베타 프라임 이론에 의한 저유량 필터의 성능 평가

Filtration Performance Evaluation of Low Flow Rate Filters by Beta Prime Theory

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ABSTRACT

The contaminant seperation performance of filters has been widely investigated for many years. However, most of the proposed filter assessment techniques have proven disappointing for practical use. Although the Multipass (Beta) Filtration test method (ISO 4572) provides valuable information in assessing filters, it has a limitation on evaluating the increasing family of low-flow and high Beta filters. The limitation stems from two main sources: the over simplified theoretical model and the inherently complicated procedure in analysis of data. Hence a new advanced filtration theory, the Beta Prime developed on a draw-down test basis is applied to predict field operating characteristics of a filter for tractor hydraulic systems in this study.

Keywords: Beat Prime, Multipass, Draw-down, Filtration Ratio, System Coefficient

Nomenclatures

$M(t)$ The number of particles of size greater than D micrometers in the filter at time t

M_o The initial value of M(t)

$N_s(t)$ The mean system concentration of particles with size greater than D micrometers at time t

N_o The initial value of $N_s(t)$

Q Volumetric flow rate through the filter

t Time

V Fluid circulating volume

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β' The Beta Prime filtration ratio

δ The system effect coefficient

τ The specific time for fluid of volume V to complete one pass through the filter ($= V/Q$)

1. INTRODUCTION

Filter utilize mechanical screens or porous media to remove or retain particulate contaminants from circulating fluid. A filter not only has to remove particles from the system but also allow the fluid to pass through.

In order to reduce the void between theoretical developments and practical applications, many efforts have been made around the world in trying to evaluate filter performance effectively. One of the earliest available hydraulic filter test specifications was MILF-5504 (October, 1958). It specified two important filter assessment methods: the bubble point test method and the nominal filter rating method.

To improve the filter assessment technique, an innovative rating method, called the Beta filtration ratio, was introduced by the Fluid Power Research Center at Oklahoma State University in 1970. The Beta filtration ratio is defined as the number of particles greater than a given size in the influent fluid to the number of particles greater than the same size in the effluent fluid during the testing process. The Beta method provides a simple figure of merit by which to rate the particle separation capability. Due to its effectiveness, the Beta has been accepted as a standard by the International Standards Organization (ISO) and many national bodies[1].

Recently, many complaints have been voiced by designers and users about higher than expected contamination levels caused by improper location of filters. And as a new trend in modern machine design, off-line type filtration process provide many advantages subjected to the system's efficiency, reliability and service life. This process usually employs low flow and high Beta type filters. Currently, a great deal of research has been done in evaluating the performance of these two types of filters. Experimental efforts to utilize the current multipass contamination control theory (the Beta method) have been disappointing. The reason stems from the fact that the Beta theory was derived from a constant filtration ratio basis. Due to the complex function of the filtration process, the filtration ratio does not remain constant during loading. An expression of effective filtration ratio to represent system filtration characteristics is deemed necessary. Furthermore, the standard Beta test (per ISO 4572) is limited in the flow rate range of 8 to 50 GPM and the filtration ratio between 2 and 75 (both are Beta ten values). The Beta system uses both the ingression process and bottle sampling technique. These two approaches prevent any attempts to obtain a high sensitivity ratio for a high Beta filter. Despite the success of Beta in dealing with the commonly used filters, it is necessary to update the Beta theory so that it may encompass a general scheme for assessing filters.

2. BETA PRIME FILTRATION RATING METHOD

Basically, the Beta method is derived from the ratio of the instantaneous upstream particle concentration and downstream particle concentration at five specific service points. The system includes an injection system which introduces a constant contaminant ingression. It is experienced that a relative constant ratio does not always exist due to the dynamic variation of both upstream and downstream particle concentrations. Regarding this fact, in practice, a minimum Beta value is adopted to specify filter performance. This sometimes sacrifices the credibility of the manufacturer. Therefore, the average Beta value is also used in some cases. As a result, it stimulates users to over-specify filter performance to meet their applications. The conflict occurring between users and manufacturers implies that there is a need of developing a practical filter rating method which may compromise both user and manufacturer.

