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ABSTRACT

This paper presents a general overview about the previous research efforts into Low Heat Rejection Engine (LHRE) concept. The purpose of this paper is to explain the effect of insulation on engine performance, heat transfer characteristics, combustion and emission characteristics. Many researchers have carried out a large number of studies on LHRE concept. Some of them are experimental work and many are theoretical studies. In the case of LHR engines almost all theoretical studies predict improved performance but many experimental studies show different picture. This paper analyzes the reason for this deviation. The operating conditions, under which the experimental and simulation studies are carried out, have been clearly discussed. The factors, which affect thermal efficiency, combustion, and exhaust emissions in LHR engine, are deduced and their influences discussed. Effect of fuel injection characteristics on LHR engine performance is also reviewed. It is concluded that much more research is needed to overcome the practical problems before LHR engines can be put into production.

INTRODUCTION

Energy conservation and efficiency have always been the quest of engineers concerned with internal combustion engines. The diesel engine generally offers better fuel economy than its counterpart petrol engine. Even the diesel engine rejects about two thirds of the heat energy of the fuel, one-third to the coolant, and one third to the exhaust, leaving only about one-third as useful power output. Theoretically if the heat rejected could be reduced, then the thermal efficiency would be improved, at least up to the limit set by the second law of thermodynamics. Low Heat Rejection engines aim to do this by reducing the heat lost to the coolant.

The diesel engine with its combustion chamber walls insulated by ceramics is referred to as Low Heat-Rejection (LHR) engine. The LHR engine has been conceived basically to improve fuel economy by eliminating the conventional cooling system and converting part of the increased exhaust energy into shaft work using the turbocharged system.

A large number of studies on performance, structure and durability of the LHR engine have been carried out since Kamo and Bryzik (1) presented a new concept of the LHR engine combined with the turbocompound system. Although promising the results of the investigations have been somewhat mixed. Most have concluded that insulation reduces heat transfer, improves thermal efficiency, and increases energy availability in the exhaust. However contrary to the above expectations some experimental studies have indicated almost no improvement in thermal efficiency and claim that exhaust emissions deteriorated as compared to those of the conventional water-cooled engines.

The purpose of this paper is to examine the causes for these seemingly contradictory results. An attempt will be made here to review the previous studies to look into future possibilities of the LHR engine from the viewpoint of combustion, heat transfer and emission.

REVIEW

SIMULATION STUDIES

In the case of the insulated engine, cycle simulations are often used as predictive tools allowing an indication of the performance potential of a given design prior to conducting costly experiments. Numerous simulation studies have been carried out to analyze the performance of the insulated engine. These simulation works predict definite improvement in the thermal

performance of Low Heat Rejection engines over the conventionally cooled engines.

In most of the cases simulations are performed on turbocharged, heavy duty, high speed and multi cylinder diesel engines. In some cases simulations are carried on single cylinder, light duty and direct injection diesel engines. Some of the simulations have included turbocompound systems and Rankine bottoming cycle (Heat recovery systems). A summary of comparison of past simulation studies performed to evaluate Low Heat Rejection engines with those of conventionally cooled engines is shown in Table. 1. (2).

All the simulations are run at different load conditions and different level insulations starting from no insulation (corresponding to a base line engine) to perfect insulation (corresponding to a perfect LHR engine). Not only that in all these investigations, a constant air-fuel ratio is maintained for both LHR engine and as well as non-insulated (base line or conventionally cooled) engines to ensure compatible combustion. Also in most of the cases the peak pressure is maintained constant between insulated and non-insulated engine.

The results consistently show an improvement in the thermal efficiency of insulated engines compared to that of baseline engine at all loads and speeds. The percentage of improvements increase with the degree of insulation. Heat recovery systems such as Turbo compound system and Rankine bottoming cycle additions have further improved the efficiency as expected. The specific fuel consumption varies from 2 to 17 %. This variation is mainly due to different amount of reductions in-cylinder heat rejections effected by degrees of insulations and different quantities of energy recovered from the exhaust

Y.Miyairi's (3) Low Heat Rejection diesel cycle simulation consists of a gas flow model, a heat transfer model and a two-zone combustion model. The heat transfer model is used to determine convective and radiative heat transfer between the gas and the cylinder valve. Using combustion model the temperature and the chemical equilibrium compositions are determined. The gas flow model is used to determine the gas flow rates between the intake system, the cylinder and the exhaust system. The simulation has run at different loads, speeds and with different insulation materials such as Iron, PSZ and ZrO_2. The investigation indicates improved thermal efficiency ranging from 2 to 2.7% compared to the base line engine. The gain in thermal efficiency due to insulation varies with different insulation materials. The investigation also indicates materials which are low thermal conductivity and lower heat capacity are advantageous in the trade off between thermal efficiency and NO emission. It also indicates increasing adiabaticity increases the emission of NO.

