

Particle Capture Processes and Evaporation on a Microscopic Scale in Wet Filters.

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Abstract

This paper details results of an experimental study of the capture of solid and liquid aerosols on fibrous filters wetted with water. A microscope cell containing a single fibre (made from a variety of materials) was observed via a microscope, with a high speed CCD camera used to dynamically image the interactions between liquid droplets, zeolite and PSL particles and fibres. Variable quantities of liquid irrigation were used, and the possibility for subsequent fibre regeneration after clogging or drying was also studied. It was found that drainage of the wetting liquid (water) from the fibres occurred, even at very low irrigation rates when the droplet consisted almost completely of captured particles. It was also found that the fibre was rapidly loaded with captured particles when the irrigation was not supplied. However almost complete regeneration (removal of the collected cake) by the liquid droplets occurred shortly after recommencement of the water supply. The study also examined the capture of oily liquid aerosols on fibres wetted with water. A predominance of the barrel shaped droplet on the fibre was observed, with oil droplets displacing water droplets (if the oil and fibre combination created a barrel shaped droplet), creating various compound droplets of oil and water not previously reported in literature. This preferential droplet shape implies that whatever the initial substance wetting a filter, a substance with a greater preferential adherence to the fibre will displace the former one.

1. Introduction

Wet filtration is a process whereby filter fibres are coated with a liquid film (usually water) during the filtration process (either artificially by jets, or naturally as a part of the influent aerosol). The carrier gas induces drag forces on the aerosol, and particularly on the droplets on the fibres. Aerosol particles are then captured by the liquid film, rather than being directly captured by the fibres. The advantage of this process is that the filtration efficiency is greatly increased, and the filter will usually be self cleaning provided sufficient liquid is available [1]. The technique has been successfully applied industrially to remove sticky, viscous particles for which filtration would not normally be possible as a conventional filter would become clogged [2]. It has also been found that the process inhibits aerosol bounce [3].

Studies have been conducted at the macroscopic scale, investigating the efficiency of the wetted fibre filter. However, there is very little work reported in the literature on the physical processes involved. Although the efficiency of wet filters for the removal of a wide range of particles has been studied previously [4], as has the clogging of filters by particles [5], evaporation rates [6] and particle bounce on wet filters [3], all these studies have been on a macroscopic scale, evaluating the performance of the entire filter, without examining the actual processes occurring inside the filter.

One of the reported advantages of wet filters is their ability to capture viscous, sticky or oily particles, which would normally clog a conventional air filter [2]. However the capture of oily particles by wet filters has not been studied previously on a microscopic scale.

The earliest work in the field of fibre wetting (which could be found by the authors) was with reference to the textile industry [7, 8]. The work was important as the drying, cleaning and long term durability of fabrics was an important issue for textile manufacturers. Such studies were mainly focused on a study of the nature of cleaning by surfactants, and the ability of substances to waterproof fabrics. Fibre wetting processes have since become important in wire/fibre coating processes, fibre composite systems, and more recently, nanotechnology. A microscopic study of the wetting and capture process is essential to a full understanding of the enhanced efficiency and self cleaning properties of the wetted fibre filter.

There are three distinct cases or shapes that occur when a droplet contacts a fibre: (a) Film flow (not very common, as the flow is usually broken into distinct droplets by Rayleigh instability); (b) a series of usually axisymmetric 'barrel' shaped droplets, commonly connected by a film (in the order of nm); and (c) axially asymmetric 'clamshell' shaped droplets. [9-15]. The stability of droplet shapes and their ability to retain their configuration (barrel/clamshell) has been examined in reasonable depth in the literature. The stability of asymmetric (usually clamshell) shaped droplets to retain their profile is given by [10], such that the droplet will only be stable if the droplet is large compared with the fibre diameter and the contact angle is comparatively small. Metastability to the 'roll-up' process (changing from barrel to clamshell) is reported to occur when the droplet volume decreases or the contact angle increases. It is further reported that for large drops with contact angles $<90^\circ$, the axisymmetric barrel shape will be stable for any fibre radius [15].

The forces which maintains a droplet at its location on a fibre has been reported in the literature as surface tension, interfacial tension, and more recently line tension. Line tensions are expressed as an excess free energy per unit length of the line of contact. It is reported that

for barrel shaped droplets, the line tension is a constant proportion of the free energy with respect to droplet size. However for clamshell droplets, the length of the three phase contact line depends on the droplet size so the line tension will influence the droplet shape [16].

Factors such as surface chemistry and surface roughness of the fibres can have a significant effect on wetting and wettability. Even the existence of local surface anomalies can mean that two completely different droplet profiles can exist on the same fibre. Most models assume a homogeneous fibre substrate, since this is the least complex case [15].

