

Analysis of BJ493 diesel engine lubrication system properties

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Abstract. The BJ493ZLQ4A diesel engine design is based on the primary model of BJ493ZLQ3, of which exhaust level is upgraded to the National GB5 standard due to the improved design of combustion and injection systems. Given the above changes in the diesel lubrication system, its improved properties are analyzed in this paper. According to the structures, technical parameters and indices of the lubrication system, the lubrication system model of BJ493ZLQ4A diesel engine was constructed using the Flowmaster flow simulation software. The properties of the diesel engine lubrication system, such as the oil flow rate and pressure at different rotational speeds were analyzed for the schemes involving large- and small-scale oil filters. The calculated values of the main oil channel pressure are in good agreement with the experimental results, which verifies the proposed model feasibility. The calculation results show that the main oil channel pressure and maximum oil flow rate values for the large-scale oil filter scheme satisfy the design requirements, while the small-scale scheme yields too low main oil channel's pressure and too high. Therefore, application of small-scale oil filters is hazardous, and the large-scale scheme is recommended.

1. Introduction

Lubrication system is the key system of diesel [1,2]. BJ493ZLQ4A diesel engine is based on the primary BJ493ZLQ3, through the improvements and redesigns of combustion and injection systems, and upgraded to exhaust level regulated by the National GB5 standard [2]. Diesel timing transmission adopts gear transmission scheme; according to the requirements for the entire vehicle's brake, air compressor for braking has been added to the diesel, the injection oil pump adopts Bosch CB18 pump with the reinforced model EGR cooler. So the lubrication system of diesel has been much improved, of which changes require in-depth analysis to guarantee the engine operation safety and reliability.

According to the lubrication system structure, technical parameters, and indices, its model was constructed using the Flowmaster flow simulation software. Such properties as the oil flow rate and pressure at different rotation speeds were analyzed for the schemes involving large- and small-scale oil filters. The calculated values of the main oil channel pressure are in good agreement with the experimental results, which verifies the proposed model feasibility. The calculation results show that the main oil channel pressure and maximum oil flow rate values for the large-scale oil filter scheme satisfy the design requirements.

The National GB5 exhaust standard of China has adopted the national emission standard level V, which requires that the automobiles must satisfy the pollution exhaust rules. As compared with the former standard, the new one is more rigorous: the CO₂ emission must be reduced by 25% for automobiles and by 43% for buses and trucks.



2. Diesel lubrication system and arrangement

As shown in figure 1, the BJ493ZLQ4A diesel lubrication system includes oil pump, oil filter, oil cooler, main shaft, connecting rod shaft, cam shaft bearing, turbo lubrication, piston cooling jet (PCJ), air compressor lubrication, timing gear shaft lubrication, and oil pump lubrication. Among these, the lubrication of the main shaft, connecting rod shaft, cam shaft bearing, gears, cylinder head, and PCJ: these parts are provided through the main and cylinder body inner oil channels [3]; while the turbo and air compressor are lubricated through the external oil pipes of the cylinder body.

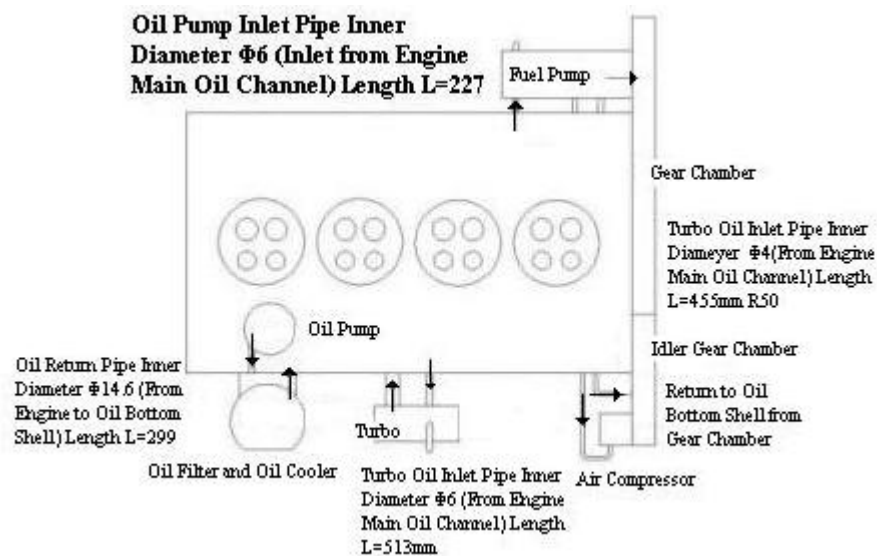


Figure 1. The BJ493ZLQ4A diesel engine lubrication system.

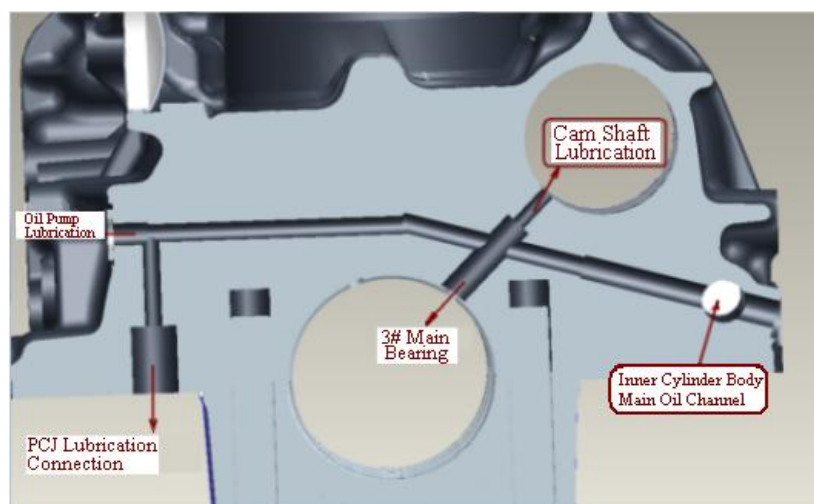


Figure 2. Lubrication oil channel and distribution of No. 3 main bearing and No. 2 cam shaft.

2.1. Lubrication of parts via main and inner cylinder body oil channels

Figure 2 depicts the conditions of the 3# main bearing and main oil channel connections. The main oil channel in the cylinder body of the diesel BJ493ZLQ4A is located at the right bottom part of the cylinder body (viewed from the back of the engine), while the main shaft neck is lubricated by a changeable oil channel (of 8.4 mm or 7 mm in diameter) with the inclination angle of 15° to the horizontal plane, and another downward oil channel (of 10 mm in diameter) with the inclination angle of 45° to the horizontal plane. The intrinsic feature of 3# main bearing oil channel arrangement is that

the main oil channel supplies oil to 3# main bearing and 2# cam bearing through the inner cylinder body oil channel, while providing oil directly to the PCJ and diesel oil pump. Figures 3-6 depict the oil-connecting conditions for 1#, 2#, 4#, 5# main bearings and main oil channels.

