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Article

Experimental Performance Study of a High Speed Oil Lubricated Polymer Thrust Bearing

Jie Zhou *, Barry Blair, John Argires and Donald Pitsch

Waukesha Bearings, W231N2811 Roundy Circle East, Suite 200, Pewaukee, WI 53072, USA; E-Mails: bblair@waukbearing.com (B.B.); jargires@waukbearing.com (J.A.); dpitsch@waukbearing.com (D.P.)

* Author to whom correspondence should be addressed; E-Mail: jzhou@waukbearing.com; Tel.: +1-262-506-3053.

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Abstract: With the demand for turbomachinery to operate at higher speeds, loads, and power, fluid film bearings that support turbomachinery must be capable of operating in these more demanding applications. Thrust bearings operating at high speeds and loads can experience high surface temperatures and thin fluid film thickness. Typically, babbitt (white metal) is the bearing lining material for most turbomachinery bearings but is limited in operating temperature and allowable film thickness. Polymer based materials are alternative materials that can operate at high temperatures and with thin films and have been in use for many decades in high load applications, such as electric submersible pumps (ESP). Test results of polymer lined thrust bearings subjected to modern turbomachinery speeds and loads are presented and compared to babbitt lined bearings of the same design and under similar conditions. The test results show polymer lined thrust bearings can operate at higher bearing unit loads than babbitt.

Keywords: hydrodynamic bearings; high speed; polymer; PEEK; thrust bearing; performance; experimental

1. Introduction

Polymers have been used as fluid film bearing material for decades. Polytetrafluoroethylene (PTFE) and Polyether ether ketone (PEEK) are two common polymer-bearing materials. Mostly due to PTFE's low friction coefficient at start-up and high load capacity, it is widely used in hydro turbine thrust bearings in both Russia and China; European interest is picking up.

When used as a bearing material PEEK is typically combined with additional materials for better strength and tribology performance. PEEK bearings are widely used in pump applications using process fluids, such as water as the lubricant. PEEK is also a preferred material in oil lubricated thrust bearings, such as in ESP applications, primarily because PEEK operates at temperatures as high as 250 ℃ while retaining good bearing qualities. However, pump and ESP applications do not approach typical and future operating conditions of modern turbomachinery applications, such as steam turbines, gas turbines and compressors. In most turbomachinery, babbitt is still the dominant bearing material even though fluid film bearings are being required to operate under higher speeds and higher loads than previously required. The continued use of babbitt bearings in these high demand applications is partially due to lack of understanding of PEEK bearing performance in those applications, especially in high speed conditions.

Active research focuses on tribological, wear and mechanical performance of PEEK and reinforced PEEK materials and the relative merits of different polymer materials, as presented by multiple resources [1–5]. A good summary of research effort on PEEK based materials is given by Quadrini and Squeo [6]. However, publication on PEEK bearing performance is quite limited. Some examples of PEEK bearing applications are presented by Pethybridge and New [7]. Ricci, *et al.* [8] compared oil-film pressure and pad temperature distribution of PTFE and PEEK lined pads predicted using multi-physics modeling. Quadrini and Squeo [6] have presented unlubricated performance of PEEK bushes.

PTFE and babbitt comparisons have been published by Ettles, *et al.* [9]. A comparison of PEEK and babbitt has not been published for high speeds and loads. This paper presents experimental data of load capacity, power loss and pad temperature of a high speed oil lubricated PEEK lined thrust bearing assembly with pads of approximately 62.5 mm × 62.5 mm size under two speeds. Also, a direct comparison between PEEK lined and babbitt lined bearing test results is given.

2. Experimental Section

2.1. Test Platform

Testing was performed on the Large Horizontal Thrust Rig (LHTR), as shown in Figure 1. Load is applied to the load piston on the left side of the LHTR with a 20.6 MPa hydraulic pump load cart. Force is applied through the load bearing to the collar, forcing the shaft to the right. The load and the movement of the shaft are then countered by the test thrust bearing in the test section, as shown in Figure 1.