The bulk of previous fibre wetting and droplet research has been largely limited to static droplets on fibres (without any droplet flow, airflow or motion processes), usually without considering the effects of gravity or other external forces. Much of the past experimental work has utilised horizontal fibres, coated with oil, in a water solution, as such a case is most relevant to the textile field. Some important work has been accomplished previously, with respect to gravitational distortion of barrel shaped droplets on vertical fibres [17, 18]. It was found that different contact angles and surface profiles existed at the top and bottom of the droplets due to the gravitational effects, however the droplets remained axisymmetric. A recent study which examined the flow processes on angled fibres in wet filters on a microscopic scale, with consideration of drag and gravity forces was a useful first step in examining wet filtration processes on a microscopic scale [19]. This work showed that barrel shaped droplets even on vertical fibres become axially asymmetric under the influence of drag forces.

This study aims to examine the capture of both solid and liquid aerosols at a microscopic scale, by filter fibres wetted with water. The study will also consider the dynamic effects of

water build up on the fibre, and the subsequent flow down the fibre. This dynamic effect leads to the self cleaning properties of the filter. A further aim of the study is to examine fibre rewetting and 'cake' removal after evaporative drying.

2. Methods

2.1 *Experimental setup*

The experimental setup is shown in Figure 1. Clean dry compressed air was used to generate aerosols from two identical three-jet Collison nebulisers, one containing distilled water, the other containing either light white mineral oil (Sigma Chemicals M-3516), sieved zeolite catalyst dust (standard fresh FCCU catalyst), or an aqueous suspension of poly-styrene latex particles (PSL – Bangs Laboratories). The parameters for the aerosols used are given in Table 1. The compressed air supply provided sufficient air volume and appropriate aerosol loading, so no dilution was required. The airflow to each nebuliser could be adjusted, as could the flow from each nebuliser into the mixing chamber, and the aerosols were injected into the centre of the airstream. The air flow velocity through the cell could be varied between 0 and 9.0 m/s, although 5.0m/s was the highest velocity used during the experiments. Variations in the flow rate through each nebuliser did produce small changes in the mean diameter of aerosol generated; this change did not exceed more than $\pm 10\%$ over the range of flow rates used. The average air velocity through the cell was 1-2m/s during all experiments, although this was altered periodically to observe specific features of the process, which will be detailed later. Since this paper is predominantly qualitative then this is not a critical issue, however flow rates and experimental conditions for the evaporation experiments were kept constant.

A diagram of the experimental microscopic fibre cell is given in Figure 2. The air and aerosols were fed into the cell inlet, then through the cell being studied. The inlet and outlet were designed so as to make the flow field and velocity within the cell as uniform as possible

(this was verified by passing a smoke through the chamber during the design stage). The cells were placed in a Zeiss Standard 25 light polarising microscope (Zeiss, Germany) with a x10 objective lens, and a high speed CCD camera (Basler, Germany) attached.

2.2 *Fibres and cell configurations*

Details of the fibres used in the experiments are given in Table 2. Fibre diameters were determined by microscopy before placement in the cells, using a Zeiss Standard 25 light polarising microscope (100 fibres of each type were measured). Fibres were placed in cells by hand (using tweezers and latex gloves to ensure no possible surface contamination). All fibres used in the experiments were cleaned prior to use (with the exception of one set of stainless steel fibres) by washing the individual fibres in acetone, flushing of acetone with distilled water, and drying in an oven at 100°C (60°C for polypropylene). One experiment used stainless steel fibres which were coated with acetone then allowed to air dry – to make the fibres wettable to water – thus producing barrel shaped droplets. The fibres were located in the cell on double sided adhesive tape during placement, then clamped between the two halves of the cell, and the cell sealed with a neoprene gasket.

2.3 *Experimental Procedure*

At the beginning of each experiment, a cell with newly installed, clean fibres was placed in the microscope and connected to the air and aerosol supply. Each fibre was used in two scenarios, (a) wetted by water initially, then subjected to solid catalyst dust as the solid

aerosol, and (b) wetted by water, then subjected to white oil aerosol particles. Images were recorded using the CCD camera and microscope objective lens at 30-60frames per second (fps) - depending on the process being studied. After each cell was examined in an experimental run, it was replaced with the next cell, again containing a fresh fibre. The tubing between the nebuliser and the cell was replaced, and the mixing chamber cleaned and dried using compressed air to ensure no collected particulates, water or white oil was present on the walls to affect the results for the following cell.

2.3.1 Capture of solid particles on fibres wetted with water, and the evaporation process

For each fibre, the flow of aerosolised water was commenced and an equilibrium film or bead of droplets was established on the fibre; then the solid aerosol (zeolite dust) flow was also commenced. Images of the capture of particles under full water and solid aerosol flow were then captured by the CCD camera. After a period of time (usually 3 minutes) the water flow was discontinued (however the air and dust flow continued). Images of the process of droplet flow and particle capture under evaporation conditions were also captured by the CCD camera. This was continued until complete evaporation had taken place, at which point, dust flow was discontinued. The aerosol flow was then restarted to examine the re-establishment of the liquid film and subsequent regeneration of the fibre. Evaporation left a “cake” of aerosol particles on the fibre, and this was removed by the self cleaning property, as the regeneration proceeded. The fibre was also imaged when evaporation was complete, and the fibre was then imaged periodically during and after the regeneration process. This imaging process allowed fibre regeneration abilities to be determined. The capture, evaporation and imaging process was conducted 3 times for each fibre type, each time using a new fibre.

