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DESIGN OF COOLANT AND LUBRICATION SYSTEM OF 3-CYLINDER COMPACT DIESEL ENGINE

GRADUATION PROJECT REPORT

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by

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ABSTRACT

In this Project, a full picture layout of a sophisticated lubrication and cooling system for a small 3-cylinder diesel engine is presented, with focus on the mechanical design methodology and manufacturing. Emphasizing design as opposed to simulation, the project utilizes fundamental engineering disciplines (e.g., fluid mechanics, thermodynamics, tribology) to engineer robust subsystem architectures suitable for next-generation engine performance and durability requirements.

The lubrication system has been designed for consistent and even distribution of oil, which is achieved with channels to the oil galleries, a piston cooler jet, and oil circulation under pressure to the passages when adjusted by the oil pressure regulator. At the same time, the cooling system was designed based on heat hotspot alleviation, with well-defined flow passages and built-in jacket configuration.

The system was designed 100% to fit in with the engine structure and manufacture limitations, and all parts had been accurately packaged, and an overall 3D CAD model produced.

This project demonstrates that through disciplined design-driven engineering, viable, efficient, and production-ready thermal management for tomorrow’s diesel engine can be developed.

ABBREVIATIONS

DPF	Diesel Particulate Filters
DKW	Dampf-Kraft-Wagen
DOHC	Double Overhead Cam
EU	Europe
EUP	Electronic Unit Pump
ECU	Engine Control Unit
GDI	Gasoline Direct Injection
GHG	Green House Gas
GT	Grand Tourers
HCCI	Homogeneous Charge Compression Ignition
HEV	Hybrid Electric Vehicle
IC	Internal Combustion
MPI	Multiport Injection
MAF	Measure Air Flow
MAP	Mass Air Pressure
MHT	Mild-Hybrid Technology
MPFI	Multi-Point Fuel Injection
MTREC	Multi Throttle Responsive Engine Control
RDE	Real Driving Emissions
NOX	Nitrogen Oxide
PM	Particulate Matter
PFI	Port Fuel Injection

PPS	Pre-Pilot Spray
RS	Ralli Sport
SCR	Selective Catalytic Reduction
SUV	Sport Utility Vehicle
SI	Spark Ignition
SPFI	Sequential Port Fuel Injection System
SPI	Single Point Injection
TBI	Throttle Body Injection
TDC	Top Dead Center
TDI	Turbocharged Direct Injection
UPS	Unit Pump System
US	United States
VAG	Volkswagen Automobile Group
VTG	Variable Turbo Geometry
VTEC	Variable Valve Timing and Lift Electronic Control System

1 Introduction

In modern diesel engine systems, high requirements are imposed on mechanical strength, economy, and lifetime, where all necessary subsystems, such as lubrication and cooling, need to be well designed and well-coordinated. These mechanisms are required for the reduction of internal friction, the diminishment of thermal stress, and the management of engine operation under a variety of operating conditions. Operating without sufficient lubrication, friction between moving parts can lead to excessive wear and tear, wasted fuel, lower mileage, and higher maintenance expenses. Similarly, an inadequately operating cooling system will result in surpassing the temperature threshold, causing thermal degradation and ultimate failure of the component.

This paper contains a complete engineering design of a combined lubrication and cooling system for a small three-cylinder vertical diesel engine, with all its auxiliaries, developed upon sound analytical and mechanical principles. CFD or FEA computer simulations were not used, and systems were designed by manual calculations for flow rate, pressure loss, temperature distribution, and geometrical restrictions while an existing diesel engine model description was used as a base. The objective was to develop subsystems to meet the thermal and mechanical needs of the engine, and to function and be manufacturable.

The lubricating system is designed to provide a continual flow of oil to key components of the engine, namely the crankshaft, camshaft, and pistons. Critical numerical parameters, such as the viscosity of the oil, the diameter of the channel, the flow and capacity of the pumping and the return geometry, were calculated by means of engineering formulae. It was also redesigned to provide super-efficient oil channels, a gravity return with dual return lines and filter pockets for outstanding performance and reliability.

The cooling system was designed at the same time, based on a thermal load analysis, the required coolant flow volume, and a set temperature control target. The vehicle definition, both vessel side and starboard side in the cylinder block flow passage of the design reboot process, accounted for more simulation output. Coolant passage sizes, radiator efficiencies, and pump capacities were determined and adjusted as required to the current engine geometry. More sophisticated enhancement cooling technologies, i.e., multi-zone coolant path for coolant routing and design phase optimization of the water jacket layout to ensure better heat extraction and lower out-of-plane temperature gradients, were adopted.

The literature, engineering standards, and design factors were used as a basis for this work. The thermally conductive materials and wear parts were combined as one in order to enhance cooling and wearing resistance.

To summarize, in this paper, a full lubrication and cooling system design based on first principles has been developed and implemented in a pre-existing three-cylinder diesel engine model. The exercise constitutes a sample case for the application of conventional engineering methods to progress higher density and lower-cost engine concepts without the need for computation simulation.

2 Internal Combustion Engines

"A motor is a device that converts one form of energy into another form of energy. However, the conversion efficiency plays an important role during the transformation from one form of energy to another. Generally, most engines convert thermal energy into mechanical work and are therefore referred to as 'heat engines.' Generally, most engines convert heat energy into mechanical work and are therefore called 'heat engines.'" (1)

"The internal combustion engine (ICE) is a heat engine that converts the chemical energy of a fuel into mechanical energy. This mechanical energy is usually provided in a rotating drive shaft. The chemical energy of the fuel is initially converted into thermal energy in the engine through combustion or oxidation with air. This thermal energy increases the temperature and pressure of the gases in the engine, and the high-pressure gas then expands, doing work against the mechanical parts of the engine. This thermal energy increases the temperature and pressure of the gases inside the engine, and the high-pressure gas then expands, doing work against the engine's mechanical components." (2)

2.1 Engine Parts

A 3-cylinder common rail diesel engine is created to achieve perfect harmony between power, efficiency, and compactness. The design of this engine has a multi-discipline systems, such as mechanical and electronic, that are implemented to cooperate to meet its reliable operating under both these loads as well as operating conditions. Understanding the performance of each of these subsystems is very important to comprehend the overall performance of the engine. The following sections examine the elements constituting the engine in detail, showing how each operates, the materials utilized, principles of operation, and how these features contribute to the performance and longevity of the engine.

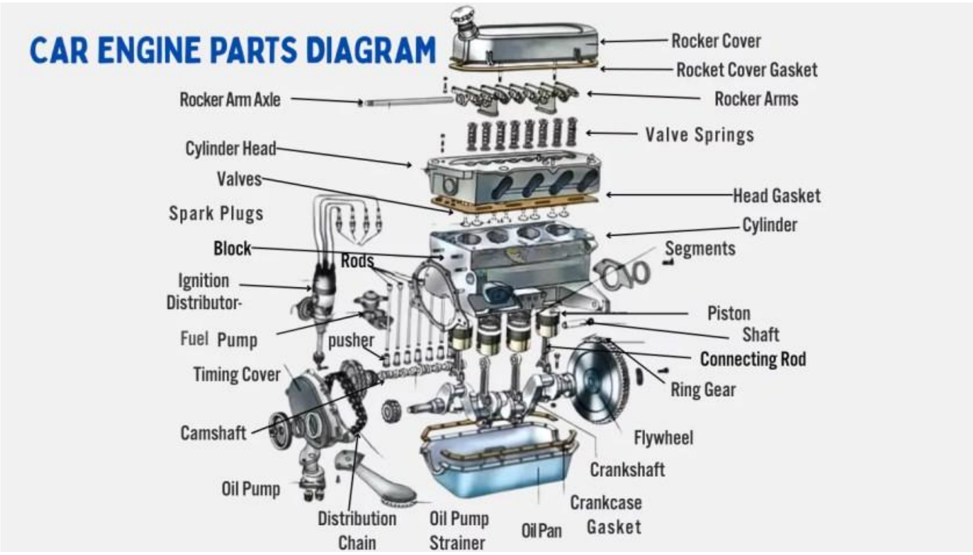


Figure 1 Engine Parts Diagram (3)

2.1.1 Cylinder Block

The cylinder block is the main bearing bulk of an engine. 3. Block The block of the engine is the foundry product, which houses the cylinders, water jacket, and oil passages. Cast iron for strength and rigidity, and aluminum for resistance to corrosion and light weight, are the most common materials. The cylinder head faces are machined to provide optimal compression and reduce friction. The block also needs bore holes for accessories and those must be able to be drilled and the block must have enough rigidity for bore holes to not distort under the high pressures diesel combustion can generate.

2.1.2 Cylinder Head

The cylinder head, positioned above the cylinder block, functions to seal the combustion chamber and contains essential elements like intake and exhaust ports, valves, and fuel injectors. Given its operation under high temperatures and pressures, it is commonly constructed from heat-resistant materials such as cast iron or premium aluminium. Contemporary designs of cylinder heads often incorporate integrated cooling channels to facilitate efficient heat dissipation and are frequently designed with overhead camshafts (OHC) to guarantee accurate valve timing.

2.1.3 Piston Assembly

Piston assembly; It consists of the pistons, rings, and connecting rod. This component converts the compression force of combustion into kinetic energy. Pistons, with strength and light weight as two primary considerations, are normally made of forged aluminium or steel. The tops of pistons are shaped to improve combustion efficiency. Piston rings serve a number of purposes: they ensure the sealing of the combustion chamber, prevent blow-by, and control oil consumption. The connecting rods, most of which are made out of forged steel, link pistons to the crankshaft and must be strong in compression.

2.1.4 Crankshaft

There is a crank which transmits motion to the transmission mechanism by converting the linear up-and-down movement of the pistons to rotation. It is usually engineered of high-strength steel or iron cast to avoid high impacts. To offset the vibrations inherent with a 3-cylinder engine layout, counterweights are incorporated in the crankshaft, and the shaft is balanced literally. The bearing surfaces (pins) have been polished and machined to minimize friction and maximize continuous oil flow to the lubrication system.

2.1.5 Camshaft

This is the camshaft that operates the intake and exhaust valves of the engine so that they open and close at the proper moment. In OHV (overhead valve) pushrod systems, the camshaft is placed inside the cylinder block, and directly above the camshaft is the pushrod system, driven by the crankshaft. Every cam is highly engineered to provide the optimum balance of lift and duration and is some shape – and the cost – to open and close intake and exhaust valves at very specific points, or "timing." Contemporary engines also comprise variable valve timing (VVT) mechanisms that are timed with the camshaft to optimize engine power during different speed and load conditions

2.1.6 Fuel Injection System

For diesel injection, high-pressure common-rail injection is usually favored. This unit injects fuel directly into the combustion chamber with a pressure of more than 2000 bar. Its construction comprises a high-pressure pump, a fuel rail, and electronically controlled injectors. This results in very accurate regulation of the injection quantity, timing, and spray pattern. With advances in injector technology, it has become possible to implement multiple injections per cycle. This enhances the quality of the combustion process and lowers engine noise while also greatly reducing smoke emissions.

2.1.7 Turbocharger

A turbocharger serves as an added supplement of the engine and provides the engine with more oxygen in order to increase the power in the engine. It is made up of an exhaust-driven turbine and a compressor which compresses and pressurizes the air that enters the intake. VGT (Variable Geometry Turbo) systems are used in present engines of 3 cylinders. These are systems that regulate the exhaust gas flow as a function of the engine speed and optimize performance at each engine speed band. This boosts low-down torque, cuts turbo lag, and increases fuel economy.

2.1.8 Exhaust System

The exhaust system not only extracts the gases produced during the internal combustion process, but also helps to minimize any potential pollution that results. This system is composed of parts like the exhaust manifold, catalytic converter, diesel particulate filter (DPF), and usually also a selective catalytic reduction (SCR) unit. From the cylinders, the exhaust gas is passed through the first section of the exhaust manifold to the turbocharger, and then on to the emission control units. These components assist in eliminating detrimental emissions, such as nitrogen oxides (NOx) and carbon, thus ensuring that the engine meets strict environmental standards. The system's sensors monitor and control in real time the flow of gases and emissions from the tailpipe.

2.1.9 Exhaust Manifold

The exhaust manifold also has the job of collecting the exhaust gases produced by each cylinder and releasing them through the turbocharger (if fitted) before passing them to another part of the exhaust system. Whether running a turbo or normally aspirated, the manifold is key to efficient transfer of exhaust energy to improve charge energy going into the engine. The arm is usually constructed of a heat-resistant material that can withstand high temperatures, such as cast iron or heat-resistant alloys, to which the pipe is welded or releasably clamped. Its construction is designed to offer optimal airflow by decreasing backpressure and by doing so results in the boost of engine performance.

2.1.10 Intake System

The air intake system has a vital role to perform, by delivering clean, steady airflow to the engine cylinders.

Diesel engines do not mix air and fuel in the intake manifold like gasoline engines but instead inject it directly into the combustion chamber. The system often includes a turbocharger and intercooler to increase air density and thereby combustion efficiency.

Today's intake systems are often fitted with valves that induce swirl and tumble effects. These cause the air-fuel mixture to become even more efficient, thereby improving engine performance. In addition, the Exhaust Gas Recirculation (EGR) system puts some of the exhaust gas back into the intake in order to reduce nitrogen oxide (NOx) emissions. However, the air-intake system must be designed to allow optimal performance, and it periodically needs maintenance.

The primary function of an intake manifold is to provide even distribution to each cylinder of incoming air. After the air leaves the turbocharger and intercooler, it goes to the manifold — a system that ensures proper, unbroken flow. Some designs employ swirl and tumble valves for more complete internal mixing. While the EGR system helps to bring down NOx levels ('nitrogen oxides'), it has an added disadvantage in that the intake manifold will eventually fill up with carbon deposits and at that point is in need of thorough cleaning. Both effective design and regular maintenance are crucial to intake performance.

2.2 Spark-Ignition (SI) Engines

Spark-ignition (SI) engines are also called gasoline engines and operate according to the Otto cycle. This cycle consists of four main strokes:

1. Intake stroke – The intake valve opens and the air-fuel mixture is drawn into the cylinder.
2. Compression stroke – The piston moves upward, compressing the air-fuel mixture; this increases the temperature and pressure of the mixture.
3. Exhaust stroke (power generation) – The spark generated by the spark plug ignites the mixture. The resulting explosion moves the piston downward, generating mechanical energy.
4. Exhaust stroke – The exhaust valve opens and the burned gases are expelled from the cylinder.

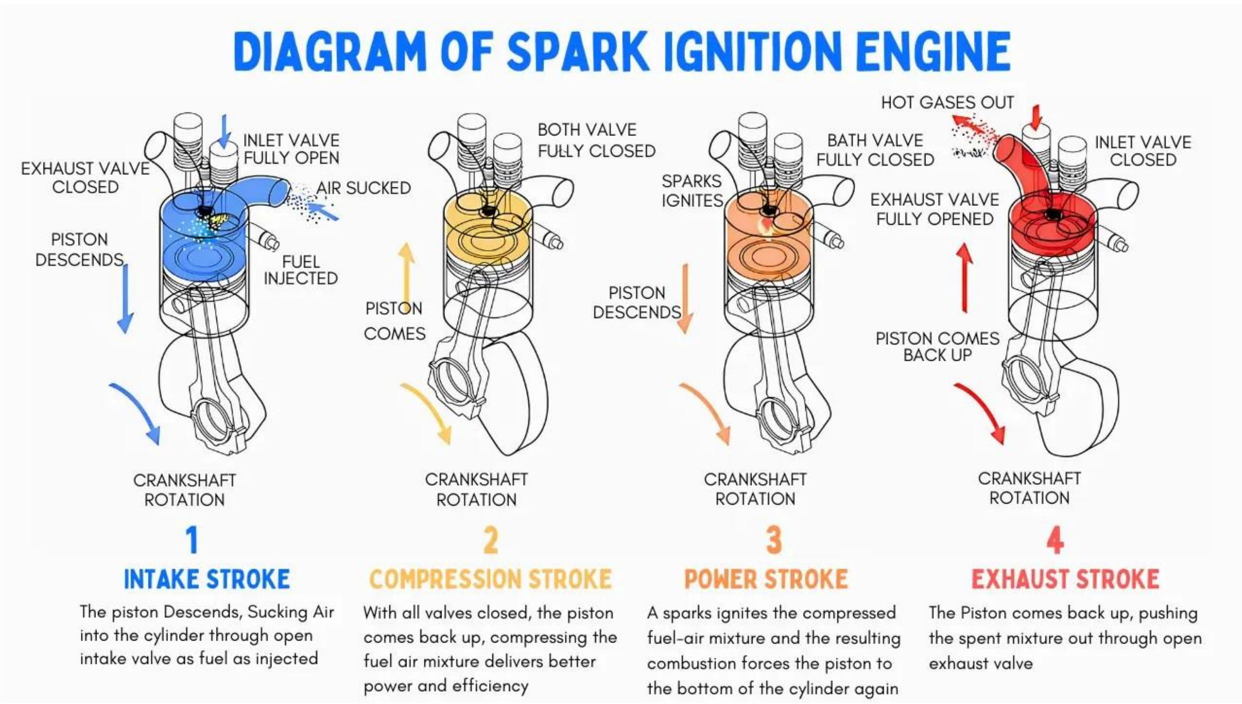


Figure 2 Four Stroke Spark Ignition Engine (4)

Spark-ignition engines function with a low compression ratio, usually between 8:1 and 12:1. This may lead to thermal efficiency that is comparably lower than that of diesels; on the other hand, such ratios make gasoline engines lighter and easier to manufacture.

In old systems, carburettors supply fuel to the combustion chamber; in new systems, fuel injectors do so. Even though these engines have lower torque at low rpm, their high maximum speed is well-suited to vehicles requiring strong acceleration. It is always necessary to use high-octane gasoline to prevent engine knock.

The simple designs, smooth operation, and compact sizes of gasoline engines make them a popular choice for passenger cars, motorcycles, and small tools such as lawn mowers.

2.3 Combustion-Ignition (CI) Engines

Rudolf Diesel has been an important figure in mechanical engineering ever since he invented the engine in the late 19th century. He patented this engine in 1893.

Diesel engines were designed to be much more efficient than steam engines thanks to the principle of igniting fuel through high pressure rather than a spark plug. In response, this concept has pioneered the development of engines that save fuel and have longer service life; therefore, diesel engines are increasingly used in many industries today.

Compressing air at high pressure and temperature, diesel engines then inject fuel into the cylinder where it burns. This principle differs from those of engines that need a spark plug to ignite the fuel. Diesel engines produce more torque with less fuel. This makes them ideal for use in high-load, long-endurance applications—cruise ships and trucks, construction equipment, and power plants are typical examples where diesel engines find wide use.

Today's diesel engines represent a vast improvement in comparison with older models. They are more powerful, use less fuel, and give a lower level of environmental damage. New technologies including turbochargers, common rail injection systems, as well as SCR (Selective Catalytic Reduction) systems for reducing exhaust emissions make a significant contribution to preserving the environment from potential harm. In addition, diesel engines have been specially designed to meet today's stringent emission limits with features like particulate filters and EGR (Exhaust Gas Recirculation) systems.

2.3.1 Working Principle of CI Engine

Diesel engines, also known as compression-ignition engines, function in accordance with the diesel cycle. In this case, the fuel is ignited automatically by the heat of the compressed air, which is highly compressed in the cylinder.

The combustion process consists of four strokes. The first is the intake stroke, which only pulls air into the cylinder. The second is the compression stroke, during which the air is compressed to a pressure of approximately 15:1 to 22:1, and its temperature increases significantly. During the next combustion period, the fuel ignites and moves the piston in the opposite direction. During the exhaust stroke, the gases that are composed are released.

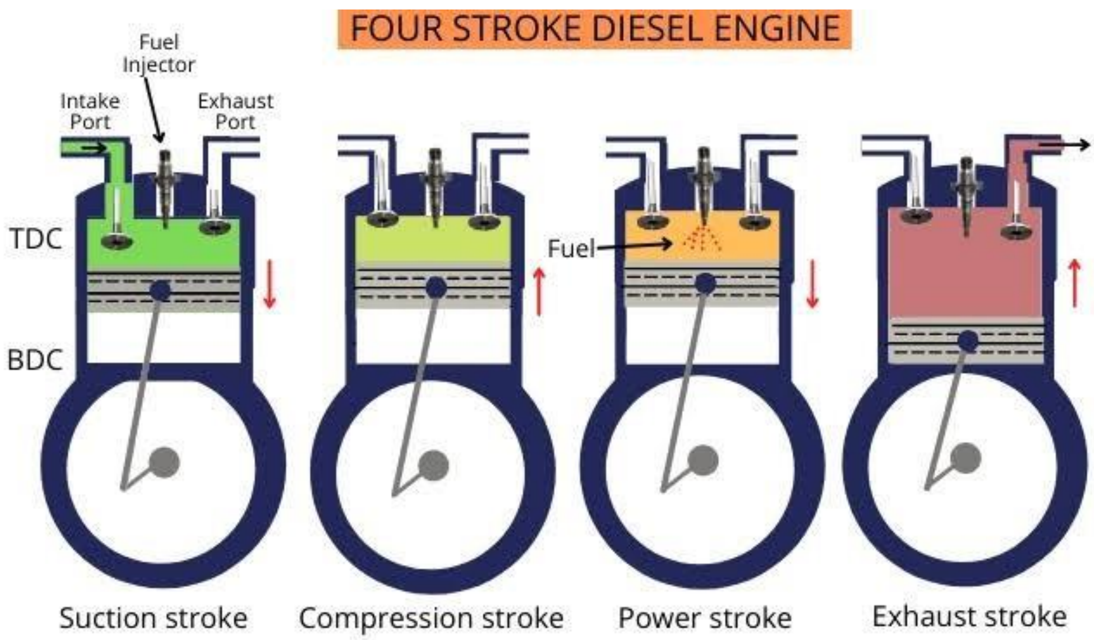


Figure 3 Four Stroke Compression Ignition Engine (5)

The high compression ratios at which diesel engines operate enable them to be more thermally efficient than gasoline engines. Fuel injection is achieved by the use of a direct injection or indirect injection engine system. Diesel engines are more efficient in heavy-duty applications as they can generate much torque at low speeds. However, they are associated with more output of air pollutant gases such as NOx and other emissions particularly. Thus, diesel engine combustion is common in power systems, transportation systems, ships, generators, and other continuous energy uses.

Diesel engines have experienced tremendous growth in recent years since the entire technology has been transformed. Various technologies such as enhanced turbocharging, common rail combustion, EGR, and injection systems have improved engine performance and reduced pollution gas emissions. Diesel particulate filters have captured most of the actual emitted soot particles. This makes diesel engines and alternative machinery competitive despite the increasing global emission standards.

2.4 3-Cylinder CI Engine

To sum up, based on a complete analysis of a 3-cylinder diesel engine, we can have the following:

This class of engine is a recent development that, for its relatively low dimensions, has high levels of effectiveness and strength. This replaces the traditional 3- or 4-cylinder engine, which has fewer moving parts resulting in lower friction, lighter weight, and it requires less service.

These motors are designed for cars and apparatus which require power of an intermediate character and in which the question of economy, compactness, or long life are significant factors to be considered.

The four basic steps of diesel combustion are: induction, compression, power, and exhaust.

- On the intake stroke, the air is sucked into the cylinder.
- The piston, during its compression stroke, compresses this air to high pressure and temperature.

Fuel is injected into the hot compressed air and ignites within the cylinder, eliminating the need for a spark plug. It provides very high thermal efficiency, and is one of the reasons why diesel engines often have better fuel efficiency than spark-ignited engines.

