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FILTERS FOR GASEOUS CONTAMINANTS: PERFORMANCE MEASUREMENT AND IMPACT ON VENTILATION SYSTEMS

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Synopsis

Filters for gaseous contaminants which are used inside HVAC systems are characterised by means of rated air flow rate, air motion resistance, trend of the mass efficiency versus time and holding capacity of the considered gas. The determination of the characteristics cannot do without the use of experimental activities, even though many aspects seem to be foreseeable through calculation models based on general laws. A test rig for granular media which uses toluene in small concentrations in the air is here presented.

1. Introduction

Gas filters are used in HVAC systems in order to separate the odours and gaseous contaminants that are present in the air. They are usually used inside thermal-hygrometric treatment units in order to decrease that part of the air which is renewed and taken from outdoors, while assuming that outdoor air is purer than indoor air. From this point of view, gas filtration makes it possible to decrease the energy demand associated to renewal air, but, on the other hand, they require more electrical power due to their resistance to air motion and an initial economic burden due to the investment, maintenance and replacement costs.

In order to take motivated decisions on the air-conditioning system, it is necessary to characterise these filters regarding as far as the performance is concerned: rated air flow rate, air motion resistance, separation efficiency and duration for representative values of the air flow rate, temperature and air relative humidity.

The rated air flow rate for fixed frontal dimensions depends on the face velocity: typical values are around 3 m/s and, for this reason, it is not possible to arrange the filtering media in flat layers because of the consequent excessive resistance to the air motion using the thickness that is necessary to guarantee acceptable duration of the filtering device. Gas filters surfaces are therefore extended [1] and the filtering material is arranged in such a way as to form a layer that is non-perpendicular to the axis of the duct and crossed by the air with a velocity which is lower than the frontal velocity by one order of magnitude.

Resistance to the air motion is measured by pressure drop. This does not vary in a measurable way during the technical life of a gas filter when the air flow rate is constant: there is therefore no final pressure drop to indicate the necessity of replacement.

The separation efficiency is the ratio between the mass flow rate of the gas held (separated from the air for a certain period of time) and the corresponding mass flow rate of gas entering the filter. The criterion to establish that a gas filter requires replacing is based on the minimum acceptable efficiency. The filter life duration and holding capacity of a gas derive from the above mentioned criterion and assume that the trend of efficiency versus time is known.

The data indicated above have been known for some time [2], in the case of various couplings between gases and filtering materials and are the result of research into gas absorption phenomena inside fixed beds made of porous materials. The theory is at an advanced stage of development and allows one to plan chemical plants for processing purposes. In the air-conditioning filter field, which is distinct from that of chemical plants, some gas filter manufacturers are able to correlate data in order to meet their customers' needs, and to foresee the characteristics, the mass and the arrangement of the material necessary for each specific application. Typical input data are: the gas that should be separated, its concentration and the air flow rate. The duration of life (e.g. 1 year) and the resistance to air motion are conventionally established, but hardly ever is it possible to

understand the criteria according to the choices made, which is probably due to understandable reasons of discretion.

However, this situation leads to a lack of diffusion of confidence among operators in the HVAC systems field and it explains why this paper considers the point of view of those who would like to use a gas filter, but who are not able to understand the common formulations of the principles of chemical engineering or willing to accept the results of an unknown calculation program used by the reseller of a product.

It is clear that from the point of view of plant management, it would be useful to have reliable and economic indicators of the trend of gas concentration downstream to the filter. From the commercial point of view, a standardised evaluation method for gas filters or, at least, for the absorbing material used inside the filters would be desirable.

2. Assessment method

In order to evaluate a commercial gas filter, designed to be used inside HVAC systems, it is necessary to first of all know the rated value of the air flow rate which is chosen on the basis of a compromise between the contrasting requirements of the air motion resistance and the life duration.

From the best comprehension of the filter functioning point of view, it is better to distinguish between the air motion resistance due to the shape of the filter from that due to the filtering material. The first depends on the previously mentioned requirement of surface extension and generates a pressure drop that is approximately proportional to the square of the air flow rate. The second may be reduced to the case of a flat layer crossed by an air flow rate with a macroscopically one-dimensional motion. It is possible to apply the considerations concerning beds of porous materials to this layer of material, thus one can conclude that pressure drop is proportional to the length and to the air flow rate, and it increases when the dimension of the material grains decreases. Therefore, for the sake of air motion resistance and electricity use, it would be favourable to use filters with large stretched surfaces and with thin thicknesses. However, it is necessary to ensure a reasonable period of time between one replacement and another.

The interval of time in which a gas filter absorbs has an insuperable theoretical limit (t^*) constituted by the absorption capacity of the material and provided by the relationship

$$t^* = \frac{m_f \cdot \left(\frac{m_a}{m_f}\right)^*}{\dot{V} \cdot c_M}$$

where:

m_f = mass of the absorbing material of the filter;

$\left(\frac{m_a}{m_f}\right)^*$ = ratio between the mass of the absorbed gas and the mass of the absorbent material;

\dot{V} = air flow rate in volume;

c_M = gas concentration in volume of the air upstream to the filter.

