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Modelling liquid saturation in filters collecting liquid aerosols

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Abstract:

The removal of (oil) mists from air streams is important in many industrial applications, such as machining and cutting operations, engine closed crankcase ventilation, and compressed gas cleaning. Filters are by far the most efficient device for removing such particles, however, the filtration of liquid aerosol particles differs so greatly from dust filtration that it is almost a field in itself, and there remain many questions which have not been fully resolved. This is predominantly due to the ability of the (liquid) aerosol particles to coalesce into droplets (and often liquid columns) within the filter, and then drain from or flow through the filter, under the influence of airflow and gravitational forces.

This work details the development of a capillary-based model for the prediction of saturation in (oil) mist filters. Experiments were conducted to determine steady-state saturation and pressure drop values in commonly used oleophillic micro-glass fibre media, using a range of different combinations of face velocity and number of layers of media within the filter element.

A novel capillary-based model was developed and fitted to experimental data, with the aid of a genetic algorithm. The model predicts filter equilibrium saturation, if the fibre diameter, packing density, and pressure drop across the filter are known. The model showed a very good agreement with experimental data, when a small correction factor was added to the model.

It is hoped that this work will assist in the advancement of mist filter theory, and the optimisation of such filter systems.

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Keywords: *Filter, Oil-mist, Capillary,Washburn-equation,Saturation, Genetic Algorithm.*

1. INTRODUCTION

The removal of (oil) mists from air streams is important in many industrial applications, such as machining and cutting operations, engine closed crankcase ventilation, and compressed gas cleaning. Filters are by far the most efficient device for removing such particles, however, the filtration of liquid aerosol particles differs so greatly from dust filtration that it is almost a field in itself, and there remain many questions which have not been fully resolved. This is predominantly due to the ability of the (liquid) aerosol particles to coalesce into droplets (and often liquid columns) within the filter, and then drain from or flow through the filter, under the influence of airflow and gravitational forces.

As liquid aerosol particles are collected by fibres in a filter, they form an initial, very thin, film on the fibres. However, such films are usually broken up by Plateau-Rayleigh instability. It has been stated (Quere 1999) for cylindrical fibres that stable films, without droplets, can only exist on fibres when the axisymmetric wavelength (λ) – usually equivalent to the droplet spacing – is *less* than,

$$2\pi(r_f + h), \tag{1}$$

where r_f is the radius of the fibre and h is the film thickness. The final axisymmetric wavelength is usually,

$$\lambda = 2\pi\sqrt{2}r_f. \tag{2}$$

Therefore the upper limit at which a film can exist on the fibre can be written as,

$$2\pi\sqrt{2}r_f = 2\pi(r_f + h), \tag{3}$$

thus imposing a limit on h of,

$$h = r_f\left(\sqrt{2} - 1\right). \tag{4}$$

However, in practice it has been found that in filters the limit is even further reduced due to the action of airflow forces to assist the film break-up. It is therefore evident that films surrounding fibres are rare, and have only been observed in exceptional cases (Agranovski and Braddock 1998; Mullins, Agranovski et al. 2004; Mullins and Kasper 2006).

The presence of these droplets within the filter, greatly increases pressure drop, and (in most cases) has been found to decrease efficiency - especially in the diffusional collection regime (Letts, Raynor et al. 2003). Therefore it can be viewed that the accumulated liquid content of a mist filter is of paramount importance, as saturation influences both pressure drop and collection efficiency. Saturation (S), can be defined as,

$$S = \frac{V_o}{V_f \cdot (1-\alpha)}, \tag{5}$$

where V_o is the volume of oil contained within the filter, V_f is the total volume of the filter, and α is the packing density (fraction of V_f filled with fibres).

S is especially critical, since most mist filter systems operating in stable flow and mass loading conditions will attain a steady-state, where influent (captured) mass is equal to the mass of coalesced liquid draining from the filter. Once this point is reached, S will remain constant, and consequently so will pressure drop and efficiency (for a given set of constant operating conditions). Decreasing S will (usually) increase efficiency and decrease pressure drop (both of which are the ideals of filter design).

There have been several attempts to model such systems. Raynor and Leith (2000) presented the most detailed treatment of the issue, and derived empirical equations to allow the prediction of efficiency, saturation and pressure drop in mist filters. They were able to predict equilibrium (steady-state) Saturation (S_e) using,

$$S_e = \frac{\alpha^{0.39}}{Bo^{(0.47+0.24\ln(Bo))}Ca^{0.11}} e^{\left(-0.04+6.6\times10^5 Dr\right)}, \tag{6}$$

where Bo is the bond number, Dr is a drainage term, and Ca is the capillary number, given as,

$$Ca = \left(\frac{\mu_g u}{T} \right) \times 10^5, \quad (7)$$

where μ_g is the gas viscosity, u is the gas velocity, and T is the liquid surface tension.

