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NOTES ON CONTAMINATION CONTROL

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ABSTRACT

Contamination control is a technology to keep working fluids clean. Using a hydraulic filter is the commonest means of keeping the working fluid clean. The contamination level of a fluid exiting a filter increases with the operating time of the filter. The pressure loss across a filter element increases when the element retains contaminants. To describe these variations with operating time, this paper proposes: (1) a filter clogging model with an effective opening area; (2) a pressure-loss model related to the effective opening area; (3) a filtration model concerned with the effective opening area and the mean lodging time of particles; (4) a quasi-single-pass test method for evaluating the filtration performance of a filter. The paper also shows a system of equations describing contamination levels in fluid power systems and discusses the relevant industrial standards which are presently widely used.

KEYWORDS

Contamination control, Element clogging, Filtration, Single-pass test

NOMENCLATURE

a_0: projection area of a representative particle
$a(x)$: projection area of a particle of size x
K_l: form factor in pressure-loss coefficient
L: length in Reynolds number
M: number of representative particles retained in an element
$n_{d,x}$: number of particles greater than x in unit volume of fluid exiting filter
$n_{u,x}$: number of particles greater than x in unit volume of fluid entering filter
n_d: number of representative particles in unit volume of fluid exiting filter
n_c: number of representative particles in unit volume of fluid at a certain point in a system
n_u: number of representative particles in unit volume of fluid entering filter
S: effective opening area
S_0: initial value of effective opening area
S_F: area of representative surface = front surface area
Q: flow rate through filter element
R: ingression rate of particulate contaminants
R_e: Reynolds number of flow in filter medium
T: mean lodging time of particles
t: time
U_E: fluid velocity in element opening area = Q/S
V_R: fluid volume in reservoir
V_s: fluid volume in system except reservoir
β: beta-value = n_u/n_d

Δp: pressure loss across filter element
Δp_0: initial value of Δp
ν: fluid kinematic viscosity
ρ: fluid density
ζ: pressure-loss coefficient

1. INTRODUCTION

The purpose of contamination control is to keep working fluids clean. Keeping working fluids clean, we can extend the life of hydraulic components and reduce failures of fluid power systems. Thus, contamination control is a basic technology supporting the reliable operation of fluid power systems.

Although there are many kinds of contamination, this paper is only concerned with particulate contamination. The number of particles in a unit volume of working fluid determines the particulate contamination level.

A hydraulic filter is the commonest means of rejecting contaminants from fluid and to keep the working fluid clean. There are two important filter performance characteristics: the first is the ability to reduce contaminants in fluid; the second is the capacity to retain contaminants. The first characteristic should be estimated by the contamination level of the fluid at the exit of a filter. The second characteristic is estimated by the amount of contaminants retained in a filter element at the end of its service life.

The service life of a filter element ends when the contamination level of filtered fluid reaches an unacceptable limit, or the pressure loss across the element reaches an unacceptable limit. Usually, the contamination level of the downstream fluid of an element increases with operating time; when it reaches the maximum allowable upper limit the element life ends. Throughout operation of a filter, contaminants are accumulated in the filter element. The accumulated contaminants induce additional fluid resistance that results in a rise of pressure difference across the filter element. When the pressure difference exceeds the limit of strength of the element, deformation or breakage will result if the filter has not been equipped with a safety valve. Thus, there is an allowable limit for the pressure difference that determines the element life. The pressure difference across a filter element is influenced by operational parameters, for example, flow rate, fluid temperature, and other fluid properties.

The phrase "contamination control" was introduced into fluid power technology in the 1960s, by E.C. Fitch, Jr.[1]. Most of the technical development in this area was stimulated by him and his co-workers. Before their work, little attention had been paid to filtration or phenomena related to fluid contamination. Since then, much experimental study of contaminants measurement, filter element performance, and the influence of contaminants on hydraulic elements has been made in many countries [2],[3]. However, the theoretical work in this subject is limited.

In this paper, the author tries to improve the filtration model of a former report [4], and intends to build a consistent set of mathematical models for contamination control. Section 2 describes a time-dependent change of filter medium, and introduces the idea of "effective opening area". Section 3 describes relations between the effective opening area and pressure loss due to filter elements. Section 4 shows a relation between the effective opening area and the filtration process. Section 5 proposes a single-pass test to identify filter characteristics. Section 6 explains the role of filters in hydraulic systems. Sections 7 and 8 give the discussion and conclusion, respectively.

