Rotating Liner Engine
A New Approach to Reduce Engine Friction and Increase Fuel Economy in Heavy Duty Engines

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The Rotating Liner Engine (RLE) Design Objectives

RLE Technologies, Inc. (www.rotatingliner.com) is developing a new cylinder liner and head seal design that will lead to reduced piston assembly friction and wear in conventional piston engines. With a Rotating Liner Engine (RLE), the cylinder liner rotates and a unique hydrodynamic face seal replaces the conventional head gasket. Its application in heavy-duty diesel engines is expected to improve efficiency and reduce fuel consumption by 3 to 7% (depending on operating conditions), and prolong engine life by a factor of two to three times.

Efficient Diesel Engines and the Lubrication Challenge

Conventional internal combustion engines have been around for more than a century. Due to inherent high efficiency and low cost, IC engines continue to dominate many commercial markets, from passenger cars to ocean going vessels to on-site power generation. Because of its very high efficiency, the diesel engine is industry's leading prime mover, and will likely remain so for the foreseeable future.

Diesel engines achieve very high fuel efficiency for a number of reasons. First, part load operation is achieved without throttling. Second, a high compression ratio leads to high thermal efficiency. Third, turbo-charging allows high specific loads by forcing higher quantities of air in a given displacement, which leads to even greater thermal efficiency.

The efficiency of diesel engines approaches 50%. This means that only about 50% (less in smaller engines) of the heat from combusted fuel is converted into useful work. Most of the lost energy is dissipated due to inherent thermodynamic limitations (heat loss to the coolant, exhaust gases, etc.). Therefore, traditional efforts for improving diesel efficiency are focused on minimizing these large thermal losses. This effort has been very effective over the decades, but further results are reaching a plateau, as limitations due to the Second Law of Thermodynamics are encountered.

About 5% of the combustion heat (or about 10 % of the potentially useful power) is lost to mechanical friction. Even though improvements in friction performance have been made via design optimizations and lubricant improvement, no significant engine redesign has been attempted in order to re-capture friction energy. The RLE design does exactly that. Through a modest redesign of certain components of the engine, the RLE captures a large portion of piston assembly friction, the largest component in engine friction, while also reducing wear. Even though the redesign is modest, it is a complementary technology that can be applied to existing engine designs. The overall thermal efficiency is expected to increase from 50% to about 52%, a very significant improvement (the corresponding reduction in fuel consumption is approximately 3 to 4% at full load).

As more recent thermodynamic improvements start taking effect, the minimization of mechanical losses will become more challenging with traditional friction reduction methods. Factors that help thermodynamic efficiency also create very high cylinder pressures, which increase piston ring friction and wear. Piston rings, which perform the critical role of sealing the gap between the piston and cylinder liner, are lubricated by a very thin film of oil. However, due to the very low magnitude of sliding speed around the top dead center position (TDC), piston rings do not "hydroplane" on the oil film as they do at mid stroke in the cylinder. Consequently, metallic contact at TDC creates wear, and can increase friction coefficient by up to 100 times. High peak pressure that occurs around TDC intensifies this phenomenon (the peak pressure in a heavy duty diesel is over twice that of a spark-ignited automotive engine). This explains why the wear area of a cylinder liner tends to be in the TDC area, while the mid portion of the cylinder has typically low wear.

Since cylinder liner wear sets a limit to the overall life of the engine, it is important to find an economical way to reduce friction in the areas around the TDC. While traditional solutions attempt to relieve the effects of the metallic contact between the piston rings and piston skirt with the liner, the RLE approach is focused on nearly eliminating the contact.

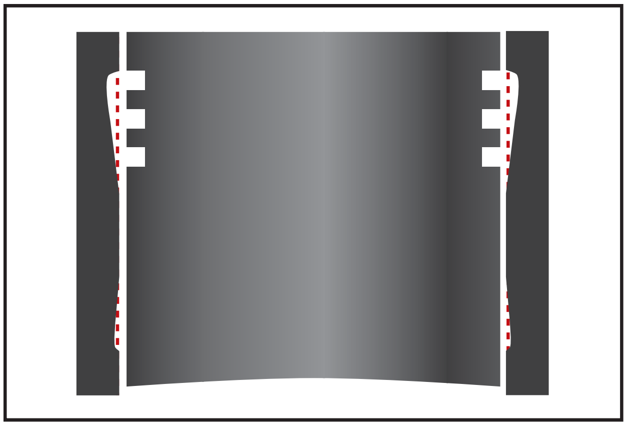

Figure 1. Pattern of bore wear for all conventional engines. Maximum wear occurs around the area where the compression ring reverses, and is amplified by gas pressure loading. Some wear also occurs at bottom dead center, but the lack of pressure reduces the depth. The bore wear sets the limit of engine life by increasing blow-by and oil consumption.