The capture of PSL particles was also studied in a similar manner (under steady state –non evaporation- conditions only). The PSL was dispersed in an aqueous suspension of water and supplied by the same nebuliser that was supplying the water for wetting purposes. The number of experimental runs for each fibre and experiment combination is given in Table 3.

2.3.2 Capture of liquid (oil) aerosols on fibres wetted with water.

The fibres were initially wetted with aerosolised water, until an equilibrium film or droplets had been established, following the same procedure as for the solid aerosol experiments. At this point the flow of aerosolised light white oil was commenced, and images were captured while both aerosols were being collected on the fibre. Either or both aerosol flows was discontinued periodically to observe particular behaviour (some droplets could only be imaged accurately with the aerosol flow stopped). Due to the very efficient generation of oil aerosol by the Collison nebuliser (Table 1), which is significantly greater than that for water, full flow could not be passed through the cell (for any length of time), otherwise all parts of the cell would become coated in oil. This severely inhibited the capture of images by the CCD camera and reduced the image quality of the images. Therefore the oil-nebuliser was often operated either intermittently, or using an adjustable “bleed” valve to dilute the flow (Figure 1). The number of experimental runs for each configuration is given in Table 3.

2.4 Image Analysis

A preliminary visual examination of the process and the individual frames captured by the CCD camera was undertaken to provide a qualitative description of the process and determine frames suitable for use in quantitative analysis. Analysis was conducted using the MATLAB Image Analysis Toolbox (Mathworks, USA). The toolbox allowed edge profiles of droplets and fibres to be determined using the 'canny' edge detection method incorporated in the toolbox. The droplet/fibre cross sectional areas were then determined in pixels and converted to size in μm^2 using the known resolution of the microscope and camera lens system (1pixel=0.7x0.7 μm). Fibres were assumed to be cylindrical (both when clean and when dust laden), and the droplets were assumed to be spherical.

3. Results and Discussion

The Results and Discussion have been divided into two main sections, (a) dealing with the capture of solid aerosols on fibres wetted with water, and (b) the capture of liquid (oil) aerosols on fibres wetted with water. It was found that regardless of fibre type, the fibres all showed similar general characteristics under these two cases. Unfortunately, the image quality was not as good as desired, even though high resolution, high speed equipment was used. The solid and oil aerosols tended to coat the optical glass, significantly reducing visibility. The images are, however, of sufficiently high resolution to observe the processes being investigated. The length scale of the images can be determined from images using the fibre diameters, given in Table 2. All images were taken from the same position with reference to airflow and gravity. In all images airflow, is from the left to the right of the image (parallel to the top and bottom of the image) and gravity is from the top to the bottom of the image (90 degrees separated from the airflow direction). All images are of the same resolution. The images taken at the 60fps frame rate tend to be “patchy”, however the reason for this is unknown. Figures 3-10 relate to the solid particle experiments while Figures 11-14 relate to the oil aerosol experiments. The results for the water do show spherical droplets, with deviations from this shape, near the water-fibre contact line. The spherical shape arises from the high surface tension of water, and the spherical assumption has been used previously [20].

3.1 Capture of solid aerosols on wet fibres

As shown in Table 1 and Table 3, two solid aerosols were used in experiments, PSL and zeolite dust. PSL was only used in conjunction with two fibre types (cleaned SS and glass), while zeolite dust was used with all 4 fibre types.

Figures 3-6 show the solid particle experiments under equilibrium (non evaporation) conditions. In all of Figures 3-6 the rate of influent water droplets was great enough so as to allow the filter to operate indefinitely and be continually self cleaning (although possibly not for the clamshell case (Figure 4)). Figures 3-5 are of droplets capturing zeolite particles, while Figure 6 details the capture of PSL (although individual particles are not visible – the particles create a general haziness within the droplet). Figure 3 shows a barrel shaped droplet of water on a coated SS fibre which has been collecting zeolite dust. Figure 4 shows zeolite particles at the centre of a barrel shaped droplet (non axisymmetric) – on a cleaned SS fibre, again with a water droplet collecting zeolite dust. Fibre types are given in the figure caption.

