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Original Research Paper

A statistical model of pressure drop increase with deposition in granular filters

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ABSTRACT

As deposits accumulate in a granular filter, pressure drop across the filter bed required to maintain a constant fluid flow rate may increase. Two pressure drop increase patterns had been observed. In slow sand filters pressure drop remains unchanged for a certain period of time then increases exponentially with the volume of filtrate; in granular aerosol filters pressure drop increases linearly with the amount of deposits from the beginning of the filtration process. New concepts of homogeneous and heterogeneous depositions were introduced in this paper. A statistical model based on these new concepts was developed. This non-linear model was able to reproduce both observed pressure drop increase patterns, including the linear one. Excellent agreements between the present model and experimental measurements were obtained. It was concluded that the two pressure drop increase patterns were indeed caused by different deposit distributions rather than different pressure drop increase mechanisms.

1. Introduction

Granular filters use granular material to separate small particles from fluids and have many important applications including drinking water purification, waste water treatment, flue gas cleaning, molten metal refinement, radioactive particle removal, etc. The increase in pressure drop (head loss) required to maintain a constant flow rate through a granular filter due to particle deposition has been the subject of experimental and theoretical investigations. In this paper major experimental observations and theoretical methodologies are reviewed; two new concepts, namely the homogenous and heterogeneous depositions are proposed; a statistical model based on these concepts is developed and verified.

Experiments revealed two drastically different pressure drop increase patterns in granular filters. In slow sand filters, which are commonly used for water purification, the pressure drop usually remains a constant for a considerable duration as deposits accumulate, then rises exponentially with the volume of filtrate [1–4]. On the contrary in granular aerosol filters the pressure drop typically increases linearly with the amount of deposit from the very beginning of the filtration process [5–7]. In addition, experiments demonstrated that in slow sand filters the pressure drop increase is concentrated to a thin layer (Schmutzdecke) at the top of the filter bed where the raw water flows into the bed, below which the filter medium remains hydraulically clean, i.e. although deposits present, they affect the pressure drop only marginally and the pressure drop in this region stays essentially the same after even a few years of operation [8]. In contrast, the pressure drop at every depth of a granular aerosol filter increases simultaneously as filtration proceeds [5].

Tremendous efforts have been made to relate these experimental observations to fundamental filtration mechanisms. Because of particle deposition, filter medium structure changes continuously. As most authorities agree [9], such changes include (1) decrease in filter medium porosity and increase in effective filter grain diameter; (2) change in filter grain surface morphology due to non-uniformity of particle deposition and formation of dendrites; (3) clogging part of pores in the granular medium. All these effects contribute to pressure drop increase across the filter.

Effect (1) can be readily evaluated by using Ergun equation [10]. Prediction thus given has been found grossly underestimate the pressure drop increase [11], which is not surprising because deposits only have negligible contribution to pressure drop as long as pores in the granular medium are not clogged [8]. Despite its inability to explain the observed pressure drop increase, Ergun equation has been adopted as the starting point by various investigators [12–14] to develop their empirical correlations between

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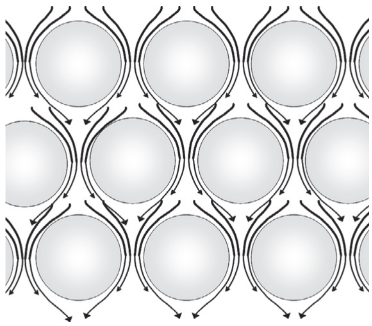

Fig. 1. Granular medium represented as layers of pores.

pressure drop increase and deposition. These correlations differ a lot in mathematical forms as they were derived from different experimental data. For example the correlation of Mints [12] is linear; while that of Toms and Bayley [4] is exponential and the one given by Ives [13] is a product of two power-laws.

Trajectory analysis was used extensively by Tien and co-workers [15–18] to study effect (2) on granular filter performance. By tracking positions of particles randomly released from the inlet of a representative geometry (a constrained tube, for example) which characterizes the "mean" geometrical features of the filter medium, they were able to calculate the deposition location of each deposited particle and subsequently they were able to determine the pressure drop increase across this model space. Their results showed power-law increases in pressure drop with deposits during granular filtration [16,17]. The difference between their prediction and experimental observations might be attributed to clogging, that is effect (3).