The simulation of K.L.Hoag et al (4) has clearly shown improvements in fuel consumption, volumetric efficiency and exhaust temperature. The simulation is carried on 450 KW Cummins V903 engine with various levels of insulation. . The Partially Stabilized Zirconia (PSZ) is used as insulation material. The improvement in fuel consumption, volumetric efficiency and exhaust temperature with respect to degree of insulation are shown in figures 1, 2, 3. Similar trends exhibited in an earlier work by Annand (5) and in recent ones by Morel et al (6, 7)

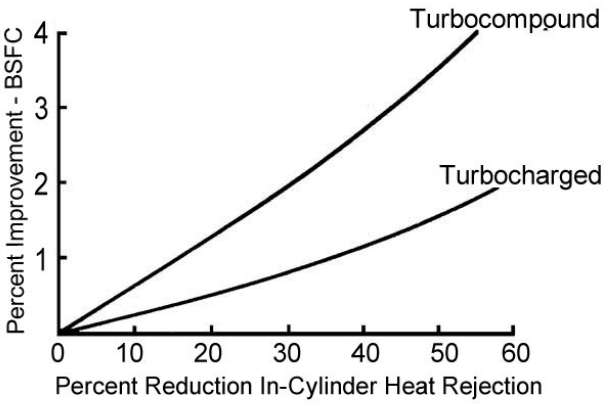


Fig. 1 Effect of insulation on fuel consumption.
[Courtesy of K. L. Hoag et al(4)]

T. Morel et al (8) have developed a comprehensive analytical methodology describing the heat transfer process in reciprocating engines. It models convection and radiation heat transfer, friction-generated heat, transient and steady state heat conduction through engine structure and couples all of these with a thermodynamic cycle model. The methodology has been applied to a matrix of insulated diesel engine designs to make an assessment of the effects of various insulating strategies, utilizing the state of the art ceramics as well as hypothetical material of very low conductivity. There investigation indicates substantial reduction in combustion chamber heat transfer and considerable improvement in brake specific fuel consumption.

J.F.Tovell (11) has developed a computer simulation for a highly rated turbocharged diesel truck engine. In this investigation comparisons are made between standard engine and engines with exhaust port, cylinder head, piston and cylinder liner insulated individually or in combination. The investigation indicates reduction of fuel consumption by about 7.5% at the expense of high exhaust temperatures and cylinder pressure. He attributes this to reduction in heat loss to the coolant by insulating the piston crown and cylinder head.

Bruns et al (14) predict even greater improvement ranging from 16 to 37% in fuel economy depending on the LHR engine duty cycle. The results of Wallace et al (15) indicate a gain of 14% in the indicated thermal efficiency for fully adiabatic condition and 7% for semi-adiabatic condition. Many of the studies report significant increases in the cylinder surface and exhaust temperatures and reductions in the in-cylinder heat transfer rates. For example the study of Morel et al (9)

shows that the surface temperature near top dead center increases from 530 K to 900 K as the insulation level increases from baseline to fully insulated. The corresponding reduction in the in-cylinder heat rejection for the insulated engine is 72% of that of baseline engine. The above are the results of simulation of LHR turbocharged and /or turbocompounded engines.

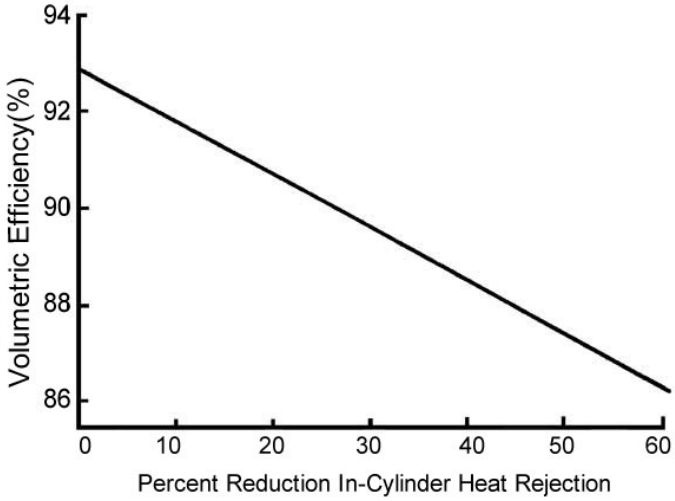


FIG 2. Effect of insulation on volumetric efficiency
[Courtest of K. L. Hoag et al (4)]