The LHTR shaft is driven by two 375 kW DC motors for a total of 750 kW. Flexible couplings are used to connect the test shaft, gearbox, and motors in a simple train. ISO VG32 mineral oil from a 5678 L reservoir is supplied to the load thrust bearing, the test thrust bearing, and the support journal bearings by an 1136 lpm oil pump. Oil flow to each bearing is individually controlled. Oil inlet temperature can be maintained and controlled with the help of in-line heaters, an immersion heater and an oil to air heat exchanger.

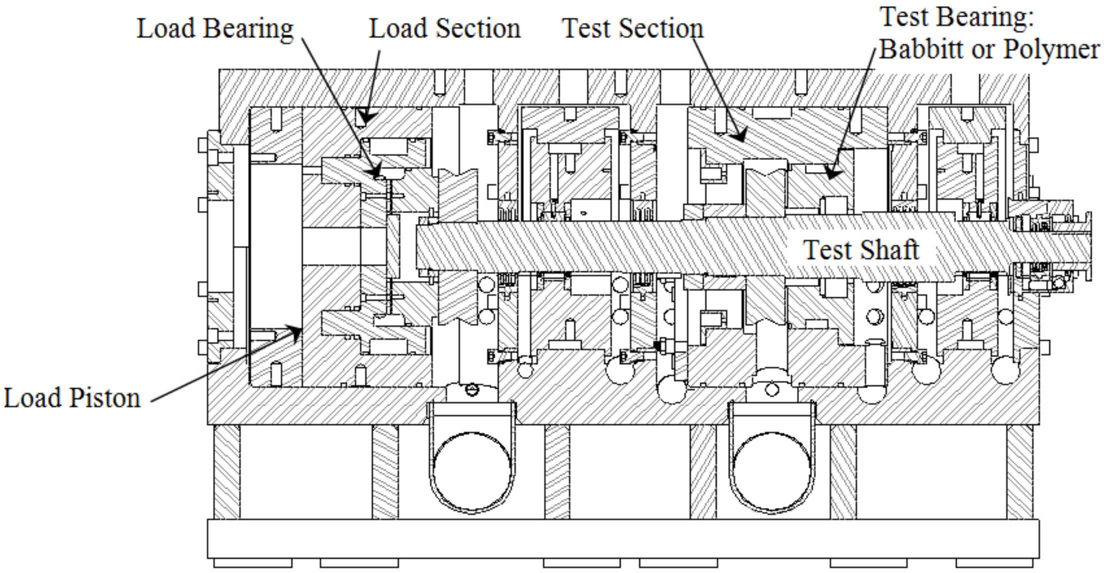

Figure 1. Large horizontal thrust rig.

The LHTR platform is controlled and monitored using several types of instrumentation. Signals from the instrumentation are sent to a data acquisition (DAQ) system, which conditions and relays data to a computer via Ethernet protocol. Typical platform monitoring parameters include rotor speed, load piston pressure and collar displacement. Typical bearing monitored parameters are oil inlet temperature, oil inlet pressure, oil inlet flow rate, oil discharge temperature, pad temperature(s) and pad load.

2.2. Bearing and Test Conditions

Both test bearings are 279 mm tilt pad thrust bearing with 8 pads each. The bearings are equalized by mechanical levers and are designed with direct lubrication (DL). Lubrication is delivered through the bearing to individual pad stops that are located between the thrust pads. Lubrication is then distributed through holes in each pad stop and directed into the pad film. DL is another key design feature for high-speed applications since it reduces power loss and oil temperature significantly, as shown by New [10].

Four of the eight pads are instrumented with a Type-T thermocouple. Instrumented pads are evenly distributed in the assembly, as shown in Figure 2. The thermocouples are installed in the steel backing material nominally 0.8 mm below the bond line. The thermocouples are located circumferentially over the pivot and radially half way from the pad inside to the outside diameter. With the pivot being offset 60% circumferentially from the pad leading edge; the location is noted as the 50/60 location, as shown in Figure 3.