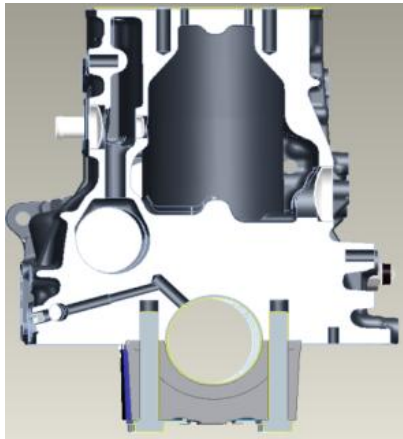


Figure 3. No. 1 main bearing and main oil channel.

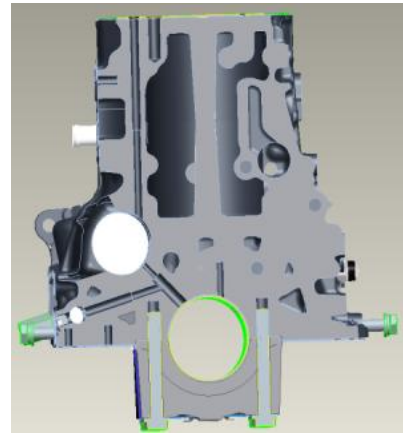


Figure 4. No. 2 main bearing and main oil channel.

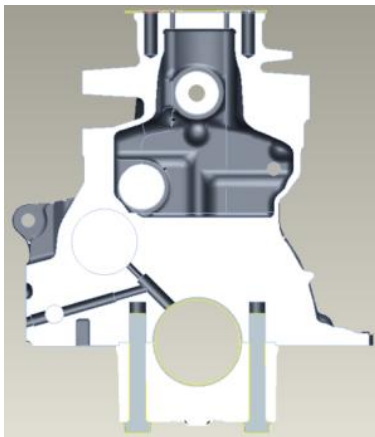


Figure 5. No. 3 main bearing and main oil channel.

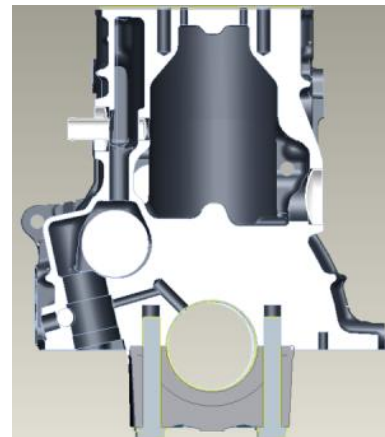


Figure 6. No. 4 main bearing and main oil channel.

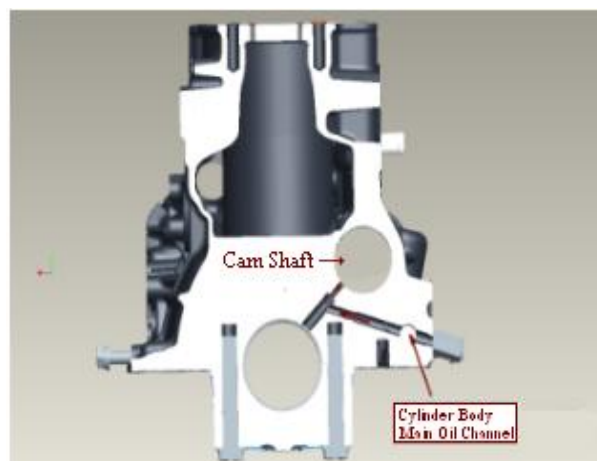


Figure 7. Cam shaft lubrication channel.

2.2. Cam shaft lubrication

As seen from figure 7, the diesel engine cam shaft is arranged at the right side of its middle line (viewed from the diesel's back), and provides oil for the main oil channel via the inner oil channel of cylinder body at 5#, 3#, 1# main shaft bearings, then returns to the oil bottom shell by the natural oil re-circulation method. The diameter of oil channel connected to the bearing bush is 6 mm, and its length is 15.5 mm.

2.3. PCJ bearing lubrication

As seen from figure 8, oil flows into the connecting pipe of piston cooling jet (PCJ) bearing, which protrudes from the cylinder body [4]. The area of injection outlet nozzle is 1.77 mm^2 , and the diameter of PCJ pipe is 3 mm.

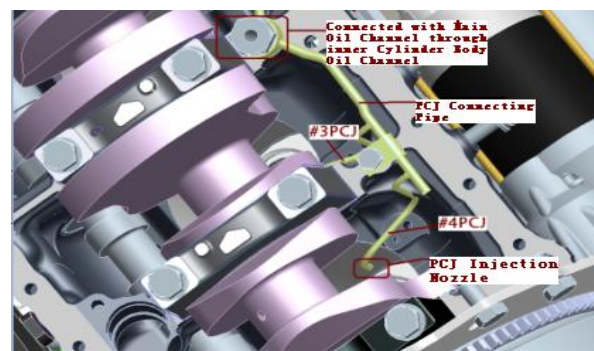


Figure 8. PCJ bearing lubrication.

2.4. Gear lubrication

As seen from figure 9, gears lubrication mainly relies on the oil provided via the main oil channel, while air compressor, oil pump and idler gear of the air compressor are supplied by oil via the external oil pipe, which is connected with the main oil channel. Idler gear A is connected with the main bearing bush oil nozzle. The diameter of the external oil pipe of the oil pump is 6 mm, the diameter of the idler gear near air compressor is 4 mm, while the diameter of spatter oil supplying pipe is 1 mm.

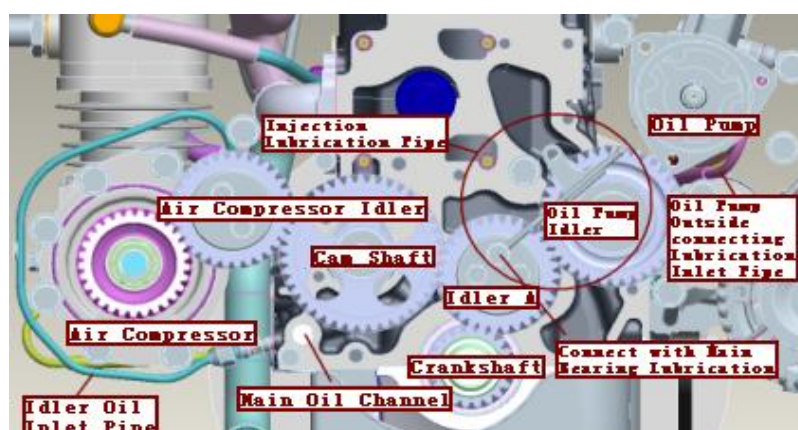


Figure 9. Gear lubrication.

