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EXPERIMENTAL DETERMINATION OF THE PERFORMANCE OF AIR FILTERS FOR GENERAL VENTILATION

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Synopsis

Filters used for general ventilation are mass produced and tested by type at rated airflow rate in order to determine the evolution of the pressure drop and the efficiencies during an artificial and shortened clogging process. For filters of better quality it is necessary to evaluate the efficiency concerning fine dust: the traditional atmospheric dust spot efficiency method is now being substituted with an innovative method which allows one to determine the fractional efficiency versus the particle diameter within a 0.2÷3 μm range. Some examples of comparative assessment of commercial filters are here provided, taking the requirements of HVAC systems into account.

1. Introduction

Air filters used inside HVAC and for gas turbine systems are usually made up of layers of fibres [1]. These fibres are artificial, made of glass or organic material, and should have a diameter as small as possible, since the efficiency increases as their diameter decreases[2]; with fibre glass it is possible to reach diameters of about 1 μm, while, with synthetic materials, the diameters at the moment are usually larger and sometimes the efficiency is improved using adhesive substances or an electrostatic charge.

The fibres are arranged in such a way as to form a layer of variable thickness, from 1 to 10 mm, which, when it is fitted to form a flat filtering surface, provides the most suitable filter for research purposes as its geometry is uniform and simple. The data obtained in this way characterise the filter media and are used when material manufacturers and filter manufacturers are in touch; they are however usually more interesting for researchers than for the end users.

Commercial filters are seldom flat as the air velocity inside the ducts is in the order of magnitude of meters per second, while the most suitable velocity for filter media is an order of magnitude lower. For this reason, filters have a frame so that they can be placed in the ducts and also a net filtering surface which is much larger than that of the inlet (which is called frontal surface). Filters therefore do not usually have a flat shape and this fact, together with the presence of the frame, produces an air motion that is not one-dimensional. This does not help one to understand the phenomena which occur inside filters, even though it is commonly supposed that the air flow occurs in a steady state. On the other hand, a flat geometry would cause a too high resistance to the motion and a too short life of the filter.

Commercial products set their performance in order to cause a pressure drop, when the filter is clean, in the 10÷100 Pa range, and, at the moment of replacement (after 6÷12 months of life), can be in the 250÷450 Pa range. The value of the pressure drop is about the same as the other components in the air handling unit and its variation is compatible with the characteristic of the fan, in order not to cause significant airflow rate decreases or a too high energy consumption.

From the user's point of view the fractional efficiency is related to the class and, therefore, to the commercial product cost. A very small part of the cost is due to laboratory test costs which ensure the quality of the industrial products and their classification. These are type tests, that is to say, they are made on a sample which is considered to be representative of the whole mass-production.

The project engineer in charge of choosing a filter should correlate the specifications to the application he is dealing with. In theory, he should know the dimensions and concentrations of the solid particles and, at the same time, how they are filtered by the products available on the market. For this reason, it is becoming necessary to qualify filters, also using fractional efficiency, that is, efficiency in number per classes of dimensions in which it is possible to subdivide the atmospheric dust.

The filtration theory [2] does not allow one to correlate measurable characteristics of a commercial filter to its performance in function of a quantity of particles with known dimensions. The theory provides the fractional efficiency value of a single fibre for each filtration mechanism and the combined effect of two mechanisms for one fibre. The effect of many fibres can be taken into consideration in order to calculate the resistance to air motion in the case of a clean filter, but not in order to foresee the fractional efficiency value, especially when the fibres are of variable sizes and arrangements and when they are already mixed with dust.

Fractional efficiency should therefore be determined by experimental means.

At the end of their technical life, filters become waste material that can be compared to urban solid waste, and therefore have to be disposed of. They are usually sent to a waste disposal yard or burnt in an incinerator: the disposal of air filters is a problem particularly in the case of gas turbine systems because of the volumes involved, thus, the possibility of incineration is beginning to be taken into consideration and, at the same time, the behaviour of commercial products to fire. In theory, it would be better to have non-flammable filters in order to prevent fires and, at the same time, easily incinerable filters in order to dispose of them without problems.

