influencing parameters, a new approach, based on the philosophy of excellence for future air-conditioned environments was proposed by Fanger [17]. The main idea of this approach is based on narrowing the air-conditioned space from the whole room space to

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the local space within the occupants' breathing zone using novel personalized ventilation (PV) system. This system has a local inlet of fresh air positioned near the occupants' breathing zone and serves gently a small amount of cool and clean air close or directly into the breathing zone of each individual where it is needed and without causing a draught. Appropriately designed PV system makes possible to achieve high local ventilation efficiency and high rates of personal air in inhaled air with a small amount of fresh personal air. At the same time very satisfactory thermal comfort for each occupant is achieved. This concept also enables a small degree of mixing of polluted and fresh air, which is the main problem in classical ventilation systems.

Research on different personalized ventilation applications evaluated numerous advantages of the system and confirmed high rates of personal air in inhaled air, good air quality and thermal comfort in the majority of cases [18] to [23].

1 PERSONALIZED VENTILATION SYSTEM - PERMICS

The concept of PERMICS for workplaces is mainly based on an analysis of other PV and local air-conditioning systems as well as on measurements from local air cleaning devices [24] and [25]. PERMICS is designed as an individual unit for use in offices with several employees, who are sitting in the same place for longer periods of time, which serves fresh air directly at the work area with individually regulated microclimate conditions. The system is designed to be applied in conjunction with total-volume ventilation and air-conditioning, especially in spaces with high heat and/or pollutant sources, due to the draught risk from larger amounts of air or lower air temperatures. The total-volume ventilation and air-conditioning system in this way assures approximately homogenous parameters for indoor air overall, while the local personalized ventilation assures the fresh air distribution within the breathing zone of the sitting occupant at the work area to fulfil individual preferences. PERMICS can be connected to the central air-conditioning system in different ways for example using a flexible duct from the wall or floor at the back side of an office desk. The system consists of two air distribution elements with air ducts, mounted on an office desk with dimensions 800 x 1600 mm and a height of 765 mm, supplemented with a partition wall at the back of the desk with a height of 800 mm above desk level (Fig. 1). Air distribution elements are located within the microclimate zone of the work area and connected with the air duct, which is separated into two parts leading to the elements, at the back side of the partition wall.

