Hydraulic System for Fan Drive Application to Cool Engine Effectively

Vikas Jambukar, Prof. Vishnu Aher, Prof. Vishnu Wakchaure

***Abstract*— New diesel emissions regulations (Tier 4 / Euro 6 / Bharat IV) put constrain on the engine size and engine cooling. The belt drive is not an efficient system to cool the engine, it has some disadvantages. The use of hydraulically driven cooling fans offers several design benefits in the field of mobile equipment. This paper aims in providing new solution in hydraulic fan drive system by integrating the controls on the motor end cover. This helps to reduce the motor size and weight, ultimately gives the compact solution. This solution is to give the most stable response as compared to any other hydraulic solution, which would be most significant difference compared to other hydraulic solutions. The advantages and limitations of this fan drive hydraulic circuits are presented together with a variety of important design considerations.**

Electronically controlled fan drive systems are basically developed to cater the need to improve overall machine cooling system and its performance. The Electronic Control Module (ECM) will typically use the engine coolant temperature and hydraulic oil temperature to determine the required fan speed. The ECM controls a proportional solenoid that modulates the fan speed. The proportional solenoid is used to control the pump flow to the motor. This may be done by using bypass valves or changing the signal to the pump.

This paper also includes the prediction of motor performance analysis with anti-cavitation valve. Different test setups used to verify the estimated parameters. The results are discussed with merits over different design parameters.

***Index Terms*— Hydraulic fan drive, hydraulic motor, engine cooling, Inverse Proportional Valve, anti-cavitation valve.**

I. Introduction

In recent years, the emissions regulations (Tier 4 Interim / Stage IIIB) mandate that new diesel engines emit significantly lower levels of NOx (nitrogen-oxygen compounds) and PM (particulate matter). As a result of these regulations, off-highway machine designers are challenged by increased costs for engines and after treatment, additional heat rejection to the environment, net vehicle power reduction, reduced installation space, reduced hydraulic flow (due to lower application speeds of the engine), and a limited amount of time to implement design changes.

Today's engine cooling concepts call for increased air flow through the radiators in order to meet the required cooling needs. Engines that meet Euro 6 and EPA010 regulations will resect 30% more heat than Euro 3 engines. This is largely due to changes in combustion, exhaust gas recirculation etc. The usage of retarder brakes increases the heat load on the engine cooling system as well. Aerodynamic optimization of truck cabins reduces frontal area and hence radiator sizes as well as air inlet cross sections. This scenario leads to cleaner emissions but also to increased fuel consumption. The design proposals in this paper describe measures to improve fuel efficiency again.

Because of new emission norms, mobile vehicle needs efficient hydraulic fan drives with pump and motor with reduced length. Existing design uses separate manifold with check valve and proportional valve in it. "Compact Motor with Inbuilt proportional Relief Valve and Anti-cavitation Valve for Fan Drive" uses different proportional relief valve and anti-cavitation valve which serve same function but in compact size and less cost. Electronically controlled fan drive systems are basically developed to cater the need to improve overall machine cooling system and its performance. The Electronic Control module (ECM) will typically use the engine coolant temperature and hydraulic oil temperature to determine the required fan speed. The ECM controls a proportional solenoid that modulates the fan speed. The proportional solenoid is used to control the pump flow to the motor. This may be done by using bypass valves or changing the signal to the pump.

In existing motor designs, the proportional solenoid and anti-cavitation valves are mounted on a manifold block which increases the overall package length by approximately one inch. This new proposed design incorporates the two valves in an existing end cover block of motor thus eliminating the need for a manifold block which reduces the overall package length. Another advantage is reduced manifold subassembly cost.

II. Existing Engine Cooling System

A. Belt-Driven Cooling Systems

Belt driven fans have been the most common method of cooling vehicle engines for more than 100 years. They've retained their widespread use because they are simple and reliable. After being aligned by the engine manufacturer, belt drives give years of trouble-free service life. However, as emission standards continue to become increasingly more demanding, vehicle designers must find innovative new ways to cool engines. First, they must develop more efficient cooling systems because reducing the power draw for cooling reduces the engine's fuel consumption or makes more engine power available for work functions. Second, engine temperature presents a strong influence on a diesel engine's fuel consumption and output of emissions. So controlling the engine's operating temperature within a

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narrow range can reduce both emissions and fuel consumption.