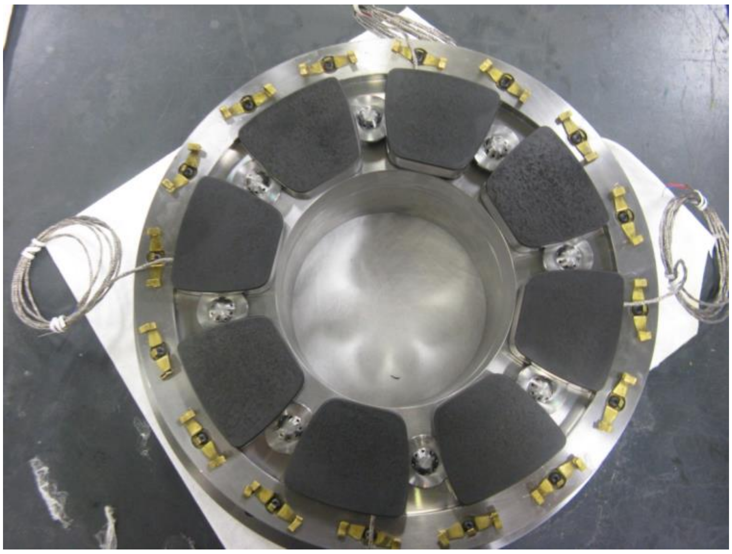

Figure 2. Tested tilt thrust bearing with Polyether ether ketone (PEEK) lined pad.

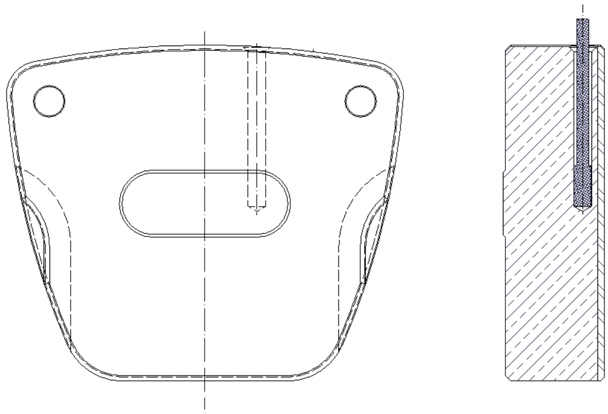

Figure 3. Thermocouple configuration.

Both PEEK lined pads and babbitt lined pads were tested. Pad backing material for both types of pads is steel. The test bearing with PEEK lined pads is shown in Figure 2. Again, the only difference between the two test bearings is the pad bearing (face) material, while all other features are the same.

The load capacity of each bearing material, for the test conditions, was determined by increasing the load until there was an indication of bearing damage or film breakdown. The PEEK lined bearing was tested at 6000 rpm and 11,000 rpm, and the babbitt lined bearing was tested at 11,000 rpm. For all tests, the oil inlet temperature was set to 48.9 ℃, and the oil flow rate was set to 125 lpm.

The test started by rotating the test shaft at a specified speed without any load to achieve the specified oil inlet temperature. Load was gradually increased to 6.9 MPa and was allowed to dwell at this load until the test rig temperature stabilized. Then, for the PEEK lined thrust bearing tests the load was increased in 0.34 MPa steps until one of the following conditions was observed: (1) a sudden pad temperature increase; (2) a sudden pad temperature drop; (3) an abnormal test rig noise or (4) the motors seized. The babbitt lined bearing was also tested with a similar test procedure but with a lower starting load and smaller load steps.

A summary of the bearing size and test conditions is presented in Table 1.

Table 1. Bearing size and test conditions.

Pad Bearing (Face) Material	Babbitt or PEEK
Pad backing material	Steel
Number of pad	8
Pad outside diameter, mm	279
Pad internal diameter, mm	152
Support System	60% Offset
Equaling	Mechanical levers
Pad Size, mm	62.5
Pad aspect ratio	1
Rotational speed, rpm	6000 [1] and 11,000
Sliding speed, m/s	67.7, 124
Lubricant	ISO VG 32
Lubricant inlet temperature, ℃	48.9
Lubricant flow rate, lpm	125

[1] Polyether ether ketone (PEEK) Only.