Some researchers have also studied the effect of insulation on the naturally aspirated engines. Notable among them are Griffiths (16), Zapf (17) and Siegla et al (13). They say incorporating LHR concepts in an naturally aspirated diesel is unlikely to Improve fuel economy because the increased temperature of the wall confining the cylinder charge depreciates volumetric efficiency, requiring additional piston displacement and with it greater friction to maintain performance. Also naturally aspirated engine fails to use the increased energy content of the exhaust gas.

Colgate (18) states that the efficacy of insulation as a means of improving thermal efficiency is questionable. His argument is that the insulated surface acts as a thermal sink and source during expansion and compression strokes respectively and the heat exchange in any direction is an irreversible loss to the cycle. The above statement brings forth an interesting point about the numerical simulations.

To accurately model, insulated engine performance, the simulation must properly account for the effect of insulation on heat transfer, friction and combustion or heat release. Because several of sub models included in the simulation are not exact representations of the processes, but are empirical correlations based on past data.

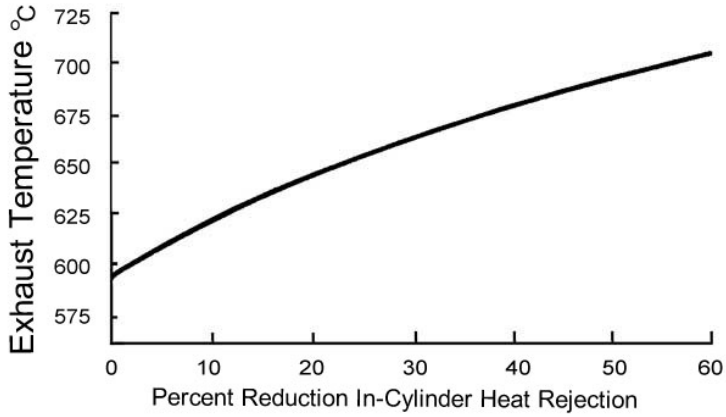


Fig. 3 Effect of insulation on exhaust temperature.
[Courtesy of K. L. Hoag et al (4)]

EXPERIMENTAL INVESTIGATIONS

As like simulation studies, numbers of experimental studies have been carried out on LHR engines. In many cases the operational constraints i.e. air-fuel ratio and peak conditions are maintained constant in both the LHR and Conventionally cooled engines. In some cases operational constraints are not maintained constant. Investigations that have been carried out at same operating conditions indicate considerable improvement in fuel consumption, substantial increase in thermal efficiency, increased availability in the exhaust and overall reduction in emissions in the case of LHR engines. However contrary to the above, some experimental investigations have indicated almost no improvement in thermal efficiency and claim that exhaust emissions deteriorated as compared to those of the conventional water coolant engine. An attempt will be made here to review the previous experimental investigations on LHR engine. A summary of past experimental studies performed to evaluate Low Heat Rejection engines is shown in Table.2 (2)

The experimental investigation of W.R.Wade et al (19) on an uncooled, single cylinder DI Diesel engine with ceramic coated cylinder head and valves, a heat insulated steel topped piston and a short, Partially Stabilized Zirconia (PSZ) cylinder liner in the area above the piston rings provided 4 to 7% improvement in fuel consumption at operating conditions typical of the EPA CVS driving cycle for light duty vehicles relative to the baseline water cooled engine. A comparison of the measured, Indicated Specific Fuel Consumption data for the uncooled and water-cooled engines is shown in fig.4. In their investigation, airflow into the insulated engine is matched to the level of the baseline water-cooled engine and a constant air-fuel ratio is maintained for the insulated and non-insulated engine to ensure similar combustion.

