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A QUANTITATIVE METHOD TO DETERMINE OIL CARRYOVER FROM HIGH EFFICIENCY COALESCING FILTERS IN COMPRESSED GASES UNDER VARYING DYNAMIC CONDITIONS AND THE INTERPRETATION OF RESULTS TO ASSIST FILTER SYSTEM DESIGN.

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ABSTRACT

Discharge air/gas from compressors is often not of the right quality for certain uses unless it is suitably treated.

The various contaminants present in compressed air/gases include atmospheric pollution, compressor wear particles, bulk lubricating oil and aerosols, water vapour and condensed water, oil/water emulsion, rust and carbon. Suitable treatment of the air/gases involves the removal of the contaminants using aftercoolers, refrigerant or desiccant dryers and filters.

Coolers and dryers are used to remove water vapour and reduce the dew point of the air, thus preventing further condensation of water downstream. High efficiency coalescing filters are used to remove the other contaminants to extremely low remaining levels.

Measurement techniques to determine the dew point of compressed air/gases are well known, but the important measurement of remaining oil content after filtration has not been so well established.

A new test method has now been developed which is capable of giving very accurate measurements of remaining oil content down to 0.001 mg/m³. The test method will be explained in detail and an outline of results from the method obtained over a period of several years will be discussed, including data collected over a varying range of operating parameters, i.e. temperature, velocity, oil loading and the effect of these on filter efficiency and filter system design.

CONTAMINANTS

Compressed air is one of the essential services in any industry. It possesses many advantages over other types of energy and an increasing number of applications for it are being discovered. Unfortunately, compressed air/gases can contain a considerable amount of contamination which can often have drastic effects on the equipment using it.

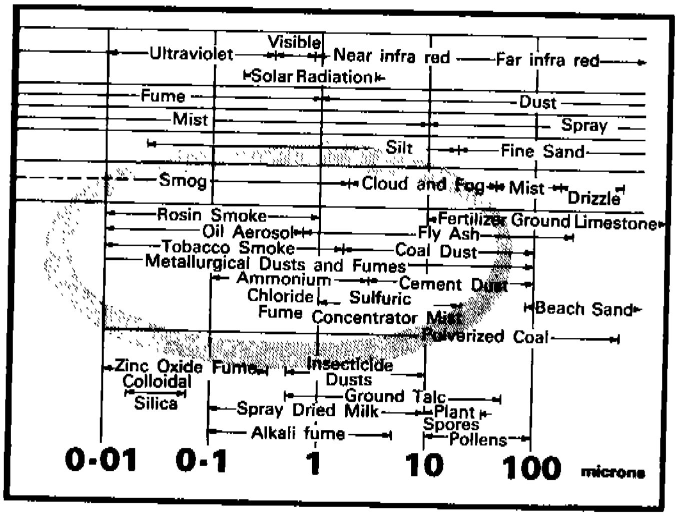
Contamination can enter a compressed air/gas system from three sources. These are namely, the atmosphere, the compressor and the piping system. Taking the atmosphere first; in a typical metropolitan environment there are something like 140 x 10^6 dirt particles per m³ (4 x 10^6/cu.ft.) Approximately 80% of these are less than 2 microns in size (a micron is one millionth part of a metre or approximately 0.04 thousandths of an inch) and are not removed by the compressor intake filter. In addition to this, there are contaminants such as hydrocarbon vapours (from unburnt fuels and industrial processes) and water vapour. All of these are drawn into the compressor and their concentration increased by the compression process.

Inside the compressor, wear particles and lubricating oil are added to the air/gas. The amount of oil contamination depends on the type of compressor and its condition but can typically vary between 5 and 50 mg/m³. To put this into context, a 286 l/s (600 scfm) A.N.R. compressor carrying over 30 mg/m³ (25 ppm) of oil during an operational period of 6000 h will deposit approximately 212 litres (47 gallons) of oil into the system. It is never an advantage to have oil from a compressor in the system as this oil is inevitably degraded and oxidized after the heat of compression. Usually it is acidic and can appear as a varnish like substance possessing properties completely opposed to lubrication. If synthetic oils are being used these can cause chemical attack on downstream components such as seals and polycarbonate parts. Carbonization of the lubricating oil in the compressor is not uncommon due to the temperature of compression and the presence of 'hot spots' results in deposits of carbon which are again carried over. It is worth taking note at this point that even using an 'oil free' compressor does not necessarily generate 'oil free' air as quite large amounts of hydrocarbons can be drawn in from the atmosphere.

After compression the air/gas then passes into the piping system. Normally, aftercooling reduces the amount of water vapour contained in the air/gas but further cooling in the system causes more water to condense. Pipe-scale and rust are also present and when these contaminants mix together with the oil they form an abrasive, creamy sludge. This combination of contaminants causes costly problems with both the equipment and the product. These can be eliminated by suitably treating the compressed air using an effective filtration system. Water vapour itself is sometimes a particular problem and cannot be tolerated in any amount, in which case a dryer is also necessary.

