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POSTER 29

A New Passive Tracer Gas Technique for Ventilation Measurements

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Synopsis

A new passive tracer gas method for ventilation measurements is described. The method utilizes passive tracer gas release from a liquid perfluorocarbon compound contained in a glass vial, equipped with a teflon membrane. Air sampling is also done passively by diffusion through a glass tube containing activated carbon. Quantitative analysis of trapped tracer compound is performed by solvent extraction and gas chromatographic separation using a liquid injection technique. Separation is done with a two-column system and quantitative analysis with an electron capture detector. The paper describes the method and results from the calibration procedure. A short description of a simplified calculation scheme and field measurement technique is also presented.

List of symbols

$\bar{c}$ time averaged tracer concentration [g m^{-3}]

$\dot{m}$ tracer gas release rate [g h^{-1}]

$\dot{m}_A$ release rate of tracer A [g h^{-1}]

m_A totally released amount of tracer [g]

M adsorbed amount of tracer in a sampler [g]

T sampling time [h]

$\tilde{q}$ estimated total effective air flow rate [m^3h^{-1}]

$\tilde{q}_A$ estimated flow rate, calculated from $\frac{\kappa_A}{\beta_A}$ [m^3h^{-1}]

$\tilde{q}_{12}$ estimated flow rate, calculated from $\frac{\kappa_j}{\beta_{1j}}$, where tracer **j** is emitted in zone 2 [m^3h^{-1}]

q_{ij} flow rate of air entering zone **i** from zone **j** [m^3h^{-1}]

α fraction of total flow rate

β_A fraction of the totally released amount of tracer A, that is adsorbed in a sampler

β_{1A} fraction of the totally released amount of tracer A, that is adsorbed in a sampler positioned in zone 1

κ_A equivalent air sampling rate for tracer A [m^3h^{-1}]

1 Background

In the last few years, the interest in the passive tracer gas technique for measuring ventilation flow rates in buildings has grown rapidly. The underlying principles for this technique, which was originally developed at the Brookhaven National Laboratories have been described elsewhere (Dietz & Cote 1982, Dietz *et al.* 1986). Today, there are a few laboratories performing the necessary chemical analysis. The possibilities and limitations of this technique have recently been discussed by several authors (D'Ottavio *et al.* 1988, Dietz 1988, Sherman 1989, Sandberg & Stymne 1989). A state-of-the-art report has recently been published (Säteri (ed.) 1991). However, there are still relatively few field measurements being reported where the passive tracer gas technique is used.

1.1 General principles

The common features of a passive tracer gas technique are the following.

1.1.1 The tracer compound is contained in liquid form in a small closed container, part or whole of which is slightly permeable to the compound. The tracer compound must possess the following characteristics:

- have negligible adsorption by materials occurring in buildings
- be completely harmless to human health at concentrations well above those which might appear inside a building during measurement
- have a high enough volatility to evaporate at the required rate
- not normally appear in indoor air
- be detectable at extremely low concentrations with a GC detector
- be commercially available at a relatively low price

Many fluorinated hydrocarbons of moderate molecular weight fulfill all of the above criteria. Thus, wholly fluorinated (perfluorinated) hydrocarbons have been extensively used. Accordingly, the method is often referred to as the PFT-method (PerFluorocarbon Tracer method).

1.1.2 The sampling of air which contains tracer is done passively using a diffusion tube, containing an adsorbent, which is not easily saturated with the main constituents of the air.

The sampling tube has an opening of accurately reproducible area and length. This may be accomplished with a capillary tube opening. Ideally, the net transport rate of tracer in the air through the opening is diffusion controlled. In this case the net rate of tracer flow is proportional to the area of the opening and to the tracer concentration difference between the air outside the tube and at the surface of the adsorbent. It is also inversely proportional to the distance between the opening and the adsorbant surface. The equivalent net sampling rate of air containing a tracer can be expressed in $g/h \cdot (g/m^3)^{-1}$ which has the dimension $m^3 h^{-1}$. Thus the sampling rate of air can conveniently be expressed in volumetric flow rate units. A typical flow rate is 10 $(ml),h^{-1}$. The sampling flow rates differ for different compounds.

Two main types of adsorbent can be used. One type is based on a heat resistant porous polymer, from which the trapped compounds are preferably desorbed by heat. The other type is based on activated carbon, from which the trapped compounds are either thermally desorbed or extracted by a liquid solvent.

1.1.3 Quantitative analysis of the amount of adsorbed tracer gas.
After sampling for a suitable length of time, the adsorption tubes are sealed and sent to a laboratory for analysis. The analysis is performed using gas chromatography (GC), though other methods might also be suitable.

Depending on the the type of adsorbent used in the sampling, either thermal desorption or liquid extraction is used. The thermal desorption technique has the advantage that 100 % of the trapped tracer is injected into the GC. When using liquid extraction, usually less than 1 % is injected. Thus the thermal desorption technique gives a much higher sensitivity. However, with the types and amounts of tracer gas that are commonly used, sensitivity is not the crucial problem. If sensitivity criteria permit the use of the liquid extraction technique, there are certain advantages. The main ones being that repeated analysis can be performed on the same sample and that standard samples can easily be prepared by dilution.

The detector commonly employed for quantitative analysis of a PFT-compound is the electron capture detector (ECD). With this type of detector, the detectability limit is in the order of 10^{-15}g. Thus an injected amount of 10^{-13}g is clearly enough to make a quantitative analysis. As shown below, this is less than the amount usually injected after liquid extraction.

A typical sampling rate with a capillary opening is 10^{-5} m^3h^{-1}. With a tracer concentration in the air of 0.12 (μg), m^{-3}, the amount of tracer adsorbed in 14 days will be approximately 0.4 ng, which is more than 1000 times the amount needed for a good quantitative analysis. The 0.12 (μg), m^{-3} tracer concentration level, is the level achieved with a tracer release rate of 200 ng, min^{-1} and a diluting ventilation air flow rate of 100 m^3h^{-1}.

Separation from other substances trapped in the adsorption medium and contamination from the extraction solvent, the analysing equipment or the trapping compound itself, are more critical issues than sensitivity.

2 Description of the method

The passive tracer gas method described in this paper (the **SIB** method) has been developed at the **S**wedish **I**nstitute for **B**uilding Research. The basic principles are the same as for the BNL method (Dietz & Cote 1982), while the analysis technique was inspired by the method used by Mailahn *et al.* (1987, 1989). The different steps of the method, i.e. tracer gas release, air sampling and analysis are described below.

2.1 Tracer gas release

At present two different perfluorocarbon compounds can be used on a routine basis. These are hexafluoro-benzene (PB) and octafluoro-methylbenzene (PMB). A tracer compound is contained in an ordinary 2 ml glass vial, sealed with a 1 mm thick teflon membrane. The membrane is kept in place with a crimped on aluminium cap with a 5 mm central opening (fig. 1a). The tracer diffusion rate is determined by intermittently weighing the vial.