The investigation undertaken by R.H.Thring (20) at SwRI using ceramic coated single-cylinder DI diesel engine

reports improvement in fuel economy of about 7 percent In Turbocharged (TC) engine and about 15 percent in Turbocompounded (TCO) engine. It also indicates 80% reduction of smoke and 50% reduction of HC and CO emissions, but NO_x emissions increase by15%.

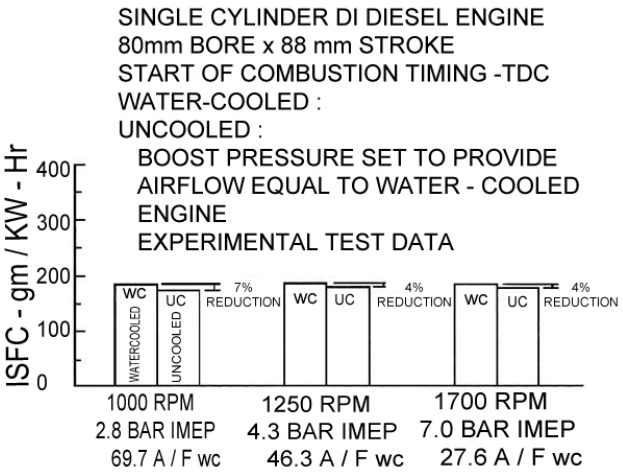


Fig.4 Comparison of the measured ISFC for the uncooled and water-cooled Engines. [Courtesy of W. R. Wade et al(19)]

In this work manifold pressure is adjusted to maintain constant air mass flow rate, the cylinder head is left cooled for durability reasons, the liner is uncooled and coatings consist of two or more layers containing different proportions of Partially Stabilized Zirconia and Chromium Oxide are applied to components such as piston crown, valves and cylinder liner. The tests are carried out using conventional diesel fuel, high temperature tolerant type lubricant (20W-50 oil) with different air-fuel ratios at two different speeds 1000 and 2000 rpm

The Cummins single cylinder NH engine coated with Zirconia plasma spray of T.Morel et al (21) shows reduction in peak heat flux and mean heat flux. This indicates that the nature of the heat transfer process is unchanged by the increased wall temperature. They attribute these reductions to insulation of the engine and increase in wall temperature. They also state that insulation and increasing wall temperatures lead to a decrease in heat transfer and thus contribute positively to thermal efficiency.

Experimental Investigation of Y.Miyairi et al (22) using single cylinder DI diesel engine indicates improved engine performance, reduced HC emissions but increased Nitric Oxide emission and decreased volumetric efficiency. They also report reduction in BSFC by 7% under naturally aspirated conditions. They attribute this to more efficient use of the in-cylinder air. The engine used for investigation is selectively insulated with monolithic ceramics such as Partially Stabilized Zirconia (PSZ) and Sintered Silicon Nitride (SSN). In the experiments, the fuel injection system and the fuel injection amount are kept the same as that of the base engine. Temperatures of the jacket cooling water and the lubricating oil are maintained at 80°C throughout the experiments. The cylinder liner is water cooled to prevent the sliding surface suffering tribological problems and to prevent the deterioration of volumetric efficiency caused by the liner surface getting too hot.

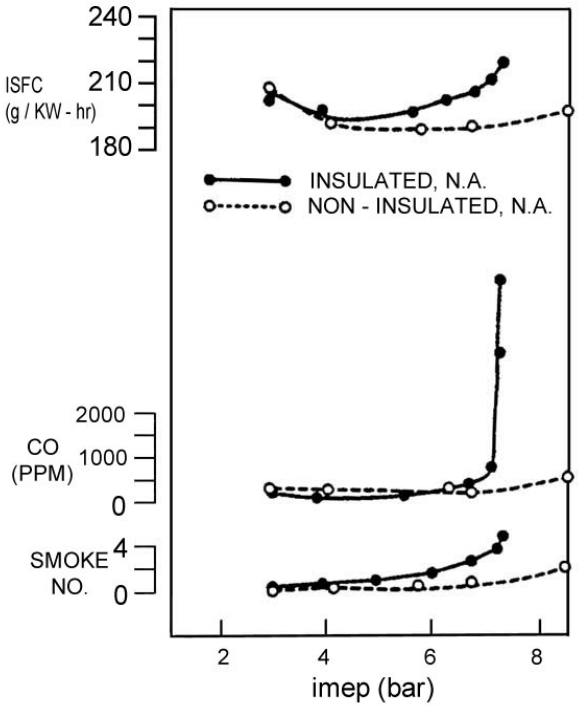


Fig 5. Comparison of performance of naturaly aspirated insulated and non-insulated engines. [Courtesy of cheng et al (25)]

