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Experimental Evaluation of Friction Power in a Single Cylinder Four Stroke Diesel Engine

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Abstract—*The internal combustion engine is the prime mover in the motor vehicle, as well as in many other modes of transport and also in the field of electrical power generation. The popularity of the internal combustion engine is testimony to its performance, reliability, and versatility. However, there are also some major drawbacks. Thermal and mechanical efficiencies are relatively low, with much of the energy of the fuel dissipated as heat and friction loss. Over the years, technology development of internal combustion engine has been aimed towards enhancing working efficiency and thereby reducing fuel consumption. Friction power losses accounts for 4-15% of the total indicated power generated. Minimizing the friction losses in the engine may be regarded as one of the most effective technologies for improving fuel economy. This paper depicts, experimental evaluation of friction power using motored strip down test. Experiment is conducted on a single cylinder four stroke diesel engine. From experimental results it is observed that, total friction power is more as compared to theoretical analysis. Finally, modifications have been suggested that can help to reduce friction power.*

1. INTRODUCTION

The purpose of internal combustion (IC) engines is to produce mechanical power from the chemical energy comprised in the fuel. The four-stroke diesel engine is one of the most efficient and versatile prime movers. Diesel engine is used for both, stationary as well as mobile applications. One of the major applications of diesel engine is in the transport sector i. e. , passenger cars, buses, trucks, trailers, locomotives, boats and ships. Single cylinder diesel engines are used for pumping sets, construction machinery, air compressor and drilling rigs. A positive feature of a diesel engine is its low specific fuel consumption and high thermal efficiency. A diesel engine has high compression ratio, thus the chemical energy of the fuel is converted efficiently into heat [10, 11]. However, the whole of this energy is not utilized for driving the piston, as there are losses to the exhaust, to the coolant and some losses by radiation. The remaining energy converted to power is called the indicated power (ip). This is utilized to drive the piston. The piston motion through the connecting rod is transmitted to the crankshaft. In this transmission, wherever energy losses due to friction, pumping etc. are taking place, the sum of all the losses is termed as friction power (fp) and the useful mechanical energy at the crankshaft is called brake power (bp). The friction power is a sufficiently large fraction of indicated power, varying between about 10% at full load to 100% at no load [13]. Friction losses affect the maximum brake torque and minimum brake specific fuel consumption directly.

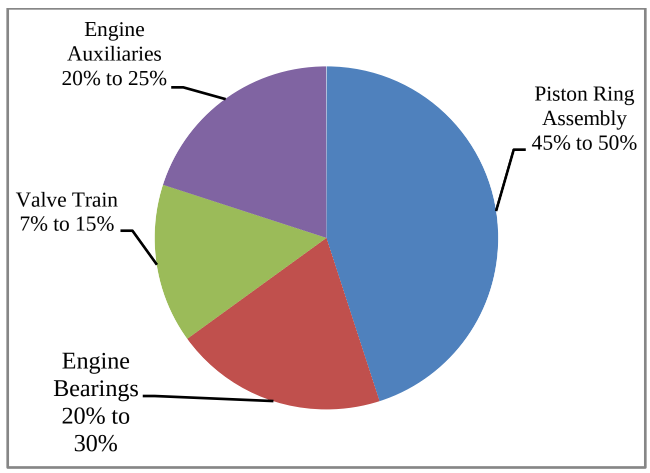

Fig. 1: Distribution of the total mechanical losses of a diesel engine.

Recently, the demands for improved fuel economy have been continually rising because of environmental protection policies, legislative pressures on emissions and increasing price of oil. Minimizing the friction losses in the engine may be regarded as one of the most effective technologies for improving fuel economy because the technology is cost effective and applicable to a great number of vehicles [2]. Researchers have studied the frictional contribution of individual engine components both theoretically and through the use of fired and motored laboratory engine tests. Fig. 1 shows a typical distribution of the total engine mechanical friction losses for a diesel engine [10].

