Design and Finite Element Analysis of composite PTFE Compression Packing with C- shape Structure

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Abstract. Gland packing is a sealing device in mechanical equipment like pumps. With the development of science and technology, new materials and new structures have appeared, giving new vitality and advancement to the packing seal. In the process of pump operation, the major problems of gland packing seals are the wear of the filler material and leakage of media through the interface. Hence, In order to improve the sealing performance of a gland packing, Different factors including design structure, the number of packing rings, type of filler material, operating condition like temperature, pressure and speed of shaft can be considered. In this study the finite element analysis of the packing seal is carried out, and the axial stress distribution, bottom pressure and friction moment of the packing seal are obtained according to its design structure and stress condition. Furthermore, the results of finite element analysis are verified by experiments.

1. Introduction
Under normal packing operation the axial stress decreases exponentially along the axis from the gland [1]. This is due to the friction between the Packing - shaft and packing - shell interface. And since the packing is compressible and the surface is rough, the radial stress is proportional to the axial stress. Furthermore, according to experimental result there is an exponential relationship between compression deformation along the axis of the stuffing box and axial pressure.

The exponential decrease in the radial and axial stress of the packing seal leads the pressure to decrease dramatically and at the bottom end of the stuffing compartment the pressure becomes very small in comparison with the media pressure exerted in the reverse direction. As a result, this leakage of media might happen.

In order to have a better performance of gland packing seal, it is crucial to consider three basic determining factors. These include operation condition, material properties and geometry of the sealing system[2].

Hence, the focus of this study is to analyze sealing performance of three composite polytetrafluoroethylene packing rings with C-ring appearance and mounted inside the stuffing box, in such a way that its split ends are arranged to be alternately. Furthermore, it will suggest the best performance geometric parameters of the C-shaped gland packing keeping the friction between the filler – shaft and filler stuffing box minimum.
2. Review of related literatures

Structural and design change of Packing seal with self-adaptation and resilience changes the internal structure to enhance the sealing effect of the packing seal. [3] Similarly by use of disc spring compensation structure, can automatically compensate for filler wear, prevent excessive preload or pre-tightening deficiencies, and improve the life of filler seal use. [4] By increasing the taper angle, there was a significant change in the magnitude of the axial stress transferred from the gland to the last packing which is in direct contact with confined fluid. This is particularly true with the PTFE packing material with a two degrees angle where the stress variation is less pronounced. [5] An increase of pressure of the medium, the coefficient of friction between the packing and the stem decrease considerably at pressures ranging from 1 to 6 MPa. [6] Regarding the friction and wear behavior of PTFE and its Composite materials, in general the friction coefficient of pure PTFE and its composites decreases when applied load increases. Pure PTFE is characterized by high wear because of its small mechanical properties. Therefore, the reinforcement PTFE with glass fibers improves the load carrying capability that lowers the wear rate of the PTFE. [7]

3. Finite elements analysis

3.1. Material properties

In the analysis of stresses and deformation of the gland packing seal, stuffing box of four gland packing rings with a design of open angles of various degrees, a shaft and shell are modeled. The material types used for the packing filler are composite PTFE materials such as Graphite PTFE packing, Carbon fiber PTFE and Coper powder PTFE, whereas the shaft and shell are both steel metal with mechanical properties listed in the Table 1.

| Properties | PTFE+ Gr | PTFE+ C | PTFE+ Cu | Shaft/housing |
|------------|----------|---------|----------|---------------|
| $\rho$ (kg/m$^3$) | 2160 | 2040 | 2100 | 7850 |
| $E$ (MPa) | 482 | 800 | 126 | 200000 |
| $\nu$ | 0.42 | 0.4 | 0.4 | 0.3 |

The rings have an inner diameter of 60 mm and a width of 12.5 mm. Furthermore, it is designed to have C- shape structural modeling with an open angle from 5 to 30 degrees. The loads of 0.1 MPa, 1 MPa, 2MPa and, 2.5MPa were applied to the packing rings.

![3D Model filler and stuffing box section view](image)

Figure 1. 3D Model filler and stuffing box section view a) & b)

3.2. Boundary condition

It is assumed that the material is isotropic and boundary conditions of fixed support at the bottom of the stuffing box. An applied downward pressure from 0.1 to 2.5MPa in mounted condition is also considered. And in dynamics case there is a water media inside the pump and the gland packing seal is responsible for sealing the water from escaping or leaking and the media exerts a pressure on the filler and stuffing box at the bottom inner surface. Therefore, media pressure at the bottom of the stuffing box. Furthermore, in all the cases the ambient temperature of 23°C is assumed.
Since the design used is a 3D model, and not symmetric geometry, it is considered as a whole and was meshed using the automatic meshing method (Figure 2) with elements of solid 187, contact 174 which was appropriate and easy for the 3D analysis of static structure. During meshing, different grid sizes are considered and the value of stress for each value of grid size (0.1mm, 0.01mm and automatic method). The value 0.1mm is so large that one part of the model has only one element. The grid size of 0.01mm is so small that the analysis took longer time. Automatic method is somehow reasonable.