Compact in design and delivering high torque at low speeds, 3-cylinder diesel engines are popular in light commercial vehicles, agricultural and small construction plant, and even in hybrid drive systems. They are solid slide-ring constructed, so not only will they save you fuel, but you'll have them a long, long time.

Compared with single-cylinder engines, 3-cylinder saves much of fuel. Single-cylinder engines get run more often in small hand tools and entry-level machines where disgusting amounts of vibration and total suckage under the 'full load' condition are both cop-outs. Although twin models have done much to vindicate it on the positive side, they are still far from having it bettered so far as balanced and smooth running are concerned, for which purposes they require fairly complex balancing arrangements.

3-cylinder engines are available with larger 4-cylinder engines and get better fuel economy in a simpler and lighter package. For this, there may be marginally reduced power and a bit less smooth running. But by contrast, V6s are powerful and generally easy to drive, but they're heavy, complex thirst buckets.

For this reason, 3-cylinder diesel engines appear to offer a good compromise: more stable than single-cylinder or 2-cylinder plants, and more efficient and compact than even more ancient 4-cylinder plants.

In these modern times with turbocharging, common-rail direct injection (CRDI), and electronic fuel management, performance 3-cylinders have come a long way to where it matches or even exceeds that of old-style 4-cylinder engines.

2.4.1 Main Characteristics of 3-Cylinder CI Engine

Three-cylinder diesel engines are common in modern engineering, backed with small size, high fuel economy, and minimum emission. These engines are ideal for light commercial vehicles, portable generator sets, small construction equipment, and wherever other space and performance considerations are required.

Such motors can produce high torque even at low velocity and are normally low vibration devices, which is advantageous to many industries. In addition, their weight also provides improved vehicle dynamics and reduced manufacturing costs.

The development of lubricant cooling systems for a compact three-cylinder diesel power unit requires a diverse application of engineering. The developments of these systems involve a combination of sciences, such as thermodynamics, fluid mechanics, tribology, and materials science. Thermodynamics can tell you how heat occurs and transfers to the entirety of the engine when it's running, whereas fluid mechanics explains how lubrication and cooling fluids move inside passageways and how the pressure on these fluids is maintained.

Tribology (the science of friction, lubrication, and wear) plays an important role when choosing the appropriate type of lubricant, as well as designing surfaces that are resistant to mechanical damage. Materials science also contributes to further advancements by determining which metals and composites can withstand high temperatures, pressure, and chemical exposure.

By properly caring for the friction generated in an engine between the moving parts—such as pistons, bearings, and camshafts—a well-engineered lubrication system will avoid energy waste. The constant oil film could prevent the surface from wear and tear, which gives support to engine efficiency to avoid the loss of performance.

At the same time, the cooling system has the added burden of dealing with the high temperatures generated by diesel combustion. Lack of effective heat dissipation will make the heat stressed and even deformed, cracked or the engine will be finally broken. This becomes even more crucial in compact engines where surface areas are reduced, and the heat is built faster.

In the current engineering procedure, these systems are not designed by hand calculations or experience-based methods at all. Rather, sophisticated computational methods, including Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) are employed to predict fluid mechanics, thermal duty, as well as mechanical integrity, under actual operating conditions. These digital applications help engineers optimize oil and cooling passages, optimize temperature distribution, and minimize pressure losses – which can make an engine more robust and efficient.

And, it is necessary to combine the scientific principle with the SIM technology while designing the three-cylinder diesel engine reliable lubrication and cooling system. This strategy clearly promotes the long-term performance of the engine, saves maintenance, and takes the environment-friendly improvement into account since it leads to less energy waste and a sustainable system.

2.4.2 Major Components and Their Functions of 3-Cylinder CI Engine

2.4.2.1 Cylinder Block

The engine is based on the cylinder block. It structurally braces and interconnects all the major mechanical assemblies. Inside the block, you'll find the cylinders, where combustion takes place, as well as oil passages and coolant channels that regulate lubrication and temperature.

- Material: It's usually made of long-lasting cast iron, or lightweight aluminum alloys are used to improve heat dissipation.
- Precision Boring: Cylinders need to be bored to ultra-tight tolerances to minimize friction and allow for proper compression.
- Oil and Coolant Channels: These are internal passages through which oil can be passed so as to lubricate moving parts of the engine, and coolant can be directed to assist in regulating high combustion temperatures.

2.4.2.2 Cylinder Head

The cylinder head seals the top of the combustion chamber, which is the edge under high pressure, as well as of the passages for the inlet and outlet of the intake and exhaust valves, and may include ports for the inlet and outlet of the fuel injectors and sometimes the thermostats and expansion plugs. This part is an important part of the engine air management and fuel system.

- Valves: Regulate the flow of air in and out of the cylinders. The crucial role of timing for efficient combustion.

- Injectors: Inject diesel fuel into the highly compressed hot air, in exactly the right amounts, resulting in rapid and complete combustion.
- Cooling Passages Incorporated into the head to prevent hot spots and thermal shock.

2.4.2.3 Piston Assembly

The piston is the component in the engine that moves to transfer the force from combustion to the crankshaft gain via the connecting rod. This assembly includes:

- Piston: Moves up and down inside the cylinder, compressing air and capturing the power of combustion.
- Piston Rings: Seals the gap between piston and cylinder wall to prevent combustion gas passage (blow-by) and control oil film.
- Wrist Pin: A pin that acts as a bearing between the piston and connecting rod.

The combustion efficiency is improved with a proper design of the piston crown to promote the synergistic turbulence, to improve air/fuel mixture.

2.4.2.4 Crankshaft and Bearings

The crankshaft's job is to translate the up-and-down movement of the pistons into rotational motion. It is constantly under stress and must be accurately balanced to not vibrate, especially in 3-cylinder applications, which can have uneven firing.

- Main Bearings: Support the crankshaft in the block and enable it to spin freely
- Rod Bearings: The links between the crankshaft and each piston by fitting into the connecting rods.
- Counterweights and Harmonic Balancer: Dissipates disturbances and provides good performance of the engine

2.4.2.5 Lubrication System

The lubricating system allows all moving parts of the engine to be lubricated so that friction won't wear them away. It's a closed-loop system that continuously circulates and filters oil during engine operation.

- Oil Pump: In the oil from the sump it circulates under pressure through passes.
- Oil Filter: Collects metal particles, dirt, and contaminants, preventing them from getting into the oil.
- Oil Jets and Passages: Direct oil to areas of friction such as the pistons, bearings, and cam lobes.

  Should lubrication fail, damage to the engine can happen quickly. For this reason, modern systems have sensors connected to the ECU that check oil quality and pressure.

2.4.2.6 Cooling System

The high compression ratios of diesel engines mean they produce lots of heat. The cooling effect is very important to avoid overheating and thermal deformation.

- Radiator: A component that removes heat from liquid by blowing air through it.
- Water Pump: Circulates the coolant between the engine and the radiator.
- Thermostat: Determines when coolant should begin to flow in response to engine temperature.

In certain configurations, oil and intercooling (turbocharged) heat exchangers, are also added to the function.

The 3-cylinder diesel motor is a good balance between power and frugality. By having fewer parts, it may be made less expensively and require less maintenance, and its state-of-the-art fuel systems and air management systems enable the engine to meet emissions standards of today. With advancements like common rail injection, VGTs and electronic engine management, these powerplants have been taken to new heights of power and smoothness, not only for industrial and agricultural use, but also to drive cars, modern cars and even hybrid systems..

2.4.3 Characteristics of Lubrication System of 3-Cylinder CI Engine

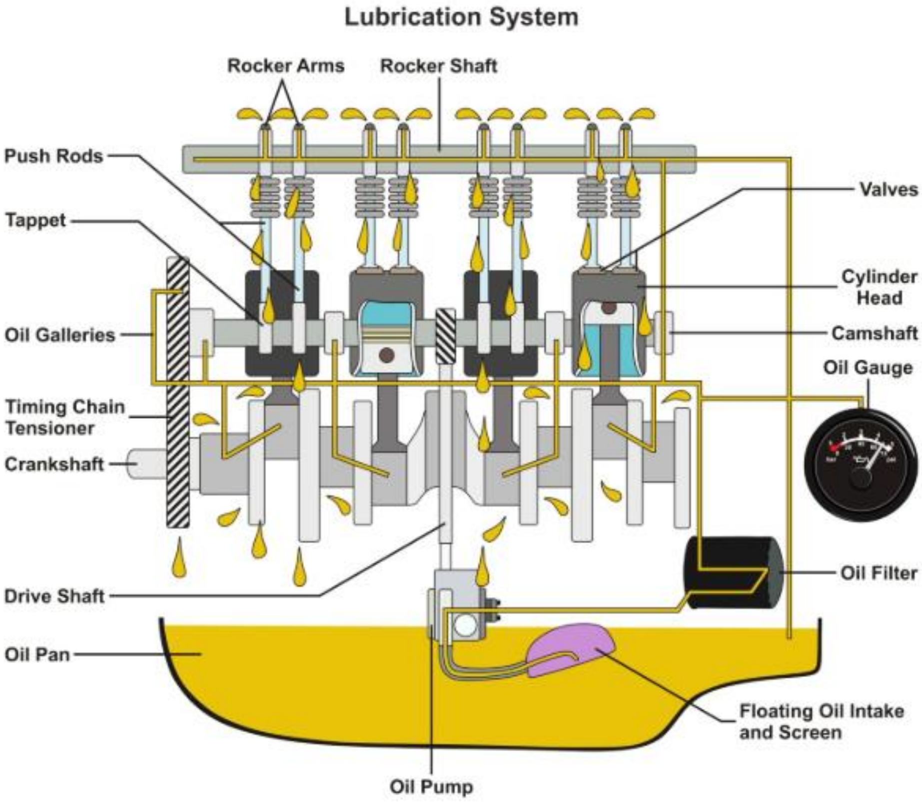


Figure 4 Basic Lubrication System of Diesel Engine (6)

The lubrication system of a 3-cylinder CI engine is an essential subsystem responsible for reducing friction, regulating the components' temperature, and preventing premature wear between the overall components of an engine. As a result of the high-pressure combustion characteristic of a diesel engine and the normal imbalance of the 3-cylinder design, this system must be very efficient, compact, and able to maintain steady performance over wide-ranging thermal mechanical load variations.

Its lubrication system is not as simple as the splash system in low power engines. A full pressure (force-fed) lubrication system is used in the majority of modern 3-cylinder CI engines. In that system, an oil pump (normally of gear- or trochoid-type) is driven mechanically from the base of the engine (the engine's oil sump) and draws oil up into an array of oil galleries, from which the oil is distributed to the appropriate components. These internal passages supply oil to critical friction surfaces, such as main and connecting rod bearings, cam journals, valvetrain parts, and timing chain devices.

One of the system's components to be considered are the piston cooling oil jets. Pressurized oil is fed to the bottom side of pistons through the nozzles. Diesel engines, in particular, are notorious for having extremely hot piston crowns as a result of high compression ratios and relatively long combustion events. The oil jet serves the purpose of cooling the piston and providing some film strength between the piston rings and the cylinder liner.

Another point of importance is filtration. The system has a full-flow oil filter that removes particulates, for example, metal particles, soot particles, and oxidized oil compounds. What is important here is to avoid faster wear and blockage of small oil passages or hydraulic lifters. Some are equipped with a by-pass valve to open if the filter is clogged.

In order to regulate oil flow and heat, some engines are equipped with a pressure relief valve and, when necessary, an oil cooler. The PRV helps keep oil pressure in check, as it recycles any overage in oil pressure back to the sump when pressures exceed a programmed threshold. An air-cooled or a coolant-cooled oil cooler may be included for thermal management of the oil, particularly under high load, high RPM operation.

As 3-cylinder CI engines are generally used in limited cooling air blowing environments, oil viscosity and oxidative stability become increasingly important. Multigrade oils (such as 10W-40 or 15W-40) are chosen to provide adequate flow at low temperatures while not breaking down under high temperatures.Newer generation setups incorporate oil pressure and oil temperature monitoring sensors which constantly relay up-to-date information back to the ECU. The ECU can react to deviations in lubrication (such as low pressure) by adjusting engine performance parameters or issuing warning signals to prevent catastrophic engine failures.

Furthermore, in BALANCE SHAFT engines that are used to cancel out the secondary vibration from the 3-cylinder, the rotating component flow, such as a rotor that is rotated inside this first stage, is required to be continuously provided with oil. Any breakdown in the supply of oil will result in extra vibration, noise, and even mechanical failure.

In a nutshell, the 3-cylinder CI engine lubrication system forms a highly sophisticated system, comprising an intricate network of pressured oil supply, selective cooling profiles (particularly piston under-crown cooling), improved filtration system, thermal control, and electronic monitoring. It needs to operate dependably through various stages of operation, from cold start to high load, and is critical for longevity, efficiency, and performance of the engine.

2.4.4 Characteristics of Cooling System of 3-Cylinder CI Engine

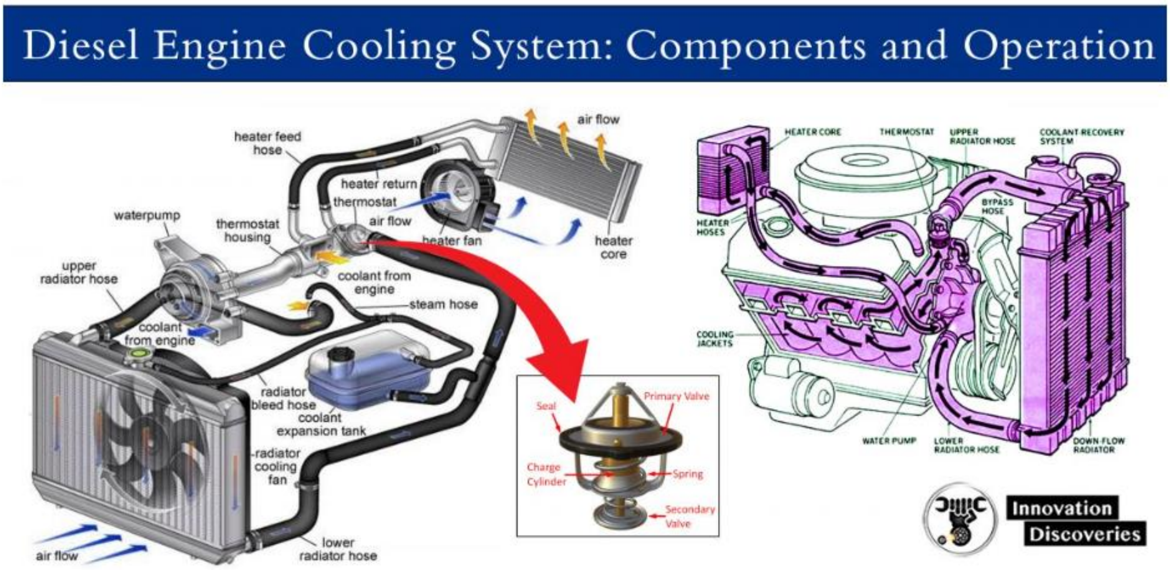


Figure 5 The Basic Cooling System of Diesel Engine (7)

The cooling system of a 3-cylinder CI engine is an important sub-system since its role is to prevent heat, an unavoidable by-product of combustion, from exceeding safe and efficient engine temperatures. Diesel engines commonly operate at high compression ratios and high internal pressures, resulting in increased thermal loads around the combustion chamber, exhaust ports, cylinder head, and piston crown. In small format engine configurations like a 3-cylinder block where surface area is scarce, a well-thought-out system to keep those hot spots cool is necessary to prevent localized overheating and to maintain the integrity of the engine materials.

In this paper, the full design of a closed-loop liquid cooling system is presented that can be attached to an actual 3-cylinder diesel engine. The system is similar to others in the industry and includes, for example, a mechanically driven pump, a radiator, a thermostat, a coolant reservoir, and cast-in cooling jackets located within the cylinder block and cylinder head.

Designing was based purely on analytical methods and geometric fit within the existing engine, not CFD.

The cooling jackets were sized to remove the correct amount of heat from thermally sensitive areas such as valve seats, injector bosses, cylinder walls, and from the upper piston region. Calculations to find the pump capacity and jacket cross-sectional area were made based on flow rate and pressure drop. The design of the coolant passages ensured that the flow of water was evenly distributed among all cylinders to prevent possible hot spots that would cause premature gasket failure or structural fatigue.

Also added was a thermostat-controlled flow device for controlling coolant flow according to temperature. On start-up of the engine, the coolant warm-up cycle begins even though the thermostat is closed. Opening the radiator will keep the coolant flow high. This will circulate the coolant through the engine block and heater core, making sure that the coolant reaches the thermostat without air being trapped. At the setpoint temperature, the thermostat opens, allowing coolant to flow through the radiator and heat to be released to the air by convection.

Material compatibility and thermal conductivity were also taken into account in the design phase. The current engine architecture, using mainly aluminum alloy components, ensures efficient heat release. The cooling lines were also carefully arranged to eliminate sharp bends and high resistance to flow, such that there is reliable flow without the need for complex control electronics or sensors.

The end result is a system that doesn’t need any extra frills like oil coolers, electronically controlled valves, or ECU-controlled fans, which falls right into line with the “Keep it simple, keep it real” nature of the engine’s use. In this way, there is no need for electronic control for the system and the driver, and passive control is feasible, so that the valve actuator can appropriately be applied to a light-duty diesel engine apparatus used for a cost-oriented application.

The cooling system we developed is, in conclusion, robust from the thermal point of view and simple constructionally for 3-cylinder Diesel engines. Coupled engineered geometry and thermodynamic calculations ensure replicable temperature control without the expense or complexity of sophisticated electronic control or simulation-driven optimization. This allows for a long-life, good performance, manufacturable design in small engine packages.Advanced Cooling Technologies

Modern diesel engines face increasing demands for efficiency, emissions control, and performance. To meet these challenges, advanced cooling technologies have been developed to optimize thermal management. These innovations include electronically controlled water pumps, thermostatic valves with bypass circuits, nanofluid coolants, and segmented cooling systems.

2.4.4.1 Electronically Regulated Water Pumps

Conventional mechanical water pumps are of constant speed and are inefficient at different engine loads. Water pumps on electronic control enable the flow of coolant according to real-time parameters of heat engendered by the engine. Advantages: • Variable Flow Control: Regulates flow of coolant to meet cooling requirements of the engine.

Advantages:

- Variable Flow Control: Regulates flow of coolant to meet cooling requirements of the engine.
- Energy Efficiency: Eliminates parasitic losses as power is only generated when required.
- Improved Warm-Up: Faster engine warm-up is possible by reducing coolant flow during warm-up phase.

Technical Description: Flow rate of the pump, Q, can be adjusted through PWM. The adjustment may change the flow rate in steps as small as 0.1%

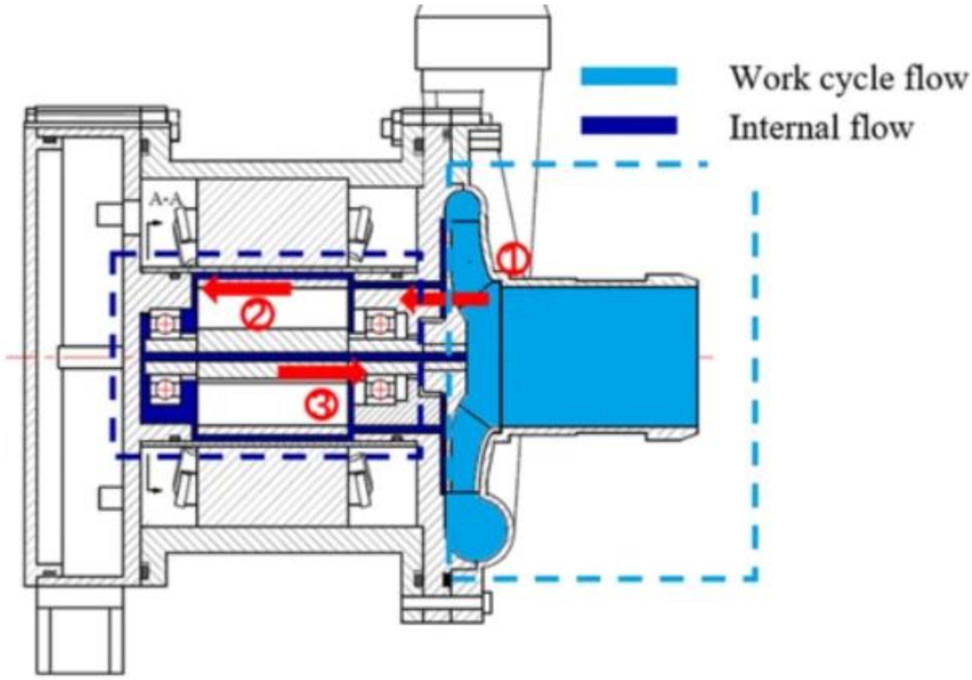


Figure 6 Operating principle of an electronic water pump used in automobiles (8)

Figure 6 Electronically controlled water pump (8)

2.4.4.2 Thermostatic Valves and Bypass Circuits

Thermostatic valves control the flow of coolant depending on its temperature (thus the engine's), letting the engine run with an ideal temperature. Bypass circuits also permit coolant flow through the block at cold starts, to speed the engine warm-up.

Advantages:

• Cooling Control: Keep your engine at the perfect temperature.

• Emissions Reduced: Faster warm-up cuts cold start emissions.

• Engine Safeguard: It will avoid the engine from overheating by redirecting the flow of coolant.

Tech Notes: Coolant temperature sensitive, it opens or closes at a set coolant temp, has a wax element in the housing to expand and contract at preset temps to change flow paths.

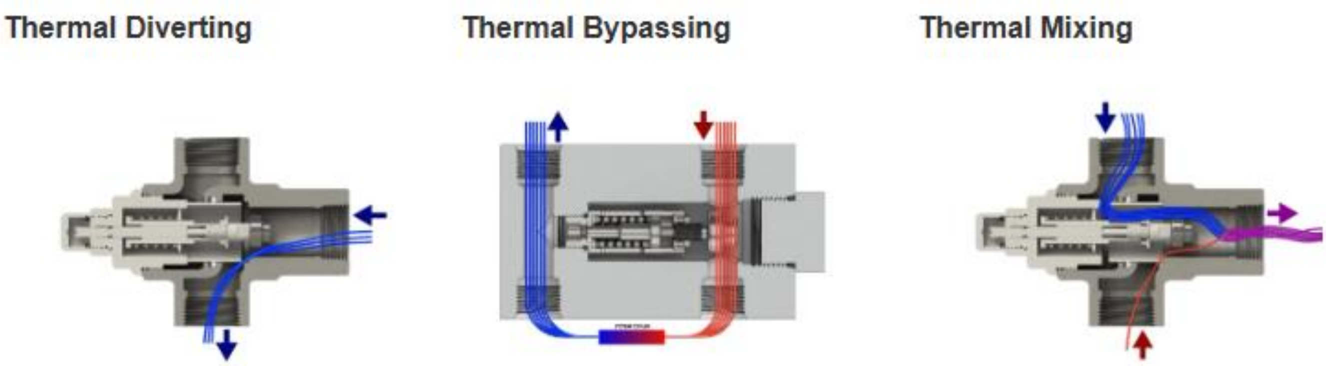


Figure 7 Thermostatic valve with integrated bypass circuit (9)

2.4.4.3 Nanofluids

Nanofluids are formulated by dispersing nanoparticles (e.g., Al_2O_3, CuO) throughout a base fluid such as water or ethylene glycol and are designed to provide improved thermal conductivity and heat transfer.

