Indoor Air 1993, 3: 143-148

 # 6888

Indoor Air
ISSN 0905-6947

Mass Transfer of Contaminants in Rotary Enthalpy Exchangers

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Abstract

The present work is a study of reentrainment of a tracer gas and formaldehyde via six rotary air-to-air heat exchangers (all enthalpy exchangers) in the northern part of Sweden. Five exchangers installed in office buildings and one in a day-care centre were included in the study. Formaldehyde in indoor air was used as a monitor pollutant and was determined in air samples collected in the ducts at four positions around the rotor of the exchanger, in the supply-air duct and in the exhaust-air duct. Air sampling of homogeneous duct air was performed simultaneously at the four positions using 2,4-dinitrophenylhydrazine-impregnated glass fibre filters. The sample analysis of formaldehyde was made by high-performance liquid chromatography. The reentrainment of formaldehyde was calculated and found to be 1-9%. These results show that a rotary heat exchanger can be used in buildings where activities produce low levels of air pollutants, provided that the exchanger is properly installed and maintained.

KEY WORDS:
Exhaust air, Formaldehyde, Nitrous oxide, Reentrainment, Rotary heat exchanger, Supply air.

Manuscript received: 21 August 1992
Accepted for publication: 3 March 1993

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Introduction

In Sweden, a large part of the energy consumed is used for heating and ventilating buildings. Accordingly, there is a great interest in keeping consumption down and thereby making financial savings. Energy-recovering equipment, such as heat exchangers, is frequently used. In such equipment, heat is transferred from the exhaust air to the supply air. Rotary air-to-air heat exchangers are the most effective type of exchanger, with a temperature efficiency of 70-85%. They can also be designed to transfer both heat and water vapour (enthalpy exchangers), the efficiency of water transfer being of similar magnitude to heat transfer. Enthalpy exchangers are important in Sweden as the relative air humidity (RH) can fall to 5-10% during the winter period. However, concern has been expressed that some indoor-generated air pollutants may be transferred between air streams by this type of heat exchanger (Johansson, Pettersson and Rehn, 1978).

Function of Rotary Heat Exchanger

The exchanger consists of a slowly rotating wheel, the heat wheel or rotor, with small axial channels (flutes) with a laminar flow of air (Figure 1). One half of the wheel is in the supply-air duct and the other half in the exhaust-air duct. The wheel absorbs heat from the exhaust air and transfers it to the supply air. The rotor is usually made of aluminium, which, if hygroscopic, is coated with a layer of aluminium oxide. The exchanger can be equipped with a purging sector (Shabara and McLaughlin, 1974), which admits supply air to clean the wheel from exhaust air while the flute is still discharging to the exhaust air stream.

Reentrainment of Air Pollutants

There are three possibilities of reentraining chemical compounds via a rotary heat exchanger:

- air leakage
- reentrainment by carry-over
- sorption.

Air leakage from the exhaust air stream into the supply air stream is minimized by maintaining a higher static pressure in the supply-air duct and also by ensuring neat and effective air seals around the rotor. Reentrainment by "carry-over" means that a small quantity of exhaust air is retained in the flutes as the rotor passes from the exhaust-air stream to the supply-air stream. It is minimized by inclusion of a purging sector. Sorptive reentrainment occurs when compounds in the exhaust air stream condense in the rotor and then evaporate into the supply air stream. This may be important, especially in the case of enthalpy exchangers.

Earlier Studies

Manufacturers' interest in reentrainment has been focused on exchangers in industrial environments. In such environments the indoor air could be heavily contaminated with solvents, ca. 500 ppm, and reentrainment could reach levels as high as 60% depending on the solvent involved (Sohlberg, 1979). However, it was suspected that reentrainment of pollutants also occurs in more normal indoor environments (ppb-levels of pollutants), such as offices and day-care centres (Johansson, Pettersson and Rehn, 1978). Previously, it was difficult to verify such suspicions because of a lack of methods for measuring pollutants in ventilation systems. Since then, methods based on tracer gas techniques have been published. Sulphur hexafluoride (SF_6) was added to the exhaust air stream and reentrained gas was detected in supply air by an infra-red technique (Barnett, Richard and Rose, 1983). This method was used in laboratory tests and showed that 1% of the added gas was reentrained in the supply air (Khoury et al., 1988). In a similar laboratory study, SF_6 and formaldehyde were used as tracer gases (Fisk et al., 1985). In this study, where the rotor was coated with a layer of lithium chloride, 5-8% of added SF_6 and 7-15% of added formaldehyde were measured in the supply air stream.