The insulated engine of Cheng and Wong (23) consistently shows poor performance at all loads. This they think may be due to a slower and non-optimized combustion, which is evidenced by the presence of soot formation. However it is important to note one salient point in their study. The comparison is made between performances of an insulated engine and an engine whose cylinder liner is cutoff, but not a conventionally cooled engine. Not only that the compression ratio

employed in the insulated engine is smaller than that of the baseline engine. In the insulated engine, the surface and the exhaust gas temperatures increased by more than 20%, and the heat flux amplitude decreased, implying a lower overall heat flux.

The investigation of Woschni et al (24) also indicates that a LHR engine performance poorly in the case of BSFC. In this attempt to explain performance deteriorations with insulations, he has stated that heat transfer to the walls actually increases with higher wall temperatures. According to his theory the hot cylinder is accompanied by a thinner boundary layer and higher thermal gradient. As a consequence, the convective heat transfer coefficient increases drastically and overcomes the effect of the reduced temperature difference between gas and wall. They also maintain that the poor performance is not due to a changed combustion process. However as pointed out by Cheng and Wong (25), their appears to be a combustion degradation in the insulated of Woschni et al (24) as evidenced in fig.5 by the presence of increased Carbon monoxide and smoke in emissions at higher loads. If the higher surface heat flux were to be the real culprit for the poor performance, it becomes difficult to explain why BSFC is lower for the insulated engine at lower loads.

Cheng and Wong (25) claim that there is not enough experimental evidence in the work of Woschni et al (24) to conclude that higher surface temperatures cause higher heat fluxes. The draw back of Woschni et al investigation is the experiments are done on a naturally aspirated engine, the volumetric efficiency would probably suffer at the higher surface temperatures occurring in an insulated engine more so at higher loads. Furthermore Woschni et al state that 5% of the input fuel energy cannot be accounted for, which is of the order of the expected improvements. The peak pressure in the case of the insulated engine is lower and there is considerable delay in the combustion process. These appear to be some of the main reasons for the poor performance of the insulated engine observed by Woschni et al.

To determine the effect of Low Heat Rejection (LHR) operation on engine performance, emissions and combustion D.W.Dickey (26) employed a single cylinder DI Diesel engine. The engine fire deck, intake valves, exhaust valves, piston crown and cylinder liner are coated with a coating of Yttria Stabilized Zirconia (7%Y_2O_3 and 93% ZrO_2). The insulated engine is tested at baseline conditions and at increased coolant temperatures (from 82^{o}C to 104^{o}C). In the experiment cylinder head coolant is replaced with a regulated supply of compressed air and the cylinder liner is cooled with Ethylene Glycol. Tests are conducted at three fuel injection timings and at different speed and load conditions. The air-fuel ratio is maintained constant using the boost pressure. The investigation indicates lower thermal efficiency, with higher smoke, particulate, Carbon monoxide and NO_x emissions, and lower Hydrocarbon emissions. The poor LHR engine performance is attributed to degraded combustion characterized by less premixed burning, lower heat release rates and longer combustion duration compared to the baseline cooled engine.

Investigation of J.A.Gatowski (27) indicates poor LHR engine performance compared to the same geometry baseline engine. Single cylinder DI Diesel engine with low heat rejection components that include a Silicon-Nitride piston cap, an Inconel fire deck, and Stainless steel port liners, all backed by air gap is tested at conditions intended to simulate the operation of a turbocharged automotive diesel engine. During the tests air-fuel ratio and air mass flow rate are fixed. The test results show that the LHR engine is worse than the baseline engine in most respects. The investigation shows higher fuel consumption and higher NO_x and HC emissions.

Investigation of D.Assanis et al (28) using an AVL single cylinder, DI Diesel engine shows the effects of ceramic coatings on engine performance and exhaust emissions. Tests are carried out over a range of engine speeds at full load for a standard metal piston and two pistons insulated with 0.5mm and 1.0 mm thick ceramic coatings. It is reported that the thinner (0.5mm) ceramic-coated piston provided 10% higher thermal efficiency than the metal piston and thicker coated piston resulted in 6% higher thermal efficiency than the conventional engine. The investigation also indicates an attractive picture in terms of LHR engine emission characteristics. It shows 30% to 60% lower CO levels, 35% to 40% lower UBHC levels, and 10% to 30% lower NO_x levels and lower smoke levels when compared to baseline engine. They reason this to more complete combustion in the insulated version.