Belt drives are durable and from an initial cost standpoint, the most economical means of power transmission. The simplest drives consist of one or more belts and a set of sheaves (pulleys). Once properly installed in a vehicle, a belt is rated for thousands of hours or tens of thousands of miles of operation and the sheaves usually last the life of the engine.

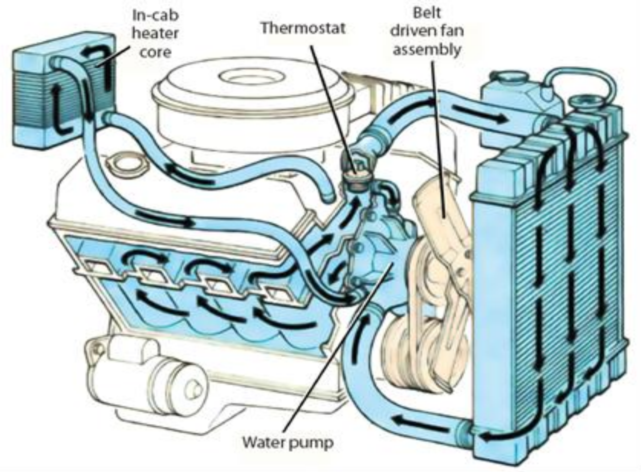

Figure 1: Belt Driven Fan Drive System

Belt drives are also efficient. When operating at their peak of performance, they can deliver 90% or more of the power they transmit from the driving shaft to the driven. However, the belt drive itself doesn't promote heat transfer, the fan does. And a rotating fan uses a substantial amount of power, whether it is running with the engine idling or operating at high speed. The faster it spins, the more air it pulls through the cooling system's radiator, and the more engine power fuel it consumes.

B. Engine Cooling With Hydraulic Drive

Hydraulic fan drives have emerged as a more effective and efficient means of engine cooling because fan speed is determined by engine cooling demand, not engine speed. The result is that the hydraulic system drives the fan at the precise speed required to provide only the amount of air flow needed. This means the fan is not wasting energy by rotating faster than it needs to, just because the engine is running at high speed. Furthermore, hydraulic fan drives take advantage of the functionality and other benefits hydraulic systems can add that are not possible with belt driven fans. Hydraulic fan drives are usually specified from standard components to serve the particular needs of a vehicle and its application. But for simplicity, a basic fan drive consists of a hydraulic gear pump to transmit the hydraulic power (flow and pressure) to a hydraulic gear motor, which drives the fan.

C. Engine Cooling With Elctro-Hydraulic Drive

An electronic control unit (ECU) monitors vital parameters and commands an electrohydraulic pressure-control valve to regulate the amount of power transmitted to the hydraulic motor. The ECU can receive inputs from temperature sensors that monitor ambient air temperature, coolant temperature, fan speed, and other relevant parameters. Typically, only water temperature is monitored to control fan speed. The ECU then uses a program developed for the specific vehicle and its application to generate a signal to the electrohydraulic valve. The valve reacts by increasing or decreasing the hydraulic pressure across the motor based on the proportional command signal. Higher pressure equates to higher available torque to turn the fan faster.

Because the signal and the valve are proportional, the fan can rotate anywhere within its range of minimum and maximum speed allowed by the electrohydraulic program. When the vehicle's engine is first started, the fan typically does not need to be rotating. This allows the engine to reach operating temperature more quickly than if the fan was pulling cold air through the radiator, which is normally the case with belt-driven fans. Therefore, the hydraulic fan drive does not waste power by driving the fan when it's not needed and does not overcool the water, so less fuel is burned and fewer emissions are released to the atmosphere.

On the other hand, when the engine requires peak heat rejection and maximum fan speed (which typically occurs only about 1% of a vehicle's operating life), the electronic control unit signals the electrohydraulic pressure control valve to maximum pressure. An axial fan moving air develops a torque load that is proportional to the square of the speed of the fan. Because motor torque is proportional to the hydraulic pressure across it, regulating hydraulic pressure provides a precise method of controlling fan speed.

The ECU provides proportional fan speed control based on water temperature, ambient temperature, or other key parameters. The result is much more precise control of engine temperature than is possible with a belt drive system. This is especially important with diesel engines because operating temperature has a two-fold effect on diesel engine performance. First, a diesel engine's power-to-fuel consumption ratio peaks within a relatively narrow range of temperatures. Second, the emissions released per pound of fuel used are lowest within another narrow range of temperatures. These two ratios overlap within an even narrower range, so operating the engine within this narrow range of temperatures provides higher fuel economy and lower emissions.