Oil aerosol is present in a very fine submicron form similar in size to tobacco smoke (Fig. 1) and has the ability to travel many miles down pipework systems without settling due to gravity and/or other effects.

FIG.1–Atmospheric pollution size comparison chart

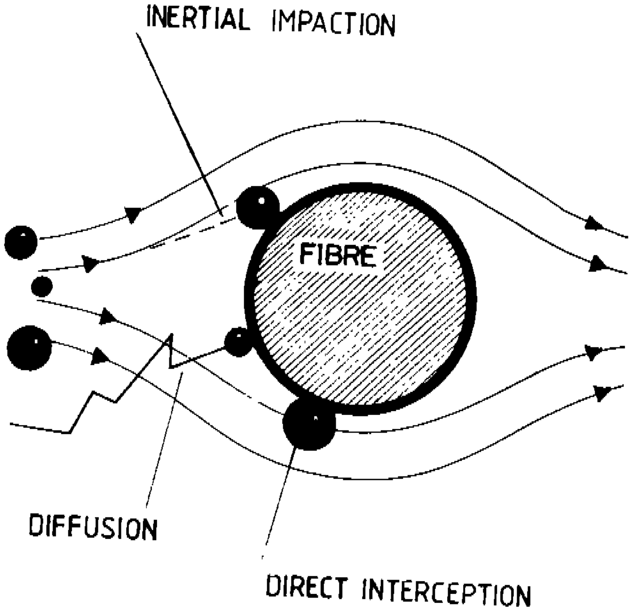


High efficiency coalescing filters are used to remove from the air/gas stream the variety of contaminants present. High removal efficiency is achieved by the use of filter systems employing borosilicate microfibre media, this media being constructed into filter elements of suitable design for specific applications.

The main purpose of this paper is to discuss the behaviour of high efficiency coalescing filters to ensure that high proven quality compressed air/gas can be made available for industrial applications.

THEORY

The main purpose of the theory of filtration is to calculate the efficiency of a particular filter system based on mathematical modelling, allowing the primary critera to be established for selection of appropriate filter materials and design parameters for use in the construction of high efficiency filter elements. The filter medium consists of a fibrous mass through which the gas containing the particles to be removed is passed. Particles are collected on individual fibres by numerous mechanisms. The most important of these are direct interception, inertial impaction and diffusion, (Fig. 2. single fibre collection efficiency.)



Particle collection mechanisms

FIG 2

Direct Interception

Occurs when a droplet or particle collides head on with one of the fibres.

Inertial Impaction

Results if a droplet or particle in the air atream fails to negotiate the tortuous path presented by the random fibres in the filter bed, collides with and adheres to a fibre.

Diffusion

Occurs when extremely small aerosols and particles wander in 'Brownian Motion' within the flow pattern of the air stream so enhancing their chances of colliding with each other and with fibres forming the filter medium.

FACTORS AFFECTING FILTRATION

When designing a filter element for a particular duty it is necessary to consider the following parameters to enable an optimum design and construction to be achieved.

(1)	Temperature	degrees celcius
(2)	Pressure	bar g (psig)
(3)	Velocity through filter medium	m/s
(4)	Oil loading	mg/m^3
(5)	Fibre diameter	microns
(6)	Packing density of fibres	dimensionless
(7)	Depth of filter medium	cm

The use of these parameters in design have been well documented (1). Two different grades of filter systems have been investigated using the new test method namely filter A and filter B, the characteristics of which are shown in Table I.

TABLE I

	A	B
Mean fibre dia microns	0.7	0.5
Packing density	0.049	0.049
Depth of bed, cm	0.22	0.22
D.O.P. Penetration %	<0.001	<0.0001

CLASSIFICATION

Filter A is designed to provide a maximum remaining oil content downstream of 0.5 mg/m^3 based on a filtration temperature of 21°C (70°F) at a pressure of 7 bar g (100 psig) using a typical compressor lubricant.

Filter B is designed to provide a maximum remaining oil content downstream of the filter of 0.01 mg/m^3 based on a filtration temperature of 21°C (70°F) at a pressure of 7 bar g (100psig) using a typical compressor lubricant.

PRINCIPLE OF OPERATION

The two filters described employ borosilicate microfibres to remove the particles of dirt and liquid oil or water (Fig. 3a, b, c.)

