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MEASUREMENT OF VOC TRANSFER IN ROTATING HEAT EXCHANGERS

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ABSTRACT

Rotating heat exchangers may transfer contaminants from exhaust to supply air in three ways: with entrained air, through possible leakage around the wheel at the separation wall, and by adsorption-desorption on the inner surfaces of the exchanger's wheel. Leakage from exhaust to supply was measured in several units, and found negligible if not absent in most cases. Leakage and pollutant transfer can be avoided or at least strongly reduced through a proper installation of the wheel, good maintenance of the gasket, proper installation of a purging sector, and by maintaining a positive pressure differential from supply to exhaust duct at wheel level.

Experiments performed on units with hygroscopic wheel show however that significant amounts of VOC's are transferred, mainly by an adsorption-desorption transfer mechanism. The proper use of a purging sector significantly reduces, but not eliminate, this transfer. Therefore, rotating wheel heat exchangers are not recommended where the concentration of VOC's in exhaust air is larger than an accepted limit..

KEYWORDS: Measurement technique, VOC, Ventilation, Heat recovery

INTRODUCTION

VOC's in buildings

Volatile Organic Compounds is a specific class of the volatile organics with boiling points from 50-100°C to 240-260°C. They exist mainly in the gas phase in the temperature and humidity ranges encountered indoors. They are ubiquitous: several hundred of those compounds have been found in the indoor air. Their origin is a plethora of various emission sources, each with own emission characteristics. They can be building related (building materials, ventilation, soil), human activity related (household and consumer products, humans, office equipment) or outdoors related (traffic, neighbouring industry) (Wolkoff, Clausen et al. 1997). Sources are also function of the nature of the VOCs:

- VOC can be free, as solvent, monomer, reaction product, and additive. The mechanism of emission is evaporation and diffusion.
- VOCs can be chemically bound. The mechanism of emission are decomposition such as hydrolysis, acidity or basicity in material, action of cleaning, mechanical wear and maintenance, humidity, microbiological, oxidative degradation and chain scission.

- VOCs can also be physically bound: the mechanism of emission is an ad-and desorption process. This kind of mechanism is expected in the RHE.

Investigations have indicated that the two major sources of VOCs indoor are the emission of the building material and the human activities. Mass transfer model have been developed to calculate the emission rates from the sources (Sparks, Tichenor et al. 1996).

The major VOCs classes are shown in Table 1

Table 1 : List of VOC classes taken from WHO

VOCs	Mean concentration ranges [$\mu\text{g}/\text{m}^3$]
Aromatic hydrocarbons	1-80
Aldehydes	1-40
Cycloalkenes	1-30
Alkanes, cycloalkanes, alkenes	1-20
Chlorinated hydrocarbons	1-10
Alcohols	1-2
Ketones	1
Other: acids, amines, glycols, siloxanes	< 1

Adsorption mechanism has been already studied on material surfaces (Jorgensen, Bjorseht et al. 1999) and it has been demonstrated that the sorption phenomena may have an impact on indoor air concentration of VOCs for materials such as: carpets, floor covering, curtains, stainless steel (van der Wal, Hoogenvenn et al. 1998). It is suspected that pollutants can be transferred from exhaust to supply ducts by rotating heat exchangers. This suspicion was confirmed by measurements with formaldehyde (Andersson, Andersson et al. 1993) and perceived air quality (Pejtersen 1996) and other studies (Ruud 1993). A study has even investigated the sorption mechanism to prevent odour transfer by rotating heat exchangers (Dehli 1993).

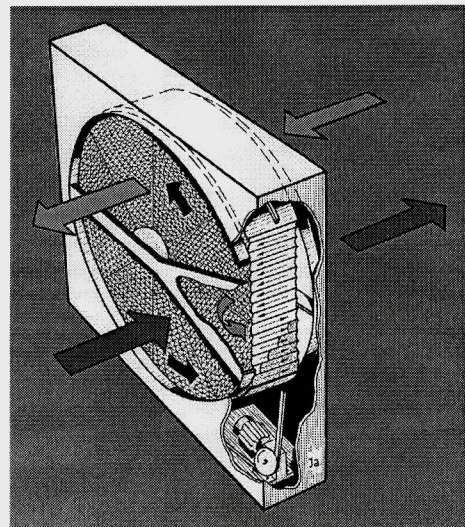
VOC's transfer through rotating heat exchangers

Re-circulation of chemical compound via rotary heat exchanger occurs through three different ways: leakage, with entrained air, and by adsorption-desorption (Andersson, Andersson et al. 1993), (Ruud and Carlsson 1996).

Pollutants present in exhaust air can be transferred with this entrained or leakage air to supply air (Schaeffler, Schultz et al. 1988). The amount of air transferred this way can be measured with tracer gases (Roulet and L.Vandaele 1991; Roulet, Foradini et al. 1994). Air leakage from the exhaust to supply duct was observed in some rotating heat exchangers (RHE). The pollutant flow rate from extract to supply resulting from a recirculation rate R is:

$$Q_{p,43} = R C_{p,4} Q_3 \quad (1)$$

where the subscript p stands for pollutants, and numbers give the location in the unit (see Figure 1).



Measurement of parasitic recirculation resulting from leakage through the RHE (Roulet, Foradini et al. 1999; Roulet, Pibiri et al. 1999) has shown that this leakage is, in most cases, less than the commonly accepted value of 4%, when the wheel is well-installed, not warped, and when pressures are properly balanced between the supply and the exhaust side of the wheel. By contrast, parasitic recirculation rates of up to 40% were observed in some cases, where the rules of common practice were not fulfilled.

The major question now to be answered with respect to the polluting effect of rotating heat exchangers is: Which pollutants are transferred, and in what quantities, in a well-installed RHE?

METHOD

In order to answer this question, concentrations of various volatile organic compounds were measured upwind and downwind of a heat exchanger, at the four locations shown in Figure 1. Transfer induces a decrease in concentration in the exhaust duct, together with an increase in the supply duct. This transfer may depend on the reactivity and the physical properties (volatility) of the VOC.

Pumps are placed at the strategic locations to sample the air through small tubes filled with a sorbing agent which guarantees total desorption (TENAX TA). Sampling rate is 0,1 litre of air per minute. VOC's adsorb themselves, as long as the medium is not saturated. The sampling tube is then hermetically sealed and mailed to the laboratory for further analysis. The VOC's are thermo-desorbed at high temperature and stored in a cold trap. The content of the trap is then injected into the column of a gas chromatograph (GC). A flame ionisation detector (FID) is used to detect and measure the amount of each compound, while a mass spectrograph (MS) is used to help in identifying the compound. The method used in these experiments is the one developed by the Swiss Federal Office of Health for the European Indoor Air Quality Audit project (Mogl, Haas et al. 1995).

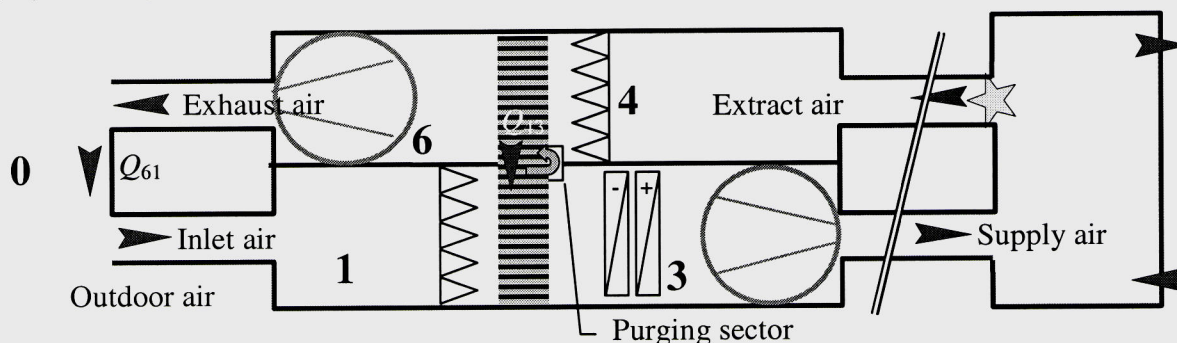


Figure 1: Schematics of an AHU showing location of VOC injection (star) and sampling points (numbers), for concentration analysis.

