Design and Analysis of High Pressure Hydraulic Filter for Marine Application

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Abstract. Filter is a critical component in a hydraulic system for maintaining the cleanliness of the fluid to required class level. In Marine applications very high reliable filter is required to operate continuously in saline environment. Design and development of high pressure hydraulic filter for Marine application is a challenging task. The design involves selection of special materials and stringent qualification tests as per International standards. The present paper describes various stages of design and development of high pressure hydraulic filter for Marine application.

1. Introduction
Hydraulic system of Marine vessel is used for various utility operation viz. sailing of vessel and operation of controls. The system oil cleanliness has to be maintained by filters to achieve prolonged operation life of valves and actuators. Filter to meet the system requirement has to be designed with utmost care to meet the specification requirement. Also, filter has to be designed to cater for high reliability in severe environment conditions, like high salinity, high and low temperature cycle, vibration, acceleration and shock. The filters used in marine vessels are subjected to shock up to 30g. The design of the components for Marine involves special materials, process planning, quality control and stringent quality acceptance test procedure to International Marine standards. Most of the hydraulic filters in modern marine vessel uses disposable filter elements made up of high strength glass fiber media. The filter rating of such glass fiber media filters varies from 5 to 25 microns. The glass fiber media has better contamination control and good service life over the conventional reusable stainless steel mesh type media [1]. The detail design and analysis of the selected high pressure hydraulic filter for Marine application are described and results of FEM analysis are presented.

2. High pressure hydraulic filter
A typical Marine filter as shown in Figure 1 considered for the present work is hydraulic pressure line filter installed between the pump and other critical components of the system. Three such filters are used for cruise, banal and alert lines. Pressure relief valve is provided before the filter to control the pressure of the system. The filter is made of grey cast iron and coated with special coating to prevent corrosion from marine environment.
The filter assembly shown in Figure 1 consists of filter head with in and out ports. The filter is integrated with four mounting holes at the top of head. It is designed with a handle type shutoff valve which disconnects the element with the fluid line to make it possible for safe removal of element, without spilling the oil. The filter head is also equipped with bypass valve, non-return valve (NRV), differential pressure indicator (DPI), bleed of valve and commuter valve. DPI is having a thermal lockout arrangement, which prevents faulty indication in case of thickening of fluid in sub-zero temperature. Drain plug is provided at the bottom of bowl. The specifications of filter are given in table 1.

Table 1. Specifications of filter

| Specification                                      | Value               |
|----------------------------------------------------|---------------------|
| Filtration rating                                 | $\beta_{10}(C) \geq 1000$ |
| Fluid flow rate                                   | 50 lpm              |
| Working pressure                                  | 205 bar             |
| Operating Temperature                             | -5°C to 100°C       |
| System fluid                                      | FHARI SHELL 2841    |
| Clean element pressure drop @ rated flow          | $\leq 0.3$ bar      |
| Assembly unit pressure drop @ rated flow           | 1.5 bar             |
| Element differential collapse pressure            | 20 bar              |
| Housing proof pressure                            | 307 bar             |
| DPI activation pressure                           | 2 bar               |
| Bypass valve cracking pressure                    | 4 bar               |
| Direction of flow                                 | OUT to IN           |

3. Design of high pressure filter

Filter design is a two-step process, first the filter element is designed to meet the specification requirement, then housing is designed which accommodates the element to withstand the specified pressure ratings with minimum pressure drop at the rated flow.

3.1 Filter element design

The filter element serves to trap contaminants. The filtration depends on the properties of the fluid being filtered i.e. viscosity, density and the concentration of the solids in suspension. The filter element is made out of glass fiber media of requisite filter rating and is supported with rayon paper and stainless steel course mesh on both sides as shown in Figure 2. Layers of media are pleated and wound over a perforated stainless steel centre tube. The pleated filter media along with centre tube, top and
bottom covers are joined carefully with special adhesive. Finally the fabrication integrity of filter element is checked. The filter element assembly is shown in Figure 3.