2. Experimental results

The filters here considered were chosen in order to be representative of the availability on the Italian market and are partially described in the table where they are marked by a number: even though the manufacturer's name and the designation of the product have been indicated, this would still not be enough to clearly identify the filter.

From a scientific point of view, the information that would be missing is: the diameter and the arrangement of the fibres, the characteristics of the binder (if present) and the apparent layer density (linked to the packing fraction). These data are necessary, even though they are not sufficient, for many cases where an effort has been made to apply the theory, and the end user and the HVAC system designer are not usually interested in this information. However, it is necessary to remember that, judging from technical and commercial brochures, the uniformity of mass-produced filter characteristics is not known and for this reason it is not possible to predict which performance variations are possible within seemingly equal mass-products.

As is known [3], filters are tested while trying to reproduce conditions that are representative of those of real life inside the laboratory (fig.1). The clogging process is carried out using synthetic dust which simulates natural dust (inorganic fraction and organic fraction, subdivided into carbon black particles and cotton linters). The concentration used during the laboratory test (at most 70 mg/m^3) is much higher than that present in outdoor air (0,005÷3 mg/m^3) in order to make the clogging process faster. Arrestance measurements are performed during this process, comparing the mass held by the filter to the injected one. The arrestance (A*) measurement is not very meaningful for F class filters (fine dust) according to the European classification and used in widespread applications, as it produces arrestance values that are close to one, in other words, the injected dust is completely held by the filter at least as can be observed on the basis of the mass measurements, and which can be seen in the