2.2 Air sampling

The diffusion samplers are made from standard charcoal sampling tubes (SKC Anasorb) which are cut 17 mm above the level of the charcoal bed (fig. 1b). The inside diameter is 4.3 mm and the diffusion length 17±1 mm. Before and after sampling the tube is protected with a plastic cap. The tubes contain a sorbent layer with appr. 100 mg activated carbon and a backup layer with appr. 50 mg.

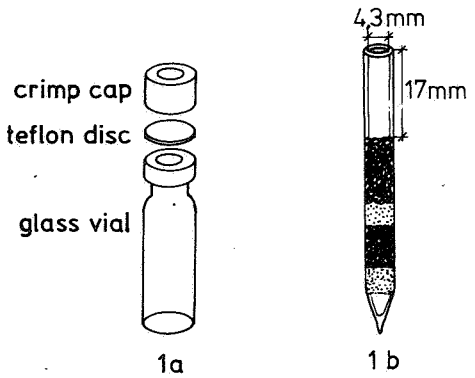

Figure 1a *Tracer gas source arrangement*

Figure 1b *Diffusion sampler arrangement. The glass tube is a standard commercial charcoal sampling tube, which is cut 17 mm above the charcoal bed.*

2.3 Analysis

2.3.1 Desorption

The desorption is done with toluene (Aristar 99.5 %). Prior to use this is further purified from low boiling contaminants by fractionated distillation at a reflux ratio of appr. 100:1. The distillate (1/3) is discarded and the residue is used as the extraction solvent. For extraction, 1 ml of the purified toluene is pipetted into the vial, to which the activated carbon has been transferred. To speed up the extraction the vial is vibrated for 45 minutes in a developing vibrator.

2.3.2 Separation

The analysing equipment is described in more detail below under the heading "GC EQUIPMENT".

1 µl of the toluene solution is injected using a direct injection technique without split, into a precolumn (8 m x 0.53 mm Carbowax fused silica). The helium carrier flow in the precolumn is 10 ml/min. The injector temperature is 140°C and the oven temperature is 60°C, isothermal. An effluent fraction from the precolumn containing the tracers (see fig. 2) is directed to a cold trap (a 0.2 m methyl silicone capillary column, cooled with liquid carbon dioxide). After collection, the trap is flash heated to 100-140°C to inject the trapped compounds into the analytical column (a 25 m x 0.25 mm fused silica column coated with methyl silicone). When reinjection to the analytical column begins, simultaneous backflushing of the precolumn occurs. The flow of helium carrier gas through the analytical column is 1.45 ml/min. When the compounds of interest have left the analytical column, the temperature is raised to 140°C during 5 minutes to clean the columns. Prior to the next injection, the injector compartment is flushed with He for 3 min. The analytical column is equipped with an EC detector.

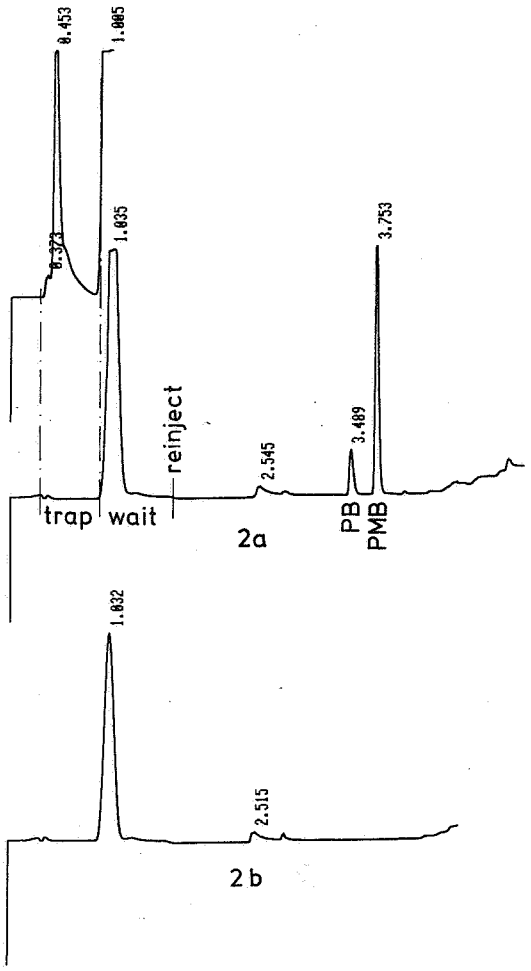

Figure 2a *Chromatogram recorded with an electron capture detector showing the separation of $2.38 \cdot 10^{-12}$ g hexafluorobenzene (PB) and $2.43 \cdot 10^{-12}$ g octafluorotoluene (PMB) in 1 µl toluene solution. The fraction trapped from the precolumn (see insert) is reinjected at 1.6 min into the analytical column.*

2b *Corresponding chromatogram of pure solvent (without tracer compounds), using the same fraction cut as in fig. 2a.*

2.4 GC-equipment

2.4.1 Gas chromatograph: Hewlett-Packard 5890A

Detectors: Electron capture detector (ECD)

Injector: Split/splitless. Autoinjection without split.

2.4.2 Columns:

Precolumn - WCOT fused silica 8 m x 0.53 mm, Chrompack CP- WAX52CB, coating thickness=2 μm

Analytical column - WCOT fused silica 25 m x 0.25 mm, Chrompack CP-SIL 8CB, coating thickness =1.2 μm

2.4.2 Column switching system: Chrompack MUSIC , which essentially is a computerized "Dean" switched system equipped with a cooled trap between the two columns.

2.5 Calibration and quality assurance

The different steps of the analysis process have been tested in the laboratory for reproducibility and accuracy.

The tracer release rate from the sources described earlier have been tested in the laboratory by intermittently weighing the bottles. After 4 weeks of equilibration the release rate from individual sources show a good constancy over time. Unfortunately, there is a variation between different sources which makes individual calibration of sources necessary. The release rate is strongly dependant on temperature - increasing approximately 5 % per degree Kelvin. An alternative (but appreciably more expensive) type of source, based on capillary diffusion shows instanteneous equilibration and a much less variation (S. D. < 3 %) in release rates between individuals.

The sampling rate of the diffusive sampling tubes has been tested in a space with controlled ventilation flow rate. A typical example is given in fig. 3. The sampling rate is shown to be constant with time. The sampling rate is preferentially expressed in cubic meters of sampled air per hour (m^3/h).

This **equivalent air sampling rate** (κ) is dependant on the diffusion coefficient of the tracer in air and is therefore different for different tracer compounds. For our design of diffusive samplers κ_{PB} is found to be $18.5 \cdot 10^{-6}$ m^3/h and κ_{PMB} = 16.5 m^3/h (a small correction, due to the fact that the recovery of the extraction is slightly less than 100 % is introduced in the κ_{PB} - see below).