2. ENGINE FRICTION MEASUREMENT

The internal combustion engine operates in all regimes of lubrication and many of the frictional interactions are significantly influenced by compression and combustion. The regimes of lubrication usuallyrelated with the cam-follower, piston rings and engine bearings of an automobile engine are shown in Fig. 2. For satisfactory performance these components depend on different modes of lubrication and certainly each can experience more than one mode of lubrication during a cycle. This makes the measurement of engine friction and particularly friction measurement at specific locations within the engine difficult. The measurement of engine friction can be categorized into three methods: fired engine tests, motored engine tests, and engine component tests. Fired engine tests measure friction in a fully functional engine with combustion. These tests are complex and costly requiring highly accurate cylinder pressure and torque measurements to calculate total engine friction. Motored engine tests measure friction as the torque required to spin the engine. These tests offer the ability to examine the friction contribution of various components within the engine but actual engine conditions are lost. Engine component tests measure friction through setups designed to simulate engine components, for example, a reciprocating piston in a fixed liner. These engine component tests offer great insight to friction mechanisms over the conditions in which they are performed but actual engine conditions are again lost and even more so than in motored engine tests [10-14].

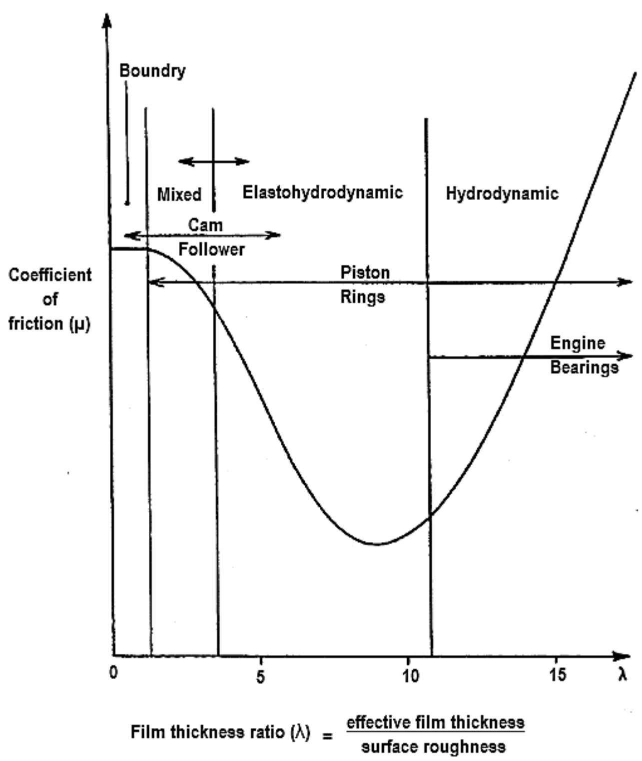

Fig. 2: Modified Stribeck diagram.

Motored engine friction does not include some combustion effects which are vital to engine friction. These include: cylinder pressure loading on the piston, the piston and cylinder liner temperatures, and the exhaust blow-down phase at the start of the exhaust process [13]. Lower cylinder pressures reduce the load from the piston rings on the liner surface and thus lower rubbing friction. The lack of combustion causes lower engine temperatures and changes the temperature relationship between engine components, affecting lube oil viscosity and changing friction properties. Exhaust gases are denser than air therefore motored pumping loads are less. On the other hand, motored engine friction tests allow for component removal to isolate the frictional contribution of various components. By motoring an engine, and sequentially dismantling it, each component of the mechanical and accessory friction contributions can be determined [11, 14]. Motoring friction tests are relatively easy to perform and have high measurement accuracy [11, 13]

3. THEORETICAL ANALYSIS

Table 1: Technical specifications of the engine.

Make	Comet Engines
Model	MPPW-5A
Rated power (bp)	5 hp/ 3. 68 kW
Rated speed (N)	1500 rpm
Bore (D)	87. 5 mm
Stroke (L)	80 mm
Injection type	Direct injection
Cooling	Water cooled

Modelling engine friction consist of models relating to friction regimes in the engine (boundary, mixed, and hydrodynamic), viscosity changes (temperature, pressure, and shear rate), and the engine components (temperature, dynamics, and mechanics of materials) [9, 12]. When all these conditions, regimes, and components are considered together the problem is extremely complex [14]. Therefore, models have been considered to estimate total friction power. Technical specifications of the engine under investigation are shown in Table 1.