The ratio $(m_a/m_f)^*$ is a theoretical value in thermodynamic equilibrium conditions which expresses the maximum quantity which may be absorbed in the previously mentioned conditions. This depends on the nature of the gas, material and the thermodynamical

conditions: temperature and relative humidity of air are particularly interesting for HVAC systems, while pressure is that of the atmosphere. Moreover, concentrations are much lower (e.g. 1 ppmv) than those for which literature data are available (typically 1000 ppmv).

The previously mentioned theoretical data of life (t^*) is not of immediate practical interest because the acceptable values of downstream concentrations (c_V) are differently defined for each application but nevertheless must be $c_V < 0.1 c_M$.

In practice, a scientifically based, comprehensible and feasible criterion is necessary. For this purpose, it is necessary to know, even though it is not sufficient, the gas concentration trend downstream to the filter. On the basis of this trend and on the downstream air pureness requirements, it is possible to establish when is the right time to change the filter: for example, when the downstream concentration has reached a pre-established fraction of the upstream value.

Practical criteria for evaluating the necessary mass of an absorbing material and its life are based on such assumptions.

The trend of filter downstream concentration versus time [4] is represented by curves of an experimental origin [5] or calculated through mathematical models [6], [7]: it is however important to know its potentiality and limits.

These curves arise from the necessity of experimenting filter performance concerning a determined gas. In a laboratory, it is usual to make an air flow rate, in representative conditions, cross the filter in which the gas of interest is injected and measuring the upstream concentration (which remains constant) and the downstream one. Sooner or later, the downstream concentration begins to increase and, if one waits long enough, it reaches the upstream value. It is obvious that this trend is valid only in test conditions but, if these conditions are representative, the information obtained may be of great use in practice. When it is not possible to experiment each condition of interest, it is necessary to be able to extend the results to different conditions, that is, a model of the filter is needed. There exist models based only on physics and chemistry laws and which are also able to reliably describe cases of practical interest, moreover, there exist empirical correlations based on experience and these are vital to the current state of knowledge.

In fig.1a, a gas filter is schematically represented: a one-dimensional system in steady state condition is assumed from the air flow rate point of view. When the challenge gas is injected into the air, it is possible to obtain an upstream concentration which remains constant in time and uniform over the whole cross-section because of the one-dimension hypothesis. As soon as the gas interacts with the filtering material layer, a concentration profile is established (fig.1b) which shows the upstream value on the left while downstream the value is null. The profile then moves towards right maintaining an l length. Fig.1c represents an intermediate condition in which the absorption zone separates the saturated material zone from that of the still fresh material. The absorption zone has an l length that results from the equilibrium between the gas flow rate and the filter separating capacity. It is clear that the L length of the filter must be greater than this zone, otherwise a downstream concentration which is not null would be obtained. Fig.1d shows the condition in which the absorption zone reaches the end of the filter and, for this reason, the downstream concentration begins to be greater than the null value.

From the point of view of the utilisation of the material, it would be better if the absorption zone could be short, at the limit of null thickness, so that, when it reaches the right end of the material, every part which is on the left is saturated. The previous description

makes one think that a concentration wave would propagate inside the material with a certain velocity which is certainly much lower than that of the air (e.g. 0.03 m in 2000 h)

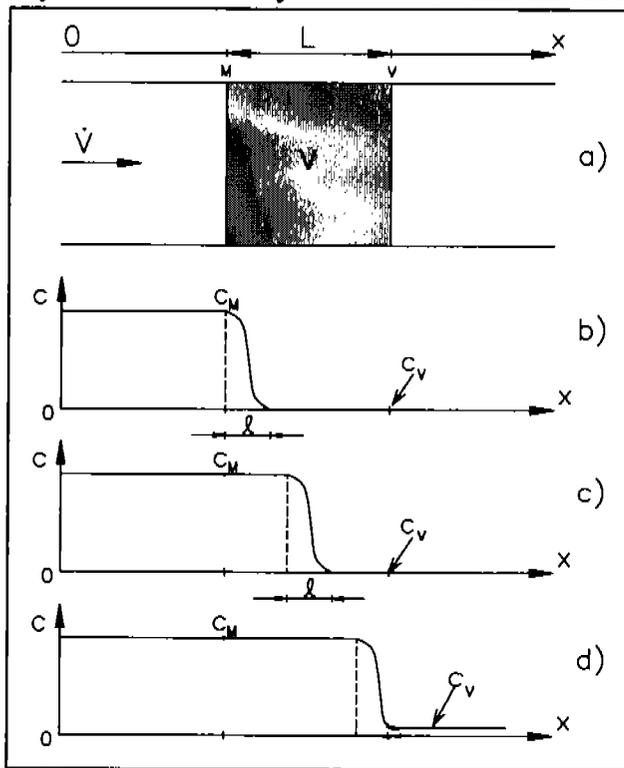


Figure 1- Concentration profiles along the filtering bed (length L)