It is conceived that, if the filtration ratio was derived from a draw-down basis on which only a constant initial system particle concentration and downstream particle concentration at some specific points were evaluated, the degree of ratio instability could be dramatically minimized. Moreover, because in a draw-down test system no particle ingression is included, it provides the advantage of using the in-line particle counter to record the system contamination condition. The use of an inline particle counter significantly reduces experimental error caused by the tramp particles in sampling bottles, which is a normal feature of the Beta test. In addition, the constant initial the saturation level of an automatic particle counter. This again reduces test error due to the dilution process. As a result, the draw-down approach is an effective technique in assessing high Beta filters.

In the Beta test, fluid circulation volume is specified by the flow rate being tested. Accordingly, a relatively small circulation volume is obtained if the flow rate is low. In most practical applications, a small circulation volume cannot provide a homogeneous (well-mixed) test condition, which is the theoretical basis of the Beta multipass filtration rating method. Accordingly, inconsistency between practical application and theoretical approach arises under low flow rate conditions.

Another problem encountered in conducting the low flow rate Beta test is the length of testing time required. It may last for several hours. The long test time required means the system needs a relatively large injection system to complete the test. This is practically inefficient

All the foregoing mentioned drawbacks experienced in the Beta rating method can be minimized by performing a draw-down test. Theoretically, the draw-down test can be investigated on the per pass concept. This approach provides a feasible way of specifying test volume according to test flow rate, filter physical size and automatic particle counter property. In practice, a volume of two times the filter physical size (with an extra volume which can provide sufficient fluid to obtain a delay time long enough for the fluid to pass through the automatic particle counter) is adequate.

The draw-down test approach formulates the basis of the Beta Prime filtration rating method. Both the schematic diagrams of Beta and Beta prime systems are shown in Figs. 1 and 2. As in the development of the Beta rating model, a constant filtration ratio, β', is defined and used in the Beta Prime system. However, unlike the technique used in the Beta approach, that filter performance is specified by a unique parameter: the Beta value; there is another system parameter, δ, used in the significance of system parameter effects during the filtration process. These parameters include the effects of caking. desorption, particle size distribution, etc. Theoretically, these effects depend on the amount of contaminant being retained by the filter. Accordingly, it is reasonable to employ a lumped coefficient to describe the system effect In the first step.

A theoretical filtration model was developed based on both the filtration ratio, β', and system coefficient, δ derived by a discrete system basis. It provides a feasible means to investigate filter performance in a practical approach. The model was promoted by Fitch and Hong [2] and modified in a more general form