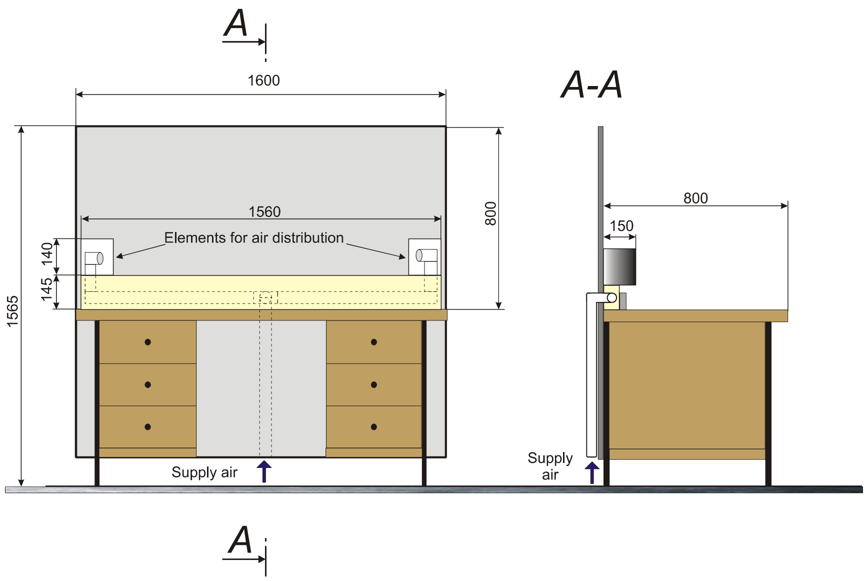

Figure 1: *Scheme of PERMICS*

2 EXPERIMENTAL METHOD – MEASUREMENTS AND SIMULATIONS

The measurements of ventilation efficiency of PERMICS with seated manikin in the test chamber with dimensions 4.36 x 4.11 x 2.97 m were made using the decay, or tracer step-down method [28] and [29]. The scheme of the experimental device is shown in Figure 2. Seated manikin was fixed in an upright position with a nose height of 1.10 m during the entire measuring procedure. The air supply rate for the personalized ventilation system was regulated using a frequency controlled supply fan, while the exhaust fan for extracting air worked under constant operating conditions for the entire experiment. The personalized ventilation was the only clean air supply in the test chamber. The outlet for extracting air was placed under the ceiling of the test chamber at coordinates (2.2; 2.8; 2.93) m.

In the experiment several different operating regimes of the PERMICS in terms of the amount of supply air and settings of inlets were tested. Altogether eighteen different measurements with variations in air flow rates, angles of inlet and meshed material covering inlet were made. In all cases isothermal conditions were simulated in the test chamber. The temperatures of the air in the test chamber and of the fresh supply air as well as the mean radiant temperature were equal. The seated manikin was thermally inactive (not heated) so there was no influence of a thermal plume on the air distribution in the breathing zone.

On-line measurements of volume flow rate and temperature of supply air were performed using into the supply duct built rotating vane anemometer and thermocouples. Carbon dioxide (CO_2) concentration was measured using a system with infrared absorption sensor at four locations, namely in fresh supply air, at the inlets of PERMICS, at the manikin head and at the outlet from the test chamber. The CO_2 concentration was measured successively at four locations at time intervals of 1 min using a switching valve. In order to decrease measurement errors, every fifth minute the measuring system was "washed up" with fresh air, since every measurement cycle then starts from the same concentration level of CO_2. In this way it is possible to obtain a concentration reading at a single location every 5 min, which is in order for measuring ventilation efficiency. For every measurement CO_2 was injected into the chamber with the mixer turned on for 20 min to achieve a uniform initial tracer gas concentration of about 3000 ppm in the whole chamber. The first concentration reading was obtained exactly 60 secs after turning the fans on. All results were calculated as concentration of CO_2 over concentration of fresh air.

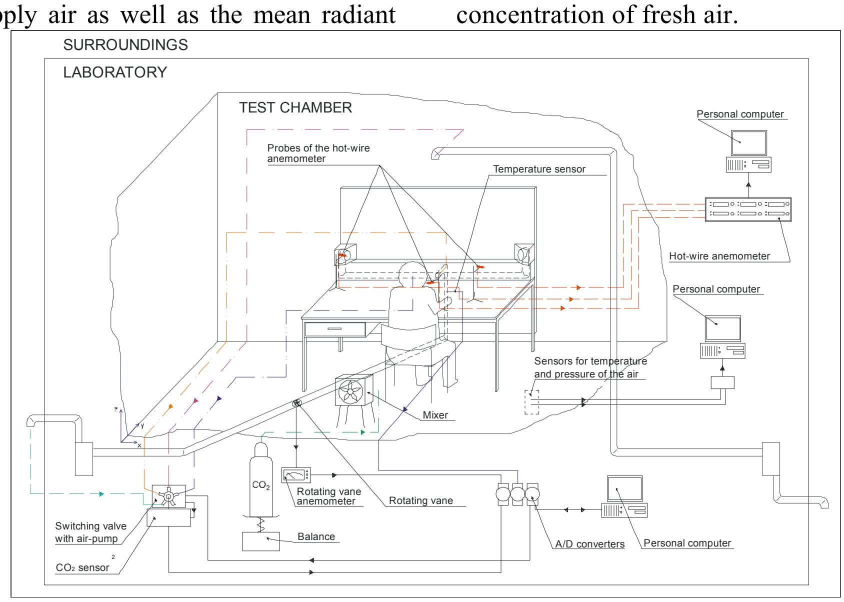

Figure 2: *Scheme of experimental device*

Temperature and relative humidity of the air at different locations as well as the barometric pressure in the chamber were measured using an integrated chamber measuring system to verify isothermal conditions. Air velocity and turbulence intensity measurements were performed using a hot-wire anemometer HW3D-ED during the experiment at three locations, namely at the manikin head, at desk coordinates (80; 0; 110) cm (Fig. 3), and in the middle of the inlet surface of the left distributional element.