2.5. Turbo

As shown in figure 10, the external inlet oil pipe of the turbo is connected with the main oil channel directly [5]. The pipe inner diameter is 6 mm, the length is about 510 mm.

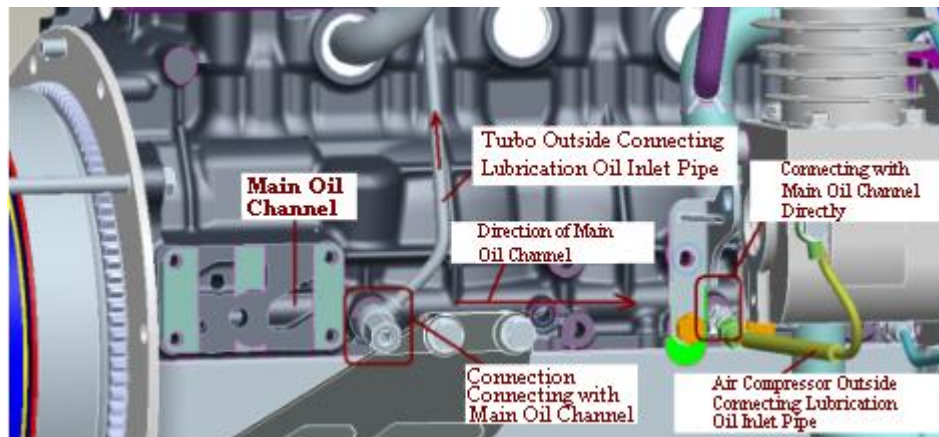


Figure 10. Turbo lubrication.

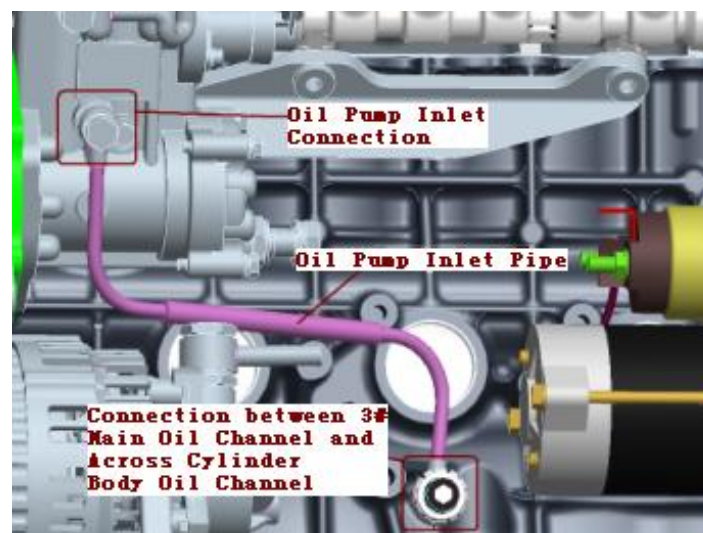


Figure 11. Oil pump lubrication pipe.

2.6. Oil pump

The diameter of oil pump external connection oil pipe is 6 mm, as is shown in figure 11.

2.7. Shaft main bearing bush

Shaft main bearing has 5 channels, its diameter is 70 mm and width is 21.9 mm, while the width of oil tank is $180^{\circ} \times 3$ mm, the depth is 0.85 mm; standard gap is 0.033-0.079 mm, under the limited size conditions, the relative gap of bearing is 0.113%.

2.8. Shaft connecting rod neck bearing bush

Connecting rod neck bearing has 4 channels, its diameter is 53 mm and width is 24.7 mm; there is no oil tank; standard gap is 0.029-0.075 mm, under the limited size conditions, the relative gap of bearing is 0.140%; the axial gap between connecting rod and shaft is 0.175-0.29 mm.

2.9. Cam shaft bearing

Cam shaft bearing of 50 mm in diameter has 3 channels of width equal to 26, 234, and 23 mm for the first, second, and third channels, respectively. There is no oil tank; the standard gap between cam bearing bushing nozzle and cam shaft bearing neck is 0.015-0.085 mm, the limit of gap abrasion is 0.12 mm, and under the limited size conditions, the relative gap of bearing is 0.17%.

3. Elaboration of models for software simulation

According to the structural features and the arrangement conditions of lubricated parts of BJ493ZLQ4A diesel, the simulation models [6] were elaborated, as shown in figures 12 and 13. The structures and principles of the lubrication models correspond to the actual engine set-up, such as the main shaft bearing, cam shaft bearing, connecting bearing, the main oil channel, and the engine's components' lubrication: turbo, air compressor, cylinders, oil pump, PCJ, positive crankcase ventilation valve (PCV), etc. The data on their sizes and properties, especially for lubrication materials and systems, can be input into the model, and they fully correspond to the actual engine operating conditions. Insofar as the simulation results are also close to the actual engine test data, the elaborated model feasibility is confirmed.