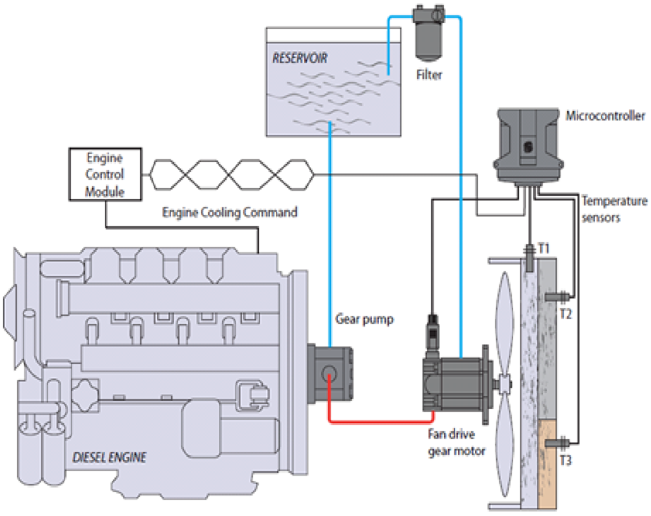

Figure 2: Fan Drive System with Fixed Displacement Pump and Motor, Controls Mounted in Separate Manifold with Microcontroller.

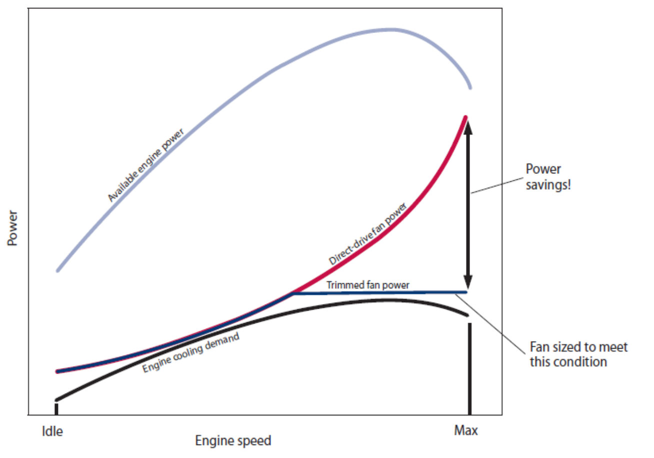

Figure 3: Power vs. Engine Speed Curve of the Hydraulic Fan Drive System

D. Takeaway of Existing Engine Cooling System

1. The existing belt drive system is not efficient solution considering new emission norms.

2. The existing belt drive system can be more efficient by increasing the number of fans, or fan size, etc. or also possible to map with engine performance. But not as effective as hydraulic fan drive solution.

3. The simplest hydraulic fan drive is with fixed displacement pump and motor, whereas this configuration is not most efficient.

4. Hydraulic fan drive with variable motor gives most efficient solution

5. Efficient power utilization is possible using proportional hydraulic speed controls which consist of proportional pressure reducing valves.

6. ECU is used to map engine input power with required cooling demand so as to fan speed.

7. By using a reverse-acting pressure-control valve in the fan drive, signal loss causes the fan to default to full speed operation, thereby protecting the engine in case of system malfunctions.

III. Problem Definitions and Objectives

The hydraulic fan drive with variable motor and ECU gives maximum energy savings. Following are the solutions with its limitations;

1. First option is to mount the control unit on pump. This option is the simplest to put controls on pump itself. But practically, there were pressure fluctuations observed. As these pressure fluctuations exceed 100 psi, the system becomes unstable results in noise and vibrations.

2. The second option is to mount the control unit with manifold on the motor, which is not a compact solution.

3. The third option is to mount the control unit using separate manifold. This manifold can be fitted somewhere away from pump and motor unit. By doing so, there is addition of hoses and connection from pump to manifold and to motor. These changes lead to leakages in the system and cost increases.

The second option in above cases is considered for analysis because option 1 does not give stable solution and option three is costlier and having lot of external connections. The option 2 is compact because the valves are mounted inside the motor end cover and no need of separate manifold. If the size does not increase by adding valves, the motor can fit near the engine easily without any changes. It means the compact design possible only by integrating the components from manifold (proportional valve and flow control valve) into motor end cover.

In addition Anti-cavitation valve integration is also required to avoid the cavitation which arises in case of motor over running conditions.

Broadly it covers following goals to fulfill the final objective.