- a) monodimensional (x) filter scheme (volume V)
- b) concentration profile - starting point (t_0)
- c) concentration profile - generic time instant (t)
- d) concentration profile - ending point (t_f)

results is given in figure 2. The curves of the flow rate allow one to distinguish two zones that correspond to the mass of the separated gas (m_a) and the mass of the unseparated gas as this has penetrated downstream, m_p , and which is equal to the difference between the upstream mass and the separated mass $m_p = (m_M - m_a)$. The check on the mass balance is simplified by using the average efficiency ($\bar{\epsilon}$) during the considered period of time and defined by the ratio between the separated mass and the injected mass over a determined period of time, and expressible versus efficiency through the following ratio

$$\bar{\epsilon} = \frac{m_a}{m_M} = \frac{\int_0^{t_f} \epsilon \cdot dt}{t_f}$$

The average efficiency clearly depends on the efficiency curve trend (which expresses the attitude of the material to absorb the gas) and on the integration period (which depends on the conventional choice of the downstream gas concentration that determines, when it is reached, the technical life of the absorbing material of the filter).

As far as the efficiency trend is concerned, the most meaningful quantity is the residence time, defined referring to fig.1 as

and which would determine the life time. In a generic instant, efficiency (ϵ) is defined as the ratio between the mass flow rate of absorbed gas (\dot{m}_a) and the upstream mass flow rate gas (\dot{m}_M) and is generally expressed by the concentrations as follows

$$\epsilon(t) = \frac{\dot{m}_a(t)}{\dot{m}_M} = 1 - \frac{C_V(t)}{C_M}$$

The breakthrough (P), instead, may be written as:

$$P(t) = 1 - \epsilon(t)$$

where:

c_M = gas concentration in volume in the air upstream to the filter;

c_V = gas concentration in volume in the air downstream to the filter.

The efficiency curve versus time is therefore obtained from the concentration curves which represent typical results of laboratory measurements. An example of such experimental

$$t_p = \frac{V}{\dot{V}}$$

where:

V = space occupied by the filtering material (ratio between the mass and the apparent density);

\dot{V} = volume air flow rate.

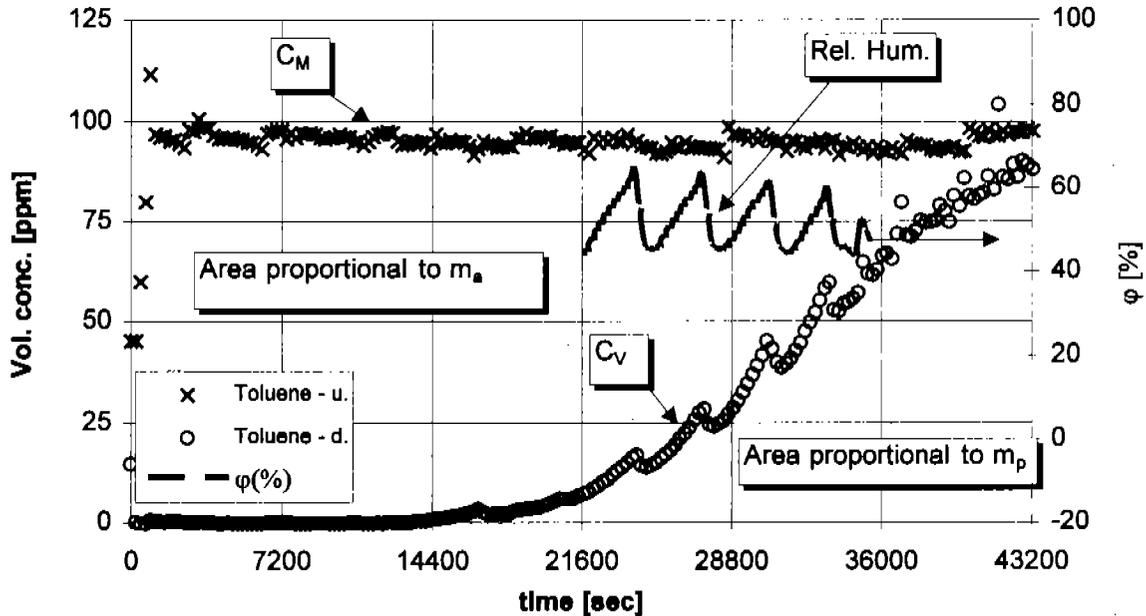


Figure 2 - Toluene volume concentration upstream (u.) and downstream (d.) the filtering material - Test conditions: $T = 24\text{ }^{\circ}\text{C}$ - $\phi = 50\%$.

This definition, which is typical of one-dimensional systems, considers the filtering material as being homogeneous. For modelling purposes, the residence time needs to be corrected by taking the maximum and the effective apparent density into consideration, in order to be more significant [7].

