
- AWARD WINNING PAPERS -

Carbon Fibres for Combined Particulate and Vapour Filtration

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ABSTRACT

Activated carbon fibres have been studied in order to determine their potential as a filtration medium capable of removing both particulates and vapours from airstreams. Carbon fibre mats have been fabricated from either pitch-based or PAN-based carbon fibres, as well as combinations with vapour grown carbon fibres (VGCF's). Their ability to remove salt particles has been assessed. Variation in salt penetration and pressure drop as a function of both the composition of the mat, and the thickness of the mat, have been studied. The results have shown that carbon fibre mats composed solely of either pitch-based or PAN-based carbon fibres can remove > 95.0 % of salt particles with a minimal associated pressure drop. PAN-based fibres are the most effective at removing particulates with > 99.5 % being trapped. Vapour grown carbon fibres (VGCF's) were shown to add little benefit to the trapping efficiency of the mats and had a marked, negative effect on pressure drop.

Activation of both the pitch-based and PAN-based carbon fibres was carried out using either carbon dioxide (CO₂) or steam (H₂O). The influence of oxidising media, activation temperature and activation time on the resulting porous structure was investigated. PAN-based carbon fibres were found to activate poorly, however, highly microporous carbon fibres were obtained following activation of the pitch-based carbon fibres. Steam activation was found to form activated carbon fibres with wider pore size distributions than those formed using CO₂. The ability of the activated carbon fibres to remove physisorbed vapours under dynamic conditions was investigated under both dry (RH<5%) and humid (RH80%) conditions. Hexane breakthrough times under dry conditions were in excess of 60 minutes for some activated fibres, however, these times were reduced under humid conditions.

The influence of activation on the structural integrity of the carbon fibres was investigated. Electron microscopy was employed to observe the fibres before and after subjection to physical grinding. Activation using CO₂ was found to significantly weaken the fibre, however, activation using steam was found to have a much smaller effect on strength.

INTRODUCTION

For the military to perform effectively in a chemical and biological warfare environment they must have equipment that imparts high levels of protection. Respiratory protection in particular is of paramount importance and several excellent review articles have been written pertaining to respiratory protection in chemical warfare environments (Hall and Sing, 1988; Evans, 1999). The filtration canister of the current UK military respirator utilises a radially pleated glass fibre particulate filter combined with a layer of impregnated granular activated carbon to remove toxic vapours. While this is an effective filter media towards chemical and biological attack, there is a drawback in the form of a pressure drop across the canister leading to significant breathing resistance. A reduction in this pressure drop, while maintaining or improving the effectiveness of the filter, is therefore highly desirable in order to reduce the user burden. The successful identification of a material that could be utilised for both particulate and vapour filtration

would have great implications for the radical redesign of individual respiratory protection. Carbon fibres are potential candidates for this, as their fibrous form can be utilised to remove aerosols, and in addition, they can be modified to impart vapour adsorptive properties.

Carbon fibres were first developed in the late-1950's and their history is well-documented (Dresselhaus *et al.*, 1988; Donnet and Bansal, 1990; Chung, 1994). They are lightweight materials that exhibit good mechanical strength properties. Early research into their modification for adsorption applications was carried out in several scientific institutes (Adams and Boucher, 1978), including military establishments (Bailey *et al.*, 1973; Arons and Macnair, 1977). It was during this time that the potential of activated carbon fibres for protection applications was realised. Several review articles detailing the history, fundamentals and applications of activated carbon fibres are available (Suzuki, 1994; Mays, 1999). In general, activated carbon fibres offer a number of advantages over conventional granular activated carbons. These include (i) very high adsorption rates, (ii) they avoid problems arising from channelling and settling, and (iii) they retain some of the mechanical properties of the original carbon fibre.

As described previously, conventional respiratory protection utilises a dual media filtration system. Glass fibres are often employed to remove aerosols, while an impregnated granular activated carbon removes toxic vapours. Novel advanced filtration systems utilising activated carbon fibres are proposed (Figure 1). Possibilities exist for either (i) a dual filter media comprising a combined particulate and vapour filter backed by a reduced layer of impregnated granular activated carbon, or (ii) a single combined particulate and vapour filter element.

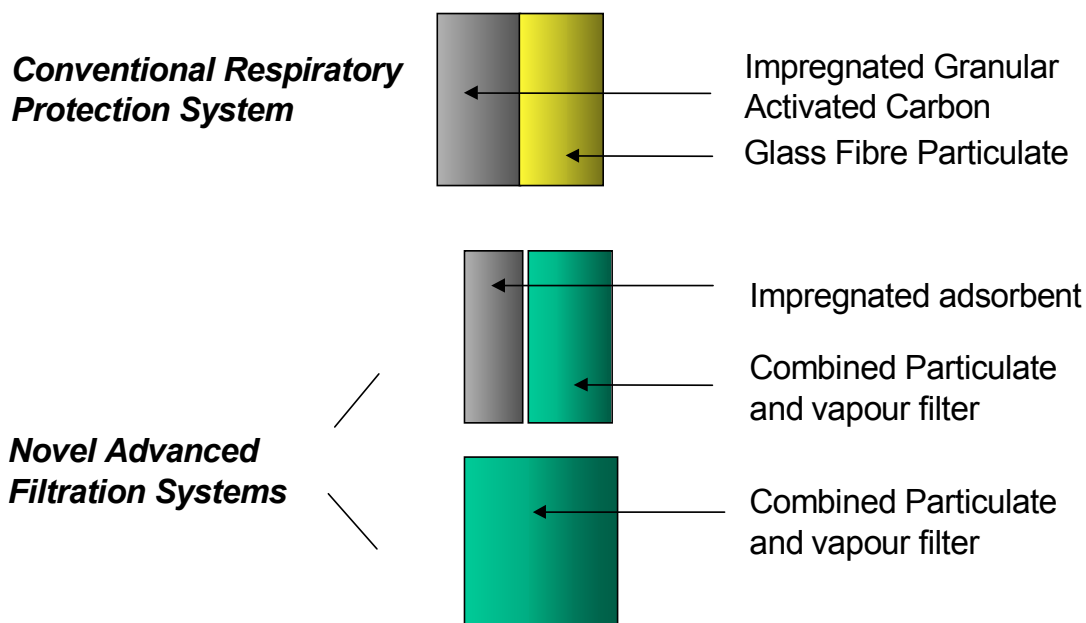


Figure 1. Conventional and novel respiratory protection systems.

Research is currently being carried out into the possible application of activated carbon fibres for combined particulate and vapour filtration. Previous studies concentrated on the use of activated carbon fibres and activated carbon cloth (Bailey and Maggs, 1973; Bailey *et al.*, 1973; Bailey *et al.*, 1974) purely for their vapour adsorbing properties. The particulate trapping efficiency of these materials was not evaluated. This paper will describe and discuss recent progress in the area of utilising carbon fibres for particulate removal as well as their modification (activation) for the removal of vapours. The impact of the

activation process on the physical structure of the activated carbon fibre, and any possible detrimental effects that this may have on the particulate trapping performance of the fibre has been investigated.

METHODS AND MATERIALS

Materials

For the purpose of the study a variety of carbon fibre types were investigated. These included two pitch-based carbon fibres (P3200 and AGM-95), a PAN-based carbon fibre (Grafil 34-700) and a vapour-grown carbon fibre, VGCF, (Pyrograf III). The characterisation data for the base carbon fibres are shown in Table 1. The P3200, AGM-95, Grafil 34-700 and Pyrograf III were manufactured and supplied by Anshan, Asbury Carbons, Grafil and Applied Sciences Inc. respectively.