Since the PSL particles were generated at the same time and in the same nebuliser as the water, they tended to be distributed evenly throughout each droplet, with little or no clumping evident. The particles also maintained their respective position within droplets when the airflow was discontinued and the droplets were stationary, which is understandable since the density of PSL is very close to that of water (1060kgm^{-3}). For the zeolite particles, which were generated independently of the water aerosol, it was found that as the particles strike the surface of the wetted fibre, they usually remain on or near the surface. However some particles appear to migrate to the centre of the droplet, and others appear to move outwards, the most common case is for the particle clumps to remain at relatively the same radial

distance from the fibre or droplet centre. In the case of zeolite the particles tended to clump together, which differed markedly from the PSL case. Zeolite particles which had been captured on a fibre (without the presence of a droplet but possibly by a film) appeared to adhere relatively strongly to the fibre, even when a droplet subsequently became attached at the same location. This clumping of particles around the fibre even when a barrel shaped droplet is evident in Figure 3. In clamshell shaped droplets (Figure 4) some particles were observed to concentrate at the centre of the droplet, however the quantity of such particles is relatively small compared to the total amount of particles captured by the droplet.

The most interesting feature of the droplets on fibres – which was only discovered in the presence of particles to allow a point of reference – is the rotation of the entire droplet and any particles suspended within. All droplets above approximately $L=30\mu\text{m}$ radius were observed to rotate, and the rotation rate varied with air flow rate and fibre size. It was found that barrel shaped droplets tended to rotate in a plane perpendicular to the fibre. This is observable in Figure 3 through the movement of the suspended particles (circled in the figure). The particles (and entire droplet) are rotating clockwise in a plane perpendicular to the fibre. This is the initial rotation as airflow is commenced ($V_{\text{air}} \approx 0.2\text{m/s}$), captured at 30fps (0.033 seconds). The rotation rate (Ω) at this point is approximately 4 revolutions/second (Hz). The rotation is observed to commence almost instantaneously in conjunction with the start of the airflow, and Ω becomes larger as the airflow velocity is increased, yet stops almost immediately when air flow is discontinued. When the airflow is discontinued and droplet rotation stops, the particles (in the case of the zeolite dust) drift slowly downwards within the droplet under gravity. This is observable in Figure 5, where a clump of zeolite particles (shown by arrow) is drifting downwards (in the direction of gravity) at a rate of approximately $20\mu\text{m}\cdot\text{sec}^{-1}$. The particle clump is approximately $10\mu\text{m}$ in

diameter. The density of zeolite is approximately 2500kgm^{-3} , however the bulk density of the clump will be significantly lower. Another important consideration which can be ascertained from Figure 3, is that although the entire droplet and suspended particles are rotating, it is clearly observable that the particles connected to the fibre at the centre of the droplet remain stationary – these are droplets which have adhered to the fibre before the droplet was present. It was observed during experiments that zeolite clumps rotating near the stationary particles on the fibre, would occasionally become attached and then remain stationary. However, shortly later these particles would usually become re-entrained into the rotating droplet.

A similar process was observed in barrel shaped droplets (Figure 4), however the rotation of the droplet was predominantly in a plane formed by the fibre and the airflow direction (90 degrees apart from the rotation of barrel droplets). This is evident in Figure 4, although is more difficult to determine the exact rotation as there are a greater number of particle clumps, and the images have been captured during rapid droplet rotation ($V_{\text{air}} \approx 3.0\text{m/s}$) at 60fps (0.016 seconds). Although the droplet rotation is not in phase with the camera speed, it is evident that the droplet is covering approximately $\frac{1}{2}$ a revolution during each frame, which corresponds with $\Omega \approx 30\text{Hz}$. In this case the main particle clump at the centre of the droplet is also rotating, and the particle clumps are not remaining in precisely the same spatial relation to each other. The imaging of the process is exacerbated by the body oscillation of the droplet in a plane perpendicular to the fibre (this oscillation is discussed elsewhere [21]) – note the position of the droplet with reference to the fibre in each frame. A further effect was also noticed when two droplets are relatively close together on the fibre (Figure 6). Single isolated barrel droplets predominantly rotate in a plane perpendicular to the fibre, and clamshell droplets predominantly rotate in a plane formed by the fibre and the airflow direction. However, when two large droplets (of either type) were very close to each other on

a fibre, the upper droplet would always rotate clockwise and the lower would rotate counter-clockwise. This rotation effect can be explained by the airflow predominantly passing above and below the pair of droplets, thus inducing the rotation. This produces evidence pointing to the air drag force causing the droplet rotation. For the case of the pair of droplets, the air flow between the droplets is slightly restricted, thus leading to less air drag on the droplet surface in this area. This slight imbalance in the air flow field, and the drag force, is sufficient to affect the direction of rotation. The directions of rotation of each isolated drop is then likely to be influenced by any asymmetry of the air flow into the cell. Therefore all droplet rotation is induced by unevenness in the airflow in the cell and around the droplet, although this conclusion requires further study. The implications of this droplet rotation mean that the area of the droplet collecting the bulk of the solid aerosols is constantly changing, with a new “face” of the droplet continually exposed to the upstream side. Thus the droplet is continually cleaning its collection surface.