The investigation of Shuji Kimuru et al (29) on LHR engine shows reduction of heat rejection from the gas to the cylinder wall. It also indicates no improvement in thermal efficiency. Thermal efficiency does not improve to that extent like heat rejection is reduced by combustion chamber insulation. They attribute this to decline in work conversion efficiency as a result of the deterioration of combustion. In the experiment high-speed photography is used to study the combustion phenomena. High-speed photography study reveals that the reduction in the angular velocity of the flame in the LHR engine is due to combustion chamber insulation. They state that this reduction is one reason for the decline in work conversion efficiency.

The investigation of Havstad et al (10) has clearly shown improvements ranging from 5 to 9 % in ISFC of an insulated engine over a baseline engine. Their measurements indicate that the in-cylinder heat transfer (heat loss) decreases by about 30% in the case of the insulated engine. In their experiments, a constant air-fuel (A/F) ratio is maintained for the insulated and non-insulated engines to ensure similar combustion in both cases. It is important to note that A/F ratio is not maintained constant in the case of Cheng et al (23) and

Woschni et al (24). They show deterioration in engine performance with insulation.

The investigation of Xiaobo Sun et al (30) compares the performance of LHR engine and the conventional metal engine. The investigation results indicate shortened ignition delay, decreased premixed combustion, extended whole combustion duration, increased fuel consumption rate, and decreased volumetric efficiency in the case of LHR engine. To improve the deteriorated fuel consumption they suggest two methods to achieve it. One is to prolong ignition delay and the other is to increase fuel injection rate. To increase ignition delay, 25% of Gasoline is blended with diesel. Findings indicate that this reduces fuel consumption rate of the LHR engine. Investigation also indicates that the same can also be achieved by raising the opening pressure of the needle valve, by increasing the cross sectional area of the multi hole orifice or by increasing the diameter of the fuel pump plunger.

The investigation of Alkidas (31) suggests that the poor fuel economy of LHR engines observed by many previous investigators is the result of insufficient air-fuel mixing and deteriorated combustion. His measurements, however, indicate that the fuel consumption of a LHR engine is equal or better than a baseline engine. Further there is a reduction in ignition delay, premixed combustion and combustion duration, and an increase in diffusion combustion in the case of an uncooled engine compared to a conventionally cooled engine. He cautions that, in order to realize the potential gains of fuel economy in a LHR engine, conversion of a cooled engine to an LHR version by mere insulation is not enough, but suitable modification to optimize the injection system may also be needed.

The study of Hideo Kawamura et al (32) indicates that a pre-combustion chamber as good potential for LHR engine. They claim that high combustion wall temperature of pre-combustion chamber improves fuel consumption and controls exhaust emissions. Their investigations on LHR engine having DI combustion chamber show a reduced heat rejection, but no improvement in fuel economy and exhaust emissions. . They attribute this to insufficient air–fuel mixing and degradation of combustion. Fig.6 shows the comparison of fuel consumption and emissions in a LHR Engine and DI water-cooled engine Investigation results also show that LHR Engine having pre-combustion chamber offers 5 to 10% lower fuel consumption and lower exhaust emission levels compared with the DI water-cooled diesel engines

The study of Moore et al (33) indicates that, of the four forms of combustion chambers insulation [(1) elimination of coolant from the liner (2) raising oil pan temperature (3) piston insulation and (4) cylinder heat insulation], the uncooled liner is the most effective means of reducing the heat rejection and in addition the parasitic energy consumption of the coolant system is eliminated.

The investigation of R.Kamo (34) has shown that LHR insulated diesel engine offers lower BSFC than its counterpart metal engine if proper fuel injection equipment is used. It indicates that pressure fuel injection with retard injection timing provide the necessary condition for combustion and favourable heat release rates. The LHR engine's piston and cylinder head are coated with 0.1mm thick and the cylinder liner is coated with 0.5mm thick of thin thermal barrier coating. The fuel injection parameters and the turbocharger are kept the same for both LHR and baseline engines. The results show 5 to 6% improved fuel efficiency at all loads and speeds. They attribute this to higher premix combustion, lower diffusion combustion, reduced heat transfer loss and higher rate of heat release in the main portion of combustion.