Table 1. Characterisation data for base carbon fibres

Sample	Code	Diameter (μm)	Tensile Strength (MPa)	Density (gcm^{-3})	Elemental Analysis (%)				
					C	H	N	O	S
P3200	Pitch-1	12 - 15	400-600	1.23-1.91	90.50	-	0.60	2.94	1.29
AGM-95	Pitch-2	12 - 15	400-600	1.23-1.91	90.50	-	0.60	2.94	1.29
34-700	PAN-1	6.9	4500	1.80	93.43	-	4.62	1.93	-
VGCF	VGCF	0.08 - 0.3	-	-	-	-	-	-	-

Fabrication of fibre mats

A known weight (25 g) of either a single type of carbon fibre, or a mixture of two types of carbon fibre, was mixed with water (3 l) and rapidly stirred for 10 minutes using an automated stirrer (Silverson SL2). The slurry was poured into a standard sheet former (Model No. 154, Messmer Buchel), drained, and the resulting fibre mat removed. The mats produced were 12 cm in diameter and varied in thickness according to both the composition and mass of fibres used.

Particulate Performance

The performance of the carbon fibre mats against a standard salt aerosol (mean diameter = $0.6 \mu\text{m}$) was tested. The fibre mats were placed in a brass sample cell and subjected to the salt aerosol at a face velocity of 30 cm min^{-1} , which is representative of the breathing flow of a typical human at rest. The penetration of salt through the sample was calculated by flame photometry. The pressure drop across the mat was measured using a manometer attached to either side of the sample cell.

In order to assess the suitability of the carbon fibres to remove aerosols, a selection of fibre-types, with varying diameter, were investigated. These included PAN-based carbon fibres ($6.9 \mu\text{m}$ diameter), pitch-based carbon fibres ($12\text{-}15 \mu\text{m}$ diameter) and vapour grown carbon fibres ($0.08 - 0.3 \mu\text{m}$ diameter). Carbon fibre mats were fabricated from either a single fibre type or a mixture of two fibre types. For the mats composed of two fibre types, one of the fibres was the vapour grown carbon fibre (VGCF). This was added primarily to enhance the particulate trapping efficiency, as previous studies have shown the importance of fibre diameter on the removal of particulates (Brown, 1993).

Activation and Characterisation

Modification of carbon fibres to impart vapour adsorbing properties was carried out by physical activation (Bansal *et al.*, 1988). Carbon fibres were heated at a rate of $5 \text{ }^{\circ}\text{C min}^{-1}$ to various temperatures between 750 and 950°C in a mildly oxidising environment, either carbon dioxide (CO_2) or steam (H_2O) at a flow

rate of 1 l min^{-1} , and held for 12 hours. The resulting physically activated carbon fibres were characterised by static adsorption techniques. Nitrogen adsorption at 77 K was carried out using an automated instrument (Omnisorp 100CX, Coulter Electronics Ltd.). Specific surface areas were derived from the isotherms using the BET equation (Gregg and Sing, 1982). Total pore volumes and the degree of microporosity and mesoporosity were obtained using the α_s method (Gregg and Sing, 1982). Water uptake was measured at 22°C using an automated instrument (Cisorp) between RH20% and RH95%. Hexane uptake at 22°C was measured using an automated instrument (Intelligent Gravimetric Analysis, Hiden).

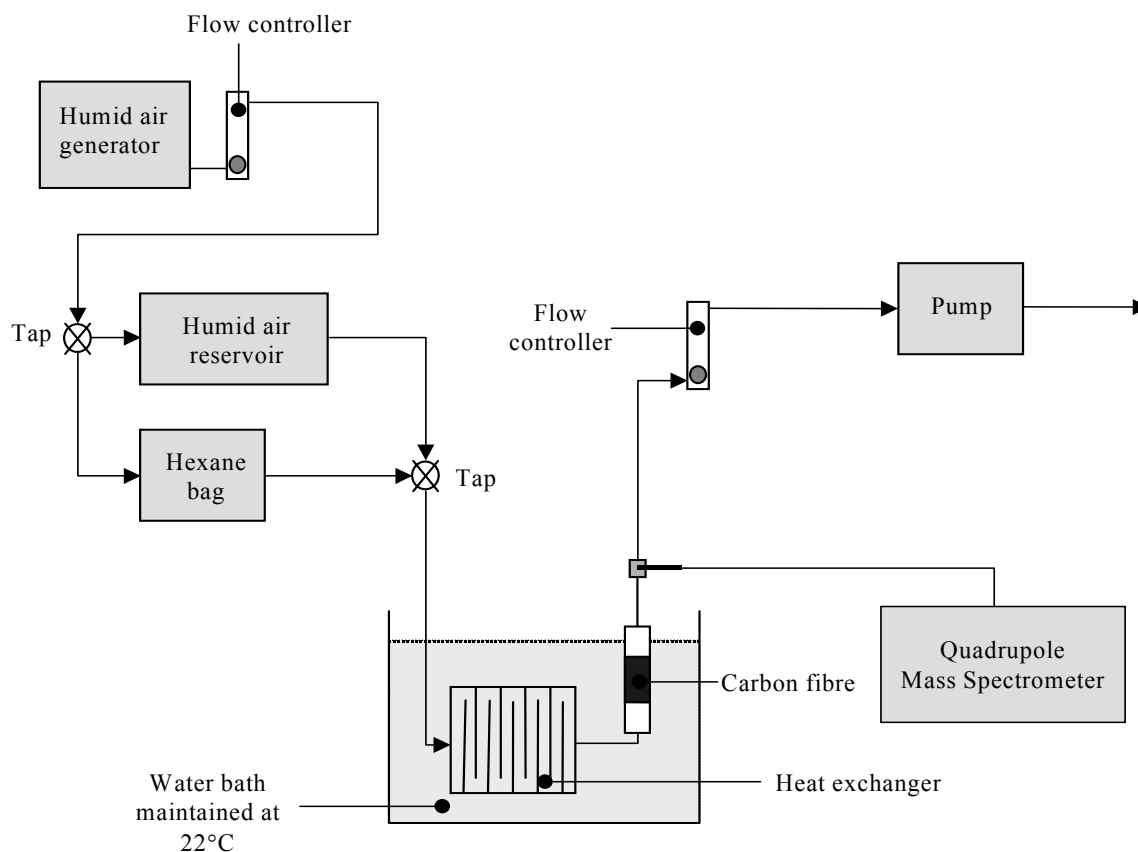


Figure 2. Dynamic filter testing apparatus.

Dynamic filter testing

The ability of the activated carbon fibres to remove vapours under dynamic conditions was investigated in both dry and humid conditions. Activated carbon fibres (0.8g) were mixed with water and wet laid into a volume analysis (VA) tube (2 cm diameter x 2.5 cm length) using a modified Büchner funnel technique. The fibres were then dried at 110°C in a vacuum oven for 4 hours. The apparatus used to test the activated carbon fibres is shown in Figure 2. The VA tube containing the fibres was placed in-line and challenged with 4000 mg m^{-3} of either dry or humid hexane, in air, at a flow rate of $1000 \text{ cm}^3 \text{ min}^{-1}$. Adsorbent testing was carried out at 22°C for all experiments. Effluent concentration was monitored using a quadrapole mass spectrometer (ESS Instruments). For the experiments under dry conditions both the hexane and activated carbon fibres were dry (RH < 5%). For the experiments under humid

conditions, the hexane was prepared to the required concentration using air of RH80%. The fibres were pre-wetted by placing them in an environmental chamber set at RH80% until they reached equilibrium.