Advantages:

- Enhanced Thermal Conductivity: They can enhance heat carrying capacity of the base fluid
- Improved Heat Transfer: The resultant benefit is greater engine cooling.
- Potential for Downsizing: Better cooling might mean smaller radiators and coolant passages

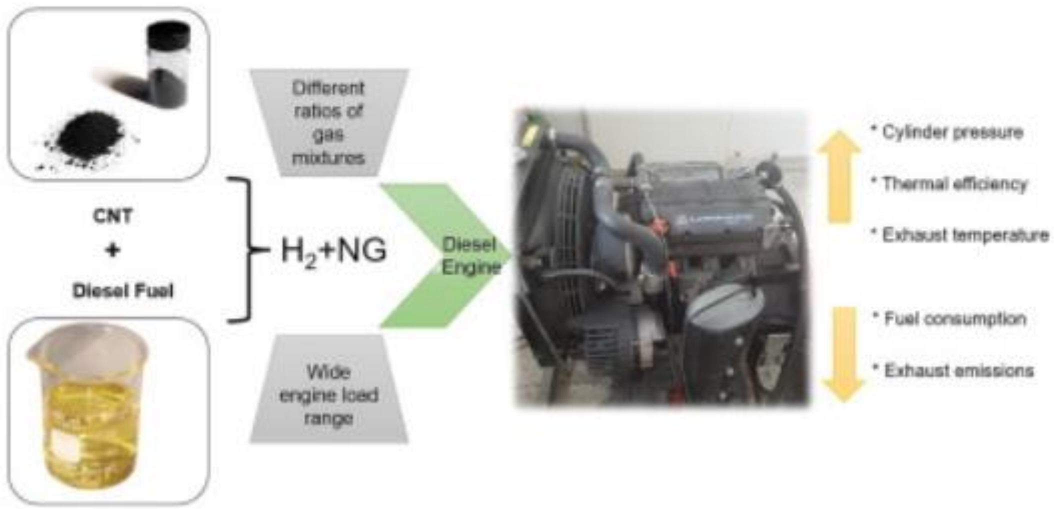


Figure 7 Nanofluid preparation (10)

2.4.4.4 Segmented Cooling

Distributed cooling, on the other hand, calls out the independent control of the cooling of separate sections of the engine, say, combining the cylinder head and block cooling so that the cycle has optimal thermal management.

Advantages:

- Focused Cooling: Targets thermal loads in various areas of the engine.
- Improved Efficiency: Keeps engine parts optimally conditioned.
- Enhanced Durability: Lower thermal stresses and reduced risk of component failures.

Technical Insight: With different cooling circuits, engineers can optimize the flow and temperature of the coolant throughout the engine sections, for better overall thermal balance.

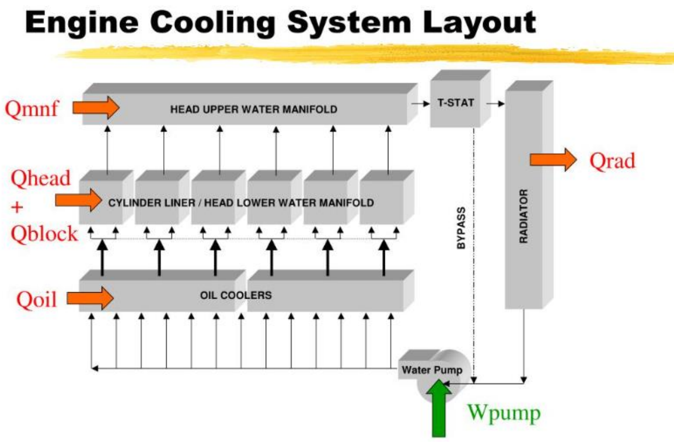


Figure 8 Engine Cooling System Layout (11)

2.5 3-Cylinder CI Engine Models

2.5.1 Ford Eco Boost

Figure 9 Ford EcoBlue 1.5L 3-cylinder Diesel Engine (12)

The 1.5L 3-cylinder Ford's advanced EcoBlue diesel engine is a core part of the company's urban diesel strategy, which provides commercial and passenger vehicle customers with greater power of choice to find the right fuel to fit their specific needs, without compromising on performance or refinement. While Ford's EcoBoost engines are gasoline-fueled, the EcoBlue is Ford's new generation diesel engine architecture, with advanced materials, low-friction designs, and sophisticated combustion and emissions technologies.

Engine Type: Inline-3, Turbocharged Diesel

Displacement: 1498 cm^3

Bore x Stroke: Approx. 84.0 mm x 90.0 mm

Compression Ratio:~16.0:1

Power Output:

- 88 kW (120 PS / 118 hp) @ ~3750 rpm
- 70 kW (95 PS / 94 hp) @ ~3600 rpm

Peak Torque:

- 250 Nm @ 1750–2500 rpm (95 PS version)
- 270–300 Nm @ 1750–2250 rpm (120 PS version)

Turbocharging:

- Variable Geometry Turbocharger (VGT)
- Electronically actuated for faster response and low-end torque

Fuel System:

- High-pressure Common Rail Direct Injection
- Up to 2000 bar injection pressure
- Piezo or solenoid-type injectors (application dependent)

Emissions Compliance:

- Euro 6d-TEMP / Euro 6.2
- Engine Weight (dry): Approx. 130–145 kg
- Redline: ~4500 rpm

Engineering Features

1. Block and Head Design

The cylinder block is made of durable compacted graphite iron (CGI) or heavyweight cast iron, which bundles structure and reliability. The aluminum alloy head has a combination of an integrated exhaust manifold that enables the system with faster warm-up and lowers the thermal mass. This promotes faster catalyst light-off while reducing cold-start emissions.

2. NVH Optimization

Three-cylinder diesel engines inherently produce second-order vibrations arising from their uneven firing spacing (240° of crankshaft rotation). The Ford engine has an internal balancer mounted in the oil sump, as well as acoustically designed power unit mounts and a dual-mass flywheel to suppress vibrations. These design elements provide NVH performance that rivals that of many competing four-cylinder engines.

3. Advanced Turbocharging

A VGT allows quick turbo response at low engine speeds and a sustained, flat torque curve all the way up to wide open throttle. VGT vanes are controlled electronically for increased response or maximum efficiency based on engine load, speed, and altitude.

4. Thermal Management System

- Valves for the control of coolant flow and thermostat controlled electronically
- Split-circuit cooling: Two unique cooling circuits enable the cylinder head and block to have independent coolant temperatures, allowing faster warm-up and lowering friction losses
- Built-in oil to water cooler for cooler oil temps
- Electrical coolant pump (In some models) for post-shutdown cooling (thermal soak control)

5. Lubrication System

- Variable displacement oil pump: Minimizes parasitic losses and alters oil pressure as needed
- Piston-cooling jets: Spray oil on the bottom of the pistons to keep them cool and enhance ring life longevity.

- Full-flow oil filtration with bypass for fail-safe protection
- Engine runs on thin viscosity synthetic oil (the usual is SAE 0W-30 or 5W-30)

6. Fuel Injection System

- Common rail injection systems by Bosch or Delphi
- Pilot, main, and post injection (multi-stage) for good combustion and emission control
- Central combustion, mounted injectors to provide an ideal spray pattern
- Closed-Loop control of Pressure with rail pressure sensor and high-pressure fuel pump (HPFP)

7. Exhaust Aftertreatment

- Diesel Particulate Filter (DPF): Collects soot particles through active and passive regeneration
- Selective Catalytic Reduction (SCR) with AdBlue (urea) injection: lowers NOx emissions.
- Low-pressure Exhaust Gas Recirculation (LPEGR) with Lean NOx Trap (LNT) (depending on market)
- EGR (Exhaust Gas Recirculation) low and high-pressure loops up to EGR cooling

The 3-cylinder 1.5L Ford EcoBlue diesel engine has become available on a range of Ford vehicles, including Ford’s popular cars and commercial vehicles in European and global markets where fuel efficiency and low emissions are key. In passenger cars such as the Ford Focus, Fiesta, Puma, and EcoSport, it provides an excellent balance of torque, efficiency, and refinement. It also drives a number of light commercial vehicles, such as Ford's Transit Courier and Tourneo Connect, employing a torquey, compact design with long service intervals to optimally serve urban deliveries and small businesses. In all applications, the engine is tuned according to the vehicle weight class and available vehicle grades.

This is an engine with a number of distinctive features that allow it to take on the contemporary benchmarks within the diesel field. Thanks to its small size and modular organization, the new engine can offer significant weight savings and can be more easily packaged in smaller cars, while the variable geometry turbocharger creates a flat torque curve at low revolutions – perfect for both city driving and heavy loads. It has the latest generation of fuel injection and is very low-emission, thanks to sophisticated aftertreatment, and meets demanding Euro 6 emissions requirements without compromising power output. Low internal friction, a variable oil pump, and split-circuit cooling further enhance thermal efficiency and fuel consumption as measured in the real world can drop as low as 4.0 to 5.0 litres per 100 km.

Reduced Cost of Ownership By offering a low total cost of ownership, with a durable and efficient design, the EcoBlue 1.5L allows private users and fleet operators to make long-term cost savings.Superior Capability With low-end torque and a smooth, linear delivery, the new EcoBlue 1.5L is optimized for both refined performance and effectiveness.

Maintained Fuel Efficiency The new engine delivers fuel efficiency thanks to advanced exhaust-gas after-treatment technologies, an individual port cooling system, and the optimized combustion system.Low Cost of Maintenance Due to long service intervals and durable components, maintenance costs are significantly reduced – making the EcoBlue 1.

Ford 1.5L 3-cylinder EcoBlue Diesel Engine The engine is a state-of-the-art compact and lightweight powerplant that combines the latest fuel injection, turbocharging, and durability technology with intelligent oil and cooling systems. It embodies the shift of engineering that is sweeping the industry towards smaller, high-efficiency diesels, whilst tackling old issues of NVH and emissions with a cocktail of intelligence. This engine is still a great part of Ford's diesel solution, especially in markets where fuel economy, torque, and low operating costs take precedence over all other factors.

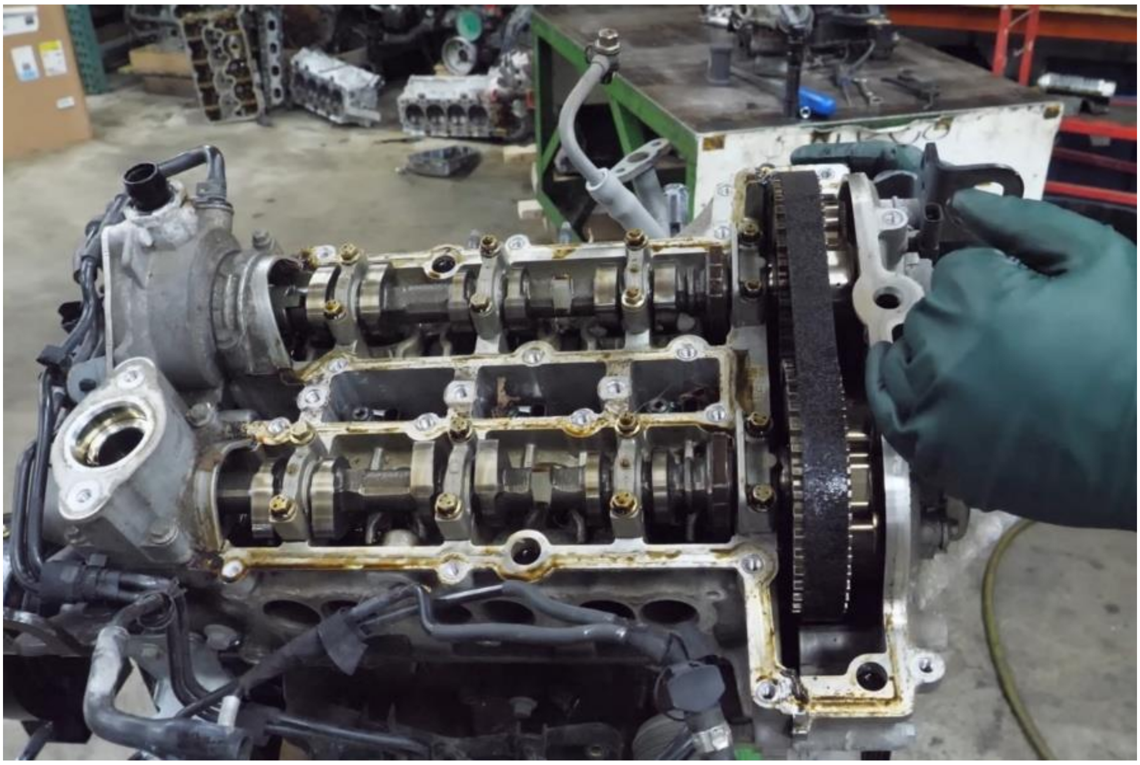


Figure 10 The Interior of Ford Ecoboost Engine (12)

2.5.2 Volkswagen Audi 1.4 TDI Ea288

The TDI EA288 1.4 is one of a line of diesel engines that form part of Volkswagen Group's modular diesel engine system and falls under the new European "Mega Diesel" strategy, created to satisfy Euro 6 and to replace the previous-generation EA189 diesels. This 1.5 three-cylinder turbocharged diesel engine was introduced circa 2014 and was designed to be highly efficient, weight efficient, and have low emissions, a compact and punchy power unit for small cars but combining bulkier cars' frugal fuel economics and urban drivability.

Figure 11 Volkswagen Audi 1.4 TDI Ea288 Engine (13)

- Engine Code(s): EA288 series (notable codes include CUSA, CUSB)
- Engine Type: Inline-3, turbocharged diesel
- Displacement: 1422 cm^3
- Bore x Stroke: 79.5 mm x 95.5 mm
- Compression Ratio: 16.2:1
- Power Output:
  - 55 kW (75 PS) @ 3000–3750 rpm
  - 66 kW (90 PS) @ 3000–3750 rpm
  - 77 kW (105 PS) @ 3000–3750 rpm
- Torque Output:
  - Up to 250 Nm @ 1500–2500 rpm
- Turbocharging:
  - Single-stage variable geometry turbocharger (VGT)

  - Common Rail Direct Injection (Bosch)
  - Up to 2000 bar injection pressure
- Redline: ~5000 rpm
- Emissions Standard: Euro 6b / Euro 6d-TEMP
- Engine Weight: Approx. 115–125 kg (dry)

Engineering Features

1. Block and Cylinder Head

The block is cast iron and is fitted with integral reinforced ribs to further reduce NVH. The cross-flow aluminium cylinder head has an integral exhaust manifold and incorporates an optimized cooling jacket around spark plug tubes and cylinder bores.

This feature contributes to the low thermal inertia of this vehicle and elevates its warm-up performance, making a major contribution to the cold start emissions reduction.

2. NVH and Balance Optimization

The 1.4 TDI EA288 is a three-cylinder engine, fitted with dual-mass flywheels, precision-balanced rotating assemblies, and advanced engine mounts to help minimize vibration. Noisiness, Vibration, and Harshness (NVH): Evergreen at low 3-cylinder vibration pattern and shows low level of NVH demands compatible to passenger car standard of luxury.

3. Turbocharging and Air Management

A GT12 turbocharger with a Garrett variable-nozzle is a key factor in the great low-end torque and impressive throttle response. It's water cooled to shrink its size and manage heat. An intercooler cools the intake air, making it denser and improving combustion. An electrically operated EGR valve together with an EGR cooler is employed to additionally regulate NOx emissions.

4.Lubrication and Temperature Regulation Lubrication:

When oils are applied to the sliding surfaces, some level of lubrication is induced.

- Oil System: Positive, gear type lubrication with full flow oil filter

- Piston cooling jets: Oil-jet cooled piston gallery
- Oil spec: VW 507.00 compatible, other low-SAPS oils with SAE 5W-30 grade possible
- Cooling: Liquid-cooled through thermostatically-controlled oil-flow paths around combustion chambers
- Divided cooling circuits: better temperature control, shorter heat-up times,

5.Combustion and Injection System

High-pressure common rail fuel system Bosch supplied

- Variant by injector type: (depending on variant) -Piezo-electric or solenoid injectors
- Multi-injections per cycle (pilot, main, post) for better combustion smoothness and NOx reduction
- 16.2:1 compression ratio – tuned for low-temperature combustion and low particle emissions

6. Exhaust and Emission Control

- DPF: The Diesel Particulate Filter (DPF) regenerates itself with late injection and exhaust temperature management.
- Oxidation Catalyst (DOC): Facilitates DPF regeneration and CO/HC reduction
- EGR: Low and high pressure loop with EGR cooler
- NOx treatment: Versions with Lean NOx Trap (LNT) or Selective Catalytic Reduction (SCR) with AdBlue injection (more so in post-2017 models)
- Embedded exhaust temperature and pressure sensors for accurate emissions mapping

Applications:

The 1.4 TDI EA288 engine, which has been fitted in Volkswagen Group A0 and A1 vehicles, is highly available, especially in markets that value low fuel consumption and CO_2 emissions performance.

This engine was in vehicles such as the Volkswagen Polo, Golf Mk7 (base model diesels), Audi A1, Seat Ibiza and Skoda Fabia and was produced between 75 PS and 90–105 PS versions. Small size, low weight, low fuel consumption (3.3 to 4.0 litres per 100 kilometres (25 to 59 mpg-US) real use) was suited to city car and subcompact use.

In commercial derivatives, such as the Volkswagen Caddy or Skoda Rapid, the engine offered exemplary reliability and low fuel consumption for fleet use.

Advantages:

1.4 TDI EA288, engineering and practical approach and advantages. A small displacement capacity with the use of turbocharging provides strong torque at low rpm, so it is great for daily use in addition to being highly fuel-efficient. Common rail injection, variable geometry turbocharging and sophisticated emission control technologies ensure compliance with strict Euro 6 emissions regulations, without sacrificing drivability.

The engine is also described as lightweight and compact, supporting improved vehicle dynamics and decreased nose weight. Maintenance wise, long service intervals, strong DPF handling, and well-maintained oil filtration is what helps the owner keep the costs down.

The engine has a modular design built from a cast iron cylinder block with an aluminum cylinder-head cover, with a plastic intake manifold, diesel particulate filter, and intercooler and light blue with alu cylinder block. It shares many parts with the 1.6L and 2.0L members of the cast iron block family, but adds components like the water-cooled intercooler to allow it to produce more power.761388_2.pisc' itemprop description761388_2 Description. End a low carbon-intensive EA288 family of diesel engines.

2.5.3 RENAULT H4B 0.9 TCE ENGINE

The H4Bt 0.9 TCe engine is a small-displacement three-cylinder petrol turbo engine co-developed by Renault and Nissan. Introduced in 2012 for use on small city cars and compact crossovers, the engine was created to comply with EU emissions regulations and offer adequate performance. It adopts a downsizing approach for better fuel efficiency and lower CO_2 emissions, without compromising low-end torque and responsiveness.

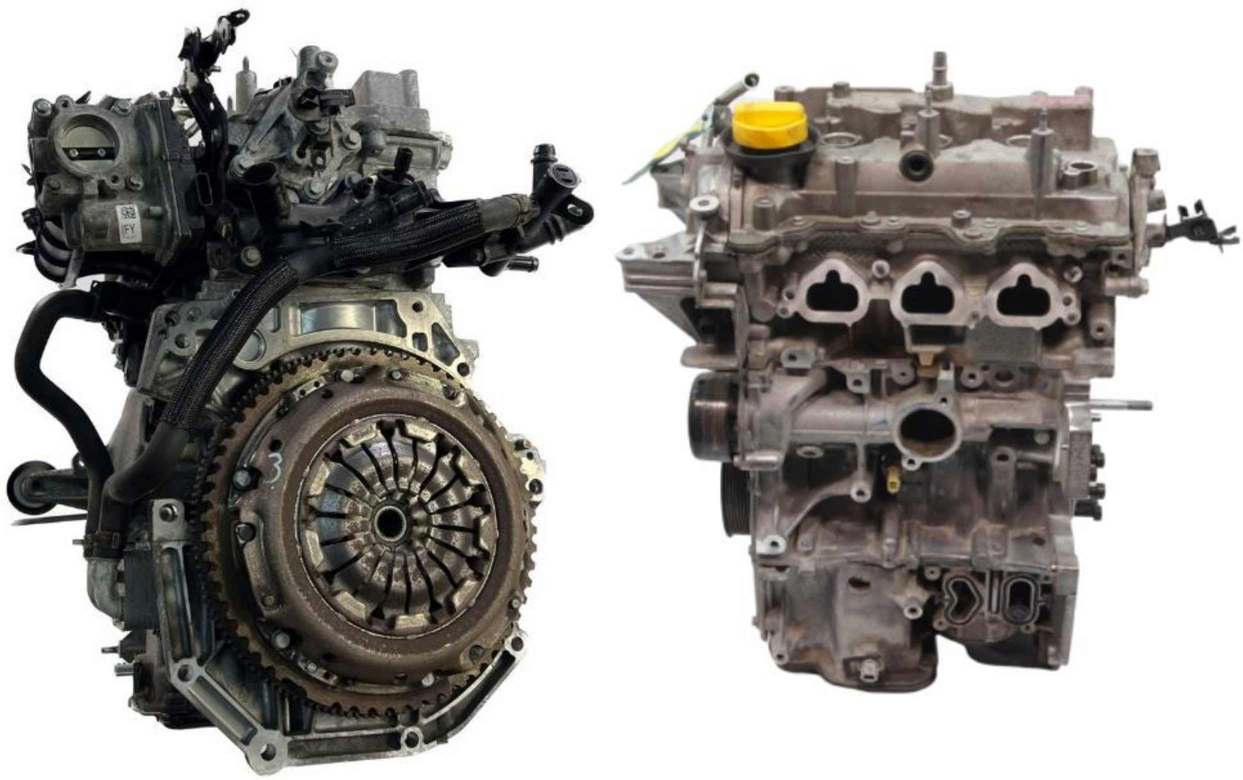


Figure 12 Renault H4B 0.9 TCE Engine (14)

- Engine Code: H4Bt
- Type: Inline-3, Turbocharged, Petrol
- Displacement: 898 cm^3
- Bore x Stroke: 72.2 mm × 73.1 mm
- Compression Ratio: 9.5:1
- Power Output:

- 66 kW (90 PS) @ 5000 rpm
- 70 kW (95 PS) in later revisions

- Torque Output:
  - 135–140 Nm @ 2250 rpm (some versions with overboost to 150 Nm)
- Fuel System: Sequential multi-point fuel injection (MPI)
- Turbocharging: Single fixed geometry turbocharger
- Valvetrain: DOHC, 12 valves (4 valves per cylinder), variable intake valve timing
- Redline: 6000–6500 rpm
- Emission Standards: Euro 5 / Euro 6b
- Dry Weight: Approx. 90–95 kg

Engineering Features

1. Construction and Layout

The engine features an aluminum alloy cylinder block and cast-iron cylinder head to reduce the weight and improve heat dissipation. The small I3 size allows easy packaging in small cars and a lower front weight balance, improving handling and fuel economy.

2. Turbocharging and Air Management

The H4Bt engine uses a fixed geometry turbocharger with a small turbine housing. The turbo is small, providing decent boost down low, perfect for the city with its "torquey" nature. Turbocharged models use an air-to-air intercooler for optimum combustion and lower detonation danger.