The Traditional Approach to the Lubrication Challenge

Over the decades, new techniques were developed to reduce the intensity of the metallic contact and its consequences. First, multi-weight oils allowed a low viscosity for a cold start while permitting higher viscosity at high temperature conditions. Also, better design of pistons skirts and piston rings, along with zinc and lead based lubricant additives were developed that were able to tolerate higher metallic contact pressure with reduced friction and wear. These improvements generally stayed ahead of increases in peak pressure for thermodynamic efficiency improvements, resulting in continuous improvement in both engine life and friction. Still, this metal-to-metal contact persists, with the piston assembly of a modern diesel accounting for 50 to 60% of total mechanical losses. This has a significant impact on total energy consumption because of the wide application of IC engines in use today. It has been estimated by a DOE study that up to approximately 1% of total fuel consumption in the U.S. is used to overcome piston ring friction. This excludes piston skirt friction which is usually lower than piston ring friction.

However, very high peak pressure of a diesel engine also leads to high specific load, so that total engine friction losses are generally only about 10% of total thermodynamic power at full load. At less than full load, engine friction accounts for a larger portion of thermodynamic combustion power, which is defined to as “indicated” power. At idle, friction accounts for 100% of indicated power. In truck applications, the operating conditions constantly change between high load, low load or idle, depending on traffic.

In other applications like marine and on-site generation, the power setting is more constant and closer to full load. In these applications the losses due to friction are a smaller percentage of total generated power, but the actual loss of energy due to friction is greater because of the higher average pressures at full or constant load.

The RLE Solution

RLE technology is a new approach to this problem. Instead of relieving the effects of metallic contact close to the TDC area, cylinder liner rotation is expected to nearly eradicate it. Our research has shown that cylinder rotation will allow hydroplaning of the piston rings in areas where the slow piston motion fails, especially at TDC.

Sleeve Valve Engines: A Precursor to RLE

In discussing rotating cylinder liners, many engineers remember Sleeve Valve Engines (SVE’s). These engines were developed by the Ricardo laboratories prior to World War II, and were used extensively during the war for high output spark ignited aircraft engines. In SVE’s the conventional valve train was replaced by a ported cylinder liner that moved along an elliptical path. Intake and exhaust ports aligned at the proper timing with ports on the block, achieving the four stroke cycle. At TDC compression-expansion, the sleeve motion was purely rotational. The cylinder head gasket was replaced by set of piston rings that sealed the moving sleeve valve and cylinder head.

The objective of the SVE design was similar to modern trends in diesel design, namely the removal of red-hot exhaust valves would improve the detonation performance of the supercharged (spark ignition) engine, allowing higher operating pressures and thermodynamic output. It was understood that extra parts would add more mechanical friction than the simple poppet valves, but it was expected that additional thermodynamic power would more than compensate for slightly more mechanical friction. However, when the first Ricardo SVE was tested against a similar poppet valve engine, it was found that the mechanical friction of the SVE was significantly lower, both under motoring (no combustion) and firing conditions. The rotary motion of the sleeve was believed to be responsible for reducing friction in the piston assembly by nearly eliminating the metallic contact of the piston rings around TDC. In fact, an experimental SVE diesel engine achieved record fuel efficiency due to reduced friction. This record was not broken until many decades later when turbocharged diesels appeared.

