First published in:

FILTECH 2011

CONFERENCE PROCEEDINGS

VOLUME I

CONTENT VOLUME I

CONTENT VOLUME II

Conference Dates:
March 22 – 24, 2011

Venue:
Rhein-Main-Hallen · Rheinstr. 20 · 65028 Wiesbaden · Germany

Organizer:
Filtech Exhibitions Germany
PO Box 1225 · 40637 Meerbusch – Germany
phone: +49 (0) 2132 93 57 60
fax: +49 (0) 2132 93 57 62
e-mail: Info@Filtech.de
web: www.Filtech.de

ISBN 978-3-941655-011-0

MODELING AND PREDICTING CLOGGING BEHAVIOR OF THE FILTRATION PROCESS WITH FIBROUS FILTER MEDIA FOR USED ENGINE LUBE OILS

Florian Gruschwitz – MAN DIESEL & TURBO SE, D-86224 Augsburg/Germany,
Prof. Dr.-Ing. habil. Hermann Nirschl, Dr.-Ing. Harald Anlauf – Karlsruhe Institute of Technology, Institute for Mechanical Process Engineering and Mechanics, D-76128 Karlsruhe/Germany
Dr.-Ing. Michael Förster, Nikolaus König - MAN DIESEL & TURBO SE, D-86224 Augsburg/Germany

ABSTRACT

Fibrous metallic filter media have been qualified for the filtration of engine lube oils for large Diesel engines with regard to fine particle retention and dirt holding capacity. For the design of real scale apparatus, a very important parameter is the clogging characteristic, i.e. how and how fast the filter loses permeability during the filtration process. Since the contaminant characteristic varies for different field applications it is impossible to experimentally consider all possible scenarios. This study shows that it is possible to describe this filtration process – i.e. the clogging process – with a mathematical filtration model and to predict different contamination scenarios.

KEYWORDS

Fine filtration, fibrous media, non-woven filters, modeling, filter clogging

1. Introduction

Lube oil systems of MAN large Diesel engines are designed to be operated without any explicit oil-changes – therefore a cleaning system has to continuously remove the contaminant input from operation. During operation with heavy fuel oil, the lube oil in large Diesel engines is strongly contaminated by combustion products and by-products, as well as particles from the ambient air. Furthermore, to neutralize acids in the lube oil, a high content of alkaline additive compounds is added to the lube oil. These form further particulate contaminants which are mainly calcium-compounds that are either decomposed, i.e. agglomerated, additives (e.g. Calcium-carbonate) or their reaction products (e.g. Calcium-sulfate). These additives may form lacquers and sludgy sediments in the system tank and are therefore to be removed by a cleaning system likewise.

At present, this cleaning task is performed by plate-type separators, but currently the applicability of automatic back-flushing filter systems is investigated. Since even very fine particles need to be retained in a cleaning system (~90 % efficiency for particles larger than x_p= 5µm), finding a suitable filter medium has been a great challenge. Diagram 1 shows a typical dirt particle size distribution for used lube oil in operation. It can well be seen, that most particles are in the range of a few (4-9) µm.

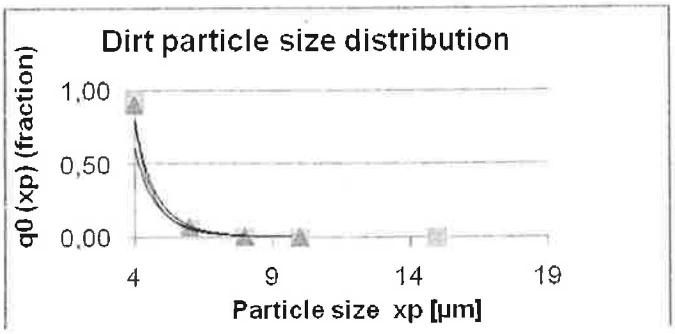

Diagram 1 – typical lube oil – contaminant size distribution

Non-woven depth filtration media have become increasingly popular in numerous industrial applications. Some of the major advantages of such media are the high dirt holding capacity, high permeability and a very fine filtration efficiency at the same time. Due to these advantageous features, these types of filter media could be qualified for the described cleaning task.

