

Effect of Coalescing Filter Element Layer Number on Liquid Content in Filter Media: Postprint

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Abstract

This study employs a test apparatus for evaluating the filtration performance of coalescing filter elements to investigate the internal liquid distribution characteristics within elements of different wettabilities through incremental increases in filter media layers, and to analyze the effects of layer count and wettability on saturation and pressure drop. The results indicate that as the number of filter element layers increases, the concave distribution trend of saturation in oleophilic filter media becomes more pronounced; specifically, the saturation of the first layer shows no significant change, the saturation of middle layers gradually decreases, and the saturation of the final layer returns to a consistent level. In contrast, the saturation curves for oleophobic filter media exhibit excellent overlap with no significant variation. As the number of filter element layers increases, the overall pressure drop trend remains unchanged for both oleophilic and oleophobic filter media; however, the wetting pressure drop of oleophilic filter media exhibits a decreasing trend, whereas that of oleophobic filter media shows no significant change.

Full Text

Influence of the Number of Coalescing Filter Layers on Liquid Content in Filter Media

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Abstract

This paper experimentally investigates the characteristics of liquid distribution in coalescing filters of different wettability by progressively increasing the num-

ber of filter layers using a coalescing filter performance testing apparatus. The influence of filter layer number and filter wettability on saturation and pressure drop is analyzed. The results show that with increasing filter layers, the saturation distribution in oleophilic filters becomes increasingly concave in shape: the saturation of the first layer shows no significant change, the saturation of intermediate layers gradually decreases, and the saturation of the final layer returns to a consistent level. In contrast, the saturation curves for oleophobic filters show excellent overlap with no obvious changes. As the number of filter layers increases, the overall pressure drop trend remains unchanged for both oleophilic and oleophobic media. However, the wetting pressure drop of oleophilic filters exhibits a decreasing trend, while that of oleophobic filters shows no significant change.

Keywords: coalescence; filter layers; filtration; saturation; pressure drop

Introduction

During long-distance pipeline transportation of natural gas, liquid impurities present in the gas can damage pipeline equipment and seriously affect the safe operation of centrifugal compressors and gas turbines. To remove entrained liquid droplets from natural gas, horizontal filter separators and vertical coalescing filters are typically installed at compressor stations and distribution stations along long-distance pipelines. Among these, coalescing filters have the highest precision requirements; according to natural gas pipeline transportation standards, they must achieve a separation efficiency of 99.8% for droplets larger than 0.3 μm . As the core component of coalescing filters, the coalescing filter cartridge directly determines the purification effectiveness of fine particles in natural gas, making the study of its filtration mechanism highly significant.

In recent years, research on coalescing filter cartridges has primarily focused on investigating factors affecting gas-liquid filtration performance [?], capillary action between fibers and droplets [?], and modeling of steady-state pressure drop and saturation [?], with most studies concentrating on oleophilic filter media. However, research on oleophobic filter media and the actual comprehensive gas-liquid filtration performance of industrial-scale filter cartridges remains limited. Kampa et al. [?] studied liquid transport during filtration, conducting experiments on multi-layered wettable and non-wettable filter media to obtain relationships between saturation and time. They proposed a semi-quantitative “jump-and-channel” model, in which filter media interiors become wetted and form multiple independent channels during filtration. Gas-borne droplets pass through these channels to subsequent layers, with liquid films forming on either the innermost or outermost surfaces depending on media wettability. They also validated this model through combinations of different wettability media. Chang et al. [?] investigated the effect of a drainage layer on liquid distribution within oleophilic filters, finding that saturation begins to increase when a liquid

film forms and explaining the underlying mechanism.

Currently, few studies have examined internal liquid distribution during gas-liquid filtration, and the transport mechanisms of liquid within filter cartridges require further exploration. Therefore, this paper employs a coalescing filter performance testing apparatus to investigate internal liquid distribution in coalescing filters of different wettability by progressively increasing the number of filter layers, and to measure and analyze the effects of layer number and wettability on saturation and pressure drop.