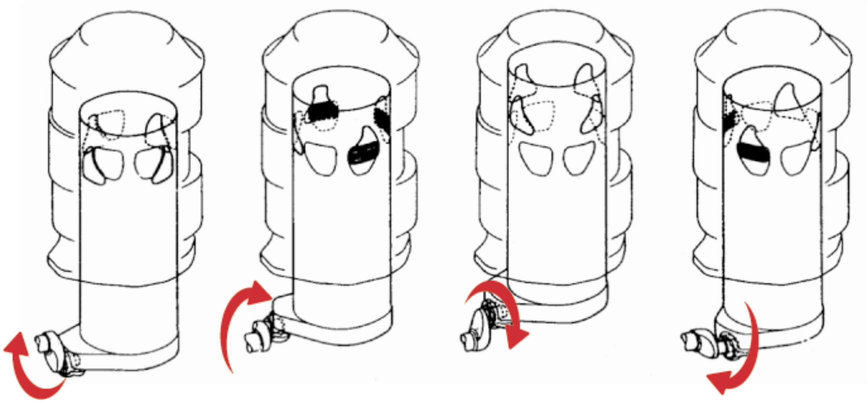

Figure 2. SVE liner motion. The ports on the sleeve (the bolder outline) align with the ports on the block (less bold outline) at the right time, and therefore achieve the gas exchange process, just like the poppet valves the sleeve valve replaces. In the compression/expansion stroke (3rd picture from the left), the sleeve ports are above the junk head piston rings (Figure 3), and therefore the ports are essentially covered and protected from combustion gases. The 3rd picture from the left also illustrates sleeve action when the piston is at TDC compression/expansion, and the liner motion is instantaneously purely rotational. This element of sleeve motion was beneficial in terms of friction/wear, and is reproduced by the RLE.

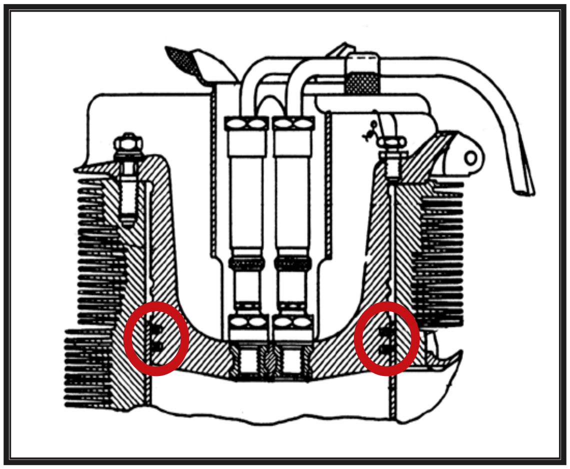

Figure 3. SVE head/sleeve sealed by “junk” head piston rings that replaced the head gasket in the 18 cylinder, 36 liter Bristol Hercules air cooled radial engine (1400-2000 hp). In spite of two sets of piston rings per cylinder and sleeve valve viscous drag being much higher than the power to operate the poppet valves, production SVE’s had total friction “usually lower” than conventional designs according to Ricardo, while it was well established that certain experimental SVE’s had significantly lower friction than conventional engines similar in all other respects.

Versions of the SVE saw large scale service during the war (over 200 million total horsepower or over 60,000 SVEs were built). Based on the maintenance experience/records from these engines, it was confirmed that the localized cylinder wear pattern of the conventional engine (Figure 1) was absent in the SVE, and that overall bore wear was more than 10 times lower. This was considered a confirmation of the above theory. Unlike the conventional engine, bore ring wear was so low that it did not set the limit of engine life. However, as the SVE aero engine was developed by Bristol and Napier in England, interest in the friction advantage was not as pronounced as in other areas of engine performance, and therefore no significant effort was spent to quantify this unexpected benefit. With improved piston ring lubrication, liquid cooled SVE’s achieved very high specific power, and a very high Brake Mean Effective Pressure (BMEP) of 350+ psi. Operation at peak BMEP could be maintained indefinitely; as opposed to only 15 minutes with poppet valve engines (BMEP is a way of expressing specific engine torque, proportional to output torque divided by engine displacement). BMEP levels of these engines were actually higher than modern diesels (stationary power and marine diesels are still limited to only 15 minute operation at peak BMEP) and their specific power (hp per liter) was about double that of a modern diesel.

Due to the performance of the SVE's, Rolls Royce, the largest British aero engine manufacturer, also developed two high output SVE's as well as an experimental two stroke ultra-high power SVE. However, before these new engines were put in large scale production, jet engines displaced all large piston aircraft engines. Within 24 months, all research in piston aero-engines, including SVE's two stroke development, ceased in England, and the piston lubrication advantages of SVE's rotary sleeve valve was forgotten.

Extinction of the SVE design was not due to an inability to compete with conventional engine design; it was due to the disruptive nature of jet engines. While the SVE could have propagated to other markets due to the inherent friction advantage, this friction benefit was never sufficiently quantified. The reason for the lack of interest in the SVE friction reduction by the aero engine manufacturers was probably because the thermodynamic advantage of knock suppression was considered of greater importance for their high specific power spark ignition engines. However, in the late forties or fifties, there were no other spark ignition high specific power engine markets for the SVE to propagate to, and the high specific output high pressure diesel engine (where the SVE friction advantage could have paid off) was at its infancy. Therefore, the SVE's and their inherent lubrication advantage fell through the cracks of time.