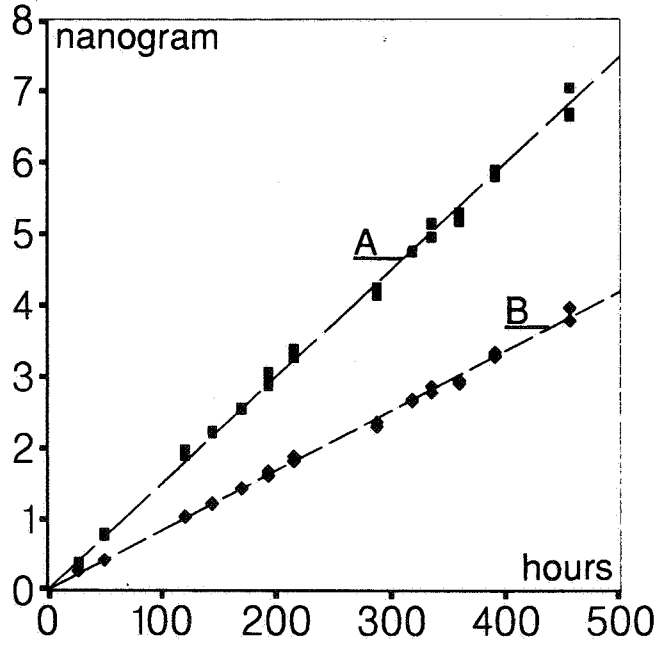

Figure 3 *Result from a diffusion sampling rate test under controlled ventilation rate. Analyzed amount of adsorbed tracer compounds are displayed for duplicate injections of extracts from two sampling tubes per occasion*

The **distribution coefficients** between activated carbon and the extraction solvent (toluene) have been studied. It was found that the presence of activated carbon did not affect the concentration of PMB in the liquid phase. PB, however, was adsorbed slightly stronger than the solvent on the solid phase - yielding only a 96 % concentration recovery in the liquid phase. To avoid computational complications, this deviation from 100 % recovery is not explicitly corrected for. Instead, it is implicitly compensated for, by the use of a lower value of the equivalent sampling rate κ_{PB} than would otherwise have been found.

2.6 Quantitative analysis

Injection to the GC is done automatically from a sampling tray with a capacity of 100 sample vials.

The quantitative analysis of the tracer compounds is performed by the use of the integrated area under the ECD-signals of the compounds after GC-separation as described above.

It is shown (fig. 4) that the integrated signal area is directly proportional to the amount injected to the gas chromatograph.

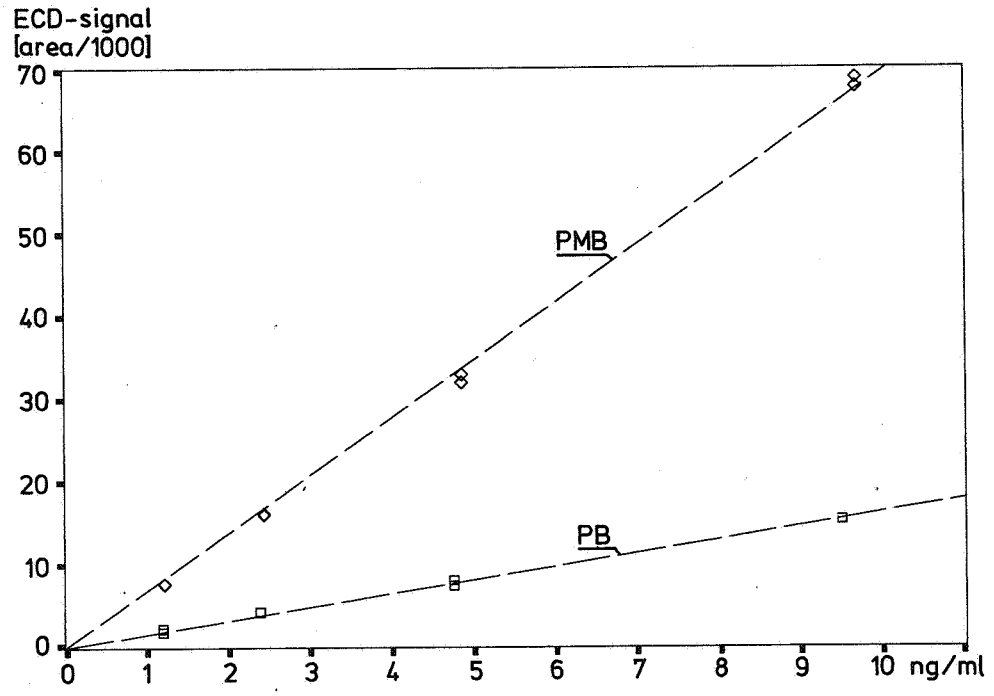

Figure 4 *Integrated ECD-signal of PB and PMB peaks for different concentrations in toluene solution. The injected amount is 1 µl*

The proportionality factors are updated every fourth sample run, by injecting an external standard sample, with accurately known concentrations of PB and PMB in toluene. A new standard solution is made daily by dilution (1:20) from a stock solution. The external standard usually employed has a concentration of appr. 10 ng/ml of PB and 5 ng/ml of PMB.

The standard deviation of the quantitative analysis of repeated injections from the same sample amounts to 1 %.

The standard deviation of the quantitative analysis of the amounts of tracers desorbed from different samplers, which are exposed under equivalent conditions, amounts to 5 %.

Capped samplers can be kept several weeks in room temperature without desorption or adsorption of tracers. However, capped samplers and tracer gas sources should not be kept together in a badly ventilated space, because adsorption has been shown to occur in heavily contaminated environments.

3 Calculation procedure and field measurement technique

The amount (M) of a tracer gas adsorbed in a diffusive charcoal sampling tube, which is exposed during a time period T, in an environment with a time - averaged tracer concentration of $\bar{c}$ is given by

$$M = \kappa \cdot \bar{c} \cdot T \qquad (1)$$

During the same period the amount (m) of tracer released from a tracer gas source in the space is given by:

$$m = \dot{m}T \tag{2}$$

where $\dot{m}$ is the constant emission strength of the source.

1 and 2 yield

$$\beta = \frac{M}{m} = \frac{\kappa \cdot \bar{c}}{\dot{m}} \tag{3}$$

where β is the fraction of the totally emitted amount of tracer in the space, which is adsorbed on a sampler during the exposure time.

Assuming a perfect mixing ventilation system with a constant ventilation flow rate of q (m^3/h), mass conservation of the tracer yields

$$q \cdot \bar{c} = \dot{m} \tag{4}$$

3 and 4 yield

$$q = \frac{\kappa}{\beta} = \frac{\kappa}{(\frac{M}{m})} \tag{5}$$

Thus, in a perfect mixing ventilation system with a constant ventilation flow rate, the flow rate q can easily be calculated from the quotient between the sampling rate (κ) and the sampled fraction β.

The name "effective" ventilation flow rate has earlier been adopted for the flow rate determined this way, even if the ventilation rate is not constant in time (Sherman & Wilson 1986). The effective flow rate is usually smaller than the true time averaged ventilation flow rate, when variation occurs.

The notation $\tilde{q}_A$ is used here to denote the flow, estimated from a tracer gas experiment utilizing tracer of type A, according to equation (5) above, even if the flow varies in time or the mixing is non-uniform.

$$\tilde{q}_A = \frac{\kappa_A}{\beta_A} \tag{6}$$

Therefore, $\tilde{q}_A$ does not usually correspond to the time-averaged total ventilation flow rate.

3.1 Incomplete mixing

A complication which nearly always occurs in real systems is incomplete mixing.