Structural Integrity Studies

An insight into the strength of the activated carbon fibres was gained by physically grinding the fibres in a vibratory ball mill. Approximately 1 g of carbon fibre was placed inside a Retsch vibratory ball mill, type MM-2, which contained four stainless steel balls (2 x 7 and 2 x 12 mm diameter). The sample was shaken at a vibration frequency of ~ 500 per minute, for 10 mins. Fibres were examined before and after milling using an electron microscope.

RESULTS AND DISCUSSION

Particulate Performance

The variation in both the salt penetration and pressure drop as a function of the relative proportions of pitch-based carbon fibre and VGCF in the carbon fibre mats (25 g fibre mats), is shown in Figure 3. It is clear that as the proportion of VGCF is increased, the pressure drop across the filter mat increases. This was expected as the 'smaller' VGCF's are densely packed and fill any voids present in the mat. Salt penetration through the mat also increased with increasing proportion of VGCF. The smaller VGCF's were expected to enhance the particulate trapping efficiency of the mat, however, this was clearly not the case. The fibre mats that contained high proportions of VGCF were quite brittle and it is probable that leak paths are introduced through cracks formed during testing. The high initial pressure drop observed during analysis supports this.

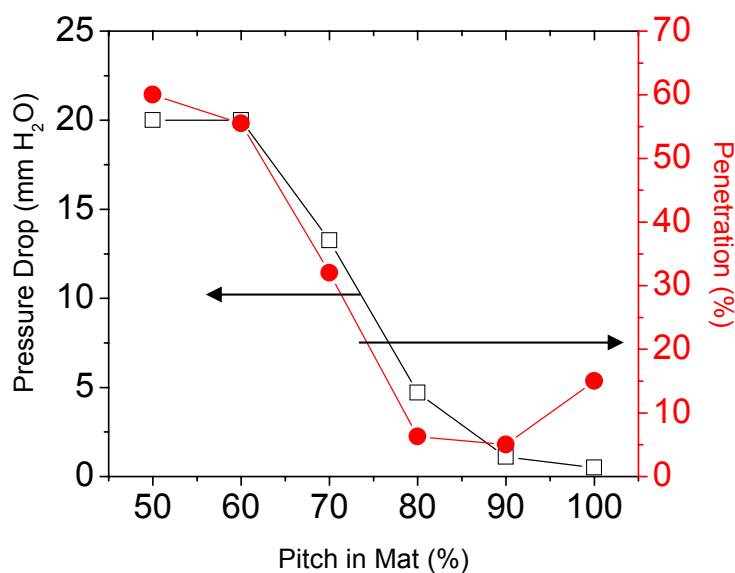


Figure 3. Particulate testing of pitch-based fibre, Pitch-1, / VGCF mats: comparison of pressure drop and salt penetration with proportion of pitch-1 fibre in mat.

For the PAN-based carbon fibre and VGCF mats (Figure 4) the results again show that as the proportion of VGCF in the mat is increased the pressure drop increases. However, there is no subsequent increase in the salt penetration and all the mat compositions give good particulate trapping efficiency (> 99 %).

The PAN-based carbon fibres are not as brittle as the pitch-based carbon fibres and the mats appear to be much more flexible and less densely packed even when they contain high proportions of VGCF.

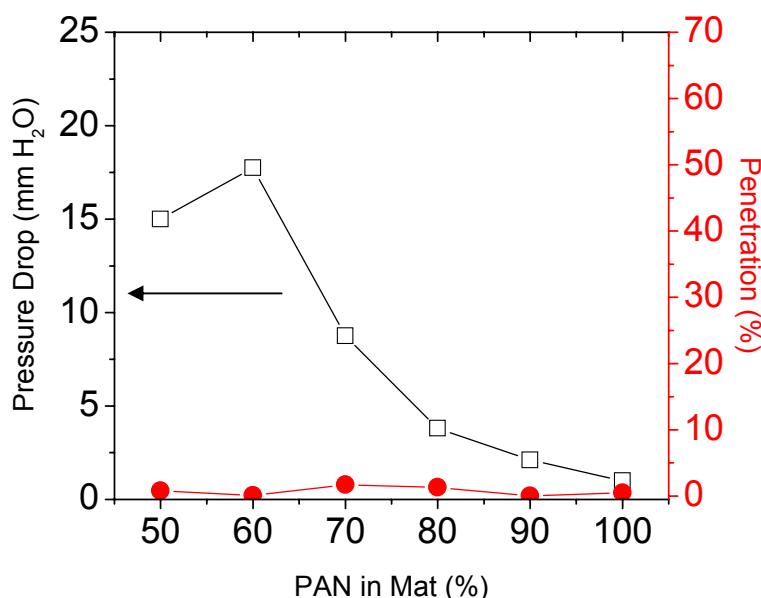


Figure 4. Particulate testing of PAN-based fibre, PAN-1, / VGCF mats: comparison of pressure drop and salt penetration with proportion of PAN-1 fibre in mat.

The results show that either the pitch-based carbon fibres or the PAN-based carbon fibres alone can effectively remove particulates without the addition of the smaller diameter VGCF's. The fact that VGCF's are not necessary is actually beneficial, as it is difficult to impart vapour-adsorbing properties to these types of fibres. This allows the complete carbon fibre filter media to be modified for vapour adsorption, thereby producing a truly combined particulate and vapour filter. The preliminary studies clearly show that even for carbon fibre mats made using an unrefined process, good particulate trapping efficiency can be achieved with a minimal pressure drop.

Activation and characterisation

Physical activation of the pitch-based carbon fibres proved successful and the results obtained are described below. Activation of the PAN-based carbon fibres by physical methods proved unsuccessful, with little increase in the porosity being observed even at high activation temperatures. At present alternative methods of activation are being pursued.

For the activation studies on the pitch-based carbon fibres, two fibres with similar characteristics, but from different suppliers, were investigated. Physical activation of the pitch-based carbon fibres was carried out in either CO₂ or steam. The physical characterisation data for the Pitch-1 and Pitch-2 pitch-based carbon fibres following activation, as determined from static adsorption measurements, are shown in Tables 2 and 3 respectively.

The nitrogen adsorption isotherms for both the Pitch-1 and Pitch-2 pitch-based carbon fibres activated using CO₂, between 750 and 950 °C for 12 hours, are shown in Figure 5. With the exception of the 750 °C activated fibres all the isotherms are BET type I in appearance, which is indicative of microporous

materials. The 750 °C activated fibre isotherm is type II, which is representative of a non-porous solid. This suggests that there is only a significant development of the porous structure above 750 °C. The nitrogen adsorption isotherms for the pitch-based carbon fibres activated using steam, between 600 and 900 °C, are shown in Figure 6. All the isotherms are BET type I, with the exception of the 600 °C activated fibre, which is type II.