2.3. Results

Figure 4 shows the load capacity of both bearings for the test conditions in this study. Load capacity is presented as unit load, which is calculated as absolute bearing load divided by total thrust pad area. At 11,000 rpm, the measured load capacities were 14.5 MPa for the PEEK lined bearing and 9.6 MPa for the babbitt lined bearing. This load difference represents a 51% increase by simply changing bearing material from babbitt to PEEK for the test conditions and bearing configuration. At 6000 rpm, load capacity of the PEEK lined bearing was 16.2 MPa, which is 12% higher than the measured load capacity at 11,000 rpm.

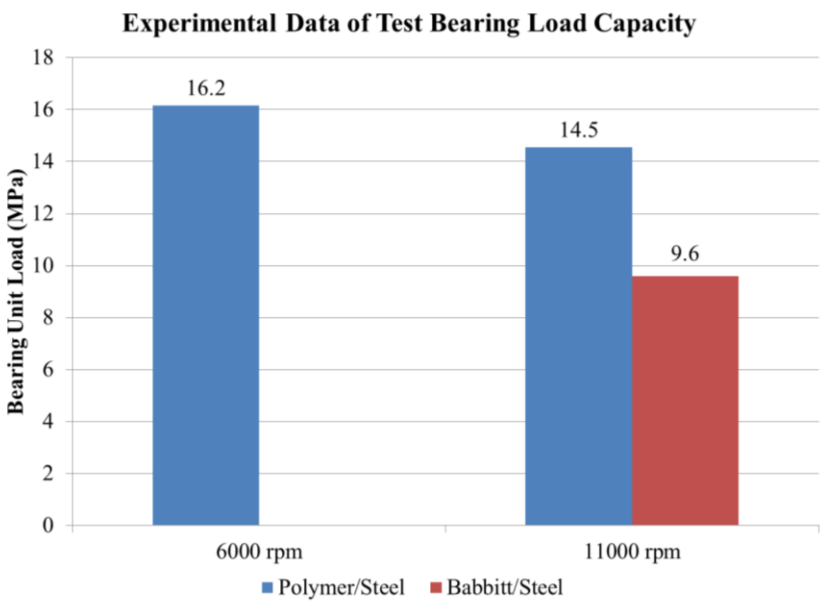

Figure 4. Load capacity at different speeds.

Figure 5 shows a PEEK lined pad after the 11,000 rpm test. The pad is in good shape except for some circumferential running marks. Figure 6 shows a typical babbitt lined pad after the 11,000 rpm test. Oil coking and babbitt creep are apparent on the trailing edge of the babbitt lined pad. Figure 7 presents a PEEK lined pad after the 6000 rpm test. Some indentations are visible near the trailing edge of the pad in the median diameter region.

Figure 5. PEEK lined pad after test, 11,000 rpm.

Figure 6. Babbitt lined pad after test, 11,000 rpm.

Figure 7. PEEK lined pad after test, 6000 rpm.

Figure 8 plots the measured power loss, as determined by heat balance of the bulk oil, of both bearings for the test conditions and bearing configuration. The power loss is calculated as

$$W = Q \times \rho \times c_p \times (T_{\text{discharge}} - T_{\text{in}})$$

where Q is the oil flow rate, ρ is the oil density, c_p is the oil specific heat, $T_{\text{discharge}}$ is the oil discharge temperature and T_{in} is the oil inlet temperature.

