Chemical Engineering Science 160 (2017) 354–361

Contents lists available at ScienceDirect

Chemical Engineering Science

journal homepage: www.elsevier.com/locate/ces

The effect of a drainage layer on the saturation of coalescing filters in the filtration process

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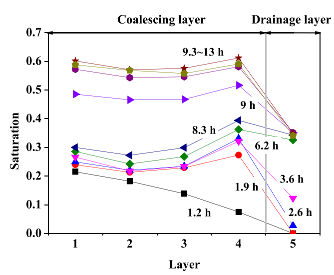
HIGHLIGHTS

- The drainage layer varied the saturation profiles in the filtration process.
- Liquid redistribution was verified by evolution of the thickness of liquid film.
- Variation on the saturation of fibrous filter was analyzed using capillary theory.
- Smaller pore size of the drainage layer led to greater saturation of the filter.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 27 June 2016
Received in revised form
15 August 2016
Accepted 27 October 2016
Available online 29 October 2016

Keywords:
Coalescence filtration
Drainage layer
Liquid aerosols
Saturation
Capillarity

ABSTRACT

The effect of a drainage layer on the saturation of coalescing filters was evaluated experimentally. The effect of the pore size of a drainage layer on the saturation was demonstrated using the capillary theory. The experimental results showed that the filter without a drainage layer began to drain in the liquid film forming stage, where the flow resistance of the liquid in the channels increased significantly, resulting in the increases in both the saturation of the filter and the thickness of the liquid film. The pressure drop, saturation and liquid film thickness profiles varied after assembling a drainage layer outside of the coalescing layer. There was an adjustment stage of the liquid film in the filtration process of the filter with a non-wettable drainage layer, which can be verified by the evolution of the thickness of the liquid film predicted using theoretical calculations. The amount of the liquid increased gradually between the coalescing layer and the drainage layer at this stage, resulting in a significant increase in the saturation of the coalescing layer. As assembling a wettable drainage layer, a pseudo-steady state appeared, where the pressure drop and penetration were steady while the saturation of each layer increased. After the pressure drop increased and became steady again, the drainage led to a drastic increase in the saturation of the coalescing layer. At steady state of all the filters, the drainage rate and loading rate were almost the same. Furthermore, the capillary theory can be used to analyze the variation on the saturation affected by the pore sizes of a wettable drainage layer. Smaller pore size led to stronger capillarity, resulting in more liquid absorbed into the drainage layer and greater saturation of the coalescing layer.

1. Introduction

Fibrous coalescing filters are widely used in manufacturing and process industries to remove liquid aerosols from gas streams, including compressed gas cleaning, engine crankcase ventilation, machining and cutting processes and a range of other process

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http://dx.doi.org/10.1016/j.ces.2016.10.047
0009-2509/© 2017 Published by Elsevier Ltd.

engineering applications (Mead-Hunter et al., 2014). In a long-distance natural gas transportation pipeline, the presence of liquid droplets may cause erosion and corrosion to the pipeline and process equipment (Gonfa et al., 2015). When present in a compressor dry gas seal system, the droplets will cause damage to the dry gas seal dynamic and static rings, leading to gas leakage and the compressor shutdown (Stahley, 2005).

The research on coalescence filtration falls into two categories. The first is at the single-fiber level, where a number of investigations have been conducted to analyze the exerted forces, shapes, coalescence and motions of the droplets along fibers (Mullins et al., 2005, 2006; Dawar et al., 2008; Dawar and Chase, 2010; Yarin et al., 2006). The second is at the level of the entire filter, where studies have been focused on flat materials and the entire filter elements (Raynor and Leith, 2000). Moreover, the effects of the operating conditions and liquid properties on filtration performance have been investigated (Contal et al., 2004; Charvet et al., 2008).

Coalescence filtration is a complex process where droplets coalesce and transport in the multilayer filter materials, of which the performance is affected by a number of parameters. Hence the filtration process and mechanism require further investigation in order to provide technical support for the optimization of the coalescing filter.

The filters used in recent works are composed of the uniform material (glass fiber or metal fiber). However, the coalescing filter is cylindrical in industrial applications and is a sandwich structure composed of a coalescing layer and a drainage layer with various materials.

A drainage layer has a significant influence on the filtration performance. However, there are only a few reports about a drainage layer. The fluorocarbon impregnated drainage layers presented better drainage and less oil re-entrainment (Hunter, 1995, 1999; Miller et al., 1988). Nevertheless, there is still a gap between the existing research results and the actual filtration performance of industrial coalescing filters.