The RLE Advantage

Unlike the ported SVE which can not meet modern emissions regulations, the RLE reduces metallic contact during high pressure combustion and can meet modern emissions regulations.

The RLE uses conventional poppet valves that are known to make a small contribution to total engine friction. The relatively high friction sleeve valve is replaced by a lower drag, purely rotating liner without axial motion and since the liner is decoupled from valving, its speed can be optimized for friction reduction. Since the combustion chamber is conventional, modern clean combustion technologies will be used in the RLE. This will allow RLE technology to be applied to existing IC engine designs. The outside of the rotating liner is lubricated hydrodynamically (like crank bearings), resulting in negligible wear. This is similar to the SVE experience. Based on empirical engine friction models and bearing theory, friction reduction due to liner rotation is about 5 to 10 times higher than the viscous drag of the rotating liner. Total piston assembly friction will be reduced by more than half at full load, at the expense of a relatively low rotating liner drag, and a slightly higher production cost of the engine. However, in commercial and industrial markets, the added production cost will be quickly compensated by the fuel savings.

The benefit of the RLE in terms of percentage improvement in fuel consumption and absolute fuel savings depends on operating conditions of the engine. In applications where low load is frequent, the percentage improvement will be higher, while in a generator engine operating at full load, the percentage improvement will be lower since the importance of engine friction diminishes at the higher loads.   In Class 8 trucks for example operating at an average EPA duty cycle, we estimate that fuel economy will improve by approximately 7% which leads to a payback period of approximately 18 months from fuel savings alone. For on-site generation, we estimate that stationary engines operating at full and constant load will only improve by about 3%. However, since total fuel usage is substantially greater, we estimate that payback will be less than one year.

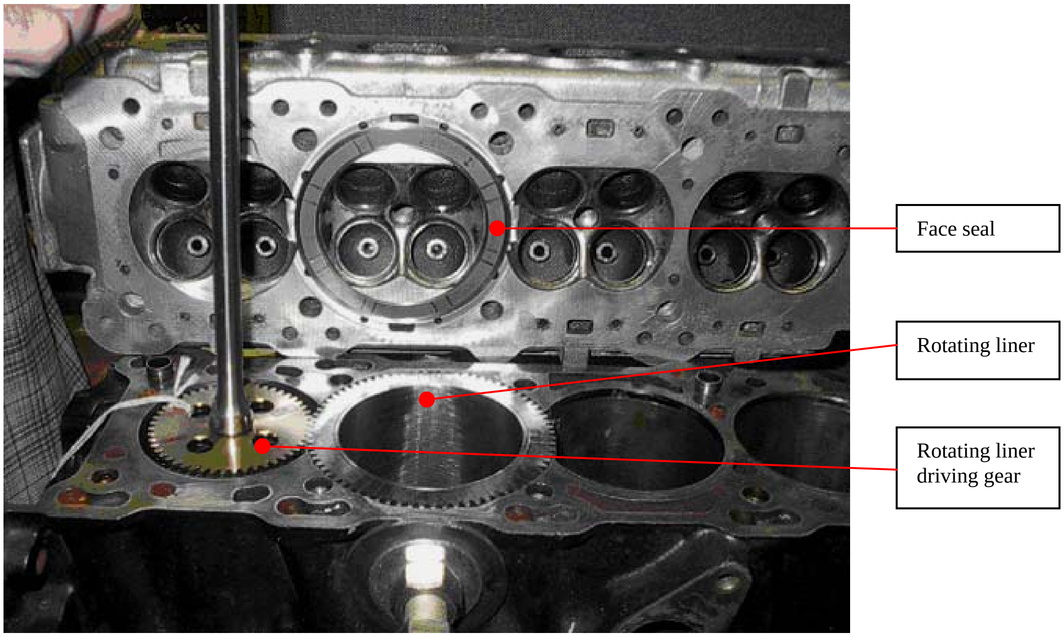

Figure 3. The RLE prototype at the University of Texas. The seal can be seen in a single cylinder engine, converted from a 4 cylinder automotive engine. Only the second cylinder from the left is active. All other throws are balanced with bob weights.