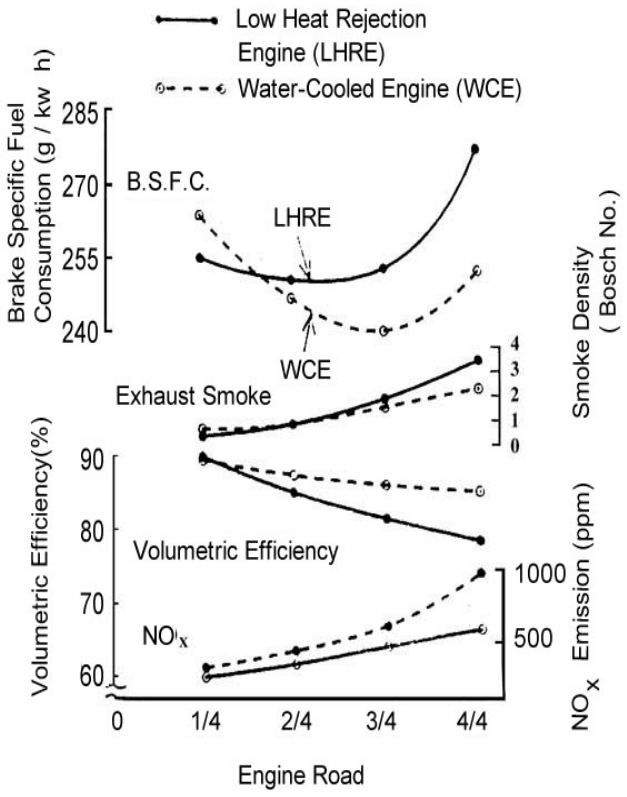


Fig.6 Comparison of Fuel Consumption and Emissions in a LHR Engine and DI Water Cooled Engine.
[Courtesy of H.Kawamura et al (32)]

TABLE -1. **Comparison of simulation results of LHR engine with those of Conventionally Cooled Engines (CCE)**

RESEARCHER (S)	TEST ENGINE	EXTENT OF INSULATION	OPERATIONAL CONSTRAINTS	PERFORMANCE OF LHRE COMPARED TO CCE
Y.Miyairi (3)	Turbocharged DI diesel engine	Various levels of insulation with different kinds of insulating materials	Constant air-fuel ratio for both and constant turbine efficiency	2 to 2.7% improvement in B. Th. Efficiency
T.Morel et al (9)	Turbocharged heavy duty and light duty engines	Different levels of insulation	Constant peak pressure and A/F ratio for both	Thermal efficiency increased with the level of insulation and at all loads for both heavy and light engines; B.Th. efficiency improves 8% which grows to 13% with Rankine bottoming cycle for truck engine; the surface and exhaust temperatures increase and heat rejection decreases
K.L.Hoag et al (4)	Turbocharged and/ or turbocompounded engine	Various levels of insulation	Constant A/F ratio for both	4% decrease in BSFC for turbo compounded and 2% for turbocharged engine at 55% reduction in the in-cylinder heat rejection.
Havstad et al (10)	Single cylinder engine with intake pressure booster	Uncooled; ceramic inserts to varying levels	Constant A/F ratio for both	12% Improvement in BSFC at 55% heat rejection
Kamo et al (1)	Turbocompounded engine	Various levels of insulation	Constant A/F ratio for both	10% improvement in BSFC; up to 70% reduction in the in-cylinder heat rejection
Morel et al (8)	Turbocharged DI truck diesel engine	Various levels of insulation	Constant peak pressure and A/F ratio for both	6% improvement in B.Th efficiency at 60% reduction in heat rejection for super insulated case
J.F. Tovell (11)	Turbocharged engine	Various levels of insulation	Constant A/F ratio for both	7.5% improvement in ISFC
French (12)	Turbocharged and /or Turbocompounded engine	Various levels of insulation	---	9% improvement in BSFC with the turbocharged and 17% increase in thermal efficiency with turbocompounding; 2 to 4% improvement in fuel consumption due to reduced friction in LHR
Donald C.Siegla et al (13)	Single cylinder IDI Turbocharged and /or Turbocompounded engine	----	Constant A/F ratio and Turbocharger efficiency	Turbocharger offers improved fuel economy

