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The effect of a drainage layer on filtration performance of coalescing filters

Cheng Chang, Zhongli Ji *, Fanyong Zeng

Beijing Key Laboratory of Process Fluid Filtration and Separation, College of Mechanical and Transportation Engineering, China University of Petroleum, Beijing 102249, PR China

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ABSTRACT

The effect of a drainage layer on the filtration performance of coalescing filters was evaluated experimentally. The "jump-and-channel" model was used to analyze saturation, pressure drop and efficiency of the filters with and without the drainage layer. The results showed that jump pressure drop dominated the wet pressure drop. The steady-state pressure drop was not proportional to filter saturation which was related primarily to the channel pressure drop. A liquid film was present between coalescing layer and drainage layer at steady state. The jump pressure drop was affected by the thickness of this liquid film. A thicker liquid film produced a higher jump pressure drop. When the drainage layer was assembled outside of the coalescing layer, pressure drop and penetration changed, and both saturation and efficiency increased significantly. A filter with a polyester drainage layer had the overall best performance. Furthermore, the dynamic thickness of the liquid film can be predicted using theoretical calculations, which allows qualitative analysis of the effect of the liquid film on filtration performance.

1. Introduction

In a long-distance natural gas transportation pipeline, the presence of liquid droplets may cause erosion and corrosion to the pipeline and process equipment [1]. When present in a compressor dry gas seal system, those droplets will cause damage to the dry gas seal dynamic and static rings, leading to gas leakage and the compressor shutdown [2]. In a gas turbine, the presence of liquid droplets can lead to overheating at the combustor, which can greatly reduce the combustion efficiency and shorten the life of the gas turbine. Filters and coalescers are used in a compressor station for purification of natural gas. Coalescing filters are the key element of the coalescer, whose performance is important for filtering small droplets, especially for those with a diameter smaller than 1 μm.

A large number of theoretical and practical methods can be used to estimate the pressure drop and efficiency when a filter is dry [3,4]. However, when a filter is clogged with aerosol particles, its filtration behavior will change significantly. A number of works have been conducted to investigate gas-solid filtration [5–7]. In the case of gas-liquid filtration, especially for the coalescence filtration, the filtration mechanism requires further investigation, because the droplets migration process in the filter material is very complex and is affected by a variety of parameters.

Coalescence filtration is a process where droplets carried by a gas are captured in a filter material. During the gas flow, droplets collide and coalesce in the filter. The coalesced liquid moves from the front of a multilayer filter material to the rear face. Finally, the enlarged droplets drain out of the filter when the gas drag force and gravity force are strong enough. Coalescing filter performance is affected by a number of parameters including operating conditions (gas velocity, droplet concentration, liquid loading rate), the properties of the liquid (liquid viscosity and surface tension), the properties of the filter material (fiber diameter, average pore size, packing density, wettability) and filter structures (disc, cylinder, plate). These parameters have a significant effect on the filter pressure drop and efficiency, which are the two most important performance criteria of a filter. Hence there is a growing need to investigate the coalescing filter filtration process and its mechanism in order to provide technical support for the optimization of coalescing filter.

The research on coalescence filtration falls into two categories: the first is the single-fiber level and the second is the level of the entire filter. At the single-fiber level, a number of investigations have analyzed the forces acting on droplets and their shapes on fibers [8,9], coalescence and motion of droplets along fibers has also been investigated [10–12] and the interactions between the fibers and the droplets have received attention [13]. These results

* Corresponding author.
E-mail address: jizhongli63@vip.sina.com (Z. Ji).

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can be used for numerical simulation of droplet movements in fibrous systems, but this simulation cannot describe the actual behavior that occurs in the filtration process. At the level of the entire filter, studies have been focused on flat materials or entire filter elements [14,15], which has included the effects of inclination, gas velocity and liquid concentration on filtration performance [16–18]. Efficiency and pressure drop models have been established based on the results of the macroscopic experiments [19,20].

However, the structure of the filter material and the entire filter used in recent work has been basically the same composed mostly of the same kind of material (glass fiber or metal fiber). The coalescing filter is cylindrical in industrial applications and is a sandwich structure composed of various materials. Coalescing filters are usually composed of a coalescing layer and a drainage layer. Droplets carried by the gas transport through the coalescing layer to form a liquid film or enlarged droplets at the rear face of coalescing layer. The drainage layer provides drainage channels for coalesced liquid to drain smoothly out of the filter.