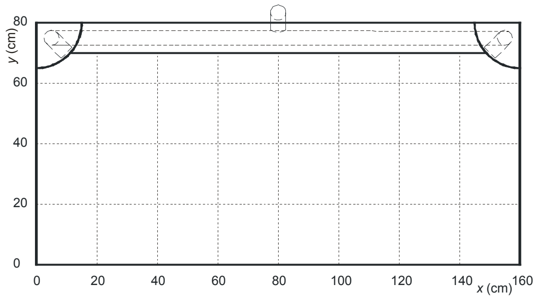

Fig.3. *Coordinates at the desk, z coordinate is the same for whole chamber*

3 RESULTS AND DISCUSSION

The obtained measurement results were analysed in accordance with the literature [26] to [29], using different indexes for assessing ventilation efficiency. The nominal time constant of the ventilation system τ_n (Eq. 1) is defined as the ratio of the room volume (V) to the volume flow rate (Q) and represents the shortest possible air-change time that takes to replace the air in the room:

$$\tau_{\mathrm{n}} = \frac{V}{Q} \tag{1}$$

Average mean age of air in the room τ_m is defined as the ratio of the second and the first statistical moment of the frequency distribution:

$$\tau_{\mathrm{m}} = \frac{\int_0^{\infty} t \cdot C_{\mathrm{e}}(t)dt}{\int_0^{\infty} C_{\mathrm{e}}(t)dt} \tag{2}$$

Local mean age of air τ_L at the seated manikin head is calculated as a ratio of the first statistical moment of the frequency distribution and the initial concentration in the room:

$$\tau_{\mathrm{L}} = \int_0^{\infty} \frac{C_{\mathrm{p}}(t)}{C(0)} dt \tag{3}$$

The air-change efficiency ε_a is calculated as the ratio between the shortest possible time that it takes to replace the air τ_n and the average time that it takes to replace the air in the room, which is equal to twice the average air age:

$$\varepsilon_{\mathrm{a}} = \frac{\tau_{\mathrm{n}}}{2\tau_{\mathrm{m}}} 100 \tag{4}$$

The local air-change index ε_L is calculated as the ratio between the shortest possible air-change time τ_n and the local mean age of air τ_L:

$$\varepsilon_{\mathrm{L}} = \frac{\tau_{\mathrm{n}}}{\tau_{\mathrm{L}}} 100 \tag{5}$$

The results of defined ventilation efficiency parameters during measurements with variable air supply flow rate are presented in Table 1. The lowest average mean age of air in the test chamber was 72.0 min at the first measurement M_01.

Table 1. *Parameters at variable air supply flow*

		M_01	M_03	M_06	M_08	M_09
Q	l/s	9.5	7.25	7.58	8.49	6.22
v_{head}	m/s	0.56	0.24	0.5	0.52	0.24
Tu_{head}	%	15.0	43.2	28.1	21.8	30.3
$v_{120,40}$	m/s	1.37	0.26	0.29	0.45	0.18
$Tu_{120,40}$	%	10.8	36.86	36.55	28.97	44.64
T_{in}	°C	24.2	22.1	19.2	22.4	21.1
$C(0)$	ppm	2766	3150	2946	3110	2641
τ_L	min	54.5	75.8	74.5	62.7	84.3
τ_m	min	72.0	101.1	96.7	84.0	110.3
τ_n	min	92.1	120.8	115.5	103.1	140.6
ε_L	%	168.94	159.36	155.1	164.53	166.8
ε_a	%	64.03	59.74	59.73	61.38	63.75

Hypothesis about connection between analysed variables was tested computing Pearson's correlation coefficients with a test of significance for the measured and calculated parameters. Pearson's correlation coefficients between the measured and calculated variables, computed using statistical software SPSS [30] and [31], are presented in Table 2. Significant connections are marked with an asterisk sign (*). Strong correlations were discovered between the inflow rate of fresh air and the mean age of air, as well as between turbulence intensity at the desk coordinate (120; 40; 100) cm $Tu_{120,40}$ and local air age at the head of seated manikin. A significant connection was found out between the local air-change index and air velocity and turbulence intensity at the manikin's head.