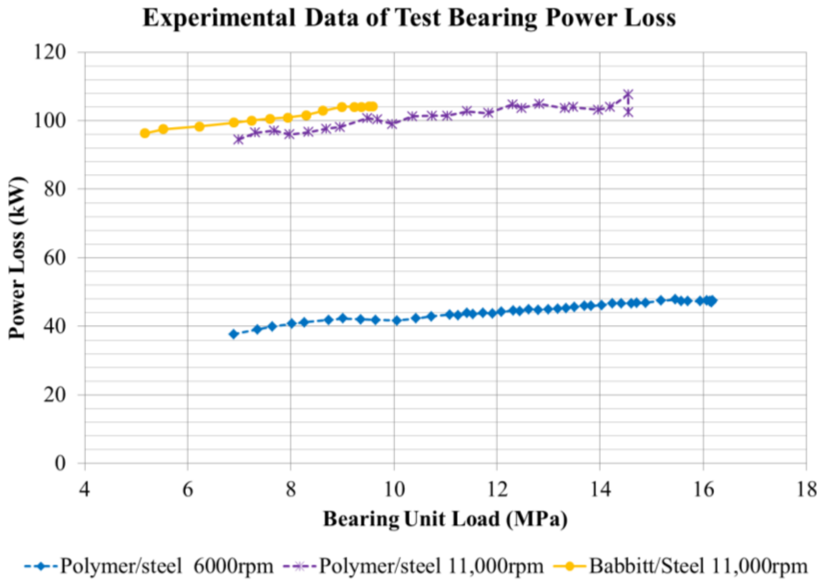

Figure 8. Power loss at different speeds.

The power loss of PEEK lined pads increased significantly with speed but very slightly with load. The power loss at 8 MPa unit load increased from 40.7 kW at 6000 rpm to 96 kW at 11,000 rpm, a 135% increase. The power loss at 6000 rpm increased 26.3% from 37.7 kW at 7 MPa to 47.6 kW at 16 MPa. At the same time, the power loss at 11,000 rpm increased 14% from 94.5 kW at 7 MPa to 107.7 kW at 14.5 MPa. These trends are typical for oil lubricated thrust bearings.

The power loss of babbitt lined pads at 11,000 rpm increased from 96 kW at 5.2 MPa to 104 kW at 9.6 MPa, as also shown in Figure 8. The power loss measurements of babbitt lined pads is nearly parallel to that of PEEK lined pads. At 7 MPa, the power loss of PEEK lined pads and babbitt lined pads were 94.5 kW and 99.4 kW respectively, a 5.2% difference. At 9 MPa, the power losses for the two materials were 98.1 kW and 104.1 kW, respectively, a 6% difference.

Figure 9 plots the oil discharge temperature. It conveys the same trend as the power loss results shown in Figure 8 since the oil flow rate and oil inlet temperature were kept constant for each test.

Figure 10 plots the maximum measured 50/60 pad temperature of the four pads with instrumentation for each test. The pad temperature at 11,000 rpm increased at a rate of approximately 1 ℃/MPa for PEEK lined pads and at approximately 9 ℃/MPa for babbitt lined pads. The low rate of the polymer pads temperature increase is due to the insulating effect of PEEK. At 6000 rpm, the maximum pad temperature, as measured by the embedded instruments, of the PEEK lined pads increased from 65.4 ℃ at 7 MPa to 72.8 ℃ at 16 MPa, while at 11,000 rpm the pad temperature of the PEEK lined pads increased from 69.3 ℃ at 7 MPa to 75.3 ℃ at 14.5 MPa. Likewise, the maximum pad temperature of the babbitt lined pads increased from 105.2 ℃ at 5.2 MPa to 146.5 ℃ at 9.6 MPa.