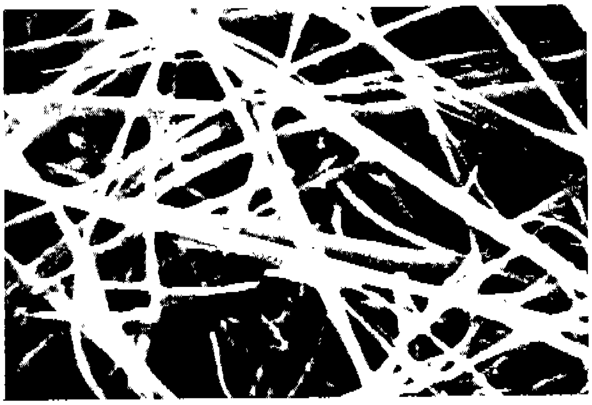


Fig. 3a: Clean filter media

Fig 3b: Minute rust particles retained

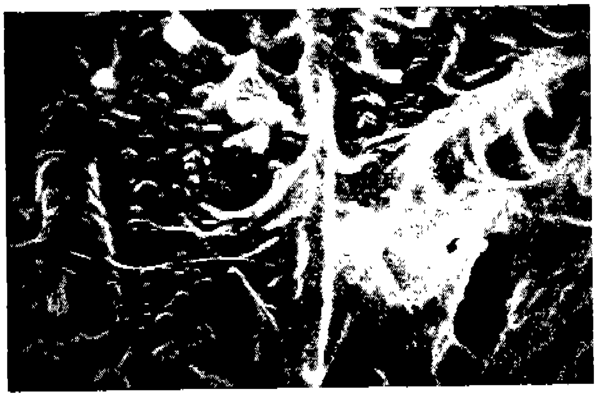


Fig 3c: Separated oil and water coalescing into bulk liquid

Flow is inside to out (Fig. 4), the compressed air/gas pass firstly through the inner layer of the filter element which provides support to the micro fibre and also acts as an integral pre-filter which removes larger particles of dirt and liquid. This gives protection to the layer of high efficiency filter material which removes the finest of particles. Solid particles are trapped permanently within the filter material. The fine liquid particles, including aerosols, after initially being trapped by the fibres of the filter material coalesce forming larger droplets, (Fig. 4a.)

These droplets along with any large droplets already present in the compressed air/gases are pushed to the outer anti re-entrainment barrier, which collects the droplets as they break free from the microfibre and allows them to gravitate within its cellular structure forming a 'wet band' around the bottom of the filter element. Clean filtered air/gases passes through the anti re-entrainment barrier above the 'wet band' where the resistance to flow is less, leaving a quiet zone of zero air/gas movement in the bottom of the filter housing. The separated liquid drops from the bottom of the filter element and falls through the quiet zone, without being re-entrained to the bottom of the filter housing where it collects and is removed by a drain (Fig. 5.)

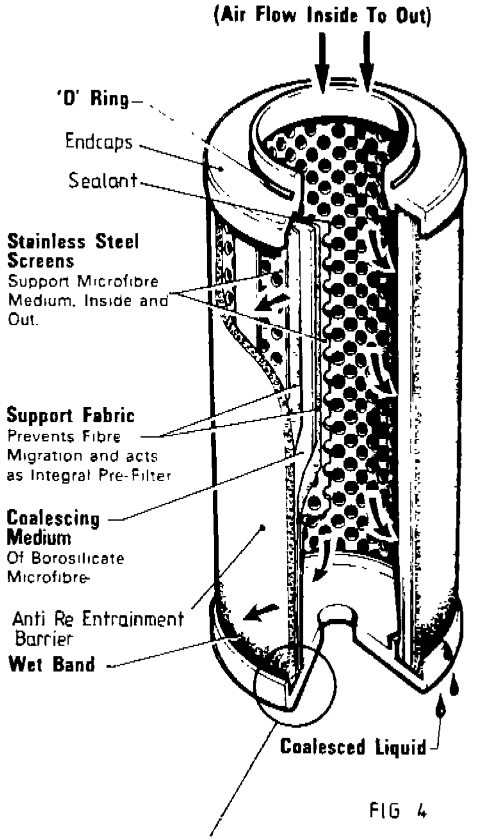


FIG 4

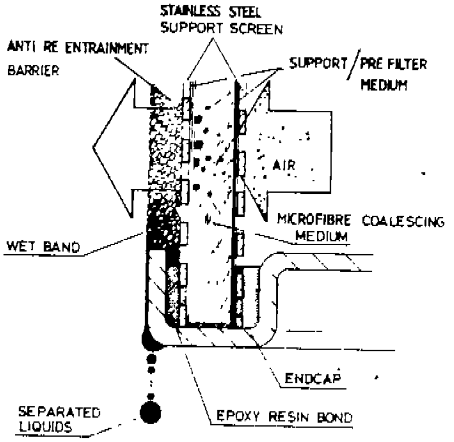
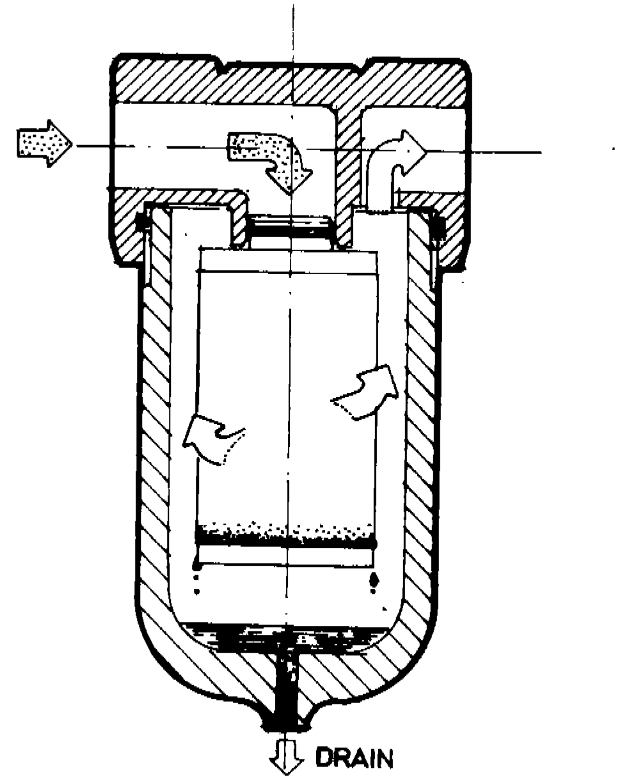