2. A MATHEMATICAL MODEL FOR CLOGGING OF MEDIUM

Particles in the fluid flow arrive at the element randomly in time and space. Some of the particles lodge on the element. The points where the particles lodge are not restricted to the front surface of the element, but are distributed in a three-dimensional space of the medium. The lodging particles decrease the free space for fluid and moving particles. This phenomenon is called clogging. As a result of particle lodging, the filtration ability and pressure loss of a filter change with time.

Since the void in the medium is distributed randomly, its average along the depth is equal to a distribution of holes on a plane surface. Therefore, we can take a plane surface as representative of a layer of medium with finite thickness. We call this surface a representative surface.

Particles have various shapes and sizes. Measurement and definition of particle size are still being studied [5]. Therefore, this paper does not deal with the matter of particles size distribution. Instead, to simplify mathematical expressions, we assume single-sized particles. The projection area of one of the particles is a representative projection area.

Now, consider a continuous steady flow of fluid in which particles are randomly distributed. Some of the particles pass through the holes on the representative surface and the other particles are captured on the surface. Figure 1 illustrates the representative surface and the arriving particles. We count the number of particles before and after passing through the holes during an infinitesimally short time. In the inflow, the counted number is n_uQdt; in the outflow, the counted number is n_dQdt.

The idea of opening area is not restricted to a particular type of element, for example, a surface-type element or a depth-type element. Our mathematical model for the filter element is a surface having this effective opening area. If the element is a simple sieve, then the effective opening area is equal to the geometric opening area. For a depth-type filter, the effective opening area is equal to front surface times void ratio.

In an infinitesimal interval, the number of particles added to our representative surface is $Q(n_u - n_d)dt$. As shown in Fig. 1, some particles arrive at the points already blocked: others arrive at the opening area. The latter particles newly block some portion of the opening area. Points of arrival on the representative surface do not depend on whether the points are already blocked or not yet blocked. Therefore, the probability of blocking by an arriving particle is proportional to the effective opening area. Consequently, the decrease of the opening area due to arriving particles is

$$dS = -\frac{S}{S_E} a_0 Q(n_u - n_d)dt$$

or, equivalently

$$\frac{dS}{dt} = -\frac{S a_0 Q}{S_E}(n_u - n_d)\,. \qquad (1)$$

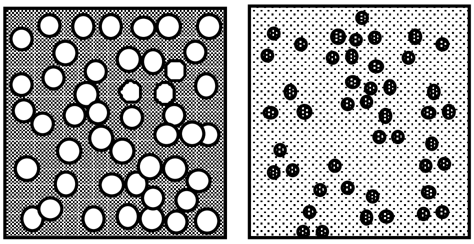
Actual particulate contaminants have a particle size distribution. For a continuous distribution, we have

$$\frac{dS}{dt} = -\frac{S}{S_E}\left[\int_0^\infty Qa(x)\left(-\frac{\partial n_{u,x}}{\partial x} + \frac{\partial n_{d,x}}{\partial x}\right)dx\right]. \qquad (2)$$

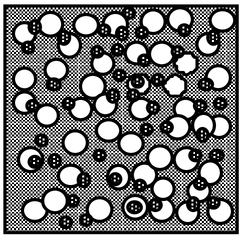
This equation shows that the effective opening area decreases with time. The change depends on the particle size distribution function upstream and downstream of the filter element. Its velocity of change is proportional to itself.

When the integral in Eq. (2) changes little over time, an approximate expression for S becomes

$$S \approx S_0 \exp\left\{-\frac{t}{S_E}\left[\int_0^\infty Qa(x)\left(-\frac{\partial n_{u,x}}{\partial x} + \frac{\partial n_{d,x}}{\partial x}\right)dx\right]\right\} \qquad (3)$$



Randomly placed holes   Randomly placed particles



Overlap of holes and particles

Fig. 1: Effective opening area

This suggests its change with respect to time is approximately exponential.

3. PRESSURE LOSS IN AN ELEMENT

For most commercially available hydraulic filters, the pressure loss by a filter element is proportional to the flow rate when the element is new. After the element has retained many contaminants, the relation between pressure loss and flow rate changes from the initial linear relation: usually still linear but with a different gradient.