While designing a filter element some basic parameters like element pressure drop, critical pressure for centre tube collapse and critical pressure for centre tube buckling are calculated.

3.2. Estimation of clean element pressure drop

An important characteristic of the filter media is their resistance to the flow of fluid. This resistance is a basic property of the filter material and is related to the physical structure of the filter element. The pressure drop generated due to fluid passing through the filter element can be obtained from Darcy’s equation as given in equation 1 [2].

\[
\Delta P = \frac{Q \times \mu \times t}{A \times k \times \varepsilon}
\]

Where:

- \(\Delta p\) = pressure drop across the porous medium (N/mm²)
- \(Q\) = fluid flow rate (mm³/s)
- \(\mu\) = dynamic viscosity of the fluid (Ns/mm²)
- \(t\) = thickness of the filter material (mm)
- \(A\) = filtering area (mm²)
- \(k\) = permeability constant for the filter material (mm²)
- \(d = \frac{d_2}{32}\)
- \(\varepsilon\) = porosity

Pleated structure is used for the filter to provide large surface area in small envelope and thereby keeping housing size to a minimum. Total filtration area can be calculated as,

\[
\text{Filtering area } A = h \times l
\]

Where

- \(h\) = height of element (mm)
- \(l\) = developed length of element (mm)
- \(W\) = pleat depth (mm)
- \(N\) = no. of pleats

Number of pleats (N) in filter element is obtained by considering pitch of 1.5 to 2mm at inner diameter of element and is given as

\[
N = \frac{\pi \times D_2}{\text{Pitch}}
\]
Filter element pleat depth ($W$) is given as

$$W = \frac{D_1 - D_2}{2}$$

...... (4)

where:

- $D_1 =$ outer diameter (mm)
- $D_2 =$ inner diameter (mm)

As shown in Figure 2, there are five sheets in filter element viz. two sheets of wire mesh, two sheets of rayon fabric and one sheet of glass fiber media. Therefore total pressure drop across filter element will be sum of pressure drop across all five sheets.

For the specified filter element the total pressure drop across all sheets is estimated as 0.2 bar which is less than the specified pressure drop of 0.3 bar.

3.3. Critical load for buckling of inner tube due to compressive load

During the extreme operating conditions the differential pressure rises very high across the filter element. This will cause buckling of the inner tube of the filter element resulting in failure due to collapse. Therefore it is essential to ensure the material selected and structural strength of the centre tube along with welded joints of top and bottom covers to withstand the high compressive load. The critical compressive load for the buckling of the centre tube is estimated from Johnson’s equation as given below [3].

$$P_{cr} = f_y \times A \left[ 1 - f_y \left( \frac{h}{k} \right)^2 \times \frac{1}{4\pi^2 \times E} \right]$$

...... (5)

Where

- Equivalent Area, ($A$) = $0.5 \times \frac{\pi}{4} \left( D^2 - d^2 \right)$
- Moment of Inertia, ($I$) = $\pi \left[ \frac{D^4 - d^4}{64} \right]$
- Least radius of gyration, ($k$) = $\sqrt{\frac{I}{A}}$

Load at Collapse Pressure ($P$),

$$P = 0.5 \times \frac{\pi}{4} \left[ D_1^2 - D_2^2 \right] \times \text{Collapse pressure}$$

...... (6)
Where:

\[ P_{cr} = \text{Critical compressive Load (N)} \]
\[ P = \text{Load at collapse pressure (N)} \]
\[ D = \text{Outside diameter of tube (mm)} \]
\[ d = \text{Inside diameter of tube (mm)} \]
\[ h = \text{Length of the tube (mm)} \]
\[ D_1 = \text{Outside diameter of element (mm)} \]
\[ D_2 = \text{Inside diameter of element (mm)} \]
\[ p = \text{Differential Collapse pressure (N/mm}^2 \text{)} \]
\[ f_y = \text{Yield strength (N/mm}^2 \text{)} \]
\[ E = \text{Young’s modulus (N/mm}^2 \text{)} \]

For the specified filter, the critical load for buckling of inner tube due to compressive load is obtained as 44500 N, which is more than the load of 2900 N at collapse pressure. Hence the centre tube will not collapse under collapse pressure load due to its strength.