Fan et al. [19] modeled clogging as a stochastic birth–death process. They treated the granular medium as a large number of interconnected pores and assumed that at every moment during filtration an open pore always has a chance to be blocked, and the probability is proportional to the number fraction of the open pores; at the same time a blocked pore always has a chance to be reopened with a possibility proportional to the number fraction of the blocked pores. The model was able to represent the pressure drop history of a waste water granular filter. However, the two possibility proportionality constants in this model can only be determined by fitting experimental data rather than being related to relevant physical variables.

Based on the existing information, it seems safe to conclude that clogging is the most important reason for the filter pressure drop increase. Compared with clogging the contribution of deposition to the filter pressure drop increase is but minimal. The random nature of the many factors affecting particle deposition implies a statistical treatment of the subject. An important link that connects the mathematical abstraction and physical reality is two new concepts, namely the homogeneous and heterogeneous depositions, which are discussed in the next section.

2. Homogeneous and heterogeneous depositions

Consider a packed bed of clean granular material through which fluid flows at a constant volume flow rate driven by a pressure gradient. The granular medium can be viewed as layers of pores interconnected in series, as Fig. 1 depicts. The layers are perpendicular to the flow direction. The number density of pores is typically very large. For example for a bed of granules of diameter $d_g = 2$ mm and bed porosity $\varepsilon = 0.36$, there are about 1.4×10^4 pores in 1 in.^{3} of filter volume [20]. As fluid flows through the bed, small particles carried by the fluid may deposit on the surface of pores and on the already deposited particles, or may be absorbed by the organisms in the bed. The rate of particle deposition is affected by a variety of factors such as particle concentration, flow speed, filter grain size, grain surface charge, grain surface morphology, organism concentration in the medium, etc. These factors differ from one pore to another. The extent of deposition in different pores of a given layer is therefore different. If the heavier deposited pores have less particle collection ability compared with the lighter deposited pores, the deposition difference among the pores will decrease and a homogeneous, or uniform, deposition distribution will form over this particular layer of pores; if on the contrary the heavier deposited pores have even greater particle collection ability than the lighter deposited pores, the difference in deposition level among pores will increase and a heterogeneous, or non-uniform, deposition distribution will form over this specific layer of pores. Based on logic, a filtration process should always fall into one of these two situations. The details of the physical and/or biological mechanisms leading to these two deposition distribution regimes are indeed irrelevant to the current study (one possible mechanism is given in Appendix A). Instead we are more interested in the inferences of these two deposition distributions.

(1) As fluid-particle suspension flows through a granular filter operating in the homogeneous deposition regime, consecutive uniformly deposited layers form until most particles in the fluid are filtered. Then we should find layers of clean pores. As a consequence, the pressure drop increase as well as deposition in such filters should concentrate to such uniformly deposited layers rather than the whole filter bed. On the other hand, for a granular filter operating in the heterogeneous deposition regime, even as part of pores being clogged at a certain layer, many pores of this layer are still open and of low particle collection ability due to the non-uniformity of the deposition distribution. As a result, much of the suspension can penetrate this layer through such open pores and produce similar partially-clogged deposition patterns in numerous successive layers, even across the whole filter. Therefore we should expect the pressure drop across all such partially-clogged layers, even across the whole filter, to increase simultaneously with time.
Immediately one recognizes the slow sand filters should operate in the homogenous deposition regime and granular aerosol filters typically run in the heterogeneous deposition regime if the present theory is at all reasonable.

(2) In the homogeneous deposition regime the amount of deposits in a clogged pore increases slowly compared with an open pore at the same layer because the heavier deposited pores have less particle collection ability than the lighter deposited pores in this regime. On the other hand, the clogged pores may still actively collect particles if the filter is operating in heterogeneous deposition regime since the heavier deposited pores have higher particle collection ability than the lighter deposited pores. One should notice in the current study "clogged" does not mean "no flow", instead it only means compared with open pores, the clogged pores have significantly less flow under the same pressure gradient.

(3) If we consider the deposit distribution among pores that are actively collecting particles at a specific layer, the homogeneous deposition obviously corresponds to small standard deviations in the deposit distribution while the heterogeneous deposition corresponds to large standard deviations. Based on these features, a statistical model of pressure drop increase with deposition is developed, which is discussed next.