Particles packed in the void in the filter medium reduce the free space where fluid and particles can move towards the pressure gradient. Thus, the retained particles increase the resistance against motion of the fluid. The pressure loss by the effective opening area is expressed by

$$\Delta p = \zeta \frac{\rho U_E^2}{2} = \zeta \frac{\rho}{2}\frac{Q^2}{S^2}\,. \qquad (4)$$

Regardless of the type of restriction, ζ is a function of Reynolds number:

$$R_e = QL/\nu S\,. \qquad (5)$$

The dimensionless coefficient ζ is inversely proportional to Reynolds number by laminar flow. By turbulent flow, ζ becomes a complicated function of Reynolds number.

To determine Reynolds number, we must define a representative velocity and a representative length. There will be no question of taking Q/S as the representative velocity. However, there is no common consent about the representative length for flow in porous media [6]. Therefore, we avoid determining the representative length here. Instead, we restrict our consideration to the flow in which the pressure loss is proportional to the flow rate through the element.

Under this restriction, we can write

$$\zeta = \frac{K_l}{R_e} = \frac{K_l \nu S}{QL}. \qquad (6)$$

Thus, a typical mathematical model for pressure loss by the filter element takes the following form:

$$\Delta p = \frac{K_l}{L}\frac{\rho Q \nu}{2}\frac{1}{S}\,. \qquad (7)$$

The constant, K_l/L, should be determined by suitable experiments.

Equation (7) shows that the effective opening area determines the pressure loss of the filter element. It will be interesting to compare Eqs. (3) and (7). When the difference between upstream and downstream contamination levels is almost constant, the differential pressure across the filter element grows as an exponential function of time. In this condition, the logarithmic plot of measured pressures against time on the linear scale lie on a straight line.

As seen from Eq. (5), the Reynolds number of the flow increases when the opening area decreases. If the flow regime changes from laminar to turbulent, the gradient of ζ against R_e will also change. Then the assumed relation (6) is no longer valid and the pressure-time curve in logarithmic scale deviates from the straight line.

4. FILTRATION MODEL FOR MEDIUM

We begin our consideration with an isolated filter element illustrated in Fig. 2. Fluid carries particles to the upstream side of the filter element and takes away some particles to the downstream side. This situation is expressed by

$$\frac{dM}{dt} = Qn_u - Qn_d . \qquad (8)$$

We call this relation "the law of conservation of particle numbers".

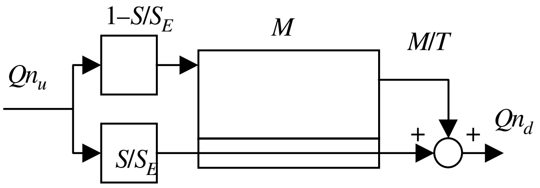


Fig. 2: Filtration model

Some of the particles arriving at the element are captured by the element while the remaining ones carry on with the fluid. Particles once captured can separate, or desorp, from the element at a later point in time. Therefore, the particles downstream of the element are a mixture of those that have passed through the element and those that have desorped from the element. For captured particles, we introduce mean stay time, *T*. In other words, the number of particles leaving the element in an infinitesimal time *dt* is (*M/T*)*dt*. Then, the number of particles exiting from the element is expressed by

$$Qn_d = \frac{S}{S_E} Qn_u + \frac{M}{T} . \qquad (9)$$

The forces acting on the retained particles increase with flow velocity. Eddies in the flow agitate local vibration of the element medium. Therefore, the rate of release of particles will increase with unsteady flow. When the flow in the medium becomes turbulent, it will also increase the release of particles. This indicates that *T* decreases with unsteady flow and with a turbulent flow regime.

A better filter has a large value of *T* with very small value of S/S_E. Finding the characteristics of S_E and *T*, we can express the filtration ability of hydraulic filters.

5. EVALUATION OF FILTRATION PARAMETERS: QUASI-SINGLE-PASS TEST

Filtration characteristics are expressed using the parameters and variables shown in Eq. (9). Evaluation of *M* is easy since it is obtained by direct integral of the right-hand side of Eq. (8). Evaluation of *S* based on Eq. (2) is not easy and may induce a large numerical error. Fortunately, we have a simple relation between *S* and *Δp* from Eq. (7):

$$S \cdot \Delta p = \text{contant} = S_0 \cdot \Delta p_0 . \qquad (10)$$

When we use this relation, Eq. (9) is rewritten as

$$Qn_d = \frac{\Delta p_0}{\Delta p}\frac{S_0}{S_E} Qn_u + \frac{1}{T}\int_0^t Q(n_u - n_d)dt \qquad (11)$$

The filtration parameters $\Delta p_0 (S_0 / S_E)$ and *T* can be evaluated using observed values of variables, *Q*, *Δp*, n_u and n_d. The unknown parameters are supposed to depend on operating variables such as upstream contamination level and flow velocity, and also on the particle size and the state of the element itself. For measurement of these parameters, therefore, we should design a test facility that can control the flow velocity and upstream contamination level. The multi-pass test facility is inconvenient for determining the parameters [4] because it induces variation of the upstream contamination level.

