Proceedings of the ASME Turbo Expo 2022
Turbomachinery Technical Conference and Exposition
GT2022
June 13-17, , Rotterdam, The Netherlands

GT2022-83145

A SELF-SUFFICIENT OIL COOLING MECHANISM FOR FLUID-FILM BEARING APPLICATIONS IN REMOTE OPERATIONS

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ABSTRACT

The Kingsbury CH Bearing System is a self-contained bearing solution that utilizes a novel pumping mechanism that supplies lubrication to individual bearings. The system includes a CH unit that houses a journal bearing and two thrust bearings as well as the oil reservoir and the internal oil supply channels while a second journal bearing is housed in the C unit. External piping connecting the C and CH units allow for maintaining the oil supply temperature for the C journal bearing. Another set of external piping connects the oil reservoir in the CH unit to an external cooling system which cools the hot oil leaving the CH bearings traditionally via a heat exchanger using cold water provided by a pumping station. Due to the self-contained operation nature of the CH system as described above, the field applications can involve remote locations where utility access could be limited; therefore, it is desirable to avoid the dependence of the cooling system on a reliable water supply. This is especially critical for applications where there is additional difficulty in maintenance of the units due to reduced crew access. In this work, we present a solution for removing the reliance upon a water-based cooling system for the CH Bearing System. Instead, an air-to-oil heat exchanger is utilized. The traditional shell-and-tube heat exchanger is replaced with a radiator/fan combination. The fan is mounted to the end of the shaft which extends through the CH housing on the non-drive end of the machine. In this way, the cooling rate becomes dependent on the operating speed of the shaft and ensures that oil is being cooled as long as the shaft is rotating. Experiments with a prototype CH test unit using this new cooling mechanism have shown that the required oil temperature in the oil reservoir was achieved using the air-based system while maintaining similar pressure drops in the lubrication lines.

NOMENCLATURE

CH Non-drive end bearing in a CH Bearing System
C Drive end bearing in a CH Bearing System
c_p specific heat constant
HP Power loss (hp)

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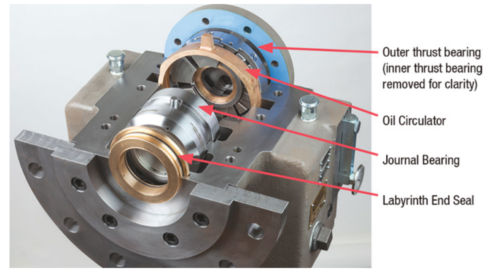
i values at inlet
n Number of pads
o values at outlet
P Static pressure (psi)
q heat rate (Btu/min)
Q Volumetric flow rate (gpm)
T Temperature (°F)
ω Rotational speed (rpm)

INTRODUCTION

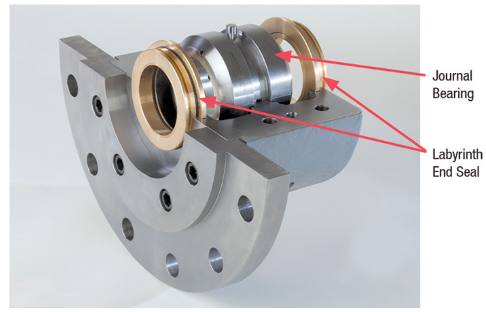
First used in the 1920s and still operating reliably in thousands of applications worldwide, the Kingsbury CH Bearing System combines a thrust and journal bearing assembly (CH) with a separate journal bearing assembly (C) in a self-contained system that eliminates the need for a traditional, external bearing lubrication system [1,2]. The CH unit includes a load-equalizing double-thrust bearing, a fixed profile journal bearing, a self-priming viscosity pump consisting of 'the circulator', a thrust collar and housing seals, some of which are shown in Fig. 1(a). The C unit includes only a fixed profile journal bearing and housing seals as shown in Fig. 1(b) and operates on pressurized oil supplied by the CH unit.