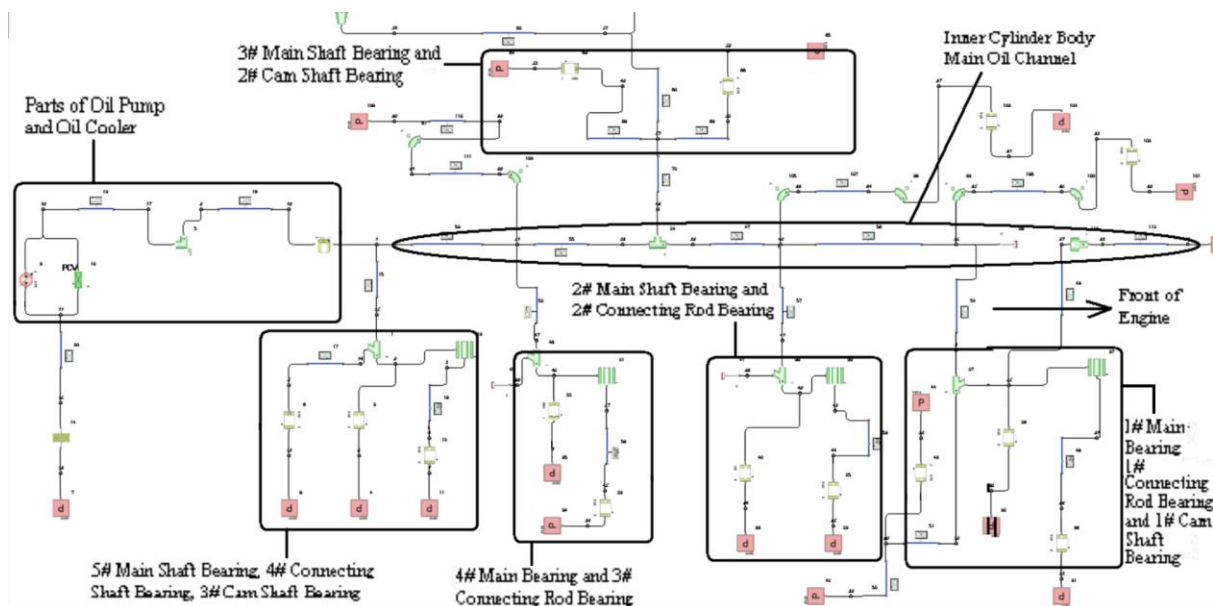


Figure 12. Model #1 of the 493 diesel lubrication system.

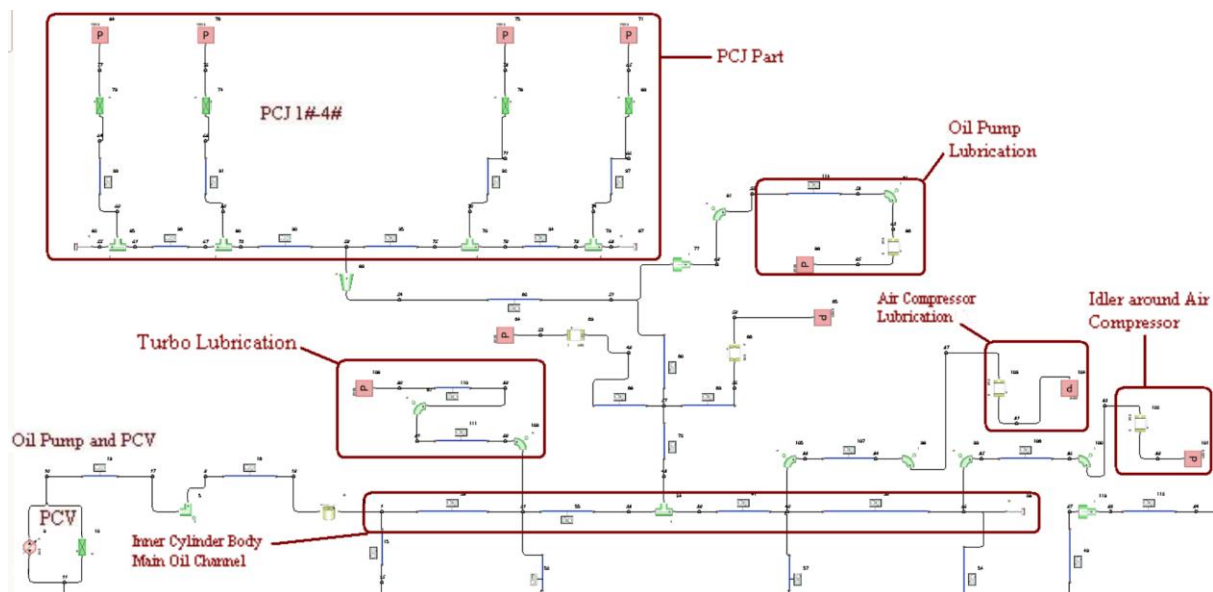


Figure 13. Model #2 of the 493 diesel lubrication system.

4. Loads and boundary conditions

4.1. Boundary conditions

The boundary conditions used in the model are listed in table 1.

Table 1. Boundary conditions.

Subject	Value	Property
Oil type	CF5W40	No changes
Oil temperature	125°C	No changes
Environmental pressure	1bar=0.1MPa	No changes
Bearing external pressure	1bar=0.1MPa	Same as the environmental one
Engine speed (rpm)	800,1200, 1500, 2000, 2800, 3200, 3600	
Oil pump speed (rpm)	400, 600, 750, 1000, 1400, 1600, 1800	Half of the engine speed
Oil pump	Nominal volume 22.70 mL/rev, Flow Rate: 37.12 L/min at 3200 rpm/6 bar=0.6 MPa	Design parameters and experimental data
Oil filter and oil cooler	0.22 m ² 0.38 m ²	Small-scale oil filter scheme Large-scale oil filter scheme
Bearing speed	Main shaft bearing: same as the engine speed Large head connecting rod: same as the engine speed Cam shaft speed: same as oil pump speed	Changes according to operating mode Changes according to operating mode Changes according to operating mode
Bearing relative gap	Main shaft bearing: φ70x21.9 mm, relative gap: 0.00113 Connecting rod bearing: φ53x24.7mm, relative gap: 0.0014 Cam shaft bearing: φ50x23mm, φ50x23mm, φ50x26mm, relative gap: 0.0017	No changes No changes No changes
PCJ	PCJ opening pressure: 2.0+/-0.25bar at 2000rpm	

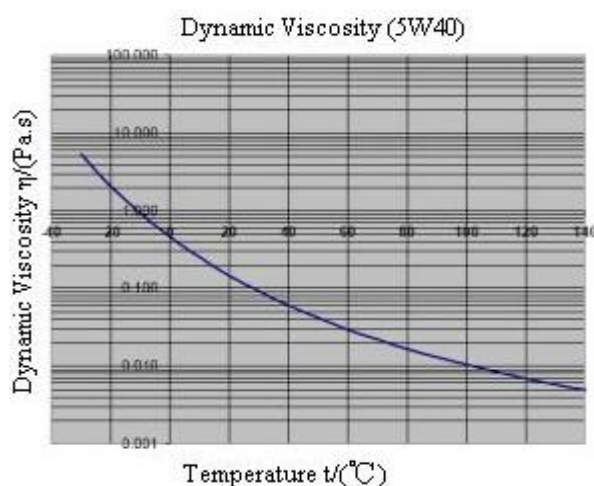


Figure 14. Dynamic viscosity vs. temperature curve of 5W40 oil.

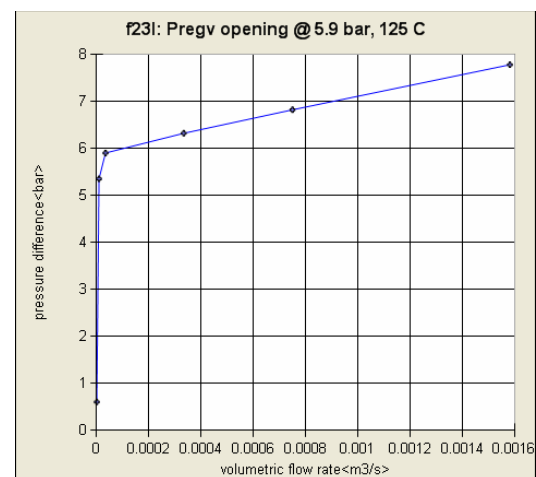


Figure 15. Pressure difference vs. flow rate curve of PCV at 0.59MPa and 125°C.