Table 2. Physical characterisation data for Pitch-1 pitch-based activated carbon fibres activated at different temperatures for 12 hours in either CO₂ or steam

Sample	Burn-off (%)	Water Uptake (%) RH80%	Hexane Uptake (%) P/P ₀ =0.95	Specific Surface Area (m ² g ⁻¹)	Total Pore Volume (cm ³ g ⁻¹)	Micropore Volume (cm ³ g ⁻¹)	Mesopore Volume (cm ³ g ⁻¹)
<i>Carbon Dioxide (CO₂) Activation</i>							
750	11	11.8	0.5	50	0.040	-	-
800	14	14.2	0.9	353	0.155	0.131	0.024
850	26	25.3	21.3	798	0.319	0.313	0.006
900	43	44.1	31.8	1531	0.624	0.600	0.024
950	67	86.2	50.5	2110	1.007	0.914	0.093
<i>Steam (H₂O) Activation</i>							
600	14	11.5	0.1	57	0.031	0.020	0.011
700	14	14.9	5.5	116	0.060	0.043	0.017
800	20	29.9	9.1	763	0.277	0.267	0.010
900	72	74.6	61.5	1887	0.942	0.849	0.093

Table 3. Physical characterisation data for Pitch-2 pitch-based activated carbon fibres activated at different temperatures for 12 hours in either CO₂ or steam

Sample	Burn-off (%)	Water Uptake (%) RH80%	Hexane Uptake (%) P/P ₀ =0.95	Specific Surface Area (m ² g ⁻¹)	Total Pore Volume (cm ³ g ⁻¹)	Micropore Volume (cm ³ g ⁻¹)	Mesopore Volume (cm ³ g ⁻¹)
<i>Carbon Dioxide (CO₂) Activation</i>							
750	11	14.3	0.9	5	0.082	-	-
800	16	14.9	10.0	252	0.117	0.086	0.03
850	30	28.5	18.4	887	0.358	0.350	0.01
900	52	47.0	41.9	1670	0.689	0.658	0.031
950	71	87.7	62.6	2079	1.004	0.918	0.086
<i>Steam (H₂O) Activation</i>							
600	33	12.4	0.9	2	0.011	0	0
700	26	15.8	12.8	435	0.194	0.162	0.032
800	45	17.4	7.9	286	0.134	0.104	0.030
850	53	16.8	46.5	520	0.232	0.205	0.027
900	90	100.3	69.1	1806	1.020	0.937	0.083

A plot of the specific surface areas, as calculated from the BET equation, against the percentage of carbon removed during the activation process (burn-off %) for the CO₂ activated carbon fibres is shown in Figure 7. An almost linear increase in the specific surface area is observed with increasing burn-off (%). The trend is not as clear for the steam activated fibres (Figure 8). For either CO₂ or steam activation, activated carbon fibres with specific surface areas in excess of 1800 m² g⁻¹ could be produced.

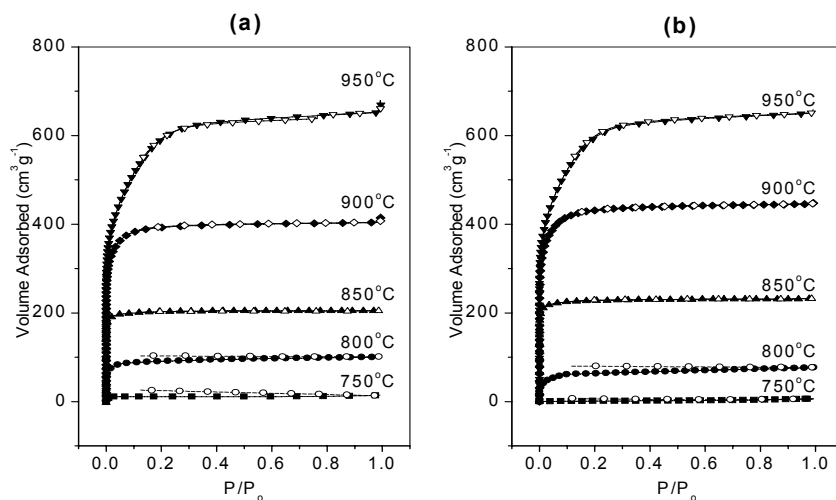


Figure 5. Nitrogen adsorption isotherms at 77K for (a) Pitch-1 carbon fibre and (b) Pitch-2 carbon fibre, activated in CO₂ at various temperatures for 12 hours.

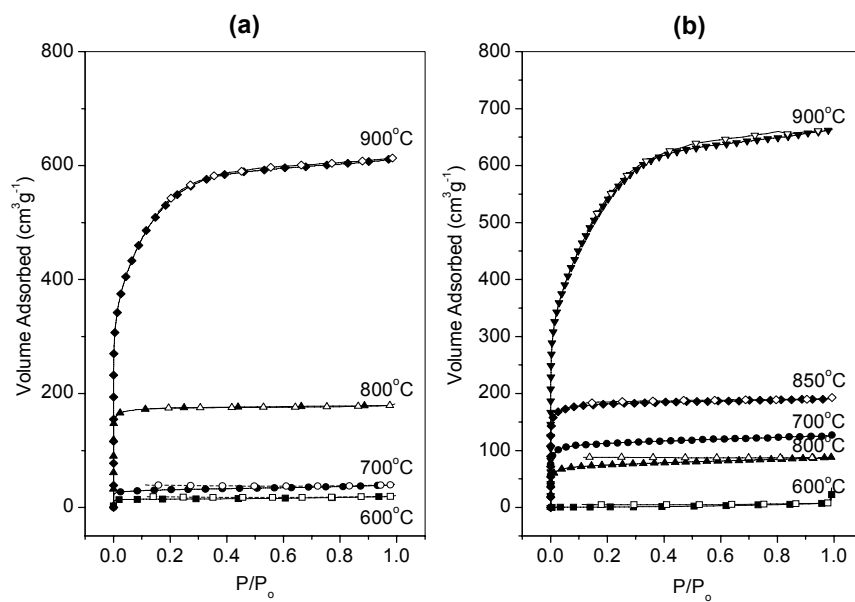


Figure 6. Nitrogen adsorption isotherms at 77K for (a) Pitch-1 carbon fibre and (b) Pitch-2 carbon fibre, activated in steam at various temperatures for 12 hours.

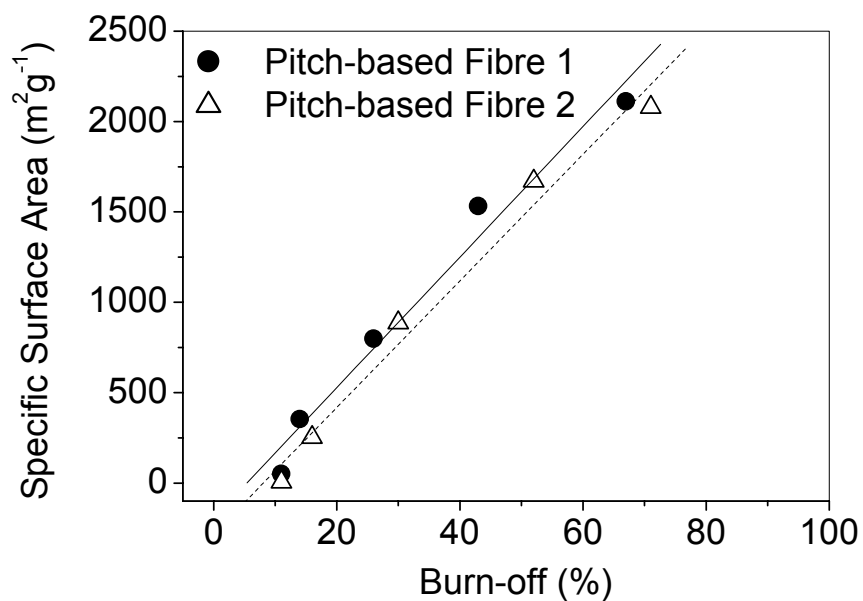


Figure 7. Variation in specific surface area with burn-off for pitch-based carbon fibres activated using CO₂ at various temperatures for 12 hours.