3.3. Analysis and simulation Result

The von mises stress analysis of the stuffing box for load of 2MPa, Graphite PTFE composite material with open angle of 10° is simulated and shown in the figure below. (Figure 3)

Figure 2. Diagram of grid after meshing  Figure 3. Von Mises stress of Stuffing box

In simulating and analyzing the axial stress of the stuffing box the axial stress increases with increasing the gland pressure in all the cases. However when using a gland pressure of 0.1 MPa, the variation in axial stress distribution becomes insignificant with bottom pressure values of less than 0.04MPa for all the three PTFE composite materials (Figure 4).

Figure 4. Axial stress distribution of fillers with open angle of 5°

Whereas increasing the loads to 1 MPa and 2 MPa the axial pressure also increases (Figure 5 – 6). Similar analysis has also been done for the three PTFE composite materials with open angles of 10°, 15°, 20° and 30°. Here the result also reveals that the axial pressure distribution have similar pattern with the previous result but the difference is in terms of value of the corresponding pressure.

Figure 5. Axial stress distribution for load of 1MPa  Figure 6. Axial stress distribution for load of 2MPa
For open angle of 5° considering bottom pressure for loads of 1MPa and 2MPa, copper + PTFE exhibits the largest bottom pressure from all the materials, graphite + PTFE comes the second and carbon + PTFE is the least one (Figure 7).

This also holds true for open angles of 10° (Figure 8) and 15°, 20° and 30° as well. These are summarized in the table shown below for a gland pressure of 2 MPa. (Table 2)

| Filler  | Bottom Pressure (MPa) |
|---------|-----------------------|
|         | 5°  | 10°  | 15°  | 20°  | 30°  |
| Gr+PTFE | 0.36 | 0.34 | 0.22 | 0.25 | 0.25 |
| C+PTFE  | 0.15 | 0.14 | 0.11 | 0.12 | 0.10 |
| Cu+PTFE | 0.38 | 0.35 | 0.24 | 0.31 | 0.26 |

The finite element analysis also allowed a further look on to the effect of open angle on the axial stress distribution of the gland packing. Table 2. shows the bottom pressure values of composite PTFE for various open angles.

Although the gland pressure of 1MPA and 2MPA can show the trend of the axial pressure and used to determine the better design, these pressure values are not appropriate pressure for sealing the gland packing. While applying these gland pressures, all the bottom pressure values are less than 1.6 MPa. Hence a gland pressure that can have a bottom pressure of value at least equal to the media pressure should be preferred. To check and see this bottom pressure of the graphite material with gland pressure value of 2.5 MPa is analyzed. The result revealed that open angles of 5° and 10° degrees are greater than the media pressure which is 1.6 MPa.
Concerning the friction (Figure 9(b)) between the filler and shaft, the result shows that for graphite filled with PTFE composite, open angle of 5° has the highest frictional torque, and 30°, 15°, 10°, and 20° follow accordingly.

4. Experimental analysis

4.1. Materials and apparatus

For the Test bench experiment stuffing box which can contain four gland packing seals with inner diameter of 60 mm, outer diameter of 85mm and width 12.5mm are designed. The four gland packing seals are designed and manufactured with materials of PTFE packing composite with graphite, carbon fiber and copper powder with open angles of 5°, 10°, 15°, 20° and 30°. Instruments like sensors, torque wrench, Vernier caliper, and display unit are used to measure the pressure /stress of the “stuffing box”.

| Measuring instruments | Model range accuracy |
|-----------------------|----------------------|
| Vernier caliper       | 0.01 mm              |
| Torque Wrench         | +/- 0.5% to 4%       |
| Sensors               | ± 3%                 |

For the experiment packing seals with five different open angles and three different types of materials, a total of eight models are designed and manufactured.

For the sack of simplicity, two sets of sensors are used. The first set with three sensors at the bottom of the stuffing box and the second set again three sensors attached at the top of the stuffing box. These arrangement and reading gave the bottom and top pressures respectively while applying a gland pressure of 0.1 to 2.5MPa. The process and mechanism of analysis is that, the sensors corresponding relationship between the Force and the voltage applied on the sensor is already known from the manufacturer specification. These quantities relationship have similarity in this working experiment since the sensors used are similar with maximum pressure of 2MPa. The voltage and the force applied have linear relation for voltage values of below 2.9v and cubic fit for voltage values of greater than 2.9v. Based on this fact, curve fitting is done to determine the actual top and bottom pressure on the gland packing seal. For this purpose mat lab is used to determine the constants (a, b, c, d, e, and f) of the equations that used to perform the curve fit. The curve fit has used two equations due to the nature of the curve of the sensor. These equations are cubic and linear equations. The curve fit used direct straight line for load force of less than 20N and cubic curve fit for load force greater than or equal to 20N. Furthermore, According to the manufacturer specification, 200N corresponds to the pressure of 2MPa, and according to the setting of the data acquisition instrument, 0-5v corresponds to the value of 0-100 of the acquisition instrument. Those constant values are used in order to determine the top and bottom pressures of our experiment. Perform cubic polynomial fitting of the pressure and voltage of the sensor, with fitting equation of:
\[ Y = a + bX + cX^2 + dX^3 \]  