The mathematical tool for dealing with tracer gas experiments in non-uniformly mixed system, is the multicell theory.

In this theory - the space is subdivided into a number of cells (N), each of which is assumed to be uniformly mixed. Mass balances are set up for each cell separately.

The theory leads to a set of N simultaneous equation systems, which can only be solved completely, by an experiment using as many different tracer gases as there are cells.

It is out of the scope of this paper to go any further into the multicell theory. This is discussed in several other papers (e.g. Sandberg 1984).

For field measurements, it is normally out of question to perform complete multicell experiments. Certain simplifications can be made, especially since limited information is often sufficient. A couple of such simplifications, which have been shown to yield satisfactory results, are given below.

3.1.1 One zone approximation

Often the only information requested is the total ventilation rate to the space. To solve the mass balance equation in this case, the only information we need is the concentration of tracer in the extracted air. In mechanically ventilated buildings and in naturally ventilated buildings, which are not too leaky, there are dedicated air extract points. If there is only one extract air terminal, a tracer gas sampler should be positioned in the vicinity of this terminal. It does not matter how the air flows in the building, or how tracer sources are distributed. All entering air and tracer must pass the air terminal.

However, even in small apartments there are normally at least two air terminals - one in the kitchen and one in the bathroom.

In the following we assume that there are two extract points (1 and 2) and that samplers have been positioned close to each of these two points. Only one tracer gas type is employed, who's concentration is C_1 and C_2 respectively at the two extract points.

We further assume that the extract flow rates at the two terminals are respectively $q/2(1+\alpha)$ and $q/2(1-\alpha)$.

where q is the total air flow rate and α can take a value between -1 and +1.

The mass balance equation gives:

$$\begin{aligned} \dot{m} &= q/2\cdot[(1+\alpha)C_1 + (1-\alpha)C_2] \\ &= q/2\cdot[C_1 + C_2 + \alpha(C_1 - C_2)] \end{aligned} \qquad (7)$$

or

$$\frac{\dot{m}\cdot 2}{(C_1 + C_2)} = q[1 + \alpha\cdot\frac{(C_1 - C_2)}{(C_1 + C_2)}] \qquad (8a)$$

In terms of the notations introduced above eq. (8) can be written:

$$\tilde{q} = \frac{2}{\frac{1}{\tilde{q}_{1A}} + \frac{1}{\tilde{q}_{2A}}} = q[1 + \alpha \cdot \frac{\frac{1}{\tilde{q}_{1A}} - \frac{1}{\tilde{q}_{2A}}}{\frac{1}{\tilde{q}_{1A}} + \frac{1}{\tilde{q}_{2A}}}] \qquad (8b)$$

$$\tilde{q} = q + q \cdot \alpha \frac{\frac{1}{\tilde{q}_{1A}} - \frac{1}{\tilde{q}_{2A}}}{\frac{1}{\tilde{q}_{1A}} + \frac{1}{\tilde{q}_{2A}}}; \quad \frac{\tilde{q} - q}{q} = \alpha \frac{\frac{1}{\tilde{q}_{1A}} - \frac{1}{\tilde{q}_{2A}}}{\frac{1}{\tilde{q}_{1A}} + \frac{1}{\tilde{q}_{2A}}} \qquad (9)$$

where the flow rate estimate $\tilde{q}$ is based on the average tracer concentration at the two extract terminals.

From this formula the relative error in the estimate due to uneven tracer distribution can be calculated.

The worst estimate will appear when $\alpha = \pm 1$ i.e. when all air leaves at only one terminal.

The maximum relative error will be $\frac{|C_1 - C_2|}{C_1 + C_2} = \frac{\left|\frac{1}{\tilde{q}_{1A}} - \frac{1}{\tilde{q}_{2A}}\right|}{\frac{1}{\tilde{q}_{1A}} + \frac{1}{\tilde{q}_{2A}}}$ in this case.

Often, it is simple to choose the position of the tracer gas source(s) so that the concentrations are approximately equal at both extract points. Of course one should avoid placing a source closer to one sampler than the other. If the one zone approximation was inadequate, one at least gets an indication of the maximum error introduced.

3.1.2 Two zone approximation

It is not unusual that the extract points are far from each other, and that an appreciable amount of outdoor air is introduced between the extract points. In this case it is often not evident where to place the tracer source or sources so that the tracer concentration can be expected to be similar at the two extracts points.

In this case it is better to divide the space into two zones, each of which contains one main air extract area. It is not necessary to know the zone boundaries or assume uniform mixing within each zone. The two types (A and B) of tracer sources should be positioned one in each zone (1 and 2), preferably in rooms with the most supply air. The samplers shall be positioned in the vicinity of the extract points. The extract flow rates at the two extract points are assumed to be q_1 and q_2 respectively.

The mass balance equations are

$$C_{1A} \cdot q_1 + C_{2A} \cdot q_2 = \dot{m}_A$$
$$C_{1B} \cdot q_2 + C_{2B} \cdot q_2 = \dot{m}_B \qquad (10)$$

where C_{1A} is the concentration of tracer A in the extract area of zone 1 and q_1 is the flow rate of extract air zone 1. The other notations follow the same rule. In terms of the time integrated tracer amounts introduced earlier, this equation system can be written:

$$\frac{\beta_{1A}}{\kappa_A} \cdot q_1 + \frac{\beta_{2A}}{\kappa_A} \cdot q_2 = 1 \quad ; \quad \frac{q_1}{\tilde{q}_{1A}} + \frac{q_2}{\tilde{q}_{2A}} = 1$$
$$\frac{\beta_{1B}}{\kappa_B} \cdot q_1 + \frac{\beta_{2B}}{\kappa_B} \cdot q_2 = 1 \quad ; \quad \frac{q_1}{\tilde{q}_{1B}} + \frac{q_2}{\tilde{q}_{2B}} = 1 \qquad (11)$$

where β_{1A} is the fraction of totally emitted amounts of tracer A that is adsorbed in a sampler in zone 1.

The equation system can easily be solved for q_1 and q_2.

3.1.3 Complete two cell system

In some cases it is desirable to treat the building as a complete two cell system, even if there is not uniform mixing within each zone. This is for example the case in two storey houses. Here, not only the total air flow rate is of interest, but also, for example, the amount of air extracted from the upper floor originating from supply to the ground floor.

Each floor is treated as one zone with its own type of tracer. The treatment is similar to that in the two zone approximation mentioned earlier, but now it is also necessary to sample the air flowing between the two zones. The tracer emission sources are preferably positioned as far as possible away from identifiable extract points and the stairway, in rooms with the most supply air. The air is sampled in the vicinity of the extract points and the stairway.