Aim of Present Study

Since ventilation and the quality of supply air are important factors in the indoor air climate, the present study is intended to ascertain whether an indoor-generated compound, formaldehyde, is reentrained. Six rotary air exchangers (enthalpy exchangers) in six office buildings were included in the study, performed during the winter period in the northern part of Sweden.

Materials and Methods

Properties of Exchangers

The six exchangers studied were all installed with the rotor in an upright position and the fans were installed after the rotor in the direction of flow (Figure 1, aspirating the air through the rotor), with well-fitting seals around the rotor. All exchangers were of enthalpy type and five were equipped with a purging sector. None of the ventilation systems was equipped with dampers for recirculating air.

Measurements using Nitrous Oxide

To enable suitable exchangers to be selected for this study, nitrous oxide, N_2O (AGA), was used as a tracer gas. Any leakage caused by unsuitable installation or improper maintenance of the ventilation equipment was checked with the gas. The nitrous oxide was admitted into the exhaust-air duct at a position far enough away from the exchanger to ob-

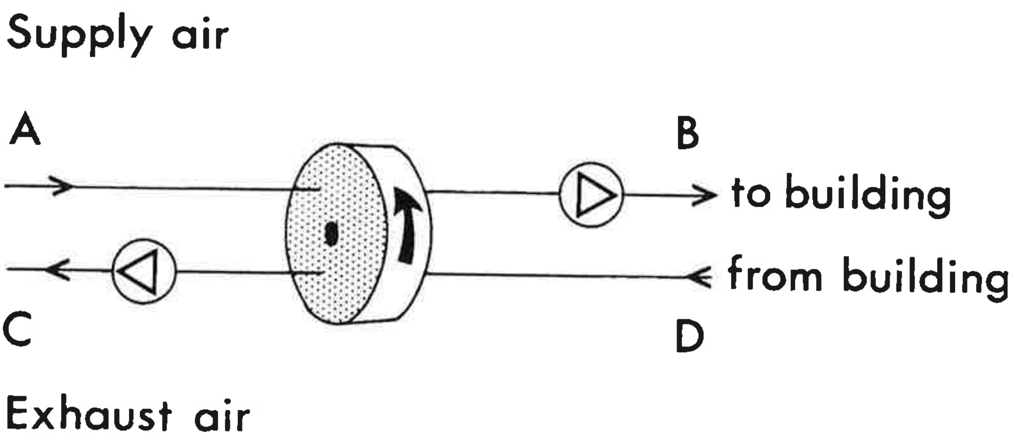

Fig. 1 Schematic outline of a rotary air exchanger, mounted between the supply-air duct and the exhaust-air duct. The symbol Ⓐ represents a fan.

tain homogeneous mixing of the gas with the air stream. The concentration of added nitrous oxide in the exhaust duct was measured at position D (Figure 1) by aspirating air from the duct and allowing it to pass through an infra-red spectrophotometer (Miran 1A). For air sampling, a vacuum pump (model DOA-P109-7D, GAST, USA) and a metal tube (i.d. 8 mm) with one of the ends capped with 45° angle were used. The tube was inserted into the duct and placed perpendicular to the air stream. The inclined capped end of the tube was applied to the middle of the duct, with the open area facing the air flow. The nitrous oxide flow was adjusted so that the measured reference level in the exhaust air stream (position D) was 100 ppm. Reentrained gas was measured in position B (Figure 1). The detection limit of this procedure was 1 ppm of nitrous oxide.

Determination of Temperature, Pressure and Angular Velocity of Rotor

Temperatures outdoors and in the ducts were measured with a mercury thermometer (A-D in Figure 1). The total air pressure in the ducts was determined at four points around the rotor, before and after passage of the rotor in the supply-air and exhaust-air ducts, respectively. The distance between the measuring points and the rotor was ca 1 metre. The equipment used was a Prandtl-tube connected to a Multer EMA 150 instrument. The values presented are means of the pressure measured over 3.0 minutes. The pressure differences between the ducts were determined by inserting the tubes of the measuring instrument in the supply-air duct and in the exhaust-air duct, respectively. The angular velocity of the rotor was determined by making a mark on the rotor and, by means of an inspection device, counting the number of revolutions during 1 minute.