The residence time t_p is also equal to the ratio between the thickness of the filtering material (L) and the average velocity of air passing through. It has been considered that the residence time $t_p = 0,1\text{ s}$ is optimal: this data is presumably the result of experience in the HVAC systems field and would mean, for example, that if the air velocity is assumed to be 0.3 m/s , the layer of the filtering material should be $L = 0.03\text{ m}$ thick.

Upstream concentrations in the case of filters for HVAC systems are usually low and the resistance to the transport of the mass is concentrated in the limit layer: this fact allows one to obtain simplified relationships for the case of interest.

Upstream filter concentrations are low because they are related to atmospheric and indoor air. Every study on this subject agrees on the fact that efficiency depends on the value of the upstream concentration and increases with it.

In order to explain this dependence, it is necessary to remember that absorbing materials are made of porous pellets of some millimetres in size. Inside each pellet are macropores, whose size is greater than 10^{-8} m , from which micropores, whose size is smaller than 10^{-8} , and often just a little larger than the molecular ones, spread out. The absorbing process inside the micropores causes the molecules to be so close to one another that they form a liquid which

completely fills the micropores, while the molecules inside the macropores only cover the walls. It can be imagined that after the concentration increases liquids form and, therefore, the possibility of absorbing increases.

The transport of the mass from the air to the walls depends on the difference of the concentrations. With a thermal analogy, it is possible to say that the gas particles inside the air flow have to overcome two physical resistances in order to reach the wall and possibly one chemical resistance in series: the first through the limit layer, the second corresponding to the wall surface, and the third one in the chemical reaction with a reagent, if any. In this case, the first resistance usually prevails while data for the transport of the mass coefficient are unavailable.

The gas that should be separated must be representative of the actual applications: a distinction is made between two main categories (organic and inorganic contaminants) is made which corresponds to outdoor and indoor contaminants. As a limited number of gases has to be chosen, nitrogen oxide and sulphur oxide are considered, for example, for the first group, as they are particularly representative of what occurs in urban and industrial environments (applications that are more considered nowadays are those for expensive computers inside petrol refineries and those for museums). Among the organic contaminants toluene is considered as, from among the various VOC (volatile organic compounds), it has an intermediate boiling temperature. This boiling temperature affects the formation of liquid in the previously mentioned micropores.

The interaction between a gas and a certain filtering material depends on the air characteristics, in particular on its pureness, temperature and relative humidity.

In some cases it is perhaps possible to take all the above mentioned variables into account in a calculation model. However, the need for data on the transport of mass coefficients, equilibrium thermodynamic conditions at low gas concentrations and the motion inside granular beds [6] still remains. On the basis of the present situation it is necessary to proceed with an experimental method having to be satisfied with tests in only some conditions which are considered meaningful and being obliged to renounce a global vision of the whole subject.

If a standardised test method could be used it would be possible to compare different commercial products.

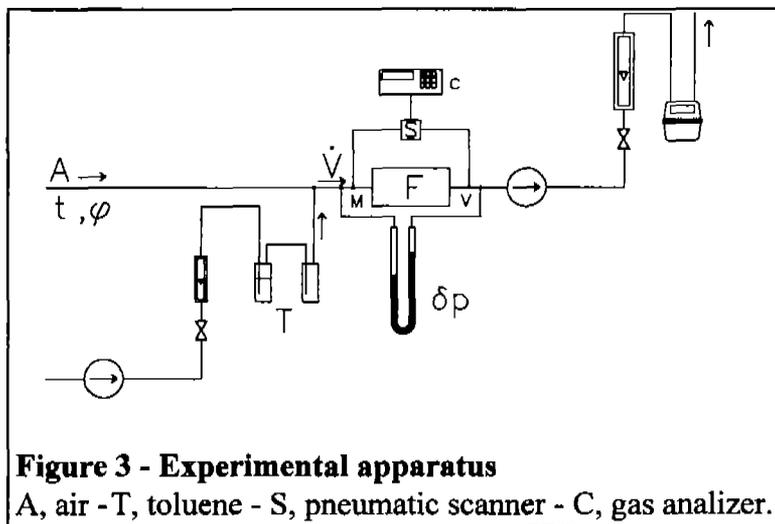
An experimental test rig which is suitable for characterising materials used to absorb gases is described in the following part. The small scale test allows to characterise the material but the results obtained in such way are not necessarily valid for filters made with this filtering material.

3. Experimental test rig

The complete test rig is sketched in fig.3: the filter is made of a porous material layer whose diameter is 0.05 m. The layer is crossed by an air flow with a 100 ppmv upstream concentration of toluene. The thickness of the layer of the filtering material (0.03÷0.1 m) is chosen in such a way as to obtain a residence time $t_p = 0.1$ s with an air velocity 0.3÷1 m/s.

The air for the test is taken from an air-conditioning unit where it is possible to set the values of temperature and relative humidity; this air is derived from a fan which maintains the duct below the external pressure.