Without any derivation we can write the so called inverse flow matrix ($\mathbf{Q}^{-1}$) which is directly obtained from the result of the passive tracer gas measurements:

$$\mathbf{Q}^{-1} = \begin{pmatrix} \frac{\beta_{1A}}{\kappa_A} & \frac{\beta_{1B}}{\kappa_B} \\ \frac{\beta_{2A}}{\kappa_A} & \frac{\beta_{2B}}{\kappa_B} \end{pmatrix} = \begin{pmatrix} \frac{1}{\tilde{q}_{1A}} & \frac{1}{\tilde{q}_{1B}} \\ \frac{1}{\tilde{q}_{2A}} & \frac{1}{\tilde{q}_{2B}} \end{pmatrix} \qquad (12)$$

where it is assumed that tracer A has been emitted in zone 1 and tracer B in zone 2. Each β value must be characteristic for all air leaving a zone (both at extract points and at the stairway).

Each term in the inverse flow matrix has its physical interpretation (see for example Sandberg (1984))

In order to be interpreted in terms of air flow rates, it is necessary to invert the matrix, to obtain the flow matrix **Q**, which is easily done with a 2 x 2 -matrix.

$$\mathbf{Q} = (\mathbf{Q}^{-1})^{-1} = \begin{pmatrix} q_{11} & -q_{12} \\ q_{21} & q_{22} \end{pmatrix} \qquad (13)$$

The q_{11} value is interpreted as the total flow rate of air entering zone 1 from all other zones including the ambient. The q_{12} value should be interpreted as the flow rate from zone 2 entering zone 1. The sum of terms in row 1 of the flow matrix is the flow rate of air entering zone 1 directly from outside. Row 2 correspondingly yields the ambient air flow rate entering zone 2. The column row sums yield the corresponding direct outflow of air to the ambient. The sum of all terms yield the total ventilation flow rate to the system.

3.2 Example

Fig. 5 shows the calculated flows according to equation 6 for different types of tracer sources, located in different parts of an apartment with balanced ventilation. The varying results for different sampler locations illustrate the non-uniform mixing of ventilation air.

If the extract air flow rates at extract points **1** and **2** (see fig. 5) are called q_1 and q_2 respectively, the two zone approximation (equation system 11) yields the following results:

$$\frac{q_1}{132} + \frac{q_2}{118} = 1 \qquad \text{for tracer A}$$

and

$$\frac{q_1}{105} + \frac{q_2}{160} = 1 \qquad \text{for tracer B}$$

Solving the equation system yields:

$$q_1 = 58.4 \text{ m}^3/\text{h} \; ; \; q_2 = 66.7 \text{ m}^3/\text{h} \; ; \; q_{tot} = q_1 + q_2 = 125.1 \text{ m}^3/\text{h}$$

By utilizing the one zone approximation, according to equation (8) instead of the two zone approximation, about the same result (125 m^3/h) is obtained for the total ventilation flow. This result is obtained whether the calculation is based on tracer A or B. The satisfactory result from the one-zone approximation is due to the fact that there are approximately equal flows (α=0.07) from the two extract points (see equation 9).

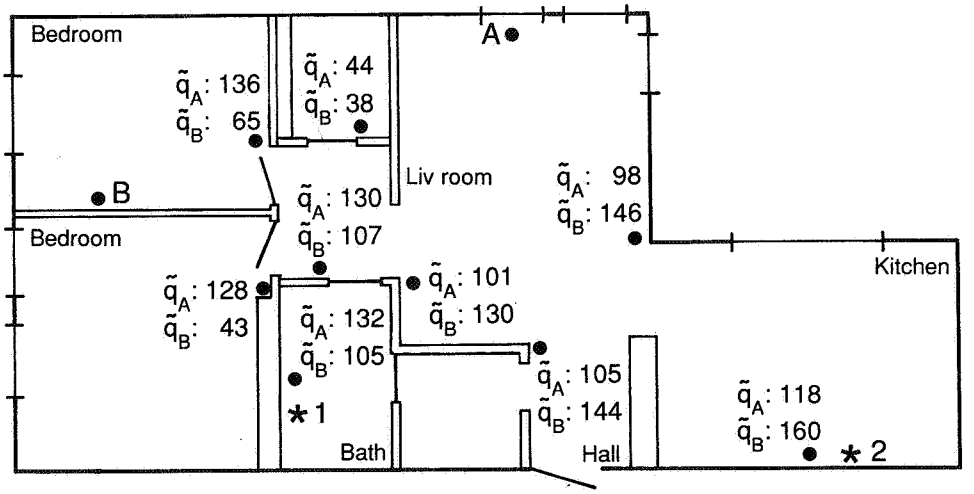

Figure 5 *Result of a passive tracer gas measurement in an apartment with balanced mechanical ventilation. Flow rates* $\tilde{q}_A = (\frac{K_A}{\beta_A})$ *and* $\tilde{q}_B = (\frac{K_B}{\beta_B})$ *(m³/h) are calculated at different samper positions. A and B denote the positions of tracer sources of type A and B respectively. *1 and *2 denote the positions of the air extract points*

3.3 Remarks

When performing a passive tracer gas measurement, we have found it to be a good practice to use two different types of tracers. Furthermore, we normally use a greater number of samplers than are necessary to calculate the total ventilation flow rate. The extra samplers give valuable extra information on the air flow pattern in the investigated space.

The practice we use, is to sample the air leaving the test space. In leaky, naturally ventilated houses, it is usually not possible to identify specific extract and supply points. This strategy is, therefore, not useful in this case. A better strategy might be to distribute several sources in order to obtain as homogenous a concentration as possible over the whole space. Sampling should be performed in many points to get an average concentration of the air leaving the system. In Sweden, however, even naturally ventilated houses are tight and equipped with extract air terminals where most air leaves the house. The practice of sampling close to identifiable extract points must be used with caution. It is not advisable to sample in a closed extract room e.g. a bathroom, where outside air also enters, for example, through a frequently opened window. The air short-circuiting in a bathroom should not be allowed to influence the computation of the ventilation flow rate available for the living space. In this case a better practice is to position the sampler outside the door to that space.

4 Conclusions

A new routine analysis method for two different perfluorocarbons, suitable for passive tracer gas measurements has been developed and extensively tested. The method is based on liquid extraction of the adsorbed tracer gases from active carbon in diffusive sampling tubes, gas chromatographic separation on a two-column system and quantitative analysis by and electron capture detector.

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POSTER 30

Use of tracergas to determine leakage in domestic heat recovery units (HRV)

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1. Introduction. (Abstract)

Tracergases provide a way to determine airflows in different situations. In some cases it is the only way to get quantitative information. This paper presents two cases in which tracergases are used for measuring the internal leakage in heat recovery units.
Internal leakage in heat recovery ventilators (HRV's) for domestic use may cause some problems:

- the real quantity of fresh air entering the building is unknown
- electrical power for the fans is used inefficiently
- smelling air a.g. from the kitchen may re-enter the building due to cross leakage from exhaust air tot supply air
- the efficiency of the HRV seems apparently better.

Most commonly used in domestic buildings in The Netherlands is a cross-stream HRV. The internal leakage in three types of HRV's is measured using N_2O as a tracergas. It is shown that major leakage occurs alongside the heat exchanger blok. Internal leakage in the heat exchanger itself however can not be neglected. The measurements show that an air leakage rate of less than 3 % of the total airflow can be obtained by careful design.