Patel and Chase (2010) conducted a study of gravity orientation and woven drainage structures in the filter media (0.06 m in diameter). The results of this work showed that the 45° downward inclined angle was the best for the filters. Further, the effect of the surface energy of woven drainage channels was investigated (Patel et al., 2012), which showed that the filter embedded with Teflon fiber drainage channels at 45° downward angles had the overall best performance.

The effect of a drainage layer on the filtration performance of coalescing filters was evaluated experimentally in the previous work by the authors (Chang et al., 2016). The "jump-and-channel" model was used to analyze the saturation, pressure drop and efficiency of the filters with and without a drainage layer. The results showed that when a drainage layer was assembled outside of the coalescing layer, the pressure drop and penetration changed, and both saturation and efficiency increased remarkably. The steady-state pressure drop was not proportional to the filter saturation. A liquid film was present between the coalescing layer and the drainage layer at steady state, of which the dynamic thickness was predicted using theoretical calculations. However, there is a growing need to investigate the effect of a drainage layer on the saturation of the filter and the thickness of the liquid film in the filtration process.

The drainage layer provides drainage channels for coalesced liquid to drain smoothly out of the filter. The coalesced liquid drains out of the filter when the gas drag force and gravity force are strong enough. Therefore, the filtration performance is significantly affected by the velocity and mass of the liquid flowing into the drainage layer which are closely related to the capillarity as liquid transports in the filter material and enters or exits the surface of the filter.

Washburn (1921) analyzed the flow of the liquids in cylindrical capillaries and porous media. The Washburn equation was developed, in which inertial and gravitational forces were neglected. For a given liquid, the volume of the liquid entering into the capillary was proportional to the square root of time. The Washburn equation is commonly applied to capillary rise problems in industry, including powders and rocks, etc. (Mullins et al., 2007; Mullins and Braddock, 2012). However, its application to fibrous filters has received little attention. Some authors (Ashari et al., 2010) demonstrated that the Washburn equation could perfectly match the experimental data obtained at initial stage.

Mullins et al. (2007) investigated the wetting process in low packing density fibrous material. The experimental result was in an acceptable agreement with the modified Washburn equation. A linear correlation was found between the capillary diameter and parameters of the filter material. Based on those results, Mead-Hunter et al. (2013) described a capillary-based saturation model. The measured values fell within ±10% of the ideal values, which meant a good agreement between the model and the experimental data.

There has been very limited work on both the filtration performance of industrial cylindrical filters and the effect of a drainage layer. The intent of this study was to investigate the evolutions of the saturation and thickness of the liquid film in coalescing filters with and without a drainage layer, and to demonstrate the effect of the pore size of a drainage layer on the saturation using the capillary theory.

2. Experimental materials and apparatus

2.1. Materials

The filters used in this study were constructed as cylindrical devices, with 105 mm in height and 50 mm in inter diameter. All the filters had the identical coalescing layer composed of 4-layer oleophilic glass fibers, which were widely used in industrial coalescing filters. One type of the filters had no drainage layer and the other filters had a non-woven drainage layer assembling outside of the coalescing layer. The drainage layer was a layer of non-wettable polyaramid (NPA) or three types of wettable polyaramid (PA) with different average pore sizes. Properties of the filter materials are given in Table 1, where the filter without a drainage layer was termed GF and the other filters were named after the drainage layer materials. The 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 angle of DEHS (di-ethyl-hexyl-sebacate) for each filter material was measured using an optical tensiometer (Attension Theta, BiolinScientific).

Table 1
Properties of experimental filter materials.

Filter	Material	Thickness (mm)	Grammage (g/m^2)	Average pore size (μm)	DEHS contact angle (deg.)
GF	Glass fiber	0.52 ± 0.02	102 ± 3	12.0 ± 0.6	49 ± 4
NPA	Non-wettable Polyamide	1.89 ± 0.08	550 ± 10	43.7 ± 4.8	105 ± 2
PA-1	Polyamide	1.88 ± 0.06	550 ± 10	46.4 ± 3.3	69 ± 4
PA-2	Polyamide	1.86 ± 0.04	500 ± 20	51.2 ± 3.6	74 ± 3
PA-3	Polyamide	1.72 ± 0.05	450 ± 20	56.5 ± 4.4	61 ± 5