In principle, the VOC's may be those present in the air extracted from the ventilated space, or a mix of compounds injected into the extract duct (star in Figure 1). Preliminary experiments performed with VOC from the ventilated space gave inaccurate results, since concentrations were too low (as they should be!). Therefore, a VOC mix was injected into the exhaust duct, in such a way that the VOC were well evaporated and mixed with the air at location 4. Locations 6 and 3 should be distant enough from the rotating heat exchanger, to ensure a good mixing after sorption and desorption on the wheel.

If there is no transfer at all, VOC concentrations at locations 1 and 3 are the same as the outdoor concentration of each compound, and concentrations at locations 6 and 4 are the

same. If some VOC's are transferred, the amount taken in extract air and the amount transferred to supply air should be balanced for each VOC. The pollutant transfer rate through the RHE is the ratio of the mass of VOC delivered into supply air to the net mass of VOC in extract air:

$$R = \frac{M_3 - M_1}{M_4} \quad (2)$$

VOC's injection and air sampling techniques

VOC's could be injected at a constant rate, as usual in tracer gas experiments. However, this is not convenient with liquid mixtures that should be evaporated. In order to be able to control the quantity of each injected VOC, to limit the amount of injected compounds, and to shorten the duration of the experiment, we used the pulse injection technique. Air sampling is started first. Immediately after this, a known mass of a VOC cocktail is injected in the extract duct, through evaporation it in a hot air flow. This injection does not need to be very short, but it should be much shorter than the sampling time. Sampling is stopped¹ after the end of the injection, with a delay of about four nominal time constants¹, ensuring that VOC concentration is returned down to background level.

The mass M injected in a relatively short pulse will result in a VOC concentration at each location i , which varies with time, starting from background concentration, growing, then decaying back to background concentration. Let $C_i(t)$ be the VOC concentration above background at location i . The total VOC mass passing at location i is then:

$$M_i = \int_0^{\infty} C_i(t) Q_i(t) dt \quad (3)$$

An approximation to infinite time can be good enough when the experiment (and the integral) is stopped at time t_f , when the VOC concentration is close enough to background, that is, in practice, after three or four nominal time constants.

Since both functions $C_i(t)$ and $Q_i(t)$ are positive and continuously derivable, we can apply the integral mean value theorem, as suggested by Persily and Axley (Persily and Axley 1991):

$$M_i = Q_i(\tau) \int_0^{t_f} C_i(t) dt \cdot \quad \text{with } 0 < \tau < t_f \quad (4)$$

This means that there exists a time τ during the experiment at which the airflow rate Q_i has a value satisfying the above equation. The knowledge of M_i (for example the injected mass) and measurements of the integral of the concentration downwind can then provide a value of Q_i .

VOC masses not directly downwind of the injection point may however differ from the injected mass M . These masses, M_i , can be calculated from the masses m_i sampled at each location by pumping the air at known rate $Q_{s,i}$ through a tube filled with an adsorbent. The sampled mass is related to concentration by:

$$m_i = \int_0^{\infty} C_i(t) Q_{s,i}(t) dt \quad (5)$$

Applying again the integral mean value theorem, we get:

¹ The nominal time constant of a ventilated volume is the inverse of the air change rate.

$$m_i = Q_{s,i}(\tau') \int_0^{t_f} C_i(t) dt \quad \text{with} \quad 0 < \tau' < t_f \quad (6)$$

Combining equations (4) and (6), we get the VOC mass passing at location i from the VOC mass collected in the sampler:

$$M_i = m_i \frac{Q_i(\tau)}{Q_{s,i}(\tau)} \quad (7)$$

In our case, both airflows, Q_i and $Q_{s,i}$ are constant during the experiment.

Which VOC's?

Lists of VOC's found most often in office buildings, as well as proposals for VOC's cocktails are found in the literature (e.g. [Brown, 1994 #2; Hodgson, 1995 #7; Maroni, 1995 #13; Molhave, 1997 #4; Wal, 1998 #10; Wolkoff, 1997 #6]). The total number of compounds should however not be too large, in order to keep the analysis at a practical level. Therefore, the list in Table 2, which includes the most significant VOC's for several classes of organic compounds, was found suitable after careful selection.

Table 2: List of VOCs used for contaminant transfer experiments.

Family	Compound (current names)	Formula	Sources	Boiling point [°C]
Alkanes	n-decane	C ₁₀ H ₂₂	paints and associated supplies	174
Alcohols	n-butanol	CH ₃ (CH ₂) ₃ OH	adhesives	117
	1-hexanol	CH ₃ (CH ₂) ₅ OH	solvent	158
	phenol	C ₆ H ₅ OH		182
Haloalkane	1,6-dichlorohexane	Cl(CH ₂) ₆ Cl	solvent, adhesives	203
Aldehydes	hexanal (caproaldehyde)	CH ₃ (CH ₂) ₄ CHO	paper, paints	128
	benzaldehyde	C ₆ H ₅ CHO		179
Cyclic and aromatic hydro- carbons	4-isopropenyl 1-methyl cyclohexene (limonene)	C ₁₀ H ₁₆	perfumed waxes and. cleaners	177
	1,3-dimethylbenzene (m-xylene)	1,3-(CH ₃) ₂ C ₆ H ₄	solvent, fuel	139
	1,3,5-trimethylbenzene (mesitylene)	1,3,5-(CH ₃) ₃ C ₆ H ₃	solvent, fuel	165
Ether	dipropylether	CH ₃ (CH ₂) ₂ O(CH ₂) ₂ CH ₃	paints and associated supplies	91

The criteria used to select VOC's were:

1. the compounds should be common in buildings,
2. they should be representative of the different organic families with the characteristic of their functional group and saturation degree; different boiling points and polarity,
3. they should be easy to analyse so as to provide significant results,
4. the compounds should be easy to handle, and should not be too toxic.

A proper way to discuss about chemicals is to know the physical properties and reactivity of the family they belong to. A quick description is given below.

To compare the behaviour of molecules from different families, the number of carbon atoms of the main chain structure varies around 6: 1-hexanol, 1-hexanal, benzaldehyde, phenol, m-xylene, mesitylene and 1-6 dichlorohexane.

Another basis was to select a family, such as alcohols, and vary the size of the molecule, propanol with 3 carbons, butanol 4 and hexanol 6 straight and phenol 6 cyclic.

2-propanone (acetone), and butyric acid, which are human emissions, were also selected, but deleted after first experiments. Acetone like propanol have too low boiling point (56.5°C and 70°C respectively) and, are not completely adsorbed into the Tenax samplers. Butyric acid, in addition to its awful smell, is not well selected in the GC column used in these experiments.