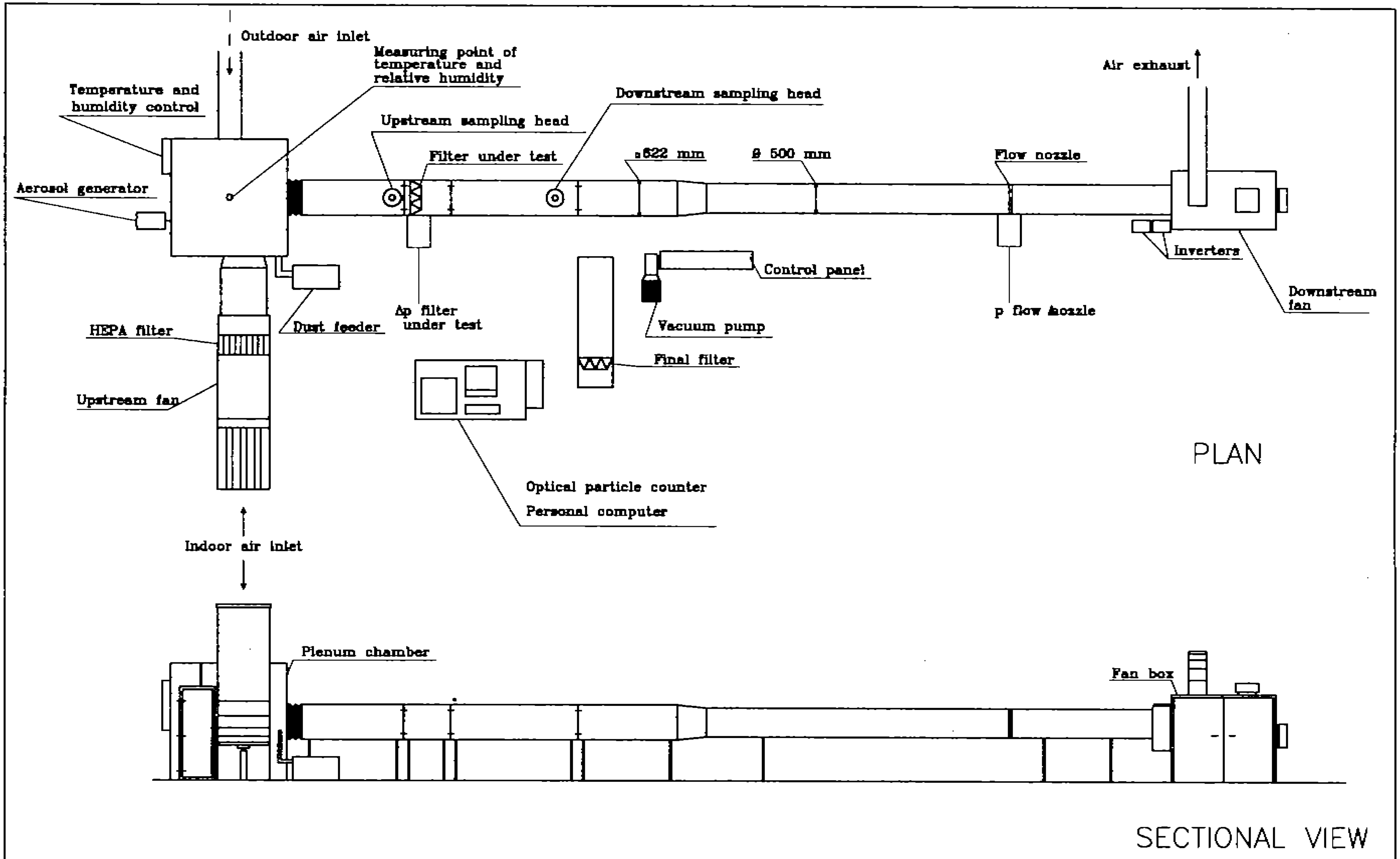


Figure 1 Test rig and set of instruments

example of fig.2a. This fact does not imply that F class filters offer uniform performances, as the mass measurements are not able to evaluate the ability to stop and hold the particles of a smaller size. It should be noted that a particle of 0.1 μm diameter has a mass equal of one millionth of a 10 μm diameter, thus smaller particles should be detected using other methods.

Up till now a method based on atmospheric dust dirtying capacity has been used and, even though this varies, depending on the place and on the time of the day, the dirtying capacity ratio between upstream and downstream of the filter being tested does not change. The so-called dust spot efficiency method consists of sampling the outdoor upstream and downstream air of the filter being tested and evaluating the opacity of the stain left on a small filter of white paper which is able to hold all the particles that are suspended in atmospheric air. It is possible to obtain a dust spot efficiency through a light transmission factor, which closely depends on the filter being tested and, at the same time, is greatly independent of the place. A dust spot efficiency value is thus obtained that is conventionally defined which seems to correspond to a superficial global efficiency, that is, based on the equivalent area of the particle surface.

The dust spot efficiency method is rather labour demanding, requires a great deal of time, above all for high efficiency filters and for places with low atmospheric dust concentrations: in practice, it determines the whole test duration of a filter that can last as long as a week. At the same time it provides a group of progressive values and an average dust spot efficiency value (see for example fig. 2a). However, this does not provide information on the size of the dust particle and on the fractional efficiency corresponding to the size classes of greater interest for F class filters, that is, between 0.1 and 5 μm.

This is the reason why the presently used test method has been updated [4] and the dust spot efficiency test has been replaced while the artificial clogging process with synthetic dust has been left unchanged. Instead of atmospheric dust, completely filtered air and an artificial aerosol, which contains a large number of particles in the 0.2÷3 μm size range have been used. By sampling the upstream and downstream air of the filter being tested, it is possible to measure the concentration, in number of particles, for the various size classes: a particle counter is required, that is, a much more expensive instrument than those used for the dust spot efficiency test. However, the measurement is performed in a few minutes and a group of data is obtained such as that shown in fig.2b.