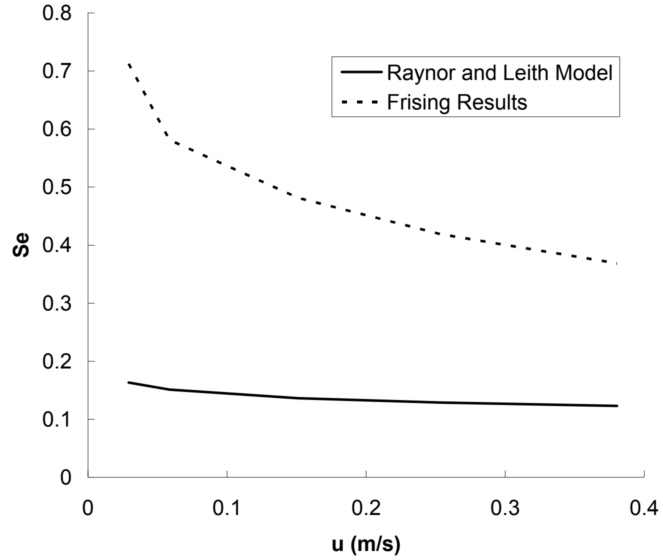

Figure 1. S_e vs u relationships for experiments conducted by Frising et al (2005) and values predicted by Raynor and Leith (2000) model (for different media parameters, however the same velocities.

While the above work was an important step forward, it has since been found that equation (6), is only applicable to filters similar to those used in the study (low packing density, thick media, composed of fibres several microns in diameter). Such filters are not representative of the media used in many modern mist filter systems, which commonly utilise microfibre glass media (fibre diameters often an order of magnitude lower that that used by Raynor and Leith (2000)). It should be noted that in equation (6), u only appears in the Ca term, which has the power 0.11, and therefore it is evident that equation (6) exhibits little deviation in S_e with changing airflow velocity. This relationship is in contrast to the very strong relationship between u and S_e which has been found by Frising et al. (2005) and also by the Authors of the current work.

Figure 1 plots the relationship between S_e and u found experimentally by Frising et al. (2005) and the predicted experimental results from the Raynor and Leith model (2000). It should be noted that the predicted valued are for the filter parameters used by Raynor and Leith model (2000), as the model cannot predict values for filters such as that used by Frising et al. (2005), as the Dr term approaches zero. However – the S_e vs u relationship would remain constant for any filter. Therefore it can be observed that the model is not applicable to such media.

Previous work by the Authors (Mullins, Braddock et al. 2007) has shown that when commonly used fibrous (mist) filter media are permitted to imbibe liquid (from a reservoir), they behave in a similar manner to a traditional system of vertical capillaries. An additional study (Mullins and Braddock 2009) examined that forced immersion/withdrawal of such media from a liquid (oil) bath, and found that such systems could be described by applying a pressure gradient between the top and bottom of the "capillary" (fibrous media), as is commonly applied in other capillary applications. Yet further work has found that in modern filter media, altering the airflow velocity acts on saturation in a similar manner to providing a pressure gradient above/below a capillary (increasing airflow velocity decreases S_e and vice versa – at a much greater rate than predicted by (6)).

Therefore, since the behaviour of an operating mist filter appears to adhere to the general relationship of a capillary system, this work will attempt to determine if a capillary-based model can be used to predict steady-state (equilibrium) saturation in mist filter media.

2. CAPILLARY MODEL

Previous work (Mullins, Braddock et al. 2007) found that in porous, fibrous media, it is possible to determine an effective capillary radius (r_c) for each media, of the form,

$$r_c = -A \log_e \left(\frac{\alpha}{r_f} \right) - B, \quad (8)$$

where A and B are material/media dependant constants – e.g. for oleophillic microfibre glass media, A=50.7 and B=42.1.

Based on the model for capillary rise in fibrous filter media as it is immersed in liquid (Mullins and Braddock 2009), a model to predict capillary rise (and hence saturation) in fibrous filter media could be derived,

$$x_\infty = \frac{\Delta P_E r_c + 2T\cos\theta}{r_c \rho g}, \tag{9}$$

where x_∞ is the equilibrium capillary rise height, θ is the contact angle, ρ is the density of the entrained liquid, g is acceleration due to gravity, and ΔP_E is the equivalent pressure drop(see below). x_∞ can be converted to a value of S or S_e if the geometry of the filter is known.