The filter under test is crossed by an airflow rate in prefixed conditions during a preliminary period of time in order to "condition" it. The concentration of water vapour is measured upstream and the constancy and consistency are checked in relationship to the



prefixed value of relative humidity set on the air-conditioning unit.

The trend of the concentration of water vapour is checked in order to find out when the equilibrium conditions are reached. The time necessary for this operation may be very long (24 h) and this fact implies practical problems inside a laboratory. On the other hand it should be remembered that

absorbent materials have such large relative surfaces ($1000 \text{ m}^2/\text{g}$ order of magnitude) that they are very difficult to obtain and guessed at.

The sampling is made upstream and downstream to the filter under test by means of two flexible pipes made of non-reactive material which lead to a distributor. This distributor switches between the upstream and downstream line every 60 s and sends the samples to an analyser which gives the carbon dioxide, water vapour and toluene concentration values. During this phase the absence of toluene in the air is controlled. At this point it is possible to inject the challenge gas, which, in the present case, is a superheated steam.

Toluene is liquid at ambient conditions as at atmospheric pressure the temperature of saturation is $110 \text{ }^\circ\text{C}$. It is contained in a glass recipient that is placed in a thermostatic bath which is kept at a temperature lower than the ambient. A small airflow rate is bubbled through the liquid so that a saturated vapour which is being superheated exits from the first recipient and passes through the second, which is at an ambient temperature. The mixture of air and toluene vapour is sucked into the main duct in which it is mixed with air. The upstream concentration is kept constant by controlling the temperature of the bath and the air flow rate, which is bubbling.

The trend of the concentrations upstream and downstream to the filter is obtained as shown in fig.2 where an example of experimental data of concentrations in conditions which can be interesting for HVAC systems is reported. In this case the temperature is constant ($T = 24^\circ\text{C}$) and the relative humidity varies in a cyclic way over a 50% value. The absorbent layer is made of commercial activated carbon and its length is $L = 0,06 \text{ m}$ while the air has a residence time of $t_p = 0,1 \text{ s}$ (challenge concentration of Toluene about 100 ppm).

4. Experimental results

Adopting the experimental apparatus described in the previous paragraphs, some tests have been performed. This first experimental campaign was aimed, mainly, to evaluate the performances of the measurement test rig and to investigate the capability of the system to perform sensitivity analyses on filtering media. The working activity is still under way, however, some preliminary results are already available.

Figure 2, as mentioned before, shows a typical filtering media behaviour and underline the critical factor represented by the influence of relative humidity, ϕ , on the filter efficiency.

The penetration of toluene downstream to the filter begins after 10000 s, that is, a

perceptible increase of concentration c_V is obtained. In particular it is possible to observe that the downstream concentration increases in correspondence to the relative humidity peaks. This phenomenon shows that the test rig is sensible to the variation of at least one of the important quantities. Precision is required in the case of the balance of the toluene mass and in the present case a mass $m_M = 21,8$ g of toluene over 43000 s was injected, while maintaining an approximately constant upstream concentration of $c_M = 100$ ppmv in the air flow. The increase of the mass of the filter corresponds to the c_V curve (whose integration in time produces a held mass of $m_a = 16$ g). The average efficiency in the interval of the total time considered is $\varepsilon = 0,73$. The trend of the downstream concentration curve is the general trend for penetration (breakthrough) curves to which, in the case of fig.2, the disturb produced by the variations of relative humidity is overlapped. This can be explained by the absorption of the water molecules by the porous surface which is therefore less available for toluene absorption thus reducing the efficiency. The phenomenon is relevant when $\varphi > 50\%$ as in these conditions the absorption in equilibrium conditions greatly increases [7]. Examples of breakthrough curves are shown in figures 4, 5 and 6. In these charts is possible to see the influence of the filtering bed thickness, relative humidity and test gas concentration on the filter performances .