1.1 Experimental Materials

The structure of the filter cartridges is shown in Table 1. Eight specifications of cylindrical wound-type filter cartridges were used in the experiments, designated as A4-A10 and B4-B10. The inner diameter of the cartridges was 50 mm, with an effective filtration length of 105 mm. Material A was an oleophilic glass fiber filter medium, while material B was an oleophobic glass fiber filter medium. The test liquid was diethyl hexyl sebacate (DEHS), as specified in current international testing standards. At 25°C, DEHS has a density of $912 \text{ kg} \cdot \text{m}^{-3}$ and a dynamic viscosity of $0.023 \text{ Pa} \cdot \text{s}$. The measured contact angles between the test liquid and materials A and B at this temperature were 66.35° and 122.68° , respectively.

The physical properties of the filter media are detailed in Table 2. The thickness and basis weight were measured experimentally, with values consistent with manufacturer specifications. The packing density was calculated from the measured thickness, basis weight, and material density.

1.2 Experimental Apparatus

A coalescing filter testing apparatus was established according to Chinese, American, and European testing standards [?], as shown in Figure 1 [Figure 1: see original paper]. This apparatus evaluates the gas-liquid filtration performance of coalescing filters. During testing, the system temperature was maintained between 24°C and 26°C, and relative humidity was maintained between 50% and 56%.

Under the action of a vacuum pump, clean upstream gas was mixed with aerosol generated from 0.18 MPa compressed gas using an aerosol generator. The filter cartridge was vertically positioned, with gas flow passing from inside to outside. Oil droplets entrained in the gas were intercepted by the filter cartridge, where small droplets coalesced into larger ones. The filtered liquid was collected in a collection bottle.

Pressure drop variations during the experiments were recorded in real time using a differential pressure transmitter (BF3051DP, $U = 0.021 \text{ mA}$, Shanghai Beifu). Aerosol concentrations upstream and downstream of the filter were measured using an optical particle counter (Weals 3000, PALAS). Changes in

filter medium weight were determined using an electronic analytical balance (AL204-IC, Class I, METTLER TOLEDO).

2.1 Effect of Filter Layer Number on Oleophilic Filter Saturation

Experiments were conducted on filter cartridges A and B at a superficial gas velocity of $0.10 \text{ m} \cdot \text{s}^{-1}$ and a liquid concentration of $500\text{--}700 \text{ mg} \cdot \text{m}^{-3}$. According to ISO 12500, the filter was considered to have reached steady state when the pressure drop changed by less than 1% within one hour; the efficiency and resistance measured under these conditions were taken as the performance evaluation data. The filter cartridge was disassembled at steady state to analyze internal liquid distribution. Each glass fiber layer was cut into $150 \text{ mm} \times 100 \text{ mm}$ rectangular pieces and weighed using an electronic balance. Comparison with the pre-filtration weight yielded the liquid holdup and steady-state saturation S , which was calculated using the following equations:

$$S = \frac{V_{oil}}{V_{void}} = \frac{m_{oil}}{\rho_{oil}V_{void}} \quad (1)$$

where $m_{oil} = m_{filter} - m_{filter,0}$, and

$$V_{void} = (1 - \alpha)V \quad (2)$$

In these equations, V_{oil} is the volume of test medium occupying the filter, ρ_{oil} is the test medium density, V_{void} is the void volume of the filter medium, m_{oil} is the liquid holdup in the filter cartridge, m_{filter} is the post-experiment filter mass, $m_{filter,0}$ is the pre-experiment filter mass, $m_{oil,max}$ is the theoretical maximum liquid holdup, V is the total filter medium volume, and α is the packing density.

After weighing, to better observe liquid distribution in each layer, light was shone from below each filter layer and microphotographs were taken from above using a digital camera (SONY). This yielded images of liquid distribution in each layer.