In special cases, when the pressure is less than 0.2MPa, the fitting is a double-point straight line:

\[ Y = e + fX \]  

During experiment results the measurements of the top and bottom values and torque are recorded at certain interval of tightening the gland. Using these values and the concept already discussed earlier the actual top and bottom pressure could be calculated and obtained.

4.2. Experimental analysis result

The result of the experiment shows that copper + PTFE has largest bottom pressure and frictional torque. When carbon and graphite composites are compared copper is not only larger but also steeper which shows that the change of bottom pressure with respect to gland pressure is higher than that of graphite. Although the bottom pressure of copper is the highest (figure 19a) in regard to frictional torque it is also the highest of all the other packing materials considered in this study. The figure (Figure 19b) shows that graphite PTFE has minimum frictional moment of all the other materials.

![Figure 11. Bottom pressure and Torque vs Top pressure of composite PTFE (10°) (a), (b)](image)

In identifying the angle to which the sealing would be better and friction is minimum value at the same type the experiment shows that the packing seal with design of 5° open angle has the best or maximum axial stress and bottom pressure. The second is a design with open angle of 10° degrees. 30°, 15° and 20° open angle design of packing seals comes third, fourth and fifth respectively. But concerning the frictional torque open angle of 05 degree is has the maximum value which means not convenient because of wear rate. Open angles 20° and 10° have the least friction respectively. Hence since open angle of 10° has larger bottom pressure with relatively minimum friction, it would be the best for sealing application from the rest of designs of open angles.

![Figure 12. Bottom pressure and Torque vs Top pressure of Graphite + PTFE (a, b)](image)

The result obtained by finite element method is validated by experimental result. In comparing the FEA with the experimental result, the trend of the axial stress distribution and bottom pressure looks
similar although there is some variation on the exact values of those parameters at certain instant of position or condition. The variation of the two methods of analysis is shown in the table below.

| Gr05° | Gr10° | Gr15° | Gr20° | Gr30° | C10° | Cu10° |
|-------|-------|-------|-------|-------|------|-------|
| Analytical Value(MPa) | 0.36 | 0.34 | 0.22 | 0.24 | 0.25 | 0.135 | 0.35 |
| Experimental Value(MPa) | 0.38 | 0.23 | 0.20 | 0.19 | 0.21 | 0.11 | 0.3 |
| Difference | 0.07 | 0.31 | 0.05 | 0.19 | 0.13 | 0.14 | 0.14 |

5. Conclusion
The analysis is done for given values of the load, design type and material properties. Based on that, the axial stress and frictional moment are both evaluated with finite element method and validated with experimental result. The outcomes of both the numerical and experimental analysis are summarized as follows:

1. Applying gland pressure values of 0.1 MPa-2.5 MPa; the gland pressure of 2.5MPa exhibits better axial stress distribution for all material types and open angle design of filler materials.
2. Both the finite element analysis and experimental teste showed that from the three composite materials, Copper + PTFE exhibit the highest axial stress distribution and bottom pressure.
3. In determining the best design of gland packing ring, the filler with open angle of 5 degree has been observed to have the largest value of bottom pressure in both methods of analysis.
4. Copper powder PTFE has the highest and Graphite PTFE exhibited the least value of frictional torque between the interface of shaft and fillers. Hence Graphite PTFE would be preferred as a best material since it has the least value of friction.
5. Regarding the frictional Moment at the interface of the filler and shaft; the ring designs can be put in increasing order  20°, 10°, 15 °, 5° and 30°. Hence open angles 20° and 10° would be taken as best design in terms of low friction.
6. Although the gland pressure 2MPa can be used to see and compare the trend of axial stress distributions, the top pressure which is appropriate for tightening the gland for leak proof operation is 2.5 MPa.

Acknowledgments
This research is conducted by the support of The People’s Republic of China through Ministry of Finance and Commerce (MOFCOM) in collaboration with Tsinghua University. In my study in Tsinghua my advisor Shuangfu Suo (Associate professor) has given me insight and expertise advice which greatly assisted me on my overall education as well as the research works. So I am so grateful to Shuangfu Suo for his advice and comments on my research work. I would also like to show my gratitude to Dr. Jianwen Shi and colleagues, for their cooperation and sharing their pearls of wisdom with me during the course of my research.

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