Physical properties and reactivity of the VOC's mixture compounds

As already mentioned VOC's encompass substances with widely varying physico-chemical properties. Among these, in particular two are of practical importance: (1) the hydrophilic character of the compound described by the water solubility which influences their retention on solid sorbent and (2) their neutral, basic or acidic character which has to be taken into consideration for the chromatographic separation. VOC with high boiling point values (240-260 °C) refer to more polar compounds (Maroni, Seifert et al. 1995).

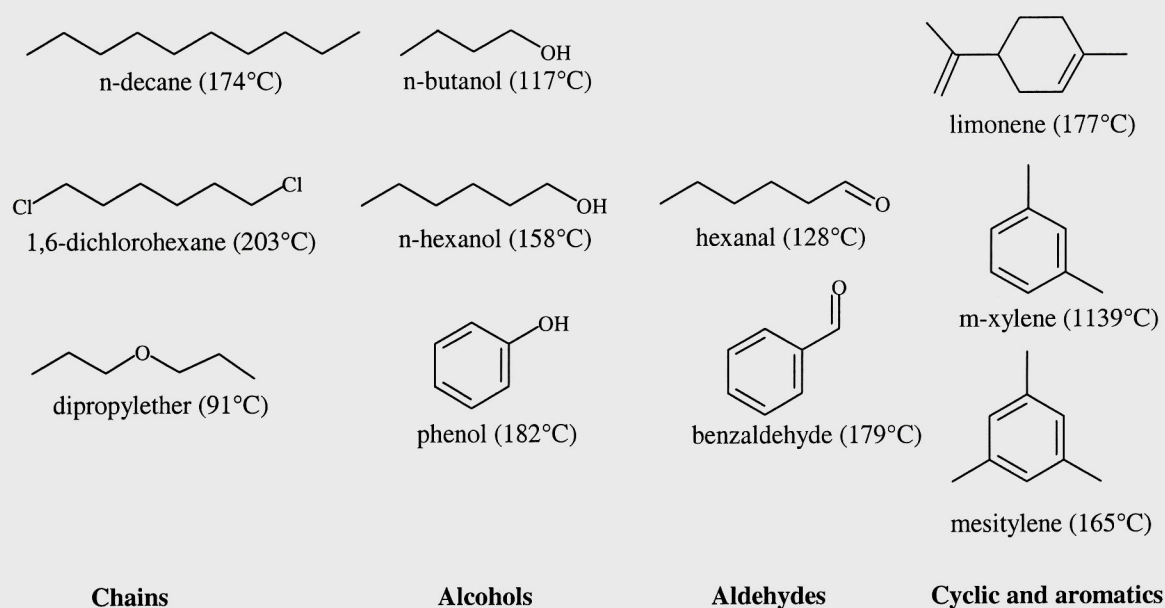


Figure 2: Structural representation of used VOCs

ALCANES C_nH_{2n+2} *n-decane* are saturated hydrocarbons with cyclic conformations or acyclic branched or unbranched structures. These non-polar molecules are insoluble in water. For a given molecular weight, their boiling point is relatively low compared to other organic compounds. The chemical bonds are simple and covalent. Their reactivity is low. They are inert to bases, acids, and common reduction or oxidation agents excepted for oxygen and halogens.

ALKENES C_nH_{2n} **ALKYNES** C_nH_{2n-2} *4-isopropenyl 1-methyl cyclohexene (limonene)* are unsaturated hydrocarbons with a double bond $C=C$ and triple bond. They are more reactive than alkanes because of the reactivity of the multiple bonds.

AROMATIC HYDROCARBONS *1,3,5-trimethylbenzene (mesitylene)*, *1,3-dimethylbenzene (m-xylene)*, *phenol*, *benzaldehyde*

The benzene structure C_6H_6 is unusually unreactive as a highly unsaturated structure. It does not undergo the addition reactions common to alkenes. The cyclic electron arrangement confers a special stability to the carbon ring. Reactions occur with the hydrogen substitutes.

ALCOHOLS $R-OH$ (hydroxyl group $-OH$ is attached to a radical R) *n*-butanol, *n*-hexanol, 1-propanol, phenol

The OH bond is polar because of the high electro negativity of the oxygen atom. The result is the association of molecules by hydrogen bandings explaining why alcohols have a rather high boiling point compared to other compounds with same molecular weight. Alcohols with low molecular weight are completely miscible with water, and they can easily replace water molecules. As the hydro carbonated chain grow, solubility decreases.

ALDEHYDES $R-C=O$ *hexanal, benzaldehyde*

The $C=O$ bond is very polar because of the high electro negativity of the oxygen atom. Therefore these compounds tend to make associations. Boiling points are rather lower than the corresponding alcohol because of the absence of hydrogen bandings.

ETHER $R-O-R'$ *dipropylether*

On such molecules, hydrogen bonds are not possible, so the boiling point is much lower than the isomer alcohol. They are water solubility diminish with the number of carbons. They are making good solvent because of their low reactivity.

HALOALKANE $R-X$, ($X=F, Cl, Br, I$) *1,6-dichlorohexane*

The physical properties of the haloalkanes are quite distinct from those of the corresponding alkanes. The $C-X$ bond has a strong dipolar character and induces reactions: anions and electron-rich species are capable of attacking the positively polarised carbon atom, cations and other electron-deficient species can attack the halogen atom.

The boiling point is relatively high because of the dipole-dipole interaction in the liquid state.

EXPERIMENTS

Air handling units

Experiments were performed on three small to medium air handling units, ventilating an auditorium and a laboratory at the EPFL, and a building at the EMPA. The characteristics measured of these units, measured using tracer gas dilution technique, are summarised in Table 3.

Table 3: Characteristics of the air-handling units used for the experiments.

Quantity	Unit	EPFL		EMPA
		Auditorium	Laboratory	Akademie
Outdoor airflow rate	m ³ /h	1'900 ± 100	2'530 ± 80	7'320 ± 1'240
Supply airflow rate		2'070 ± 70	2'900 ± 200	9'450 ± 1'220
Extract airflow rate		1'790 ± 40	1'860 ± 50	5'790 ± 140
Exhaust airflow rate		1'600 ± 200	1'500 ± 200	3'660 ± 1'700
Recirculation flow rate		130 ± 50	100 ± 200	1'440 ± 1'490
External recirculation		100 ± 100	300 ± 100	690 ± 1'240
Room mean age of air	min	15 ± 1	10 ± 1	20 ± 1

The ventilation efficiency in the auditorium and laboratory is close to 50%, showing a total mixing of the air. The units, as well as their air inlet and exhaust grilles are close to each other.

Both EPFL units are equipped with a rotating heat exchanger, whose wheel is made of an aluminium honeycomb with a hygroscopic coating. The wheel has a diameter of 785 mm, is 200 mm thick and rotates at 11 rpm. It is made of thin aluminium sheet, sinusoidal corrugated with a wavelength 4,2 mm, and peak-to-peak amplitude 1,9 mm. A flat foil is placed between corrugated foils (Figure 3). The aluminium sheets are treated to have a hygroscopic surface (Figure 4)

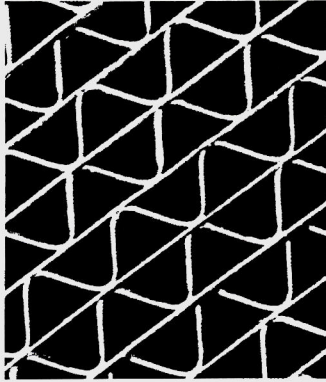


Figure 3: EPFL wheel structure

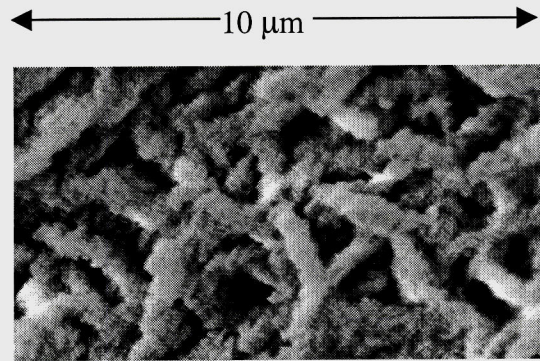


Figure 4: SEM image of a new hygroscopic coating.