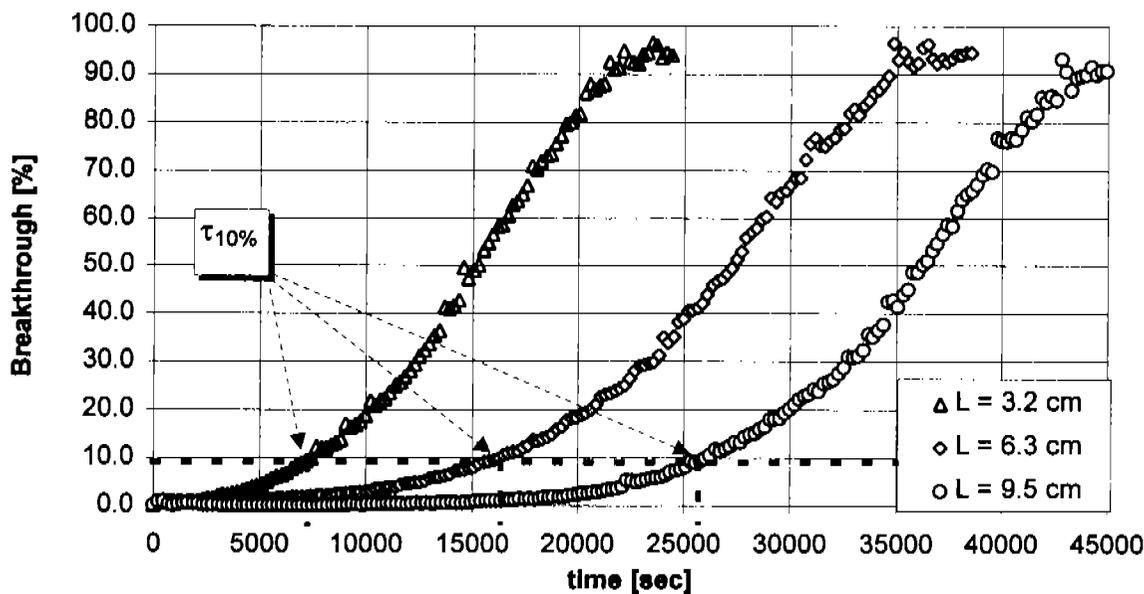


Figure 4 - Breakthrough curve - $T = 23^\circ\text{C}$, $\varphi = 50\%$ - Influence of bed thickness, L .
 $(\tau_{10\%} = \text{breakthrough time corresponding to 10\% of penetration})$

The usefulness of these curves, which can be obtained in the laboratory, depends on the realism of the conditions. The weakest point is represented by the high upstream concentrations (100 ppmv in order to not have tests that last too long) but relationships which make possible to correct this distortion exist [4].

Figure 4 refers to constant air temperature ($T = 23^\circ\text{C} \pm 1^\circ\text{C}$) and relative humidity ($\varphi = 50\% \pm 3\%$); it is possible to see that the filter efficiency strongly depends on parameter L and, in particular, it increases increasing the bed thickness. On the opposite, charts on figure 5, related to a fix bed thickness of 6.3 cm, point out the weak influence of relative humidity φ , on the filter behaviour. This fact may appear in contrast with fig. 2, however, it must be kept

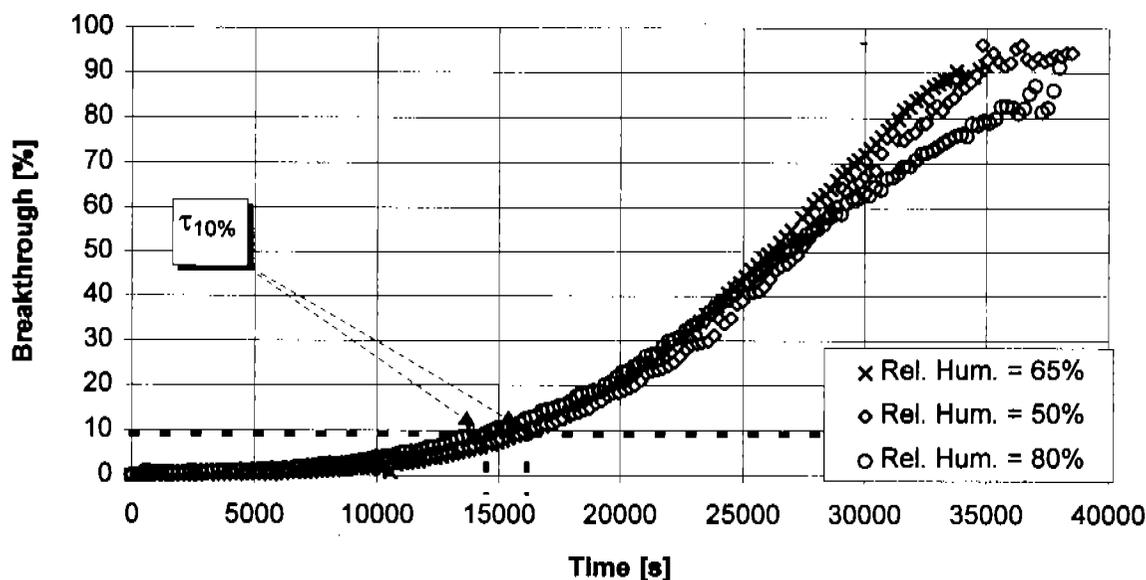


Figure 5 - Breakthrough curve - T = 23°C, L = 6.3 cm - Influence of relative humidity.
 ($\tau_{10\%}$ = breakthrough time corresponding to 10% of penetration)

