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# Thickness shrinkage of microfiber media in gas–liquid coalescence filtration

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ABSTRACT

The performance of gas–liquid coalescing filter media depends on material properties and operating conditions. To optimize the filter performance, highly porous filter media are fabricated with micron-sized fibers with diameters typically in the range of about 5–20 μm. In recent experiments with fiber diameters less than 5 μm the thicknesses of the media were observed to decrease as the amount of liquid held in the media increased.

This paper reports on empirical measurements of the shrinkage of the media due to the presence of the liquid drops. This shrinkage phenomenon is attributed to capillary forces compressing the media primarily in the thickness dimension. The shrinkage depends upon the fiber diameter and the wetting properties of the fiber surfaces.

The shrinkage caused variations in media properties (pore size, porosity, and permeability) and affected the coalescence performances of the media. The objective of this work was to measure the shrinkage, the effect of the thickness shrinkage on the media properties, and the effect on coalescing filter performance.

Experiments were conducted on two media materials (glass fibers and stainless steel fibers) with fiber diameters ranging from 1.5 μm to 22 μm wetted by three organic liquids (Sullube-32, Ultra Low Sulfur Diesel and Viscor 1487) and by water. The results show the shrinkage phenomenon varied with amount of liquid in the media and the fiber material.

The effects of shrinkage on the filter properties and coalescence performance were compared to mechanically compressed media to similar thickness. The mechanically compressed media had higher pressure drops but also higher separation efficiencies.



## 1. Introduction

Gas–liquid coalescing filter media are widely used in industrial applications for human health, environmental protection and process requirements. The performances of the filter media depend on operating conditions such as rate of gas flow, temperature, humidity, distribution of the dispersed liquid aerosol [1–3]. The material properties, such as fiber size, permeability, porosity, fiber surface wettability, fiber orientation and structure, also have a vital impact on the performance of the filter media [4–6]. Fine fibers have higher capture efficiencies in removing fine aerosols and are commonly used in practice.

Many media made of fine fibers are fabricated using binders to hold the fiber structure together and provide rigidity [1,5–13]. The binders can reduce media porosity and alter surface properties of the fibers which can adversely affect filter performance. Typically, when glass or polymeric fiber media are wet laid to form non-woven filter media, chemical binders are applied to hold the fiber structures together to prevent fiber shedding during filtration operation. Often the binders provide enough rigidity to offset internal capillary forces and shrinkages due to capillary forces are not normally observed or considered in filter performance [5–13]. However, stainless steel fiber media do not apply chemical binders but apply heat to partially melt or soften the surfaces of the fibers to cause the fibers to fuse at their points of contact. This fusing mechanism is enough to prevent fiber shedding but the media structures are soft and compressive enough that capillary forces may cause significant changes to the macroscopic thickness when wetted by captured liquids.

Shrinkage can occur in woven and nonwoven fabrics and filter media by several mechanisms including thermal [14,15]

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and chemical reactions [16], and through polymer chain relaxation in polymer fibers due to interaction with solvents [17]. Shrinkage of fabrics of several different materials has been reported, including cotton fabrics [18], cotton–polyester blended fabrics [19], silk fabrics [20], wool fabrics [21] and polymer fibrous mats [22]. In regard to fibrous filter media, shrinkage can happen during the manufacturing processes such as sintering [23] or shrinkage can occur when the filter is put into service. For those filter media used in high temperature applications, the heat-shrinkage of the media can significantly change the filter properties [24]. Moreover, shrinkage may also occur due to surface wetting properties and capillary forces during coalescence filtration applications. Mullins et al. [25] noted that some low packing density filter media became thinner during wetting processes. At the microscale Mullins et al. [26] observed movement of fibers and fibers being pulled together due to capillary forces between drops and fibers, Hatt et al. [27] concluded that swelling and shrinkage of storm water filter media was the most probably cause for the variation of the infiltration capacity of the filters during wet and dry periods. As far as the authors are aware, no systematic study has been performed to quantify the effects of shrinkage of filter media due to capillary forces.

Shrinkage is affected by small scale structures in the fibrous media and interactions between the fiber materials and the liquid droplets. The work here only considers the effects of fiber size of media made of layers of nonwoven stainless steel and glass fibers and their interaction with several liquids. The underlying mechanisms of small scale structures affecting the shrinkage should be considered in future work.

The objectives of this work are to (i) explore the shrinkage mechanism of high porosity nonwoven microfiber media; (ii) measure the effect of thickness shrinkage on media properties (porosity and permeability); and (iii) compare the performance of media effected by shrinkage to the performance of media mechanically compressed to similar medium thickness.