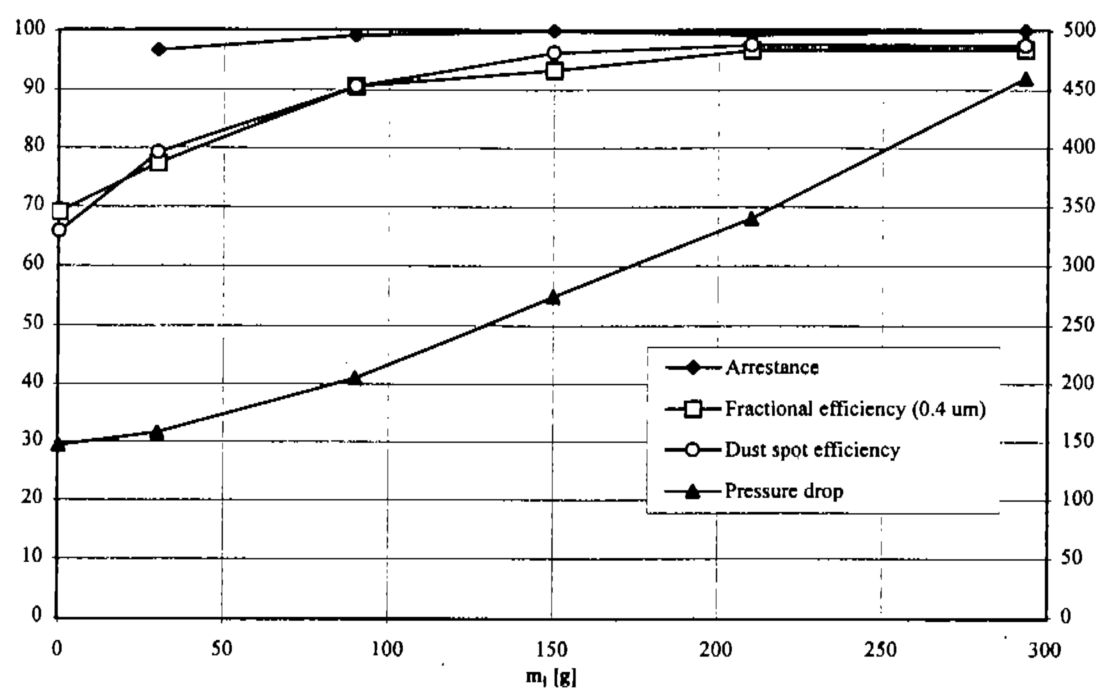
Systematic tests on commercial filters have been performed using the test rig available at the Department of Energetica at the Politecnico di Torino, adding this new method which has negligible impact on the filter being tested, so that, in fact, it has been simply been used alternating with the traditional method.

The filter media used are fibre glass and synthetic fibres. The different shape of the filters includes "pockets" of different kinds. "Pockets" is the generic name of the surfaces stretched according to the way in which the filtering material is arranged: they are called self-supporting when they are dihedrals formed by mini-pleated paper in fibre glass with a binder. The "pockets" are called non-supported when they are formed by folding and sewing a layer of fibrous material; for one of the tests here presented the initial flat layer has been folded in the laboratory and arranged on a W-form frame (W filter) which was designed and constructed for testing generic filter media (fig.3).