FIG 4a



Gas Liquid Separation Flow Path

FIG 5

ELEMENT INTEGRITY

Once an element design has emerged based on computer predictions using mathematical modelling, it should give high efficiency performance over a range of operating conditions where its efficiency related parameters may vary to some degree. In practice, the integrity of such a filter may be established by employing such test procedures as the D.O.P. test (Method ASTM D 1986) and Sodium Chloride test (Method BS3298). These test methods do not quantify in terms of oil carryover what the end user may expect from his own particular installation.

This test method, the subject of this paper, takes a practical approach to the measurement of filter performance and applies itself in a suitably quantitative manner giving accurate and repeatable results, with the facility to vary the parameters affecting the efficiency of the filter to abnormal degrees, thus exposing the filter to arduous duty and allowing its performance to be carefully monitored.

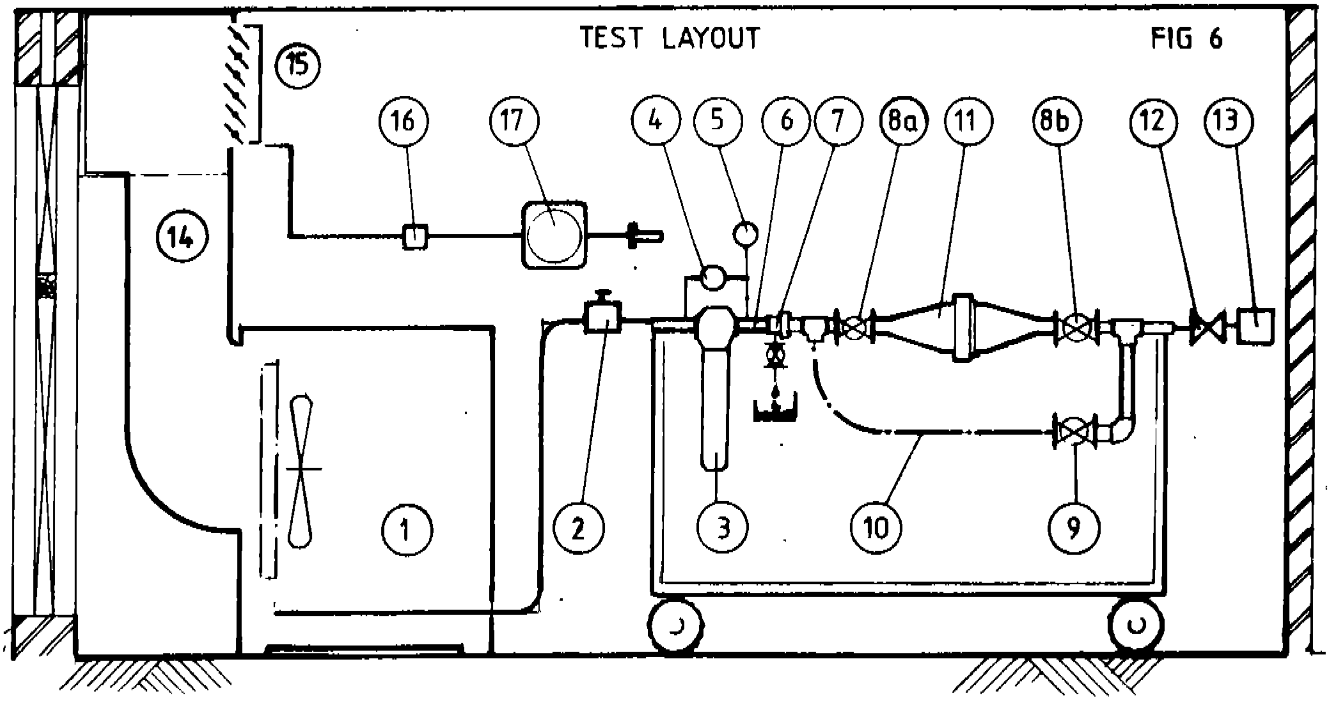
INTRODUCTION TO TEST PROCEDURE

The test equipment shown in Fig. 6 and described below has the benefit of enabling large volumetric flows to be handled and therefore eliminates the possible errors of small scale sampling and testing. The system was first installed in 1978 and has been used regularly to build up a good base of filter performance data over the years when thousands of individual readings have been taken.

