

Development of Engine Lubrication System with New Internal Gear Fully Variable Discharge Oil Pump

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ABSTRACT

Over the past decades, the automotive industry has made significant efforts to improve engine fuel economy by reducing mechanical friction. Reducing friction under cold conditions is becoming more important in hybrid vehicle (HV) and plug-in hybrid vehicle (PHV) systems due to the lower oil temperatures of these systems, which results in higher friction loss. To help resolve this issue, a new internal gear fully variable discharge oil pump (F-VDOP) was developed. This new oil pump can control the oil pressure freely over a temperature range from -10°C to hot conditions. At 20°C, this pump lowers the minimum main gallery pressure to 100 kPa, thereby achieving a friction reduction effect of 1.4 Nm. The developed oil pump achieves a pressure response time constant of 0.17 seconds when changing the oil pressure from 120 kPa to 200 kPa at a temperature of 20°C and an engine speed of 1,600 rpm. Test results confirmed that the developed oil pump controlled the oil pressure with an undershoot of about 12%. The oil jets were also stopped from -10°C. The internal gear tooth profile was also improved and reduced the friction of the rotor by 34% compared to a conventional trochoidal tooth profile. This paper describes the details of the design of the new internal gear rotor, the structure of the new F-VDOP, the engine oil circuit, and the test results. This new oil pump improves fuel economy by 1.2% under the LA#4 cold test cycle.

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INTRODUCTION

Over the past decades, improving fuel economy has become one of the most important objectives for automakers and one recent trend for powertrains is the growing mainstream popularity of hybrid vehicles (HVs) and plug-in hybrid vehicles (PHVs). Since the engines used by both HVs and PHVs operate for shorter periods than conventional engines, the engine oil temperature remains lower. Under cold conditions, the oil pressure increases due to the higher viscosity of the engine oil. As a result, the mechanical friction of engine increases. Therefore, to help resolve this issue, it is important to reduce the oil pressure under cold conditions to the minimum necessary level for each engine part [1][2]. For this reason, measures to improve fuel economy under cold conditions are becoming more important. To improve fuel economy under both cold and hot conditions, a number of automakers have adopted vane-type fully variable discharge oil pumps (F-VDOP) [3].

In contrast, switching variable discharge oil pumps (S-VDOP) have been unable to fully reduce friction under cold conditions [4][5].

To help resolve this issue, a new internal gear fully variable discharge oil pump (F-VDOP) was developed. Although conventional internal gear oil pumps with a trochoidal tooth profile are considered to have low pumping efficiency [6][7], the total efficiency of the new pump was increased by adopting a new rotor with a refined tooth profile. This measure facilitated the development of a highly efficient oil pump that utilizes the fundamental merits of internal gear pumps, namely fewer component parts and low pulsation.

Adopting this oil pump in a new 2.5-liter engine reduces friction by dynamically lowering the oil pressure from cold conditions, and helps to switch the oil jets on and off hydraulically. When installed in a vehicle, this engine achieved a 1.2% improvement in fuel economy under the Los Angeles Driving Cycle #4 (LA#4).

1. AIMS OF NEWLY DEVELOPED FULLY VARIABLE DISCHARGE OIL PRESSURE SYSTEM

Two types of conventional variable oil pressure systems are the mechanical variable discharge oil pump (M-VDOP) and the switching variable discharge oil pump (S-VDOP). They can control oil pressure according to each target to reduce friction at hot conditions (Fig. 1). However, because these pumps control the oil pressure by switching the reserve value on and off, neither are capable of fully lowering the oil pressure when the oil temperature is low (i.e., when the base oil pressure is high). As a result, these pumps cannot reduce friction and cannot stop the oil jets under cold conditions. In this case, an additional switch valve was required to accomplish the oil jet switching function. In addition, even under hot conditions, these pumps have to be controlled using excess oil pressure with respect to the engine oil pressure demand in consideration of part tolerances.