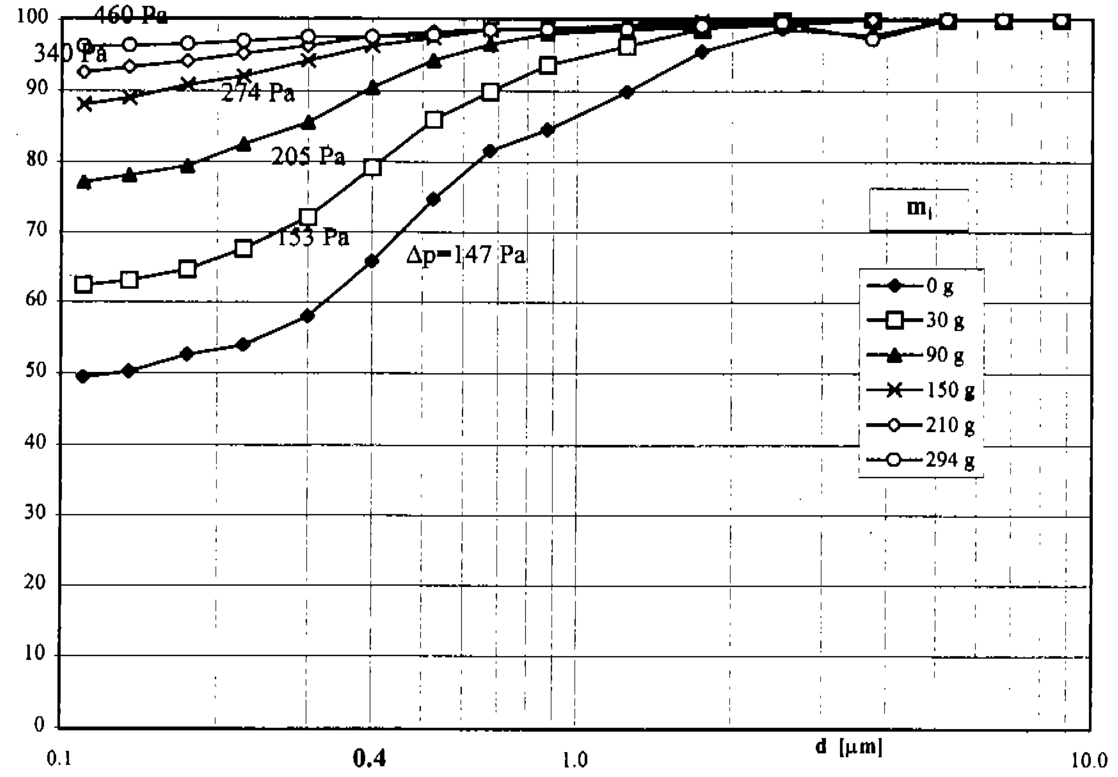
The area of the filtering surface (A) is equal to 1 m^2, in the case of the W filter, and it is much larger in the other cases; it does not have a close correlation to the filter mass (m_f), because of the presence of the frame.

Figure 2 Performance of filter n. 1 (see table)

a) Arrestance (A^*), dust spot efficiency (E), fractional efficiency (ε) for d=0.4 µm, pressure drop (Δp) versus the mass of the synthetic dust injected (m_i)



b) Fractional efficiency $\varepsilon(d)$ versus diameter d of liquid particles during the artificial clogging