Measurement of Formaldehyde

The levels of formaldehyde in the supply-air and exhaust-air streams were determined at four points A-D (Figure 1) by a chemosorption method employing 2,4-dinitrophenylhydrazine-impregnated glass fibre filters (Levin et al., 1985). Six parallel (simultaneous) samples were collected at the centre of the ducts with the above equipment. In one case, where the air flow was not homogeneous, fan-shaped equipment was used for sampling. Five metal tubes (i.d.

Table 1 Results of duct pressure measurements (P_A-P_D, Figure 1), determination of rotor velocity and reentrainment of nitrous oxide.

Exchanger number	Pressure mm Wp				Revolutions rpm	Rentraiment Nitrous oxide %
	Supply air		Exhaust air			
	Before P_A	After P_B	Before P_D	After P_C		
1	-4	-40	-30	-60	7.0	1
2	-4	-20	-20	-40	15	<1
3	-3	-20	-20	-30	6.0	<1
4	1	-20	-30	-50	10	<1
5*	-20	-30	-20	-40	6.0	3
6	-10	-20	-30	-40	12	<1
Ref**	-5	-20	-25	-40		

*Without purging sector, ** Pressure values from Sohlberg and Norbäck, 1966.

Table 2 Results of formaldehyde duct measurements (sample points A-D, Figure 1) and calculation of reentrained formaldehyde (see text). Each concentration is the average of six simultaneous measurements. In exchanger number 6 the measurements were repeated at different outdoor temperatures.

Exchanger number	Outdoor air °C	Levels of formaldehyde in ducts, μg/m³					Reentrainment of formaldehyde, %
		A	B	D	C	[B–A+C]*	$\frac{B-A}{D}\times 100$
1	+3	1.5	2.1	14	12	13	4
2	–4	0.7	1.1	6.7	4.9	5.3	6
3	–7	2.6	2.7	8.1	8.1	8.2	1
4	–5	2.2	2.3	6.2	6.4	6.5	2
5**	4	0.6	1.2	17	15	16	4
6	1	3.7	5.0	21	21	22	6
6	–10	1.6	2.2	11	11	12	5
6	–15	0.9	2.1	13	11	12	9

* See text. **Without purging sector.

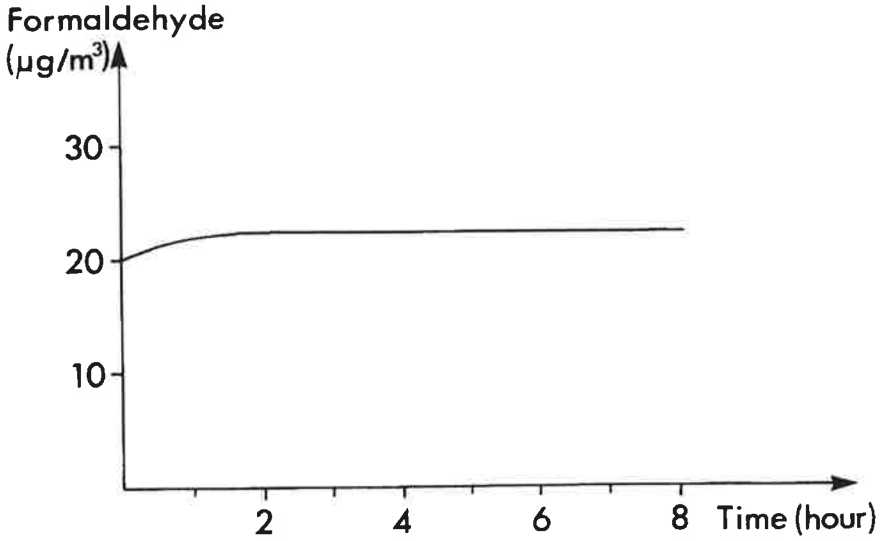

Fig. 2 Change in the formaldehyde air level over 8 hours, when the emission of formaldehyde is supposed to be 20 μg/m³ formaldehyde, the ventilation 1 air exchange per hour, and the reentrainment via a rotary air exchanger 10%.