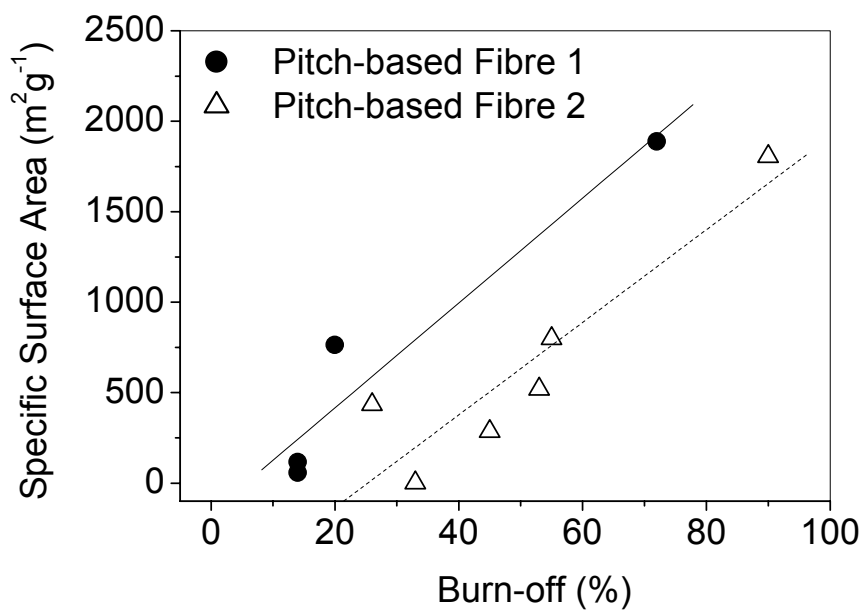


Figure 8. Variation in specific surface area with burn-off for pitch-based carbon fibres activated using steam at various temperatures for 12 hours.

The variation in micropore volume with burn-off (%) for the CO₂ and steam activated pitch-based carbon fibres is shown in Figure 9. Clear differences can be observed between porous structures of the activated carbon fibres prepared from the two mildly oxidising media. For the CO₂ activated fibres there appears to be an almost linear increase in the micropore volume with burn-off (%). However, for the steam activated fibres, microporosity was mainly formed during the initial stages of activation (< 20 % burn-off). Above this burn-off value little increase in micropore volume is observed until very high burn-off (> 60 %). The variation in mesoporosity for the CO₂ and steam activated carbon fibres is shown in Figure 10. Little change in mesoporosity is observed until very high burn-off values. This holds true for both the CO₂ and steam activated fibres and suggest that, at high burn-off, pore widening is occurring due to the gasification of the aromatic ring system.

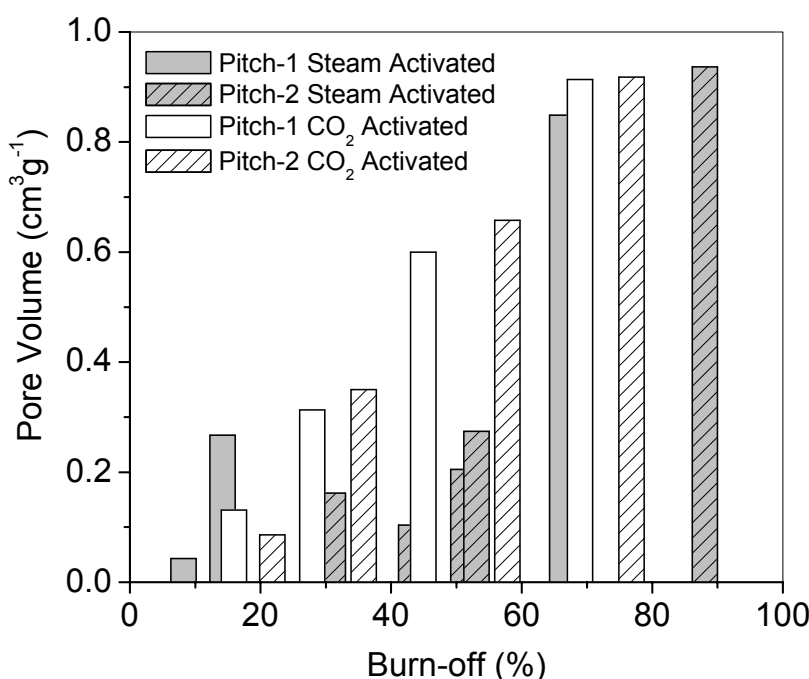


Figure 9. Variation in micropore volume with burn-off (%) for both the CO₂ and steam activated pitch-based carbon fibres

Adsorption of water vapour

It is well known that water has a detrimental effect on the ability of activated carbons to remove toxic vapours (Hall and Sing, 1988). Water adsorption on activated carbons is assumed to occur through hydrogen bonding to hydrophilic centres, located on the edge of aromatic sheets. Due to the polar nature of water, its adsorption on carbons is greatly influenced by the presence of polar surface groups, such as phenols, lactones and carboxylic acids. These groups can act as primary adsorption centres and, depending on the number of groups present, water adsorption tends to begin at higher or lower relative pressures.

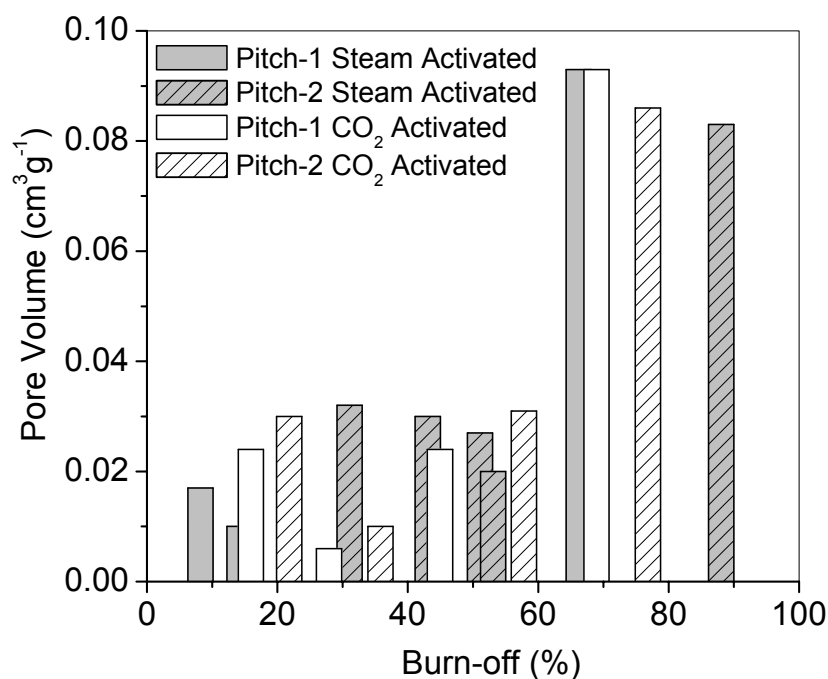


Figure 10. Variation in mesopore volume with burn-off (%) for both the CO₂ and steam activated pitch-based carbon fibres

Water adsorption isotherms (Figure 11) were obtained under static conditions at 22°C for both the CO₂ and steam activated Pitch-1 pitch-based carbon fibres. The water isotherms are all type V in appearance. Increasing the temperature of activation increases the uptake of water (Figure 12), and water adsorption begins at higher relative pressures. This suggests that at high activation temperatures surface functionality is removed and pore widening occurs. This is supported by the pore volume information obtained from the nitrogen adsorption isotherms, which shows that at very high burn-off, the structure becomes more mesoporous. The water isotherm for the 950°C CO₂ activated carbon fibres, and the 900°C steam activated carbon fibres are typical of materials with relatively large amounts of mesoporosity. The weight uptake of water was determined at RH80% which is typically used to represent a high relative humidity. The uptake at high burn-off is considerable, with the activated carbon fibre almost adsorbing its weight in water.