Total friction power (fp) is defined as the difference between indicated power and brake power. Mathematically,

$$fp = ip - bp \tag{1}$$

Form the technical specifications of the engine, brake poweris known. Mechanical efficiency (η_{mech}) is defined as ratio of brake power to indicated power, i. e.

$$\eta_{mech1} = \frac{bp}{ip_1} \tag{2}$$

$$0.8 = \frac{3.68}{ip_1}$$

$$\therefore ip_1 = 4.6\ kW$$

$$\therefore f_{p1} = 4.6 - 3.68$$

$$\therefore f_{p1} = 0.92\ kW \quad (3)$$

Therefore, from above calculations the total friction power of the engine is 0. 98 kW, which is 20% of the indicated power or power developed inside the cylinder. This data will be beneficial to compare with the experimental results.

4. EXPERIMENTAL SETUP

A single cylinder four stroke diesel engine was employed. The engine specifications are shown in Table 1. The engine was coupled with a 3-phase, variable speed, AC motor, as shown in fig. 3. Firstly, motored friction test was carried out to evaluate total friction power of the engine. Then, strip-down test was done to evaluate friction contribution of different engine components.

4.1 Motored friction test

It is considerably more complex and less accurate to discrete total friction into parts to determine the fraction of the total contributed by different engine components. One of the best ways to do this is to motor the engine i. e. , drive an unfired engine with an external electric motor connected to the crankshaft. When an engine is motored, the ignition is turned off and no combustion takes place [14]. The power supply to the motor is measured, which is a measure of engine friction power. Following procedure was followed to conduct the experiment.

Ensure that engine is rigidly mounted on the test bed and check all connections.

1. Check the lubricating oil level.
2. Cut-off the fuel supply.
3. Start the motor and assign the constant input speed.
4. Let the motor to drive the engine for some time, so that, stable operating conditions are reached.
5. Then note down the torque required by the motor to crank the engine.

The torque required by the motor to crank the engine at three different speeds is shown in Table 2.

Table 2: Total motoring torque.

Sr. No.	Speed, N (rpm)	Torque, T (Nm)
1	500	3. 7
2	1000	5. 5
3	1500	8. 2

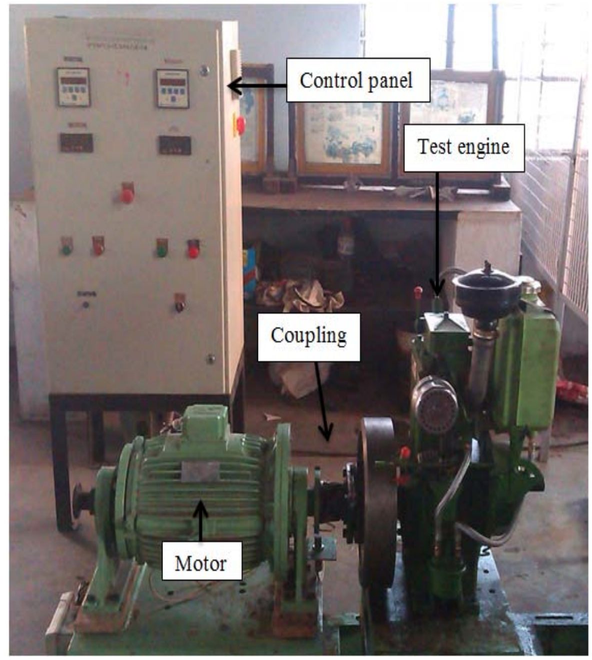

Fig. 3: Motored friction test.