All barrel and clamshell droplets showed the same behaviour as above, dependent on the droplet type, rather than the fibre type to which they were attached. The barrel shaped droplets on the glass fibres behaved in the same way as the barrel shaped droplets on the coated SS fibres, and the clamshell shaped droplets on the polypropylene fibres behaved in the same manner as the clamshell droplets on the cleaned SS fibres.

There is some theory relating to rotating fluids (usually relatively large columns or cylinders) which supports these findings [22]. The dimensionless Ekman number (E), is the ratio of the viscous forces to the Coriolis force (essentially an “inverse” Reynolds number) and is given as,

$$E = \frac{\nu}{\Omega L^2}, \quad (1)$$

where L is a typical length scale such as the radius of the droplet, and ν is the kinematic viscosity of water ($1.004 \times 10^{-6} \text{ m}^2 \text{ s}^{-1}$ for pure H_2O at 20°C). The spin up time (t) of a volume of fluid from rest is given by ([22] p36),

$$t = \sqrt{\frac{L^2}{\Omega \nu}}. \quad (2)$$

A plot of t for the droplets in Figures 3 and 4, is shown in Figure 7. A range of Ω values are given as this varies with the air flow velocity, however the rates in the previous images were $\Omega \approx 4 \text{ Hz}$ for the barrel shaped droplet and $\Omega \approx 30 \text{ Hz}$ for the clamshell. It is evident that the spin up times even for relatively slowly rotating droplets is a fraction of a second, which supports experimental observations that spin up and spin down is rapid. The E values (Figure 8) are important because they relate to the thickness of the boundary layer between the rotating and non-rotating portions of the droplet. E values > 1 (and certainly values > 10) will mean that the entire droplet is rotating as one solid body, in effect almost a rigid body rotation. It is reported that for larger (than the scales we are dealing with here) columns of rotating fluid $E \ll 1$ is usually the case where rotation (of outer layers) is observed [22]. In the case of the clamshell droplet (Figure 4), the droplet size is larger (beginning to approach the rotating columns mentioned previously) and it is evident that E is approaching such values ($E=0.29$ at $\Omega = 30$). Therefore the larger droplets would be expected to behave less like a rigid body, demonstrated by the particle clumps in Figure 4 changing their respective positions (to one another) within the droplet as it rotates.

In the case of barrel shaped droplets, with the water and zeolite loadings given in Table 2, the fibres were self cleaning, even though the particle loading was quite high compared to the water aerosol loading. The droplets laden with particles frequently flowed down the fibres,

as found previously on fibres with barrel shaped water droplets uncontaminated by particles [19].

For the clamshell shaped droplets, no significant flow down the fibre occurred, however the large droplets showed a significant capacity to contain particulates, and frequently blew off the fibre (rather than flowing down) with any entrained particles. This case is not advantageous to self cleaning as it is likely to lead to re-entrainment of the particles back into the airstream. Since clamshell droplets do not have a film connecting the droplets, there was an increased likelihood for particles building up in the area of fibre between droplets. This supports previous work which found that wet filters composed of ‘nonwetable’ fibres (fibres which form clamshell droplets with water) were not effective at self cleaning compared to wettable filters (filters composed of fibres which form barrel shaped droplets or films with water) [5].

3.2 Particle capture and droplet flow under evaporation conditions

The work in Section 3.1 related to particle capture under equilibrium conditions – where particle loading is not sufficiently high or irrigation not sufficiently low that the fibre (at least in the case of fibres producing barrel droplets) will remain self cleaning indefinitely. The following phase of the experiment relates to operating conditions where the irrigation or water aerosol flow, was reduced or even discontinued, and induces evaporation, leading to ‘cake’ deposition on the fibre. In a real filter the severity of the cake deposition would be sufficient to significantly block the filter. Figure 9 shows a typical example of the capture and droplet flow process during evaporation conditions. Figure 9(a) shows a large droplet on

the fibre shortly after discontinuation of water flow. Note that the droplet is very cloudy from captured particles. The airflow had been temporarily stopped to improve image quality (normally 1-3m/s) for other images. Figure 9(b) shows the droplet 30 seconds later, already significant evaporation of the droplet is evident, and the droplet is now completely opaque from captured particles. Note that air and aerosol flow is still continuing, with the two particle removal processes evident – not only do the droplets remove aerosols which are directly captured, they also entrain aerosols captured by the already dried fibre as they move down. This is evident from close observation of Figure 9(c) and Figure 9(d) (shown by arrow) as the droplet moves down slightly some particles are observably entrained from the fibre into the droplet. Figure 9(e) Shows the point at which the droplet first stops flowing down the fibre, over one minute after the flow of aerosolised water was stopped, with Figure 9(g) showing the completely evaporated droplet with only captured particles remaining. At this point in all experiments all aerosol flow was stopped and clean, dry air passed through the cell to ensure that complete evaporation had occurred. At this point the flow of aerosolised water was re-commenced.