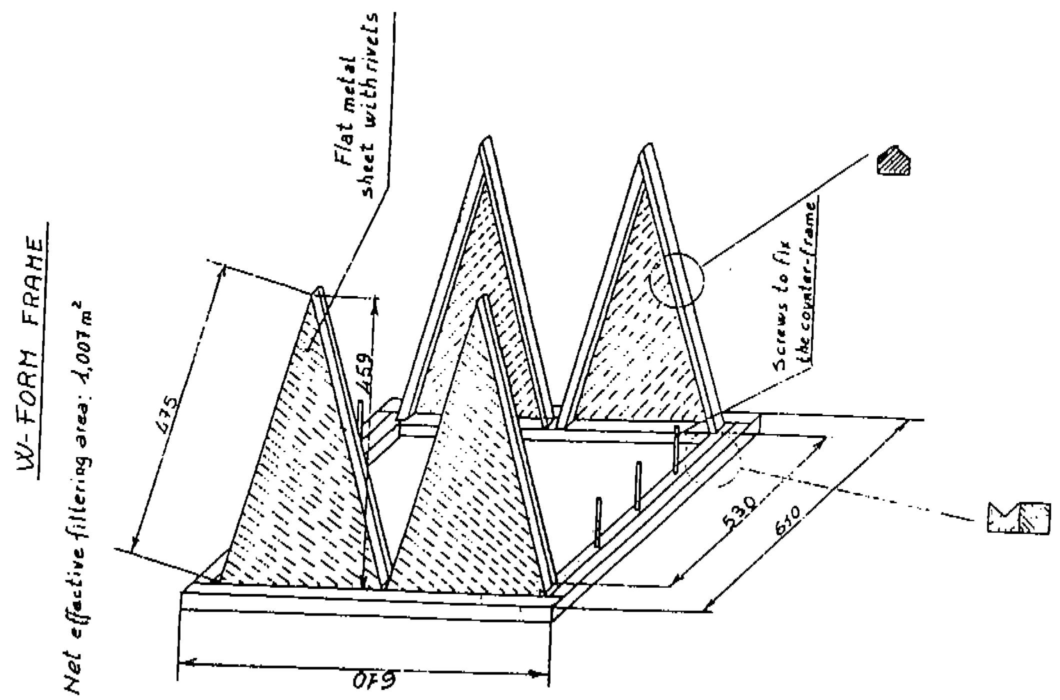


Figure 3 - W-form frame for testing filter media

The rated airflow rate of the filter ($\dot{V}_n$) is that which is indicated by the manufacturer and reflects its commercial policy: a high airflow rate corresponds to a greater filter utilisation and to a shorter life in case of the same final pressure drop or to a higher energy consumption for ventilation for the same life of the product.

The crossing air velocity (w) of the filtering material is of the order of decimeter per second while the face velocity in the filter (calculated in the frontal section with area A'=0.36 m^2) is of an order of magnitude that is greater for commercial filters; the W filter is an exception, as far as the surface and airflow rate is concerned, while it has a realistic value for w.

The initial pressure drop (Δp_i), that is, with a clean filter and at rated airflow rate, indicates the flow resistance that the air faces while crossing the filter; it is worthwhile to remember that the resistance to the flow motion is partly due to the material and partly due to the geometry of the filter, and that this resistance expresses an overall effect which does not necessarily correspond to the local situation.

The geometry being three-dimensional, it is possible to have non-uniformity of the air distribution, even when the filter is clean; this effect would of course increase during the clogging process.

The initial dust spot efficiency value (E_i) is the most important data for filter classification. According to the current European standard criterion, if E_i>20% the filter is an F class filter, that is, suitable for fine dust; in the other case it is classified as G, that is, suitable for coarse dust and therefore intended for use in less demanding applications.

The initial efficiency in number (ε_i) is obtained with the new method (see fig.2b, lower curve); the value entered in the table refers to the single size class around the diameter of the particle d = 0.4 µm.

The mass (m_a) of synthetic dust collected over the whole test, that is, when the final pressure drop was reached at the rated airflow rate, expresses the filter dust holding capacity. Also in this case, the value should be considered as an average value:

- in space, because it is not clear whether the filtering surface is clogged in a uniform way;
- in time, because the part of the injected dust which is held results from the combined effect of the dust that immediately passes through the filter and that of the dust which is first stopped and then released.

The final dust spot efficiency (E_f) is the value which is obtained at the final stage of the whole test when the final pressure drop is reached at the rated airflow rate (fig. 2a).

The final efficiency in number (ε_f) is entered only for a size class around $d = 0.4$ μm and is obtained with the new method. In fig. 2b, the upper curve describes the fractional efficiency trend at the end of the filter clogging process carried out with synthetic dust.

It is necessary to point out that the experimental data here presented were obtained by testing one sample for each filter; if the tests were performed again on filters with the same commercial name, the differences, if any, could be attributed to:

- the laboratory, as far as repeatability is concerned;
- the network of laboratories, as far as reproducibility is concerned;
- the manufacturer, due to the fact the sample may not be representative of his production.

The testing laboratories defend themselves by statistically treating data in order to improve the repeatability of the tests, by inter-laboratory tests in order to assess reproducibility and by formal mechanisms that limit their responsibility to the received product. However, this behaviour does not protect the end user who is therefore only protected by putting the product quality systems into effect.

3. Analysis of experimental results

The totality of the air filters here considered represents typical commercial products that are presently available in Italy: it is therefore predictable that the obtained experimental results could be representative of the rated airflow rate, pressure drop and current values of the efficiencies current values. The element of originality is represented by adding fractional efficiency values within the 0.2÷3 μm size range: the values entered in the table show the fractional efficiency in number for the 0.35÷0.45 μm size range. The question concerning the possible use that may be made of these results is still open: in order to try to clarify the answer to this question, it has been subdivided into three cases: the user's, the manufacturer's and the researcher's point of view.

The end user of the filter would like the chosen product to be able to:

- avoid dirtying the downstream surfaces and/or avoid the sensation of dusty air;
- have a long life without modifying the airflow rate;
- be non-flammable;
- be easily disposed of.