3. Fuel System and Combustion

Power comes from its multi-point injection (MPI) system, simpler and cheaper to build than direct injection. While the MPI limits performance scalability, it keeps particulate emissions low without GPFs. It has a 9.5:1 compression ratio to prevent knock and remains thermally efficient

4. Thermal Management

A thermostat-controlled liquid cooling system maintains even temperatures and aids quick warm-up, reducing emissions and mechanical wear. The exhaust manifold joins the cylinder head, reducing the combustion chamber-catalyst distance, improving Euro 6 cold start emissions.

5. Lubrication System

- Wet sump lubrication
- Oil-cooled pistons with under-crown oil jets
- Fixed-displacement oil pump
- Low-friction parts like thin piston rings and low-mass assembly reduce mechanical losses
- Uses synthetic oils meeting Renault RN0700/RN0710 specs

6. NVH and Driver Feel Enhancement For the odd firing 3 cylinder engine, balance is mitigated by:

- Unbalanced flywheel weight serving as a balance shaft equivalent
- Engine mountings designed to separate low-frequency vibrations
- ECU calibrated throttle response to reduce lag and vibration

Applications

The Renault H4Bt 0.9 TCe engine is widely used in compact cars by the Renault-Nissan-Dacia Alliance. It drives models like Renault Clio IV, Renault Captur, Renault Twingo III, Dacia Sandero, Dacia Logan, Dacia Dokker, Dacia Lodgy, and Smart ForFour (with Daimler). It was also used in some Nissan Micra/March (K13) trims in specific regions. Its small size, high torque at low revolutions, and good fuel economy made it popular in economy cars focused on emissions and space efficiency.

Advantages

The H4Bt 0.9 TCe downsized engine offers many advantages. It has modest displacement with boost, performing better than N/A engines with similar consumption (4.5–5.0 L/100 km in real-world conditions). It is light, aiding handling dynamics and fuel economy. Thanks to MPI, it avoids particulate emissions issues common in direct injection engines, reducing need for GPFs. Its simple design ensures low running costs, and the timing chain enhances dependability, offering cost benefits for long-term owners. The compact exhaust manifold and fast catalyst light-off assist EU 6 compliance and limit cold-start emissions.

3 Lubrication System of 3-Cylinder CI Engine

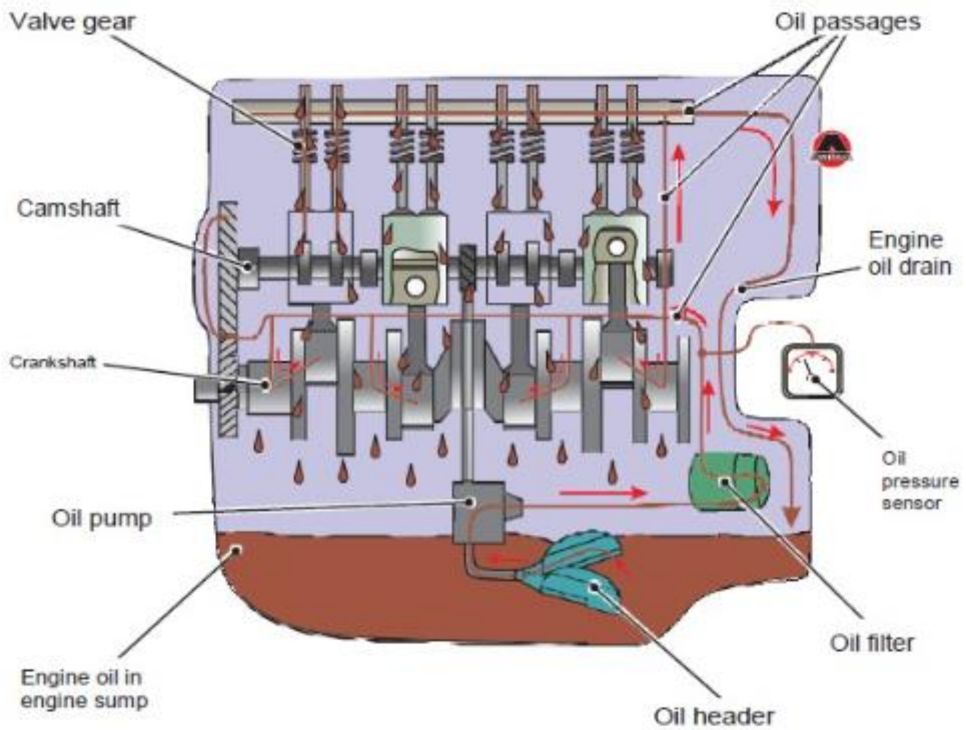


Figure 13 Simplified diagram of lubrication system (15)

The three-cylinder diesel engine lubrication system is a well-designed sub-system to reduce internal friction, prevent the wearing in all components, and control the thermal stability of the engine operation modes. This is more of an issue with a 3-cylinder engine than a 4-cylinder engine due to the tighter, more crammed-in nature of the 3-cylinder engine, and the need to get good oiling flow paths (especially for the likes of high-stressed crankshaft bearings, piston assemblies, and valvetrain) to and from the oil pump.

The oil pump is located at the heart of the lubrication system, usually being installed within the engine sump or somewhere adjacent to the sump. It receives oil from the sump and pressurizes it, forcing the oil through a series of rough or machined passages. Distribution occurs in two steps - first the oil flows from the main gallery (or "arterial line" as it is typically referred) to the sub-gallery, then from the sub-lines to the various parts of the engine.

A few of these critical oil passages are machined into the cylinder block. Oil is delivered via the slot back up the center to the camshaft lobes, rocker arms, valve stems, and hydraulic lifters. This additional lubrication is necessary to properly time the valvetrain and to prevent heat stress around the combustion chamber area. Simultaneously, oil siphons into the lower cylinder passages and lubricates the crankshaft journals and the connecting rod bearings.

Here, high-pressure oil puts a full film over the bearing areas with vastly less metal-to-metal contact and a great deal more lifespan of the rotating parts. Drilled passages in the crankshaft are used in most engines to provide direct oiling to the big-end bearing. Indeed, there are piston cooling jets incorporated in the lower block design in the current engine. The 'nozzle' sprays oil in the bottom of the piston which cools it and also helps prevent the piston crown from getting super hot. This is particularly important in diesel engines due to their very high cylinder pressure and temperatures. After the oil has run through these stations, it is able to return to the sump under gravity without the need to pool out, guaranteeing no starvation under vehicle dynamic attitudes.

The oil return design constantly circulates, filters, and re-circulates oil without surging or aeration. With more advanced lubrication systems, they also have variable oil pressure control valves which alter the oil pressure based on engine load and temperature. This enhances fuel economy and also serves to minimize parasitic losses by engaging the oil pump only when necessary.

Turbulence minimizing both bypass and flow channels combined with high-efficiency filtration provides continuous performance and long engine life. Cylinder head and crankcase breathing spaces are finally also considered in the lubrication layout. The small oil mists are intentionally released with exhaust and re-groomed to keep the pressure up and oil use down. Now, when you take those and you slice and dice those with feedback-controlled devices, the lubricating system of a modern diesel 3-cylinder engine becomes a dynamic system that reflects the different (mechanical and thermal) requirements of an engine at any point in time.

This information should design the conduit dimensions of the one for a 3-cylinder diesel engine in the current size calculation, pressure drop consideration, were to be discussed also the volumetric flow required for other operating conditions

3.1 Types of Lubrication System Architectures

In internal combustion engines, especially compact and high-performance ones such as three-cylinder diesel engines, the decision by design is crucial for the performances, reliability, life of an engine of the architecture of the lubrication system. Various types of lubricating systems have been established for use in automotive engines, the different systems having unique technical particulars, flow principles, as well as suitability for different operating conditions. The following will introduce the main Lubrication System type features, technical parameters, and applications of description of.

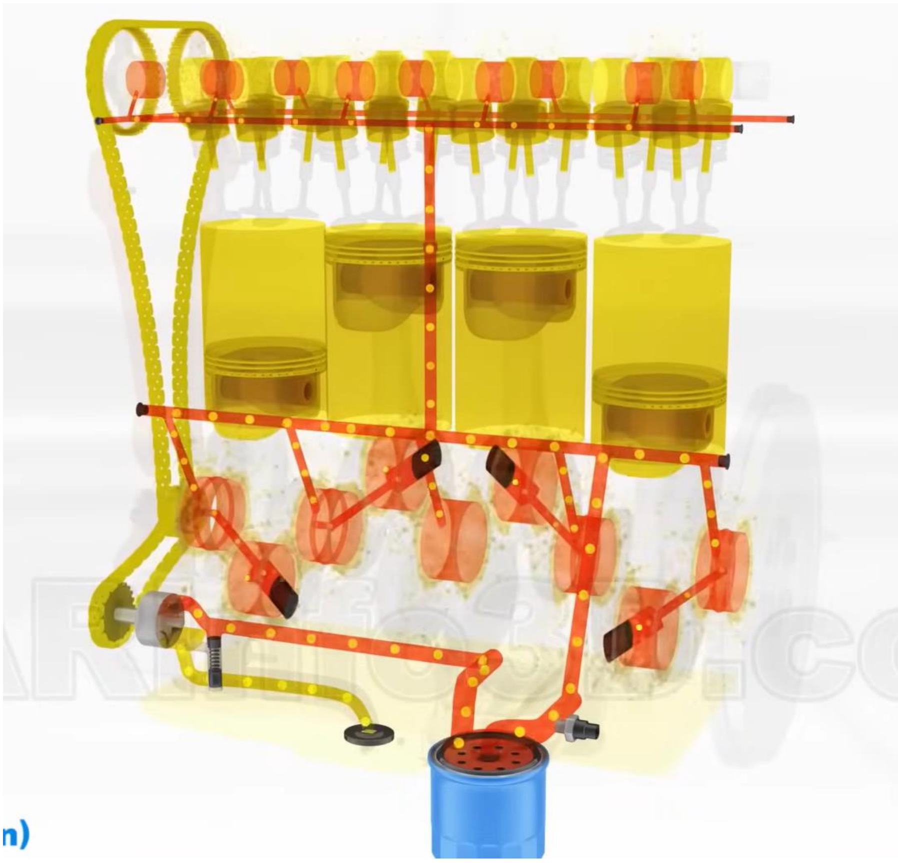


Figure 14 Schematic Lubrication Channels of 4 Cylinder Engine (16)

Various lubrication systems are known. These lubrication modes have been classified into hydrostatic, hydrodynamic, elastohydrodynamic, boundary, and mixed lubrication regimes whose efficacy depends on factors such as lubricant properties, surface geometry, applied load and speed.

Here we just list some of them:

3.1.1 Splash Lubrication System

This is the type of lubrication system in which the oil in a sump is splashed solidly onto certain parts in the form of oil-spray. Splash lubrication is one of the oldest and simplest systems to lubricate internal combustion engines and it is frequently used for automotive engines. It works without pressurized oil and is fed solely by momentum and gravity from oil hanging in the galleries and in the crankcase. A common feature in low-capacity output engines, motorcycles, and stationary installations, it references the basic action of splashing engine parts by dipping them in an oil bath as they pass through a sump of oil. In such a system, a pool of oil is placed in the sump or the crankcase.

Dippers or scoops, fitted at the ends of the connecting rods and carefully designed, dip into the oil and splash it around so that, with the revolution of the crankshaft, it is thrown upwards. This oil from splashing then goes to those cylinder walls, crankshaft journals, piston skirts, and timing gears to provide a film of oil thereon which, though relatively thin, is adequate. Some designs even have splash trays to direct oil to key surfaces and promote more even coverage.

Key components typically include:

- Oil Pan (Sump): It is housing for the lubricant.
- Dippers/Scoops: Lugs on the big-ends of the connecting rods to start the splash.
- Splash Trays and Baffles: Metal plates that assist in directing and controlling the pattern of the spray of oil.
- Oil Breathers or Ventilation: Avoids pressure buildup in the crankcase and helps oil vapors to flow.
- Gravity Return Channels: Channel oil back to the sump after it passes over the parts.

The system of the splash lubrication is simple so that it can be provided at a low price, and maintenance is little. There are no high-pressure pumps, sophisticated filters, or electronically operated valves.

The system is passive and does not sacrifice mechanical failure points commonly available on many other systems. It is also suitable for horizontal and vertical engine layout, is suitable for a variety of basic mechanical configurations.

But this convenience has its downsides. This type of lubrication is passive and a function of engine speed and movement of components and becomes ineffective in high-speed or heavily loaded mechanical operations. Insufficient splash volume at low speeds can result in poor lubrication and too much oil at high speed can cause oil to be thrown too quickly, resulting in local over-heat or dry areas. In addition, as the flow control or the pressure regulation is not properly conducted, so such wear may take place in the region where no oil is splashed directly.

From the point of view of cooling, a splash lubrication has a poor cooling capacity. Unlike lubrication systems with piston cooling jets or heat exchangers, splash systems depend only upon the heat take-up capacity of the oil film and natural convection. Hence, they are not suitable for use in engines running under continuous high temperature and high rpm conditions.

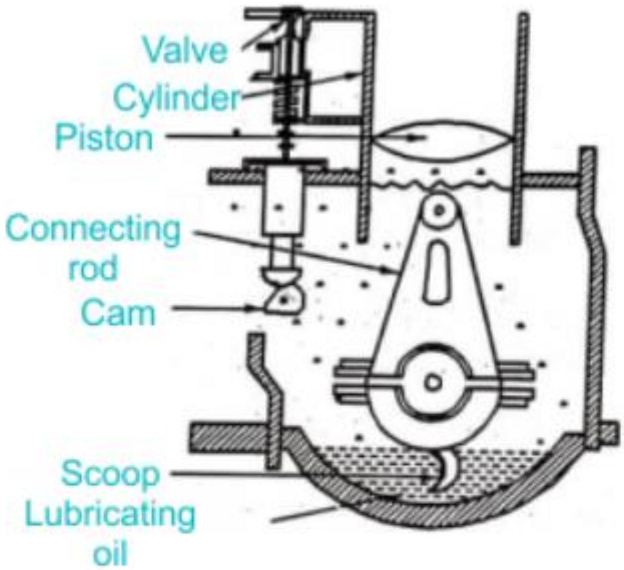
Despite these limitations, splash lubrication continues to be used in:

- Small two-stroke and four-stroke engines.
- Portable generators and air compressors.
- Small agricultural and construction equipment.
- Basic power tools and gearboxes with moderate load demands.

Compared with other lubrication principles, splash lubrication has a lower complexity and offers less lubrication precision and cooling advantages. It doesn't need oil pressure sensors, variable displacement pumps, or bypass valves.

Today, with performance, emissions, and durability being highly regulated on modern engine designs, splash lubrication by itself on the main bearings is rarely used. Instead, it may be a part of hybrid systems, like semi-pressure lubrication, whereby key elements are pressurized with oil and the rest rely on splash.

In summary, although splash lubrication is not ideal for current advanced-performance diesel or gasoline engines, it continues to have its place where simplicity and low cost are dominant factors over closed-loop and sophisticated control or optimization.



. Figure 15 Splash Lubrication System (17)

3.1.2 Semi-Pressure Lubrication System

Its Semi-Pressure Lubrication System is a half-breed engine oiling design, using both pressurized oil feed and splash lubrication, with an eye toward a reliable, yet simple system. It is a popular system for small- and medium-sized internal combustion engines (such as those in lawnmowers, road vehicles, and watercraft) because of the relative simplicity of the design and the acceptable levels of engine wear and efficiency.

1. Working Principle

In a semi-pressure lubrication system as described in:

- Essential engine components (i.e., main crankshaft bearings and camshaft journals) receive lubrication from pressurized oil that comes from a mechanical oil pump.
- Non-essential or Upper engine oiling (cylinder walls, piston skirts, and valve train) is accomplished from oil that has accumulated in draining back to the sump being slung

off first by the spinning crankshaft then by the connecting rods (via oil scoops) as they move or swing within.

- The average oil pressure in these systems is between 0.4 and 1.0 kg/cm² (40 and 100 kPa), lower than that of full pressure systems but sufficient to deliver to the targeted tissue.

2. Components

A common semi-pressure lubrication system is of the type comprising:

- Oil pump (mechanically driven, low-pressure type)
- Main oil gallery with limited distribution lines
- Oil strainer and in some cases a basic filter screen
- Relief valve (to regulate maximum system pressure)
- Sump (wet or shallow dry type) to which the oil is inducted

3. Applications

- 2- and 4-stroke, small diesel and gasoline engines
- Compact equipment engines, farming, industrial, turf, 'small plants,' agricultural engines
- Specified engine types including compact engines, farming engines, industrial engines, and turf 'small plants' engines for static and non-static engines must fulfill the requirement.
- Mopeds, scooters, portable generators
- Perfect for low-cost, low weight, and minimal complexity applications

4. Advantages

- Easy handling of simplified design vs. full pressure systems
- Reasonable for moderate speed and load applications
- Savings in production and maintenance costs

- Low risk of complete system failure (for the reason that it is dual mode)

5. Limitations

- Not applicable for high-speed and high-load running where mishandling can cause an uneven oil feed
- Lower parts can be over-oiled at low rpm
- No provision for piston cooling jets or hydraulic lifters
- Typically simplistic oil filtration, which may leave the oil open to contamination with time.

The semi-pressure system is an economical design that provides basic pressure oiling to critical parts yet assures reliable oiling to less critical parts via splash lubrication. Its hybrid design is especially appealing for small diesel engines, industrial equipment, and cost-sensitive applications requiring weight and basic simplicity and reliability.

The Semi pressure lubrication system is used for our engine design.

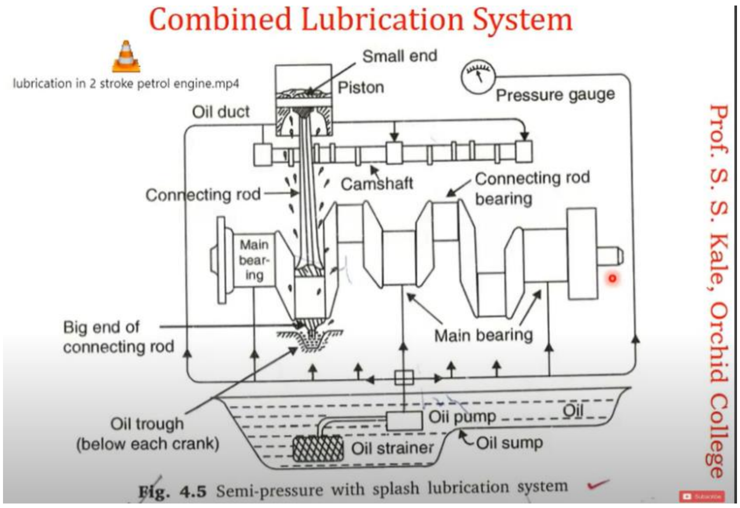


Figure 16 Semi-Pressure Lubrication System (18)

3.1.3 Pressure (Forced) Lubrication System

The forced lubrication system (pressure lubrication system) is used in most internal combustion engines of modern design, including cars and trucks, as well as large diesel engines and many other types of equipment. It uses a centrally positioned oil pump to supply oil at pressure to an interconnected series of galleries and bores throughout the engine. This guarantees that a steady, controlled, and consistent stream of lubricant is available to the vital engine parts, including crankshaft bearings, camshaft lobes, valve lifters, and piston cooling jets. This provides very low wear reflecting the minimal physical contact between moving parts; it also helps to dissipate heat. Pressure-regulated flow prevents upper and lower engine components from starving for fluid, no matter the engine's position or speed..

1. Design and Operating Principles

- The oil feed pressure is normally in the range of 2-5 bar and is, of course, engine-speed and load-dependent.
- For 3-cylinder engine(normal), the pump capacity is 10–20 L/min
- The system usually includes:
    - Oil pump (gear or rotor type)
    - Oil filter
    - Relief valve (to prevent excessive pressure)
    - Oil cooler (if thermal load is high)
    - Oil pressure sensor (for actual measurement and ECU input)

2. Main Subtypes and Delivery Configurations

Various modifications and additional subsystems can be included in pressure lubrication systems, depending on machine complexity, precision needs, and maintenance efforts:

Single-line system : Oil is supplied from the central pump to several points by parallel layout. Despite the "single-line" tag, it can accommodate up to 100 lubrication points using a low-pressure dry sump system in light-to-medium machinery.

Single-Point System: A system that is used primarily in wet sump applications in which oil is supplied to a single point per part. Such units may be used anywhere to disperse a plurality of similar units at spaced locations to be used at multiple stations and frequently in combination with automatic feed lines and metering devices.

Dual Line System: Equipped with two alternating discharge lines. The oil is pumped through one line in the first cycle, and each injector is turned on, and pumped through the second in the second cycle. This two-inlet design improves reliability and consistency of flow.

Grease Gun Lubrication: Typically close-coupled and most commonly utilized on manual, air, and automatic grease system lubrication points. Grease can sit in a closed container before use, such as in high-volume maintenance-intensive industrial machinery.

Automatic Systems: Integrated into machine lines, these systems automate tasks, decrease contamination concerns, and offer accurate control of lubricant application rates. They are suitable for volumetric, progressive and zoned lubrication systems and are found in today's production lines.

Manual Lubrication Helpers: Manual systems are still in operation, but have been improved by the integration of control equipment such as grease meters, cordless guns and RFID tags for identification of lubrication points. Acoustic feedback devices may also be employed to diagnose the presence of lubricant in bearings.

Positive Displacement Injectors (PDI): For splash or hybrid systems, PDIs provide a very accurate shot of oil by squirting oil at high pressure (>55 bar) controlled by an injection pump. When the desired pressure is achieved, a spring-loaded piston dispenses a constant volume of oil to each lubrication point, providing uniform flow and preventing system clogging.

3. Advantages

- Greater intertwining of lubrication distribution and cooling.
- Facilitates incorporation of hydraulic valve lifters and piston cooling jets.
- Applicable on real-time pressure feedback and flow regulation of ECU.
- Mechanical wear is reduced, reliability is improved, and equipment life is extended.

Finally, the pressure lubrication system is a key component of modern engine design that provides strong, smart, and efficient lubrication management. Available in a full complement of system designs, from simple single-point configurations to complex dual-line or PDI solutions, it's suitable for all sectors and will extend the life cycle of mechanical systems.

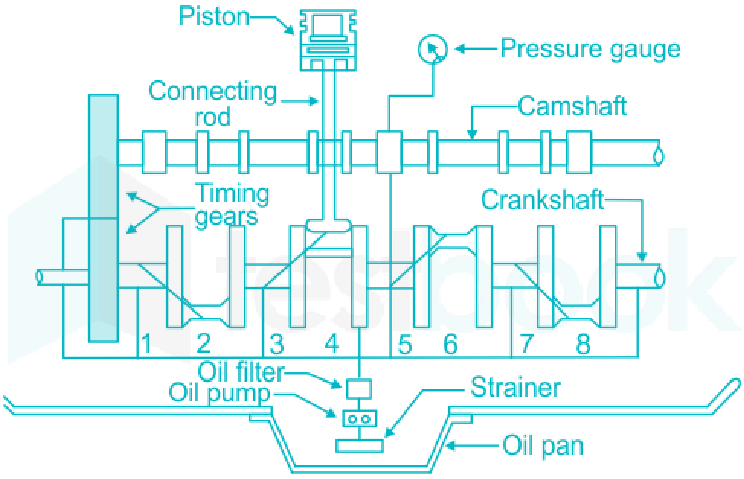


Figure 17 Pressure Lubrication System (19)

3.2 Lubrication System Design Principles

3.2.1 Overview of the Lubrication System

The lubrication system was described with an overview. It is also equipped with a highly efficient lubrication system that delivers oil effectively to the moving parts of the 3-cylinder diesel engine. Its principal function is to provide support for the workings, such that friction and wear are reduced, and to dissipate heat. Lubrication A well-designed lubrication system helps to protect the life and reliability of your components by eliminating metal-to-metal contact, even under the most extreme operating conditions. Principal design criteria include a span of adequate pressure at each bearing, adequate flow to pertinent locations (bearings and piston cooling jets), while minimizing pressure drops within the oiling system. With well-chosen dimensions of channels and the properties of the oil, the system will be able to operate stably at various engine speeds and loads and ensure the required pressure and flow rate of the oil.