Initial model development determined that if the pressure drop across the entire filter (ΔP) was utilised, then the model would predict x_∞ (and hence S_e) <0. Therefore some form of manipulation of the pressure drop should be applied to give an 'equivalent' pressure drop that can be used in the model. This manipulation needs to be utilised as a way of accounting for the fact that we are modelling a system where the air flow is horizontal (i.e. flow through the filter, perpendicular to the filter face) as a vertical system of capillaries, subject to a pressure gradient. This theoretical system of vertical capillaries may be viewed as a 'bunch' of rigid hollow tubes; where the pressure gradient is the difference between the pressure at the top of a capillary (above the liquid) and the liquid pressure at the base. This theoretical system is static (i.e. there is no horizontal air flow through the capillary tubes). Thus there needs to be a way to relate the measured pressure drop in the 'real' system to an 'equivalent' pressure drop in our theoretical system.

The 'equivalent' pressure drop is then,

$$\Delta P_E = -\varepsilon \Delta P \ , \tag{10}$$

where ε is the dimensionless equivalency factor, which is itself a function of both capillary and fibre diameter.

$$\varepsilon = \frac{d_f\left(\pi d_c + d_c\right)}{\pi d_c^2} \tag{11}$$

As the pressure drop of a filter is proportional to its thickness, the filter thickness is considered to be an intrinsic property of the pressure drop. Therefore a term for thickness is not utilised in the determination of ε. Equation (11) may therefore be applied to both the single and two layer filters used in this work.

3. METHODS AND MATERIALS

The model above was compared to experiments conducted by ourselves (Mullins et al., In Press) and experimental results published by Frising et al. (2005). The experimental apparatus is detailed in the aforementioned works. The experiments used a range of filters, and covered the whole spectrum of oil-mist filter operation, from influent loading rates near zero, to relatively high loading rates of several grams of oil per m^3 of air.

In order to compare model predictions to experimental results, the modeled x_∞ values were converted to S values, based on known filter parameters. As the filters used in both the experimental studies were cylindrical, some geometric approximations as to the wetting profile were necessary. The Washburn model assumption of a perfectly defined boundary between wetted and non-wetted zones - with no saturation gradient was assumed. This assumption is obviously a simplification of the system, however is thought not to have influenced the outcome.The model was fitted to data using a Genetic Algorithm (GA), (Mullins et al 2005).

4. RESULTS AND DISCUSSION

When applied, the capillary model (9) predicts values of x_∞ that are below those observed in experiments. So a correction factor, c_f, is applied to (9). This is to correct for the fact that the 'capillaries' are not hollow tubes but are an array of randomly distributed fibres, which have the effect of increasing the capillary rise height. Such that;

$$x_\infty = \frac{\Delta P_e r_c + 2T\cos\theta}{r_c \rho g} c_f \,, \qquad (12)$$

It should be noted that this correction factor is independent of the equivalency factor given in (11).

The model was fitted to the experimental data by using a genetic algorithm encoded in MATLAB. This model was fed a text file which contained upper and lower limits for each of the variables required for calculating x_∞. These limits were within the error margin that exists for each parameter as given in Section 3.1 (e.g. in the case of packing density the upper and lower limits were within the range of 0.042 and 0.082).