2 Problem definition and objectives

Due to the high content of particles in the oil, even the described filter media with their comparatively high dirt holding capacity, show a pronounced clogging behavior. For the system design (esp. the necessary filter area) – considering the filter regeneration back-flushing times, this characteristic of clogging has to be known – and ideally (within a certain range) be predictable. The clogging speed and characteristic is an important input parameter for real scale system design.

While the general quality and properties of the engine oils and contaminants are known - or at least a range can be described – unfortunately for this design task, oils from different engines – even for the same installation – may show very different contamination properties (esp. in terms of amount). An important task for the development of a new filter system – and to qualify its field applicability – is thus to predict the filtration behavior on basis of known parameters. Ideally, parameters can be changed in line with an analysis of sensitivity – enabling the pursuit of optimization in the pre-field phase already. For this the exact filtration mechanism (qualitatively – where and how the particles are retained in the depth filter material) is to be known and the aim is a mathematical model to help quantifying the results. These insights will also help to further improve the regeneration system design of these back-flushable filters.

3 Materials and method

3.1 Characterization of the filter medium

The filter media that were used for the experimental works are made of metallic fibres with a diameter of around 10 µm as shown in figure 1 -left. These media consist of various layers of fleece – with a gradient structure: on the up-stream and down-stream sides the fleece – even though the fibers have the same diameter – is not as densely packed and therefore shows very high permeability. The middle part of the medium however is made of a rather dense packing of fleece. Figure 1 –right side-shows a microCT picture of a cut through the filter medium where this gradient structure is visible. It can be shown that this is the area where the fine filtration process takes place and this part of the filter medium is therefore the most relevant for the filtration process.

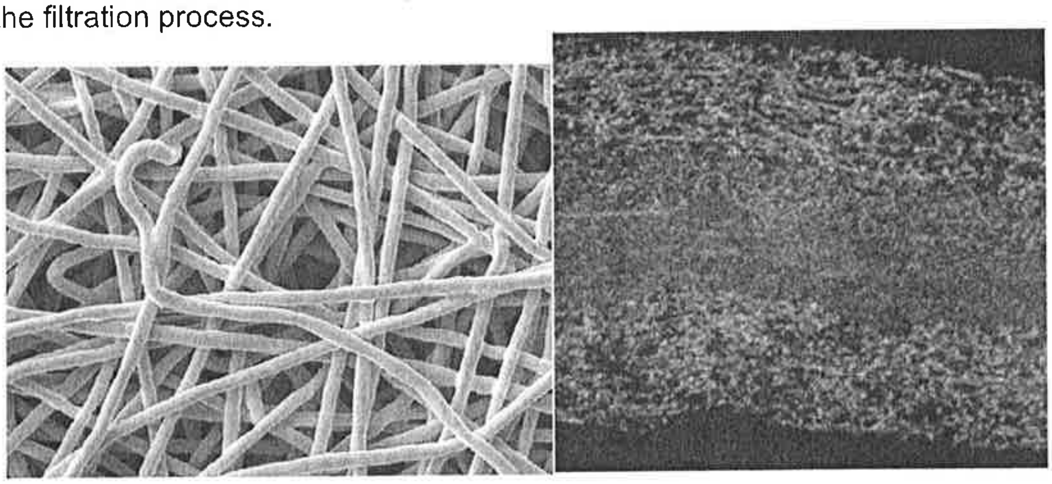

fig. 1 – (left) SEM image of filter medium - (right) sectional view of filter medium - microCT image

3.2 Experimental setup

The studies were performed at a laboratory test installation that is built according to the German VDI standard 2762:1997 (figure 2). The oil filled in the pressure cell is subjected to a constant pressure and filtered through a round filter sample at the outlet. The filtrate is collected in beaker placed on an electronic balance. As the balance is connected to a computer, the filtrate rate can be easily measured and recorded.

