Contents lists available at ScienceDirect

Chemical Engineering Research and Design

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

Performance of a depth fibrous filter at particulate loading conditions. Description of temporary and local phenomena with structure development

*Ewa Sikorska, Jakub M. Gac, Leon Gradoń**

Faculty of Chemical and Process Engineering, Warsaw University of Technology, ul. Waryńskiego 1, 00-645 Warsaw, Poland

ARTICLE INFO

Article history:
Received 15 July 2017
Received in revised form 3 February 2018
Accepted 14 February 2018
Available online 22 February 2018

Keywords:
Fibrous filters
Porosity development
Process simulation
Water

ABSTRACT

Optimization of a depth filter structure requires information about the filter's performance during its loading with particles. In this paper a macroscopic model of filtration process was proposed. It was based on the description of the loading process of three different gradient fibrous filters produced in the melt-blown technology process. Due to the contamination deposition on fibers, a new method of determination of the filter porosity transition, was suggested. It was based on growth of the deposit mass accumulated in individual filter layers, which was defined upon the scanning electron microscope images, the clearance of layer samples, and the overall increase of the filter mass. Local phenomena, i.e. the agglomerate structure, its spatial distribution and resuspension, were exposed through a two-stage character of the process. The empirical correlations obtained for deposition kinetics and pressure drop development are helpful in filter design. By knowing the desired contamination removal, fiber diameter and porosity can be verified mathematically, so that the filter will work the most efficiently. The proposed description of the structural loading of the multilayer filter is simple and reliable. Further research on biotic and abiotic particle transport mechanisms should be performed.

1. Introduction

Fibrous filtration is an efficient and promising method of water purification. Nowadays, many researchers improve standard fibrous filters by modifying their structure and properties. For example, the chemical or texture modifications provide some special properties, like bacteriostaticity (Zhao et al., 2017) or unique ion absorption (Tomaszewska et al., 2016). Nevertheless, the basis of the filter material is still a properly designed structure. A reliable filtration model, which uses such structures, could reduce the amount of laboratory effort necessary to produce empirical data for more effective filter design.

The aim of this work is to define a simple model of depth filter behavior during its loading, which will be useful for the filter structure design. The object of research is particularly a polypropylene multilayer filter produced with the use of melt-blown technology process. This manufacturing technique enables formation of fibers characterized by a specific diameter distribution and desired packing density. By knowing what parameters determine the production process, finally the optimal structure of the fibrous filter designed for particular contamination removal can be formed.

Depth filtration is a process where pores of filter material are larger than removed solids and separation results from particle transport inside the filter volume. Separation efficiency fluctuations, pressure drop development and filter lifetime are not influenced by the sole initial fibrous structure of the filter but also through the way in which deposits accumulate on fibers during the initial, operational and breakthrough phases (Tien, 2012). No sieve effect can be noticed, thus resuspension of deposits during late stages of filtration is a frequent problem, which should be always borne in mind (Przekop and Gradoń, 2016).

* *Corresponding author.*
E-mail address: Leon.Gradon@pw.edu.pl (L. Gradoń).

https://doi.org/10.1016/j.cherd.2018.02.020

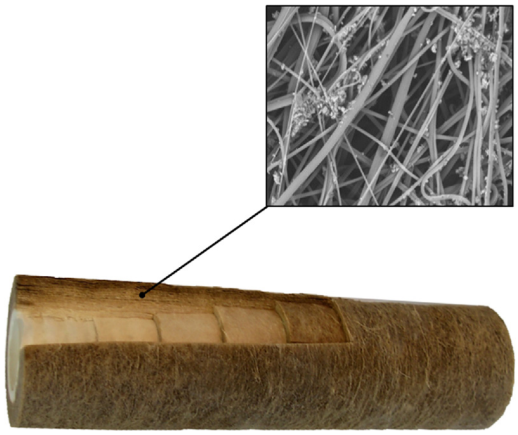

Fig. 1 – Fibrous filter loading with particles.

A comprehensive prediction of the depth filtration process in microscopic models, the models which investigate pathways of particles, can foresee the local phenomena (Ziskind et al., 2000). However, their use is complicated and time consuming. Quick approximation of filter behavior is possible in macroscale simulations, where the material balance is analyzed for an infinitesimal volume of a filter material. These models due to their practical meaning were closely investigated in this work.