The testing equipment is portable and can be used for onsite tests where filter sampling discs can be transported back to the laboratory for analysis. A feature of the test procedure development was to carry out co-operative tests with an overseas client and exchange sample discs by air to check the repeatability of the analysis procedure. The system as described uses a 150 mm dia sample disc but can of course be scaled to meet specific requirements.

KEY TO TEST LAYOUT

1. Oil lubricated compressor
2. Pressure control
3. Filter/filters under test
4. Differential pressure gauge
5. Pressure gauge
6. Temperature sensor (air/gas line)
7. Wall flow separator
8a
8b By-pass valves
9. By-pass valve
10. By-pass leg
11. Expansion chamber/sampling disc holder
12. Flow controller
13. Flow measuring device
14. Compressor cooling air
15. Thermostatically controlled hot air vent
16. Temperature controller (ambient)
17. Temperature recorder (ambient)



TEST LAYOUT

FIG 6

DESCRIPTION OF TEST EQUIPMENT

The compressor (1) is of the oil flooded rotary screw type. Oil laden compressed air is delivered via a pressure controller (2) to the test filter (3). The differential pressure gauge (4) is used to establish the operational equilibrium has been reached before readings are taken. Pressure gauge (5) records line pressure. Outlet air temperature is measured at (6). In addition to air borne contamination it is possible to have wall flow of liquids and a wall flow separator (7) is fitted. Air flow is normally directly through valves (8a, b) and sampling disc holder (11). Air flow is controlled by the flow controller (12) and measured by the flow measuring device (13). When sampling takes place air is diverted through the by-pass leg (10) by closing valves 8a and 8b and opening valve (9). This allows depressurisation of the sampling disc holder (11) by a valve on the downstream side (not shown). To take a sample, air is redirected through the sampling disc holder (11) by closing valve (9) and opening valves 8a and 8b for the desired time (see operating procedure.)

Cooling air from the compressor is ducted away (14) and used to control the test room ambient air temperature using the hot air vent (15) and temperature controller (16). Ambient temperature is recorded using temperature recorder (17).

OPERATING PROCEDURE

The test apparatus was set up in open loop, discharging into the atmosphere. A test element was mounted in the housing (3) and with the valve (12) and valve (9) on the rig closed (8a, b open), the rig was pressurised to line pressure with the pressure regulator (2). Valve (12) was then gradually opened until the required flow was achieved, then for each test the following sampling procedure was followed:

a) Valves 8a, b were closed and valve 9 opened to direct the air flow through the by-pass leg (10).

b) The sampling disc holder (11) was depressurised and removed from the rig, then a clean sampling disc was placed in the holder.

c) The holder was replaced and pressurised by gradually opening valve '8a' (care was taken to avoid shock pressurisation, since the filter disc may have been damaged.)

d) Valve '8b' was opened ('9' closed), diverting flow through the filter disc, adjustments being made to flow rate and pressure if necessary.

e) After the required test duration (normally 2-10 minutes) valves '8b' and '8a' were closed in that order and valve 9 opened, and the sampling disc holder was depressurised and removed from the rig.

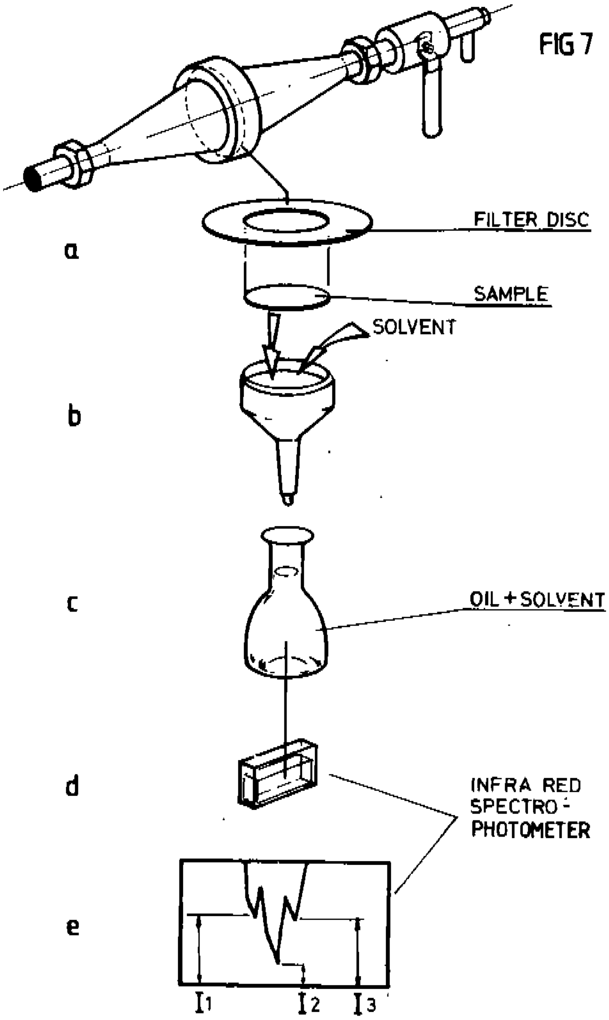
f) The exposed sampling disc was taken from its holder and placed in a polythene sachet to await analysis, a new disc was inserted and the procedure repeated from step b.