There are only a few reports about work on the drainage layer. Patel et al. [21,22] conducted a study of gravity orientation, woven drainage structures and surface energy of woven mesh (500 μm pore openings) in the filter media (0.06 m in diameter). The results of this work showed that the filter embedded with Teflon fiber drainage channels at 45° downward angles had the overall best performance. There has been very limited work on industrial cylindrical filter performance, with only some discussion of coalescing filter design reported in patents. Hunter [23,24] and Miller et al. developed a coalescing filter with a coalescing layer composed of micro-glass fibers of 0.5–10 μm fiber diameter materials and a drainage layer made up of open-celled foam plastic material or fibrous felt. The results of their work showed that the low surface energy drainage layer had better performance in terms of reducing oil carry over and removing the oil from the filter materials.

The intent of this study was to investigate the distribution of liquid in the interior and surface of a coalescing layer with and without a drainage layer, to analyze the effects of a drainage layer on wet pressure drop and saturation and to provide a better understanding of the effects of a drainage layer on filtration performance.

2. Experimental

2.1. Materials

The filters used in this study were constructed as cylindrical devices, 105 mm in height and with a 50 mm inside diameter. All the filters had the identical coalescing layer composed of 4-layer oleophylic glass fibers, which is widely used in industrial coalescing filters. One type of filter had no drainage layer and the other filters had non-woven drainage layer assembled outside of the coalescing layer. The drainage layer was a one-sheet layer of polyester (PET), polypropylene (PP), polyaramid (PA) and wettable polyaramid (W-PA). Properties of the filter materials are given in Table 1, where filters are named after the drainage layer materials used and the filter without drainage layer was termed GF. Thickness and grammage were measured using a digital caliper and an electronic analytical balance (AL204-IC, Mettler Toledo). The average pore size of the filters was determined using a capillary flow porometer (Porometer 3G, Quantachrome). The contact angles of DEHS (di-ethyl-hexyl-sebacate) for each filter material were measured using an optical tensiometer (Attension Theta, BiolinScientific).

2.2. Experiment apparatus

The experiment apparatus used for the filter measurements is shown in Fig. 1. The oil used for the experiments was DEHS (di-ethyl-hexyl-sebacate), with density 912 kg/m^3 and dynamic viscosity 0.023 Pa s at 25 °C. System temperature was controlled between 24 °C and 26 °C, with relative humidity between 50% and 56%. The face velocity was controlled at 0.1 m/s. The loading rate was controlled at 2 g/h. All filters were constructed in triplicate. Compressed air was pre-conditioned by passing through a HEPA (high efficiency particulate air) filter. The conditioned air passed through an aerosol generator (ATM 240, TOPAS) to generate the aerosol. Aerosol mixed with clean air flowed into the bottom of the vertical filter. The aerosol flowed radially through the filter from inside to outside. Filtered droplets drained out of the filter. The filtered gas was pumped using a vacuum pump.

The concentration of the droplets and their particle size distribution were measured using an optical particle counter (Welas 3000, PALAS) at the filter upstream and downstream. The typical upstream particle size distribution of the aerosol was at the range of 0.3–6.0 μm with mean diameter around 0.9 μm. The pressure drop and flow rate were measured using a differential pressure transducer (3051CD, Rosemount) and rotameter. A steady state was obtained when both pressure and penetration became constant. Filter materials of both coalescing layers and drainage layers were weighed using an electronic analytical balance (AL204-IC, Mettler Toledo) after each test. Then coalescing layer was disassembled to 4 layers, each of which was a 150 mm × 100 mm rectangular piece. Comparing the weight of the filter before and after the experiment, the saturation (S) of the filter material can be calculated as

$$S = \frac{m_{\text{oil}}}{m_{\text{oil,max}}} = \frac{m_{\text{filter}} - m_{\text{filter,0}}}{m_{\text{oil,max}}} \quad (1)$$

where m_{oil} is the mass of the oil captured in the filter material, $m_{\text{oil,max}}$ is the maximum oil holding capacity of the filter material, m_{filter} is the mass of the saturated filter material and $m_{\text{filter,0}}$ is the mass of the dry filter material.

2.3. Performance of filtration

The filter performance is characterized by the pressure drop across the filter and the separation efficiency. Usually, a higher separation efficiency leads to a higher pressure drop. Energy consumption will increase as the pressure drop increases. Quality factors [4,26] were used to evaluate the filtration performance in

Table 1
Properties of experimental filter materials.

Filter	Material	Thickness (mm)	Grammage (g/m^2)	Average pore size (μm)	DEHS contact angle (°)
GF	Glass fiber	0.58 ± 0.01	100 ± 2	12.0 ± 0.5	43 ± 3
PP	Polypropylene	2.20 ± 0.10	550 ± 10	43.6 ± 2.1	93 ± 2
PET	Polyester	1.60 ± 0.17	550 ± 10	39.2 ± 2.7	104 ± 1
PA	Non-wettable polyamide	2.16 ± 0.07	550 ± 10	40.3 ± 2.1	110 ± 1
W-PA	Wettable polyamide	2.14 ± 0.12	550 ± 10	38.8 ± 2.0	31 ± 1