4.2 Strip-down test

In this test engine components were dismantled sequentially to determine their contribution to total friction, as shown in fig. 4. Initially, the camshaft gear was disengaged, so that valve train system can be separated. Detached camshaft gear also separates fuel pump system, so in this case it is considered as a part of valve train system. Then engine is motored without cylinder head and valve train system and torque is measured. The difference in torque is characterized as the frictional contribution of valve train system. Then, piston is removed along with the connecting rod and the engine is motored again. The difference in torque is assigned to the piston and the rod. It is not possible to directly separatethe piston friction from the rod friction [11]. In the end, crankshaft is motored which gives the direct frictional contribution of crank bearings. During this test, motoring torque is measured at a constant speed of 1500 rpm. The torque required by different engine components is shown in Table 3.

Table 3: Engine component torque.

Sr. No.	Component	Torque (Nm)
1	Valve train	3. 2
2	Piston assembly	4. 2
3	Crankshaft bearings	0. 8

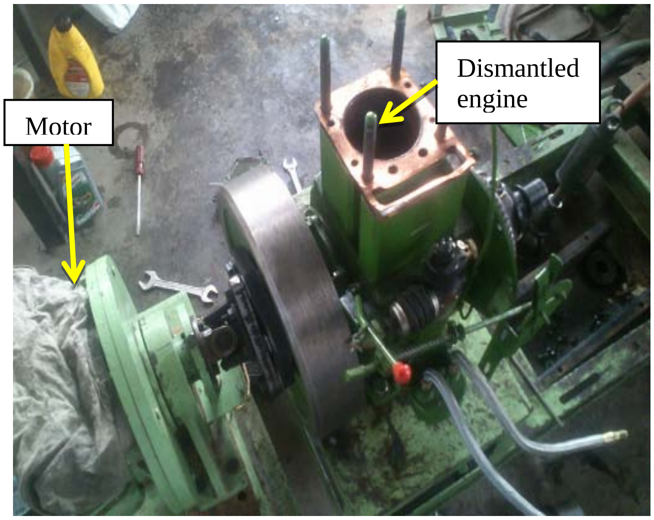

Fig. 4: Dismantled engine for Strip-down test.

5. RESULTS AND DISCUSSION

The results obtained for the two different tests are discussed below. As a general convention, a constant engine speed of 1500 rpm is considered for further analysis. Using the torque value in Table 2 the total friction power(f_{p2}) is calculated as,

$$f_{p2} = \frac{2\pi NT}{60000}$$

$$\therefore f_{p2} = \frac{2\pi \times 1500 \times 8.2}{60000}$$

$$\therefore f_{p2} = 1.28\ kW \quad (4)$$

Now, from the calculated friction power, mechanical efficiency of the engine can be determined as,

$$f_{p2} = ip_2 - bp$$

$$1.28 = ip_2 - 3.68$$

$$\therefore ip_2 = 4.96\ kW$$

$$\eta_{mech2} = \frac{bp}{ip_2}$$

$$\eta_{mech2} = \frac{3.68}{4.96}$$

$$\therefore \eta_{mech2} = 0.74 \quad (5)$$

The mechanical efficiencies obtained from experimental and theoretical analysis is presented in graph below (fig. 5). It can be clearly observed that, actual friction power (eq. 4) of the engine is 6% more ascompared to the theoretical value (eq. 3).

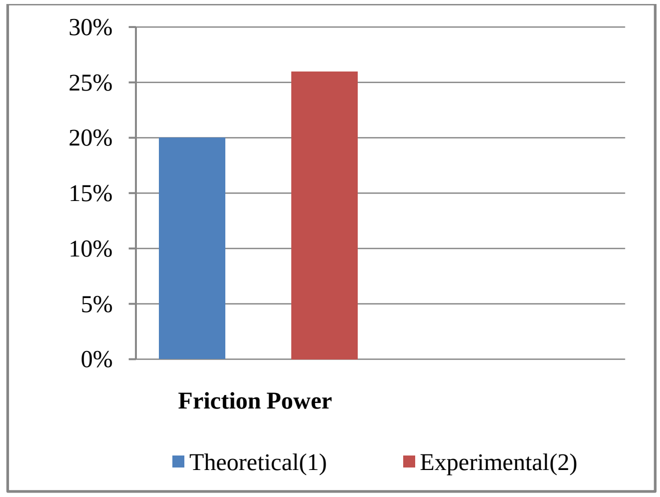

Fig. 5: Total friction power.