Secondly is shown how internal air leakage in a (rotating valve) back flow heat recovery ventilator is measured. This type of heat recovery ventilator uses an accumulating mass to recover heat. Due to this principle a certain amount of leakage from exhaust air to supply air is unavoidable. The exact amount of air leakage can be measured using a continually sampling infra-red absorption analyser. With the results it was proved that the efficiency of the heat recovery was only minimal influenced by the leakage.

2. Leakages in heat recovery units

All possible leakage flows for a cross flow heat recovery ventilator are give in figure 1.
At first is being noticed that leakage flows I'_{12} and I'_{34} parallel to the head flows I_{12} en I_{34}, can never be determined by measuring on the outside of the heat recovery unit. The effect of this leakage flow is only a decreased efficiency. This could also be caused by a bad K-value (in $W/m^2.K$) of the heat recovery ventilator. Both causes ara disindistinguishable, therefor these leakage flows will be left out of consideration [1].

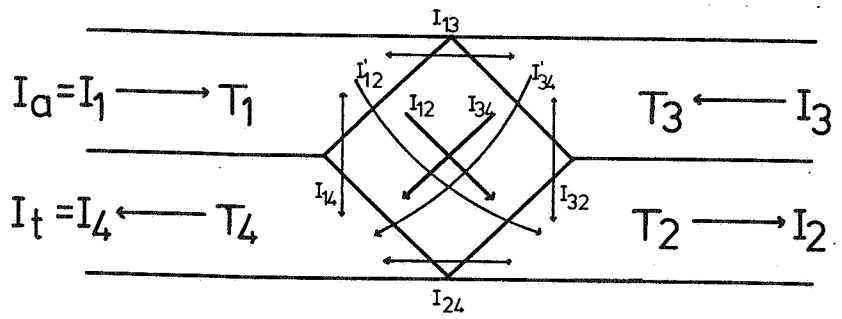

Figure 1. Leakage flow scheme.

The direction of the other 4 leakage flows are caused by the static pressures P_1 up to P_4 of the different compartments of the heat recovery unit.
The relation of these static pressures is dependant of the position of the ventilators in the unit. The pressure distribution of the examined heat recovery units was
$P_3>P_4>P_1>P_2$.

3. Theoretical background of the measuring procedure.

In a practice situation, whereby the behaviour of a unit is examined, the following measure values are known (see figure 2):

- temperatures T_1 up to T_4 in °C
- volume flows I_1, I_4 in m^3/h
- tracergasconcentration C_1, C_2 and C_4 in ppm
- ventilatorcapacity Q_2, Q_4 in W.

From the measured concentrations follow the leakfraction F_t (from exhaust domestic air to supplied fresh air) and F_a (from intake fresh air to exhaust domestic air).

$$F_t = (C_4/C_1) \quad (3.1a)$$
$$F_a = 1 - (C_2/C_1) \quad (3.1b)$$

On the basis of the known leakfractions can now be determined the resulting volume flows in the unit (I_{12}, I_{34}), the resulting leak flows (I_{14}, I_{32}):

$$I_{12} = I_1 - F_t \cdot I_4 \quad (3.2a)$$
$$I_{14} = F_t \cdot I_4 \quad (3.2b)$$
$$I_{34} = (1 - F_t) \cdot I_4 \quad (3.2c)$$
$$I_{32} = F_a \cdot (I_1 - F_t \cdot I_4)/(1 - F_a) \quad (3.2d)$$

and also the still unknown volume flows (I_2, I_3):

$$I_2 = I_{12} + I_{32} \quad (3.3a)$$
$$I_3 = I_{34} + I_{32} \quad (3.3b)$$

On the basis of the now known volume flows and the known electrical power of the ventilators the heating of the air through the ventilators can be known.

$$T_2' = T_2 - Q_2/(\rho \cdot C_p \cdot I_2) \quad (3.4a)$$
$$T_4' = T_4 - Q_4/(\rho \cdot C_p \cdot I_4) \quad (3.4b)$$

With ρ = the density of the air in kg/m^3
C_p = the heat capacity of air in W/kg°C

From these measured temperatures follow the corrected temperature efficiency of the heat recovery unit on exhaust (η'_a) and supply (η'_t)

$$\eta'_a = (T_1 - T_2')/(T_1 - T_3) \quad (3.5a)$$
$$\eta'_t = (T'_4 - T_3)/(T_1 - T_3) \quad (3.5b)$$

These efficiencies can be corrected for the occurring leakages assuming a worst case leakage situation.

$$\eta'_{a,c} = (\eta'_a - F_a)/(1 - F_a) \quad (3.6a)$$
$$\eta'_{t,c} = (\eta'_t - F_t)/(1 - F_t) \quad (3.6b)$$

The largest of both corrected efficiencies is equal to the **energy efficiency** of the heat recovery unit, the smallest of the both corrected efficiencies is equal to the **sensible heat recovery efficiency**.

Theoretical the corrected efficiencies are equal to equal volume flows. In case of unequal volume flows the corrected efficiency can be measured backward to an efficiency for equal design volume flows, assuming that the K-value of the heat recovery block is almost constant. Herefor the ratio of the volume flows will be calculated at first:

$$Y_t = I_{34}/I_{12} \quad (3.7a)$$
$$Y_a = I_{12}/I_{34} \quad (3.7b)$$

and calculating the heat-transfer-number:

$$Z_t = (l_{34}/l_o) \cdot \ln [(Y_t \cdot \eta'_{t,c} - 1)/(\eta'_{t,c} - 1)/(1 - Y_t)] \quad (3.8a)$$

$$Z_a = (l_{12}/l_o) \cdot \ln [(Y_a \cdot \eta'_{a,c} - 1)/(\eta'_{a,c} - 1)/(1 - Y_a)] \quad (3.8a)$$

With l_o as the design volume flow. The efficiency of equal design volume flows is:

$$\eta_{t',g} = Z_t/(1 + Z_t) \quad (3.9a)$$

$$\eta_{a',g} = Z_a/(1 + Z_a) \quad (3.9b)$$

The procedure is theoretical only correct for back flow heat recovery ventilators in a worst case leakage situation but also appears to be good in practice for cross flow heat recovery ventilators.

4. Internal leakage measurement in test set up among working conditions.

4.1. Measure situation.

In figure 2 is given the measure set up for the determination of internal leakage among working conditions. The air supply and air exhaust holes are provided with a rulable airresistance (f.i. a butterfly valve) and with a supply for measuring air volume flows.
The rulable air resistances are being set up so that the real pressure distributions in the canals around the units arise.