1 mm) were positioned in the duct with the ends equally distributed in a plane perpendicular to the air flow. The tubes were all connected to a glass bottle in which the air streams were mixed. Six parallel samples were collected from this bottle. The air samplers consisted of two cartridges (in series), the first containing double filters and the second a single filter (a control filter). The sampling air flow was 1 *l*/min and was regulated by glass capillaries. All samples were collected simultaneously at the four points over a period of three hours. Six parallel samples were collected at each sampling point. For analysis (Levin et al., 1985), the filters were removed from the cartridges and extracted with acetonitrile. The double filters were extracted together. All samples were analysed by liquid chromatography, HPLC.

HPLC Equipment

A Waters HPLC system consisting of an M-6000 A pump, an M-710 B autosampler, an M-730 printer/plotter, and an M-440 absorbance detector (365 nm), was used. The column was a Waters Radial-PAK A (100 × 5 mm i.d., octadecyl silane, 10 μm particles). The mobile phase was 40% water in methanol (Merck p.a.), and the flow rate was 0.8 m*l*/min. Under these conditions, k' was 2.2 for the formaldehyde hydrazone.

Results and Discussions

Requirements of Rotary Air Exchangers

The aim of the present study was to determine the levels of reentrainment in exchangers installed in such a way as to minimize leakage at the rotor (into the supply air), which means a lower pressure in the exhaust-air duct as compared with the supply-air duct. This state is achieved when both exhaust and supply fans are installed after the rotor (in the flow direction, Figure 1), both aspirating air through the rotor. Proper maintenance – with regular controls and necessary changes of filters – was also a requirement. Exchangers with the fans installed on the same side of the rotor (position B and D, Figure 1) were excluded from this study. The reentrainment of nitrous oxide was high under such conditions, especially when a damper for recirculated air was installed between the ducts, near the rotor. The measured reentrainment could be as high as 50% in spite of the fact that the adjustment facility showed a closed position of the damper.

Measurements in the Ducts

The air-pressure measurements are shown in Table 1 and are compared with recommended values from a manufacturer (Sohlberg and Norbäck, 1966). For technical reasons, the rotors are not totally tightened at the ducts. The pressure in the ducts should be such that all leakage of the supply air passes into the exhaust air (contaminated air) and out of the building. Comparison of duct pressure, in pairs, on both sides of the rotor means that the pressure in both cases should be lower in the exhaust air ducts ($P_A > P_C$, $P_B > P_D$, Figure 1). The purging sector is also based on a similar pressure situation, where contaminated air in the flutes is forced by supply air into the exhaust air. Table 1 shows that the measured pressure values do not agree with the recommended values in all cases. In exchangers 1 and 5 the pressure in the supply-air duct is lower than that in the exhaust-air duct ($P_B < P_D$). In these exchangers, leakage into the supply air is possible.

The results of measurements with nitrous oxide are shown in Table 1. The level of reentrainment is ≤1% in five of the exchangers. In the 6th (number 5 in Table 1, without purging sector) the reentrainment is 3%, probably on account of the carry-over effect.

To obtain an idea of the leakage at the rotor (into the supply air), measurements with nitrous oxide were also made with the rotor in standstill positions (revolving to 8 different positions of the rotor). In these situations, the reentrainment by leakage in all exchangers was less than 1% (below the detection limit of the method with nitrous oxide).

The air pollutants that are most effectively reentrained by sorbtive reentrainment are small, polar, water-soluble compounds with a high diffusion constant in air (Fisk et al., 1985). Formaldehyde is a gas which fulfils these requirements and was therefore chosen as a model substance in the current study. The evaluated method for determination of low levels of formaldehyde in air (μg/m^3 range) is a prerequisite for the study (Levin et al., 1985). Formaldehyde is found in outdoor air as well as in indoor air and is one likely factor causing the sick building syndrome. In Sweden, formaldehyde was responsible for problems caused during a period when particle board contained an excess of formaldehyde in the adhesive.

