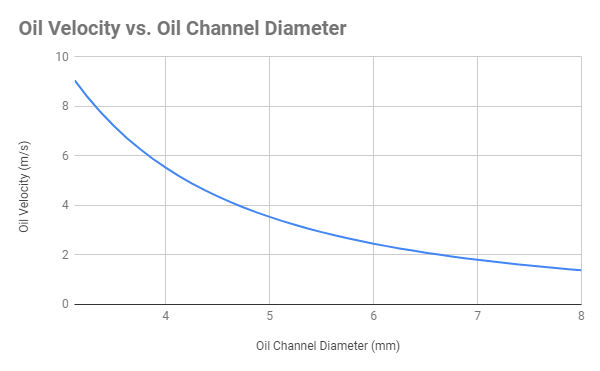
**Lubrication**

*Theory of Operations*

The starting point for the oil is the oil pan, or sump. It is then run through the oil strainer at the bottom of the pan, and flows through an intake tube through the oil pump and through a full flow, and fine filter. There is also a bypass valve before the filters to ensure required pressure is always met through the system if the filters become clogged. The regulated pressure for the pressure relief valves is 78psi. The total flow of oil through the system (and thus the pump) is 1.23gal/min at maximum rated RPM, with an estimated total volume of oil in the system of 1.27 gallons. The selected pump is a helical gear style of pump and is an electric pump powered by the actuator. An electric pump was chosen so that it could easily sit outside the crankcase and the camshaft/s would not have to be extended to drive the pump, and also an additional timing chain on the crankshaft would not be needed. After flowing through the filters, the oil goes to a pressure relief valve directly outside the main engine block drillings to ensure that the system is never too highly pressurized. These drillings are drilled as a secondary operation, and some have specific extrusions made for them through the block to ensure there is enough material around them to prevent leaks. These drillings take the oil to three different places. The first destination is the main crankshaft bearings with a flow rate of 0.97gal/min which is the required flow for the crankshaft bearings and connecting rod bearings. From here the oil leaks out of the bearings, and also flows through a drilling within the crankshaft to the connecting rod bearings. Here, the oil again leaks out the side and also flows through drillings in the connecting rods to the piston pin. The pistons are lubricated through the oil that leaks out of the sides of the bearings. This oil drips onto the spinning crankshaft and is flung onto the pistons through splash lubrication. Another engine block channel takes the oil to the camshaft bearings with a flow rate of 0.09gal/min which is the flow rate required for all bearings combined. Here the oil again leaks out onto the spinning shaft to lubricate the surrounding components as it lubricates the camshaft as well. The third place that the oil channels deliver oil to is the tappets, or valve lifters, at the base of the pushrods with a flow rate of 0.04gal/min. This flow rate was estimated using the surface area of the valves to be coated, and the max flow rate through the main engine drillings. The oil flows into these lifters and this helps control the accuracy of the lifters over the rise and fall of the cycle. From the lifters, the oil then flows through the pushrods, which have center bores drilled through them. Since these bores only carry a fraction the the oil flowing through the system, they only need to be wide enough to carry the oil needed for two valves each, as that is where the oil goes after flowing through them. This smaller flow of oil allows the bores drilled through the center of the rods to be small enough so such that it should not cause them to yield under the stress of normal operating conditions. After flowing through the rods, the oil enters holes drilled into the rocker arms above the cylinder head. From here oil is sprayed out onto the valve heads and surrounding areas. There are oil return channels drilled through the cylinder head, piston chamber, and engine block to allow the oil sprayed over the valves to return to the sump. The drillings have been placed at the lowest point on the cylinder head to ensure that all the oil will return to the sump. At all other places where the oil is sprayed out, it then flows back down the sides of the engine block and crankcase where it is returned to the oil pan for refiltering and circulation. As the engine is run and components wear, the oil begins to degrade slightly, and debris particles from the engine begin to build up. The filters are meant to catch particles large enough to damage the engine and extend the operating life of the oil and overall system, however they, along with the oil itself, must be changed periodically. Since it is difficult to estimate the amount of wear particles that will be deposited in the oil through purely theoretical calculations the initial oil change period will be specified as the recommendation of the oil used. The oil used for analysis and recommended type is SAE 10W-40 which is a multigrade oil, so a maintenance period of 5,000 miles is specified. However,as physical models are produced and testing can occur, this will be modified to fit the particular wear properties of this engine. The oil filter should also be changed will every oil change. It should be noted that the mounting for the filter and pump have not been included in the design of this engine. Because an electric pump was specified, it was decided that the mounting would be left to the bike manufacturer for easier maintenance, as an inlet to the engine drillings has been design into the bike, so the manufacturer must only connect the pump to the inlet. The mounting for the filter was also deemed to be out of scope for this project, as it can simply be mounted with the pump which was did not have a designed mount either.

*System and Bearing Design Process*

The first thing considered when designing the lubrication system for this engine was the required oil flow rate for the system, as determined by bearing dimensions and valve lubrication requirements. Chapter 13 of the Juvinall textbook was used for the bearing design [#]. The first step in this process was to choose the L/D ratio for the bearings. After researching bearings and bearing design, it was determined that the optimal ratio was 0.5. This was selected for the crankshaft and camshaft dimensions, however due to journal length restrictions on the nested connecting rod bearings, they have an L/D ratio closer to 0.25. Next, the clearance of each bearing was selected in an iterative process to achieve desirable results from the calculations. The final clearances selected are: c\_crankshaft = 0.00098in, c\_connectingrod = 0.0016in, c\_camshaft = 0.00098in. These values were selected such that a minimum film thickness would be achieved on the order of 3.94e-5in. This was an optimum range as given by the textbook. The minimum film thickness is calculated using equation #. Using these values, the graphs in chapter 13 of Juvinall were then used to calculate the total leakage rates for every bearing. This was then combined with the estimated valve oil flow rate to come to the final, overall engine oil flow rate. After this flow rate was determined, the velocity of the oil through the main drillings and was compared to the diameter of the drillings to choose appropriate values for each (see figure below). The channel diameter was chosen to be 7mm (0.28in) with a velocity of 4.04mph.