1. Achieve the required performance of the motor to fulfill engine cooling demand without any stability issue

2. Achieve the end cover life of 1M pressure cycles as per NFPA standard

3. No cavitation inside the motor in case of over running conditions

IV. Motor with Integrated Valves

Existing design has all valves integrated into the manifold. The circuit diagram of motor is shown in Figure 4. The circuit is divided into two parts; first part is showing only motor whereas the second part shows the valves and connections. The second part is integrated in to the manifold. The separate manifold was designed to integrate all valves into it. After assembling the manifold unit, the unit is then assembled on to the motor. This design gives good performance results with required stability.

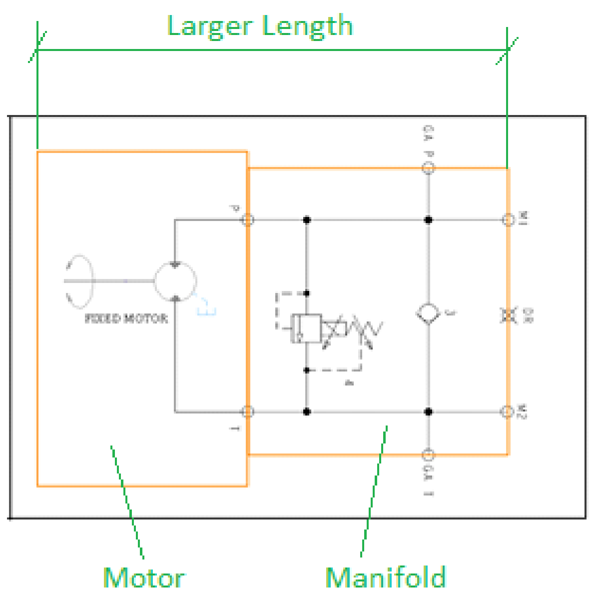

Figure 4: Hydraulic Fan Drive System with Valves in to Separate Manifold Mounted at Backside of Motor

A Need of Integrated Fan Drive Motor

The existing design with manifold is only suitable for prototypes. The main reason is length and weight of the design. Because of the additional manifold, the length becomes more with addition of weight. The cost of the unit also more because it required separate manifold, end cover machining to fit the manifold on it.

The integrated system with all valves in it does not required manifold in it. So length of the unit could be shorter, weight could be lighter and cost is also lesser. But it also need to remember that the space will be constrain to integrate all valves in to end cover which may leads to different failures in the motor.

The motor is integrated with following features;

a) Inverse proportional relief valve which sets the pressure of the system and gives signal to pump to adjust motor speed. The ECM (electronic control module) senses the temperature of engine and generates the respective current. This current is the input signal to proportional relief valve.

b) Anti-cavitation valve is to prevent the cavitation of the motor during deceleration and spin down. These are the conditions in which pump does not generate sufficient flow to fulfill motor requirements. Reduced flow creates vacuum at the motor suction which intern reduces pressure below partial pressure and arises cavitation. By introduction of the check valve in the circuit this condition will get eliminated as it allow flow from delivery side back to suction side of motor. So ultimately motor suction will get the required flow at which speed it runs.

c) Flow control valve to maintain the delta pressure across the system pressure line and proportional relief valve. In load sensing pump there is always the difference between system pressure and load pressure. This difference helps to adjust the pump flow as per load. Same difference needs to be used by putting proportional relief valve in the circuit so to adjust the flow of the pump according to relief valve. This orifice is sized such that it only allows 1 lpm flow at 300 psi delta pressure.

d) Load sense port to provide signal to the flow compensator of the pump. This port senses the actual load pressure and send it to load sense piston pump which intern adjust the flow accordingly.

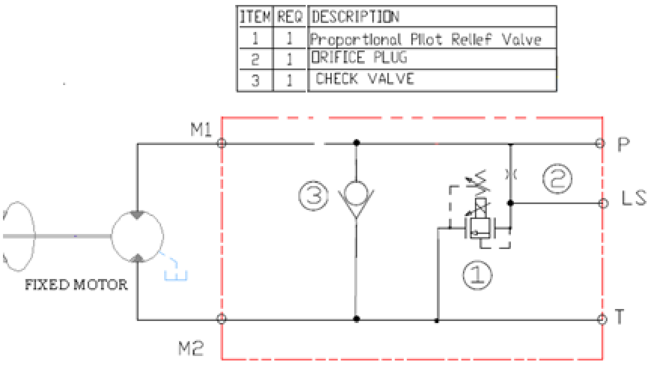

Figure 5: Hydraulic Fan Drive System with Integral Valves in Motor End Cover

B Anti-Cavitation Valve Design

Anti-cavitation valve is to prevent the cavitation of the motor during deceleration and spin down. These are the conditions in which pump does not generate sufficient flow to fulfill motor requirements. Reduced flow creates vacuum at the motor suction which intern reduces pressure below partial pressure and arises cavitation. By introduction of the check valve in the circuit this condition will get eliminated as it allow flow from delivery side back to suction side of motor. So, ultimately motor suction will get the required flow to run motor at desired speed.