4.2. Features of medium and parts

- Properties of 5W40 oil

The 5W40 oil viscosity-temperature curve is shown in figure 14. The curve and its relevant data refer to the actual conditions obtained from the suppliers [7] and were exported from the Flowmaster database, of which data exhibit a good fit with the experimental results. Positive Crankcase Ventilation Valve (PCV) PCV feature's curve is plotted in figure 15.

- Features of Oil Pump

Oil pump's curves are plotted using the available experimental data. Figures 16(a) and 16(b) depict the volume efficiency-pressure and flow rate-pressure curves, respectively, of the oil pump at different rotation speeds.

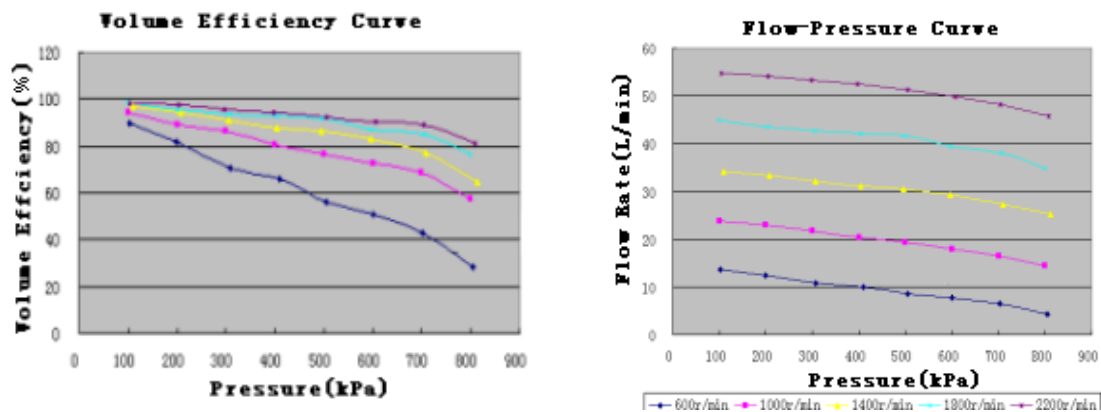


Figure 16. Volume efficiency vs. pressure (a)-L and flow rate vs. pressure (b)-R curves.

- Properties of Oil Filter and Oil Cooler

Large- and small-scale oil filter schemes [8,9] have been adopted in the oil filter design. For both schemes, the simulation of the diesel's lubrication system operation was performed separately. According to the data provided by suppliers, the effective area of small-scale oil filter is 0.22 m^2 , standard flow rate is 33 L/min , the recommended flow rate is below 30 L/min ; while the effective area of large-scale oil filter is 0.38 m^2 , standard flow rate is 45 L/min , the recommended flow rate is below 40 L/min .

- Piston Cooling Jet (PCJ) features of the injection nozzle.

The pressure difference-flow rate curve of PCJ is shown in figure 17.

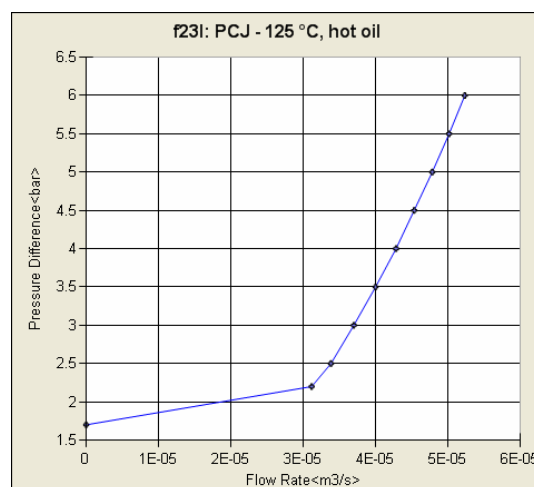


Figure 17. PCJ pressure difference vs. flow rate curve (input) at 25°C .

5. Selection of benchmarks for calculation

For analyzing the effects of two oil filter and oil cooler parts on the diesel's lubrication system, separate calculations were performed for the oil cooler with the large- and small-scale oil filters [10].

The boundary conditions for the both schemes are basically the same, except for the oil filter and oil cooler curves. Seven benchmark rotation speeds were selected, namely 800, 1200, 1500, 2000, 2800, 3200, 3600 rpm, whereas 800 rpm corresponds to the idle speed point, 1200, 1500, 2800 rpm are transition speed points, 2000 rpm is a predicted PCJ full point; 3200rpm is the rated point; 3600 rpm is the primary optimization point. For these benchmarks, which characterize diesel's properties and features, the calculations of the lubrication system's total oil flow rate, branch flow rate of the parts and each point's pressure values were conducted.

6. Calculation results and discussion

6.1. Calculation results of small-scale oil filter scheme

6.1.1. Pressure distribution. As shown in figure 18, with an increase in the diesel engine rotation speed, the parts' oil pressure increased constantly. When the engine speed was below 2800 rpm, the pressure of the parts increased rapidly. When it exceeded 2800 rpm, the oil re-circulation flow rate of PCV increased (between 3.2-6.3 L/min) with speed, the pressure increase of parts slowed down. For rotation speed between 3200-3600 rpm, the pressure of the inner main oil channel remained unchanged at about 0.376 MPa, while the oil pressure of parts exhibited a steady state [11,12].

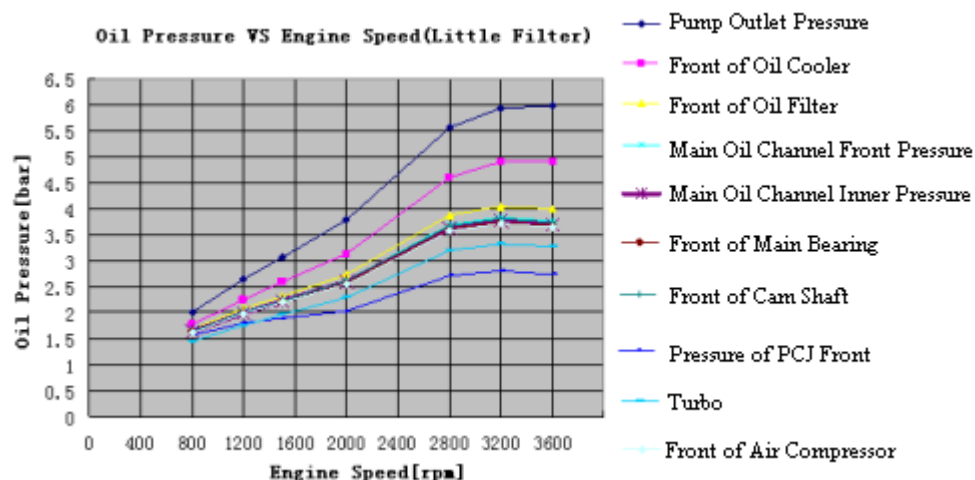


Figure 18. Oil pressure- engine speed curves for various parts of lubrication system with a small-scale oil filter.