3.2.2 Components of the Lubrication System and Their Functions

The principal parts of the lubrication system of the engine and their functions are:

- Oil Sump (Pan): The oil sump is an oil reservoir where lubricating oil is retained. The sump will catch the returned oil through gravity and it is the home of the pump's oil pick-up tube. It thereby promotes the flow of oil and aids in dissipating the heat from the oil.
- Oil Pump: Positive-displacement pump (usually a gear or rotor pump) that pulls oil out of the sump, sifts through it, and pressurizes it. The pump is dimensioned to deliver the necessary flow (in the order of 10's of liters/min) to the engine. It guarantees that oil circulates properly after starting and maintains adequate oil pressure whenever the engine is running. There is a pressure relief valve built in that allows overpressure oil to recirculate and return to the sump if oil pressure becomes too high (thus preventing cold start or high RPM damage).
- Oil Filter: A filter element situated right after the pump which screens out impurities, metal fragments, and sludge out of the oil. It then allows only clean oil to flow through which is necessary for protecting fine-clearance parts such as bearings from abrasives that wear it out. A bypass valve is typically incorporated to ensure oil flow in the event that the filter is clogged (preventing oil starvation).
- Main Oil Gallery: The main oil feed hole drilled in the engine block. It is kind of a distributing artery, carrying pressurized oil from the pump (after the filter) out to different branch channels, and ultimately to every bearing and part. The diameter and the arrangement of the main oil gallery are selected such that the oil is distributed in a uniform manner and the pressure drop in the entire engine is kept to the minimum possible value. In that design, an 8mm diameter, longitudinal bore (the main oil gallery), running the length of the block, makes certain that the oil has a low resistance path to all three-cylinder bearings and top-end areas.

- Bearing Supply Channels: These are the holes or passages that divert the oil from the main passage to the engine’s main bearings (crankshaft journals) and other bearings. From the main gallery, a drilled passage (usually around 6–8 mm in diameter) runs to each main bearing and provides the oil to the bearing oil feed hole. These passages are generally short and therefore tend to have nozzles of a size sufficient to deliver a full flow to the bearings, yet maintain gallery pressure. The bearings usually have oil grooves to spread oil coming, provide the full coverage oiling to the journal, 360°. From the main bearings, oil flows into the crankshaft’s central passages for access to the connecting rod bearings.
- Crankshaft Internal Oil Passages: Crankshaft cross-drilled oil passages direct oil flow from each main bearing journal to the appropriate connecting rod (big-end) journal. Oil is provided through these passages and flows all the time the crankshaft is in motion to the connecting rod bearings on every revolution. When the oil feed in the main journal matches, pressurized oil flows through to the rod bearing, with the internal oil holes aligned. These passageways are dimensioned to allow a sufficient flow to the rod bearing without unduly weakening the structure of the crankshaft. They're made so that all is well under centrifugal force at high rpm and enough oil will get to the rod bearings for hydro lube, by design. This pressurized oil is delivered to the connecting rod bearings where it creates a film that reduces friction between the rod bearing and crank pin, and the excess thrown off helps to lubricate cylinder walls and, from the bottom, cool the pistons.
- Piston Cooling Jets: As an added measure to safeguard the engine in high-heat situations, each cylinder's piston features oil jets that spray the underside of the crown. These are typically supplied by the main oil gallery (or main bearing feed) and create a mist of oil around the pistons and cylinder walls. There are two primary purposes: to cool the pistons (so as to avoid excessive heating in the pistons and upper cylinder) and to add extra lubrication to the cylinder liners. All of the nozzles have a non-return valve that only opens at a certain oil pressure (in order to give priority to the bearings at low oil pressure or at start-up). When it’s running at normal pressure, it opens the jets and

delivers a carefully measured flow of oil designed to keep the piston temperatures in check.

- Valve Train Oil Passage: From the substantial oil supply into the main oil gallery (or from a main bearing feed), a gallery dedicated to feeding the overhead valve train — camshaft bearings, rocker arms, or cam lobes — is led up to the cylinder head. In this setup, the drill's long bore in the block (typically through it or alongside a head bolt passage) feeds oil to the cylinder head's camshaft housing. This ensures that a steady flow of oil is supplied to the camshaft journals, cam lobes and valve rockers or lifters. Metered oil to the top end avoids overwhelm (windage oil consumption). Lubrication of the camshaft and valve mechanism is important for minimizing wear in relation to these high-friction surfaces and also helps cool the valve springs and guides.
- Pressure Regulator/Relief Valve: Pressure Regulator/Relief Valve: (usually built into the oil pump as described above, but included here independently in operation) It keeps the hydraulic oil pressure of the system within tolerable limits (for instance, ~4 bar at wide-open throttle). At low temperature or high engine speed, a bypass is effected, through which excessive oil can pass and the pressure does not become too high. This serves to provide a pressure which is uniform on components without over-pressuring the seals, and without losing power due to pumping loss.
- Oil Return Passages: Once lubricating and cooling are done, oil has to return to the sump and this takes place by gravity. The return holes, passages and return holes for used oil allowed to rise are formed in the engine block and the engine head. Those are generally big cast or drilled passages for oil (and oil vapors) to retreat from the head end (valve train locale) and from the case areas back into the sump. Correct return flow prevents oil accumulation in the head and in the crankcase around the crankshaft, which reduces the risk of oil starvation in the sump and minimizes drag due to oil windage. The return being un-pressurized, although it must be large enough to accommodate the oil being pumped throughout the engine.

These elements combine to form a closed loop lubricating circuit. The parts of the system are designed and fitted to guarantee that the oil makes it where it's needed and then continues its loop adequately. The design of the principal oil network and pressure-flow considerations are described in detail below.

3.2.3 Main Oil Gallery Design

The main oil gallery is a central oil channel in the engine. It is usually a longitudinal hole in the engine block intersecting the main oil gallery but may be a cross hole to the main oil gallery. To such an end, in the 3-cylinder engine, with the main oil gallery, oil flow distribution to all 3 cylinder portions is highly effective while simultaneously keeping the pressure loss from the output outlet of a pump to the farthest bearing minimized.

Layout and Geometry: The gallery is located in the block so that it is able to feed all main bearings and secondary oil feeds. Typically it loosely follows the crankshaft, above or off to the side of the main bearing caps. With this system, the gallery runs through the entire block's length (~40 cm) and all of the engine main bearings (and any other oil feeds) feed from this pressurized line.

The gallery diameter was selected as 8 mm so as to keep the flow capacity at a most favorable level. This size is large enough in order to transport the whole volume oil flow without a high velocity causing a high friction loss and turbulence. Yet the bore is small enough to keep the oil high enough in pressure throughout to fit within the constraints of casting a compact engine block.

Material and Construction: The oil gallery is formed by either drilling the cast engine block or by adding a cored passage during the casting process. In both cases the gallery ends are closed with screwed plugs for maintenance access. The gallery bore smoothness is crucial – rough walls or sharp edges can add to resistance against flow – so the drilling provides a fairly smooth inside. Furthermore, the gallery is straight for straighter (also straighter with fewer bends) flow. All gallery branches are radiused or chamfered at junctions introducing a branch to minimize any turbulence and local pressure drop.

Pressure Loss Consideration: The design team studied the pressure loss throughout the main gallery using the theory of fluid mechanics to check if the oil pressure at the far end was within the allowable range. For the viscosity and flow rate of the oil at working temperature, it can be seen that the pressure drop from one end of the gallery to the other is very small (in the range of a few kPa). Using the Hagen–Poiseuille relation for flow through a pipe it was checked that an 8 mm gallery diameter provides a small pressure loss for the standard flow of oil (this calculation assumes that the oil is flowing laminar through the gallery, which is a fair assumption because of the high viscosity of the oil and the small flow rate in the gallery). The upshot is that the final main bearing in the oil circuit gets nearly the same pressure of oil as the first, which is good for ensuring even bearing lubrication. The gallery diameter also represents a safety factor: it is free to pass more oil if the pump's capacity rises (e.g., at higher engine speeds or a higher capacity pump) without creating back pressure and starving the last bearings

Oil Feed Distribution: Oil feed oil galleries to main bearing journal, with hole in main bearings. These feed holes cross the main gallery at right angles (or slightly inclined) and feed oil into the annular space in the main bearing shells. Every in and out connection is strategically placed to match up with the oil circuit within the block. Entrance of these feeder channels into the gallery have chamfer to avoid pressure drop spikes or eddies. The engine's cylinder spacing dictates the spacing between feed points; for a 3-cylinder engine, there are usually 3 main bearing feeds (and possibly one for the SC and TC if they are main bearings). The front gallery is essentially a manifold ensuring all the feeds to the heads get oil at once (when the pump is running).

3.2.4 Bearing Supply Channels (Main Bearing Oil Passages)

The bearing supply channels are simply the oil passages that carry oil from the main gallery to the engine's bearings—and this includes crankshaft main bearings, but also camshaft bearings, and wherever else it is needed. In the lubrication arrangement for this engine, each main bearing is supplied with oil from a separate drilled passage from the main oil passage to the bearing oil inlet. These feed paths are important in that this is where the relatively high-pressured oil is injected into the narrow interface between the bearing and journal to form the hydrodynamic lubrication film.

Design and Dimensions: All of the main bearing oil passages are rather short since the main gallery is typically next to the bearings. The size of these passages is a compromise of pressurization versus flow. It might, by a small amount, in which case the passage could reduce flow or cause a pressure drop just before the oil enters the bearing. If this is too large, the oil speed will start to decrease, and the pressure may take longer to establish, and it also uses more space within the block. Typically, these passages in practice have an average diameter of about 3-5 mm. In our case the overall diameter is similar to the main gallery (3 mm) for the bearing feeds. This dimension allows a strong flow of oil (about few liters/min/bearing) to reach each main bearing without losing too much pressure in the gallery. The little smaller size with respect to the main gallery, helps to keep a pressure high upstream of the gallery and at the same time it's above the minimum flow necessary for the bearing.

Orientation and Drilling: The bearing feed channels are usually drilled at a downward angle from the main gallery towards the bearing saddle area. They end on a hole in the block saddle or cap same as included in a bearing shell. As the bearing shells are fitted in place and the bearing surfaces being thereby positioned respectively, the feed hole opening into passage permits oil to pass from the passage to gap between the crankshaft journal and bearing. The orientation of these holes is crucial – the engine will rest so that these holes line up to allow priming (oil can fill the passages), and will operate so that the oil supply is continuous and, as the crank rotates, oil will always fill the bearing clearance.

Analogous feed routes can also lead from the main gallery to other bearings, such as the camshaft bearings (for an overhead cam engine, a vertical or inclined passage leads from the gallery up into the head) or an auxiliary shaft if there is one. These oiling passages may contain smaller passages orifices or restrictors such as metering orifices (for example, the cam bearings in an engine may require less flow than the crank bearings). One such vertical channel (ca. 3 mm diameter) is drilled in our engine to supply oil to the valve train. To guarantee priority lubrication for the crankshaft and connecting rods, the flow to the upper end is metered (restrictor or a smaller passageway) so that the largest part of the oil is sent to the crank and piston cooling jets before elsewhere. A limited amount passes to the area of the camshaft, enough for the valve train to operate.

Ensuring Reliable Lubrication: The geometry and course of the bearing lubricating ports is also determined including manufacturing tolerances and potential plugging. The channels are as straight and uniform in diameter as possible to prevent any place where detritus could settle.

Also, since these are high-flow, high-velocity passages, the engine assembly process ensures they are clean and devoid of casting sand or metal fragments. Some even have a galley plug in the ends of the oil passageways that can be removed during an overhaul to mechanically clear oil passageways.

Getting oil directly to each bearing using those supply passages is necessary for each main journal to establish a complete hydrodynamic oil film, which is required to support and preserve the life of the crankshaft.

3.2.5 Crankshaft Internal Oil Passages

The oil passage in the crankshaft is not only a part of the external oil circuit, but it also becomes an internal oil circuit of a moving crankshaft. This three-cylinder engine's crankshaft has been cross-drilled with passages on the inside to deliver oil from the main bearings, which get oil from the block as we've learned, to the connecting-rods' bearings, which sit upon the crank's spinning lobes. This inside oiling is what makes it possible for the conrod big-ends to be pressure-lubed despite being non-spinning and dummy connected to the oil gallery.

Layout: For most connecting rod journals there is an oil passage drilled in the crank web that leads to and from the respective main journal to the rod journal. In a three-bearings-per-cylinder design, each main bearing would feed between one and two rod journals in this manner in an engine with (e.g.) four main bearings. The holes are typically angularly bored through the crankshaft throws. For example, if oil is made to enter the main journal from the top, it will go through the diagonal passage on the crank and due to the alignment of the holes, will come out at the rod journal. These internal holes are generally on the order of 3-5mm in diameter, known to be of a size suitable to support high oil pressures in the crank and not become an area of excessive crankshaft weakening, while at the same time being large enough to flow the needed quantity of oil to the rod bearings.

Operation during Rotation: When the crankshaft revolves, oil is forced into the revolving channels under pressure at the main bearing. The configuration provides a continuous supply of oil: the oil passages leading to each of the rod journals are always at least one each time coming into the open state to the high-pressure oil in the main bearing. Therefore, during each revolution, oil is mistakenly but often pumped into the rod bearing at such a rate that the rod bearing is in essence continuously lubricated by hydrodynamic action. The inertial loads and centrifugal outwards force on the oil in the crank passages, too. At this point centrifugal force assists to sling oil out by the rod bearing clearance. It's these passages that get designed around to deliver oil right to the heart of the rod bearing.

Cooling and Supplementary Lubrication Effects: The engine oil which circulates through the connecting rod bearings performs at least one other function in addition to lubrication, i.e., it also assists in the transfer of heat from the bearing to the piston assembly. When the rod bearing is lubricated, it is partially expelled through the side clearance of the bearing, through a great number of small orifices, as a very fine spray into the inside of the crankcase. This oil splash helps enough lubricate other components (cylinder wall providing cylinder lubrication by wetting the piston skirts and rings) and the small end bushings of the connecting rods. The crankshaft oil passages in our engine are designed to somehow target the underside of the pistons. In conjunction with the specific piston cooling jets, this provides efficient cooling and lubrication of each piston. The used oil then flows down to the sump.

Structural Considerations: There are several considerations when drilling oil passages in the crankshaft to avoid weakening the crank. The holes are typically drilled in low-stress regions of the crank webs, and are typically drilled non-axially in a stepped or angled manner such that a large, straight cross-section is not produced and thus the strength of the crankshaft is not impaired. Passages are typically chamfered and cleaned after they are drilled. Pressed-in or threaded plugs sealing the holes where the main and rod journals pass make sure that oil goes where it should on its way throughout the engine and provide an oilway entrance for cleaning during service in a similar vein to the oil gallery plugs of the block. That is normal practice in this engine. Every oil passage is plugged at the ends, and the materials and treatment of the crank (i.e., nitriding or fillet rolling) account for the amount of holes so the fatigue strength is not compromised.

The crankshaft internal oil passages are 'extended distribution' system that in turn, resupplies the most distant bearings in the engine (the connecting rod big-ends but also see 'wet sump' vs. 'dry sump'), critical to their high-speed operation. With the addition of these passages, the engine is provided with full pressure lubrication of all principal rotating interfaces.

3.2.6 Lubrication Pressure and Flow Design Considerations

A key consideration in the design of a lubrication system is the need for adequate oil pressure and flow, independent of engine operating conditions. This includes selecting the correct oil viscosity, the pump capacity, and the passage sizes to ensure that every component is supplied with an adequate amount of oil without creating too much pressure, which could dissipate energy or cause foaming of the oil. The following summarizes the pressure and flow (rate) differences and decisions presented:

- Oil Pressure Targets: Basically to achieve around 4 bar of oil pressure everywhere in the engine under normal circumstances (the exact target is typically somewhere around 4 bar at rated speed). At idle, much lower (usually 1-2 bar) but still enough to maintain an oil film on the bearings. The pump has a pressure relief valve adjusted to open when pressure is higher than the set value (approximately 5 bar), so that the system itself and the pressure can behave in a controlled manner. This carefully crafted design keeps the oil pressure up to provide adequate lubrication without being so high that the engine loses power and you blow out seals and gaskets.
- Oil Pump Sizing: The oil pump was sized for the engines at all RPMs. Overall oil flow demand calculations summed up the oil demands of the main & rod bearings (cooling flow requirements), the camshaft bearings, and the piston cooling jets. For instance, it might "take" 1–2 L/min flow to keep every main and rod bearing cool and lubricated, and may "require" ~0.5 L/min flow for each cooling jet, etc. Based on these requirements, the pump is designed to provide approximately 15 L/min at a moderate engine speed (cruising RPM) and up to 30 L/min at full-throttle RPM. These figures allow for keeping more than enough oil flowing, even under the most strenuous of circumstances. The output of the pump was also compared with the vehicle engine's oil pump that gave us a rough idea that our design is in a practical state. By having a modest overflowing design, the system ensures enough oil supply at any stage in the engine age (where increased clearances may increase flow requirements) or operating temperature (where thinner oil might increase leakage flow).

- Oil Viscosity and Type: The oil is selected based on its desire to obtain a specific pressure and flow response. This 3-cylinder diesel requires multi-grade motor oil like that of synthetic SAE 15W-40. This oil has a high Viscosity Index, which means it is thin enough to flow quickly to all the dry metal surfaces of your engine at start-up (15 weight at crank speed, reducing pump load and reducing start-up wear) and it thickens up enough to protect your engine at operating temperatures (40 weight when it's hot) so it will maintain a good film of oil on all the parts. The viscosity at working temperature (~ 100 °C) was considered in all flow calculations. For example, at this temperature, 15W-40 oil would have a dynamic viscosity on the order of 0.01 Pa·s (depending on the exact additives and the degree of natural paraffin in the crude). With this flow, the design team assessed oil withdrawal from each passage. The oil is formulated so that the flow remains largely laminar in the galleries and the pressure drops are known in advance. Also, a quality diesel engine oil with an appropriate additive package (including anti-wear items like ZDDP, dispersants, and detergents) assures that boundary lubrication conditions (such as start-up or extremely high loads) are handled, without scuffing. The system is also capable of using synthetic oils (such as 5W-40) which have higher flow at extremely low temperatures and resistance to thinning at high temperatures. Indeed, a 5W-40 synthetic could have been used to improve cold-start lubrication and obtain still more stable viscosity at high operating temperatures, which would protect the engine even more effectively—this option was mentioned as one due to its decidedly improved viscosity stability at high temperatures against mineral oils.
- Pressure Loss Calculation: The pressure loss in the lubrication circuit was analyzed as a part of the design calculation to ascertain that the pump can develop the desired pressure at all the locations. The oil passages (gallery, channels, crank holes, etc.) were formed into a system of pipes, the flow through each being examined separately. Although in this paper we do not present derivations of the formulas we use, the main idea is that small passages have much higher resistance than large ones. This rationalized that the main gallery and main bearing feeds were relatively large (8 mm and, as mentioned, 6 mm, respectively) to minimize resistance. More trivial flow areas (such as crank inside holes to rod bearings, or the valve train feed) might be smaller

because the length or volumetric output flow is less. The maximum path—pump—filter—main gallery—bearing feed—crankshaft—rod bearing—was evaluated as the worst-case oil path in the system. The pressure drop computed for this worst-case path is a very small fraction of the total oil pressure (a drop of maybe 0.2 bar out of 4 bar depending on the flow and temperature). What this also means is that the design satisfies the requirement that all bearings be subjected to at least the minimum pressure requirement. If this drop had been excessive the design would need a substantially larger diameter passage or a higher pump flow rate. In our case, sufficient dimensions were selected. Note that as oil flow increases with engine rpm, pump pressure drops (and oil weight may drop also slightly with increased temperature), but the pump's pressure relief valve takes care of this by bypassing any excessive flow and pressure to keep the system in balance.

- Flow Distribution and Balance: Distribution balance of oil was also checked. The principle of "priority main oiling" is used – the main oil gallery feeds the main bearings where it is circulated through the engine first i.e. the crankshaft (one of the most important components of maintaining an engine's longevity) is the first to receive pressurized oil when there is pressure in the pump. From the primary bearings, oil now goes to the rods, and not until then does it go to the top end and pistons jets. Some of this prioritization is accomplished by geometry (gravity makes oil want to go to the lower main bearings first anyway) and some of it is in the form of restrictions that are sized to direct oil accordingly. For instance, the valve train feed line may include a restrictor or a smaller diameter so that it does not take an undue flow from the main gallery. The piston cooling jets, on the other hand, would usually have a spring-loaded valve which only opens at say ~2 bar, so until the main gallery pressure is above that (~2-2.5 bar for the 4G63) so I (say) know that oil is getting to mains then the jets won't flow. When open, they are capable of delivering oil when the engine is under load (and therefore when oil pressure is higher), which is precisely when piston cooling is required most. These design features allow the system to dynamically control oil distribution: at low pressure/flow the bearings have the highest priority in terms of oil, at high pressure all components are provided with enough oil including cooling jets.

- Thermal Effects and Oil Temperature Control: The system operating pressure is based on the normal oil operating temperature of 90–100 °C (engine oil). A cold start sees more viscous oil and this can produce the highest pressure spikes. The relief valve (as I mentioned) addresses this by bypassing oil when the oil is up to the set pressure (i.e., to prevent pressures that can damage the oil filter or fine passages). On the other extreme, if the oil is very hot (like if the engine is under heavy load and is in a hot environment), the viscosity will lessen and the pressure may be reduced. The pump is then sized and bearing clearances chosen such that with very thin oil, the flow increases more than offsets these losses and a protective film is preserved. In addition an oil cooler could be built in (which is outside the scope of this portion of text, but indeed many diesel engines do have an oil cooler) to regulate the oil temperature at a certain desired value, and consequently the viscosity within a desired interval.

In short, EPR and DR design criteria make certain that, from idle to wide open throttle (i.e. max RPM), the lubrication system is capable of delivering oil at the right pressure, in all nooks to which it is supposed to go. The engineering calculations support a choice of having an 8 mm main gallery and associated passage dimensions, as these confirm that these choices would result in pressure losses much below those permitted and exhibit good lubrication performance.

3.2.7 Functional Description of the Lubrication Process

Combining the greater overview above, the process of how the lubrication system is applied in the engine can be split stepwise:

1. Oil Pickup and Pressurization:

When the engine starts, the oil pump pulls oil from the sump through a pickup tube that has a mesh strainer (to prevent large debris from entering). The pump will then be used to pressurize the oil. The pump's output very quickly starts the oil pressure in the system ratcheting up. Opened by the relief valve of the pump, high pressure (especially during cold start) is led off in order to achieve the fast filling of the system pressure into the intended operating pressure.

2. Filtration:

Pressurized oil enters the oil filter first. Contaminants and particles are retained in the filter element. This stops abrasives from circulating. The filter's bypass valve is in the "closed" position otherwise and all oil is filtered. A bypass is there to open if the filter clogs or the oil is very cold, which presents a high resistance through the filter; by opening the bypass, oil will still travel to the engine (although it will not be filtered) - it's a safety to stop the engine from becoming starved of oil. Under normal circumstances, by the time oil gets to the end of the filter, it is pressurized and clean.

