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Experimental investigation on liquid distribution of filter cartridge during gas-liquid filtration

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ABSTRACT

Fibrous filter cartridges are commonly used to separate the liquid droplets from aerosols. As the droplets are captured and coalesce in the filter layers, the pressure drop across the filter increases dramatically. Liquid saturation and distribution in the filter cartridge have a significant influence on the pressure drop, which has rarely been previously investigated. The study reported in this paper describes the distribution characteristics of the liquid in the filter layers and inside and outside of the filter cartridge during the gas-liquid filtration process. To obtain the vertical distribution of the liquid saturation, the filter cartridge was divided into three sections and the cylindrical filter elements (termed filter-plugs) were fixed inside the filter layers at various heights. A vertical aerosol sampling device was installed in the filter to determine the aerosol concentration inside and outside of the filter cartridge. The experimental results showed that non-uniform liquid distribution characteristics existed at various heights in the filter cartridge during the different stages of the filtration process. The outlet concentration increased from the top to the bottom of the filter cartridge, which corresponded to the various stages of gas-liquid filtration process. In addition, the distributions of the vertical aerosol concentration inside and outside the filter cartridge were different due to the gas flow direction and the tubular structure of the filter cartridge.

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1. Introduction

Fibrous filter cartridges are widely used to remove dust and liquid droplets from high sulfur natural gas and oil mists from compressed gas. The mechanisms of gas-solid and gas-liquid filtration are quite different. During gas-solid filtration, the pressure drop across the filter increases as the dust loading on the filter layers, but the filter cartridge can be used long-term if it is periodically cleaned using pulse-jet. However, the filter media used for gas-liquid filtration is disposable. Liquid coalescence and drainage occurs in the filter layers to accomplish the gas-liquid separation [1].

Research on gas-liquid filtration has mainly focused on two salient aspects of the process. The first is the behavior of liquid droplets on the fiber or in the fiber bundle [2–5]. Studying this aspect can help in the understanding of the liquid migration in the filtration system, which can lead to the development of an accurate filter performance model [6–8]. The second is the separation performance of the filter, particularly the influence of material properties and operating parameters on the pressure drop and the filtration efficiency [9–12]. In this aspect, experimental investigations have been conducted, which were designed to reflect actual working conditions [13–15].

When the operating and environmental parameters are constant, the filtration process can be divided into four stages according to the evolution of pressure drop. These stages include the beginning, wetting, unsteady coalescence and steady coalescence [2]. The captured droplets gradually coalesce on single fibers in the beginning stage. Subsequently, the droplets rearrange as a result of gas dragging force and/or the capillary forces and become clogged in the filter layers. The liquid then begins to drain downward after the droplets have gathered to a certain extent degree [15]. The drainage flow rate gradually increases until it attains the liquid capture rate and then the steady coalescence stage is achieved. At this stage, the liquid saturation and the outlet concentration remain stable, so that the pressure drop and filtration efficiency are in dynamic balance.

The stages of the gas-liquid filtration are determined by the migration and saturation of the liquid inside the filter layers. The saturation and the distribution of the liquid in the filter medium have significant influences on the pressure drop and filtration efficiency. Macro liquid distribution diagrams have been presented to describe the inside of the filter layers, where the captured liquid appears primarily at the bottom of the filter layers [16–18].

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However, the amount of the liquid distributed in the longitudinal and transverse sections of "filter fields" must also be clearly known, which is essential for determination of more accurate models.

In the longitudinal aspect, the draining liquid migrates to the bottom of the filter cartridge over a long distance. Charvet et al. [7] reported that when the filter was vertical and the gas flow was horizontal, the uneven drainage at various heights in the filter medium results in non-uniform airflow at each height. However, Raynor and Leith [16] observed that there was a resistance to movement of the liquid as the liquid droplets began to drain and the droplets moved more rapidly once they overcame this inertia. If the liquid drained rapidly after the initial period, the liquid distribution would be relatively uniform with height. Kampa et al. [19] also demonstrated that there was no systematic variation in vertical oil distribution at steady state.

In the transverse aspect, Contal et al. [2] tested the saturation of every filter layer at four stages of the filtration process and found that the liquid at the inlet side would extend over the medium of entire filter until a steady state was achieved where the liquid would spread evenly over the filter layers. Frising et al. [18] defined liquid saturation at a set liquid volume as the liquid packing density and divided the filter medium into several layers along the direction of flow. The authors postulated that the liquid packing density of the various filter layers changed with the filtration stage. A semi-empirical model of the pressure drop was established, but the jump phase of the pressure drop during the actual process was not included in the simulation curve [18].

