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Permeability of filter cartridges used for natural gas filtration at high pressure

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A B S T R A C T

The permeability of cylindrical filter cartridges commonly used for natural gas filtration was investigated in this reported work. Sample cartridges were composed of polyester, polypropylene, polyamide and three types of glass fiber with different fiber diameters. The pressure drop and permeability coefficients of the filters were measured at absolute pressure 0.1 MPa and 11 MPa, with a face velocity up to 0.25 m/s. At 0.1 MPa, the resulting permeability coefficients k_1 ($1.08–40.68 \times 10^{-12}$ m^2) and k_2 ($0.74–1.04 \times 10^{-7}$ m) were typical of the fiber media used in filtration applications. The parameter k_1 was accurately predicted using the Kuwabara model with a packing density in the range $0.05 < \alpha < 0.30$. At 11 MPa, k_1 ($0.72–2.29 \times 10^{-12}$ m^2) and k_2 ($0.23–0.37 \times 10^{-7}$ m) were significantly lower than at atmospheric pressure. The filter materials experienced a significant change when used in the field. After high-pressure test, the average pore diameter of glass fiber increased and the thickness of needled felt decreased greatly, while the fiber diameter experienced little change in all of the filter cartridges. The permeability coefficients decreased at high pressure. Therefore, the change in the permeability coefficients of the filter should be considered when predicting the pressure drop of the filter cartridges at high pressure. Filter designers can use the data presented in this study to select filter materials based on the variations in permeability coefficients.

1. Introduction

Natural gas is expected to become one of the fastest growing global fossil fuels in the near future. Global demand for natural gas is predicted to grow by 1.9% per annum, reaching 497 billion cubic feet per day by 2035 (BP, 2014). The primary method for transmission of natural gas is by pipeline. Chinese natural gas imports are predominantly from central Asia, via the secondary west to east gas pipeline, which is the longest gas transmission pipeline in China with a total length of 9000 km, comprising 25 compressor stations and a nominal diameter of 1219 mm. The maximum pressure of this pipeline is 12 MPa and it has a design capacity of 300×10^8 m^3/a. The pipeline gas can reduce the energy loss by the transmission of gas at high pressure and the capacity can be improved for a given size of pipeline (Mokhatab et al., 2006; Woldeyohannes and Majid, 2011).

In long-distance natural gas pipeline transmission, the presence of black powder and droplets may present potential safety hazards throughout the gas networks. These conditions may result in corrosion of the pipeline, clogging of instrumentation and filters and accelerated deterioration of valves (Azadi et al., 2011, 2012). Fouling of the compressor dry gas seal system may result from suspended particles that can cause damage to the dry gas seal dynamic and static rings, leading to gas leakage and compressor shutdown (Stahley, 2005). To remove impurities from the gas, cyclone separators, filter separators and coalescers are generally installed in the compressor and distribution stations to purify the gas (Baldwin, 1998; Xiong et al., 2008). Filter cartridges are the key elements of the filter separation equipment. In this regard, research of the cartridge permeability behavior is needed to determine how this affects the filtration performance of filter cartridges.

This reported research dealt with the gas permeability of porous media in particular, granular media, cellular media and fibrous media (Innocentini et al., 2005). Moreira et al. (2004) investigated the influence of structural parameters on the permeability of ceramic foams and concluded that pore diameter is the most important structural parameter in a ceramic foam medium. The

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performance of filter material at high temperature has also been evaluated by several researchers. Innocentini et al. (2009) studied the performance of porous ceramic membranes used for filtering hot aerosol at temperatures up to 700 °C. The reported test results showed that the permeability of the filter material increased with the temperature of the gas. These findings agreed with the results reported by Barg et al. (2011).

The permeability of a porous medium can usually be quantified by Forchheimer's equation for a wide range of fluid velocities (Innocentini et al., 2005; Moreira et al., 2004). Filter cartridges used for natural gas purification are usually hollow cylinders, in which the orientation of the fluid is radially inward or outward. In the case of radially outward, the gas flow through hollow cylinder is shown in Fig. 1. The integral of the Forchheimer's equation for a hollow cylinder with a compressible flow can be summarized by Eq. (1).

$$\frac{\Delta P}{(D_i/2)} = \frac{\mu_o}{k_1}\ln\left(\frac{D_o}{D_i}\right)v_{so} + \frac{\rho_o}{k_2}\left(\frac{D_o - D_i}{D_o}\right)v_{so}^2 \tag{1}$$

For compressible fluids, the pressure drop ΔP in the fluid can be calculated by the expression (Innocentini et al., 2005):

$$\Delta P = \frac{P_i^2 - P_o^2}{2P_o} \tag{2}$$

The maximum flow resistance of the filter cartridge for the gas is about 2% of the gas pressure, in which the difference in compressibility of the gas across the filter cartridge is negligible. Eq. (2) can be simplified to:

$$\Delta P = P_i - P_o \tag{3}$$

In Eqs. (1)–(3), D_i and D_o are the inner and outer diameters. The parameters v_{so}, ρ_o and μ_o are face velocity, density, viscosity of the gas based on P_o. P_i and P_o are the absolute gas pressures before and after the filter cartridge.