The component removal test or strip down test shows that, the torque required for piston assembly is more than other components. Using the torque values in Table 3, the friction power of each component is tabulated below in Table 4. The percent contribution of the component friction in the total friction power (actual) is present in fig. 6.

Table 4. Component friction power.

Sr. No.	Component	Friction power (kW)
1	Valve train system	0. 50
2	Piston assembly	0. 66
3	Crank bearings	0. 13

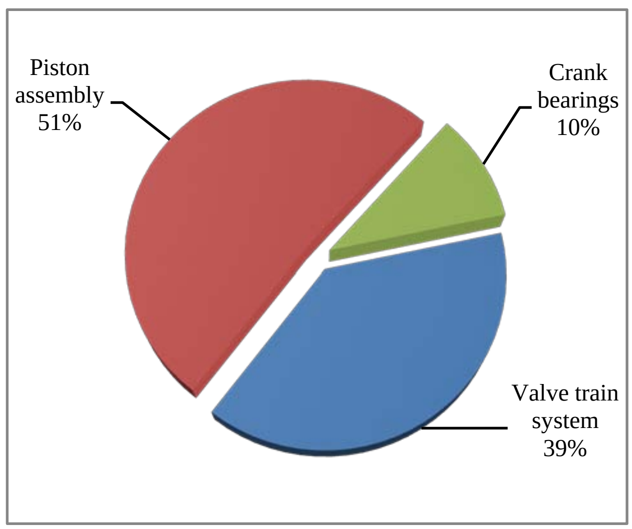

Fig. 6: Component friction contribution.

The piston assembly friction accounts for almost half of the total frictional losses. So, the friction losses in the piston assembly are required to be minimized. Also, minor modifications in other parts of the engine, together may lead to substantial reduction in total friction power. Some of the friction reduction techniques such as, wrist pin offset, moly-coated piston rings, friction reduction coatings and low viscosity oils, are explained below.

6. FRICTION REDUCTION TECHNIQUES

In this section, a review has been made on the techniques to minimize the overall friction losses in an engine.

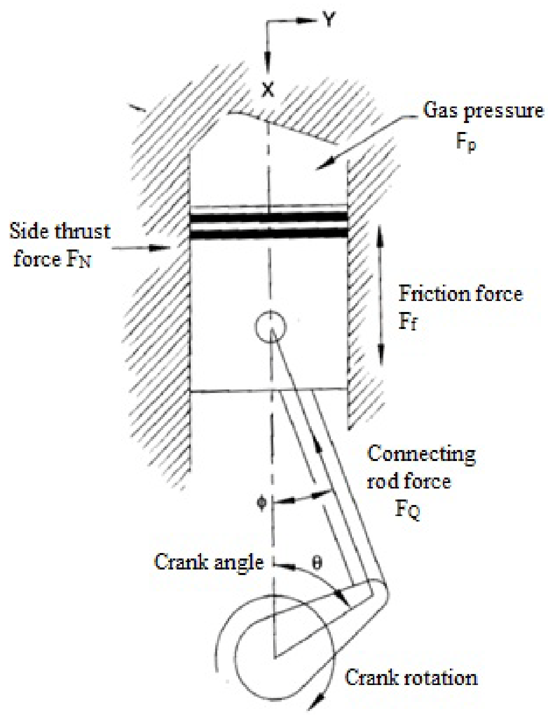

Fig. 7: Force balance on piston.