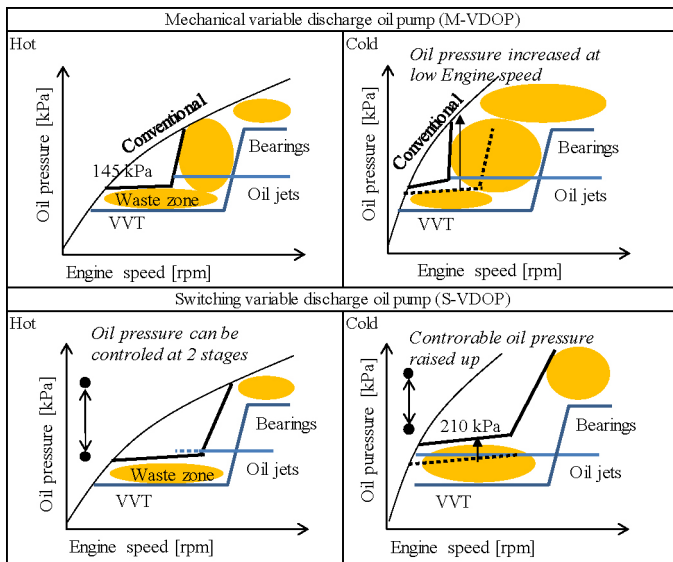


Figure 1. Oil control map of previous M-VDOP and S-VDOP.

To help resolve these issues, the aim of the newly developed FVDOP and lubrication system is to control the oil pressure to the level of demand from each engine part and reduce friction from cold conditions.

The target control start oil temperature was set to -10°C to ensure the reliability of the main bearings under low oil temperature. The target main gallery oil pressure was lowered to 100 kPa considering the reliability of the variable valve timing (VVT) and main bearings. Therefore, after factoring in the oil filter loss, the target oil discharge pressure was lowered to 125 kPa. Consequently, the oil jet valve opening pressure was set to 170 kPa. At this value, the F-VDOP would be capable of stopping the oil jets, even considering the hysteresis of the control valve, which would enable the elimination of the oil jet switch valve (Fig. 2).

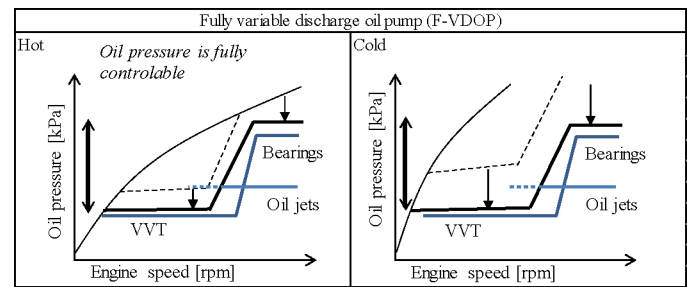


Figure 2. Oil pressure control map of new F-VDOP.

Stability is an important requirement for oil pressure control at 100 kPa. Oil pressure undershoot mechanisms have the adverse effects of lowering the engine and oil pump rotation speed too quickly and increasing oil leaks due to the oil quantity demand of various devices. Considering the gear changes performed by a manual transmission and other severe usage environments, the F-VDOP oil pressure response target was set to a time constant of 0.4 seconds. Table 1 summarizes these targets.

Table 1. F-VDOP development targets.

Oil: 0W-16, 1,600 rpm		New F-VDOP	S-VDOP
Target oil pressure at main oil gallery	-10°C	100 kPa	—
	20°C		210 kPa
	80°C		145 kPa
Target oil pressure at oil pump outlet	-10°C	125 kPa	—
	20°C		—
	80°C		—
Oil pressure response time constant	-10°C	0.4 sec	—
	20°C		0.6 sec
	80°C		0.2 sec
Oil jet opening pressure		170 kPa	200 kPa

2. DEVELOPMENT OF HIGH-EFFICIENCY INTERNAL GEAR ROTOR

A number of automakers have developed F-VDOP variants. High-performance vane-type F-VDOP have already been adopted on mass-production vehicles. However, despite a track record of developing internal gear oil pumps, this newly developed oil pump is Toyota's first internal gear-type F-VDOP. However, previous research has indicated that vane oil pumps have better total efficiency than internal gear oil pumps.

In contrast, the merits of internal gear pumps include fewer component parts, which enables greater reliability, lower cost, and lower pulsation. Therefore, this development examined the feasibility of adopting an internal gear oil pump with a more efficient internal gear tooth profile.