Sampling of formaldehyde in the air streams was performed simultaneously at the four sampling points (A-D, Figure 1). Six parallel samples were taken at each point to control both the sampling and the analysis methods. The overall relative standard deviations were 1-6% (exhaust air) and 3-12% (supply air). In exchanger number 6, the measurements were repeated at different outdoor temperatures. The calculated reentrainment of formaldehyde was 1-9% (Table 2), in all cases lower than 10%, with a relative standard deviation of 15-29%. This is in agreement with values of 7-15% reentrainment of formaldehyde reported from the laboratory study (Fisk et al., 1985).

The sampling air flow and thereby the sample volume, were controlled by glass capillaries. The air flow through the capillaries depends on the temperature of the air when it is passing through the capillary. Accordingly, measurements of air temperature in the tubes near the glass capillary were made and showed a small difference (0-3 °C) between tubes connected to the four sampling points. This temperature difference does not have a decisive influence on the determined air sample volumes and thus neither on the determined formaldehyde levels. Nor do the small pressure differences in the ducts (Table 1) have a decisive influence on the sample volume. Thus, the determined formaldehyde levels at the four sampling points can be compared directly.

The ventilation systems are of a very narrow design and space is saved around the exchangers. The straight parts of the ducts are too short to enable flow measurements of the air streams to be performed with standard methods. The reentrainment calculations are therefore based on a supposition that the supply-air flow and the exhaust-air flows are equal but this is not the case in reality. A situation with different flows will affect the determination of formaldehyde reentrained because of sorption (dilution effect). The supply-air flow is usually smaller than the exhaust-air flow. An effort is made to balance the ventilation by attaining a small underpressure in a building (to prevent moisture transfer in the walls). This means that the calculated reentrainment of formaldehyde is overestimated in this case. The reentrainment is less than 10%. To calculate the reentrainment, measurements at A, B and C (Figure 1) are necessary. However, measurements at C were also made to control the movement of the formaldehyde in the exhaust-air stream around the exchanger. Therefore, the level at D (in the exhaust-air stream) was compared with the calculated level [B-A+C] in Table 2. These values should be equal, based on a formaldehyde mass balance if supply and exhaust flow rates are equal. As the table shows, there is a small difference of ca 1 μg/m^3, because of the variation of the method. In the published method, where SF_6 was used, a loss of 30% of the added gas was reported and explained by adsorption of SF_6 on the rotor (Khoury et al., 1988). No data were reported regarding the installation of the fans or pressure determinations. A possible explanation is that the measuring points for the tracer gas were too close to the rotor (the closest distance was 1.[illegible] m), which means that the duct air is not homogeneous.

A necessary condition in ventilation studies is that air samples collected in the ducts should be representative of the composition of the duct air. This means that the air should be mixed and homogeneous when sampled. It is especially important when samples are collected after the rotor (in flow direction). The sampling point should be located beyond the extractor fan and the first curvature of the duct.

When the duct air was not homogeneous in this study the fan-shaped sampling equipment was used.

Low Reentrainment but what about Accumulation?

The current reentrainment study shows that the reentrainment is <10% in the six exchangers where the ventilation equipment was installed with extractor fans and without dampers for recirculated air. If systems with recirculated air are avoided, the contribution of contaminants with similar properties as formaldehyde to the indoor air by the rotary heat exchanger could be accepted. It will have an effect similar to a small decrease (10%) of the air change rate. Concern has been expressed, however, that there is a risk of high accumulation of reentrained pollutions in the indoor air, but this is not the case. This may be illustrated by the following theoretical example. Suppose there is a source in a room which starts to emit 20 $\mu g/m^3$ of formaldehyde continuously. Ventilation is started one hour later (one air rate change per minute) and the reentrainment via a rotary air exchanger is 10%. In Figure 2, the curve shows the variation of the formaldehyde level during the day. As can be seen, the curve reaches a constant level. After 8 hours the level of formaldehyde has changed from 20 $\mu g/m^3$ to 22 $\mu g/m^3$, a negligible increase.

The results obtained from this study do not provide any reason for stopping the use of rotary air exchangers in buildings with low-contaminating activities, such as offices. However, a prerequisite is that the exchanger should be properly designed, installed, operated and maintained.

Acknowledgement

This study was financially supported by the Swedish Council for Building Research. The authors wish to thank Margit Sundgren, National Institute of Occupational Health, and Kjell-Ove Mattson, Labour Inspectorate, for their skilful technical assistance.

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