The viscosity pump lubricates the entire system (both CH & C) by means of shaft rotation which increases the pressure of the oil that is drawn up from the reservoir in the CH housing into the gap between the thrust collar and the circulator. As long as the shaft rotates, and oil is available at the correct level in the reservoir, the CH Bearing System is designed to operate as a complete self-contained, equalizing unit, regardless of the direction of shaft rotation. The oil flow provided autonomously by the action of the rotating shaft provides lubrication to the two thrust bearings and the journal bearing via internal passages within the CH housing as well as to the journal bearing in the C housing via external piping. The sump in the C housing is connected to the sump in the CH housing with another external drain piping that completes the oil circulation loop. Additional details of the CH Bearing System can be found in [3].

Oil temperature in the CH oil sump is traditionally regulated by the use of a shell-and-tube heat exchanger that is mounted to the oil reservoir of the CH housing. The heat exchanger relies on water as coolant provided from an external supply and the pressure built up in the thrust cavity that drives the hot oil through the cooler and then back into the oil sump. The self-contained nature of the CH system lends itself well to applications in remote locations where access to typical utilities is limited or perhaps non-existent. These locations also tend to have smaller operations crews, if any, which makes routine equipment maintenance and inspections even more challenging. For these reasons, it is desirable to further extend the self-contained nature of the CH system such that even the oil cooling system is independent of external utilities.



(a) CH unit (not showing the collar and the inboard thrust bearing for clarity)



(b) C unit

FIGURE 1: INTERIOR COMPONENTS OF THE CH HOUSINGS.

In this work, we present experimental validation of an air-based cooling mechanism that provides adequate cooling to the oil lubricant in the CH sump that removes the need for the water source for use as the refrigerant as well as the external power needed to pump it though the heat exchanger. This is achieved by using the ambient air as the refrigerant that is blown over a radiator by a fan that is mounted at the end of the shaft that is supported by the CH bearing system.

The rest of the paper is organized as follows: first, the test rig used to evaluate the performance of the shaft-driven oil-cooling system is shown. The working principles of the cooling mechanism is described and the test matrix utilized for the analysis of the cooling performance is presented. Next, the operating performance of the air cooler is demonstrated at varying rotational speeds and finally, conclusions and discussion of the analysis follow.

EXPERIMENTAL CONDITIONS

CH Bearing Test Rig

The test rig used for the experiments conducted with the air cooler is shown in Fig. 2. The support structure and auxiliary units are hidden for clarity. A 60 hp electric motor is used to rotate a shaft that is 110.6 in long and has a diameter of 4.331 in at the location of the journal bearings. The shaft extends out of the CH housing by 7.265 in where the impeller of the air cooler

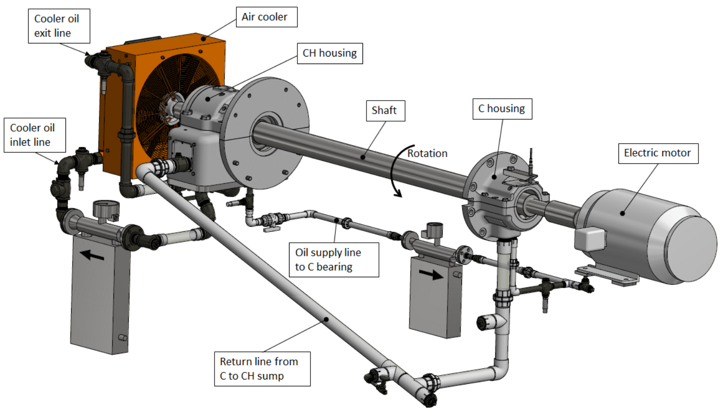
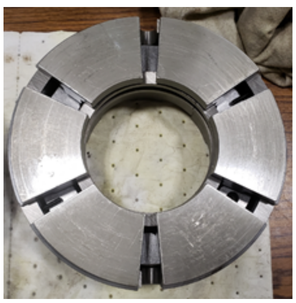
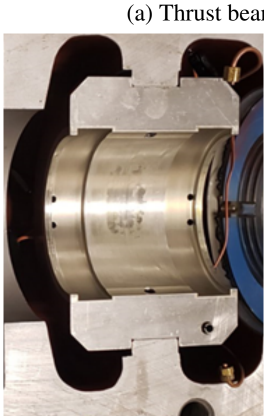


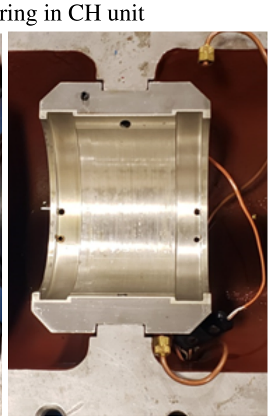
FIGURE 2: SCHEMATIC OF THE CH BEARING SYSTEM TEST RIG.