Table 2 lists the main parts' oil pressure design requirements and simulated contrasting conditions. The simulated results indicate that under small-scale oil filter conditions, the pressure of the main oil channel cannot satisfy the design requirements for the diesel optimized condition and requires the experimental verification.

6.1.2. Flow rate distribution conditions. Figure 19 depicts the oil flow rate distribution conditions of the lubrication system parts for the small-scale oil filter scheme. With an increase in the engine rotation speed, the total oil flow rate is increased from 7.18 L/min to 38.8 L/min. While the engine speed is between 2800 and 3600 rpm, the main shaft bearing oil flow rate is in the range of 12.5 to 14.95 L/min; connection rod large head shaft bearing oil flow rate is from 5.7 to 6.5 L/min; the PCJ effective flow rate is between 8.2 and 8.52 L/min, which exceeds the requirement of 8 L/min for the

piston cooling.

The maximum values of oil flow rate are: 1.16 L/min for turbo (at 3200 rpm) and 0.15 L/min for air compressor (at 3600 rpm), while the maximum value of the oil pump quantity rate is 0.35 L/min (at 3600 rpm). Under the increased rotation speed condition of 3600 rpm, the oil flow rate of oil filter is 32.5 L/min, which exceeds the maximal value of 30 L/min recommended by the producer, but this value is slightly less than the small-scale oil filter's standard flow rate of 33 L/min. Therefore, application of the small-scale oil filter scheme under increased rotation speed conditions may be hazardous due to inadequate oil supply.

Table 2. Design requirements and calculation results for small-scale oil filter conditions.

Requirements	Calculated value (bar)	Conclusions and proposals
Pressure of main oil channel exceeds 1.5 bar at 125 °C	1.64	Approved
Pressure of main oil channel exceeds 3.85 bar at 125 °C for the engine speed of 3200 rpm	3.76	Experimental verification is proposed
Turbo: the oil pressure is larger than 1.5 bar at 125 °C for the engine speed above 1000 rpm	1.8	Approved
Air compressor: the oil pressure is larger than 3.0 bar at 125 °C for the engine speed of 3600 rpm	3.6	Approved
Pressure from main shaft bearing to connecting rod shaft neck exceeds 2.2-2.8 bar at 125 °C for the engine speed of 3200 rpm	3.7	Approved

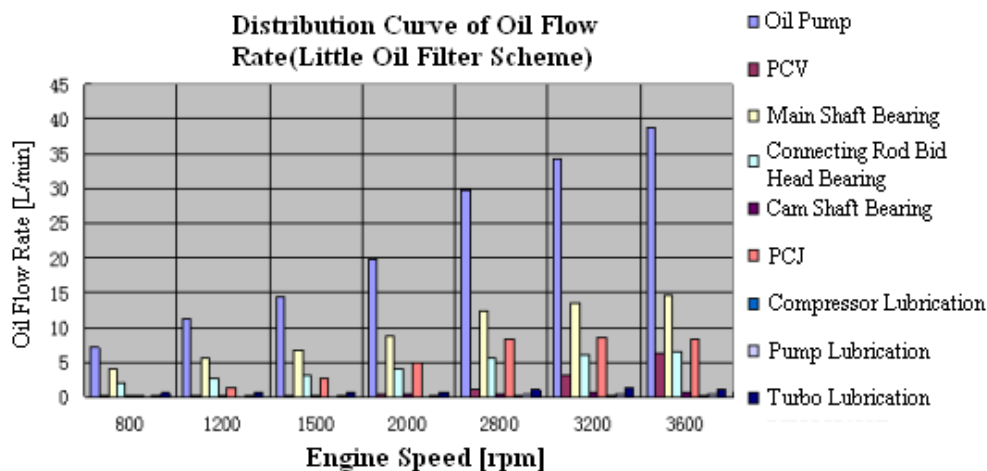


Figure 19. Oil flow rate distribution of various parts of the lubrication system (small-scale oil filter).

Flow rate design requirements and calculation results for the small-scale oil filter scheme are listed in table 3.

Table 3. Flow rate design requirements and calculation results for mall-scale oil filter scheme.

Requirements	Calculated value	Conclusions and proposals
Oil pump: effective exhaust rate 37.12 L/min at 3200rpm for the oil pressure of 6 bar		Needs to be approved
PCJ open pressure position: 2+/-0.25 bar; engine speed of 2800 rpm; recommended flow rate of 8.0 L/min or 2.0 L/min for each PCJ	8.2-8.5 L/min	Needs to be approved
Main oil channel's inner diameter is 15 mm, the inner diameter from oil pump to main oil channel needs to ensure that the oil flow	About 3 m/s	Approved

velocity is below 5-6 m/s, to ensure that the pressure loss is minimal.
About 3 m/s. Under condition of increased rotation speed at 3600 rpm, the oil filter flow rate is less than 30 L/min

32.5 L/min

Hazardous,
requires test
verification

6.2. Calculated results for the large-scale filter scheme

6.2.1. Pressure distribution conditions. As seen from figure 20, in case of the large-scale oil filter and oil cooler scheme application, the oil pressure in lubrication system parts increased constantly with the diesel engine speed. Thus, at rotation speed below 2800 rpm, pressure in all parts increased rapidly, and the main oil channel inner pressure rose from 0.164 MPa to 0.259 MPa; at the speed above 2800 rpm, pressure rise slowed down due to the increased PCV leak rate; while at the speed in the range of 3200-3600 rpm, the main oil channel inner pressure remained in the range of 0.38-0.39 MPa, and steady pressure values in all parts were observed.