As the filter is a component that can be disposed of it is considered in a different way from the other durable elements of the HVAC systems. The user keeps the pressure drop value under control, or at least the final value that indicates the need of the replacement and which can be found in the manufacturer's technical brochure in correlation to the rated airflow rate.

When the filter is not replaced there are usually no clear negative signs. In fact, air filters can work under overload conditions and may last for a long time, but in an unpredictable way.

A second problem is connected to the growth of micro-organisms which, once again, do not lead to clear signs in the short term: the most detectable element for those close to the filter is its odour. From experience gained over the years it has however been found advisable to change the filter after one year. However when this is not done it should also be admitted that there are no immediate consequences.

As far as efficiency is concerned, the situation is different, as it is not actually possible to measure and, even if it were known, its interpretation would be difficult: there is no intuitive idea of the effects of the particles not held by the filter. The soiling of the surfaces depends on the square of the particle diameter; often surfaces are not visible and some time can pass between a noticeable soiling and perceivable consequences. The smallest particles have a negligible mass and surface so they can only be guessed at.

A clear advantage of the new test method for air filters is that it provides broader information: it is possible to know how the efficiency in number varies in function of the particle size, within the 0.2÷3 μm range. These particles are not visible, but are those that prevail (in number) in the atmospheric dust: the trend of the fractional efficiency curve versus particle diameter may be useful for the end user mainly if used in a comparative way, that is, starting from a reference situation. For example, it is known that when the air used inside the varnishing cabins is not filtered properly the effects can be seen on the varnished surface, and the users' experience would advise them of variations in the filter efficiency for the application they are interested in. The information constituted by the fractional efficiency is an input data that is useful for the designer of the ventilation systems only at present while in the future it will be necessary.

From the filter manufacturer's point of view, it is important to produce reliable products which can ensure a good margin of profit. The mechanical resistance of a filter is very important, so that it can reach the final pressure drop in a good condition, and thus there will be the possibility of characterising it in such a way as to evaluate its characteristics in an advantageous way. For this reason, the tests which allow one to compare competitors products are considered interesting, while the burden of being significant of real life conditions is left to the test method. Filter test methods in the laboratory are not representative of every real life condition, nevertheless it is necessary to resist the temptation of pointing out this fact in order to justify a commercial product which has lower performance than expected, and even forgetting it in other cases. It is important for the manufacturers to be able to use the tests that have already been carried out using the old method and for this reason it is useful to compare dust spot efficiency values with those of fractional efficiency. The data obtained during these tests and shown in the table confirm the good agreement, for F class filters, between the initial dust spot efficiency values and efficiency in number relative to 0.4 μm size values. The agreement obtained when the filter is clean also seems to remain when the filter becomes dirty, as can be seen from the values of ε_f.

For filter manufacturers it is important to demonstrate that their products can be incinerated, but not flammable: these two characteristics seem to be antithetical and deserve more attention than which is currently given. There already exists a test method for flammability [5] that requires the filter to work in the test conditions, and to be put in touch with a gas flame and then to measure the opacity of the combustion products: it is interesting to note that the possible combustion occurs in a cold environment because of the airflow through the filter. This test is performed using a clean filter and it is obvious that those who are not satisfied with the results, claim that it is not representative as the filtered material is not taken into account. The mass of this material is in fact not negligible compared to the mass of the clean filter (see table) and its contribution to flammability cannot be excluded.

Table - Filters for general ventilation characteristics

	Material	**Shape**	**A**	**m_f**	V_n	**w**	**Δp_i**	β_i
	Fibre	P.= Pockets	[m²]	[kg]	[m³/h]	[m/s]	[Pa]	
1	glass	Rigid P.	19	5.35	4250	0.06	145	22
2	glass	Rigid P.	19	5.66	4250	0.06	215	33
3	polypropylene	Non-rigid P.	8	2.09	3400	0.12	50	13
4	polyester	W-form	1	0.66	900	0.25	30	94
5	glass	Rigid P.	19	5.08	3400	0.05	95	23
6	glass	Non-rigid P.	8	1.92	3400	0.12	85	20
	E_i	**$\varepsilon_i(04)$**	**m_a**	**E_f**	**$\varepsilon_f(0.4)$**	β_f	**m_a/A**	**$(\beta_f-\beta_i)/(m_a/A)$**
	[%]	[%]	[g]	[%]	[%]		[g/m²]	[m²/g]
1	69	66	292	90	91	70	15	3
2	89	92	192	95	97	70	10	4
3	32	6	399	46	32	110	51	2
4	15	6	280	43	31	870	280	3
5	74	72	511	-	96	110	27	3
6	66	65	633	88	90	110	81	1