Adsorption of hexane

Hexane adsorption isotherms at 22°C were obtained under static adsorption conditions in order to obtain an understanding of the adsorption capacity of the activated carbon fibres for physisorbed non-polar species. The variation in weight uptake of hexane at a partial pressure of 0.95 with burn-off, for both the CO₂ and steam activated Pitch-1 pitch-based carbon fibres are shown in Figure 13. The results clearly show that as the burn-off (%) is increased there is a corresponding increase in the uptake of hexane. It is clear that the carbon fibres activated at high temperatures (900-950°C) have very high capacities for adsorbing hexane.

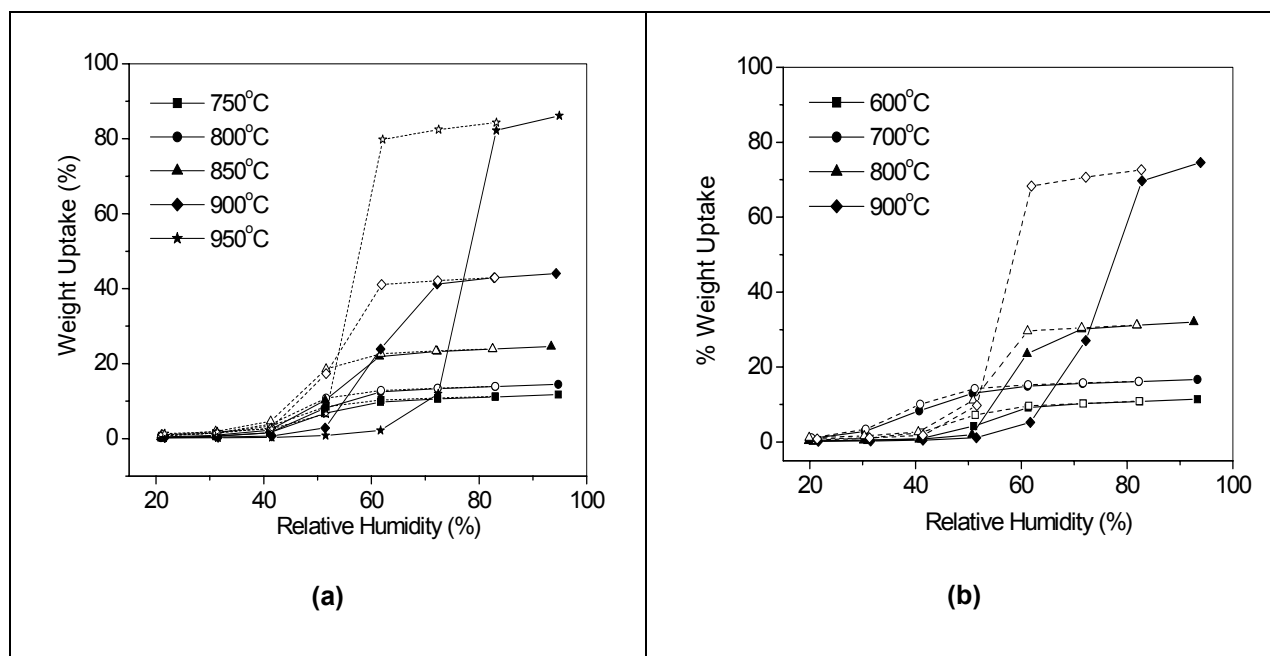


Figure 11. Water isotherms at 22 °C for Pitch-1 pitch-based carbon fibres activated using (a) CO₂ and (b) steam, at various temperatures, for 12 hours.

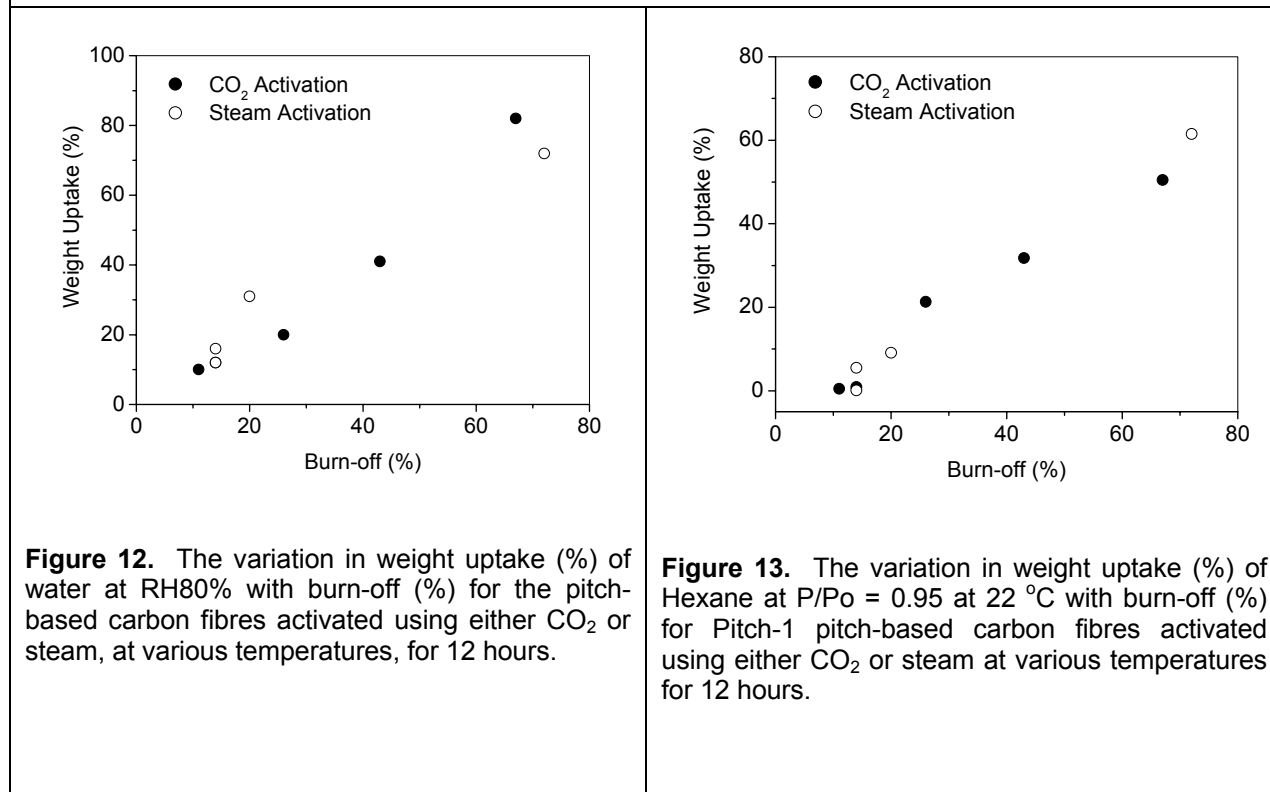


Figure 12. The variation in weight uptake (%) of water at RH80% with burn-off (%) for the pitch-based carbon fibres activated using either CO₂ or steam, at various temperatures, for 12 hours.