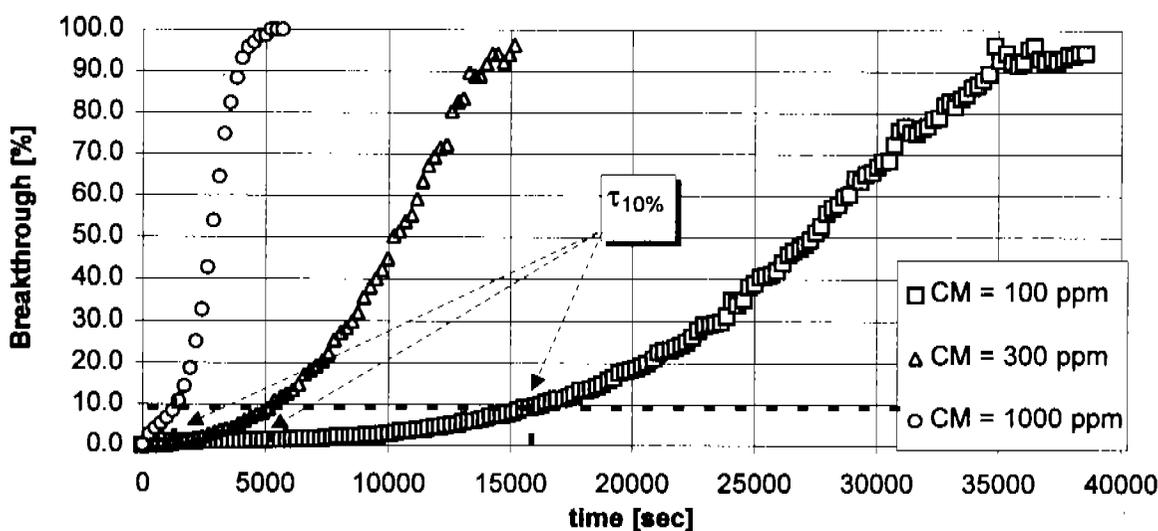


Figure 6 - Breakthrough curve - T = 23°C, L = 6.3 cm, $\phi = 50\%$ - Influence of upstream test concentration.

in mind that these last tests have been performed on “pre-conditioned” filtering media and hence the water vapour has already been absorbed by the filter and is at the equilibrium during the measuring period.

For what concerns the breakthrough time, a weak point is represented by choice of the allowable downstream concentration. The data available in fact are based on very different conventions, that is, t_f is determined in each case in correspondence to $c_f/c_M = 0.005$ or 0.01 or 0.1 . In order to reduce this confusion, which certainly does not help the operator, it is necessary to establish the time duration over which it is possible to calculate the concentrations to be matched with the acceptable threshold values [8]. Figure 7 and 8 show

breakthrough times related to a C_V value equal to 1%, 5%, 10% and 25% of the C_M value.

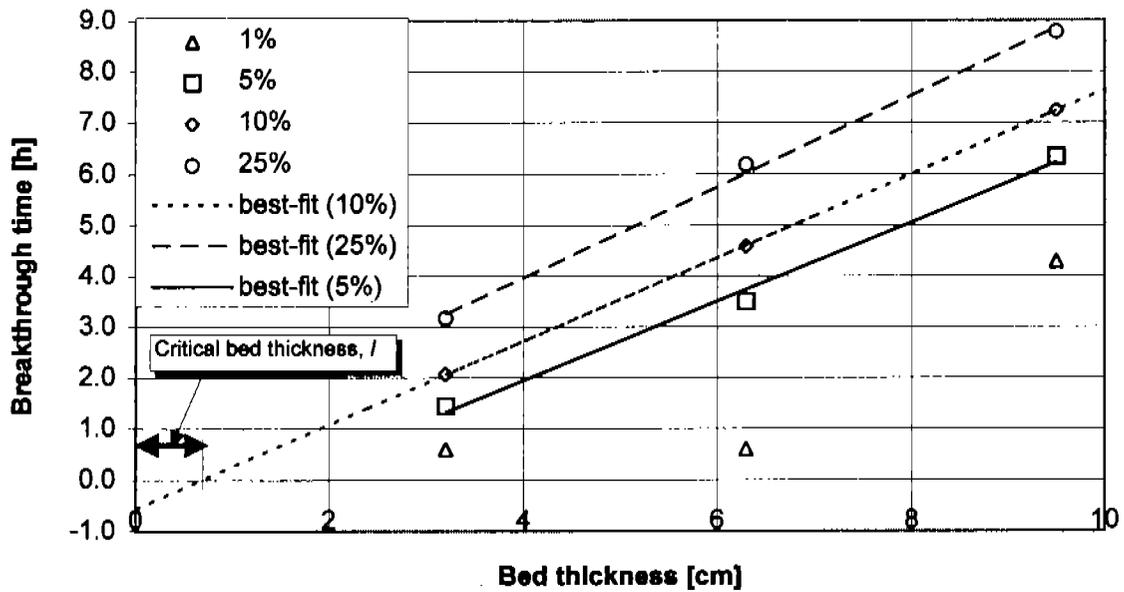


Figure 7 - Breakthrough time vs. bed thickness, L - test conditions $T = 23^\circ\text{C}$, $\phi = 50\%$