2-1. Improvement of Internal Gear Rotor Tooth Profile

The total efficiency of an oil pump is the product of two items: its mechanical efficiency (i.e., sliding friction) and volumetric (pumping) efficiency. Sliding friction is related to the cube of the outer rotor

diameter multiplied by the rotor tooth width. Therefore, to reduce friction while maintaining the discharge volume, the outer rotor diameter must be reduced and the gear face width increased.

$$\text{Total efficiency} = \text{Mechanical efficiency} \times \text{Pumping efficiency}$$

However, in the case of a trochoidal gear profile, enlarging the rotor tooth width lowers the charging efficiency of the volumes between the inner and outer rotors, and increases the susceptibility to cavitation. Therefore, a new tooth profile was developed with a focus on improving the charging efficiency.

Charging efficiency was improved by enabling oil to pass between the inner and outer rotors at locations other than the inlet and discharge boundaries (Table 2). As a result, oil can pass between neighboring teeth, thereby increasing the charging efficiency and suppressing cavitation. This design has the effect of enlarging the rotor teeth width and maintaining the discharge volume, while making the outer rotor diameter more compact. In stand-alone tests of both rotors under the same discharge volume, the newly developed tooth profile reduced the friction of the rotor by 34% compared to the conventional trochoidal tooth profile (Table 2).

Table 2. Differences between conventional and new rotors.

	Conventional rotor	New rotor
Shape		
Qth	10.5 cc/rev	10.5 cc/rev
Size of outer rotor Diameter × Width	φ 57×13.2	φ 46.5×19
Number of teeth	6	9
Sliding friction		
Pulsation @4000rpm	1	0.6 (▲40%)

2-2. Discharge Efficiency Comparison

After improving the efficiency as described in Section 2-1, the total efficiency of an internal gear oil pump equipped with the new rotor was compared with that of a vane oil pump. Due to the differences in development timing, the efficiency comparison was carried out after changing the specifications of the rotor (Table 3). Although Section 2-1 described a rotor with a discharge volume of 10.5 cc/rev, the comparison was performed with a discharge volume of 15 cc/rev. Figure 3 shows the layout of this stand-alone test.

Table 3. Detail specifications of the new internal gear and vane type rotors.

	Internal gear type	Vane type
		
Capacity	15 cc/rev	14.8 cc/rev
Number of teeth	inner: 9, outer: 10	6
Size of outer rotor	φ 51×21.4	φ 54×20
Capacity per tooth	1.67 cc/rev/tooth	2.47 cc/rev/tooth

The efficiency comparison test was carried out using SAE30 oil at 100°C. The efficiency was measured under the oil pump outlet gage pressure controlled by the pressure control valve, by changing the outlet oil pressure to 50 kPa (assuming low oil pressure control) and 200 kPa (assuming high oil pressure control). Also two engine speeds were selected: idling speed and a typical normal engine speed of 2,000 rpm. The efficiency of the tooth profile was compared under the initial position (same as the full discharge conditions, not eccentric position).

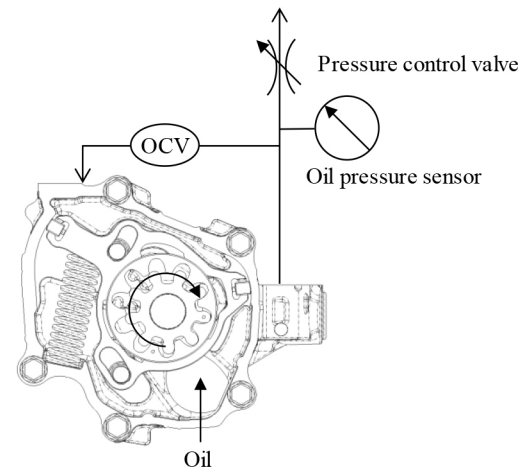


Figure 3. Test layout.

The results showed that the internal gear oil pump had higher total efficiency under all operating patterns. At an outlet pressure of 200 kPa, the total efficiency of the internal gear oil pump was 8% higher (at 2,000 rpm) than the vane oil pump. Although the vane oil pump had the same or higher pumping efficiency at both engine speeds and discharge pressures, the total efficiency was more than offset by the superior mechanical efficiency of internal gear oil pump. Pulsation was also compared at the initial position and an engine speed of 3,000 rpm. Since the internal gear oil pump has a smaller discharge volume per tooth, the pulsation of this oil pump was lower. In consideration of its superior total efficiency, discharge pulsation, and the number of the parts, the development selected the internal gear oil pump (Table 4).