3.4. Estimation of critical radial pressure for buckling of inner tube

The filter element is subjected to high radial pressures which will result in failure of the centre tube along with top and bottom cover. Therefore it is important to estimate the critical radial pressure that the filter element could withstand based on the specified collapse pressure rating. The critical radial pressure should be more than the specified collapse pressure rating required for the filter. It is given by equation 7 in the following [3].

\[ P_{cr} = \frac{\pi^2 \times D \times P_1}{l^2 \times a} \]

Where,

\[ D = \frac{E \times h^3}{12 \times (1 - \mu^2)} \]
\[ n_1 = \frac{n \times l}{\pi \times a} \]
\[ Z = \frac{l^2 \times (1 - \mu^2)^{0.5}}{a \times h} \]
\[ P_1 = \frac{(1 + n_1^2)^2}{n_1^2} + \frac{12 \times Z^2}{\pi^4 \times n_1^2 \times (1 + n_1^2)^2} \]

Where
\[ h = \text{Thickness of tube, (mm)} \]
\[ a = \text{Inside radius of tube (mm)} \]
\[ l = \text{Length of tube (mm)} \]
\[ E = \text{Young’s modulus (N/mm}^2 \text{)} \]
\[ \mu = \text{Poisson’s ratio} \]
\[ n = \text{No. of modes} \]
For the specified filter, the critical radial pressure is obtained as 696 bar, which is more than the specified collapse pressure of 20 bar, hence the centre tube will not collapse.

4. **FEM analysis of centre tube**

In order to study the pattern of stresses experienced by the centre tube under the specified operating conditions, an FEM analysis has been carried out using ABAQUS software. The material of stainless steel to AISI: 316L has been selected with the mechanical properties as shown in Table 2. The FEM analysis is discussed in the following.

Centre tube has been modeled as eight node shell element for a sector of 45° such that one period of the hole pattern is included in the model. Fixed boundary condition is applied on both end nodes where it is held at top and bottom covers and the pressure load is applied appropriately. A static analysis has been carried out and the maximum stress in the centre tube is computed as 97.5 N/mm$^2$ for the working pressure of 205 bar. The stress pattern of the filter element is shown in Figure 5.

![Figure 5. FEM analysis of centre tube](image)

### Table 2. SS316L Material properties

| Property             | Value   |
|----------------------|---------|
| Density              | 7900 kg/m$^3$ |
| Young’s modulus      | 200000 N/mm$^2$ |
| Poisson Ratio        | 0.3     |
| UTS                  | 540 N/mm$^2$ |
| (0.2%) Proof strength| 400 N/mm$^2$ |
| Endurance limit      | 270 N/mm$^2$ |

4.1 **Filter housing design**

The filter housing consists of a filter head and filter bowl. They are coated with protective coating to prevent rusting from saline and humid environment of sea. The filter head provides housing for non-return valve and shut off valve mechanism. The handle type shut off valve is made up of ball and seat arrangement and is designed to serve leak proof joint up to maximum pressure of 1.5 times the operating pressure. The ball is made from stainless steel and seat is made up of soft teflon material to acquire perfect seating and leak proof arrangement. The filter bowl is used to house the filter element, and is provided with drain port.

4.2 **Filter bowl**

The filter bowl is coupled with filter head with help of threads. During the replacement of filter element, the bowl is withdrawn from the filter head and the new element is positioned with bowl and reassembled.

The filter head and bowl are designed to meet the following pressure requirements:

- Normal working pressure: 205 bar
In order to study the pattern of stresses experienced by the bowl under the specified operating conditions, an FEM analysis has been carried out. Fixed boundary condition is applied on bowl top portion where it is mounted. The maximum stress distribution on bowl of the filter is observed to be 239.3 N/mm² as shown in Figure 6.