3. Main Gallery Distribution:

Filtered pressurized oil is routed through the main oil gallery, which typically runs the length of the block. This will instantly charge the gallery with oil and pressure it over its entire length. This is effectively due to the fact that the main gallery is a distribution manifold – once it has oil, so do all the branches that then come from it. Due to its large diameter, the passage allows oil movement with very little resistance, therefore, pressure is almost constant moving from one end of the block to the other.

4. Oil Delivery to Main Bearings:

Oil is delivered from the main gallery to each main bearing through these passages where it is directly supplied to the main bearings, which support the crankshaft. Oil is squeezed into the gap at the top of each main bearing, and creates a hydrodynamic wedge as the shaft wobbles to ward off the heat. This oil acts as a film that supports the crankshaft journals, thereby preventing metal-to-metal contact. The arrangement is such that the most remote main bearing from the pump (usually the rear main bearing) will receive oil at substantially the same pressure as the foremost bearing since the gallery is characterized by a low pressure drop. A part streaming as well to the bearer oil swirls, which is to retain (radially outward) so it can reach and also penetrate an interior oil hole of a crank.

5. Connecting Rod Bearings Lubrication:

When the crankshaft turns, oil is directed through the crankshaft to lubricate every connecting rod bearing. Centrifugal force causes oil leaving the main bearing to enter the drilled passage in the crank throw and to impinge on the rod bearing interface. This usually occurs once per revolution for a rod journal (the oil hole in the crank is aligned with the main bearing feed). But because of the steady pump, and the film of oil, the rod bearing never really is dry at alignment. The connecting rod bearing is supplied with pressurized oil which establishes a film between the rod bearing (positioned in the connecting rod big-end) and the crank pin. This film prevents metallic contact and removes heat from the bearing. As the oil is too much on the edges of the Rod-Bearing, an overflow of oil is thrown off as mist in the crankcase.

6. Valve Train and Camshaft Lubrication:

Alongside the main oiling to the crankshaft, the engine releases oil up a vertical passage to the cylinder head where the camshaft and valve mechanism are lubricated. Engine oil pressure flows through a metered orifice or passage into the overhead camshaft bearings and rocker arms (or lifters) when oil pressure is adequate. As it drains along the return, drain paths and back into the sump, oil seeps from clearances into cam lobes up at the top end. Flow to the top is often limited in comparison with that of the crankshaft, but is ample to maintain a film of oil, to quench the valve springs and tappets, and to keep the cam lobes well oiled. Gravity will cause oil in the head to pool slightly and then drain; oil does not accumulate excessively in these areas since they are designed with drain holes. The first cylinder upper block feed in the previous section directs oil to this region to ensure that even the components furthest from the sump. Note that in the provided image, the oil sump is at the bottom of the engine and is referred to as a sump due to gravity; however, sumps are not frequent in all engines. As pressure builds in the system, the piston cooling jets open and start spraying oil at the underside of the pistons. The jets ensure that a continuous film of cooling oil that absorbs heat from the piston crown in addition to lubricating the undersides of the pistons, piston rings, and cylinder walls. The jets are targeted, ensuring that the oil reaches the central, major thrust surfaces of the cylinder. In this engine design, each cylinder has its oil jet fed from the main gallery. The oil has fulfilled its cooling and lubrication roles and will thus have to return to the sump due to gravity.

The oil lubricating main and rod bearings drains into the crankcase and down its walls. Oil returning from the top end (cam/valve area) is delivered to the sump through dedicated passages in the corners of the block and head. The 3-cylinder powerplant has a relatively short stroke of just 84mm, which was possible thanks to the engine's inline 3-cylinder configuration with its large drain holes: this made it possible to have the liquid return back to the oil reservoir in a timely manner, not allowing for any build-up. A solution to the oil problem was worked out so that the lines were designed so that oil can't pool and get trapped (which could lead to starvation during heavy cornering if not). Through the repetitive process of coming back to the sump the oil is primed for the next time the pump picks it up, and the loop repeats.

Correct crankcase breathing (see venting) so that returning oil is not impeded by air pressure and any oil mist (aerosol) is fumed off through the oil separators. Under the bullet point item "Oil Return Path" in the component description it is mentioned how the gravity-assisted return paths recycle the oil away from the friction.

In all of this, the functional sum of the parts is clear: the pump pushes stuff around, the gallery and channels make sure it's all distributed somewhat equally, and the various valves/jets just modulate it where necessary according to pressure. The end product is a solid lubrication circuit that keeps engine internals protected at any rpm and under any driving condition.

While the engine is running, the oil not only lubricates but also cools the bearings and pistons. This two-fold function is particularly significant in a high compression diesel engine because loads due to temperature are considerable. Not only is there always fresh oil, but also failure particles are constantly flushed out to the filter, which is therefore cleaning every ounce of oil – constantly.

To summarize, the lubrication system of the 3-cylinder diesel engine is a carefully planned combination of galleries and channels and appropriate components (pump, filter, jets etc.) calculated to obtain a good pressure and flow rate of oil. Everything has its place in the system, from the central oil gallery supplying the bearing feeds and crankshaft drillings, to the cooling jets and return paths; Everything is there to ensure the system provides outstanding temperature and recirculation benefits.

The choices — such as an 8 mm main gallery, certain oil passage diameters, large pump capacity, and multigrade oil — were based on computational models and industry-standard design assumptions to ensure that each critical engine element will achieve proper lubrication in all operating circumstances. By eliminating harsh pressure drops and maintaining balanced flow the system provides engine longevity and performance that only spray patterns can offer. All formulas and calculations which supported these decisions prove that the lubrication system will operate properly and I do not give them here – concentrating on clear tasks in the context: constant oil supply, pressure under control, all areas of the engine covered. This comprehensive lubrication schedule forms the basis for the engine's longevity and enables it to run friction- and wear-free for as long as it is in use.

3.3 Engineering Theory of Lubrication System Design

In this section, the lubrication network of a 3-cylinder diesel engine has been developed and studied using the basics of fluid mechanics. The objective is to provide effective oiling with as little pressure loss as possible to ensure sufficient lubrication of the entire engine (main bearings, connecting rod bearings, camshaft, piston-cooling jets, etc.) under all circumstances. Design rationales are documented drawing on quantifiable Hagen–Poiseuille equations for laminar flow for oil gallery diameters, length, and for drilled channels. All quantities are expressed in SI units; a table with the pressure drops in each section of the lubricating loop is presented.

3.3.1 Fluid Mechanics Calculations

The fluid mechanics calculations are needed for the design for lubrication system. The system includes pipes, pump, filter, radiator etc. For this reason, these formulations are significant:

The volume flow rate is,

$$Q = V * A \tag{1}$$

If we put pipe area formula on in its place,

$$Q = V * (\frac{\pi * D^2}{4}) \tag{2}$$

and we leave alone the diameter of pipe,

$$D = \sqrt{\frac{4 * Q}{\pi * V}} \tag{3}$$

and lastly the velocity formula is extracted,

$$V = \frac{4 * Q}{\pi * D^2} \tag{4}$$

where,

Q = Fluid volume flow rate (m^3/s)

V = Velocity of fluid (m/s)

A = Cross-sectional area through which the fluid is of flowing (m^2)

D = Diameter of pipe (m)

In addition to these, the Reynold's number is important for characteristic of flow.

$$Re = \frac{Inertial\ Forces}{Viscous\ Forces} = \frac{\rho * V_{avg} * D}{\mu} \tag{5}$$

The kinematic viscosity is,

$$\nu = \frac{\mu}{\rho} \tag{6}$$

If we put the kinematic viscosity in its place,

$$Re = \frac{V_{avg} * D}{\nu} \tag{7}$$

where,

Re = Reynolds number

V_{avg} = Average velocity of fluid (m/s)

ρ = Density of fluid (kg/m^3s)

D = Characteristic linear dimension (Diameter of pipe) (m)

μ = Dynamic viscosity (Pa.s)

ν = Kinematic viscosity (m^2/s)

The Reynold number is a dimensionless number used in fluid mechanics to indicate whether fluid flow past a body or in a duct is steady or turbulent.

$Re \leq 2300 \quad \rightarrow \quad$ Laminar Flow

$2300 < Re < 4000 \quad \rightarrow \quad$ Transitional Flow

$Re \geq 4000 \quad \rightarrow \quad$ Turbulent Flow

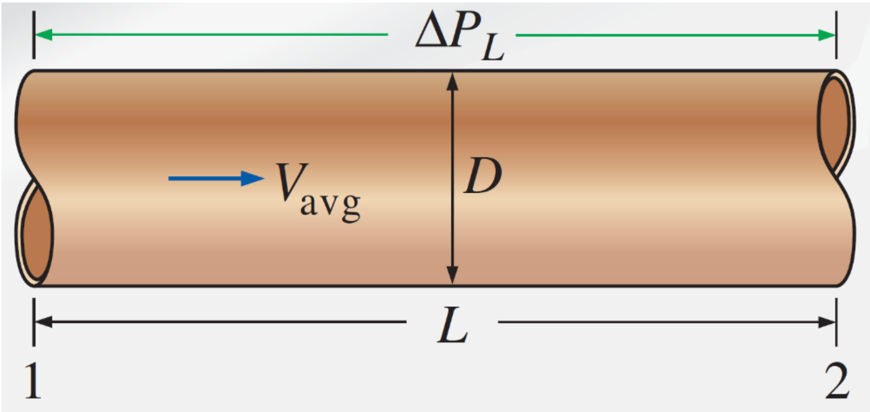


Figure 18 Steady Flow in Pipe (20)

Pressure Loss,

$$\Delta P_L = h_L * (\rho * g) = \; f * \frac{L}{D} * \frac{\rho * V^2}{2} \tag{8}$$

Major loss for head loss,

$$h_{L,major} = \frac{\Delta P_L}{\rho * g} = f * \frac{L}{D} * \frac{V^2}{2 * g} \tag{9}$$

Minor loss for head loss,

$$h_{L,minor} = K_L * \frac{V^2}{2 * g} \tag{10}$$

Minor loss is ignored because we do not have any information about the value of K_L. In order to find the value of K_L, it is necessary to collect data from the pipes. Since this is not possible now, the $h_{L,minor}$ value will be taken as zero.

$$h_{L,total} = h_{L,major} + h_{L,minor} = h_{L,major} \tag{11}$$

Also, Colebrook equation is needed for turbulent flows.

$$\frac{1}{\sqrt{f}} = -2 * \log\left(\frac{\varepsilon * D}{3.7} + \frac{2.51}{Re * \sqrt{f}}\right) \tag{12}$$

Instead of this we can use the f equation that approximates by S.E. Haaland

$$\frac{1}{\sqrt{f}} = -1.8 * \log\left(\frac{6.9}{Re} + \left(\frac{\varepsilon * D}{3.7}\right)^{1.11}\right) \tag{13}$$

The friction factor is below formula for laminar,

$$f = \frac{64}{Re} \tag{14}$$

The pipes are made in engine block made by gray cast iron (A48 Class 30 / 35). So, ε is pipe roughness, it is constant, and its value is 0.2 – 0.8 µm.

There are some rules when calculating the total head loss in series and parallel connections. In series connections, we add the head losses for each pipe and give us the total head loss value. In parallel connections, there is a common head loss, and this gives us the total head loss value.

$$h_{L,total,series} = n * \frac{\Delta P_L}{\rho * g} = n * f * \frac{L}{D} * \frac{V^2}{2 * g} \tag{15}$$

$$h_{L,total,parallel} = \frac{\Delta P_L}{\rho * g} = f * \frac{L}{D} * \frac{V^2}{2 * g} \tag{16}$$

Where n is the number of pipes used.

Energy equation

$$\frac{P_1}{\rho * g} + \alpha_1 * \frac{{V_1}^2}{2 * g} + z_1 + h_{pump,u} = \frac{P_2}{\rho * g} + \alpha_2 * \frac{{V_2}^2}{2 * g} + z_2 + h_{turbine,e} + h_L \quad (17)$$

The $h_{turbine,e} = 0$ because of there is no turbine.

The $h_{pump,u}$ comes from power equation,

$$W_{elect} = \frac{\rho * Q * g * h_{pump,u}}{\eta} \quad (17)$$

So,

$$W_{pump} = \rho * Q * g * h_{pump,u} \quad (18)$$

After few calculations the pump loss is,

$$h_{pump,u} = (z_2 - z_1) * h_L \quad (19)$$

These fluid mechanics calculations are needed for determine to regime, speed, pressure loss, needed pressure power of flow. At the same time, the calculations are used for **specify geometry of the pipes**.

3.3.2 Oil Flow and Pressure Drop Calculation

To size the oil passages, the Hagen–Poiseuille equation for incompressible laminar flow in a circular pipe is used. This equation relates the volumetric oil flow rate to the pressure difference across a channel of diameter and length for a fluid with dynamic viscosity.

$$Q = \frac{\pi * D^4 * \Delta P}{128 * \mu * L} \quad (20)$$

Where:

- Q is the oil flow rate (m^3/s),
- D is the internal diameter of the oil passage (m),
- ΔP is the pressure difference across the passage (Pa),
- μ is the dynamic viscosity of the oil (Pa·s), and

- L is the length of the passage (m).

For design purposes, this equation is rearranged to solve for the required pressure drop in each section of the lubrication system given a target flow rate and chosen channel dimensions:

$$\Delta P = \frac{128 * \mu * L * Q}{\pi * D^4} \tag{21}$$

Using the above relationship, the engine's lubrication passages are dimensioned to achieve an optimal balance between sufficient flow rate and minimal pressure loss. An appropriate oil viscosity is assumed based on operating temperature. The oil pump is selected to provide a nominal flow at the regulated oil pressure (on the order of 3–5 bar). This flow must pass through the main oil gallery, branch channels, and crankshaft oilways with acceptable pressure drops to ensure at least the minimum required pressure reaches all bearings.

The proper sizing of a lubrication channel depends on parameters such as flow rate (Q), pipe diameter (d), and dynamic viscosity (μ).

3.4 Mathematical Calculations

The oil type is SAE 10W-40. The viscosity of the oil is 0.012 Pa.s for 100 °C and the density of the oil is 840 kg/m^3. The needed flow rate is 10 L/min, this equals 1.67×10^{-4} m^3/s. At the same time the input pressure of flow is 4 bar. We will make calculations by using these inputs. The roughness value of gray cast iron (A48 Class 30 / 35) accepted as 0.5 μm.

For instance, when we calculate the main oil gallery flow:

The diameter of the channel is 8 mm and thus;

The cross-sectional area is

$$A = \frac{\pi * D^2}{4} = \pi * \frac{(0.008)^2}{4} = 0.000050265\, m^2$$

The desired mass flow rate is 1.67×10^{-4}, thus;

$$V = \frac{Q}{A} = \frac{1.67 * 10^{-4}}{0.000050265} = 3.3224\ m/s$$

If we want to calculate the Reynold's number of the flow, we use the equation (5):

$$Re = \frac{\rho * V_{avg} * D}{\mu} = \frac{840 * 3.3224 * 0.008}{0.012} = 1860.52$$

Result of this calculation, we observed that the flow is laminar as desired.

After that we need to calculate the head losses for determine the pressure loss and the needed pump power.

The Darcy Friction factor is found by using the equation (14)

$$f = \frac{64}{Re} = \frac{64}{1860.52} = 0.0344$$

$$h_{L,major} = \frac{\Delta P_L}{\rho * g} = f * \frac{L}{D} * \frac{V^2}{2 * g} = 0.0344 * \frac{0.4}{0.008} * \frac{3.3224}{2 * 9.81} = 0.4634\ m$$

The minor head loss coefficient is accepted as 1.5.

$$h_{L,minor} = K_L * \frac{V^2}{2 * g} = 1.5 * \frac{3.3224}{2 * 9.81} = 0.254$$

The total head loss

$$h_{L,major} + h_{L,minor} = 0.7174$$

After that the total pressure losses and other values are calculated and make a table which includes these results.

Table 1 Calculated Pressure Drops in Lubrication Channels

Kanal	**Uzunluk (m)**	**Çap (m)**	**Debi (m^3/s)**	**Viskozite (Pa·s)**	**ΔP (kPa)**	**ΔP (bar)**
Main Oil Gallery	0.40	0.008	0.000167	0.012	7.974	0.08
Bearing Feed Channel	0.06	0.003	0.000167	0.012	60.482	0.60

Crankshaft Internal Channel	0.07	0.003	0.000167	0.012	70.562	0.71
Total	—	—	—	—	139.017	1.39

Note: The flow data in the table are illustrative for purposes of explanation. The real oil flow to each branch obviously depends on the oil circuit material of the engine (bearing clearance, orifice diameter of the oil jet, etc.), but the scale is the one indicated above. Pressure drops are computed with oil viscosity. The pressure losses would grow approximately proportional with μ at lower temperatures and higher oil viscosities, but these would still stay within the safe range as long as the oil pump creates adequate pressure during those conditions.

It can be seen from Table 1 that the main oil gallery has the highest flow, but due to the large inner diameter, the pressure drop caused is only minor. The smaller branch drilling to the main bearing leads to a slightly higher pressure drop, but nevertheless only in the range of 0.01 bar, which is negligible in relation to the system pressure. In the case of the crankshaft internal oilway (which is the longest path), however, the flow through it is relatively small and thus this has a very low pressure loss value (in the region of 0.005 bar). The feed of the bearing side of the cylinder head is also a passage with a small diameter but the flow rate is much smaller and the pressure loss is small. The total of all the pressure drop through the worst-case lubrication path (pump → main gallery → main bearing feed → oilway in crankshaft → rod bearing) is approximately the sum of these. For the values above, this adds up to only about 0.04–0.05 bar at running temperature that still is totally not too much for the pump (which holds, e.g., ~ 4 bar). Even in situations where oil viscosity is high (cold start), the pump relief setting (e.g. 6 – 8 bar) will be sufficient to prevent the increased losses starving the bearings of oil.

Finally, the flow-circuit channel design of the lubrication system is verified by these calculations that each part of the oil circuit can provide necessary oil flow without too much pressure drop. The main gallery, side branches, and crankshaft oil drillings have been designed with the best compromise between fluid dynamic need, mechanical strength, and pressure drop. This precise configuration and validation of the oil galleries ensure a dependable lubrication of all movable internal components of the 3-cylinder diesel engine, which results in less friction, less wear, and longer life. The confidence in the serviceability of the lubrication system under all engine operation conditions and the conquest of contributions of “hand-waving” based design methods are made by Hagen–Poiseuille-based analysis.

4 Cooling System of 3-Cylinder CI Engine

4.1 General View

The cooling system of a light 3-cylinder diesel engine is a challenging task that needs to be developed in a methodical and iterative process, considering the reduced spatial volume, high local heat fluxes, and constraints made by the engine block geometry. The following 6-step approach describes the method deployed in the present research:

4.1.1 Problem Definition

The first step is to identify those hot spots within the engine. This is achieved using:

- Infrared camera scans (IR camera scans from control cases)
- Review of literature on hotspots (e.g., valve bridge, piston crown area, exhaust port walls).

The datasets validate that the exhaust-proximate cylinder end region, upper combustion, and injector bosses are always exposed to high thermal loads (>150 °C), requiring targeted cooling solutions.

4.1.2 Preliminary Layout

Based on the CAD structure of the engine, a conceptual design of the coolant channel is designed. This includes:

- Circumferential grooves located around each cylinder sleeve
- Exhaust ducts V-shaped exhaust ducts plus aligned with the exhaust valve seat
- Ganged manifolds for even distribution between head and block

Top-priority is to eliminate sharp corners, minimize dead space and ensure that the flow has access to every thermally sensitive area.

4.1.3 Geometry Optimization

Following simulation feedback, channel geometries are iteratively optimized:

- Inlet/outlet diameter tuning to balance flow rates
- Cross-sectional area shaping (e.g., from circular to elliptical) to increase contact area
- Junction smoothening to minimize vortex formation
- Implementation of flow-directing ribs in extended water jackets

This stage is to obtain an even coolant coverage with hydraulic loss reduction for optimal thermal management performance.

4.1.4 Material Selection

Channel material and coating are selected based on:

- Thermal conductivity requirements
  (e.g., Aluminum: ~205 W/m·K preferred over Cast Iron: ~80 W/m·K)
- Chemical compatibility with long-life coolants
- Resistance to erosion and cavitation under cyclic flow

Protective ceramic coatings and anodized linings are considered in high-risk areas, such as high-pressure inlets and bends.

4.1.5 Final Design Completion and CAD Integration

During this last stage, the design of the lubrication and cooling systems has been completed. According to the geometrical limitation and thermal demand of the 3-cylinder diesel engine model, all the layouts of the channels were designed by using SolidWorks CAD software.

The finalized cooling and lubrication channel networks were fully incorporated into the design of the engine block and head casting with regard to flow continuity and manufacturability, as well as space constraints. The design was based on analytical calculations (flow rate, pressure drop, and thermal management) and is characteristic of being an approach absent the use of simulation tools.

In the spirit of encouraging clarity and reproducibility, detailed CAD views and section drawings of the final channel designs are offered in the Appendix of this paper. These diagrams show the internal routing, dimension aspects, and general layout of the constructed components.

In diesel engines, especially 3-cylinder compact configurations, the need for a highly responsive and evenly distributed cooling strategy is critical. Uneven heat distribution can cause thermal fatigue, cylinder distortion, and reduced engine performance. The compact design limits the space available for cooling channels, making it essential to optimize the cooling system for maximum efficiency.

To address these challenges, several strategies can be employed:

1. Optimized Coolant Flow Paths
2. Use of High Thermal Conductivity Materials
3. Advanced Cooling Technologies

4.2 Types of Cooling Channel Architectures

The geometry of cooling channels plays a critical role in determining the effectiveness of thermal management within internal combustion engines. An optimal design balances three key factors:

- Coolant Velocity
- Uniform Flow Distribution
- Minimized Pressure Drop

Optimized cooling channel geometry can keep high heat transfer performance and low hydraulic resistance. Poor channel designs can result in dead spaces, fluid separation, and poor heat transfer.

To enhance thermal and hydraulic performance, a number of design modifications have been proposed and investigated for modern cooling channels:

- Non-Circular Cross-Sections:
  - An oval or elliptical profiles again add wetted surface area without adding too much in the way of hydraulic resistance.
  - These geometries enhance heat transfer, and yet are stereologically compact.
- Smooth Curvature and Bend Minimization:
  - Fluid vortices and flow separations along sharp edges and corners which result in thermal dead zones.

- Smooth bends keep flowlines intact and lower local turbulence.

- Flow-Directing Features:
  - The water jacket can have the ribs, vanes or baffles embedded therein to direct the coolant toward areas that are thermally stressed.
  - These features promote longer residence time on hotspots and minimize bypassing flow.
- Variable Cross-Section Along Channel Length:
  - Variable channel widths to control speed and distribute pressure, resulting in optimal cooling where it's needed most.

Efficient heat rejection in diesel engines, especially in small 3-cylinder layout requires a range of cooling jacket designs. These designs help with cooling, heat dissipation and overall engine temperature control, which in turn prevents overheating/makes your engine last longer. Here we go over the main cooling duct methods for use on such engines.

4.2.1 Water Jackets

An internal passageway within an engine block or cylinder head through which coolant (water) circulates, surrounding the combustion chamber and exhaust ports. They are responsible for transporting the coolant, which absorbs heat around critical engine components and expels it through the radiator.