PROCEDURE OF ANALYSIS Fig. 7

Analysis is carried out using infra-red spectrophotometer techniques.

The object of the analysis is to determine oil carryover (mg/m^3) however, the absorbance of the oil on the sampling disc needs to be calculated first from the spectrograph.

FIG 7



Schematic Diag. Analysis of Sampling Filter Disc

To obtain the spectrograph the following procedure was followed:

a) The sampling disc was removed from the holder.

b) A section of the sample disc was punched out.

c) A known volume of solvent was filtered through this disc, to remove the oil present using a measuring cylinder to collect filtrate (V,ml).

d) This volume was transferred into an absorption cell and placed in the I.R. spectrophotometer with clean solvent as reference.

e) With the I.R. spectrophotometer operating on its longest scanning time, a spectrograph between 3000 cm^{-1} and 2800 cm^{-1} was recorded. The concentration of oil in solution is proportional to absorption of IR - light at three wave numbers (reciprocal of the wave length).

f) From the peaks produced, using the formula:-

$$A = \log \frac{(Io)^3}{I_1 \times I_2 \times I_3}$$

the absorbance of oil in the disc is obtained.

CALCULATION OF OIL CARRYOVER

To obtain the oil carryover the following equation needs to be used.

$$\text{Concentration} \quad (C) = \frac{A}{\text{gradient*}} \quad (\mu g/ml)$$

$$\text{Carryover } (\mu g/ml) = \frac{C \times V \times r}{Q \times t}$$

Where

A = absorbance
V = volume of filtrate (ml) described above
Q = flow rate (l/min)
t = time (min)
r = ratio of sample disc to total effective disc area

* gradient = obtained from calibration graph of absorbance vs. oil concentration using specific lubrication oil. (Energol HP32 = 0.0207)

FILTER ELEMENT - TEST CHARACTERISTICS

The operating characteristic of a coalescing filter will attain a state of equilibrium in a dynamic mode with the concentration of bulk liquid (and aerosol) present in the system. That is, after installation in the 'dry' condition (no liquid present in the filter medium) the coalescing action of the element allows a saturation condition to be achieved, at which point the operational differential pressure drop is essentially constant (Fig. 8). The filter element continues in this mode until solid particulate collects causing a significant change in the operational pressure drop. All filter elements used in the tests were allowed to attain an equilibrium condition prior to oil carryover determination. These control tests were conducted at rated flow, constant line pressure and temperature, with all other relevant variables constant. This procedure provided a datum point for filter performance and allowed multi-variable experimentation to be carried out, thus interpretation of results could be made accounting for random chance effects.

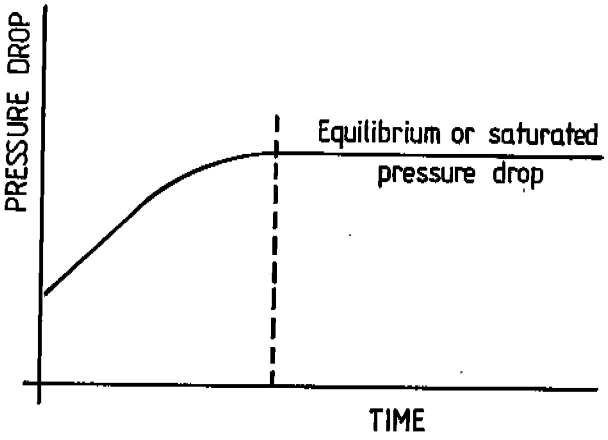


FIG. 8

TREATMENT OF RESULTS

The data obtained from experimentation was treated in a statistical manner to allow some degree of confidence that the results obtained were due to the effect of the particular variable and not due to experimental or random errors.

A paired sample analysis allowed linear regression on the data. Graphical representation could then be made indicating each sample mean, its standard deviation and the linear regression line. Two sample 't' tests calculated the mean and standard deviation for two sets of samples and by comparison of these values arrived at a value for 't'.

Location of 't' value on the table showing 'Percentage' points of the 't' distribution for the specific degrees of freedom 'df'. A value for Alpha* could be determined. This could then be converted into a degree of confidence.

*
Statistical Tables By J. Murdoch and J.A. Barnes 2nd Edition.

RESULTS

(i) Effect of Temperature (refer Fig. 6)

The temperature at filtration was controlled by varying the ambient air temperature taken in as a coolant by the compressor. Use of thermostatically controlled dampers on the compressor air duct (air coolant) allowed re-circulation of ambient air across the compressor. The temperature range attained using this method was 15-55°C. Oil carryover was determined for filters A and B at filtration temperatures shown in Table IIA/IIB and graphically in Fig. 9. Upstream oil carryover values were obtained using stated test procedures without the test element in situ.