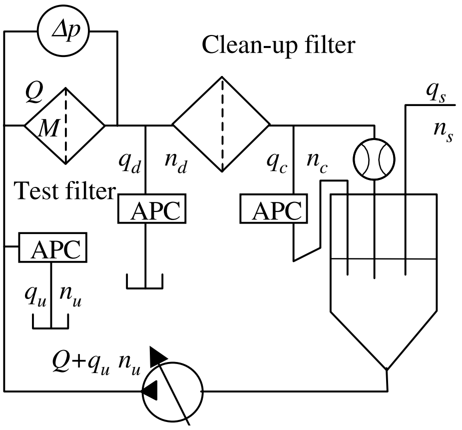


Fig. 3: Quasi-single-pass test

For this test, it is essential to put the upstream level under our control independent of system variables. One possible method is to use a single-pass test. However, we need a tremendous amount of fluid to perform a real single-pass test.

If we remove the essential part of contaminants in the fluid downstream of the testing filter, then the fluid can be used again as a clean fluid. Adding new contaminants to the fluid and supplying it to the upstream of the filter, we can satisfy the condition of the single-pass test. The idea is illustrated in Fig. 3. We call it a quasi-single-pass test.

We carry out the test and parameter identification with the following procedure [7].

Slurry of a predetermined concentration of contaminants is supplied to the reservoir with constant flow rate. The pump supplies fluid flow to the test filter. Flow from the filter is filtered by the clean-up filter and returns to the reservoir. The contamination level of the fluid at the upstream side of the test filter is kept constant because the fluid returning to the reservoir is sufficiently clean. The contamination level in the downstream of the clean-up filter is monitored to confirm its cleanness level. The test is stopped when the pressure difference Δp reaches a limiting value, or when the downstream contamination level exceeds a limiting value. Carrying out this experiment, we obtain the data for u_s, u_d, Δp and u_c at suitable running times. Using thus obtained data, we can evaluate the parameters shown in Eq. (11), namely, p_0, S_0/S_E and T, with the aid of a suitable parameter identification technique, for example, the least-squares method.

We can use this test rig as long as the fluid downstream of the clean-up filter is satisfactorily clean. A basic question about the quasi-single-pass test is whether it is possible to reject essential part of the contaminants downstream of the filter. The author carried out a few experiments into this and got a positive result [7].

6. FILTRATION IN A FLUID POWER SYSTEM

In this section, we will briefly review the effects of filters in hydraulic circuits. Some contaminants are generated in the system through wear, surface layer separation, and other physical or chemical processes. Some contaminants exit from the fluid through sedimentation or by sticking to the internal walls of system components. The remains are included in the system fluid, and are expressed by one input variable, R. Particles in the system escape to outside when fluid leaks from the system. Usually, the leakage is small; hence, it does not have a serious influence on the contamination level of the system fluid. The function of a filter is to retain these contaminants and keep the contamination level below a specified level.

The contamination level of fluid in a hydraulic system varies from place to place in the system; and the inserting position of the filter influences the level. The filter position in a system can be classified as off-line or on- line.

An off-line filter system is illustrated in Fig. 4. The law of conservation of particle numbers applied to the system, the reservoir, and the filter are as follows:

$$V_s \frac{dn_s}{dt} = Q_s(n_u - n_s) + R \tag{12}$$

$$V_R \frac{dn_u}{dt} = -Q_s(n_u - n_s) + Q(n_d - n_u) \tag{13}$$

$$\frac{dM}{dt} = Q(n_u - n_d)\,. \tag{14}$$

There are four unknown variables, n_u, n_d, n_s and M in the above three equations. Therefore, we need additional equations that express the characteristics of the filter:

$$n_d = \frac{S}{S_E} n_u + \frac{M}{QT} \tag{15}$$

$$\frac{dS}{dt} = -\frac{S a_0 Q}{S_E}(n_u - n_d)\,. \tag{16}$$

Now the number of unknowns and the number of equations are the same. Hence, solving these equations, we can predict the contamination level of the system.