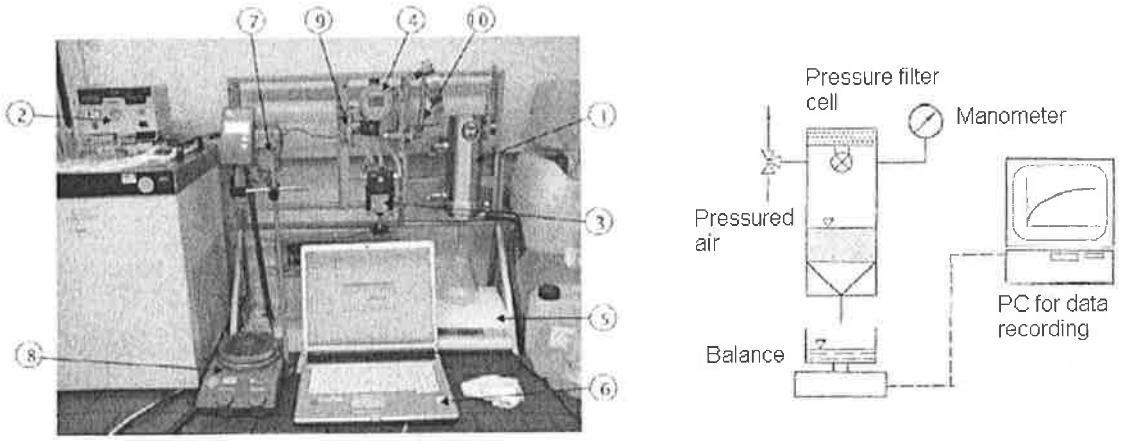

fig. 2 - Experimental setup laboratory scale

3.3 Characterisation of the filtration mechanism

Basis for the development of a model that is able to simplify the real process and makes it possible to describe it with a mathematical correlation is always a general idea of the process.

For the presented case, the system that is to be modeled is filtration medium – consisting of numerous layers of metal fibers– and a fluid containing particles of a range of sizes that is flowing through. Most of the particles- starting with a minimal diameter – are to be retained inside this filter medium – with the aim of getting a filtrate with a considerably reduced content of particles in it. During the described filtration process, the filter media is in such a way altered that the filtrate flow (for constant filtration pressure) is diminishing in scale. As for the case of a constant filtrate flow, the resulting differential pressure is increasing.

As described by Hermia [Her-82] there are four basic filtration models that describe the particle deposition on the filter medium: cake filtration, intermediate filtration, standard filtration and blocking filtration (figure 3)

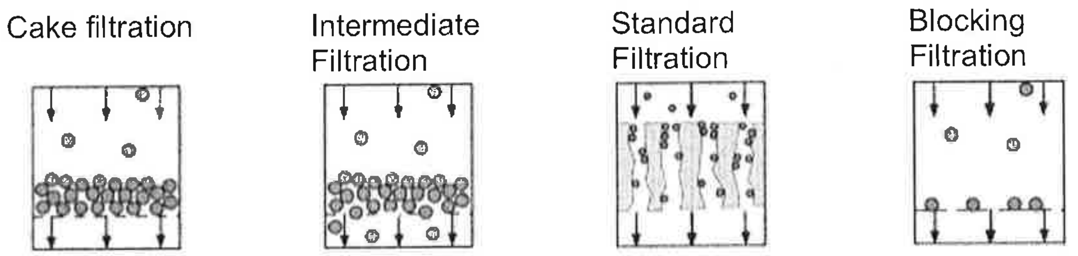

fig. 3 – Hermia's standard filtration models [Luc-04, p.163]

In the study, all models were examined for the applicability and the model of standard filtration could give a perfectly matching mathematical description of the experimental results, even though it has to be mentioned that the blocking filtration model can equally very well describe the later part of filtration: this is when retention of larger particles may become more and more present for the integral process.