(a) Thrust bearing in CH unit



(b) Lower half of the journal bearing in CH unit



(c) Lower half of the journal bearing in C unit

FIGURE 3: BEARINGS USED IN THE CH BEARING TEST RIG.

unit is connected via an adapter that is screwed at the end of the shaft. The spacing between the front of the air cooler and the lab walls was about 2.5 times the recommended value so the air flow into the cooler was not restricted.

The air cooler was comprised of a radiator attached in front of a casing that houses the impeller that is rated to provide 10,200 cfm air flow with 301 ft/s maximum tip speed (corresponding to 3186 rpm) with 7.45 hp power consumption. The casing of the air cooler was connected to the CH housing using special brackets made from 0.25 in thick mild steel plates to provide structural support and reduce vibration.

The bearings in the CH unit, as shown in Fig. 3, include a double-sided, equalizing thrust bearing of 9.0" outer diameter with 6 center-pivot, babbitted, steel, tilting pads on each side of the collar that are rated to $14,000$ lbf axial load at 3000 rpm when lubricated with ISO VG 46 oil. The journal bearing in the CH and the C units are fixed-profile babbitted, steel bearings with a rating of 6500 lbf of radial load at 3000 rpm.

The oil circulator is another critical part inside the CH unit that wraps around the thrust collar with a tight clearance formed between the collar outer surface and the inner surface of the circulator. Two axial holes at the lower part of the circulator connects with the oil inlet and exit paths in the lower section of the CH housing that allow the shaft rotation to circulate oil within the cavity between the circulator and the thrust collar. It is made of light material such as cast bronze.

The remaining parts of the CH bearing test rig involves the external piping that provides the connection between the oil reservoirs in the CH and C housings as well as the radiator in the air cooler and the thrust cavity in the CH unit. With the start of the motor, pressure builds up in the circulator exit and oil from the CH sump is fed into the bearings. Some of the pressurized oil is provided to the C bearing via external piping of 0.75 in diameter. Oil exiting the C housing is returned back to the CH sump by positvely sloped piping of 2 in of diameter.

The hot oil exiting the thrust bearings are sent to the cooler via piping of 1.5 in diameter. The shaft-driven impeller of the air cooler rotating at the speed of the shaft sucks the air in through the radiator from the ambient in the test lab and the warm air exiting the radiator is blown axially towards the opening between the back of the air cooler and the CH housing. Cooled oil is fed back into the CH sump using piping with 1.5 in of diameter.

Data Acquisition System The CH bearing test rig utilizes 17 J-type and six Bayonet style thermocouple probes, six Omega, four Schlumberger pressure sensors and two Micromotion Coriolis flow meters for monitoring the bearing and oil conditions. The thermocouples have a range of 24°F - 1400°F (0°C - 760°C) and accuracy of 0.4% of reading while the pressure sensors have $+/-$ 0.25% BSL accuracy and $<$ 1 ms response time. One thrust bearing pad on each side of the collar is instrumented with a pad temperature sensor according to the API standard at the 75/75 radial and circumferential location with respect to the pad leading edge. A total of nine proximity probes were used to monitor the vibration levels of the shaft and the housing of the air cooler, out of which one was used for the axial displacement of the thrust collar. A laser tachometer probe was mounted on the C housing facing the exposed surface of the shaft for the measurement of the rotational speed.

Transient data obtained from the instrumentation is sampled at 1 hz frequency. Proximity probes and tachometer data was averaged using 12,750 samples/sec while temperature, pressure and flow meter data was averaged at a rate of 12 samples/sec. A moving average of the transient data was calculated for a period of 10 seconds in real time and the steady-state temperature data is auto-logged when the deviation of the temperatue reading is within 2.5 F of the moving average. All data was collected using LabVIEW software by National Instruments Corporation.