Fig. 7 presents the forces that act on a piston at an angle θ, when the piston is moving away from top dead centre. Angle φ represents the angle between connecting rod and cylinder axis. The X axis signifies the centreline of the cylinder (positive in downward direction during power stroke). The Y axis is in the radial outward direction (zero at the centreline). The side thrust force (F_N) is the reaction force in Y direction to the force in the connecting rod and lies in the plane of the connecting rod. The left side of an engine (rotating as shown in fig. 7) is called the major thrust side of the cylinder, because of the high pressure during power stroke. This high pressureinstigates a strong reaction force in the connecting rod, which in turn producesa large side thrust reaction force. The connecting rod is on the other side of the crankshaft during exhaust and compression strokes. Thus, the resulting side thrust reaction force is on the other side of the cylinder wall (right side in fig. 7). This is called the minor thrust side due to the lower pressures and forces involved. A force balance in the X direction gives

$$\sum F_x = m \cdot a_p = -F_Q + F_p \pm F_f \quad (6)$$

Where: m = mass of the piston; a_p = acceleration of piston; F_Q = force of connecting rod; F_p = force on piston; F_f = friction force between piston and cylinder wall. The sign on the friction force term depends on the crank angle θ (negative when 0˚< θ< 180˚; positive when 180˚< θ< 360˚).

There is no motion in Y direction, so force balance gives,

$$\sum F_x = 0 = F_Q \sin\varphi - F_N \quad (7)$$

Combining eq. (6) and (7) gives the side thrust force on the piston as:

$$F_N = \{(-m \cdot a_p) + F_p \pm F_f\} \tan\varphi \quad (8)$$

As the pistonmoves back and forth inside the cylinder, the side thrust force also varies with crank angular position. Pistons that have less mass and shorter skirts are used in modern engines, to reduce friction. The piston inertia lowers due to less mass and reduces the acceleration term in eq. (8). Shorter piston skirt reduces rubbing friction because of the smaller surface contact area. In some engines, the wrist pin is offset from centre towards the minor thrust side of the piston by 1 or 2 mm. This reduces the side thrust force and resulting friction on the major thrust side [14].

The piston ring is perhaps the most complex tribologicalcomponent in the IC engine. In one single stroke of thepiston, the piston ring couldundergoboundary, mixedand hydrodynamic lubrication, as explained in fig. 2. There are two types of rings, compression and oil control rings incorporated in the piston assembly [14]. The top piston rings (compression rings) are subjected to high pressures and loading due to high gas pressures developed during the power stroke. So, wear resistant coatings, generally chromium plated, are applied to the outer ring surface. Molybdenum (moly) coating has less friction coefficient and shows better wear resistance as compared to chromium plated rings. Hence, moly-coated piston rings can be incorporated to reduce piston assembly friction [11, 12].

Another technique to reduce frictional losses is to reduce the surface roughness of the engine components [3, 4]. Hard coatings such aschromium nitride (CrN) or titanium nitride (TiN) can beapplied to keep the surface roughness low [6-8]. These coatings can be applied to the components such as, gudgeon pin, crank-pin diameter, camshaft and follower. This can reduce the overall friction power of the engine.

Viscosity of the lubricating oil has an impact on engine friction power [2]. As diesel engines operate under high temperature, lubricant viscosity is increased due to oil oxidation, evaporation of the light compounds and nitration and contamination by soot. There is a trend towards the use of low viscosity engine lubricants, intendingto obtain improved fuel economy through the reduction of friction losses. High viscosity mono-grade lubricant produces higher friction power than low viscosity multi-grade oil. Low viscosity oils have potential to reduce the friction losses by 2-3% [5].

Thus, the friction reduction techniques mentioned above can be implemented to reduce the total friction power of the engine. These techniques may be regarded as efficient ways to reduce friction losses, because these techniques does not require any major design modification in the engine and can be implemented in the existing engine easily.

7. CONCLUSION

A motorized friction test was conducted to evaluate the total friction power of the engine. It was observed that the total friction power of the engine is more than the theoretical analysis. Then, strip-down friction test was performed to evaluate friction contribution of piston assembly, valve train system and crank bearings. It was observed that the piston assembly friction contributes 51% of the total friction power. Finally, friction reduction techniques are suggested that will help to minimize the total friction power of the engine.

8. ACKNOWLEDGEMENT

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