The possibility of incinerating filters is a problem that is considered in countries which usually incinerate solid waste and in the case of plants that use a great deal of filters, such as gas turbine groups. In this last case, the possibility of complete burning (excluding metallic frames, for example) and the presence of substances that can generate emissions into the smoke is important: for example, plastic materials with chlorine (the manufacturer's responsibility) or heavy metallic substances in the collected dust (the user's responsibility). Filters are not incinerated alone but together with solid urban waste in a high temperature environment, which is very different from that which occurs during flammability tests. There are no common methods available at the moment to test the possibility of incinerating air filters.

From the researcher's point of view, it is important to express filter characteristics in such a way that they can be traced back to general laws and therefore to allow one to investigate the phenomena in order to give some indications on the development of knowledge and, if possible, on commercial products [6]. From this point of view, filter resistance to air motion is naturally expressed by a concentrated resistance coefficient that pertains only to the filter and which does not depend on the airflow rate, as the pressure drop does. This coefficient is indicated by β in the table and has been calculated either in the initial conditions (β_i) or in the final ones (β_f for Δp_f=450 Pa for filters n. 1,2,3,5,6 and Δp_f=250 Pa for filter n. 4), by means of the equation $\beta=2\Delta p/\rho w'^2$ where ρ is the air density and $w'=V_n/A'$ is the frontal velocity. Collected dust is responsible for the increase of the coefficient, therefore it is natural to establish a relationship with the mass divided by the area of the filtering surface (m_a/A). If this ratio were the same for different filters, it would be a particularly meaningful parameter. However, if one looks at the table, it does not seem to be so and this is generally what has happened to all attempts to generalise air filter performance. The reason for this is that filters have only been characterised by overall experimental data and they are not related, in a precise way, to the characteristics of the filtering media and the commercial product. On the basis of the filtration theory, it is possible to criticise, above all, the choice of the previously indicated β coefficient because filter resistance to motion depends on the contribution of the material (generally, proportional to the crossing air velocity w) and on the contribution of the shape, which is not flat (generally, proportional to the square of the frontal velocity w'). For example, in the case of filter 1 in the table, the pressure drop due to the material is less than half of the indicated value for the filter. Remarks of this kind make very difficult to attempt any kind of simple correlation: this fact does not prevent manufacturers from improving their products as the functionality of the systems does not require, as in many other cases, their satisfactory description from the scientific point of view.

Nowadays, the point of equilibrium between different requirements is represented by research [7] that deals with the problem of the technical life of filters and which tries to limit empirical relationships as much as possible. The overall impression is that modern means of calculation are sufficient to deal with the problem, from the quantitative point of view, even when taking the efficiency variability with the particle size into consideration. Instead, "qualitative" relationships, such as the efficiency of a group of fibres, for example, are not applicable to commercial products, even though they are very refined from the scientific point of view. There probably exists situations in which scientific interest is greater in the aerosol field and not so high in the ventilation environment as it is hard to obtain original and conclusive results, while in the industrial field these products have such small margins of profit that investments are justified only in the case of immediate commercial results.

4.Conclusions

Filtration efficiency for thin particles can be measured using the new method here described which provides fractional efficiency in number and, for this reason, it is possible to obtain much more information, in a shorter time, compared to the dust spot efficiency method which is still used. On the basis of experimental data obtained on products that are representative of the Italian market, the agreement between the old and new method is satisfactory for fine filters. With this further information, the possibility of joining HVAC system performance with the measurable characteristics of filters is closer.

5. References

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