A new index based on the relative decrease in tracer gas concentration in the first minute of system operation dC(1) is defined as:

$$dC(1) = \frac{C(0) - C(1)}{C(0)} = \frac{\Delta C(1)}{C(0)} \qquad (6)$$

Pearson's correlation coefficients between the ventilation effectiveness variables and the index dC(1) were calculated (Table 3). Strong correlation exists between dC(1) and measured air velocity and turbulence intensity as well as between dC(1) and the calculated local air-change index and local air quality. A new index dC(1) thus combines both velocity field and air quality parameters.

The dependence between the local air-change index ε_L and dC(1) for all measurements is shown in Fig. 4. Superior to other regression models is cubic regression model with the determination coefficient (Eq. 7).

$$\varepsilon_L(dC(1)) = 2431.3dC(1) - 12296dC(1)^2 + \\ +20090.8dC(1)^3 \qquad (7)$$

Results of the measurements show that air distribution has a major influence on air quality in the breathing zone of the seated person, which is determined by the local air-change index and by the local age-of-air. Comparison between different operating regimes shows that with a small amount of laminar air flow equal air quality parameters as with a larger amount with higher values of turbulence intensity may be achieved, because there is no actual mixing of air in the laminar flow case as fresh air is able to push old air out of the breathing zone.

In the next step the operating conditions from the experimental analysis of the PERMICS were simulated using commercial CFD package CHAM PHOENICS. Numerical simulation was carried out in two stages because of the nature of the problem.

Table 1. *Table of correlation coefficients (* correlation is significant at 0.05; ** correlation is significant at 0.01). P Corr is the Pearson correlation coefficient, Sig. is significance, and N is the number of measurements)*

		Q	v_{head}	Tu_{head}	$v_{120,40}$	$Tu_{120,40}$	τ_L	τ_m	ε_L	ε_a
Q	P Corr	1	.357	-.522(*)	.533(*)	-.652(**)	-.515(*)	-.938(**)	-.258	.213
	Sig.	.	.073	.013	.011	.002	.014	.000	.151	.198
	N	18	18	18	18	17	18	18	18	18
v_{head}	P Corr	.357	1	-.891(**)	.667(**)	.080	.368	-.407(*)	-.741(**)	.098
	Sig.	.073	.	.000	.001	.380	.066	.047	.000	.349
	N	18	18	18	18	17	18	18	18	18
Tu_{head}	P Corr	-.522(*)	-.891(**)	1	-.660(**)	.024	-.227	.620(**)	.677(**)	-.280
	Sig.	.013	.000	.	.001	.464	.182	.003	.001	.130
	N	18	18	18	18	17	18	18	18	18
$v_{120,40}$	P Corr	.533(*)	.667(**)	-.660(**)	1	-.582(**)	-.195	-.499(*)	-.251	.094
	Sig.	.011	.001	.001	.	.007	.219	.018	.157	.356
	N	18	18	18	18	17	18	18	18	18
$Tu_{120,40}$	P Corr	-.652(**)	.080	.024	-.582(**)	1	.823(**)	.474(*)	-.401	.185
	Sig.	.002	.380	.464	.007	.	.000	.027	.055	.239
	N	17	17	17	17	17	17	17	17	17
τ_L	P Corr	-.515(*)	.368	-.227	-.195	.823(**)	1	.427(*)	-.686(**)	-.051
	Sig.	.014	.066	.182	.219	.000	.	.038	.001	.420
	N	18	18	18	18	17	18	18	18	18
τ_m	P Corr	-.938(**)	-.407(*)	.620(**)	-.499(*)	.474(*)	.427(*)	1	.301	-.507(*)
	Sig.	.000	.047	.003	.018	.027	.038	.	.112	.016
	N	18	18	18	18	17	18	18	18	18
ε_L	P Corr	-.258	-.741(**)	.677(**)	-.251	-.401	-.686(**)	.301	1	-.131
	Sig.	.151	.000	.001	.157	.055	.001	.112	.	.303
	N	18	18	18	18	17	18	18	18	18
ε_a	P Corr	.213	.098	-.280	.094	.185	-.051	-.507(*)	-.131	1
	Sig.	.198	.349	.130	.356	.239	.420	.016	.303	.
	N	18	18	18	18	17	18	18	18	18