Figure 9(h) shows the first droplet to reach the ‘clump’ of particles once flow has been restarted. Although difficult to determine from the image, Figure 9(i) shows the droplet completely encompassing the ‘clump’ of particles left by the dried barrel shaped droplet, which is contained in the upper half of the new droplet. Figure 9(j) shows the fibre 1 minute after Figure 9(h), immediately after the first droplet has flowed down the fibre, and it is evident that the passage of one droplet has almost completely removed the clump of particles. An interesting finding, which was found throughout all evaporation experiments, was that particles deposited as part of evaporating droplets were much more readily removed than particles deposited directly on to the fibre. This is easily explained in terms of the forces

involved. A particle which impacts a liquid droplet and subsequently is dried onto a fibre (by an evaporating droplet) will possess a much weaker adhesion to the fibre than a particle which has directly struck and adhered to a dry fibre. This is because of the significant ability of the droplets to absorb the collision forces which is a finding from previous (macroscopic scale) work [3]. Figure 9(k and l) show the continuation of the regeneration process, and that, although significant regeneration occurred, it was not complete, as much of the directly deposited particles could not be removed.

The images of each fibre from each experiment were analysed in the Image Processing Toolbox; initially when coated with a cake of particles, then after sufficient operating time under water flow, when it was judged that no further cake removal was occurring. For each of the two cases the fibre cross sectional area was determined, and converted into a cylindrical measure of the cake volume (the fibre volume was subtracted). The difference between the ‘cake’ and ‘clean’ volumes of the collected particle mass was used to determine the percentage regeneration values, according to,

$$R = \left(\frac{V_{CA} - V_{CL}}{V_{CA}} \right) \times 100, \quad (3)$$

where R is the percent regeneration, V_{CA} is the cake volume and V_{CL} is the cake volume after ‘cleaning’ (when no further particle removal from the fibre is occurring). A quantitative study of the regeneration process is given in Table 4. Although the total bulk of collected solid particulates was not the same between different fibres, the comparison is examining the percentage values of the collected particles which could be removed, thereby allowing a comparison in the regenerative abilities of different fibres.

The fibres with barrel droplets showed a significantly greater ability to regenerate fibres than those with clamshell droplets (see Table 4). It is likely that the main reason for this is the far greater droplet and film coverage of the fibre in the barrel case, making it less likely that a particle will strike a 'dry' section of fibre (devoid of droplets or film). A second reason is that in the barrel case, there is a greater portion of each droplet on the upstream side of the fibre, allowing more effective absorption of the impact forces before a particle can contact the fibre. Both of these reasons will mean that any cake which forms on a fibre containing clamshell droplets is likely to be denser and thus more difficult to remove. Of the fibres which form barrel shaped droplets (with water), the glass fibre was the most effective at regeneration, possibly due to the more frequent flow down the fibre. The regeneration times are given as approximate values (to the nearest minute) since it was difficult to determine the actual time at which all regeneration that was possible to occur had taken place.

3.3 *Capture of oil aerosols on wet fibres*

When droplets of a pure liquid collect on the surface of a fibre, they form either into a clamshell or barrel shape, with a smooth, defined surface. It has been found in the previous section that the presence of solid particles in the liquid does not significantly alter the shape of the droplet. However, in the case of the capture of oil droplets on fibres wetted with water, several 'compound' droplet shapes were found to occur, often as irregular, non-uniform droplets. It would be incorrect to term these as emulsions, as the water and oil components remained relatively separate, not completely mixed, which is the usual definition for an emulsion.

The observations from the oil and water experiments are shown in Figures 10-13. It is difficult to determine the differences between the oil and water droplets from the greyscale images of the experiments (the distinction is clear using the colour images with the phase contrast microscope used). However the distinction will be explained in the text. All fibres were wetted with water initially, forming either clamshell or barrel droplets, depending on type of fibre (Table 2). There were marked differences between the compound droplet shapes (created between the oil and water aerosols) on the four different fibres used. However there was one significant finding which was common to all fibre types - whichever fluid the fibre was wetted with initially (oil or water), the ultimate overall droplet shape would be a barrel, as this appeared to be the most preferential shape which allowed the droplet to adhere most strongly to the fibre. Therefore, if a fibre was wetted initially by a liquid (oil or water) which created clamshell droplets with the particular fibre, then the opposite liquid added (which normally created barrel shaped droplets), the barrel shaped droplets would displace the clamshell (if the clamshell volume was large) and the clamshell droplet would be attached to the outside of the barrel droplet, or be shed from the fibre. If the clamshell volumes were small (i.e. then the barrels would tend to encompass them). Emulsion-like combination droplets were also sometimes observed, however these generally separated into their component liquids. This phenomenon of barrel shaped droplets displacing clamshell droplets is most easily shown by Figure 10. Figure 10(a) shows a water-clamshell droplet on a polypropylene fibre. As oil aerosol contacts the fibre, it can be observed that the contact angle decreases (Figure 10(b)), until eventually, when enough oil is coating the fibre, (Figure 10(c)), the droplet has “rolled out” from a clamshell into a barrel shape. However the droplet is now a “compound” droplet of oil and water. In the main droplet of Figure 10(c), a crescent shape is discernible on the droplet. The water exists as an