![FEM Analysis of filter Bowl](image)

**Figure 6. FEM Analysis of filter Bowl**

### 4.3 Filter bypass valve design

The bypass valve as shown in Figure 7, limits the differential pressure across the element and can provide uninterrupted flow when element is clogged. It is mounted in the filter head between the inlet and outlet port.

Bypass Valve serves to:

1. Prevent collapse of the element
2. Ensures uninterrupted fluid supply to system till clogged element is replaced
3. Ensures that the differential pressure across the filter unit is within the specification

The poppet type bypass valve allows unidirectional flow only.

The design requirement of bypass valve is to maintain a pressure difference of not more than 4 bar between inlet and outlet ports. This set pressure is known as cracking pressure of the valve. If the pressure difference between inlet and outlet increases beyond set pressure of 4 bar the force generated is enough to compress the spring thus unseating the poppet from retainer and allowing the fluid to pass.

The dynamic friction acting between the seal and the stud is

![Bypass valve](image)

**Figure 7. Bypass valve**
also being considered in the design calculation, since it contributes significantly in resisting to the movement of poppet. The frictional force acting on O-ring seal can be estimated from the following equation given below

\[ f = \mu F \]  

Where,

\[ \mu = \text{Co-efficient of friction between seal and stud} \]

Compressive or radial force \( F \) on seal is given by,

\[ F = \pi \times d_o \times D_o \times E \left[ 1.25 \left( \frac{x}{d_o} \right)^{1.5} + 50 \left( \frac{x}{d_o} \right)^6 \right] \]  

Where

\[ d_o = \text{O-ring wire diameter (mm)} \]
\[ D_o = \text{O-ring diameter (mm)} \]
\[ E = \text{Young’s Modulus of elasticity (mm)} \]
\[ x = \text{Seal deformation (mm)} \]

Spring deflection per coil is given by,

\[ \delta = \frac{8 \times W \times D^3}{G \times d^4} \]  

Where,

\[ D = \text{spring coil mean diameter (mm)} \]
\[ d = \text{spring wire diameter (mm)} \]
\[ G = \text{Modulus of rigidity (N/mm}\^2) \]
\[ W = \text{Axial Load on spring (when solid), (N)} \]
\[ \tau = \text{Allowable shear stress in spring material (N/mm}\^2) \]
\[ = \frac{\text{Tensile Strength} \times 0.5}{\text{Factor of safety} \times \text{Wahl’s factor (k)} } \]
\[ k = \text{Wahl’s stress correcting factor} \]
\[ = \frac{4C - 1}{4C - 4} + \frac{0.615}{C} \]
\[ C = \text{spring index} \]
\[ = \frac{D}{d} \]
Force balance on poppet is done as shown,

Differential pressure force = spring pre-compression force + frictional force

\[
\Delta p \times \text{Area} = \text{stiffness} \times \text{precompression} + f \quad \cdots (11)
\]

For the specified filter, spring pre-compression required for accurate opening of valve at differential cracking pressure of 4 bar has been computed as 7 mm. Other dimensions of spring are selected from standard design data book.

5. Conclusion
The high pressure glass fiber media cleanable filter required for hydraulic system of the Marine hydraulic system has been designed with respect to pressure drop, critical radial pressure and compressive load factors. An FEM analysis has also been carried out to study the level of stresses experienced under collapse pressure. The critical radial pressure estimated is well within the collapse pressure rating of the filter. The stresses observed due to the maximum working pressure are well within the yield strength of the filter element. Hence the design of filter has been accepted for further manufacturing and qualification testing for obtaining Navy certification.

REFERENCES
[1] Parker filtration’s Handbook of Hydraulic filtration- Parker Hannifin, Hydraulic Filter Division, Europe.
[2] Fluid mechanics and hydraulics by Dr. Jagadish Lal
[3] Design of filter element, M/s.Pal filter, U.K.