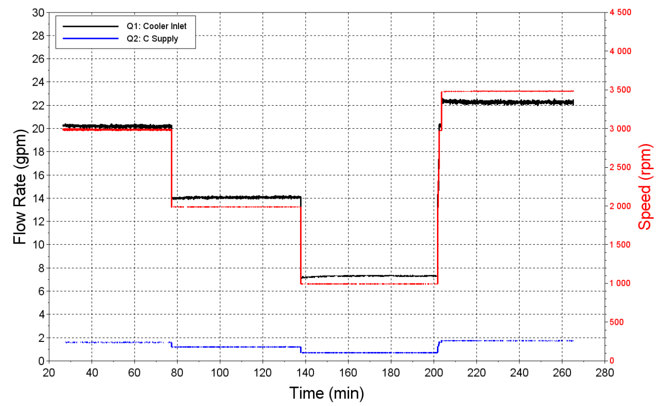
Experiments were conducted at 1000, 2000, 3000 and 3500 rpm operating speeds for a radial load of 400 lbf that corresponds to 24.5 psi on the journal bearings. No axial load was imposed on the thrust bearings and the radial load supported by the journal bearings corresponded to the weight of the shaft only. Each test case was performed at a given speed for at least one hour although the auto-log was triggered much sooner. Thirty seconds of transient data is recorded manually at the end of one hour of testing at each speed and averaged to obtain the steady state average of the testing variables at that speed.

RESULTS

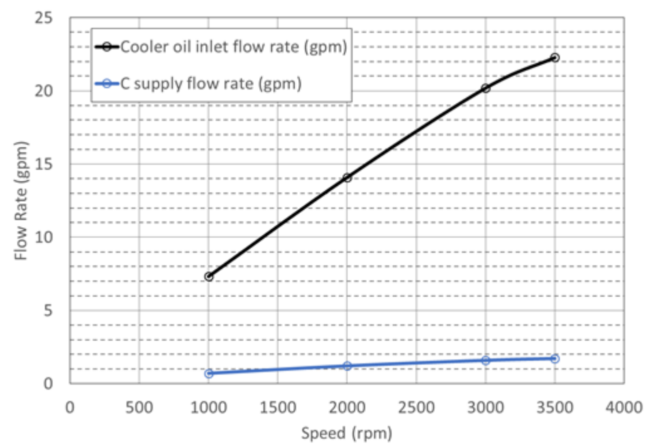
One of the important outcomes of the experiments conducted with the CH test rig using the air cooler is that the oil flow rate provided to the bearings is comparable to the values when traditional shell-and-tube type heat exchangers are used. The measured pressure drop across the radiator of the air cooler was observed to be within 1 psi of the manufacturer's equation.

Figure 4 shows the transient profile of the flow rate of the hot oil leaving the CH thrust bearing cavity as indicated with the black lines measured by the flowmeter placed in the piping connecting to the inlet of the air cooler. The blue curve in the same plot indicates the flow rate of the oil supplied to the C housing as it is measured by the flowmeter placed in the piping connecting to the inlet of the journal bearing at the C unit. As it is observed from Fig. 4(a) both flow values are dependent on the speed of the shaft, which is shown in red and indicated on the secondary vertical axis in Fig. 4(a).

Steady-state profile was achieved quickly at each speed tested and the values averaged from the transient profile is plotted in Fig. 4(b). The flow of oil consumed by each bearing in the CH housing was not available to measure; however, it can be assumed that the flow demand of the journal bearing in the CH housing (Q_3) is similar to the one that is required by the journal bearing in the C housing (Q_2) as they are identical designs carrying equal loads and assuming the pressure losses in the supply line to the C housing isn't significant. In addition, cooler inlet flow (Q_1) can be assumed to be equal to the total flow supplied to the thrust bearings at steady state.