The purging sector is a rectangle 100 mm high and 40 mm thick. The purging sector was correctly used in the laboratory unit. The auditorium unit, however, was found with the wheel turning in the wrong way, making the purging sector inactive.

The measured ventilation efficiency in the EMPA Akademie is about 70%, showing a displacement ventilation. The rotating heat exchanger is made of Hexcore®, a honeycomb consisting of a synthetic fiber material (Nomex®). It has no hygroscopic coating. The wheel has a diameter of 1580 mm, is 140 mm thick and rotates at 5 rpm. The diameter of one honeycomb cell is 1.5 mm. The wheel has no purging sector and the fans are not at their ideal positions. This explains the high recirculation flow rate of about 15%.

Pressure differential were measured in all units just before or after the experiments. These are shown in Table 4. It can be seen that a negative pressure between supply and exhaust ducts allows vitiated air to pass from exhaust to supply through possible leakage. This is especially remarkable in the EMPA unit, where the fans are both on the same side of the wheel.

Table 4: Pressure differentials in the units [Pa]

Filters		Auditorium unit		Laboratory unit		EMPA unit	
		in	out	in	out	in	out
Across wheel	Inlet -supply	88 ±5	80±5	85±5	82±5	97±2	109±3
	Extract - exhaust	107±5	110±5	60±5	67±5	94±1	88±1
Between supply and exhaust	Cold side	125±5	54±5	30±5	21±5	-230±2	-283±5
	Warm side	-72±5	-125±5	-125±5	-137±5	-423±2	-475±5

The climatic conditions just before or after the experiments are shown in Table 5 for the EPFL units, and in for the EMPA unit

Table 5: Climatic conditions in units

Unit		Auditorium unit					Laboratory unit			
	Expt.	A+1	A+2	A+3	A-1	A-2	L+1	L+2	L-1	L-2
Dew point	Inlet	-	-	0.1	-	0.1	3.8	-2.5	3.8	-2.5
	Supply	-	-	1.1	-	1.1	3.8	-0.9	3.8	-0.9
	Extract	-	-	2.3	-	2.3	4.6	-0.2	4.6	-0.2
	Exhaust	-	-	0.9	-	0.9	3.8	-1.6	3.8	-1.6
Temperat.	Inlet	4.4	4.4	9.7	4.4	9.7	15.2	13.1	15.2	13.1
	Supply	20.0	20.0	20.4	20.0	20.4	21.0	22.2	21.0	22.2
	Extract	18.0	18.0	20.2	18.0	20.2	22.4	22.2	22.4	22.2
	Exhaust	10.0	10.0	13.0	10.0	13.0	18.1	15.5	18.1	15.5

Table 6: Climatic conditions in the EMPA unit

	Humidity [%]	Temperature [°C]
Inlet	61	19.5
Supply	46	24
Extract	43	24.6
Exhaust	58	20.7

Experimental protocol

After having started the air pumps of adsorption samplers placed at locations 1, 3, 4 and 6, a known amount of a cocktail made of equal masses of all VOC's given in Table 2 was injected within about 30 seconds into the extract duct, using an evaporation device illustrated in Figure 5.

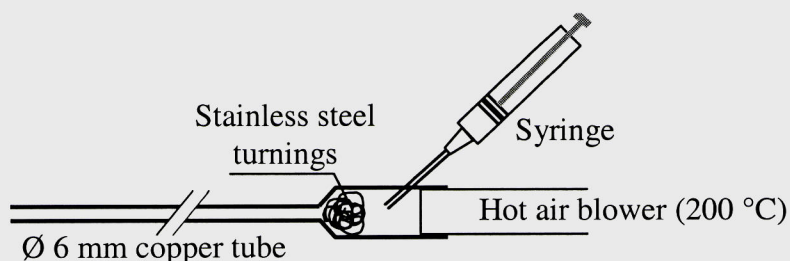


Figure 5: Flash evaporation device for injecting the VOC's.

The amount injected is such that the resulting concentration values are clearly above the concentration outdoors, but below the saturation limit of the samplers. Air sampling then continued for about one hour, to ensure that. This sampling time is more than twice the time needed to change the air, which is itself the double of the room mean age of air (Sandberg and Sjöberg 1984).

Sampling continues for about 1 hour, that is 4 to 6 nominal time constants, until the whole system is clean.

RESULTS

Experiments were performed in various conditions several times. In order to avoid adsorption in filters, these were taken out during experiments. Experiments were performed with the rotating heat exchanger turning in the right direction, i.e. with an active purging sector, and in the wrong direction, thus suppressing the effect of the purging sector.

The reproducibility of experiments is not perfect, but acceptable for most components, as shown in Figure 6 and Figure 7.

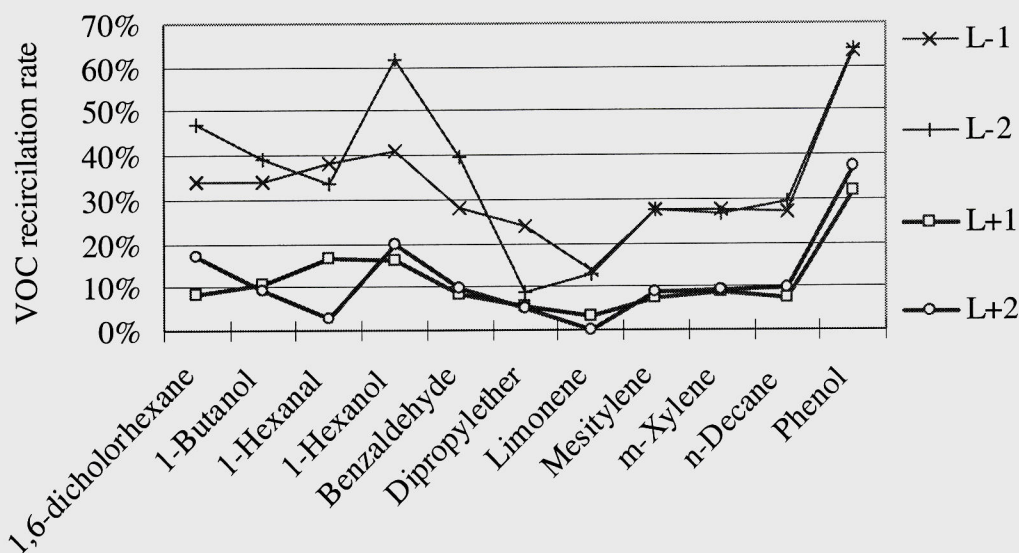


Figure 6: Recirculation rates for various VOC's in the laboratory unit in four experiments, i.e. two experiments with purging sector (L+1 and L+2) and two without (L-1 and L-2).