The key technical challenge to the success of RLE technology is the seal between the rotating liner and cylinder head. Instead of conventional piston rings used in SVE's (Figure 3) which add another blowby path, a gapless face seal design has been developed. This seal achieves low friction, low wear, and very low leakage. Research at the University of Texas at Austin, funded by several sources including the Department of Energy, solved the challenge of lubricant delivery to the RLE face seal. This research achieved hydrodynamic seal lubrication (no metallic contact, no wear) while preventing contamination of the combustion chamber by the seal lubricant. This seal was tested on a single cylinder light duty gasoline engine designed and developed by RLE Technologies, Inc. personnel at the University of Texas engine lab under the supervision of Dr. Ron D. Matthews, Head of the General Motors Foundation Combustion Sciences and Automotive Research Laboratories. Practically zero gas and oil leakage and low seal friction were confirmed. Also, during motoring testing of the RLE, friction of the rotating liner was measured via a rotating torque cell on the driving mechanism. This measurement proved that liner rotation minimizes metallic contact in the TDC area. Testing also indicated significant friction reduction of the RLE prototype compared to a similar gasoline engine with a conventional cylinder, albeit at these low pressure conditions.

RLE Technologies has applied the learning curve from its first prototype (alpha engine) and has started the design of a high pressure single cylinder beta engine in order to demonstrate the advantages of its technology in heavy duty diesels. FEA analysis coupled to hydrodynamic and thermal analysis of the seal and rotating liner assembly indicates that a redesigned seal can handle the peak pressure of a modern diesel. After the remaining design is finalized, the Company plans to build and test a high pressure six cylinder diesel Charlie engine and compare its performance with a conventional engine.

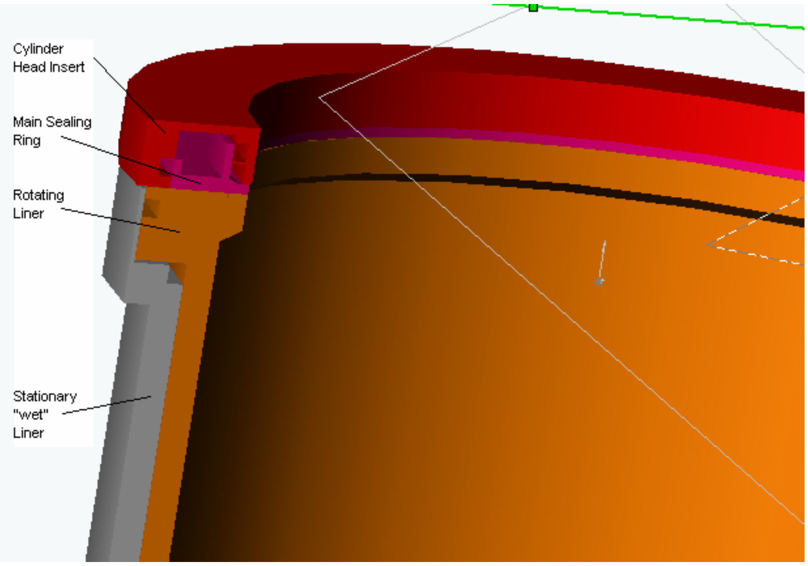

Figure 4. Section of RLE's design for a high pressure diesel engine. This design has been developed with the aid of finite element analysis software that combines pressure and thermal distortions with hydrodynamic solutions.

Diesel Exhaust Emissions Regulations and the RLE

RLE technology is being developed at the right time because lower friction reduces fuel consumption which, in turn, reduces emissions. In the case of particulate matter (PM), this reduction will be more than proportional. Diesel engine exhaust emissions are heavily regulated, demanding a number of operating changes, many of which will severely impact efficiency and lubrication, which ultimately affects cost of owning and operating these engines. Engines which are able to meet the 2003 emissions regulations have actually shown a loss in engine performance. Without improvements in fundamental engine design, the 2007 emissions regulations may cause even larger efficiency losses. In order to meet these regulations, modern diesel engines operate at even greater pressure. Excess air in the combustion chamber reduces nitrogen oxides (NOx), but also increases peak pressure with little added thermodynamic benefit. As a result, friction and wear of the piston assembly increases. Required recirculation of exhaust gases (EGR) also increases friction because of increased metallic contact due to more acid in the cylinders. Also, new diesel engines will require exhaust catalysts to meet 2007 emissions regulations. These catalysts are often incompatible with the conventional zinc-based additives that lubricate metallic contact. Rotating liner engine technology overcomes or avoids most of these challenges. The value proposition of RLE technology is compelling and offers an attractive way of diversifying the original engine manufacturers' market risks.

The RLE Solution

RLE Technologies, Inc. based in Austin, TX is developing this exciting new solution. For more information regarding the technology please contact Dr. Dimitrios Dardalis, Chief Technology Officer at dardal@rotatingliner.com. For information concerning the Company please contact Mr. Rick Yeager, President at ryeager@io.com.