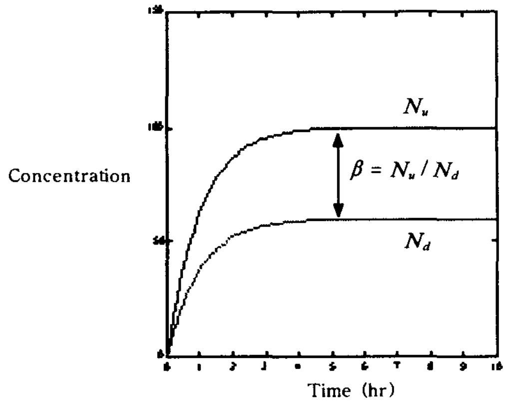

Fig. 1 Typical Beta Model

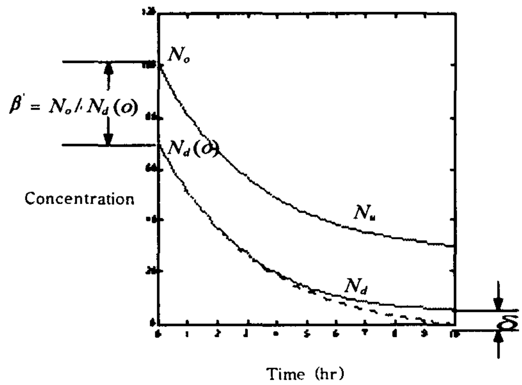

Fig. 2 Typical Beta Prime Model

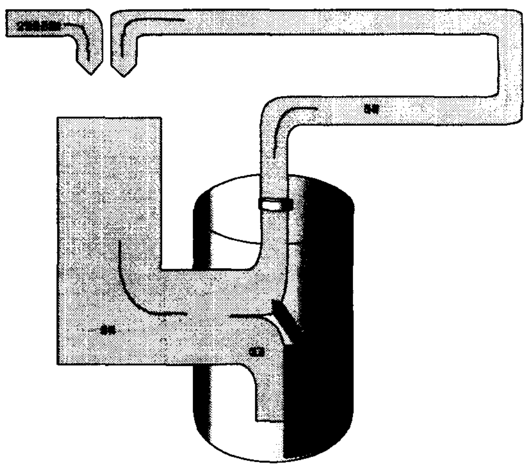

Fig. 3 Filtration System

by considering the associated material balance of the test system on Fig. 3.

The theoretical relationship that describes the particle balance appropriately and rigorously in the draw-down test has been improved by Onsoyen (11) and is expressed as:

$$N_s(t+dt)V = N_s V - \left(1 - \frac{1}{\beta'}\right) N_s(t)Qdt + \delta M(t)Qdt \qquad (1)$$

Equation (1) states that the number of particles in the fluid at time t + dt is equal to the number of particles in the fluid at time t minus the number of particles being removed from the fluid by the filter during time dt, and the number of particles being caked or desorbed from the filter during time dt. This statement is based on assumptions that the system is a homogeneous system and the filtration ratio and system coefficient are constant.

Furthermore, another particle balance equation regarding the particle number being retained in the filter is:

$$M(t) = N_o V + M_o - N_s(t)V \qquad (2)$$

Rearranging Equations (1) and (2), a first-order, differential equation can be obtained:

$$\frac{dN_s(t)}{dt} = \frac{1-\beta'(\delta V+1)}{\beta'\tau} N_s(t) + \frac{\delta}{\tau}(N_o V + M_o) \qquad (3)$$

In the draw-down test, it may be further assumed that the filter retains no contaminant initially. In other words, M_o is equal to null.

By solving Eq. (3) and formulating the relationship of the particle concentration between the downstream and upstream, the particle concentration downstream can therefore be described as:

$$N_d(t) = \left(\frac{1}{\beta'} - \delta V\right)\left(N_o + \frac{\delta N_o V}{A}\right) e^{At/\tau} - \left(\frac{1}{\beta'} - \delta V\right)\frac{\delta N_o V}{A} + \delta N_o V \qquad (4)$$

where, $A = (1/\beta') - \delta V - 1$

Accordingly, by knowing the initial particle concentration, N_o, and the downstream particle concentration at different specific operating points, the value of β' and δ can be explicitly defined. On the other hand, the system contamination level can be predicted if the initial particle concentration and the Beta prime value and system coefficient are known for the filter being used.

The Beta prime value is defined as the filtration ratio derived from an ideal test condition. In other words, it represents filter performance without system effects, for example, desorption. Accordingly, it is the constant filtration ratio adopted in the Beta rating system. This is clearly expressed in Eq. (4). As can be seen, if δ is equal to zero, namely, there is no system effect, then:

$$N_d(t) = \frac{N_o}{\beta'} e^{\frac{1-\beta'}{\beta'}\frac{t}{\tau}} \qquad (5)$$

Equation (5) is a typical exponential function which has the same form as the Beta model.

The physical explanations of β' and δ are graphically illustrated in Fig. 2. Obviously, the effective Beta filtration ratio can be obtained by taking the ratio of $N_s(t)$ and $N_d(t)$.