Although the distribution and migration of the liquid in the filter layers have a direct influence on the pressure drop and the filtration efficiency, it is difficult to measure these quantities experimentally. Weighing the filter element or filter layers during flow interruption is a common method employed to obtain representative data [2,20]. However, the accuracy of the data is often in doubt, because the distribution of the liquid in filter layers changes as a result of the flow interruption. It has been reported that there are great discrepancies in the liquid distribution between the static and the operating cases [21]. However, Frising et al. [22] demonstrated that after a break in aerosol flow, the pressure drop increased when the aerosol flow was once again engaged in one stop-start cycle. Bredin and Mullins [20] also observed that pressure drop and saturation increased with a rearrangement of the liquid during filter flow interruption.

At present, most of gas-liquid filtration research has focused on planar filtration, but a few studies have dealt with filter cartridge or cylindrical filter element [20,23]. Owing to the small size of the filtering apparatus and its large processing capacity, the filter cartridge is widely used in the filtration industry of natural gas, compressed air and gas turbine. This reported study focused on one type of filter cartridge commonly used in the purification of natural gas. Experiments were conducted to understand the saturation distribution characteristics of a select filter cartridge during the filtration process and the gas-liquid filtration characteristics of this filter cartridge were studied in detail.

2. Experiment approach

The specific experimental parameters used to test the selected filter cartridge are shown in Table 1. The filter cartridge has been widely used in China's natural gas pipelines, because of its stable performance and low cost. There is no metal framework inside or outside this filter cartridge. It is manufactured by spiral-wound ribbon polyester fibrous material as shown in Fig. 1.

Table 1
Properties of filter cartridge for experiment.

Filter	Outside diameter/inside diameter/length (mm)	Fiber diameter (μm)	Layers	α	Contact angle for DEHS (°)
A	114/80/914	25 ± 5	10	0.18	⩽15

2.1. Test facility

Fig. 2 shows the experimental system used to determine the performance of the filter cartridge. It consisted of a liquid atomization device, a filter barrel and sampling and testing devices. The air was introduced using a centrifugal vacuum blower (G6-14, Shanghai Huagu Blower Co., Ltd., China), which could make the negative pressure of inlet up to 30.2 kPa.

A set proportion of compressed air and liquid formed a large number of atomized droplets using an atomizing nozzle (1/4J +SU11, Spraying Systems Co., USA). Then the atomized droplets were mixed with clean air to form an aerosol, the concentration of which could be adjusted. The aerosol entered from bottom of the filter barrel to the inside of the filter cartridge and then passed through the filter cartridge. Most of the liquid was detached in the filter layers and subsequently drained to the gatherer at the bottom of filter barrel, while the filtered gas discharged from the top of filter barrel. A flowmeter and a valve were located on the downstream side of the filter and the gas flow was held constant using a programmable logical controller (S7-200CN, Siemens Numerical Control Ltd., Nanjing, China) during the filtration process.

L-shaped sampling tubes were used on both upstream and downstream sides of the filter. The inner diameter of sampling tube was adjusted to offer isokinetic sampling, ensuring matching velocities for the sample gas and the gas in the main pipeline. In this way, the test results represented the actual situation in the main pipeline. The concentration and size distribution of the inlet aerosol was varied by adjusting selected parameters, such as the flow and pressure of compressed air, DEHS fluid volume, etc. The inlet aerosol parameters were held constant in this study, where the number concentration was about $8 \times 10^4\ \mathrm{P\,cm^{-3}}$, the mass concentration was about $300\ \mathrm{mg\,m^{-3}}$, the inlet droplet size ranged from 0.3 to 9.0 μm, the number median diameter was 0.8 μm and the volume median particle size was approximately 4.2 μm.

Sample gas flows were passed through an aerosol spectrometer (Welas 3000, PALAS Gmbh, Germany) for online measurement, where the concentration of droplets and the distribution of the droplet size were determined. A differential pressure transmitter (3051 CD, Rosemount Inc., USA) was used to measure the pressure

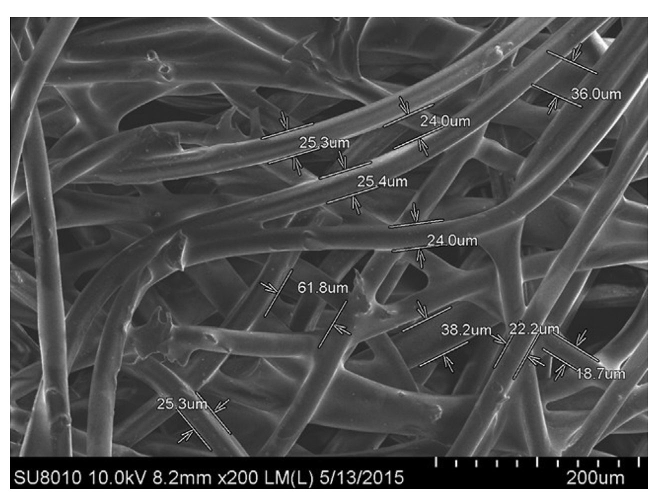

Fig. 1. SEM photo of the medium used for filter cartridge.

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