Flow rate 120 l/s at 7 bar g (250 scfm at 100 psig)

TABLE IIA FILTER A

Temperature at filtration °C	Measured oil concentration mg/m³ (mean)	
	Upstream	Downstream
17	5.2	0.13
37	5.2	0.14
45	5.2	0.14
53	5.2	0.15

TABLE IIB FILTER B

Temperature at filtration °C	Measured oil concentration mg/m³ (mean)	
	Upstream	Downstream
17	5.2	0.005
33	5.2	0.006
44	5.2	0.005
53	5.2	0.006

Compressor Oil: Energol HP32

(ii) EFFECT OF VELOCITY

Varying velocities through the filter element were achieved by control of the volumetric flow rate through a constant filter area. The range of velocities achieved were 0.1-0.8 m/s. Results obtained on filters A and B are listed in Tables III A/B. Removing the filter under test and sampling the airstream made it possible to calculate the oil loading in the air being presented to the filter under test at each velocity (Fig. 10).

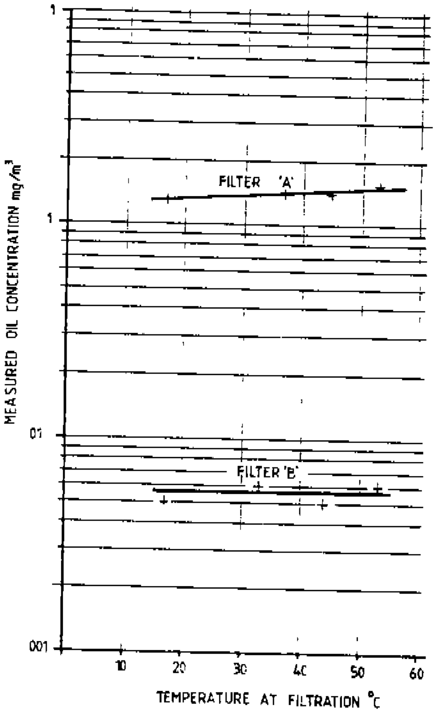


FIG 9

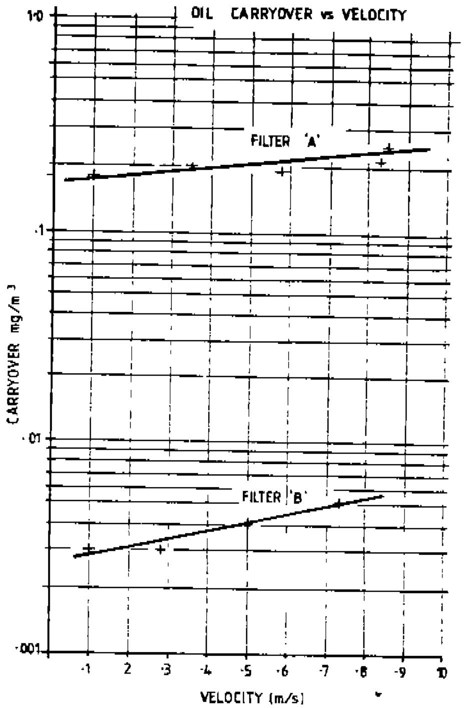


FIG 10

TABLE III A FILTER A

Velocity	Measured oil content mg/m^3 (mean)	
m/s	Upstream	Downstream *
0.1	3.32	0.18
0.35	2.78	0.20
0.58	2.94	0.19
0.83	3.38	0.22
0.85	3.38	0.25

TABLE III B FILTER B

m/s	Upstream	Downstream *
0.1	3.32	0.003
0.28	2.78	0.003
0.50	2.94	0.004
0.73	3.38	0.005

Compressor oil: Energol HP32
* Temperature at Filtration 35-36°C

(iii) EFFECT OF OIL LOADING

(refer Fig. 6) - test rig

To vary the oil loading presented to the filter under test the additional test equipment shown in Fig. 11 was needed. This was introduced immediately following the pressure regulator (2) in Fig. 6. This allowed variation of oil loading in the range 5 mg/m^3 - 750 mg/m^3.

It was decided to assess filter A only as this grade would normally be specified for high oil loading and may act as a prefilter for the filter B.

Carryover figures obtained are shown in Table IV and graphically in Fig. 12.