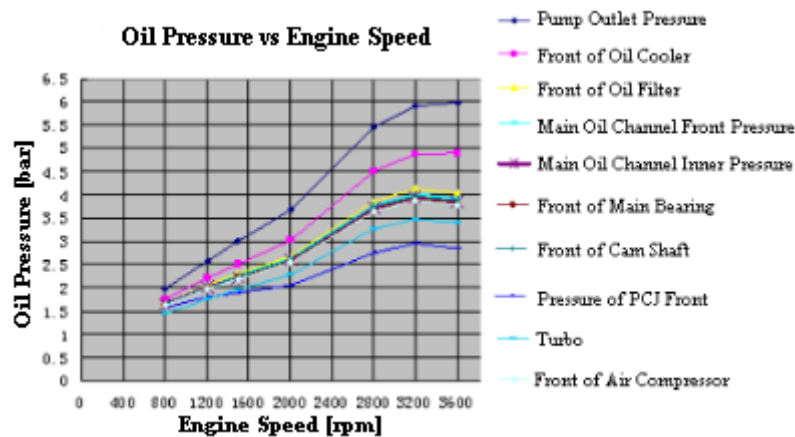


Figure 20. Oil pressure-engine speed curves of various parts for the large-scale oil filter scheme.

The oil pressure requirements and calculated values for the large-scale oil filter conditions are listed in table 4.

Table 4. Design requirements on the oil pressure and calculation results for the large-scale oil filter.

Requirements	Calculated value (bar)	Conclusions and proposals
Pressure of main oil channel exceeds 1.5 bar at 125 °C in idle speed	1.64	Approved
Pressure of main oil channel exceeds 3.85 bar at 125 °C for the engine speed of 3200 rpm	3.9	Approved
Turbo: the oil pressure exceeds 1.5 bar at 125 °C for the engine speed above 1000 rpm	1.8	Approved
Air compressor: the oil pressure exceeds 3.0bar at 125 °C for the engine speed of 3600 rpm	3.9	Approved
Pressure from main shaft bearing to connecting rod shaft neck exceeds 2.2-2.8 bar at 125 °C for the engine speed of 3200 rpm	3.95	Approved

As seen from figure 21, prior to reaching the oil cooler, oil flows into through a pipe of 10 mm in diameter and makes a turn at the right angle, which results in the pressure drop of about 0.045 MPa (at 3600 rpm), according to the calculations, In addition, a pressure drop in the oil pump transfer pipe is estimated as 0.05 MPa (at 3600 rpm), which is due to the fact that the oil transfer pipe diameter of 10

mm is too small, and the oil flow velocity is too high. Since the combination of these two geometric features leads to the total pressure drop of 0.095 MPa (at 3600 rpm), it is proposed to increase the oil channel diameter in these two points under the condition that the cylinder body structural integrity is not violated.

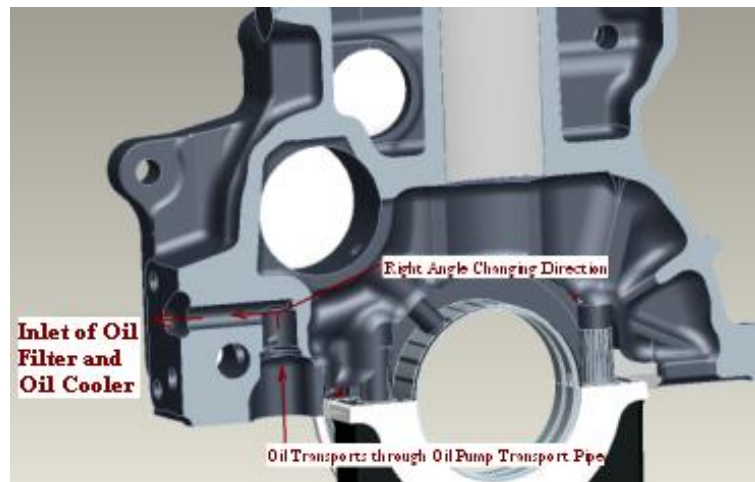


Figure 21. Oil channel geometry prior to oil flow to oil cooler and filter.

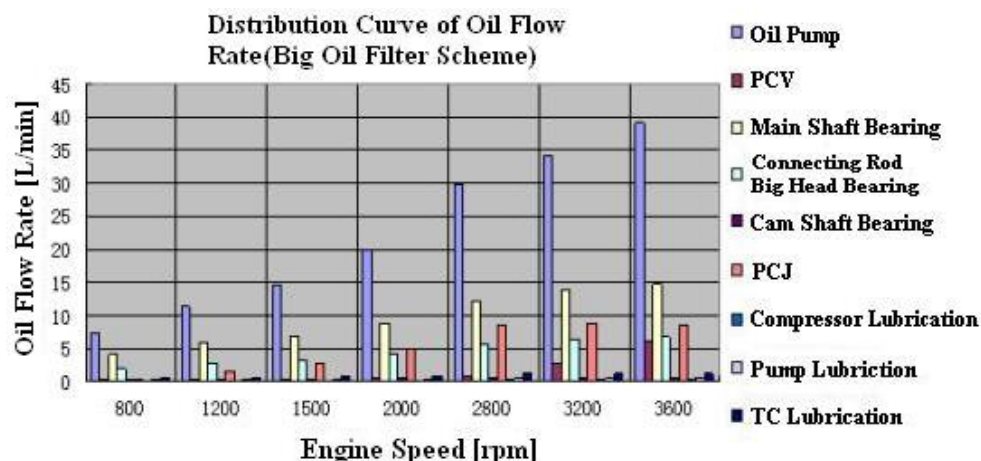


Figure 22. Oil flow rate distribution of various parts of the lubrication system (large-scale oil filter).

6.2.2. Flow rate distribution conditions. As shown in figure 22, the flow rate in lubrication system parts increased in the range from 7.19 to 39.2 L/min with the diesel engine speed: at 2800 rpm, the oil pump outlet pressure is 0.547 MPa, which exceeds the value of 0.54 MPa, which triggers the PCV opening, so the PCV begins to release at 2800 rpm, and the oil flow rate of PCV is 0.855 L/min, the main oil channel inner pressure being 0.37 MPa after releasing.

While the engine speed is below 2800 rpm, the main bearing oil flow rate is 4.07-8.75 L/min, connecting rod big head bearing oil flow rate is 1.89-4.02 L/min, cam shaft bearing flow rate is below 0.31 L/min, PCJ effective flow rate is 2.78-4.92 L/min, turbo compressor (TC) oil rate is below 0.8 L/min, oil pump flow rate is below 0.21 L/min, and air compressor flow rate is less than 0.084 L/min.