almost spherical “ball” from the crescent shape to the right hand side of the droplet, while the remainder of the droplet is oil, including the portions creating the contact angle with the fibre. If the water flow was reduced relative to the oil flow, or the velocity increased, the water droplets would be evaporated or shed from the fibre – either by being blown off or flowing down the outside of the oil droplets.

Figure 11, of a coated SS fibre demonstrates the largest and most unusual droplets observed. The images have been heavily analysed using the MATLAB Image Analysis Toolbox, and unfortunately they are of the lowest image quality. This experiment used the highest loading rates of oil and water aerosol, and there were problems with oil-coating of the optical glass sides of the cell and these problems were more severe than in the other experiments. The fibre initially had barrel shaped water droplets on its surface. As oil aerosols landed on the water droplet, they were observed to “skate” across the surface of the water droplet (not discernible from the image), until they coalesced into clamshell droplets. These clamshell oil droplets often existed in the middle of barrel shaped water droplets (Figure 11(b)). In Figure 11(a) and Figure 11(c) it is difficult to determine the difference between clamshell and barrel shaped droplets, as the droplets are pulled off the fibre in the direction of airflow, making them all axisymmetric (although some have been highlighted).

In the case of the cleaned SS fibres (Figure 12), the initial clamshell shaped water droplets (Figure 12(a)) were again ‘rolled back’ (as in Figure 10) to create barrel shaped oil droplets (Figure 12(d)). However, rather than the water droplets being pushed to the outside of the newly formed oil droplet (as in Figure 10 with the polypropylene fibre), small clamshell shaped water droplets remained contacting the fibre, and are discernable in Figure 12(c). Most of the water droplets, either blew off the fibre or flowed down. It will be noted that in

this case, the compound droplets are an irregular shape, unlike the droplets in previous images. This case was rather different to the others, as the water or oil was less likely to coalesce into separate liquids. Therefore this case produced droplets closest to emulsions – with multiple droplets of oil or water existing inside a droplet of water or oil respectively. This behaviour was responsible for producing the irregular droplet shapes found.

In the case of the glass fibre (Figure 13), the water remained on the fibre in small barrel shaped droplets, with the oil collecting as separate barrel shaped droplets that appeared to be located outside of the usual water film joining the barrel shaped water droplets.

It is evident that the barrel shaped droplet is a preferential case for oil and water on fibres, with oil displacing clamshell shaped water droplets and vice versa. This droplet displacement did not occur on the glass and coated SS fibres for which water formed a barrel shape, which supports the theory. A quantity work has been undertaken and reported in literature, to determine preferential formations or energetic states for droplets [11, 15, 16]. The barrel shaped droplet has a greater adhesion force to the fibre, and has a greater “preference” (i.e. is more ‘philic’ – hydrophilic or lipophilic) to adhere to the fibre than does a clamshell droplet, thus has the ability to displace clamshell shaped droplets on the fibre.

4. Conclusion

There are a number of conclusions useful to wet filtration, which can be drawn from this work. The mechanisms of solid particle capture and fibre cleaning by water droplets, both directly capturing particles and entraining and cleaning particles from the fibre is important to the understanding of the process. The motion of captured particles within droplets is also relevant, as well as the persistent flow of droplets when saturated with particles while the droplet is evaporating.

If wet filters are allowed to dry (and ultimately clog), then particles deposited by evaporating droplets appear easier to regenerate, than dust deposited directly onto fibres. This is due to the greater ability of the water droplets (compared to the bare fibre) to absorb the particle impact forces, making the resulting adhesion weaker. Fibres with barrel shaped droplets are also better able to regenerate than those with clamshell droplets, most likely due to the usual lack of a film joining clamshell droplets, allowing a greater number of particles (than for the barrel case) to be captured directly by the fibre, rather than by droplets.

There is significant evidence that the barrel shaped droplet is preferential on fibres where both oil and water are used, and will form regardless of the fluid which was initially wetting the fibre. This has implications for the collection of viscous oily aerosols on fibres which form barrel or clamshell shaped droplets with water. In the former case the oil particles would be easily removed, whilst in the latter they would tend to form clamshell droplets, clogging the filter.

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TABLES AND FIGURES

Table Captions

Table 1. Aerosols used in experiments – all generated using a 3-jet collision nebuliser. Note particle concentrations measured immediately post nebuliser.