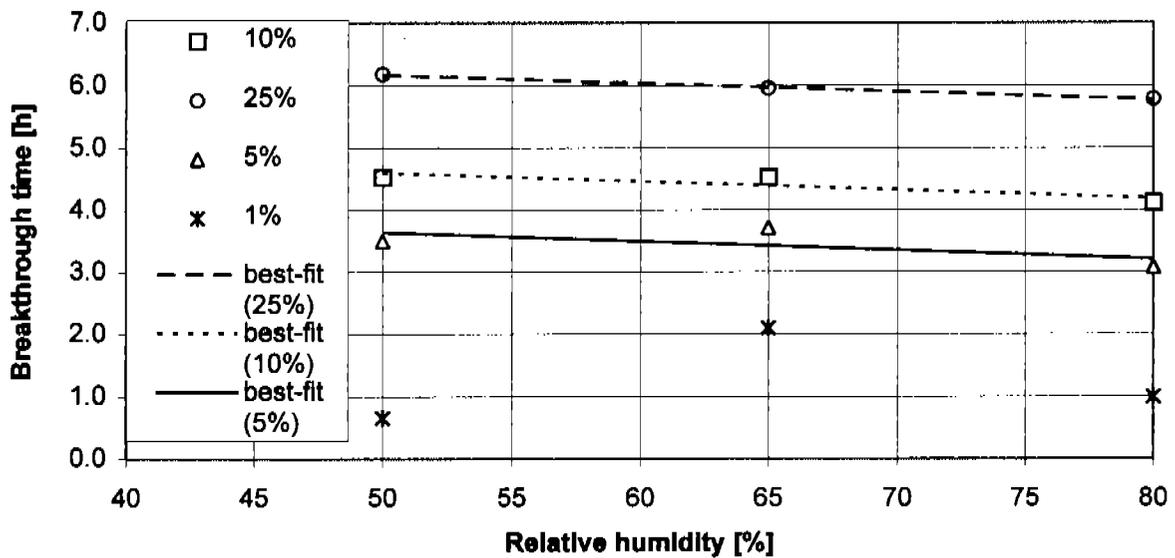


Figure 8 - Breakthrough time vs. rel. hum., ϕ - bed thickness $L = 6.3$ cm, $T = 23^\circ\text{C}$

In particular figure 7 points out the profile of τ vs. the bed thickness, L , while curves of figure 8 show the same parameter vs. the relative humidity. Data related to $\tau_{1\%}$ seem to have poor reliability for both cases. This is, probably, due to the influence of the environmental background concentration that, in this case, has the same magnitude of C_V value. For other values of τ , instead, a striking linear trend is found ($R^2 > 0.9$) in the case of figure 7. This is in good agreement with theoretical models [5]. It is possible to see that the breakthrough time strongly increases with L . Furthermore, from the knowledge of the slope of the best-fit curve is possible to determine the filtering media dynamic adsorption capacity N_0 . In the case of

$\tau_{10\%}$ it follows $N_0 \approx 8 \cdot 10^{-2}$ g of toluene per cm^3 of activated coal. This means 0.16 g of toluene per g of coal (the experimental value, obtained by means of weigh measurements, was 0.11 g of toluene per g of coal). Relative humidity, instead, (fig. 8) shows, once more, to have a weaker influence on the breakthrough time (at least in the field of value lower than 80%). In these case, moreover, the results are spread around the linear trend (R^2 varies from 0.43 up to 0.99), in particular for what concern the lower values of penetration (1%, 5%). In the end, the breakthrough time (10%) determined from figure 6 shows the filter performances as function of the upstream concentration. A comparison between experimental results of fig. 6 and the breakthrough times assessed by means of the Nelson and Correia model [4] has pointed out a systematic over-estimation of the theoretical model (between 30% to 60%)

5. Conclusions

At the moment there is a growing commercial interest in gas filters used inside HVAC systems. In order to allow a comparison between different products it would be useful to have a standardised test method and above all a calculation method for the life time which could realistically take the situation in Europe into account. In particular, the choice of the downstream concentration (C_v) to be used in order to assess the filter life is still a critical issue. In fact, if the concentrations are instantaneous it is necessary to replace the filter as soon as the limit condition is reached and the life time could thus be too short. If the concentrations are calculated over the average life times assumed for commercial products (usually 1 year) there is a relatively long period of time in which the instantaneous concentration goes over the limit value even though the average still has not reached this value. This point is here considered to be very important in order to allow a widespread and effective use of gas filters. In order to develop the independent knowledge inside Italy it would be useful to build a test rig to characterise materials, which could allow one to obtain experimental results in well defined conditions of temperature and humidity of the air which contains a low concentration of toluene. From the research point of view many efforts have already been made but there is some space left for the difficult subjects of mass transport, equilibrium conditions at low concentrations and motion resistance inside granular beds. In the end, experimental results obtained so far seem to be satisfactory and, even if some improvements of the test rig are still necessary, the measurement procedure allows fast and reliable assesment of filtering media performances.

5. References

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