For the model of standard filtration, the depth filtration mechanism is the starting point: the fluid passes in a perpendicular movement through the filter medium were particles are retained due to diverse mechanisms, as soon as a particle comes into contact with a filter fiber surface – larger particles are retained by ways of a sieving effect. The dominating mechanism how small particles come into contact with the filter fibers and are deposited is the blockage effect as schematically shown in figure 4: all particles that are on fluid flow lines where y0 is smaller than the particle radius come into contact with a filter fiber and are deposited there.

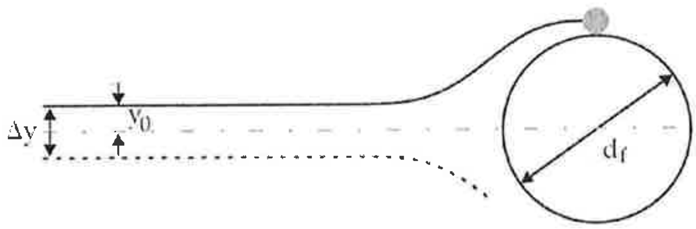

fig. 4 - Blockage effect

The deposited particles inside the filter structure are schematically shown in figure 5 – left side – on the right side is a SEM image of particle loaded filter fibers that can validate this.

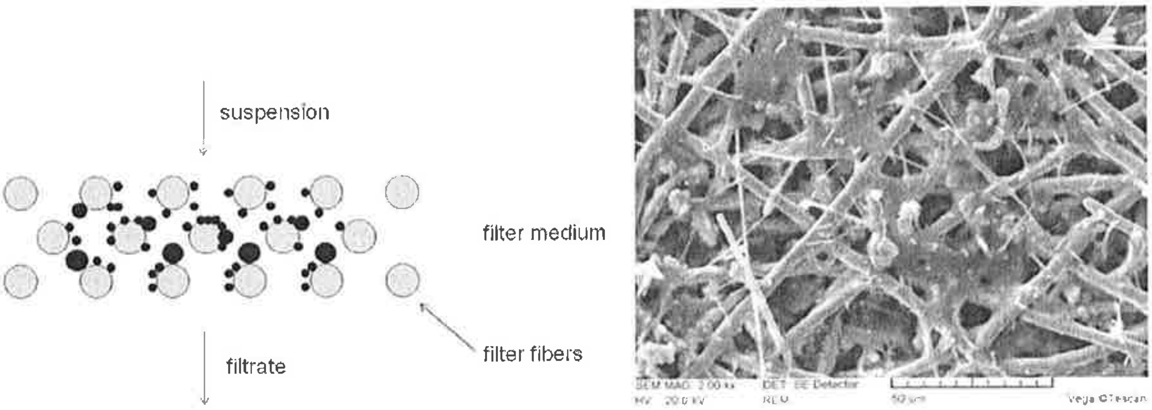

fig. 5 - particle deposition (left: schematic, right: SEM image of real filter)

3.4 Mathematical model development

The theoretical basis for the fluid flow through a permeable medium is described by Darcy:

$$\dot{V} = \frac{\Delta p \, A}{\eta \, R_m} \quad (1)$$

He gives a mathematical correlation for the fluid flow $\dot{V}$ through a porous medium that depends on the differential pressure ΔP, the area A, the dynamic viscosity of the fluid η and the specific resistance of the porous medium R_m. For a situation with no clogging of the filter (constant R_m), this equation very well describes the real situation for an oil filtering medium. This equation, of course, cannot describe a dynamic situation i.e. a clogging medium or the deposition mechanisms of particles in and on the filter medium.

Hermia [Her-82] developed a two-parameter-equation of which the earlier named models can all be deducted from:

$$\frac{d^2t}{dV^2} = C\left(\frac{dt}{dV}\right)^q = \frac{dR}{dV} \quad (2)$$

This equation describes the characteristic clogging speed of a filter during a filtration process in relation to a resistance (reciprocal flow rate). In other words: the rate of increasing filter resistance is correlated with the resistance of the filter as such. q is a parameter that depends on the applicable clogging model: High values (max. 2) describe very fast clogging, whereas in case of very low values (min. 0) a slow rate of clogging is described. For the standard filtration model, the value is 3/2. Thus, besides the fluid flow through the medium, in this case also the deposition mechanism can be described.