TABLE IV FILTER A

Flow rate 120 l/s at 6.3 bar g (250 scfm at 91.5 psig)
Temperature 35 - 36°C
Velocity 0.2 m/s

Oil Loading mg/m^3	Oil Carryover mg/m^3
149	0.15
164	0.14
228	0.15
318	0.18
520	0.18
703	0.19

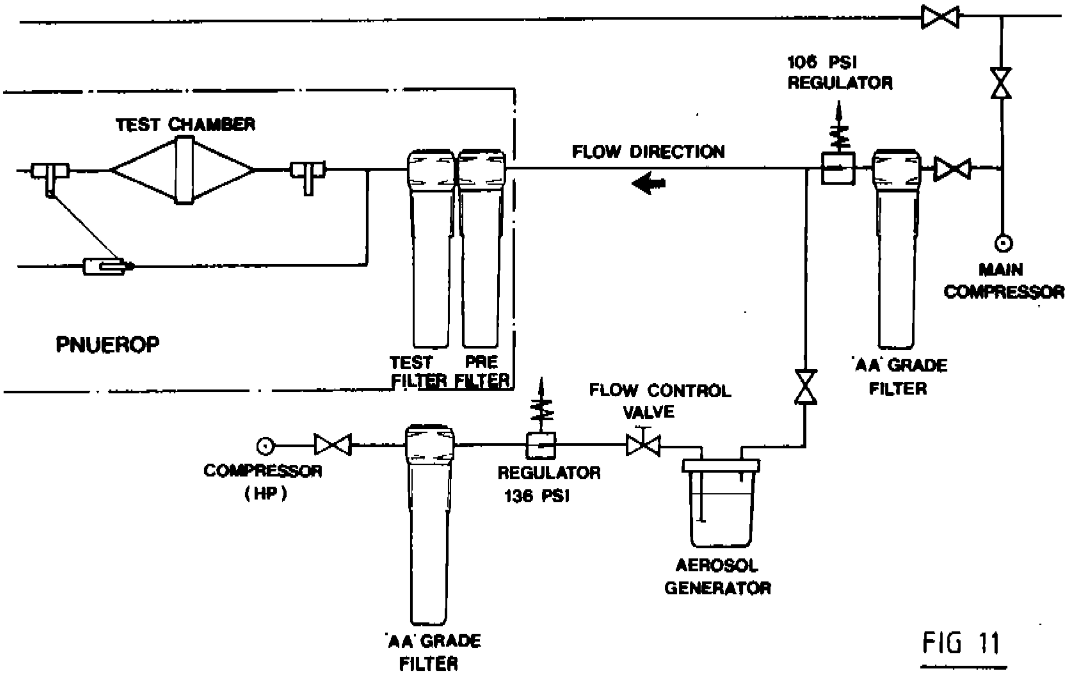


FIG 11

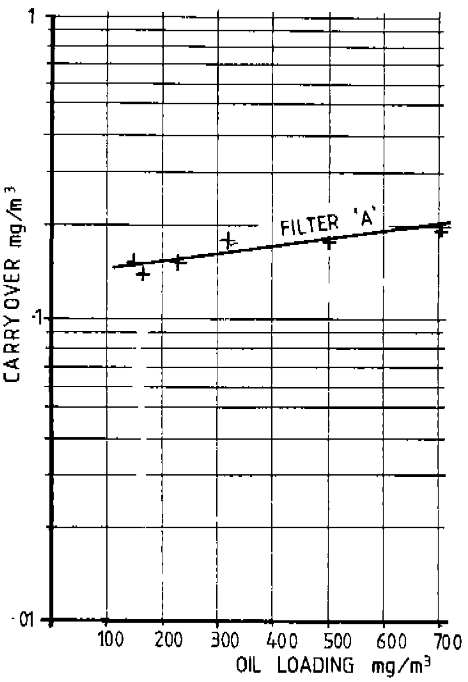


FIG 12

CONCLUSION

The two filters as described have been tested to determine their performance over a wide range of operating conditions. It is believed that this is the first time such an exhaustive test programme has been undertaken on filters of the high efficiency coalescing type. The test method employed was found to be easy to operate by Test Engineers and gave reproduceable and consistant results.

The test equipment, has a major advantage over other test systems previously available. This is the ability to sample the total volume of air/gas flow from a filter system thus eliminating errors caused by small scale sampling techniques. The Authors have noted in other work (not published) that the performance of small terminal filters (e.g. 10 l/s at 7 bar g) is not representative of main line filters operating at high flow rates and in close proximity to the compressor where discharge temperatures will normally be higher than ambient and where contamination levels are normally much higher than found in terminal applications. The test system described is capable of handling flow rates of 120 l/s (250 scfm) at 7 bar g (100 psig) and is capable of being scaled to suit particular requirements. The test method is, because of the sampling procedure, suitable for use on short and long term filter testing thereby allowing the long term filter performance to be determined.

It is interesting to note the consistancy of performance of the two filters tested over the range of dynamic conditions investigated. Filter efficiencies in percentage terms however fall well below results from integrity testing and act as a warning that integrity test results should be kept in context. Integrity testing is of course very valuable to ensure the quality of manufactured filter systems and is widely used for this purpose. There is however no substitute for quantitative measurements obtained in a realistic dynamic operation. The test method described is of value to filter manufacturers and users. It makes a real contribution to the state of the art and will assist filter designers to further develop their products in the future.

The test system was adopted as a *Pneurop Recommendation in 1982 (2) and is being considered by I.S.O. (International Standards Organization)

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C.T. Billiet, J.I.T. Stenhouse

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* European Committee Of Manufacturers Of Compressors, Vacuum Pumps and Pneumatic Tools.