If we have the parameters expressing the filter performance, namely, Δp_0, S_0/S_E, and T, we can predict the contamination level of the system. It must be noted that the so-called beta, n_u/n_d, depends on the system parameters and configuration. In other words, it is not a parameter given by the filter, but a system variable.

An on-line filter system is shown in Fig. 5. For this system, we can write five equations as before, while there are six unknowns. We can find another necessary equation considering system configuration; for example, if the sub-system 2 is a reservoir with fluid volume V_2, then the required equation is $n_2 = n_s$.

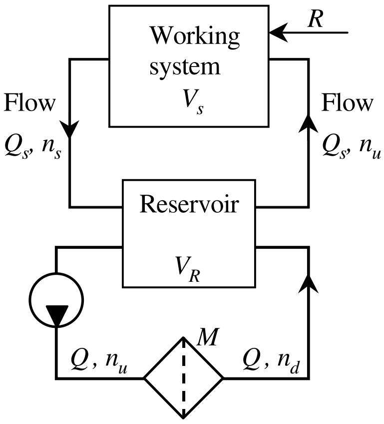


Fig. 4: Off-line filter system

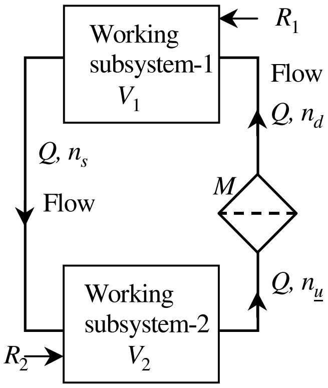


Fig. 5: On-line filter system

7. DISCUSSION

In the 1960s, Fitch, E. C. Jr. proposed the following filtration model:

$$n_u = \beta n_d\ , \ \text{(Fitch model)}. \qquad (17)$$

He assumed β (beta-ratio, beta-value, or beta) to be a characteristic constant of the element. The Fitch model and its assumption formed the basis for evaluating the performance of hydraulic filters performance of hydraulic filters. National and international standards [8,9], and the catalogues of filter manufacturers use beta-value as the constant that characterises a filter element. In ISO 4572-1981(E), beta-values measured at four different operating instants are required to be within 10% of their mean value. The inevitable change of beta-value with operating time was regarded as a measuring error.

The concept of a constant beta contradicts our experience. First, many observations have revealed that the beta is a function of time. Second, the beta depends on flow velocity. Third, if we put a used filter into a fluid power system filled with clean fluid, then we observe that the fluid becomes contaminated by dirt contained in the element. In the last case, the beta becomes less than unity and a better filter shows a smaller beta. Thus the initial idea about beta led to confusion.

Hong and Fitch revised the filtration model to include separating particles and assumed a model [10,11] different from Eq. (17). Their revised model resulted in time-dependent values of beta and they proposed a new filter rating which they call beta prime.

The revised ISO standard (ISO16889) for the multi-pass test, however, took different direction [12]. The new definition of beta by ISO16889 is the ratio of time mean of the particle numbers at element upstream and time mean of the particle numbers at element downstream. The new beta obtained is independent of time variation of filtration characteristic. However, filter users need to know the time variation of fluid contamination level when they are running their hydraulic systems.

To respond to the needs of filter users, determination of the parameters shown in this paper and applying them to the analysis described in Section 6 will be necessary. However, when a filter is exposed to flow pulsation, or frequent switching of flow, it might show less ability to retain contaminants than the analysis. This will occur when the filter is used as an in-line filter as shown in Fig. 5.

It was frequently pointed out that a filter in an unsteady flow shows a lower beta relative to that obtained by steady flow [13, 14]. Although filtration performance under unsteady flow is an important subject, we did not deal with it in this paper. For that, we must develop a more sophisticated mathematical model.

8. CONCLUDING REMARKS

To estimate hydraulic filter performance characteristics, the author proposed:

1. A filter-clogging model with effective opening area
2. A pressure-loss model related to the effective opening area
3. A filtration model concerning the effective opening area and mean lodging time of particles
4. A quasi-single-pass test method to evaluate filtration performance of a filter.
5. A system of equations that describes contamination levels in hydraulic systems.

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