As described, for the standard filtration, the deposition is in such a way that the majority of the particles are smaller than the capillary diameters of the medium, can therefore enter the interior structure of the medium and are retained inside of the filter structure. The cross section area is diminishing by the retained particles.

This leads to another ideal assumption of the model description: the real porous structure is transferred to a capillary system, so that the fluid flow through the medium can be considered as a capillary flow. The mathematical model was developed by Hagen-Poiseuille:

$$\dot{V} = \frac{\Delta p\, N\, {A_K}^2}{8\, \pi\, \eta\, h} \qquad (3)$$

As it can be easily seen, this is a modified Darcy equation, with:
N - number of capillaries , A_K - cross section area of the capillaries and h - capillary channel length. With the porosity ε, N can also be described as:

$$N = \frac{A\, \varepsilon}{A_K} \qquad (4)$$

The described pore constriction is mathematically described as

$$A_K = A_{K0}\, (1 - k_S V) \quad (5)$$

and

$$A_K = A_{K0} - \Delta A_K \quad (6)$$

In other words: this expression postulates that the initial pore cross section area is proportionally decreasing with the filtrate volume V. To determine the constant k_S a mass balance for the solid matter is done with:

$$wV = \Delta A_K h_0 N_0 \varrho_s \quad (7)$$

This expression correlates the mass of deposited particles in the filter medium (right side) with the mass of solid matter in the suspension (left side). ΔA_K is the constricted capillary cross section area due to the particle deposition, $\varrho_s$is the density of the solid matter, w is the mass content of solid matter in the fluid and V the fluid/filtrate volume. It can be clearly seen that this expression postulates deposition of all solid matter in the fluid in the medium, which is nearly the case for the micronic particles in reality.
When equation 7 is transposed to an expression of ΔA_K and this term is used in equation 6, a description of the particle deposition model can be deducted:

$$A_K = A_{K0}\, \left(1 - \frac{wV}{A h_0 \varepsilon_0 \varrho_S} \right) \quad (8)$$

With this, a model can be deducted that summarizes the geometrical properties of the filter voids into parameters and shall now be done for the model of standard filtration [Luc-88, p.61].
The aim of this procedure is to find – by ways of experimental testing – the unknown parameters (specific resistance of the filter medium and the specific resistance due to the deposited particles). For the deduction of the parameters for resistance, the deposition model is put into the Hagen-Poiseuille equation:

$$\dot{V} = \frac{\Delta p N A_{K0}^2}{8\, \pi\, \eta\, h_0} \left(1 - \frac{1}{h_0 \varepsilon_0 \varrho_S} \frac{w}{A} V\right)^2 \quad (9)$$

With equation 4: $$\dot{V} = \frac{\Delta p A}{\eta}\, \frac{{\varepsilon_0}^2 A}{8\, \pi\, h_0\, N_0} \left(1 - \frac{1}{h_0 \varepsilon_0 \varrho_S} \frac{w}{A} V\right)^2 \quad (10)$$

further: $$\dot{V} = \frac{\Delta p A}{\eta} \left(\frac{A^{1/2} \varepsilon_0}{N_0^{1/2} 8^{1/2} \pi^{1/2} h_0^{1/2}} - \frac{A^{1/2} \varrho_S^{3/2}}{N_0^{1/2} 8^{1/2} \pi^{1/2} h_0^{1/2} \varrho_S^{5/2}} \frac{w}{A} V\right)^2 \quad (11)$$

now with: $$R_S = \frac{8\pi\, h_0 N_0}{{\varepsilon_0}^2 A} = \frac{8\pi\, h_0}{\varepsilon_0 A_K} \quad \left[\frac{1}{m}\right] \text{ and } r_S = \frac{A \varrho_S^3}{8\, \pi h_0^3 N_0} \quad \left[\frac{kg^3}{m^{10}}\right] \quad (12),(13)$$

results: $$\dot{V} = \frac{\Delta p A}{\eta} \left(\frac{1}{R_S^{1/2}} - \frac{w r_S^{1/2}\, 1}{A \rho_S^{5/2}} V\right)^2 \quad (14)$$

and with integration over t and separation of the variables the amount of filtrate:

$$V = \frac{A\,\Delta p t\,\rho_S^{5/2}}{\Delta p w R_S^{1/2} r_S^{1/2} t + \eta \rho_S^{5/2} R_S} \quad (15)$$