Figure 13. The variation in weight uptake (%) of Hexane at P/Po = 0.95 at 22 °C with burn-off (%) for Pitch-1 pitch-based carbon fibres activated using either CO₂ or steam at various temperatures for 12 hours.

Dynamic Filter Testing

Adsorption isotherms are typically obtained under static conditions on activated carbons that have been outgassed under vacuum. However, this does not give a clear indication of the ability of the adsorbent to remove vapours from flowing air. Therefore, the ability of the activated carbon fibres to remove a non-polar physisorbed vapour (hexane), under dynamic adsorption conditions was evaluated.

The breakthrough curves for Pitch-1 pitch-based carbon fibre activated in CO₂, under dry and humid conditions, are shown in Figure 14. The breakthrough curves for both the dry and humid hexane 'challenges' are similar in shape. However, the breakthrough times under humid conditions are considerably lower. From the shape of the breakthrough curves it is apparent that following the initial breakthrough, maximum breakthrough is achieved in a relatively short time. A plot of the time to breakthrough of hexane against burn-off (%) is shown in Figure 15. Under dry conditions an almost linear increase in the time taken for the hexane to breakthrough is observed with increasing burn-off. Under humid conditions the corresponding time to breakthrough is reduced when compared to the dry samples.

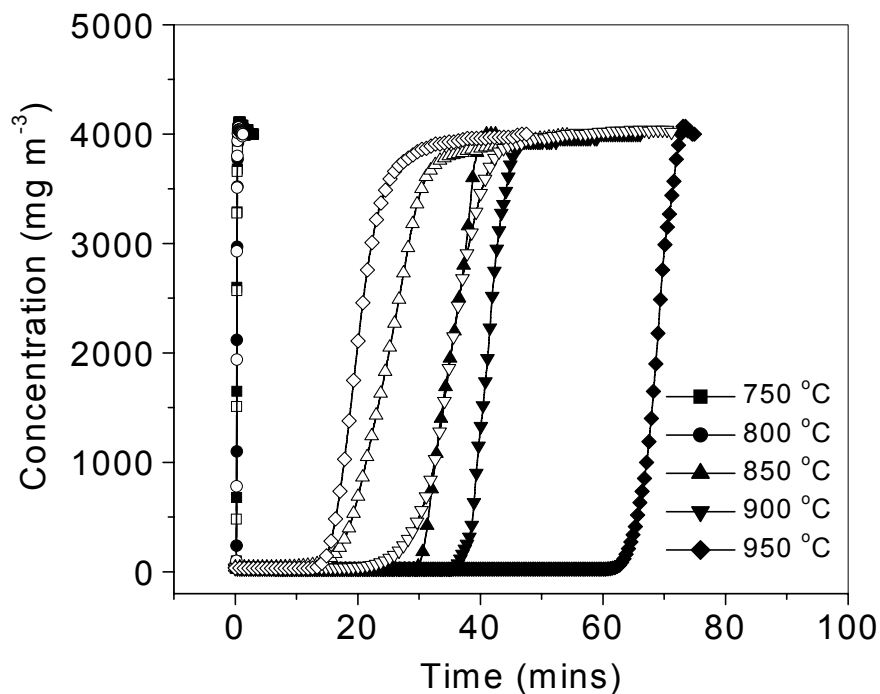


Figure 14. Dynamic hexane breakthrough profiles at 22 °C under both dry (closed symbols) and humid (open symbols) conditions for physically activated Pitch-1 carbon fibres.

It is also noticeable that for the activated carbon fibres with a burn-off of ~70 % the time to breakthrough is significantly reduced when compared to the corresponding value under dry conditions. It appears that an optimum burn-off exists that provides adequate performance under dry and humid conditions, in this case at ~45 %. The results clearly show the competing effect of water, and its detrimental effect on filter performance. The effects of water adsorption on filter performance have been described previously (Hall and Sing, 1988; Evans, 1999).

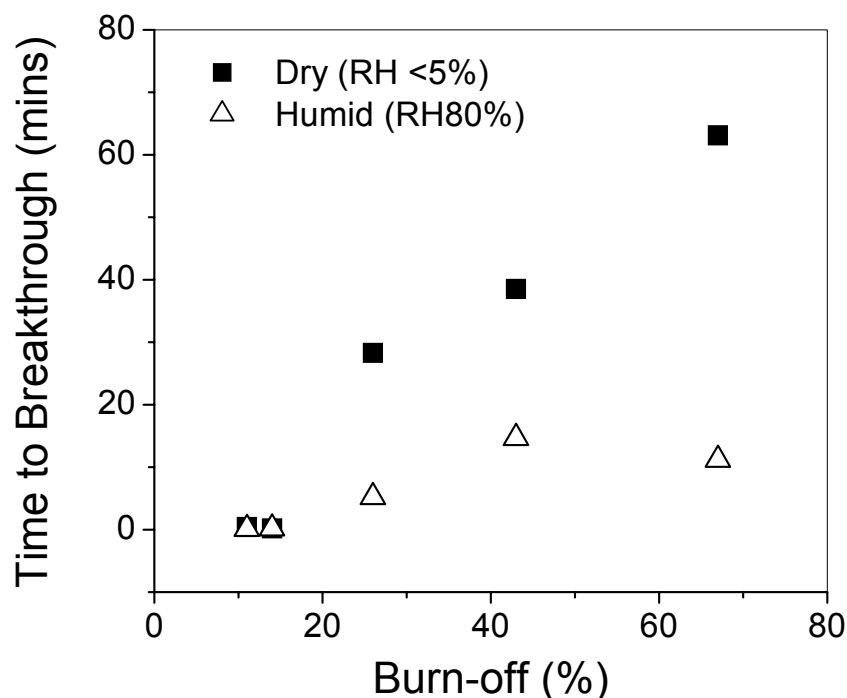


Figure 15. Variation in time to breakthrough with burn-off at 22 °C for the physically activated Pitch-1 pitch-based carbon fibres under dry and humid conditions.

Physical Structure and Structural Integrity

For successful particulate filtration the carbon fibre must retain its fibrous form following activation. The activation process removes large proportions of the carbon fibre mass and it is important that this does not have a detrimental effect on the physical structure. In order to determine the effects of activation on the carbon fibres, observations were carried out under an electron microscope.

SEM micrographs for the base, CO₂ activated, and steam activated carbon fibres are shown in Figure 16. The base pitch-based carbon fibre has a smooth fibre surface. The CO₂ activated carbon fibres appear to have extensive pitting randomly distributed over their surface, especially at high burn-off values (> 40 %). It is apparent that as the degree of burn-off is increased, the frequency and size of the pits formed is also increased. The origin of this pitting is uncertain. However, similar findings have been observed previously following the CO₂ activation of both Kevlar® and Nomex® fibres (Tomlinson *et al.* 1995). In this instance metallic residues on the fibre surface, such as copper (Cu), calcium (Ca), nickel (Ni) and potassium (K) were suggested as providing catalytic sites where localised gasification of carbon caused pitting.