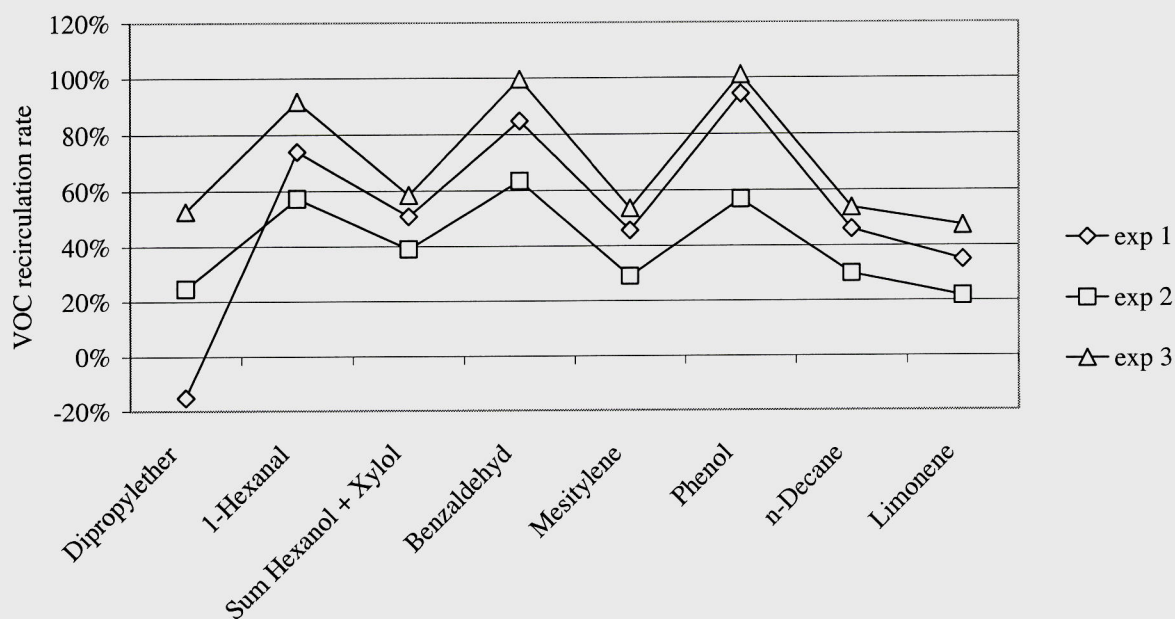


Figure 7: Recirculation rates of the three EMPA experiments for various VOC's.

The experiment was performed three times with different sampling times. In order to avoid adsorption in filters, these were taken out during experiments. Results are shown in Table 7 and Table 8

Table 7: VOC transfer rate in the performed experiments in both EPFL units

	Auditorium unit					Laboratory unit			
Purging sector	With			Without		With		Without	
Expriment Nr.	A+1	A+2	A+3	A-1	A-2	L+1	L+2	L-1	L-2
1,6-dicholorhexane	26%	16%	38%	-4%	58%	8%	17%	34%	47%
1-Butanol	9%	10%	29%	16%	42%	11%	9%	34%	39%
1-Hexanal	15%	14%	23%	15%	29%	17%	3%	38%	34%
1-Hexanol	36%	32%	45%	30%	54%	16%	20%	41%	62%
Benzaldehyde	10%	12%	31%	18%	49%	8%	10%	28%	39%
Dipropylether	10%	13%	13%	5%	22%	5%	5%	24%	9%
Limonene	11%	10%	13%	16%	14%	3%	0%	14%	13%
Mesitylene	5%	9%	20%	15%	31%	7%	9%	28%	28%
m-Xylene	4%	8%	13%	10%	20%	9%	9%	28%	27%
n-Decane	8%	10%	25%	16%	42%	8%	10%	27%	29%
Phenol	51%	44%	54%	50%	71%	32%	37%	64%	64%

Table 8: VOC transfer rate in the EMPA experiments

Expriment Nr.		1	2	3	average	δ
sampling time	min	91	91	45		
Dipropylether	%	-15	25	53	21	41
1-Hexanal	%	74	57	92	74	32
Sum 1-Hexanol/m-Xylol	%	51	39	59	49	22
Benzaldehyd	%	85	63	100	83	34
Mesitylene	%	46	29	54	43	26
Phenol	%	94	57	101	84	38
n-Decane	%	46	30	54	43	25
Limonene	%	35	22	47	35	20

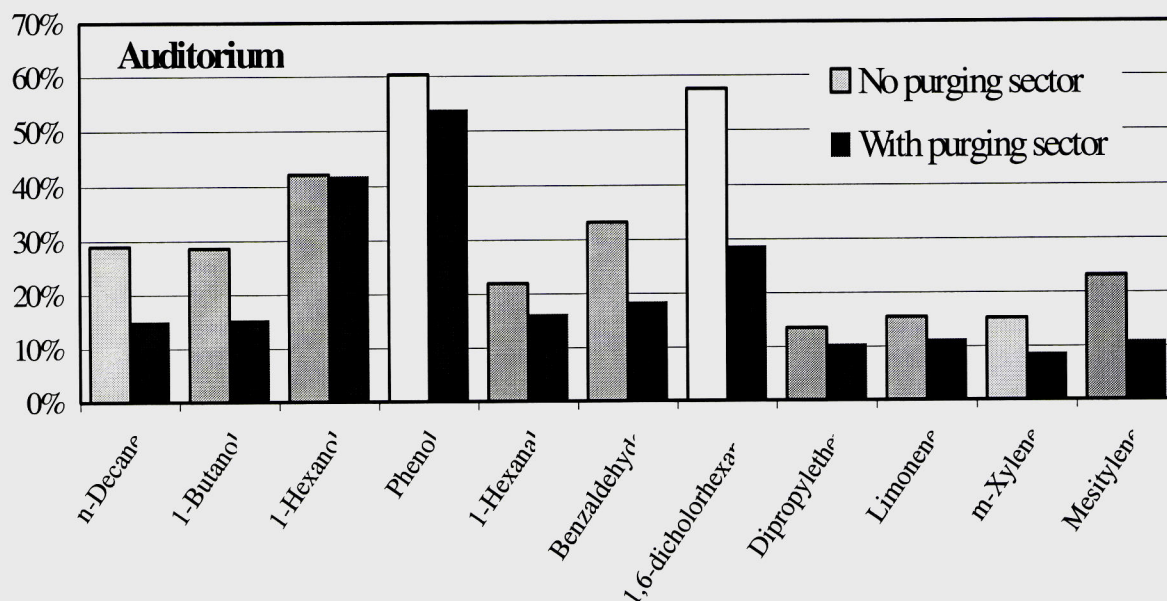


Figure 8: Average VOC recirculation rates measured in the EPFL auditorium(leaky) unit, with and without purging sector, leaky unit.