The Reynolds number (Re_f) of the fiber can be used to assess the flow regime and the Forchheimer number (F_o) represents the permeability correlations of the fibrous materials, which have been calculated by (Hutten, 2007; Wang et al., 2007)

$$Re_f = \frac{\rho_o v_{so} d_f}{\varepsilon \mu_o} \tag{4}$$

$$F_o = \frac{\rho_o v_{so}(k_1/k_2)}{\mu_o} \tag{5}$$

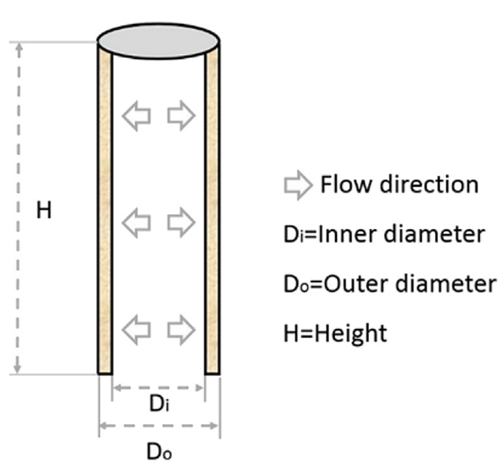

Fig. 1. Radial gas outward flow through a hollow cylinder.

The Forchheimer number (F_o) is related to the linearity in the pressure drop curve. For $F_o \ll 1$, inertial effects can be negligible. However, when $F_o \gg 1$, viscous effects can be disregarded (Innocentini et al., 2012). For cylindrical filter cartridges, the viscous term and inertial term can be computed from

$$\left(\frac{\Delta P}{(D_i/2)}\right)_{\text{viscous}} = \frac{\mu_o}{k_1}\ln\left(\frac{D_o}{D_i}\right)v_{so} \tag{6}$$

$$\left(\frac{\Delta P}{(D_i/2)}\right)_{\text{inertial}} = \frac{\rho_o}{k_2}\left(\frac{D_o - D_i}{D_o}\right)v_{so}^2 \tag{7}$$

Natural gas filtration usually occurs at high pressure, where fluid properties, features of dust and liquid droplets can be very different from those at atmospheric pressure ($\approx$0.1 MPa). At high pressure, gas density and viscosity increase and the filter medium structure deforms, resulting in restrictions in the flow path (Innocentini et al., 2012).

Efficiency and pressure drop are the most important performance criteria of any filter. The efficiency is usually determined by using particle counters. However, most of these devices can only be used at atmospheric pressure and room temperature, which causes difficulty in determining the impurity content in natural gas at high pressure. Pressure drop can be determined using a differential pressure transmitter in the compressor station. But this device is also ineffective for evaluating the filtration performance due to the variations in natural gas. Therefore, there is currently no available scientific method employed in the field operations to evaluate filtration performance.

The present study was conducted primarily on gas at atmospheric pressure to evaluate disc shaped filter media. There is a very limited number of reports in the literature concerning the use of industrial cylindrical filter cartridges for natural gas filtration at high pressure. Therefore, the effect of pressure on the filter material can be better understood by investigating filtration performance at high pressure, which will provide basic data for the design of fibrous filter cartridge.

In this study, the permeability of filter cartridges commonly used for natural gas filtration was studied at atmospheric pressure (0.1 MPa) and high pressure (11 MPa). It is commonly known that routine laboratory analysis can be performed to determine the permeability of a filter at atmospheric and high pressure. However, this reported work focused on the relationship between the filter material parameters and the variation in permeability coefficients, rather than permeability test method. The pressure drop and permeability coefficient were measured and the details behind the variation in the permeability coefficient were determined.

2. Material and methods

2.1. Filter material

Cylindrical filter cartridges were composed of fibrous filter material, including polyester (PE), polypropylene (PP), polyamide (PA) and three types of glass fiber (GF) with various fiber diameters. The fiber diameter (d_f) of each medium was acquired using an SEM (scanning electron microscope) (SU8010, Hitachi). Grammage (G_f) was obtained from the filter manufactures. The thickness (L) of the filter materials was measured using a digital caliper. The fiber density (ρ_f) was obtained from the literature (Hutten, 2007). The packing density (α) was calculated from L, G_f and ρ_f. All the filter cartridges had the same geometry and size. The major properties and surface details of test filter cartridges are given in Table 1 and Fig. 2.