The steam-activated fibres have much smoother fibre surfaces than their corresponding CO₂ activated fibres even at very high burn-off values (>80 %). Any metal impurities which caused pitting in the CO₂ activation study would be expected to be present on the fibre surface during steam activation, therefore pits would be expected in the steam activated fibres. However, this is not the case. Again, similar

observations were found with steam activated Kevlar® and Nomex®. The reasons for these differences may be due to steam activation occurring in the diffusion control regime.

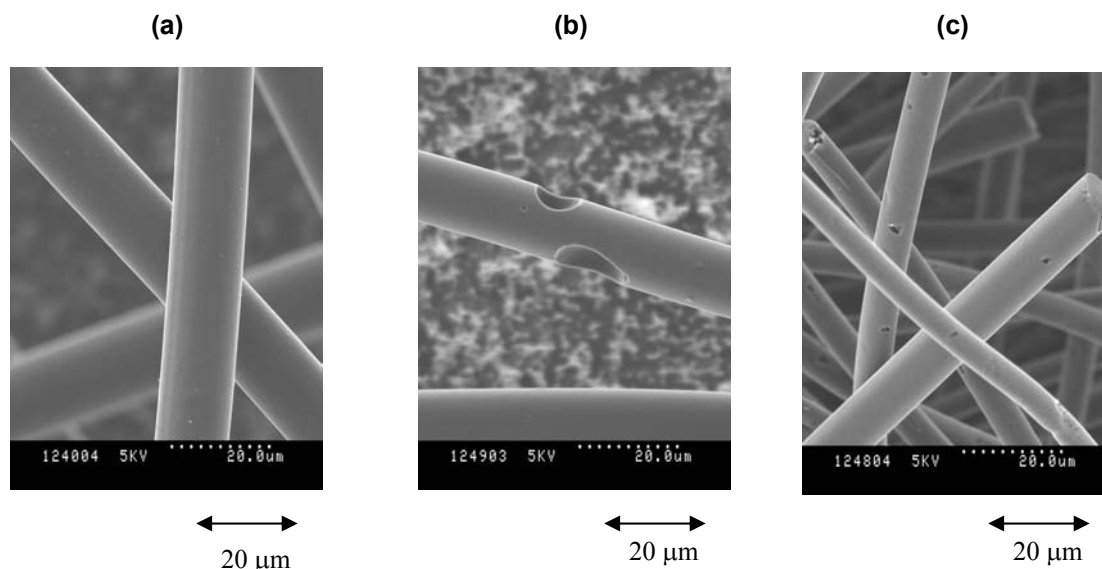


Figure 16. SEM micrographs for (a) base Pitch-1 pitch-based carbon fibre, (b) CO₂ activated Pitch-1 fibre (43% burn-off) and (c) steam activated Pitch-1 fibre (72% burn-off).

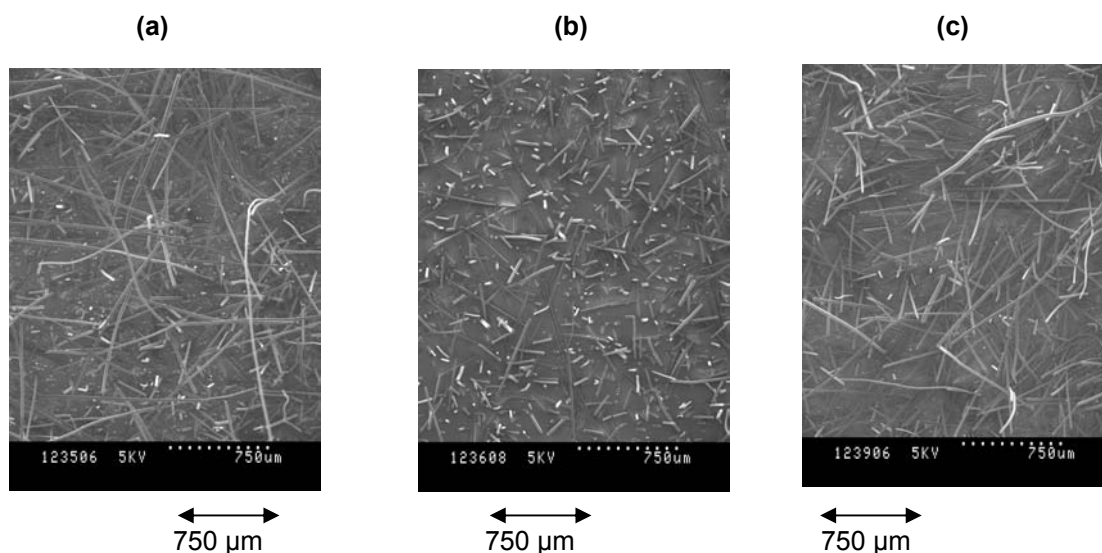


Figure 17. SEM micrographs for (a) base Pitch-1 pitch-based carbon fibre, (b) CO₂ activated Pitch-1 fibre (43% burn-off) and (c) steam activated Pitch-1 fibre (72% burn-off), following physical grinding in a vibratory ball mill for 10 minutes.

During use, the filter media in a respirator will be subjected to physical stress. Therefore, the fibres must be strong enough to withstand these stresses and remain intact. Carbon fibres are very strong prior to activation, however, following activation it has been shown that defects may be present. It is therefore important to assess how these defects affect fibre strength. Physical grinding of the Pitch-1 carbon fibres following activation was carried out in order to simulate 'rough-handling' of the filter media. The SEM

micrographs for the base, CO₂ activated, and steam activated fibres following physical grinding are shown in Figure 17. The base and steam activated carbon fibres remained intact following physical grinding. However, the CO₂ activated fibres broke up, indicating that CO₂ activation weakened the structural integrity of the fibre to a much greater extent than steam activation. This observation is in agreement with previous studies by several authors (Alcañiz-Monge *et al.*, 1994; Rodriguez-Reinoso *et al.*, 2000). The weakening of the CO₂ activated fibres is attributed to the creation of larger proportions of microporosity within the fibre. This leads to a deepening of the porosity and, therefore, to a greater number of defects within the structure. The retention of strength in the steam activated carbon fibres is due to the dominant mechanism being the widening of existing porosity from the external surface inwards, and not the creation of microporosity within the fibre. These observations suggest that steam activated carbon fibres have greater potential for applications where they may be subjected to large physical stresses.

CONCLUSIONS

This paper has discussed the potential for activated carbon fibres to be used for combined particulate and vapour filtration. Preliminary investigations have shown that carbon fibre mats have the potential to effectively remove aerosols from air streams, with a minimum associated pressure drop. Initial studies into the physical activation of PAN-based carbon fibres have proved unsuccessful. The pitch-based carbon fibres have been successfully modified to impart vapour-adsorbing properties. Activation studies have shown that activation temperature plays a significant role in determining the porous structure of the activated carbon fibre. CO₂ activated fibres appear to have greater proportions of microporosity compared to steam activated fibres, which have much wider pore size distributions.

Dynamic breakthrough tests have shown that, under dry conditions, activated carbon fibres are capable of removing non-polar physisorbed species from air streams for significant amounts of time. Under humid conditions the performance of the activated carbon fibres is reduced. Structural integrity studies have shown that the CO₂ activated pitch-based carbon fibres are brittle in comparison to the base carbon fibre, and those activated in steam.

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