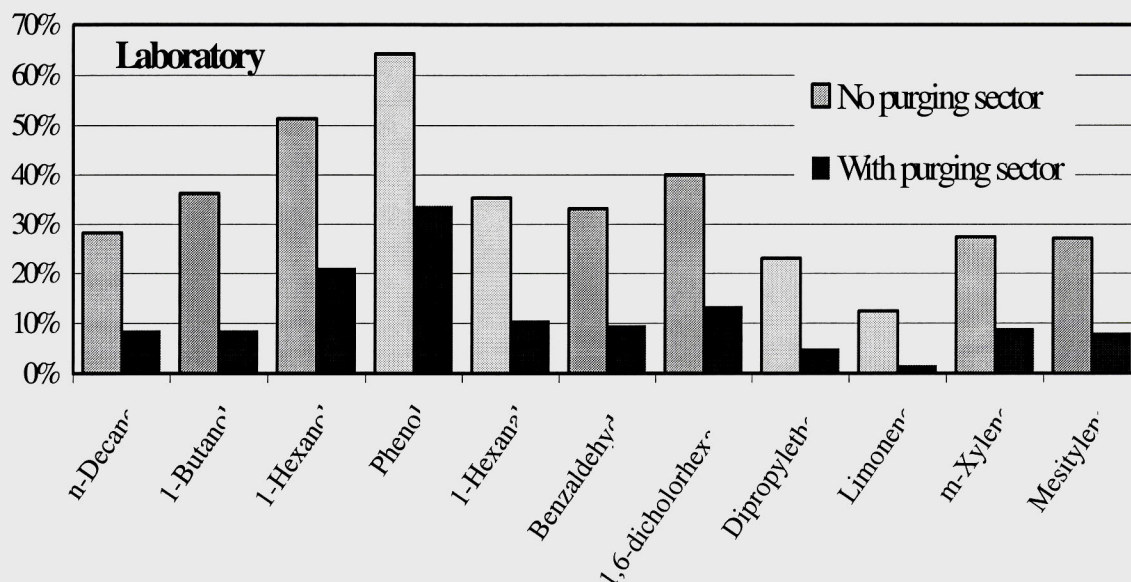


Figure 9: Average VOC recirculation rates measured in the EPFL laboratory unit, with and without purging sector.

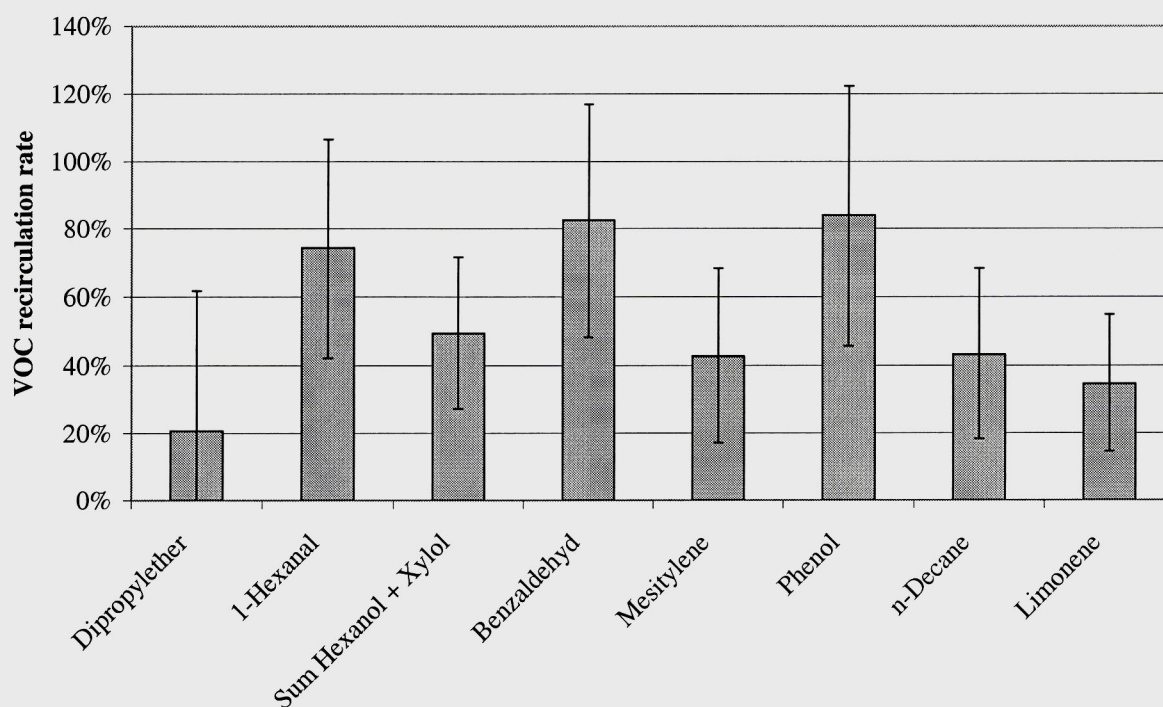


Figure 10: Average VOC recirculation rates in the EMPA unit

Adsorption – desorption only can explain the differences in recirculation rates for the various chemical compounds. It should be noticed that this phenomenon is observed also in the EMPA unit, in which the wheel is not hygroscopic.

The recirculation rates measured in the same conditions (without purging sector) in a unit with hygroscopic wheel (EPFL laboratory) and with a non hygroscopic wheel are clearly correlated (Figure 11). The line in this figure is a least square fit line, which correlation coefficient $R = 0,79$, and slope unity. The average difference between recirculation rates is 22%, close to the recirculation rate resulting from internal leakage in the EMPA unit.

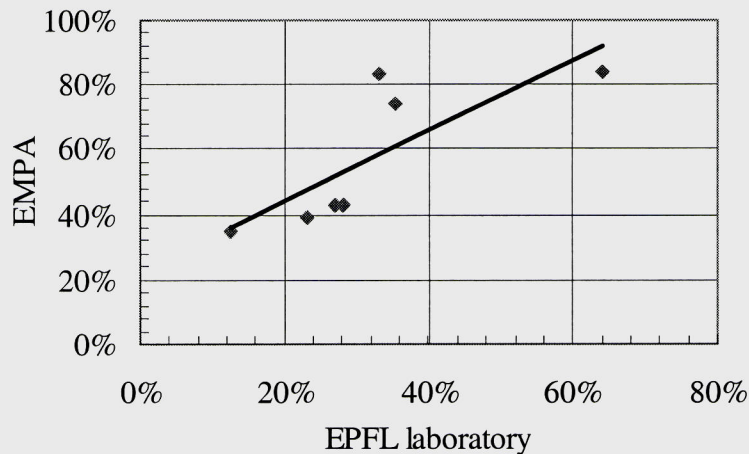


Figure 11: recirculation rates for each chemical compound measured in both EPFL laboratory and EMPA Akademie units, in both cases without purging sector.

DISCUSSION

Transfer processes

As already said, contaminant transfer through rotating heat exchangers results from leakage, entrained air and adsorption-desorption. Since sulphur hexafluoride, the tracer gas used for airflow rates measurements, is not significantly adsorbed on the exchanger wheel surface, the recirculation rates given in Figure 7 include only leakage and entrained air. These recirculation rates are $7\pm3\%$ for the auditorium unit and are not significantly different from zero in the laboratory unit.

Entrained air

A part of the extract air is transported to supply duct by the rotation of the wheel, as shown in Figure 12. All the exhaust air contained in a sector of the wheel is entrained back in the supply air.

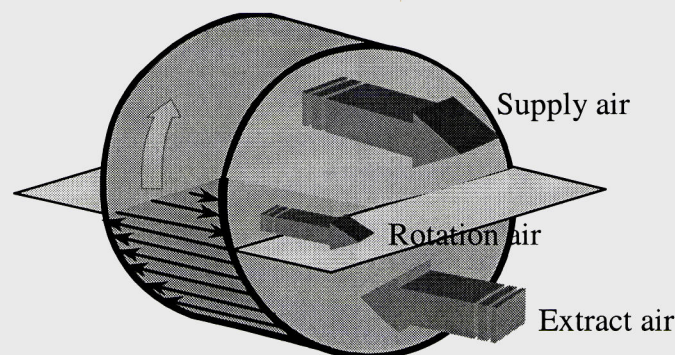


Figure 12: Some extract air is entrained in the supply airflow by the rotation of the wheel.

This is avoided by installing a purging sector, which returns this vitiated air back to the exhaust duct (Figure 13).