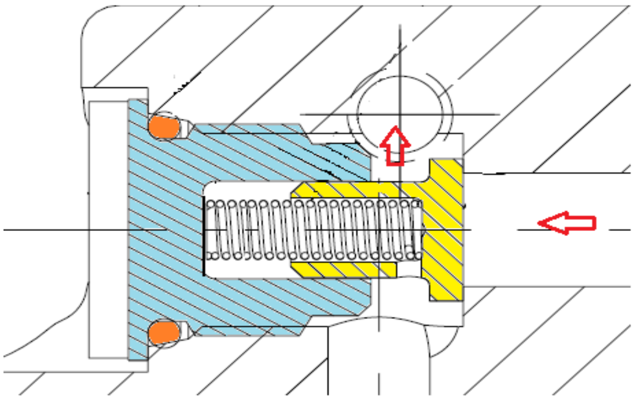

Fig. 6: Construction of Anti-Cavitation Valve

Simulink model used to predict the performance of the system to check if the pressure goes below the partial pressure of the oil at certain temperature. If the pressure goes below the partial pressure, at this condition bubbles can form and finally cavitation are certain.

V. Experimental Analysis and Results

A. *Experimental Setup*

Motor performance on the fan drive system must be checked from power saving and stability prospective. The experimental set up similar to actual fan drive need to prepare and verify the performance of the actual system is very important. Following points needs to verify through this testing

1. Proportional relief valve pressure settings
2. Power saving curve verification with theoretical curve
3. System stability

Figure 7 shows the pump, motor and actual loading similar to fan drive mounted on motor shaft. The pump is connected to the engine/electric motor shaft. The main intension of this circuit is to save the engine power which is required for engine cooling. The load sensing port of the motor is connected to the pump load sensing port using hose connection. The motor loading setup is used to provide similar loading conditions of actual fan drive system. Pressure, speed, flow and temperature sensors used to measure the respective parameters.

There is separate relief valve which used to load the motor i.e. to increase the system pressure. The proportional relief valve pressure setting is depends on the input current signal to it. This current signal is from the ECU (Electronic Control Unit) which converts engine temperature into current. Here in place of ECU signal, need to manually provide current signal to proportional valve to set pressure. For each current signal there is separate trim speed of motor. After giving the certain input current, need to vary external relief valve setting to increase system pressure. Vary the input engine speed, at trim speed the pump rpm will increase but there will not be any increase in motor rpm. Need to record this speed for all different current signals.

Fig. 7: Performance Test Set up

B. Results and Discussion

The motor performance for the fan drive system is very important from power saving point of view. As hydraulic system was replaced from mechanical system mainly for power saving or reduce the engine sizes. Due to new norms like Bharat IV, Euro 4 or other specific to respective countries, there are limitations on the engine sizes and weights. If the hydraulic fan drive can save some energy then there is definite chance to reduce the engine size.

As shown in the test set up, pump of similar configuration of actual fan drive used in the test circuit. The input current to proportional relief valve is adjusted such that trim speed can be set at 2000 rpm and 1000 rpm. Three motors were tested and test results are recorded.

The pump was kept at full stroke and engine speed increased gradually as shown in the plots (Magenta line). The motor speed is shown by sky blue line. The first motor tested at 2000 rpm trim speed. After 2000 rpm the pump speed in increased in the steps but there was no increase in speed of motor. This is because the trim speed was achieved and pump de-stroked such that it will give only the required flow to run the motor 2000 rpm. Even if increase in the pump speed there was no changes in the motor speed. As the pressure is constant shown by yellow and red lines, the power at the motor output shaft is constant. It means that even if the engine speed increased for other use, the fan will take only required power. So, new motor will not use full speed flow and pressure to run the fan.