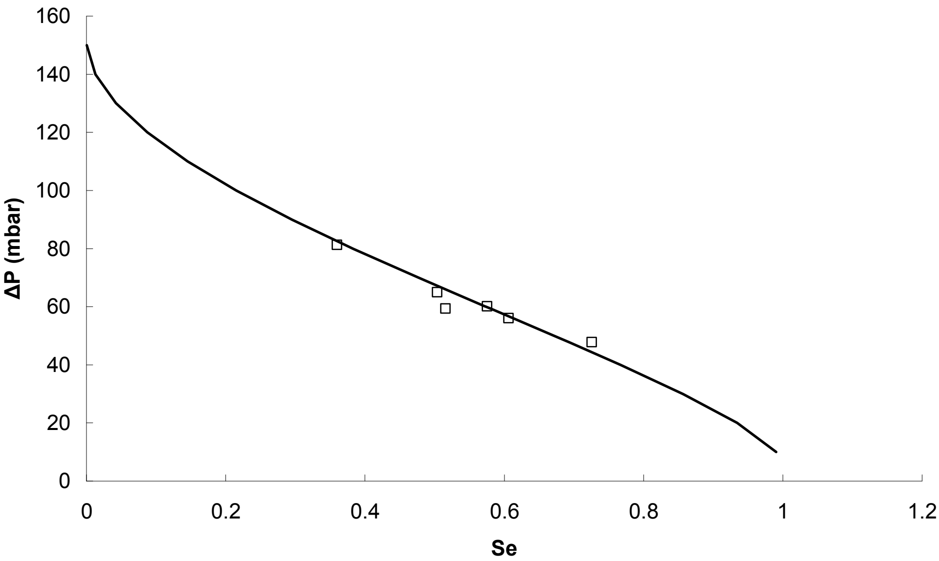

Figure 2. Experimental and theoretical filter saturation S_e as a function of ΔP_e.

The (dynamic) contact angle θ between the oil and the glass fibres is not known precisely, so as with the other variables a range was established, between 72 and 88°, corresponding to the values obtained in previous work using the same media (Mullins, Braddock et al. 2007). The fit obtained (Figure 2) was with a contact angle of 78.9° and a c_f of 2.45.

There is a good fit between the model predicted and experimental results as can be seen by the sum of squares value of 0.0055 and by examination of the plot in Figure 2; where the model values are indicated by the solid line.

To demonstrate that the model works for filters other than those tested by the Authors, the results presented by Frising et al (2005) were also compared to the model. Using the Enguage Digitizer software 3 key data points were extracted and the pressure drop information was used in the capillary model (9).The correction factor in this case was 3.9, indicating that the correction factor is filter dependent. The model is shown in Figure 3 and was fitted using the same MATLAB encoded genetic algorithm, with a text file containing the upper and lower limits for the variables associated with these filters.

Given the good fit it may be concluded that Figures 2 and 3 demonstrate the validity of the model. It also indicates that, as expected, the scaling factor is dependent on the filter being used and therefore is a function of one or several filter properties. If this function can be determined then it should be possible to determine the saturation of a filter for a given pressure drop from easily measurable properties of the filter.

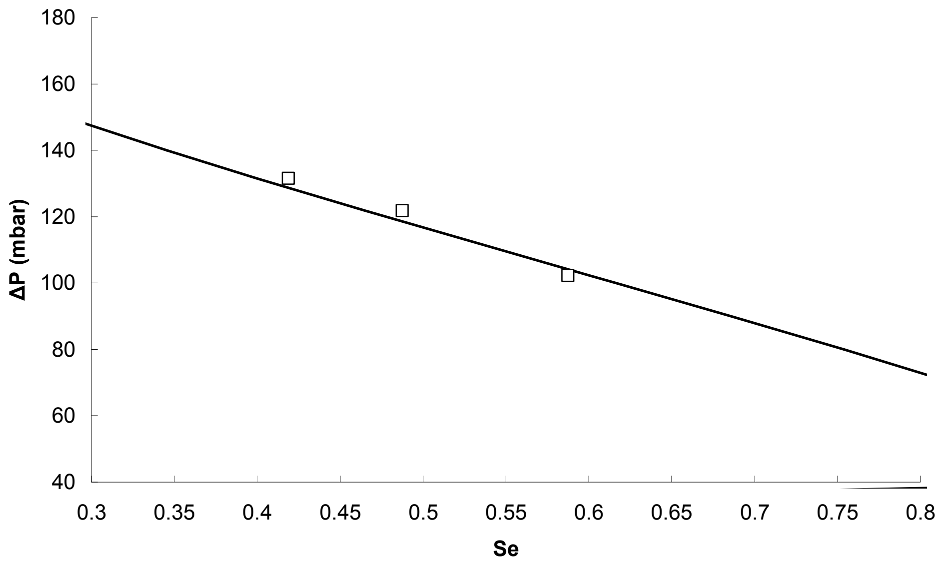

Figure 3. Experimental and theoretical filter saturation S_e as a function of ΔP_e for the filters used by Frising et al (2005).

5. CONCLUSIONS

This work has shown that it is possible to predict liquid saturation in single and multi-layer fibrous filter media using a capillary-based model. The work has also detailed several important relationships with respect to saturation and pressure drop in single and multi-layered filter media. However, further work is required in order to predict the scaling factor based on media properties.

It is hoped that this work will assist in the advancement of mist filter theory, and the optimisation of such filter systems.

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