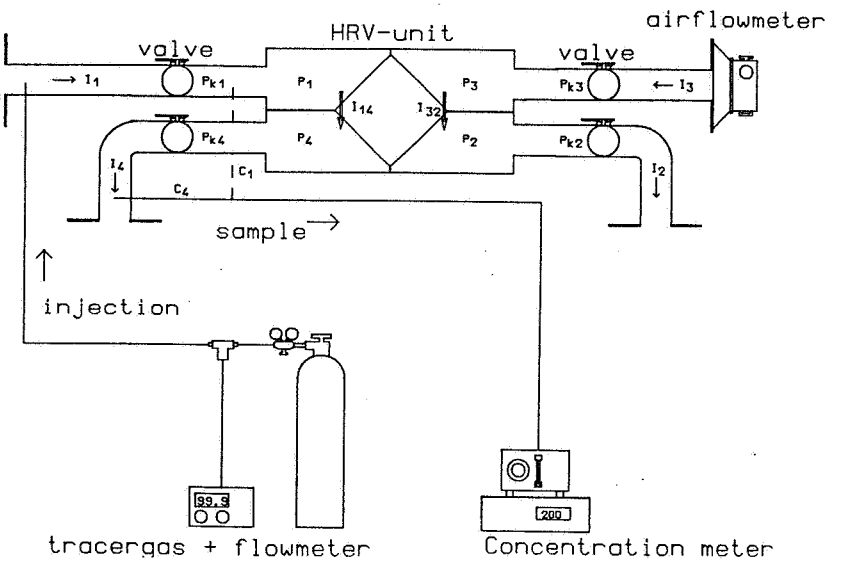

Figure 2. Measure set up

The exhausted volume flow (l_1) and the supplied volume flow (l_4) will be set up on practice values (225 m^3/h). The volume flows l_1 up to l_4 will be measured and also the pressures in the air canals P_{k1} up to P_{k4} and the pressures in the compartments of the heat recovery unit (P_1 up to P_4).
The resulting leakage flow $l_t = l_{14}$ from exhaust to supply will be determined by injection of a tracergas (N_2O) in the exhausted airflow.
After sufficient mixture the tracergasconcentration will be measured in the exhausted airflow (C_1) and in the supplied airstream (C_4).

If the external leakage can be neglected, the following resulting leakage flow will exist:

$$l_{14} = (C_4/C_1) * l_4 \quad (4.1)$$

This expression is only operative if the draw air volume flow I_{32} of draw to exhaust will be determined in the same way according:

$$I_{32} = (C_2/C_3) * I_2 \qquad (4.2)$$

4.2. Measuring results

The internal leakage is measured with 3 units (figure 3 up to 5). The measured resulting leakage flows; from exhaust to supply to the building (I_{14}) and supply from outside to exhaust out of the building (I_{32}) are mentioned for 2 measure situations in table 1.

Unit	measure situation	leakage flow [m^3/h]	
		I_{14}	I_{32}
A (fig. 2)	(regular)	< 2	17
	(modified)	< 2	11
B (fig. 3)	(regular)	< 2	< 2
	(modified)	< 2	< 2
C (fig. 4)	(regular)	3	22
	(modified)	< 2	11

Table 1. Internal leakage on the basis of tracergas measurement.

From table 1 it appears that leakage from exhaust to supply almost doesnot exist. This is accountable in the ground of the occurring pressure distributions in the unit (see figure 2).
Leakage from exhaust to supply can only be measured with unit A and unit B. The rest leakage in the improved situation is ascribed to a part leakage via the heatrecovery block and a part leakage along the sides of the heat recovery block and the cover. The leakage via the heat recovery block will be small. On the basis of measure information these leakage is about 3 to 5 m^3/h in case of 300 Pa pressure difference.

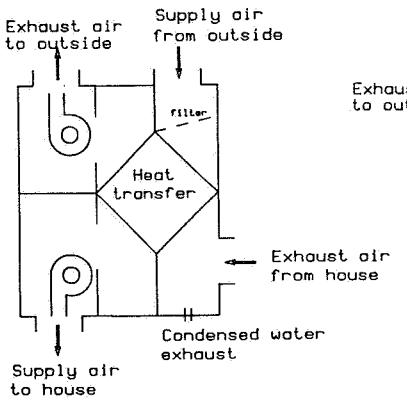

Figure 3: Unit A.

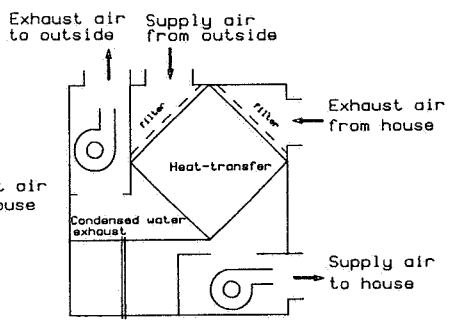

Figure 4: Unit B.

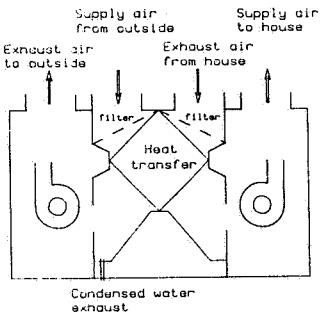

Figure 5: Unit C.

5. Proposal to standardization

From the measure results it appeared that the resulting leakage flow from exhaust to supply (I_{14}) can be reduced to less than 1% of the supplied airflow. As a provisional standard on the basis of the measurement results wil be used in [2]:

- the ventilation air supplied to the dwelling cannot consist of more than 1% exhausted dwelling air, as a result of **internal leakage** in the heat recovery unit.

From smell spreading and the loss of ventilator capacity the resulting internal leakage ($l_{14} + l_{32}$) is of importance. As a provisional standard is mentioned in [2]:
- the **total result internal leakage** among working condition is not allowed to be more than 2,5% of the total air volume flow. In case of a airflow of 2 x 225 m^3/h this is at most 11m^3/h.

6. Back flow heat recovery ventilator

6.1. Working principle and leakages.

Finally the application of leakage measurement with tracergas on the back flow recovery ventilator. The unit is concerning air capacity comparable with other heat recovery units for application in dwellings [3].
The air flow supplied by the unit to the measure dwelling was 149 m^3/h, the exhausted airflow was 184 m^3/h.

On the basis of the working principle (figure 7) of the unit 3 types of leakage can occur (see figure 6):
- leakage during the overturn of the shuttle valve ("short circuit").
- leakage through back flow of exhausted dwelling air from the canals and the accumulation mass.
- leakage between the shuttle valve in the final position ("steady" leakage).

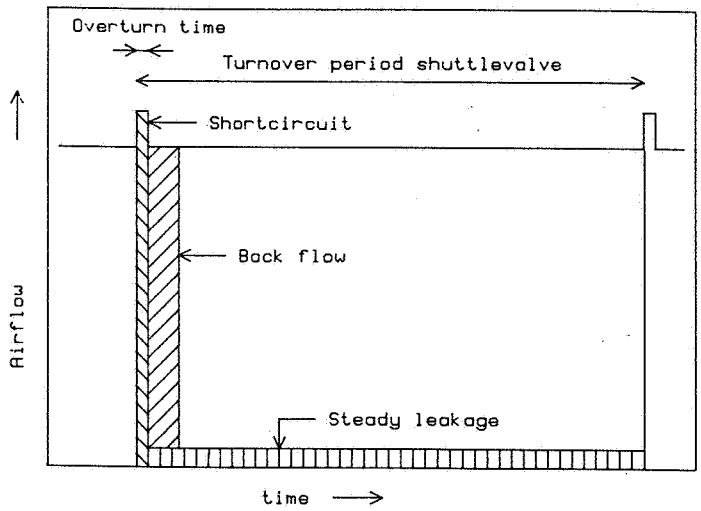

Figure 6: Possible occurring leakages.