(a) Transient flow profile



(b) Steady-state flow profile

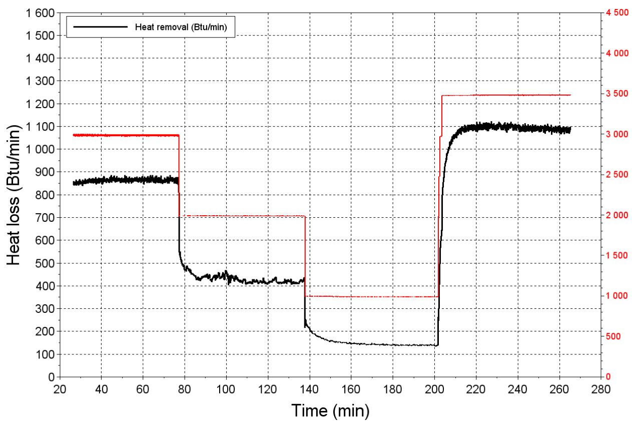
FIGURE 4: FLOW RATES MEASURED DURING THE EXPERIMENT.

The measured oil flow rate being cooled by the air cooler (Q_1) was used to calculate the heat removal rate by Eq. 1 given as:

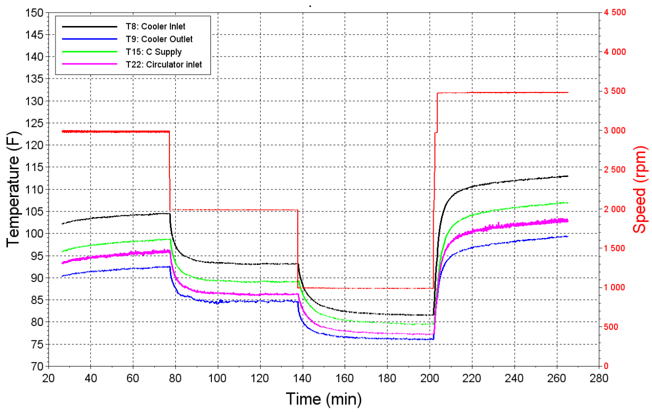
$$\Delta q = Q_1 \left(\rho(T_i)c_p(T_i)T_i - \rho(T_o)c_p(T_o)T_o\right). \tag{1}$$

The density and the specific heat capacity for ISO VG 32 oil were calculated according to $\rho(T) = -0.01931T + 55.55916$ and $c_p(T) = (0.388 + 0.00045T)/0.8735^{0.5}$, respectively.

Figure 5(a) shows that the cooler was able to maintain a steady heat removal rate at all speeds during the majority of the one-hour testing period at each speed and the cooling capacity was linearly proportional to the speed of the shaft. It was also observed that the 2.5 °F criteria to establish steady-state operation of the rig was achieved much quickly at the lower speeds compared to the 3000 rpm and 3500 rpm cases. The steady-state values of temperature of the oil in the CH sump was recorded at

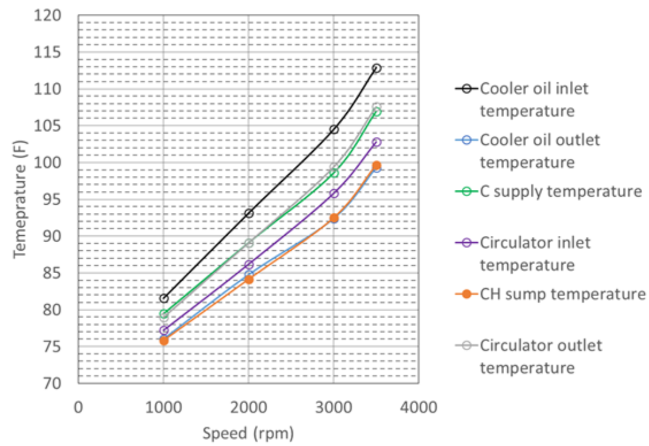


(a) Transient heat removal

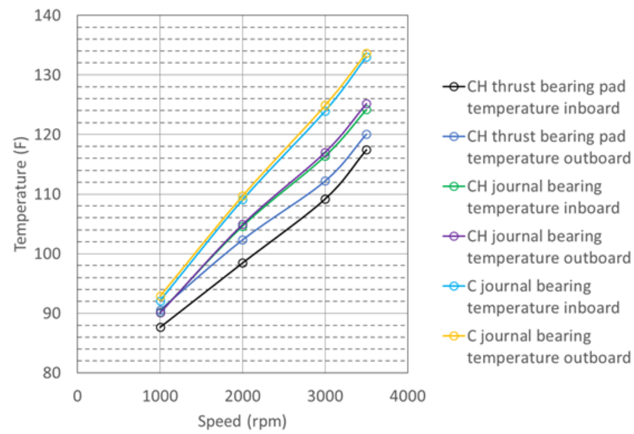


(b) Transient oil temperature

FIGURE 5: TRANSIENT HEAT REMOVAL AND OIL TEMPERATUES MEASURED DURING THE EXPERIMENT.