The conservation law has been widely used by many authors for a description of depth filtration process. The kinetics of a deposit accumulation was described as irreversible, including only accumulation of solids (Tien et al., 1979; Iwasaki, 1937), or reversible, throughout a breakthrough stage (Gitis et al., 2010; Adin and Rebhun, 1977). However, all of the existing approaches regarding a multi-stage character of the process were based on experiments performed with granular filters. Compared to fibrous filtration, differences were observed not only in the shape of the collector, its size or filter depth but also in flow conditions. Altogether, it made the existing models useless for application to the fibrous filtration description.

Typical fibrous filters consist of layers differing in porosity and fiber diameter. Such structure provides an efficient capture of multi-sized contamination. However, during filter design it has to be considered as a system of separate layers. With the filtration process' time the development of deposit mass also causes a continuous transition of boundary conditions and local permeability field. A proper definition of these changes leads to a proper description of the process.

Filter characterization during the non-steady filtration process time can be described in two macroscopic ways. The first method is based on the fiber diameter's expansion. The deposit can create a layer uniformly covering the filter material (Zywczyk et al., 2015; Henry et al., 2012). From our observations it was concluded that in case of water filtration, contamination accumulates compactly on fiber intersections, as can be seen in Fig. 1, consequently affecting the pore size rather than the fiber itself. Therefore, the previous technique seems inadequate. We decided to use a second method of loading description, via porosity changes. A clue of the problem was a proper definition of the porosity of a fibrous structure covered by a deposit.

Porosity is a measure of void spaces in a material. It can be measured with porosimeters, optical methods, geometric or mass considerations (Dullien, 1979). For years these methods have been developed by many researchers (Jakiewicz et al., 2014; Noiriel et al., 2005; Maschio and de Arruda, 2001), although they still have some limitations. The measurement of porosity changes inside a fibrous filter during the filtration process was never before the subject of detailed considerations, although it has a crucial impact on particle transport phenomena. In the paper, a quantitative description of the filter porosity development based on a scanning electron microscope images and the overall filter mass is proposed. The local phenomena, i.e. the agglomerate structure and the deposit resuspension are described in detail and converted to a macroscopic view in a model definition.

Results of computer simulations and experimental validations are compared and summarized in Conclusions.

2. Materials and methods

2.1. *Filter production*

One of the most promising methods of fibrous filter production is a melt-blown technique (Hutten, 2007). In a single production cycle a mono-, multilayer or a mixed-fiber structure can be easily produced (Bodasinski et al., 2015).

For the purpose of our research the designed filter structures were produced by Amazon Filters Sp. z o.o. A scheme of the stand for production of fibers by blowing of a melted polymer is shown in Fig. 2.

A granulated polymer is poured into a container (1) and the extrusion screw (2), driven by an electric motor with the gear system (4), transports the polymer into the die (5) with desired flow rate. Polymer is heated and melted to the desired value of its temperature using an electric heater (3). The die construction enables a formation of the melted polymer jets in the nozzle system (Fig. 2b). Single cylindrical jet formed in the nozzle hole of diameter D is exposed to the stream of the hot air (6) flowing tangentially to the surface of the polymer jet. The shear-stress at the interface polymer-air causes the stretching of melted filaments. In the zone of cooling, T_0, the polymer filament is solidified and then collected on the mandrel with the perforated filter core on it (7). The mandrel rotates and moves to-and-fro under the die. The filter structure is formed. Taking into account the momentum, mass and energy balances of the system (Fig. 2c) we are able to estimate the operational condition for formation of fibers of defined diameters d_f (Gradon et al., 2005).

The control of the process parameters enables us to produce filters with desired morphology. The distance between the die and fiber collector influences fiber packing density within the filter structure. The fiber diameter is essentially determined by the flow-rates of polymer and air, and temperature of both media (Selomulya et al., 2005).

For the purposes of this research three multilayer polypropylene filters, composed of six layers differing in porosity and fiber diameter, were produced. The mean fiber diameter of all the layers was in a range between 1 and 26 μm and their initial porosity between 0.67 and 0.85. These filter structures were designed for the removal of particles of 0.5, 1 and 3 μm in size and larger with required efficiency. The cartridges were 10″ (ca. 25.4 cm) long with 2.5″ (6.4 cm) of external diameter with thickness of filtration layer 1″ (2.5 cm). The filters were tested in conditions typical for water filtration.

2.2. *Experimental validation*

2.2.1. *Filter performance*

Filtration experiments were carried out under the constant flow conditions of 600 L h^{-1}, which during the industrial use is