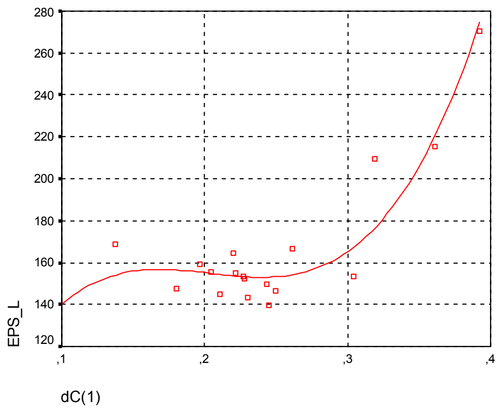

Fig.4. *Scatter graph for local air-change index ε_L (EPS_L) and dC(1) dependence at the head of seated person*

In the first part of the simulation a steady-state solution of the velocity and pressure field was calculated and then used in the second part of simulation. The second part was a transient simulation performed using a steady-state solution form the first part to determine the residence time and consequently the field of contaminant concentration. Therefore a new variable named *C*1 was defined, which represents contaminant concentration in the chamber. In both stages of numerical simulation the Chen-Kim turbulence model was used, which has been found the most suitable in this case [32]. Different supply flow rates were simulated using boundary conditions from the various measurements. The results of both measurements and simulations for d*C*(1) in the breathing zone, the decrease of concentration in the first minute of system operation, $\Delta C(1)$, and the relative difference between measurements and simulations relative to measurements are presented in Table 4. The differences between measurements and simulations exist and are up to 26%, mainly due to the inaccurate determination of the velocity and pressure field in the chamber. The main reasons for these deviations in the determination of the velocity and pressure field are inaccurate boundary conditions as a result of a very complex inlet profile at the air inlets of PERMICS and turbulence modelling. Complexity of inlet profile at the air inlets disables accurate description of boundary conditions used in the CFD model.

Table 3. *Table of correlation coefficients (* correlation is significant at 0.05; ** correlation is significant at 0.01). P Corr is the Pearson correlation coefficient, Sig. is significance, and N is the number of measurements.*

		dC(1)
Q	P Corr	-.273
	Sig.	.137
	N	18
v_{head}	P Corr	-.635(**)
	Sig.	.002
	N	18
Tu_{head}	P Corr	.529(*)
	Sig.	.012
	N	18
$v_{120,40}$	P Corr	-.329
	Sig.	.091
	N	18
$Tu_{120,40}$	P Corr	-.318
	Sig.	.107
	N	17
τ_L	P Corr	-.448(*)
	Sig.	.031
	N	18
τ_m	P Corr	.380
	Sig.	.060
	N	18
ε_L	P Corr	.762(**)
	Sig.	.000
	N	18
ε_a	P Corr	-.405(*)
	Sig.	.048
	N	18

The results of the unsteady simulations for two cases are shown in Fig. 5. These simulated predictions may be accurate only if the velocity and pressure field are accurately determined. The difference between the measurement and simulation results of local air-change index was estimated by comparing simulations relative to measurements, using

$$\Delta\varepsilon_L = \frac{\varepsilon_{L,sim} - \varepsilon_{L,meas}}{\varepsilon_{L,meas}} 100 \qquad (8)$$