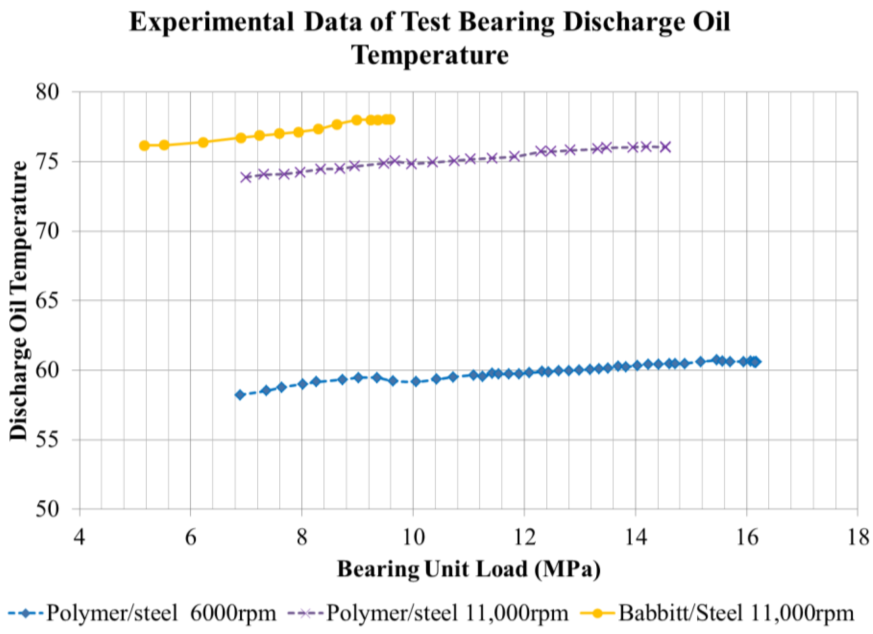

Figure 9. Oil discharge temperature at different speeds.

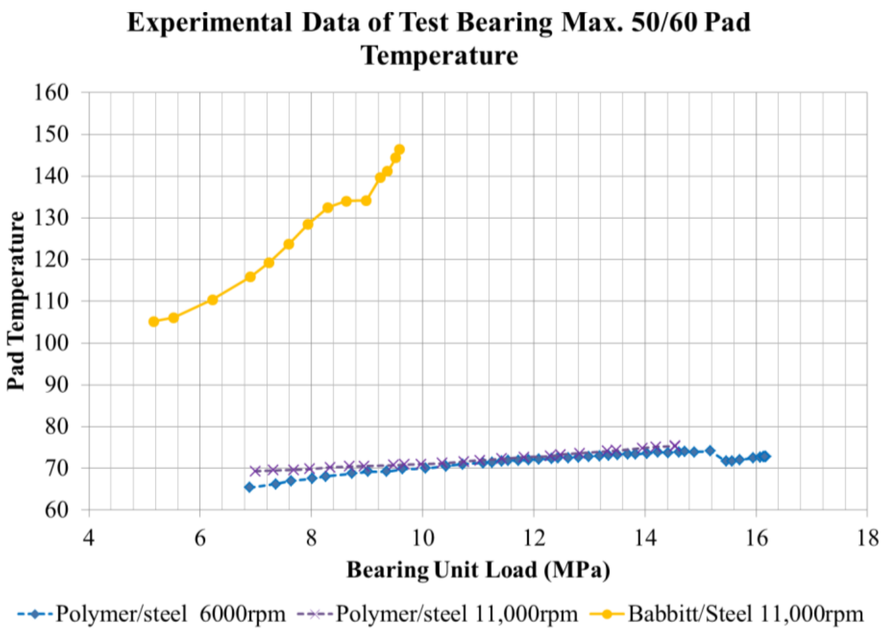

Figure 10. Pad temperature *versus* load.

2.4. Results Discussion

2.4.1. Load Capacity

Three factors limiting the load of a babbitt bearing were presented in [11]. They are fluid film thickness, material's temperature, and mechanical strength of the bearing material and of the pad support, such as pivot and lever contact. These same limiting factors can be applied to PEEK lined bearings. A PEEK bearing material can withstand higher temperatures than babbitt and will retain its mechanical strength at elevated temperatures better than babbitt, as shown in Table 2.

Table 2. Material properties.