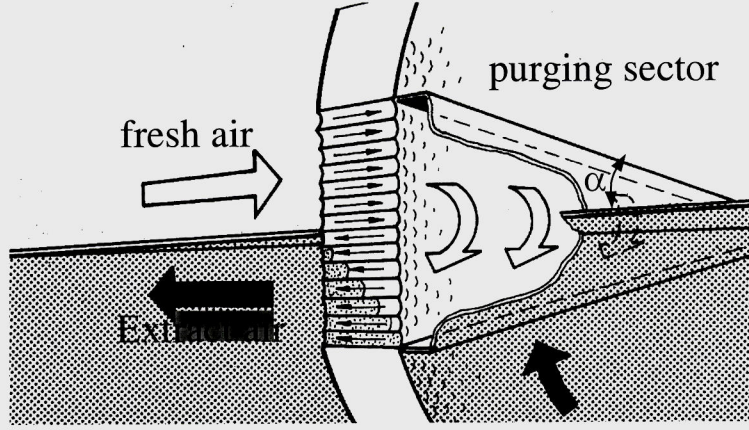


Figure 13: Schematics of a purging sector

The channels in the wheel are narrow, and the flow is laminar. In this case, the discharge velocity, u , is, in a duct of length L and radius r :

$$u = \frac{\Delta p r^2}{8 \mu L} \quad (8)$$

where μ is the viscosity. Assuming ideal plug flow, the time needed for the air to pass through the wheel is:

$$t_{plug} = \frac{L}{u} \quad (9)$$

and the purging time, i.e. the time during which one channel passes in front of the purging sector having an angle α [radian] is:

$$t_{purge} = \frac{\alpha}{\omega} \quad (10)$$

where ω is the angular speed of the wheel, in radians per second. The volume of extract air that may pass to the supply air is then:

$$V_{poll} = \pi r^2 L \frac{t_{plug} - t_{purge}}{t_{plug}} \quad (11)$$

where r is the radius of the channel, assumed circular. The volume of supply air passing through the channel when it is in the supply duct is:

$$V_{in} = \frac{(\pi - \alpha)}{\omega} \pi r^2 u_{in} = \frac{(\pi - \alpha)}{\alpha} \pi r^2 u_{in} t_{purge} \quad (12)$$

Therefore, the recirculation rate, R , resulting from lack of purging is:

$$R = \frac{V_{poll}}{V_{in}} = \frac{\omega L (t_{plug} - t_{purge})}{(\pi - \alpha) u_{in} t_{plug}} \quad (13)$$

where u_{in} is calculated using equation (8) with $\Delta p = p_{supply} - p_{inlet}$

Plug flow is however unrealistic. Another simple model is Poiseuille flow. In this case, the velocity profile in the channel is parabolic. As above, no diffusion is taken into account.

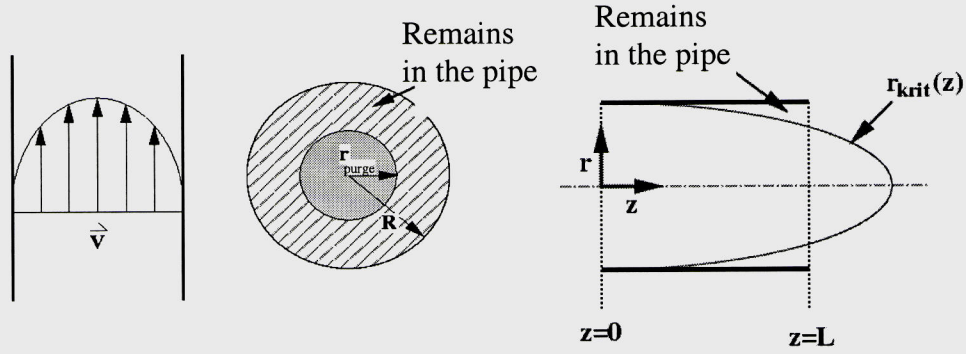


Figure 14: Poiseuille flow

In this case:

$$V_{poll} = \int_0^L \int_{r_{crit}}^r 2\pi r dr dz = \frac{\pi r^2 L^2}{4u_{purge} t_{purge}} \quad (14)$$

where u_{purge} is calculated using equation (8) with $\Delta p = p_{exhaust} - p_{inlet}$

The recirculation rate, R , resulting from lack of purging is then:

$$R = \frac{V_{poll}}{V_{in}} = \frac{\omega L^2}{4(\pi - \alpha)u_{purge} t_{purge} u_{in}} \quad (15)$$

This quantity is always positive, which means that, assuming Poiseuille flow, there will always be some recirculation by entrained air.

In order to compare this model with experiments, calculations were performed with input data as shown in Table 9. Three input data sets were used. Dataset 1 corresponds to data measured in the auditorium unit. In dataset 2, the pressure differential between exhaust and supply ducts is tripled. In dataset 3, the purging time is reduced by increasing the rotation speed of the wheel, and by reducing the purging sector.

Table 9: Calculated recirculation by entrained air

	Quantity	Unit	Data set 1	Data set2	Data set 3
Data	$p_{supply} - p_{inlet}$	Pa	88	88	88
	$p_{exhaust} - p_{inlet}$	Pa	125	392	125
	Wheel rotation ω	Radian/s	0.288	0.288	0.393
	Purging angle α	Radian	0.126	0.126	0.087
Analysis	u_{purge}	m/s	2.75	8.62	2.75
	u_{in}	m/s	3.87	3.87	3.87
	t_{purge}	ms	109	109	55
	t_{plug}	ms	73	23	73
	$t_{plug} - t_{purge}$	ms	-37	-86	17
Plug flow	R	%	0	0	0.63
Poiseuille flow	R	%	0.33	0.11	0.87
No purging sector	R	%	1.97	1.97	2.66

These calculations show that, if there were no purging sector (or if the wheel rotates in the wrong sense), the recirculation rate could be about 2% of extract airflow rate. The recirculation rate with purging sector should be very small.

CFD simulations were also performed at Sulzer Infra Lab to take account of the thermal diffusion. The results are illustrated in Figure 15 to 17, which show the concentration of exhaust air in one single alveolus, 55 milliseconds after starting purging. When diffusion is limited, the purged region looks parabolic (Figure 15). The flow becomes closer to plug flow when the diffusion coefficient is larger (Figure 16) and when the air velocity is reduced (Figure 17)

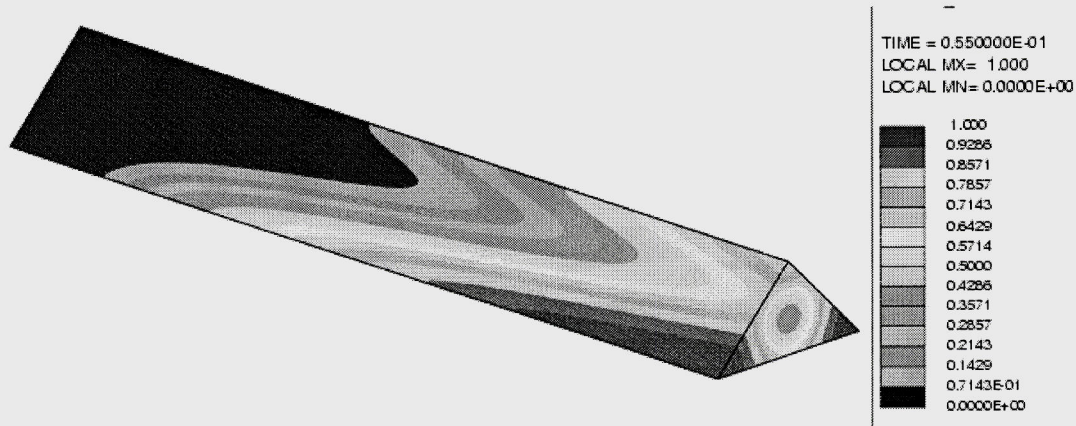


Figure 15: Contaminant concentration in one alveolus, as calculated by CFD. 3 m/s air inlet velocity. Gas with small coefficient of diffusion (Ether: $D=7.8 \cdot 10^{-6} \text{ m}^2/\text{s}$).