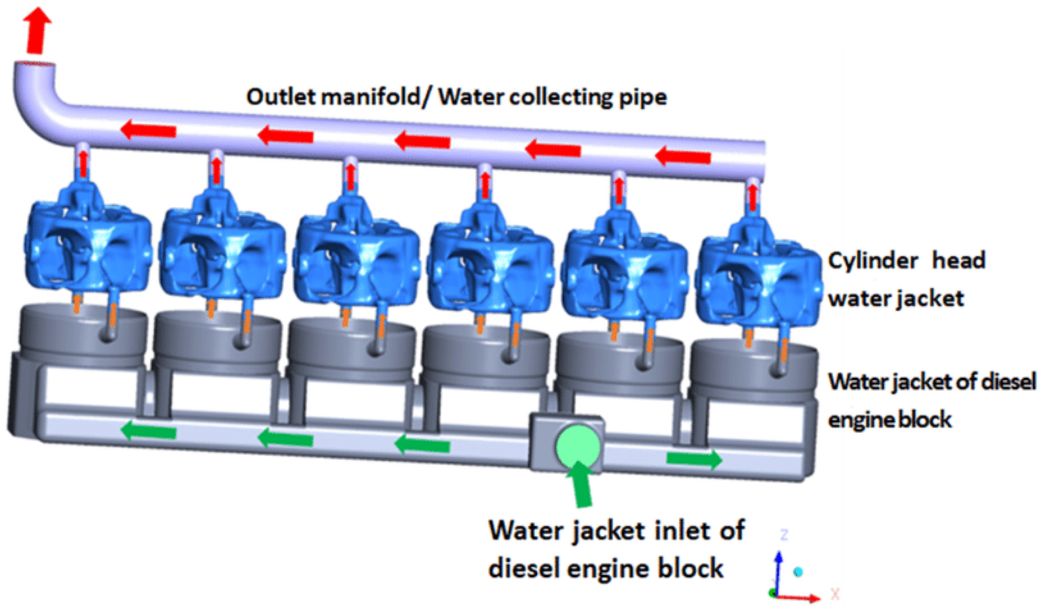


Figure 19 Cross-sectional view of a representative water jacket geometry within the engine block.(21)

For 3-cylinder diesel engines, the small dimensions make isometric water jackets necessary, but sufficient cooling and required strength are difficult to compromise on.

4.2.2 Split-Circuit Cooling (Dual-Loop Systems)

Split-circuit cooling Separate currents are guided over the engine block and cylinder head. This division makes specific thermal management feasible, solving the different cooling demands for each engine part. Split-circuit systems improve engine efficiency and reduce thermal stress by controlling the temperature of the cylinder head and block separately.

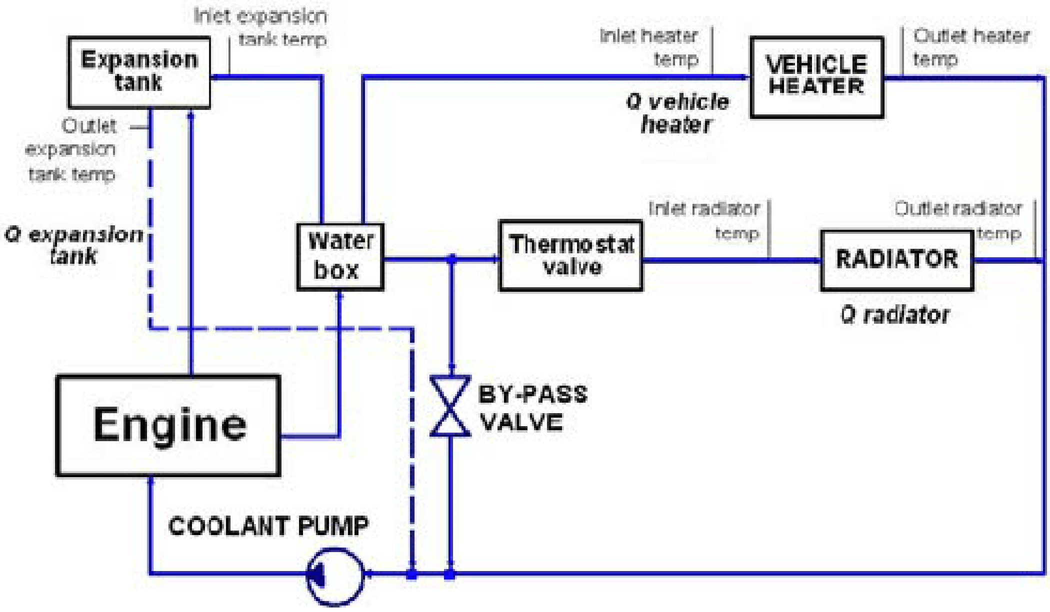


Figure 20 Schematic diagram of a typical automotive engine cooling system (22)

4.2.3 Targeted Cooling Ducts

Efficient cooling ducts are precision-molded to direct airflow around the motor, helping to maintain optimum motor operating temperatures. These passages are critical to avoid hot spots and achieve even cooling.

4.2.4 Crossflow vs. Downflow Radiator Circuits

Radiator structure is one of the most important factors for the performance of the cooling system. There are two main configurations:

- Crossflow Radiators: While coolant still flows from top to bottom, this type of radiator design has coolant flowing across the radiator, which makes it shorter and wider. This arrangement is advantageous in automobiles having restricted vertical space.
- Downflow Radiators: The path of the coolant is from the top to the bottom of the

radiator. Such a conventional arrangement may be found in many older and/or larger vehicles.

The decision between a crossflow or downflow radiator design is a function of the vehicle packaging and cooling system needs.

4.2.5 Modular and Hybrid Cooling Systems

Current diesel engines are characterized by a high number of modular, hybrid and multifunction cooling systems that are combinations of different cooling technologies in an attempt to manage a complex heat rejection layout. These systems may utilize water jackets, split-circuit cooling, and selectively directed ducting, among other features in a single construction. LİNK

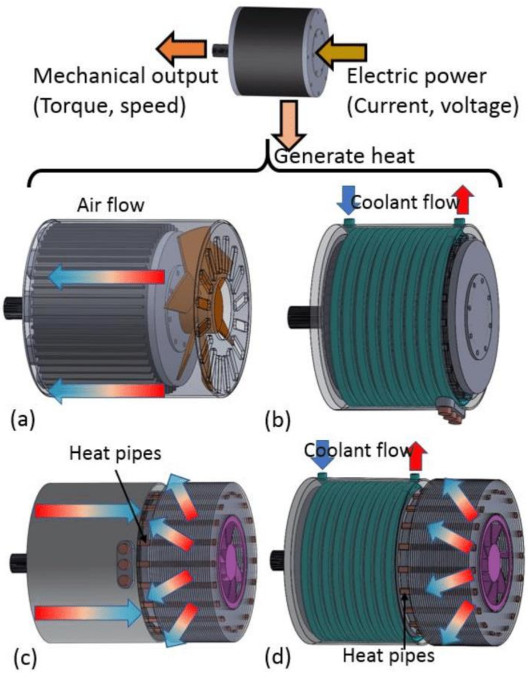


Figure 21 Comparison of motor cooling techniques: (a) forced air cooling, (b) liquid coolant jacket cooling, (c) radial heat pipe integration, and (d) hybrid heat pipe with coolant flow design. (23)

Integrated systems of this type provide improved flexibility and efficiency, and are particularly useful in small engine applications where space is at a premium.

4.3 Engineering Theory of Cooling System Design

The cooling system dissipates heat released during the combustion process and also maintains engine operating temperatures in the best possible range for performance and longevity. An efficiently optimized cooling system always extracts heat evenly away from the processor and prevents the creation of hotspots. While the current cooling system for this concept is relatively immature, initial studies have shown that the use of strategically placed coolant passages, water jackets optimized for the thermal environment, and high effectiveness radiators are essential to provide uniform heat removal over high temperature areas.

4.3.1 Heat Transfer Mechanisms in Cooling Systems:

Conduction: The heat passes from combustion to the coolant through engine block, cylinder head. This process is facilitated by the use of high-temperature-conductivity materials. Convection Heat is absorbed by the coolant and removed from the engine with minimum variation in temperature, benefiting from fully optimized fluid flow.

Radiation: Radiators allow the heat to radiate into the ambient environment; airflow is a major contributing factor to the efficacy of this style of cooling.

Efficient heat management in internal combustion engines, and in particular in small combustion engines with 3 cylinders and diesel operation, requires cooling ducts to be positioned appropriately. The flows in these channels play a great role in the thermodynamic equilibrium in the engine due to the position and orientation of them.

Design Goals The main design objective of the system is: Turbulent flow is often desired in engine cooling applications, which has the advantage of promoting heat transfer by convective enhancement without unnecessarily high pressure loss. This equation also illustrates close relationship between flow rate and channel diameter suggesting that modest increases in diameter can lead to significant increases in flow capacity (proportional to d^4).

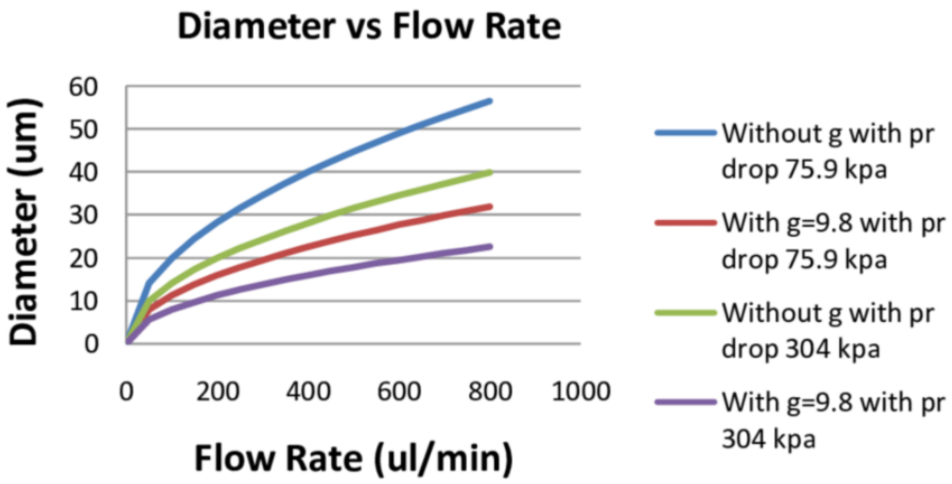


Figure 22 Channel Diameter and Flow Rate Relationship (24)

Graph illustrating the relationship between channel diameter and flow rate, demonstrating the significant increase in flow rate with larger diameters due to the dependency as per the Hagen–Poiseuille equation

4.3.2 Pressure Drop vs. Heat Transfer Tradeoff

Higher coolant velocity will be conducive to the convective heat transfer and pumping power. The channel geometry, therefore, needs to be a compromise between the thermal efficiency and hydraulic losses. Because of the confined installation space and high heat flux, the cooling channel geometry of 3-cylinder diesel engines shall be well-optimized.

Using theoretical models such as the Hagen–Poiseuille equation, combined with geometric optimization rules, engineers can design systems that have both high thermal performance and energy efficient hydraulic behavior.

4.3.3 Thermal Hotspot Mitigation

Mitigation measures may be taken based on hotspot information. The area around the hot spot generated in the vicinity of the exhaust valves and the HCCI combustion of the piston crowns, which are susceptible to high temperature. And, intensified cooling is required in these regions to avoid thermal fatigue and component deterioration.

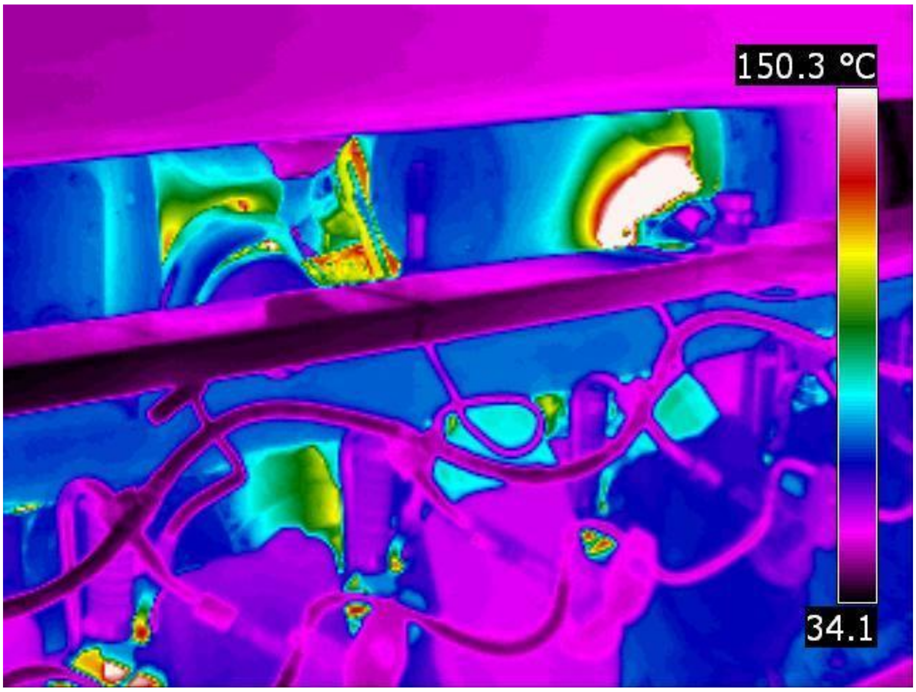


Figure 23 Thermal Image of Localized Thermal Hotspots (25)

Infrared thermal image showing localized thermal hotspots near the exhaust region of an internal combustion engine.

4.3.4 Cylinder Wall Uniformity

Keeping a uniform temperature all the way around the cylinder liners is vital for preventing differential expansion, which may cause distortion of the cylinder and poor sealing.

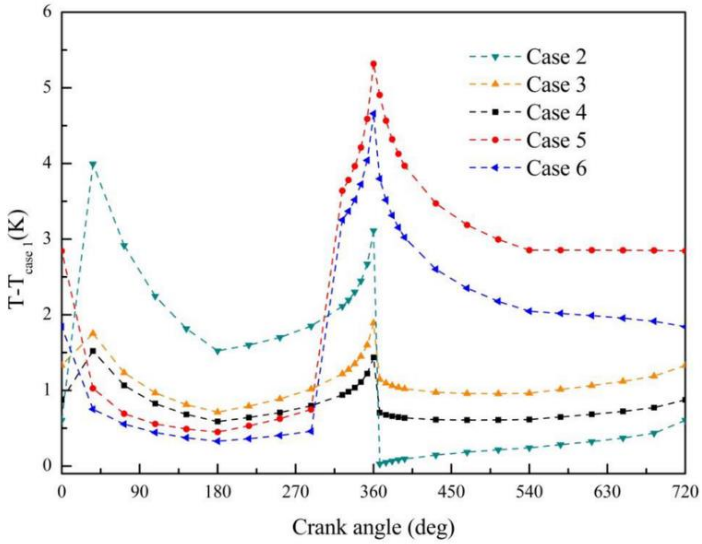


Figure 24 Variation of cylinder wall temperature across different engine operating cases (26)

4.3.5 Combustion Efficiency

The injector tip and the center of a combustion chamber are prone to be cooled too much, possibly due to poor combustion, thus causing incomplete combustion and inefficiency and emissions increases. Let us therefore strike a balance between cooling the exhaust gases and the heating of catalyst to normal operation temperature.

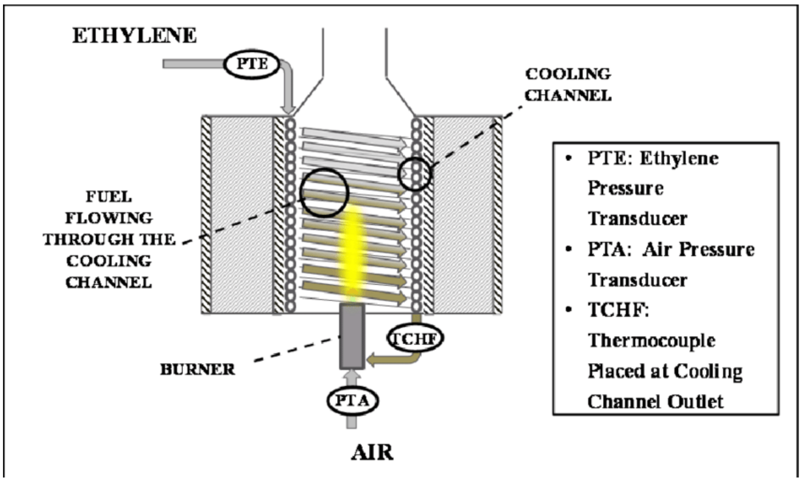


Figure 25 Schematic of cooling channel thermal measurement setup with ethylene–air combustion (27)

4.3.6 Coolant Flow Optimization:

Multi-loop cooling circuits provide customized cooling for the various engine zones according to their thermal requirement. Electrically operated water pumps and thermostatically controlled valves provide fast-acting flow cooling which can be used to better optimize ongoing cooling.

The choice of the right coolant is also an important point of the system design. Modern coolants such as the use of ethylene glycol-based antifreeze contain corrosion inhibitors that stop working over time due to normal use.

Moreover, nanofluid coolant enhance heat transfer characteristic has been achieved with the addition of nano-sized particles (Al2O3, CuO, SiC) in the coolant over the length of time by increasing the thermal conductivity out of the coolant.

4.4 Material Selection and Heat Transfer Performance

The choice of materials is an important factor for the long-term durability, wear and thermal degradation resistance in engine components. Because the lubrication and the cooling systems are in direct contact with engine constituents, careful selection of materials that include metal alloys, surface coatings, and synthetic lubricants is crucial for optimum performance.

1.High-Performance Alloys:

The engine block and cylinder head are to be subjected to high thermal and mechanical loads. ACM1: AlMgSi-alloy ACM1 has Good thermal conductivity and The property tester is very good. For such parts as bearings and piston rings, Ni-Cr-based alloys offer good wear resistance.

2.Nanocoatings and Surface Treatments:

Piston skirts and cam lobes are treated with Diamond-Like Carbon (DLC) for less friction and greater wear resistance. Cylinder head ceramic coatings enhance heat rejection and thermal barrier by reducing heat transfer from cylinder head to engine compartment walls.

3.Heat-Resistant Synthetic Lubricants:

Current synthetic base oils (PAO's & esters) provide better high temperature viscosity stability than mineral oils do. Additives such as MoS2 (molybdenum disulfide) and boron nitride are introduced to the base oil and these additives enhance lubricity under extreme conditions and also provide anti-welding.

With the above material technologies, it is possible to further improve the lubrication and the cooling system, which can in turn improve both the system efficiency, the energy losses and the lifetime of engines. The CFD, FEA and testing strategy that we designed is expected to provide a further optimization of the system to meet the requirements of today's high performance diesel engines.

The choice of materials has a significant impact on both the heat transfer performance and durability of cooling systems for engines, and on the ease by which such systems can be manufactured. The heat rejection rate from the combustion chamber to the coolant medium is directly affected by the thermal conductivity of the material. Accordingly, a compromise of thermal properties, strength, corrosion resistance, and economics must be given to the choice of materials along with the selection of polymeric gasket material

Table 2 Commonly Used Materials in Cooling System Components Their Tradeoffs

Material	Thermal Conductivity (W/m·K)	Density (g/cm³)	Corrosion Resistance	Machinability	Application Area
Aluminum Alloys	~205	~2.7	Moderate	Excellent	Cylinder head, block
Cast Iron	~80	~7.2	High	Moderate	Cylinder liners, block
Copper	~390	~8.9	Low (without coating)	Moderate	Specialized heat exchangers
Ceramic Coatings	<5–30 (varies)		Excellent	-	Liner coatings, thermal barriers

4.5 Thermodynamics Calculations about Cooling System Design

The rate of heat conduction through a solid engine component can be estimated by Fourier's law of heat conduction:

$$Q = k * A * \frac{\Delta T}{L} \tag{22}$$

Where:

Q = Heat transfer rate (W)

k = Thermal conductivity of the material (W/m·K)

A = Cross-sectional area of heat flow (m^2)

ΔT = Temperature difference across the material (K)

Thus, materials with higher k values allow faster heat dissipation, which is essential in maintaining optimal cylinder head and liner temperatures during operation.

To quantify heat transfer within the engine, the following equations are utilized:

- **Fourier's Law for Conduction:**

$$q = -k * A * \frac{dT}{dx} \tag{23}$$

Where:

q: Heat transfer rate (W)

k: Thermal conductivity (W/m·K)

A: Cross-sectional area (m^2)

dT/dx: Temperature gradient (K/m)

Newton's Law of Cooling for Convection:

$$\dot{Q} = \dot{m}c_p(T_{inlet} - T_{exit}) = hA_s(\frac{T_{inlet} + T_{exit}}{2} - T_\infty) \tag{24}$$

Where:

$\dot{Q}$: Heat transfer rate (W)

$\dot{m}$: Mass flow rate of water (kg/s)

c_p: Specific heat capacity of water (J/kg·K)

T_{inlet} and T_{exit}: Water inlet and exit temperatures (°C)

h: Heat transfer coefficient (W/m²·K)

A_s: Lateral surface area of the pipe (m²)

T_∞: Ambient temperature (°C)

The lateral surface area for each pipe is given by:

$$A_s = \pi DL \tag{25}$$

These relations are useful when it comes to designing the cooling channels, which need to guide the heat transfer through the engine components in a certain way.

The design of a suitable cooling system is crucial to keep the temperature level inside the internal combustion engine, especially when big diesel engines are set up in a small space. The management of the heat is really difficult. The cooling system also has to absorb heat and disperse it away from the engine and prevent components from exceeding their temperature constraints during combustion.

The combustion of liquid fuel in internal combustion engines (ICEs) results in the conversion of chemical energy to mechanical work. However, much of this energy dissipates as heat. Only a third to a half of the energy released in burning the fuel actually provides useful work; the rest is waste heat lost in the exhaust gases, through the surfaces of the engine, and as friction. Such surplus heat must be properly controlled so that the engine is not overheated to cause functional degradation and lower efficiency.

If we can also find the numbers, the fan is on a 30% load for h/c of the engine. The design of the fan is outside the scope of this work. So here, we will assume some value and then size the cooling passages of the system.

In a three-cylinder diesel engine having a water-cooling system, the engine block temperature is kept constant at 90°C and the cooling water returning to the engine from the radiator is at 75°C. It is found that 30% of the total heat load of the engine is dissipated directly to the atmosphere with the help of a fan. The other 70 percent of that heat has to be removed by the coolant circuit of the engine. On the basis of this information, we can determine the rate of heat transfer ($\dot{Q}$) flowed out from the coolant circuit alone without fan intervention. Next, we will find the temperature of the coolant as it leaves after picking up heat from the engine. Based on this data and the average coolant temperature, we are going to determine:

- (U), The overall heat transfer coefficient
- (A), The required heat transfer surface area
- (L). The corresponding cooling channel length

Generally, 3 cylinder diesel engines generates 40 kW Power.

It is known that 70% of the total heat generated by the engine is dissipated through the cooling channels. The heat carried by the coolant $\dot{Q}$ (Watts) can be estimated supposing a total heat load Q_{total}.

In a conventional diesel powerplant, less than a third of the fuel's energy gets converted into mechanical work that turns the crankshaft. Approximately 25% of the energy is dissipated through the cooling system (coolant and oil cooling). A further 10% is lost in the form of exhaust gases as heat.