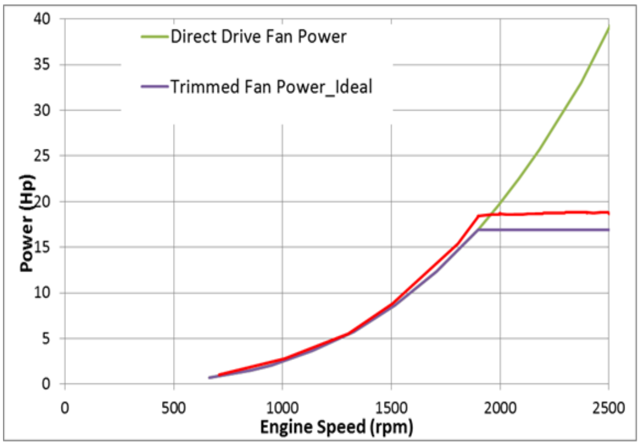

Fig.8: Power Vs engine speed

The Figure 8 shows the power Vs speed plots for three motor which were tested. The Y-axis shows the power and X-axis shows the engine speed values. The green line shows the theoretical engine power curve whereas blue line shows theoretical power curve if the hydraulic fan drive is used. After certain power value (17 Hp in Figure 8) even if the speed increase, the power does not increased because the hydraulic fan drive decreases the flow from pump means ultimately saves the power.

The red line is the actual power Vs speed curve for motor 1 in Figure 8. The actual test results are matching approximately the theoretical plot, it shows that the design of hydraulic fan drive system in line with the theoretical analysis. There is some difference mainly because the efficiency assumed in theoretical analysis and actual test results are different. In actual testing the efficiencies varies with respect to pressure and speed but in theoretical analysis it was assumed fixed values.

When the power shift from the speed that is the trim speed, the curve does not follow the smooth transition mainly because the valve opening or performance characteristic is also not smooth. There are always some losses associated with those openings.

In addition, three motors with new end cover assembly are tested to get the output results. The pressure gauge connected before and after the anti-cavitation check valve means at inlet and outlet of the motor. The pressure reading with inlet and outlet flow sensors are recorded. Below are the three readings which are the minimum pressures, noted during the test. These three pressures are at the motor input pressure sensor.

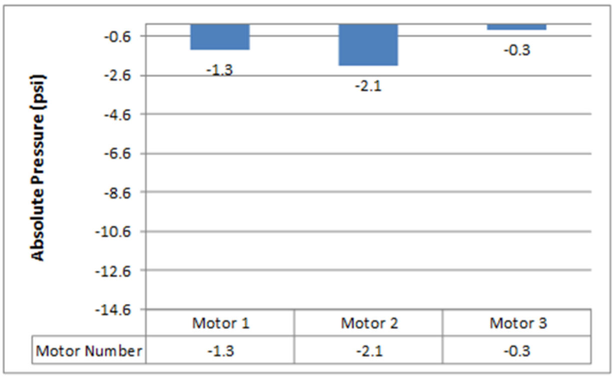

Fig. 9: Performance Test Results

The Fig. 9 shows the power Vs speed plots for three motor which were tested. The Y-axis shows the power and X-axis shows the engine speed values. The green line shows the theoretical engine power curve whereas blue line shows theoretical power curve if the hydraulic fan drive is used. After certain power value (17 Hp in Fig. 10) even if the speed increase, the power does not increased because the hydraulic fan drive decreases the flow from pump means ultimately saves the power.

VI. Conclusions

The main aim was to integrate the valves into end cover without increasing the dimensions and achieve same performance.

While looking at the results, the integration of the proportional reducing valve, anti-cavitation check valve, load sense port and flow control valve (orifice) in the end cover is possible. The motor performance and life is well above the requirement. The fatigue life shows the motor end cover sustain the high pressure spikes of 1 M cycles. The test results of end cover also verifies the design calculations and maintain the lower pressure maintain more than partial pressure of 14.5 psi. Overall following are the top level conclusions are;

1) The integrated motor achieved performance to fulfil engine cooling demand without any stability issue

2) The motor is the compact with length reduction by 1 inch over existing design.

The anti-cavitation valve performance was also in-line with the predicted calculations. The lower pressure at the motor inlet observed was more than partial pressure (-14.5 psi). Overall below are the top level conclusions of the project;

1)The integrated motor achieved performance to fulfill engine cooling demand without any stability issue.

2)The motor does not cavitate as the oil pressure does not fall below partial/critical pressure. So, overall no cavitation inside the motor in case of over running conditions.

ACKNOWLEDGMENT

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