Figure 2 [Figure 2: see original paper] shows the saturation of each layer within filter cartridges A4–A10 after experiment termination. The saturation curves for different layer numbers are approximately wedge-shaped. For all cartridges, the first layer saturation is essentially identical, intermediate layer saturation gradually decreases, and the final layer saturation is roughly the same. Analysis suggests that the number of layers has minimal effect on first-layer saturation. Gas-borne droplets are directly intercepted by the first layer, whose saturation depends primarily on the inherent properties and structure of the medium (fiber morphology, specific surface area, pore distribution, surface chemical energy) rather than layer number. Under constant concentration and gas velocity, the first layer reaches a characteristic saturated state. According to the “jump-and-channel” theory [?], oil droplets initially coalesce and penetrate through

high-permeability regions, then seek channels in low-permeability regions. With increasing layer number and strong capillary action between oleophilic fibers and droplets, many droplets are intercepted and rapidly absorbed by surrounding clean fibers, resulting in fewer droplets being intercepted by subsequent layers and fewer channels forming in each layer. For filter A10, layers 1, 3, 5, and 7 were selected for comparative analysis.

As shown in the disassembly photographs in Figure 3 [Figure 3: see original paper] (bright regions indicate wetted areas, dark regions indicate clean areas), the bright area decreases progressively, indicating reduced wetted area. This demonstrates that for oleophilic media, increasing layer number reduces saturation in each layer. The saturation increase in the final 2-3 layers is attributed to the presence of a liquid film. Kasper et al. [?] indirectly verified the existence of an external liquid film. After gas flow cessation, oleophilic media absorb this film. For media with relatively low porosity, this back-absorption creates new liquid transport channels, causing increased saturation in subsequent layers. The similar saturation values in the final layers across different cartridges indicate that layer number has minimal effect on liquid film thickness.

2.2 Effect of Filter Layer Number on Oleophobic Filter Saturation

Figure 4 [Figure 4: see original paper] shows disassembly photographs of B10 (bright regions indicate wetted areas, dark regions indicate clean areas). Layers 1, 3, 5, and 7 were selected for comparison. Except for the first layer, the wetted areas of the remaining layers are approximately equal. Figure 5 [Figure 5: see original paper] presents the saturation curves for each layer within oleophobic filter cartridges of different layer numbers. All cartridges show a consistent trend: first-layer saturation is uniform at approximately 0.55, after which saturation stabilizes at 0.1 with essentially identical values across all layers. Combined analysis of Figures 4 and 5 reveals that filter layer number has no effect on oleophobic filter saturation.

Analysis suggests that the consistently high first-layer saturation, which far exceeds that of other layers, results from mechanisms similar to those in oleophilic media. Oil droplets in the gas first contact and are largely intercepted by the first layer, whose liquid absorption capacity is minimally affected by layer number variations. Under constant gas velocity and concentration, the first layer ultimately reaches a characteristic saturated state regardless of total layer number. According to the “jump-and-channel” theory [?], for oleophobic media, liquid forms a film on the first layer at the droplet contact side after rapid filling. During film formation, gas “compression” forces some liquid into the first layer. Additionally, due to the relatively high packing density and small pore size of oleophobic materials, capillary action is strong, causing the first layer to absorb some liquid. Saturation then drops sharply and stabilizes at a consistent level across all layers for cartridges of different depths. According to the “jump-and-channel” theory [?], increasing layer number effectively increases channel length. Combined with the inherent characteristics of oleophobic media—where

fiber capillary action is weaker than in oleophilic media—channel numbers do not decrease as significantly as in oleophilic media during transport, as shown in the disassembly photographs in Figure 4. Therefore, under identical concentration and gas velocity conditions, all layers reach the same saturated state at steady state.

2.3 Effect of Filter Layer Number on Oleophilic Filter Pressure Drop

As shown in Figure 6 [Figure 6: see original paper], layer number variations do not affect the overall pressure drop trend in oleophilic media. Initial pressure drop increases with layer number due to increased fiber thickness and greater resistance to gas flow. To investigate the effect of layer number on liquid transport, wetting pressure drop was calculated as the difference between stabilized pressure drop after filtration and initial pressure drop.

Figure 7 [Figure 7: see original paper] demonstrates that wetting pressure drop decreases with increasing layer number. Analysis suggests that because oleophilic fibers have high surface energy, large areas become wetted during filtration, with wetted area decreasing significantly as layer number increases. According to Contal et al. [?], pressure drop increase results from liquid filling the voids between fibers, creating substantial resistance to subsequent gas flow. This explains why, despite increased fiber resistance with more layers, wetting pressure drop decreases for oleophilic media due to greatly reduced wetted area. The previous saturation analysis and disassembly photographs in Figure 3 clearly show this reduction in wetted area, which significantly affects pressure differential magnitude. Therefore, for oleophilic media, more layers result in lower wetting pressure drop, not because of layer number itself but due to reduced wetted area.