After the engine speed reached 2800 rpm, the PCV recirculation oil flow rate increases to the maximum of 6.17 L/min (at 3600 rpm), the total flow rate of the main oil channel inlet is 12.3-14.8 L/min, the oil flow rate of connecting rod big head bearing is 5.63-6.65 L/min, the oil flow rate of cam shaft is about 0.5 L/min, the maximum value of PCJ effective flow rate is 8.75 L/min (at 3200 rpm),

the maximum oil flow rate of the turbo is 1.22 L/min (at 3200 rpm), the maximum oil flow rate of the pump is 0.355 L/min (at 3600 rpm), and the maximum oil flow rate of the air compressor is 0.15 L/min (at 3600 rpm).

The large-scale oil filter's design requirements and calculation results are listed in table 5.

Table 5. Design requirements and calculation results for the large-scale oil filter scheme.

Requirements	Calculated value	Conclusions and proposals
Oil pump: effective exhaust rate of 37.12 L/min at 3200 rpm for the oil pressure of 6 bar		Needs to be approved
PCJ open pressure position: 2+/-0.25 bar; engine speed of 2800 rpm; recommended flow rate of 8.0 L/min or 2.0 L/min for each PCJ	8.5-8.75 L/min	Needs to be approved
Main oil channel's inner diameter is 15 mm, the inner diameter from oil pump to main oil channel needs to ensure that the oil flow velocity is below 6 m/s, to make sure that the pressure loss is minimal.	About 3m/s	Approved
About 3m/s	33.1L/min	Approved
At rotation speed of 3600 rpm, the oil filter flow rate is below 30 L/min		

6.3. Comparison of two oil filter schemes and the experimental results

6.3.1. Comparison of two oil filter schemes. Comparison of the simulation results and recommendations for the large- and small-scale oil filter design schemes is shown in table 6.

Table 6. Comparison of the large- and small-scale oil filter design schemes.

Subject	Small-scale oil filter	Large-scale oil filter
Maximum pressure of the main oil channel	3.77 bar at 3200 rpm	3.94 bar at 3200 rpm
Pressure drop of oil cooler	0.86 bar at 3200 rpm	0.74 bar at 3200 rpm
Pressure drop of oil filter	0.21 bar at 200 rpm	0.11 bar at 200 rpm
PCJ front pressure	1.89413 bar at 1500 rpm	1.89454 bar at 1500 rpm
Maximum oil provided by oil pump	38.8 L/min at 3600 rpm	39.17 L/min at 3600
Flow rate of parts at 3200 rpm	Oil flow rate Oil pump: 34.2 L/min PCV: 3.21 L/min Main bearing: 13.58 L/min Large head connecting rod bearing: 6.15 L/min Cam shaft: 0.46 L/min PCJ: 8.52 L/min TC: 1.16 L/min Oil pump oil quantity: 0.326 L/min Air compressor oil quantity: 0.134 L/min	Oil flow rate oil pump: 34.2 L/min PCV: 2.6 L/min Main bearing: 13.8 L/min Large head connecting rod bearing: 6.25 L/min Cam shaft: 0.46 L/min PCJ: 8.75 L/min TC: 1.28 L/min Oil pump oil quantity: 0.332 L/min air compressor oil quantity: 0.134 L/min
Oil filter recommended maximum flow rate	30 L/min	40 L/min
Comparison of calculated flow rates and recommended limits	32.5>30 L/min (exceeds the recommended flow rate)	33.1<40 L/min (approved)

As follows from table 6, for the small-scale oil filter scheme, the maximum oil flow rate is 32.5 L/min (at 3600 rpm), which exceeds the flow rate margin of 30 L/min recommended by the producer.

This can lead to a dangerous situation with engine overheating, so the cooling ability needs to be experimentally verified. In case of the large-scale oil filter scheme, the maximum oil flow rate is 33.1 L/min (at 3600 rpm), which is less than the flow rate margin of 40 L/min recommended by the producer, and thus satisfies the design requirements. Therefore, the large-scale oil filter scheme should be finally adopted.

6.3.2. Comparison of calculated and experimental results. The comparison of calculated results with the available experimental data on the actual engine performance makes it possible to verify the applicability and accuracy of the simulations related to the oil pressure behavior in the main oil channel of BJ493ZLQ4A diesel engine. As seen from figure 23, the calculated and experimental results exhibit a very close correlation, which proves the applicability and efficiency of the elaborated lubrication system model.

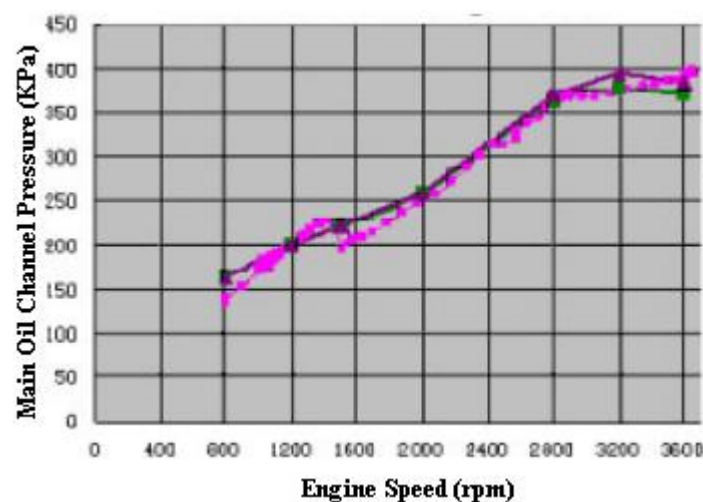


Figure 23. Comparison of the simulated and experimental results of the oil pressure in main oil channel: small-scale oil filter simulation (■), large-scale oil filter simulation (▲), experimental data (●).

Noteworthy is that the simulations involve input data obtained from different engines, so there might be some difference between the diesel engine actual condition and calculated one. During the computation process, the model can be refined and adjusted according to the accurate data on properties, e.g., of PCV or PCJ, which are provided by suppliers of diesel engine parts.

7. Conclusions

- Two simulation models of the 493ZLQ4A diesel lubrication system have been elaborated for the small- and large-scale oil filter and oil cooler schemes. The comparison of simulated and experimental results on oil pressure behavior of the main oil channel has revealed their good fit and confirmed the feasibility of the elaborated models.
- In the small-scale oil filter scheme, the main oil channel's pressure is somewhat lower than that of the design requirements, while the oil filter's maximum oil flow rate exceeds that recommended by the producer, which implies some risks in the application of this scheme. Therefore, the small-scale scheme cooling ability should be experimentally verified. In the large-scale oil filter scheme, the main oil channel inner oil pressure and the maximum oil flow rate fully satisfy the design requirements. In both schemes, the air compressor's front oil pressure exceeds the margin.
- Two geometric features were found to provide the excessive pressure drop between the oil pump outlet and the oil cooler inlet. It is proposed to increase the oil channel diameter in these

two points under the condition that the cylinder body structural integrity is not violated.

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