The exhausted air from the dwelling will be blowed into the dwelling as a result of all 3 types of leakages. Except smell spreading, apparently these leakages also influence the efficiency of the unit.

6.2. Measurements

The occurring leakages are measured with the help of a tracergas. The tracergas (figure 7) is injected in one of the exhaust canals. The tracergasconcentration in the exhausted air is measured in the canal after the exhaust ventilation. From the relation of the

injected quantity tracergas and the measured tracergasconcentration in the exhausted air, the exhausted quantity is determined. Also the short increasement of the exhausted air quantity during the overturn of the shuttle valve is measured on this manner. Herefrom the occurring leakage is determined.

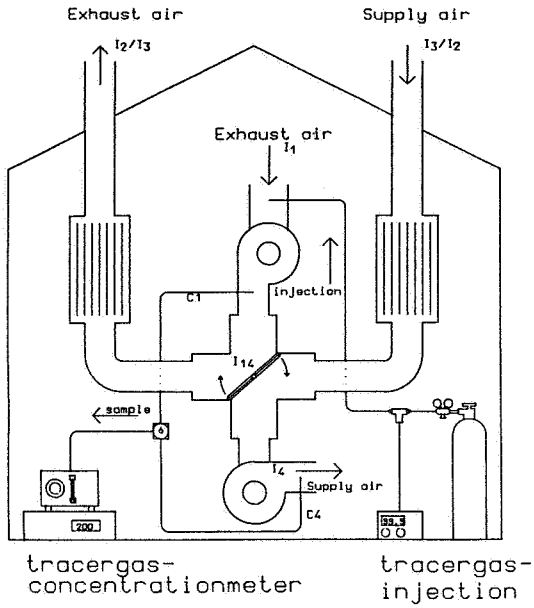

Figure 7: Measure set up.

The tracergasconcentrationmeter has a certain slowness. The rapid concentration changes during and after the turnover of the shuttle valve will be spread over a longer period. This has no influence on the average concentration which eventually is important for the determination of the leakage. Considering the minimal measure reach of the tracergasconcentrationmeter it appeared that less than 1% leakage along the shuttle valve takes place in the end position. The measured average leakage can be calculated back to the real leakage (table 2).

	time [s]	leakage flow [m^3/h]	average percentage [%]
leakage during the turnover of the shuttle valve	0,9	202	1,3 %
leakage through backflow of air from the canals	2,8	184	3,7 %
Stationary leakage via the shuttle valve in the end position	76	< 2	< 1 %

Table 2. The measured air leakage of exhausted inside air to supplied outside air, divided in time and quantity.

6.3. Efficiencies

The measured efficiencies of the heatrecovery unit can be corrected for the leakage. Herewith the following suggestions are made:

1. The measured efficiency can be corrected with the help of an average measured

leakage percentage.

2. The temperature of the leakage air is equal to the temperature of the exhausted inside air.

Both suggestions are justified [3]. Suggestion 2 means that it is assumed that these leakage takes place directly from the exhausted inside air to the supplied air of the dwelling. This is pointed out with the "worst case" situation because the influence of the leakage on the efficiency is at its maximum and therewith the correction on the measured efficiency is the highest.
The efficiency of the unit is measured during a period of 3 weeks. The measured average efficiency is a lineair equation (figure 8). Considering this efficiency as a function of the temperature difference ΔT between inside and outside air and corrected for the leakage and inequal supplied and exhausted volume flow.

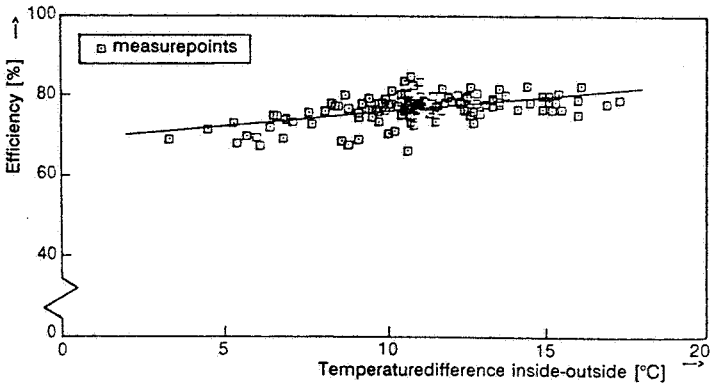

Figure 8: Measured efficiency (corrected for leakage).

6.4. Conclusions

From the measurements appears that the shuttle valve of the unit in the final position closes sufficiently to prevent leakage along this shuttle valve. The leakage during and short after the turn over of the shuttle valve is normal for the heat recovery principle and therewith unavoidable. The measurements have showed that these leakage can be estimated on the basis of the turnover time of the shuttle valve and the volume of the canals between the shuttle valve and outside. The unavoidable leakage percentage is about 2,4% in case of a minimal canal volume and dependent of the volume flows.

7. References

[1] Cauberg, J. and Gerwen, R. van: Detection of leakage in heat recovery units with tracer gas and the influence of leakage on the efficiency. Report 9939-1* Cauberg-Huygen Raadgevende Ingenieurs B.V., 1988 (in Dutch).

[2] Gerwen, R. van and Weevers, C: Leakage in heat recovery units: Field tests and proposal for standardization. Report 890332-1* Cauberg-Huygen Raadgevende Ingenieurs B.V., 1990 (in Dutch).

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* Research reports by order of the Dutch Agency for Energy and the Environment (NOVEM).

Apendix A.

Definitions apply in this paper:

- **Resulting leakage flow** (l_{14}, l_{32})
  The nett volume flow which comes via several ways eventually from the exhausted inside air in the supplied outside air resp. from the exhausted outside air in the supplied inside air.
- **Leakage fraction** (F_1, F_2)
  The part of the supplied outside air, consisting of exhausted inside air resp. the part of the exhausted inside air consisting of exhausted outside air. If the leakage will be mentioned in percents there will be spoken of leakage percentage.
- **Efficiency** (η_a, η_b)
  With efficiently is undoubtedly meant the temperature efficiency. This is the relation of the reached temperature difference and the largest temperature difference. This reached temperature difference can be measured in the exhausted and supplied outside air (η_t) or in the exhausted and supplied inside air (η_a).
- **Measured efficiency**
  The temperature efficiency measured on the basis of the measured temperature of the airflows without the heat recovery unit.
- **Temperature corrected efficiency** (η'_a, η'_b).
  The temperature efficiency measured on the basis of the measured temperature inclusively the effect of heating up through the ventilators.
- **Corrected efficiency** ($\eta'_{a,c}$, $\eta_{t,c}$).
  The temperature efficiency inclusively the effect of heating up through ventilators and the effect of leakage.
- **Energy efficiency**
  The relation of the recycled sensible heat and the maximal to recycle sensible heat considering the fact that the maximal temperature difference can only be covered by the smallest volume flow.
- **Sensible heat recovery efficiency**
  The relation of the recycled sensible heat and the maximal to recycle sensible heat considering the fact that the maximal temperature difference can only be covered by the largest volume flow.