Using A6 as an example, the pressure drop evolution for oleophilic media is shown in Figure 8 [Figure 8: see original paper]. The process can be divided into four stages: (1) rapid pressure drop increase, (2) slow pressure drop increase, (3) intermediate growth rate between stages 1 and 2, and (4) final stabilization.

Analysis suggests that in Stage 1, droplets enter the first filter layer and form liquid transport channels. However, due to material properties, droplet arrival rate at the first layer surface exceeds channel formation rate, causing droplet accumulation and liquid film formation. This film creates significant flow resistance, resulting in rapid pressure drop increase. In Stage 2, droplets progressively enter subsequent layers, forming interlayer transport channels that impede gas flow and cause gradual pressure drop increase. In Stage 3, when droplets reach the final layer, adhesion between droplets and oleophilic fibers exceeds internal droplet cohesion, causing accumulation and formation of a thin liquid film [?]. The sharp increase in downstream droplet concentration at this stage confirms film presence. When droplet weight exceeds adhesion force, droplets detach from the film. Under constant concentration and gas flow, equilibrium between incoming and exiting droplets establishes the final steady state (Stage 4).

2.4 Effect of Filter Layer Number on Oleophobic Filter Pressure Drop

As shown in Figure 9 [Figure 9: see original paper], layer number variations do not affect the overall pressure drop trend in oleophobic media. Comparison of pressure differentials in Figure 10 [Figure 10: see original paper] reveals no significant difference with increasing layer number, with values fluctuating around approximately 5.5 kPa.

The pressure drop process also exhibits four stages: (1) nearly linear increase, (2) rapid increase, (3) gradual increase to Stage 4 (stable state). Unlike oleophilic media, the first two stages for oleophobic media both show rapid increase. Stage 1 involves liquid contacting and rapidly filling the first layer, forming a surface liquid film. Due to weak capillary action between oleophobic fibers and droplets, fibers are not easily wetted, and droplet arrival rate at the first layer far exceeds the rate of internal absorption and transport, causing film formation and linear pressure drop increase. After film stabilization, the first layer gradually becomes wetted, voids fill with liquid, and transport channels form, impeding gas flow and causing pressure drop increase. Stage 3 involves effects from remaining layers, similar to Stage 2 for oleophilic media. According to Mullins et al. [?] capillary management theory, oleophobic fibers have low surface energy, causing oil droplets to more easily coalesce into large droplets on the outermost layer. When droplet weight exceeds surface forces, detachment occurs, leading to final stabilization.

Analysis suggests that for oleophobic media, saturation analysis shows no significant change in each layer's saturation with increasing layer number. The disassembly photographs in Figure 5 also reveal approximately equal wetted areas across layers. This results from oleophobic material properties: weak fiber capillary action prevents wetted area expansion. Although layer number increases, wetted area per layer remains essentially unchanged, resulting in no significant pressure drop variation. This further confirms that wetted area magnitude is the primary factor affecting pressure drop.

Conclusions

This study employed a coalescing filter performance testing apparatus to investigate internal liquid distribution in coalescing filters of different wettability by progressively increasing filter layer number, and to measure and analyze the effects of layer number and wettability on saturation and pressure drop. Based on experimental results, the following conclusions are drawn:

1. With increasing filter layers, the saturation distribution in oleophilic media becomes increasingly concave: first-layer saturation shows no significant change, intermediate-layer saturation gradually decreases, and final-layer saturation returns to a consistent level. Filter layer number does not affect liquid film thickness.
2. With increasing filter layers, oleophobic media show excellent saturation

curve overlap with no significant changes. First-layer saturation is higher than other layers at approximately 0.55, while saturation in all other layers remains consistently at 0.1.

3. With increasing filter layers, the pressure drop trend remains unchanged for both oleophilic and oleophobic media. However, wetting pressure drop decreases for oleophilic media while showing no significant change for oleophobic media. Wetted area significantly influences these effects.

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