3. EXPERIMENT

Figure 4 illustrates the schematic diagram of the testing system used to verify the Beta prime method. The system was designed specifically for low flow filters. The stand will allow the flow rate through the test filter to vary from 0.05 gpm to 1.0 gpm. Care was taken to assure the minimization of particle trap areas within the system. An in-line particle counter was used to record the downstream particle concentration.

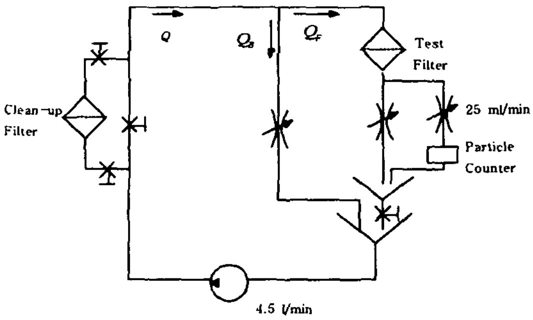

Fig. 4 Beta Prime Test System

Following is the actual test procedure used to verify the Beta prime theory:

1. Conduct cleanup of system by using a cleanup filter. The background particle concentration level should be less than 10 particles per milliliter greater than 10 micrometres.
2. Inject ACFTD into the system and allow it-to mix until a stable initial concentration level is achieved.
3. Install test filter into the test circuit.
4. Record the downstream particle concentration at a predetermined increment. This increment is equal to the time for the fluid to complete a pass.
5. Best fit experimental data with the Beta prime model, Eq. (4), to calculate both the Beta prime value and the system coefficient. This can be obtained either by graphical approach or by computer technique.

In this study, three different kinds filters for a tractor on Fig. 5 were selected for illustration purposes. They are identified as Filters A, B, and C, respectively.

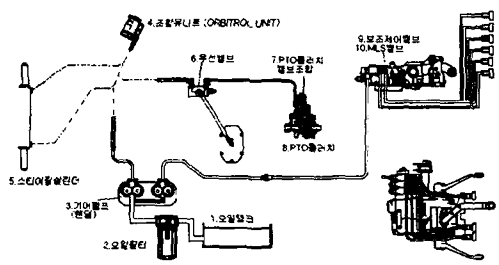

Fig. 5 Hydraulic System for a Tractor

Following the test procedure, a series of tests were conducted. A filter flow rate of 1 lpm and a 2 liter circulating volume were used for each test. The corresponding test results are presented in Fig. 6. It can be seen that the test results behave very well with the Beta prime model. The calculated Beta prime values and system coefficients are (1.55, 0.0072), (5.82, 0.0036), and (22.66, 0.0018) for filters A, B, and C, respectively. Filter performance can therefore be specified by β' and δ.

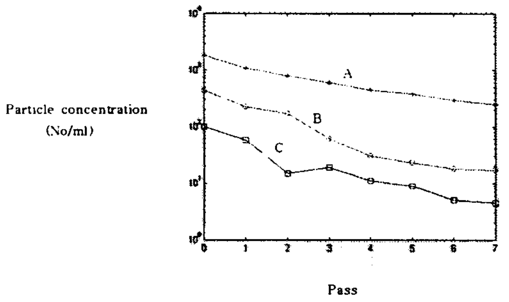

Fig. 6 Filter Test Results

4. CONCLUSION

The developed Beta prime filtration rating method has been proven more rigorous in theoretical approach and more practical in application as compared to the standard Beta rating procedure. Furthermore, the use of both the filtration ratio β' and system coefficient, δ, to specify filter performance provides an effective means for predicting system contamination condition for field application. This technique minimizes the confusion between users and manufacturers in specifying filters. Moreover, the Beta prime employs the draw-down test concept and uses the in-line particle sampling technique, which makes the evaluation of low flow rate high Beta type filters possible.

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