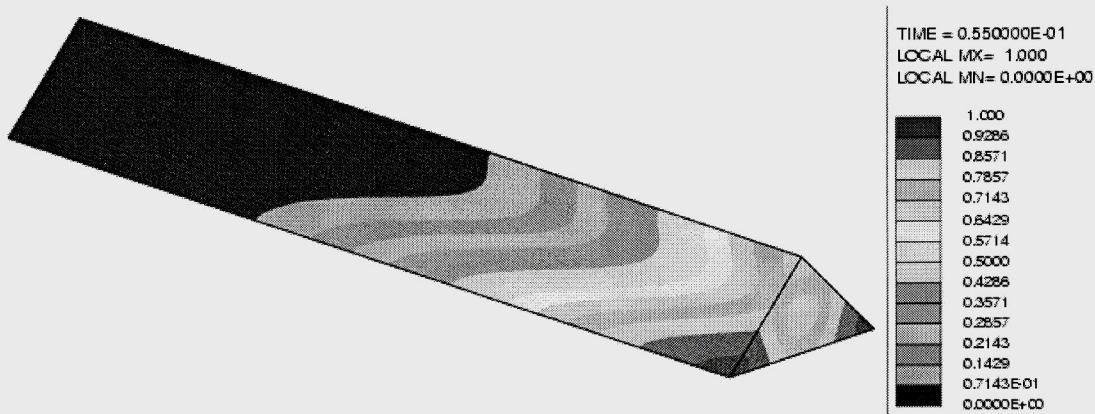


Figure 16: As in Figure 15, but with large coefficient of diffusion (Air: $D=30 \cdot 10^{-6} \text{ m}^2/\text{s}$). The transport (washing out) of the contaminant is closer to plug flow.

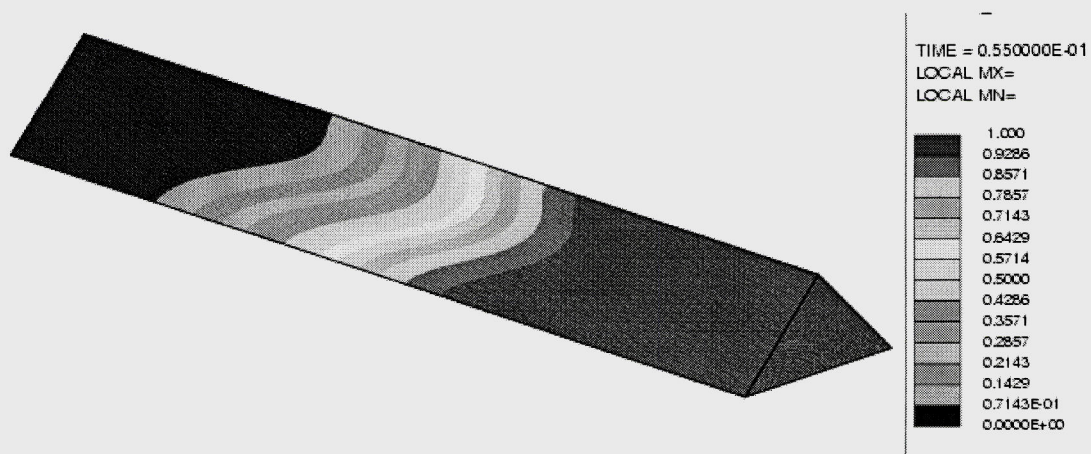


Figure 17: As in Figure 16, but with only 1,8 m/s inlet velocity.

The following conclusions can be drawn from modelling the flow in the purging sector:

- With plug flow, it is theoretically possible to completely avoid recirculation with a well adapted purging sector.
- When viscosity is taken into account (Poiseuille flow), some recirculation will always remain, even with large purging sector.
- Real flow, including diffusion, is between plug flow and Poiseuille flow.
- The recirculation rate resulting from entrained air only is about 2% without purging sector, and less than 1% with purging sector.

Adsorption-desorption

Leakage and entrained air would result in the same recirculation rate for all chemical compounds, this rate being larger than 7% for the auditorium unit, and a few percent for the laboratory unit.

Whenever a gas is in contact with a solid, there will be equilibrium between the molecules in the gas phase and the corresponding adsorbed species (molecules or atoms), which are bound to the surface of the solid. This position of equilibrium will depend upon a number of factors: the relative stabilities of the adsorbed and gas phase species involved, the temperature conditions, the pressure of the gas above the surface.

The differences among compounds shown in Figure 8 and Figure 9 can be explained only by a physico-chemical behaviour such as adsorption. The smallest recirculation rate is for limonene. These are close to the rates that could be expected from leakage or entrained air.

On the other end, it is clear that phenol, hexanol and dichlorohexane present a strong adsorption, which cannot be completely cleaned up in the purging sector.

Potential for improvement

Uncoated wheel should present less adsorption, to the cost of reduced efficiency. But it is relevant to note that also non-hygroscopic rotors after being in use for a couple of years may become hygroscopic (Ruud and Carlsson 1996).

Several methods are available to give latent heat exchanging function to a honeycomb rotor; impregnating porous honeycomb with desiccative salt, forming a desiccative layer on a aluminium surface by chemical corrosion, or applying adsorbent layer (Okano, Kuramitsu et al. 1999). Various types of desiccants are used for hygroscopic wheel coating Silica gel, molecular sieves (zeolites) and aluminium oxides are responsible for physical sorption, or adsorption. Water molecules are trapped in the pore structure. Lithium chloride and calcium chloride react chemically with water, i.e. absorption phenomenon. These materials have very good affinity for water, and can also adsorb or absorb in various proportions other compounds presents in the air carried trough the ducts, such as VOC. The surface of the desiccative layer, a mesopores or micropores structure, has also an incidence on the sorption phenomenon.

A Japanese company, has investigated in details the mechanism of sorption and desorption (SeibuGikenCo. 1999), (Okano, Kuramitsu et al. 1999). They have developed new wheel coating. Aluminium sheet sprayed with a fine powder of desiccative ion exchange resin, and finally treated with an anti-bacterial and anti-mould coating. These sheets are corrugated and made into a honeycomb. The resin adsorbs the water in two ways, by hydratation of the ions, and by means of osmotic pressure. It eliminates the troubles of odour transfer without any sacrifices of heat exchange efficiency. Such materials do not adsorb odours. In the case of hydratation, there is no space around the hydrated ion for other molecules. Osmosis prevents odour molecules from penetrating the resin.

CONCLUSIONS

Experiments clearly show that a part of the VOC's present in extract air may be recycled to supply air on the heat recovery unit in the absence of purging sector, or when the purging sector is not well used.

The low transfer rates observed in the laboratory unit with purging sector for limonene, dipropylether, m-xylene, mesitylene, n-decane, hexanal, 1-butanol and benzaldehyde confirm the results of found by (Andersson, Andersson et al. 1993) for formaldehyde in different units, and attest the efficiency of a purging sector.

Some compounds such as dichlorohexane, hexanol and phenol however easily "pass" the purging sector and are recycled in significant quantities to the supply air.

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