Next, the pressure losses through the system were calculated to determine the necessary operating pressure for the pump and relief valves. This was determined using equation #. The value calculated from this equation was supplemented by an additional 10psi for every 1000RPM as suggested by multiple sources found online. The final pressure losses to overcome for the engine is estimated at 78psi. Looking at other engines, typical operating pressures are 60-70psi (goldwing source) so it is acceptable to say that this engine should operate at 78psi. Once the flow rate and pressure through the system was determined, the oil pump could be selected. In the case of this engine, space was limited within the crankcase and timing chain area, so it was determined that an electric pump would be selected. This also ensures that oil flow through the engine will be sufficient at lower RPMs, as the pump speed is not directly related to crankshaft speed, so higher flow rates can be achieved at lower speeds. An electric pump also has the advantage of being able to be mounted anywhere, so the mount for the pump, and filter, was determined to be out of scope for this reason.

Once all the above values were calculated, the physical design and modelling of the system to begin. This started with the crankshaft oil drillings being implemented into the design. The channels in this engine are rather unique in that there is a single drilling from the main bearing that forks into three smaller drillings near the connecting rod bearing holes. This is because of the nested connecting rod design. It should be noted that the outer bearings have slightly longer oil paths to reach the bearings, resulting in lower pressures. This was determined to be unimportant however, because the outer bearings support the forked connecting rod, and will thus have half the load placed on them as the main bearing, and so will require less oil pressure to operate effectively.

The next component to be designed was the bearings. Using the calculated dimensions and looking at other engine bearings, each bearing was developed. They are split into a top and bottom half, with the bottom half having the hole through which the oil enters the bearing, except for the connecting rod bearings which have the oil hole on the top half. The material for the bearings was done using a trade study of other bearings that are in use in engines today. The material designation for the bearings is a bimetal AST800 Wrapped Steel with Bronze. This is a steel backed bronze material that has been known to be excellent for lubricated applications, with high load capacity, excellent heat dissipation, and good fatigue properties and has been widely used in the automotive industry.

After the bearings were developed, the oil channels for the engine block were implemented. The first channel from the filter outlet is at the maximum diameter of 0.28in, and all of the subsequent diverging channels are drilled at a reduced diameter of 0.16in, with some more localized channels at a diameter of 0.12in such as in the cylinder head. It is important to note that all channels are a combination of straight lines, to ensure that they are possible to be drilled into the block as a secondary machining process, with some channels being drilled through extra extrusions in the block to ensure that all channels have sufficient area to be drilled through. Another special note about the drillings: the valve lifters are of course in motion through the engines operation, so the oil must have special channels to enter the lifters over the full course of motion. This is done by casting a trapezoidal cut into the lifter sleeve, with a width that is equal to the total lift of the cam. As this is a contact area, some oil will of course leak out onto the cams, providing more lubrication to the camshaft as well. Oil return channels were also included through the cylinder heads, piston chambers, and engine block to make it possible for the oil used for the valves to return to the sump.

The next component to be designed was the oil pan, along with the oil plug and dipstick. It should be recognized though that the oil pan is not in fact a unique part, but rather the bottom of the crankcase. In addition to reducing the number of parts in the engine and manufacturing processes to be performed, this also reduces noise emissions. Vibration of the oil pan and associated fasteners are a significant contributor to engine noise and the elimination of this part will help keep the engine quieter, which is an important aspect considering the target audience of this engine. The oil pan slopes down at the rear of the engine, ensuring that during acceleration the intake tube will always be submerged. The two main factors considered when designing the pan was the total oil required for operation (1.27 gallons) and the reduction of crankshaft dipping. Crankshaft dipping is when the crankshaft comes into contact with the oil sitting sump which is undesirable as it causes unnecessary power losses for the drivetrain. It must also be considered that the oil in the sump will shift as the bike accelerates and turns. It is difficult to estimate the maximum acceleration and tilt of the biek before production occurs, so an estimated 1-2in of space was allowed between the expected top of the oil and the bottom of the crankshaft. The drain plug was then inserted into the back corner of the sump, opposing the pump inlet drilling. It will be suggested that the engine be mounted such that the drain plug sits on the side of the bike that will be tilted when the bike is at rest, ensuring that all the oil will drain from the system during an oil change. Next, the dipstick and dipstick tube were placed into the engine block. The dipstick reaches into the lowest part of the sump and will be marked post production and analysis so that the minimum and maximum oil levels will be marked on the stick. It is also recommended that the engine be run briefly before an oil check and then let rest for a short period of time. This warms up the oil in the engine and allows it to more fully drain back into the sump, which allows for more accurate oil level readings and quicker draining of the oil.

All other components of the lubrication system have been specified with manufacturers and prices in the BOM. These parts include the intake tube and adapters, pressure relief valves, pump mounting bolts, O-rings, temperature sensor, drain plug, check valve an oil strainer. The exact filters and filter mount has been deemed to be out of scope, as they can be mounted together with the pump which has not been mounted to the bike as it is electric and may be mounted anywhere, within reason. All of the bearings are also considered purchased parts as they will be purchased from manufacturers with more expertise and experience in that area. This will be done for all lubricated bearings for crankshaft, camshaft, connecting rod, and the wrist pin which has a needle bearing.