Table 4. *Results of unsteady simulations and measurements of tracer gas concentration decrease in the breathing zone of a seated person 1.1 m above the floor and the relative difference between measurements and simulations*

	$dC(1)$		$\Delta C(1)$ (ppm)		Relative difference regarding measurements (%)
	Simulation	Measurement	Simulation	Measurement	
M_01	0.173	0.137	478	379	-26.0
M_03	0.176	0.240	553	620	10.9
M_06	0.222	0.218	655	652	-0.4
M_08	0.186	0.220	579	685	15.5
M_09	0.211	0.235	557	689	19.2

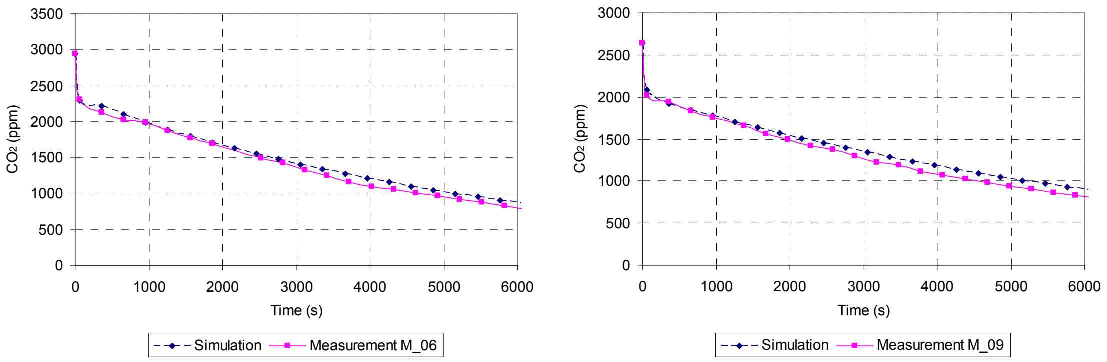

Figure 5: *Trend of tracer gas concentration decrease for measurements and simulation for two cases M_06 and M_09 (Table 1)*

The maximum difference between measured and simulated local air-change index was 7.49% (Table 5). However, the relative decrease of tracer gas concentration, described with index dC(1), was confirmed by simulation results. Thus, dC(1) may be used for estimation of ventilation efficiency.

Table 5. *Local effectiveness of ventilation and the relative difference between the results predicted from the simulation and the measurements; local air age and the relative difference between the results predicted from the simulation and the measurements*

	$\varepsilon_{L,sim}$ (%)	$\varepsilon_{L,meas}$ (%)	$\Delta\varepsilon_L$ (%)
M_01	156.6	169.0	7.32
M_03	156.6	159.4	1.78
M_06	153.6	155.0	0.92
M_08	156.1	164.6	5.16
M_09	154.3	166.8	7.49

Comparison of the local air-change index with the typical values of different ventilation types (Table 6) shows that a local ventilation system is advantageous over a conventional ventilation system. It has a potential to improve the level of air quality in the breathing zone and to lower energy consumption for ventilation at the same time.

Table 6. *Ventilation effectiveness for different types of ventilation [32]*

Ventilation type	Air change efficiency (%)
Ideal complete mixing	50
Piston flow	100
Displacement flow	50-100
Short circuiting flow	0-50

4 CONCLUSIONS

The performed measurements and simulations of different operational regimes of PERMICS system show that a concept of personalized ventilation system is very effective. It was found from measurements that the newly defined index of relative decrease of tracer gas concentration in the first minute of system operation dC(1) is connected with velocity field as well with the ventilation effectiveness parameters. The main benefit of this parameter, verified by simulations of analysed operating conditions, is that it allows relatively accurate measurements of local air-change efficiency and makes them quick and easy in comparison with ordinary ventilation efficiency measurement procedures. The existing measurement procedure can lead to a large degree of uncertainty in measurements due to each successive reading bringing its own uncertainty. The newly defined parameter dC(1) has the advantage of direct measurement of ventilation efficiency in a much shorter time.

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