R_S in this model description is the specific (unclogged) filter resistance, and therefore should be identical to the filter resistance of Darcy's expression R_M. The factor r_S is introduced to give an expression for resistance due to the deposited particles; due to the rather arbitrary mathematical transformation, this figure defined by the unit $\left[\frac{kg^5}{m^{10}}\right]$ may therefore be seen merely as a factor than as a direct correlation of a real physical process.

R_S and r_S are obtained by experimental procedure: The amount of filtrate for a specific period of time is registered with an electronic balance. Known parameters are: solid matter content w, the solids density ϱ_s, the fluid viscosity η, the filter area A and the constant differential pressure Δp.

In a t/V-t diagram the curve is straight proportional and takes a linear form (as shown in diagram 2)

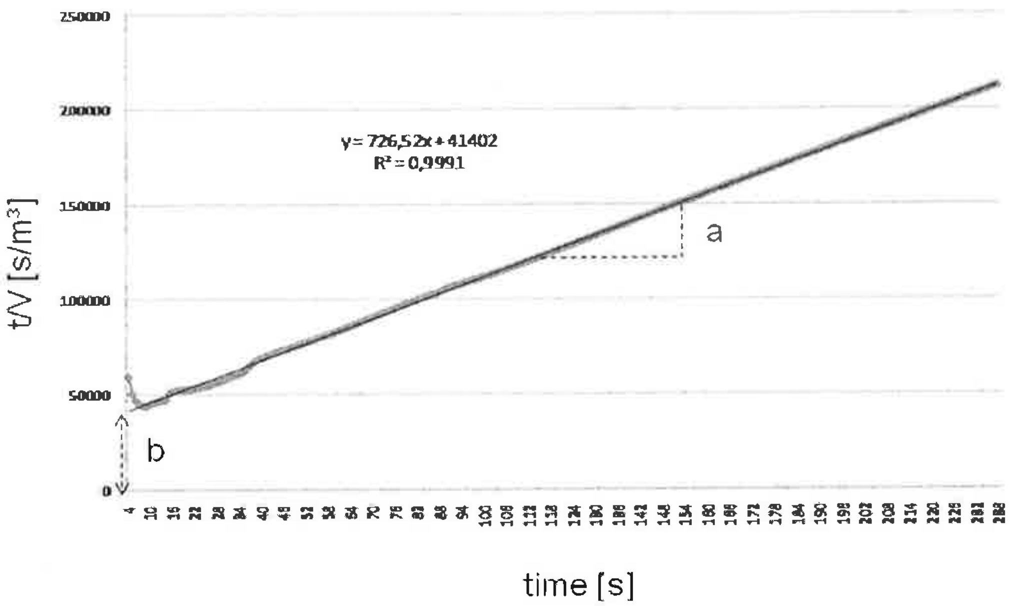

diagram 2 – linear presentation of the filtration process

Equation 14 can be changed into an expression for t/V, giving the presented proportional equation:

$$\frac{t}{V} = \frac{w r_S^{1/2} R_S^{1/2}}{A \rho_S^{5/2}} \,[\text{"}a\text{"}]\; t + \frac{R_S \eta}{A \Delta p} \,[\text{"}b\text{"}] \quad (16)$$

The interception point with the ordinate ("b") gives the value for filter resistance R_S which should be – as earlier described – identical with the filter resistance R_M concluded with the Darcy expression (1). Now knowing R_S, via determination of the linear slope ("a") of the function graph, the parameter r_S can be deducted. The functional slope gives a characteristic value for the clogging speed or characteristic – that can be correlated to the particle content (the amount directly scalable via w) in the oil.
Knowing these parameters, furthermore the amount of filtrate V can be predicted for a time t that is extrapolated with equation 15.