At the same time, we can assume the engine has 24% thermal efficiency averagely. Thus:

$$E_{fuel} = \frac{P_{mechanical}}{\eta} = \frac{40}{0.25} = 166.7\ kW$$

Heat to be rejected via cooling:

$$Q_{cooling} = E_{fuel} * (0.4) = 166.7 * (0.25) = 40.73\ kW$$

This value indicates that we have to discharge averagely 40.73 kW heat from engine.

The coolant (water) inlet-exit temperature is another significant factor for calculation. For 3-cylinder engines, the coolant enters 75 °C and exits 90 °C.

The film temperature is needed for get to important coefficients of water:

$$T_f = \frac{T_i + T_e}{2} = \frac{75 + 90}{2} = 82.5\ °C$$

Our liquid's significant values are:

Prandtl number, Pr = 2.15

Thermal conductivity, k = 0.672 W/mK

Specific heat, c_p = 4199 J/kgK

Density, $\rho = 969\ kg/m^3$

Dynamic viscosity, $\mu = 0.344 * 10^{-3}$

These values are determined from Çengel's Heat Transfer Table A-9 according to water at 82.5 °C.

After this information we can use the equation (25). The heat transfer rate is 40.73 kW.

$$\dot{Q} = \dot{m}c_p(T_{inlet} - T_{exit}) = \dot{m} * \left(4.199\frac{kJ}{kgK}\right) * (75 - 90) = 40.73\ kW$$

$$\dot{m} = 0.000647\ kg/s$$

The needed average water velocity is 1.5 m/s. Therefore, the mass flow rate formula is:

$$\dot{m} = \rho * V * A = 969 * 1.5 * A = 0.647\ kg/s$$

$$A = \frac{\dot{m}}{\rho * V} = \pi * \frac{D^2}{4} = 0.000444881\ m^2 = 444.881\ mm^2$$

$$D = \sqrt{4\pi A} = \sqrt{4\pi * (444.881\ mm^2)} = 23.8\ mm = 0.0238\ m$$

This means that averagely 23.8 mm pipe diameter is needed for dissipate the 40.73 kW heat from the engine with the fan system.

In addition that the convection calculation will be realized. We should know that the Reynolds number, as a result of the flow regime is laminar.

$$Re = \frac{\rho * V_{avg} * D}{\mu} = \frac{969 * 1.5 * 0.0238}{0.344 * 10^{-3}} = 100.562$$

According to this regime we should do make calculations. Firstly we should to find the entry length of the flow.

$$L_{t,laminar} = 0.05 * Re * Pr * D \tag{26}$$

$$L_{t,laminar} = 0.05 * Re * Pr * D = 0.05 * 100.562 * 2.15 * 0.0238 = 0.257\ m$$

Our estimated pipe's total length is longer than entrance length. Thus, we can accept as the flow is fully developed.

Then the Nusselt number should be determined according to heat transfer table because of our flow is fully developed.

T_s = 3.66 according to Yunus Çengel's Heat Transfer Book.

$$Nu = \frac{h * D}{k} \tag{27}$$

So the heat transfer coefficient is:

$$h = \frac{Nu * k}{D} \tag{28}$$

So;

Our heat transfer coefficient is:

$$h = \frac{Nu * k}{D} = \frac{3.66 * 0.672\ W/mK}{0.0238\ m} = 103.341\ W/m^2K$$

And finally the convection heat rate is:

$$\dot{Q} = h * A_s * \Delta\mathrm{T} \tag{29}$$

For our system:

$$\dot{Q} = h * A_s * \Delta\mathrm{T} = 0.103341\ * \mathrm{A}_s * (90 - 75) = 40.73\ \mathrm{kW}$$

$$A_s = \pi DL = \pi * 0.0238 * L = 26.275\ m^2$$

$$L = 3.51\ m$$

5 Conclusion

The study has achieved the full design and CAD-based integration of a lubricant and cooling system for an installed compact 3-cylinder diesel engine.

Also fully developed is the lubrication system with optimized oil routing, precisely calculated flow paths, and pressure-stabilized channels for reliable lubrication of all important engine components, such as crankshaft journals, pistons, and camshafts. Other elements, such as turbulence-reducing channel geometry, enhanced filtration design, and correctly chosen oil viscosity in conjunction with the above-mentioned features, combined enable the system to optimally reduce frictional losses and increase component longevity among various operating scenarios.

Finally, the cooling system has been completely designed and engineered using analytical engineering techniques. The cooling jackets and flow paths were designed to control heat loads in key areas like the combustion chamber, the valve seats, and cylinder walls. The system configuration, which included the mechanical pump, the radiator, and the thermostat location, was developed according to the original engine configuration. Design guidelines were established on the basis of estimated heat load and flow rate, maintaining stable heat removal at a low cost without the need of advanced control electronics or device simulations for optimization.

Before entering the geometric modeling phase, both sub-systems were subjected to a detailed engineering calculation that had a significant impact on the definition of the final design. The lubrication system values of flow rate (Q), pressure drop (ΔP), and the oil velocity for the lubrication were estimated through the Hagen–Poiseuille equation to provide enough lubrication in different load and temperature conditions. The dynamic viscosity characteristic of the lubricant over a range of temperatures was also considered to ensure film stability and to minimize energy consumption. The cooling-coil system was also sized by heat transfer calculations, based on calculated cooling loads that would be imposed on the system.

Thermal loads were calculated according to fuel energy distribution and heat rejection ratio, and the channel size was then determined to maximize flow and minimize thermal stress.

These final designs have all been incorporated into the existing 3D CAD model of the engine, with the corresponding images included in Section 5 of this report to offer a visual representation of the internal routing and channel layout.

The results of this project show the potential effects of systematic fluid subsystem design on the reliability, performance, and longevity of the internal combustion engine. With the use of some basic metrics and concentrating on the practical, the lubrication and cooling systems developed meet the requirements of the contemporary diesel engines using the universally expensive or complicated solutions.

Finally, this work offers a solid base for the application of thermally and mechanically optimized subsystems in small compact diesel engines. The designed systems are not only manufacturable and efficient but also easily applied to multiple light-duty economic systems for industrial or transportation applications where simplicity, robustness, and efficiency are the main considerations.

6 . Appendix

6.1 CAD Visualizations of Channel-Integrated Components

6.1.1 Lubrication Channels – CAD Models

6.1.1.1 Cylinder Block

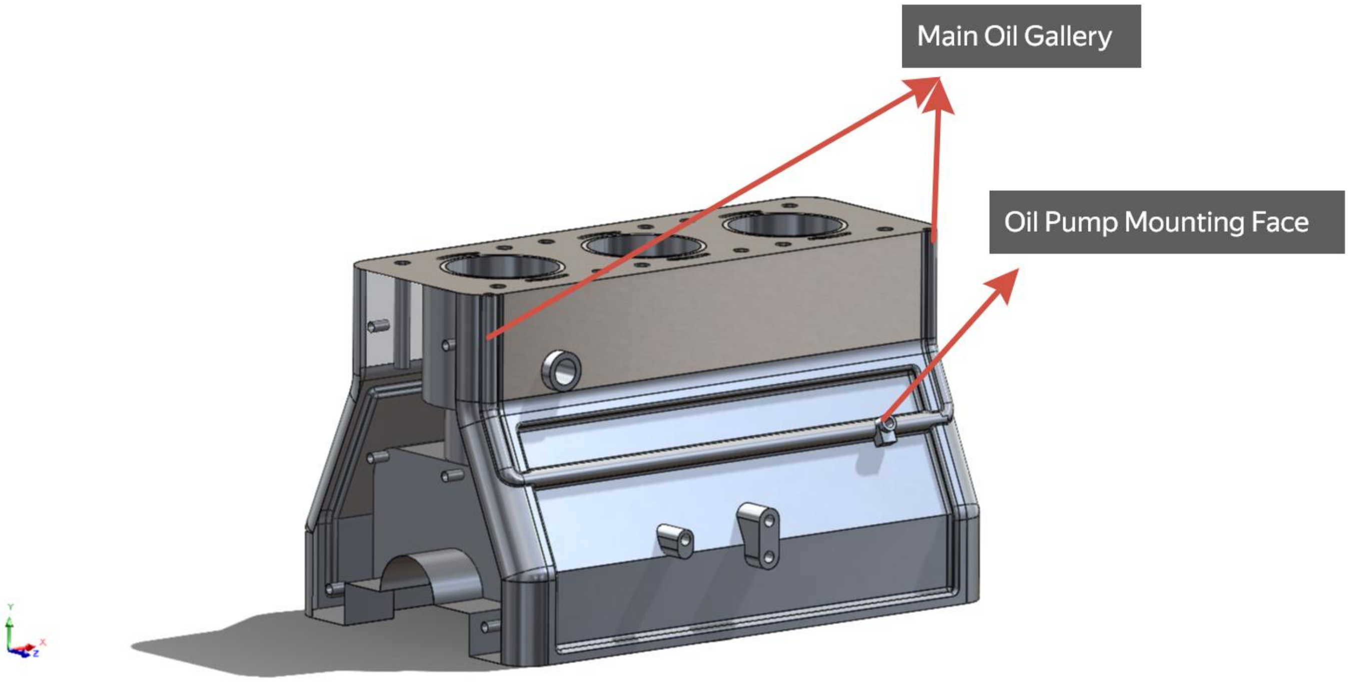


Figure 26 Main Oil Gallery

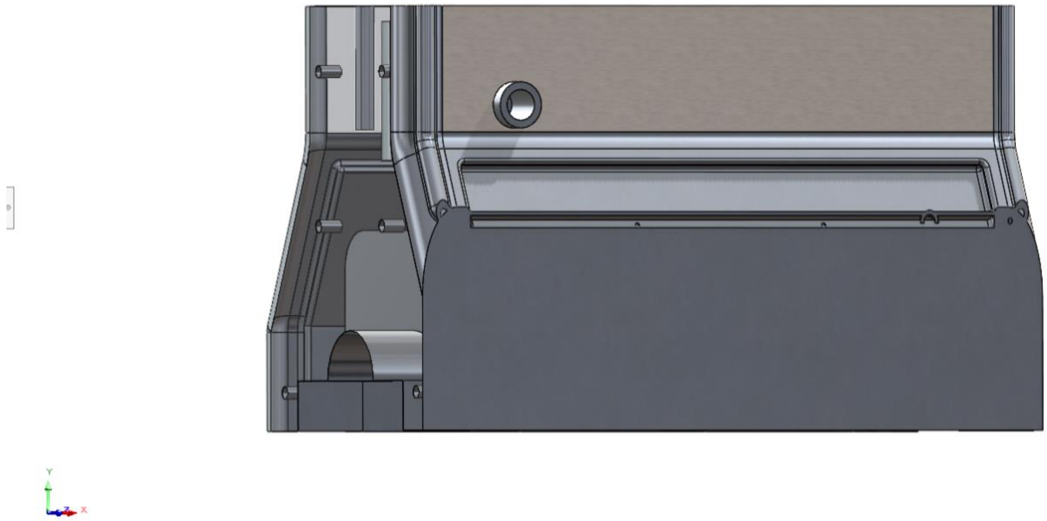


Figure 27 Cross Sectional View of Main Oil Gallery

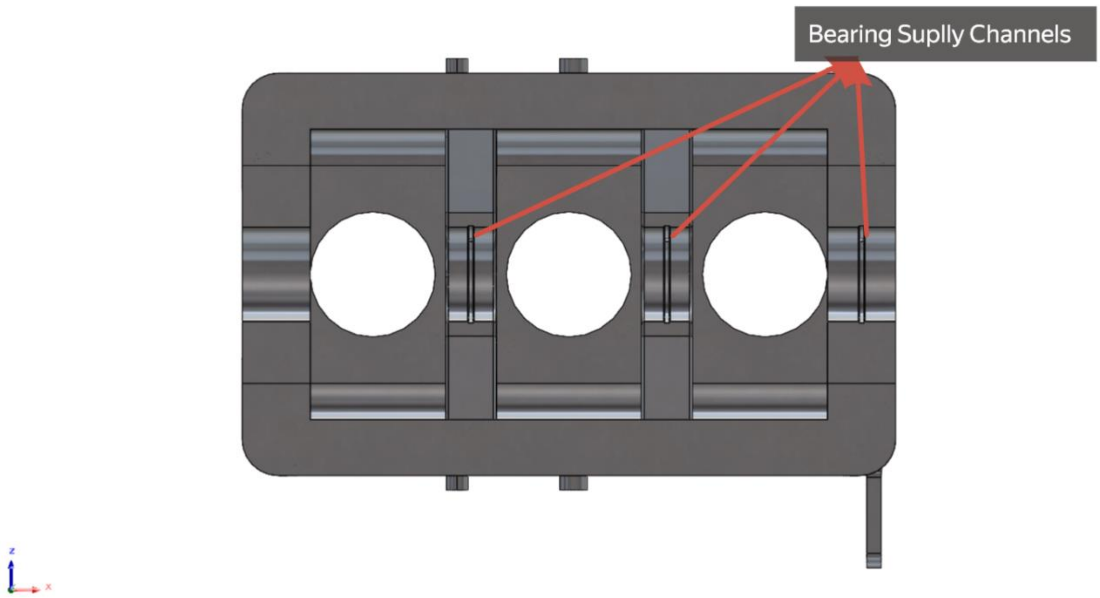


Figure 28 Bearing Supply Channels

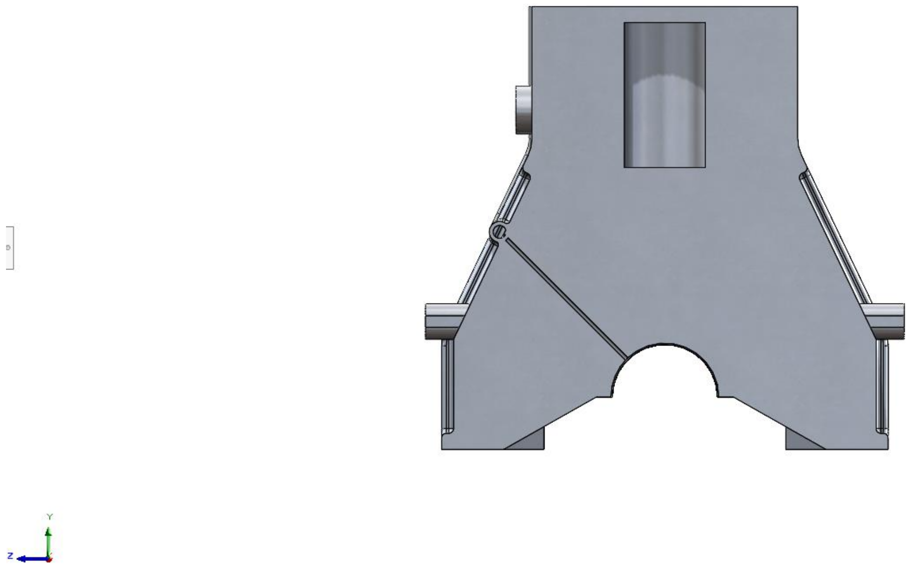


Figure 29 Cross Sectional View of Bearing Supply Channels

6.1.1.2 Crankshaft

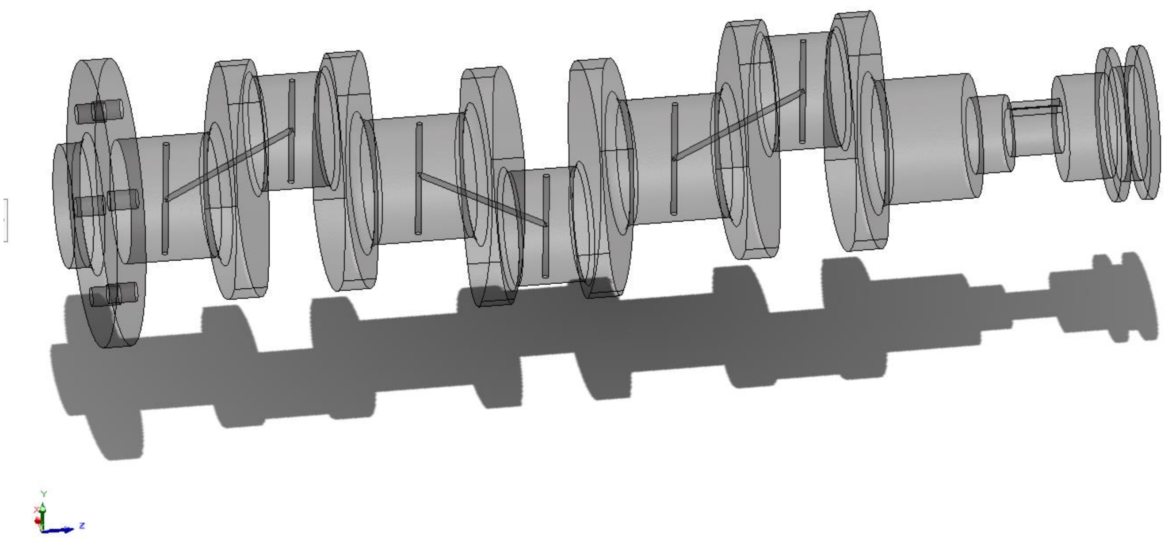


Figure 30 Lubrication Channels of Crankshaft

6.1.1.3 Connecting Rods

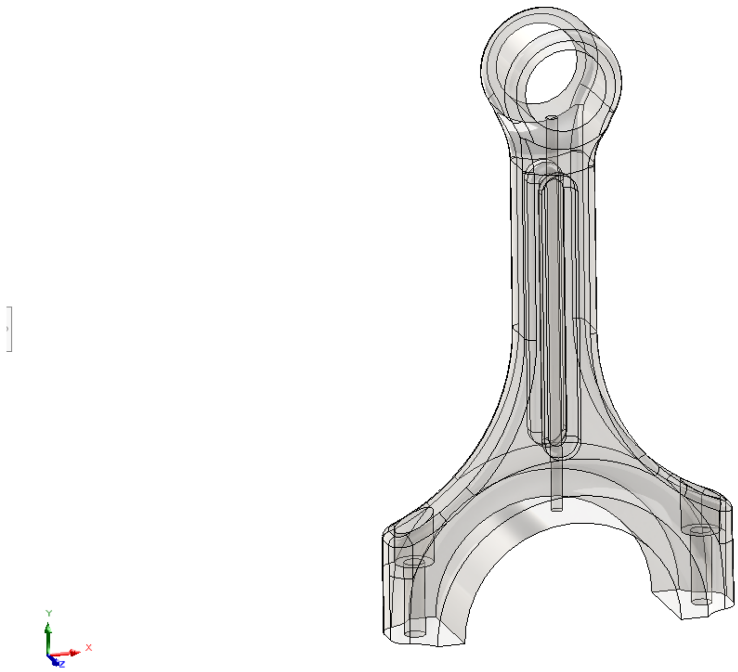


Figure 31 Lubrication Channel of Connection Rod

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6.1.2 Coolant Channels – CAD Models

6.1.2.1 Cylinder Block

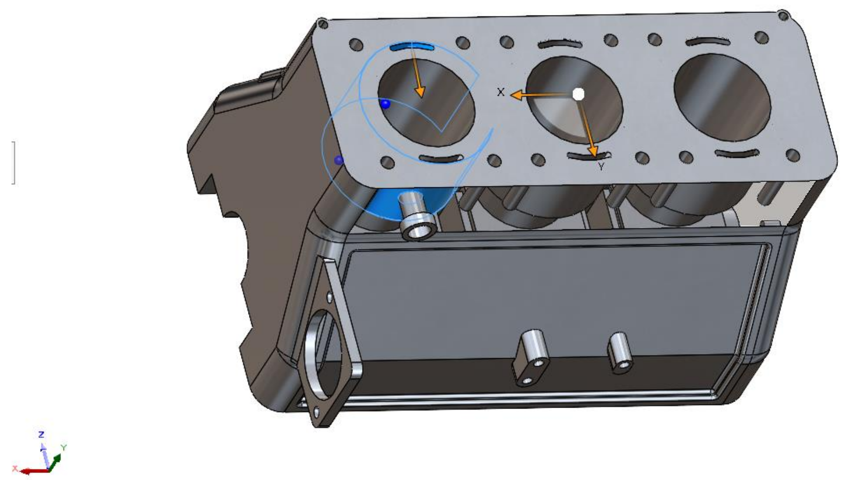

Figure 32 Coolant Channels, Water Jackets of Cylinder Block

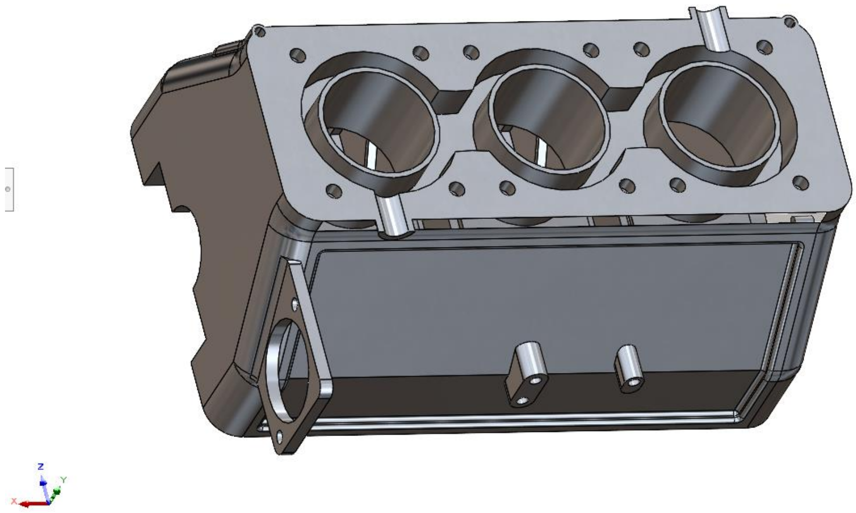

Figure 33 Cross Sectional View of Water Jackets

6.1.2.2 Cylinder Head

Figure 34 Cooling channels and jackets at Cylinder Head

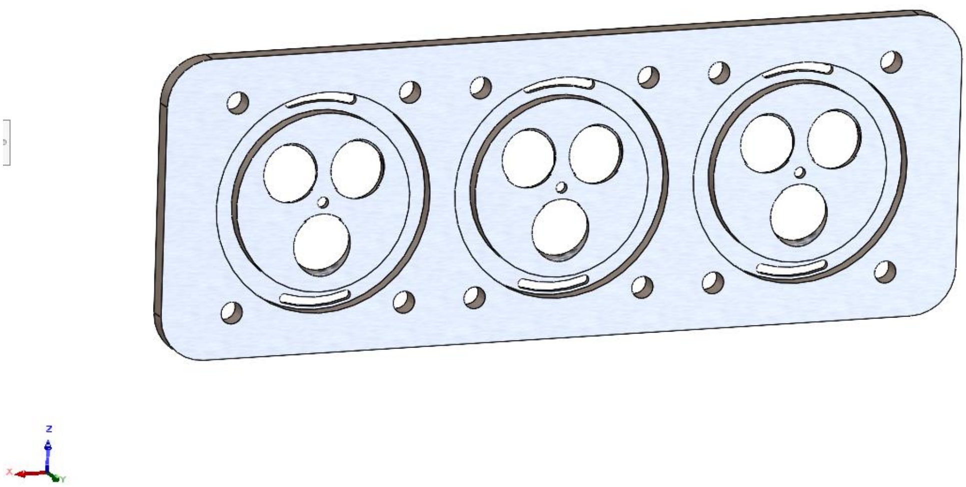

Figure 35 Cross Sectional View Of Cylinder Head

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