(a) Steady-state oil temperature



(b) Steady-state bearing temperature

FIGURE 6: OIL AND BEARING TEMPERATUES MEASURED DURING THE EXPERIMENT.

various locations in the oil reservoir and is shown in Fig. 6(a). The sensor located in the CH sump where the return line from the cooler connects showed identical temperature levels as the cooled oil exit temperature as indicated by the orange and blue lines in Fig. 6(a); however, the temperature values at the location of the sump where the circulator draws the oil shows slight higher levels. This is due to the fact that there is a mixing process going on with the hot oil being received into the CH sump from the C housing and the cooled oil supplied by the air cooler. Additionally, the difference between the temperature at the exit of the circulator and the temperature in the 0.75-in supply at the location where it connects with the C housing were observed to be insignificant, which suggests that heat loss from the exterior piping into the lab environment was small. The temperature of the oil exiting the circulator was higher than the temperature of the oil entering the circulator. This is the resultant of the oil shearing within the gap between the circulator and the thrust collar as well as the conduction of the heat from the collar into the oil.

Consequently, the bearing temperatures, as indicated by Fig. 6(b), follow a similar trend as the sump temperatures show as functions of speed. Both bearings had two pad temperature sensors which were placed symmetrically with respect to the axial centerline of the bearings. Figure 6(b) shows that temperature profile in the loaded section of the bearing was axially uniform since both sensors on each side of the bearing were identical at each speed. It was assumed that the journal bearings in the C and the CH housings should operate similarly since they were identical bearings except the thickness of the journal shell; however, it was observed that the journal bearing in the CH housing had lower pad temperatures compared to the bearing at the C housing. In Fig. 6(a) it is shown that the temperature of the oil being supplied to both of the journal bearings were not different. The reason for the journal bearing in the C housing running hotter could be due to the pressure losses in the supply line that provides oil to the C housing sump. The same plot also shows that there was a slight difference in the pad temperatures measured in the inboard and the outboard thrust bearings which was observed to be within the uncertainity levels expected for tilting pad thrust bearings that are not loaded.

CONCLUSIONS

In this paper, experimental results obtained at the CH bearing test rig utilzing a self-driven oil cooling mechanism are presented. It was observed that the CH rig operation with existing bearings and circulator was comparable to previous experiments using water-cooled heat exchangers. Steady operation was observed to be achievable; however, it was found that the time to establish steady-state conditions were significant with unloaded thrust bearings and lightly loaded journal bearings, especially at higher speeds. Speed dependency of the oil supply temperature made it especially difficult to assess performance.

The cooling system was designed for providing adequete cooling for oil entering the radiator at 130 °F. The experiments at the speeds tested during this work showed that the cooling provided was more than sufficient compared to the heat generation by the bearings. Vibration levels at current conditions were not found to be significant. Significant bubble generation or churning were not observed at current speeds and the self-priming feature of the CH Bearing System was not found to be effected.

Future work will consider inclusion of a self-sufficient mechanism such as a thermostatic valve or a fan clutch to regulate the amount of cooling provided to the oil sump in the CH housing. Air conditioning operation in the lab environment was observed to have an effect on the performance at current heating levels by causing a fluctuating profile on the transient temperature values recorded; therefore, a controlled-environment study that replicates extreme ambient temperature variations such as in a desert condition, is planned.

ACKNOWLEDGMENT

The author would like to thank the Kingsbury, Inc. for permission to publish this paper. The authors acknowledges their late mentor Scan DeCamillo for his contributions regarding the content of this paper and dedicates this work to his memory.

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