4. Results and conclusion

With the described mathematical model, it is possible to approximate the filtration process with a regression coefficient R^2 of approx. 0.99 for all tested filtration pressures and relevant temperatures. The model was validated for three different metal fiber fleece filter media in the fine filtration range.

While R_S is filter medium specific and does not change for different oil grades, r_S is a parameter that summarizes the clogging characteristic due to the deposited particles from the filtered oil combined with R_S as a "clogging predisposition" of a filter medium (high R_S usually describes a very fine filter material and thus a high clogging tendency) and paired with the particulate matter content w in the oil. All three factors result in the value for the slope of the linear function and show nearly a linear proportionality with the particle amount w in the oil as exemplarily shown in diagram 3.

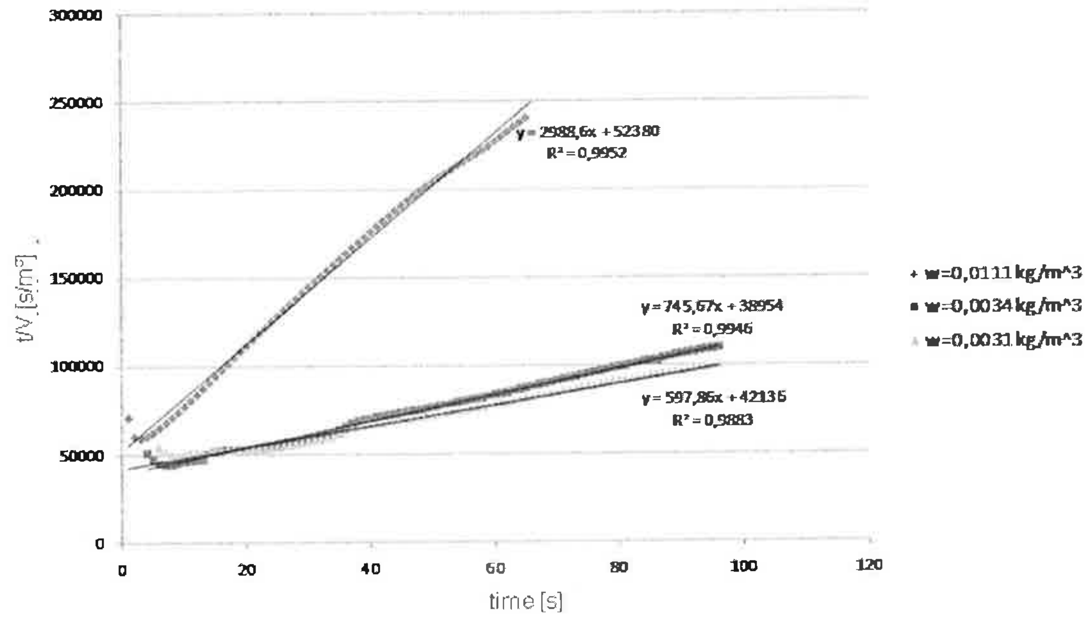

diagram 3 – linear presentations for different particle loads

This way, the filter behavior, i.e. its clogging characteristic, can be extrapolated for different particle load scenarios (directly scalable for varying content w).

It can be concluded that it was possible to successfully apply a mathematical model which enables to predict the filter behavior for varying particle content in lube oils. This helps for an optimized development of automatic back-flushing filters for the field application.

References

Her-82 – J. Hermia: Constant pressure blocking filtration laws: applications to power-law non-Newtonian fluids, Trans.Inst. Chem. Eng., Vol. 60, 1982, p.183-187

Luc-88 – K. Luckert: Modellierung der Fest-Flüssig-Filtration und statistische Datenanalyse, PhD Dissertation, Technical University Magdeburg, 1988

Luc-04 – K. Luckert et al – Handbuch der mechanischen Fest-Flüssig-Trennung – Vulkan Verlag, Essen, 2004