## 2. Dry uncompressed filter media properties

The filter samples used in the shrinkage experiments include stainless steel (SS) fibers (with average fiber diameters of 1.5 μm, 2 μm, 4 μm, 5 μm, 6.5 μm, 8 μm, 12 μm or 22 μm) and glass (GLASS) fibers (with average fiber diameters of 2 μm or 6 μm). The dry and uncompressed properties of the filter media are summarized in Table 1.

The media samples of stainless steel (SS) fibers were supplied by Bekaert Inc. (Belgium) and contain no chemical binder. The glass fiber media were supplied by Hollingsworth & Vose Company. All of the SS media samples and the 6 μm glass fiber media were supplied as thin sheets of commercial media having sheet thicknesses varying from about 1 to 2.5 mm. The SS and glass fiber sheets were stacked without mechanical compression to construct the test samples with the thickness of 1 cm. The 6 μm glass fiber media from Hollingsworth & Vose contains a small amount of binder for mechanical strength. The 2 μm glass fibers were provided in bulk as loose fibers by Hollingsworth & Vose and were formed into monolayer filter media of thickness of 1 cm via a custom made vacuum molding apparatus [28]. For structural strength a small amount of binder (Megasol® S50 and starch, Wesbond Corporation) was used to hold the fibers together.

The permeabilities in Table 1 were measured by passing air through the media using an air permeability test (Frazier Precision Instrument Company, Inc.) and calculated based on Darcy's law

$$\frac{Q}{A} = \frac{k\Delta P}{\mu L} \tag{1}$$

where $Q$ is the volumetric flow rate; $A$ is the cross-sectional area of the filter medium; $k$ is the permeability; $\mu$ is the viscosity of the air; $\Delta P$ is the pressure drop across the filter media; and $L$ is the media thickness. The porosities in Table 1 were measured via a custom made pycnometer using a gas-expansion method. Each sample was tested in triplicate.

## 3. Change in porosity due to mechanical compression

The reduction in thickness of a medium is caused by a compressive deformation of the fiber matrix and corresponds to a reduction of the pore volume of the medium. The reductions in the thicknesses of media reduce the average porosities ($\varepsilon$) and permeabilities ($k$).

For comparison, the dry media were mechanically compressed by applying an external force to the outside flat surfaces to reduce the thickness of the media. The average porosities of the mechanically compressed or wetted and shrunk media were calculated via mass continuity balance, assuming the forces are not large enough to change the intrinsic densities of the fibers, which gives

$$(1-\varepsilon)L = \text{constant} \tag{2}$$

Here $\varepsilon$ is the average porosity (volume fraction of the void space) and $L$ is the thickness of the medium. We define $\varepsilon^a$, $\varepsilon^L$ and $\varepsilon^f$ to be the volume fractions of the air, liquid and fibers within the media. These quantities are related through the definition of volume fraction and porosity by the expressions

$$\varepsilon^a + \varepsilon^L + \varepsilon^f = 1 \tag{3}$$

$$\varepsilon^a + \varepsilon^L = \varepsilon \tag{4}$$

The changes in $L$ due to compression or shrinkage by capillary forces causes each of the volume fractions to change as constrained

**Table 1**
Properties of the filter samples used in the shrinkage experiment. All filter media were disk shaped with diameters of 2.5 cm and dry and uncompressed thicknesses of 1.0 cm.

| Filter sample | Fiber material | Mean fiber diameter (μm) | Mass per area (g/m$^2$) | Porosity (%) | Permeability (m$^2$) | Supplier | Additional description |
|---|---|---|---|---|---|---|---|
| SS 1.5 μm | 316 stainless steel | 1.5 | 750 | 99.1 | $1.71 \times 10^{-10}$ | Bekaert Inc. (Belgium) | Multi-layers No binder |
| SS 2 μm | | 2 | 750 | 98.8 | $2.80 \times 10^{-10}$ | | |
| SS 4 μm | | 4 | 750 | 98.8 | $5.39 \times 10^{-10}$ | | |
| SS 5 μm | | 5 | 750 | 99.3 | $9.92 \times 10^{-10}$ | | |
| SS 6.5 μm | | 6.5 | 750 | 98.6 | $1.36 \times 10^{-9}$ | | |
| SS 8 μm | | 8 | 900 | 99.6 | $1.40 \times 10^{-9}$ | | |
| SS 12 μm | | 12 | 750 | 99.1 | $2.58 \times 10^{-9}$ | | |
| SS 22 μm | | 22 | 900 | 98.3 | $2.50 \times 10^{-9}$ | | |
| GLASS 2 μm | B-glass | 2 | 900 | 96.3 | $1.02 \times 10^{-10}$ | Vacuum molded in lab | Monolayer |
| GLASS 6 μm | | 6 | 750 | 96.3 | $3.25 \times 10^{-10}$ | Hollingsworth & Vose | Multi-layers |