Properties	Babbitt	PEEK
Density, kg/m^3	7400	1450
Modulus, GPa	52.4	12.5
Tensile Strength (20 °C), MPa	77	140
Tensile Strength (100 °C), MPa	40	106
Metling Point, °C	241	343
Thermal Conductivity, W/mK	55	0.87
Specific Heat, kJ/kgK	0.23	1.8

As illustrated in Figure 4, the load reached by the test thrust bearing at 11,000 rpm increased 51% from 9.6 MPa to 14.5 MPa simply by changing bearing lining material from babbitt to PEEK. The importance of this fact is that a PEEK lined thrust bearing can be designed as either (1) a smaller sized thrust bearing for the same applied load than a babbitt lined bearing, resulting in much lower power losses and lubricant flow rate requirements; or (2) a thrust bearing of the same size as a babbitt lined bearing that can withstand 50% more load.

Also shown in Figure 4, the 16.2 MPa load reached by the PEEK lined pads at 6000 rpm is 11% higher than that at 11,000 rpm, which was 14.5 MPa. Because the 11% difference is insignificant, the minimum film thicknesses is not the main reason for the load limiting since film thickness is speed dependent and is expected to be thicker for the higher speed, which it was not.

2.4.2. Power Loss

Figure 8 shows that the measured power loss of the tested PEEK lined bearing was lower than that of the tested babbitt lined bearing at 11,000 rpm. However, the 5%–6% power loss difference is insignificant. Thus, the tested PEEK lined pads and babbitt lined pads have similar power losses under the same speed and load conditions. This observation for PEEK and babbitt pads is in agreement with the direct comparison between PTFE lined pads and babbitt lined pads of two thrust bearings that were tested [9].

2.4.3. Temperature

Figure 10 shows that the PEEK lined pads had a lower maximum 50/60 temperature over the tested range for the embedded instruments than the babbitt lined pads. At 11,000 rpm, the PEEK lined pads temperature increased 6.1 °C from no load to 7.55 MPa load; the babbitt lined pads temperature increased 41.3 °C from no load to 5.2 MPa load. The PEEK trend is similar to the measurements with PTFE pads [8].

The measured 50/60 temperatures of the PEEK thrust pads at 6000 rpm were lower than the pad temperatures at 11,000 rpm under the same unit load. The measured temperature difference over the full load and speed range was very small, ranging from 1 °C to 3.5 °C, which is not typical with babbitt lined pads. However, these results are reasonable if considering the thermal insulating effect of PEEK. Further tests with multiple thermocouples on the pad surface and through the pad thickness will be beneficial to determine the full temperature distribution in the pad.

3. Summary and Conclusions

This paper presents the load capacity test data and associated performance data of oil lubricated PEEK lined tilt pad thrust bearing under two speeds for the first time. Results show that:

- A PEEK lined thrust bearing was successfully loaded to 14.5 MPa at 11,000 rpm and 16.2 MPa at 6000 rpm without significant indication of bearing distress. The same bearing with babbitt lined pads was only loaded to 9.6 MPa, as shown in Figure 4, before indication of distress. An increase of 50% in load for the PEEK lined thrust bearing was observed over the babbitt lined thrust bearing at 11,000 rpm. Taking advantage of PEEK bearing material, a smaller bearing with lower loss can be designed for the same load or the same bearing can be designed for higher loads by replacing the babbitt lining with a PEEK lining.
- The test thrust bearing with PEEK lined pads did not show significant power loss difference when compared to a bearing with babbitt lined pads of the same design and test conditions, as shown in Figure 8.
- With temperature sensors embedded in the pads 0.8 mm below the bond line, a small range of temperature variation over a wide load and speed range was observed with PEEK lined pads, as shown in Figure 10.

Based on the test results, polymer lined thrust bearings can operate at higher bearing unit loads than babbitt lined bearings for the studied conditions. When babbitt cannot meet high speed and load requirements, it is recommended to consider alternative materials, such as bearing grade PEEK, for those applications for its higher working load, higher working temperature, and, thus, higher safety margin.

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Author Contributions

Jie Zhou and Barry Blair conceived and designed the experiments; Don Pitsch and John Argires performed the experiments; Jie Zhou, Don Pitsch and John Argires analyzed the data; Jie Zhou wrote the paper.

Conflicts of Interest

The authors declare no conflict of interest.

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