Table 2. Fibres used in experiments.

Table 3. Number of experimental runs with each fibre type and experimental method. Each experimental run had a duration of 5-30 minutes.

Table 4. Fibre regeneration ability for zeolite dust.

Figure Captions

Figure 1. Experimental setup.

Figure 2. Experimental cell.

Figure 3. Rotation of barrel droplet (and captured particles) around fibre. Fibre is stainless steel (coated), particles are zeolite dust, liquid droplet is water, $V_{\text{air}} = 0.2 \text{ ms}^{-1}$. Each image (a-f) is 0.033 seconds apart. Note that the captured particles adhering to the fibre remain stationary while the particles in the liquid rotate with the liquid drop in a clockwise direction when viewed from above. Representative particles have been highlighted to show rotation.

Figure 4. Rotation of clamshell droplet (and captured particles) around the centre of the droplet (in the plane of the image). Fibre is stainless steel (cleaned), particles are zeolite dust, liquid droplet is water, $V_{\text{air}} = 3.0 \text{ ms}^{-1}$. Each image (a-f) is 0.016 seconds apart. Note that the particles in the liquid rotate with the liquid drop in a clockwise direction.

Figure 5. Captured particles within barrel droplet falling under gravity ($V_{\text{air}}=0\text{ms}^{-1}$). A single clump of particles is highlighted (arrow). Particles are zeolite dust, droplet is water, fibre is SS (coated), and airflow is switched off. Figure (b) is 2 seconds after Figure (a), and figure (c) 5 seconds after Figure (a).

Figure 6. Counter rotation of twin barrel droplets – not discernible due to resolution, direction of rotation shown by arrow. Droplet is water, fibre is glass, particles (not individually visible) are PSL. $V_{\text{air}}=0.2 \text{ ms}^{-1}$.

Figure 7. Plot of spin up time (t) against rotation rate (Ω), for the barrel and clamshell droplet sizes in Figures 3 and 4 respectively. A range of Ω values is given as the final Ω is dependent on the air flow velocity.

Figure 8. Plot of Ekman number (E) against rotation rate (Ω), for the barrel and clamshell droplet sizes in Figures 3 and 4 respectively. A range of Ω values is given as the final Ω is dependent on the air flow velocity.

Figure 9. Particle capture processes during barrel droplet evaporation. $V_{\text{air}}=1-3\text{ms}^{-1}$
Figure (a) droplet heavily laden with captured particles shortly after water flow discontinued – (taken as 0 seconds – all times cumulative from $t=0$ at (a)). (b) Air and solid aerosol flow only continuing (30 seconds later) – flow down fibre still continuing. (c) Demonstration of particle entrainment from fibre into droplet (30.5 seconds) - demonstrated by comparison with (d) Note that the droplet has moved slightly down the fibre and ‘cleaned’ a section of fibre (30.533 secs). (e) Droplet motion down fibre has completely stopped (60 seconds) – droplet is now heavily laden with particles. (f) Significant drying of the droplet has occurred (75 seconds later). (g) All moisture now evaporated (105 seconds). (h) Liquid aerosol flow recommenced (225 seconds (2 minutes allowed to ensure complete evaporation)). (i) Particulate mass still attached to fibre, in upper half of droplet (245 seconds). (j) Droplet has just flowed down removing majority of particulate mass (was located where thinnest fibre portion now is)(275 seconds). (k) 455 seconds, note the decrease in fibre thickness, droplets still cleaning particles. (l) 15 minutes later (22mins 35 secs).

Figure 10. Polypropylene fibre – oil and water. (a) clamshell shaped water droplet, (b-c) increasing oil decreasing water), (d) oil only – water partly shed partly evaporated, note oil droplets with water droplet on right hand side in (c) (shown by arrows).

Figure 11. Water and oil particulates captured simultaneously on the same fibre (shown by arrows). Fibre is stainless steel. (a) multiple clamshell/barrel droplets (oil/water respectively) connected together ($V_{\text{air}}=1.5\text{m/s}$). (b) barrel shaped water droplet and clamshell shaped oil droplet at the same location ($V=0\text{m/s}$). (c) large combination droplet ($V_{\text{air}}=1.0\text{m/s}$). MATLAB edge detected profiles have been overlaid on images to improve clarity.

Figure 12. Cleaned SS fibre with oil and water. (a) predominantly water (b) upper droplet is mainly oil (with some small water droplets), lower is mainly water (with some small oil droplets) – droplets close to “emulsions”. (c) predominantly oil – note small clamshell shaped water droplets adhering to fibre in the middle of large (main) oil droplet (some water droplets shown by arrow). (d) completely oil – all water evaporated or shed from oil droplet.

Figure 13. Glass fibre – oil and water. The oil is contained within the barrel shaped water droplets, and is not individually discernible.