TABLE-2. **Comparison of experimental results of LHR engine with those of Conventionally Cooled Engines (CCE)**

RESEARCHER (S)	TEST ENGINE	EXTENT OF INSULATION	OPERATIONAL CONSTRAINTS	PERFORMANCE OF LHRE COMPARED TO CCE
W.R.Wade et al (19)	Single Cylinder Direct Injection Diesel Engine	1 mm thick Zirconia coating to cylinder head face and the valve heads, a short solid PSZ cylinder liner in the area above the piston rings and heat insulated steel topped piston	Same air flow rate by boosting pressure, same air-fuel ratio	4 to 7% improvement in fuel consumption
R.H.Thring (20)	Single cylinder DI Diesel Engine	0.03 inch coating containing a mixture of PSZ and Chromium Oxide to piston crown and valves.	Same air flow rate, different air-fuel ratio, at two different speeds	Improvement in fuel economy of about 7% in TC and 15% in TCO
T.Morel et al (21)	Single cylinder heavy duty turbocharged engine	Piston and cylinder head coated with 0.05 inch of Zirconia (PSZ); valves coated with 0.03 inch of PSZ also reduced coolant passages in head	The engine is cooled by water circulated in the same manner as in the cooled engine	In-cylinder heat transfer decreases with increased wall temperature; no degradation of combustion process
Y.Miyairi et al (22)	Single cylinder DI Diesel Engine	Combustion chamber walls of the engine are insulated with ceramic materials of SSN and PSZ	The fuel injection system and fuel injection amount are kept constant. The cylinder liner is water-cooled.	Reduction in BSFC by 7% under naturally aspirated conditions
Cheng and Wong (23)	8-cylinder engine modified for single cylinder operation	Piston and 85% of cylinder head insulated with 1.52mm of Zirconia. Head water cooled, liner not cooled in both LHR and CCE	BMEP and air flow rate kept constant but not A/F. Same RPM and intake pressure, air flow adjusted	Poor performance at all tested loads; up to 17% higher BSFC; degradation of combustion process, exhaust and surface temperatures higher
Woschni et al (24)	DI Single cylinder NA Engine	Piston crown is the only part insulated by Nimonic 80A and air gap. Deep bowl piston design	----------	In-cylinder heat transfer increases with increased wall temperature. Performance mixed in terms of BSFC and poor in terms of ISFC.
D.W.Dickey (26)	Single cylinder direct injection Diesel Engine	0.76mm thick coating of Yttria Stabilized Zirconia (YSZ) to firedeck, intake and exhaust valves and piston crown, and 0.64mm thick YSZ to cyl.liner	Same air-fuel ratio, different speed and load conditions, at three different fuel injection timings	Lower thermal efficiency with higher smoke, particulate, CO, NO_x levels. Degraded combustion.
Havstad et al (10)	Single cylinder DI Engine with intake pressure booster	Solid PSZ ceramic inserts for head, liner walls and the piston top; uncooled cylinder head and liner.	Same air flow by boosting pressure; same A/F; same RPM and IMEP	Better performance; 5 to 9% lower ISFC; about 30% reduction in the in-cylinder heat rejection
R.Kamo et al (34)	Six cylinder turbocharged DI Diesel Engine	0.13mm thin thermal barrier coating of LT-450 (90% ZrO_2 and NiCrB) for piston top and cylinder head and 0.5mm thick Iron Titanate coating cylinder liner	The baseline and the engine LHR are run at 93% of rated load and at speeds 1600 to 2600 rpm,intake air temperature for LHR Engine is maintained constant	5 to 6% improvement in fuel efficiency at all loads and speeds; higher premix combustion; lower diffused combustion; reduced heat transfer loss; higher rate of heat release in the main portion of combustion

EFFECT OF INSULATAION ON COMBUSTION

The combustion chamber wall temperature of an LHR engine is higher than that of a conventional water-cooled engine. Hence the charged air in a cylinder absorbs heat emanating from the high temperature chamber wall. Therefore the charged air expands, this lessening the amount of intake air. However if the increase in power output is to be realized, a turbocharger using higher exhaust energy and which increase the amount of intake air, or better still, a turbocompound system that recovers that exhaust energy and converts it into additional power should be connected with the LHR diesel engines. The results of investigation of Suzuki et al (35) on an uncooled turbocharged engine shows that the excess air ratio decreased by about 1 to 7.6% compared to that of water cooled, turbocharged base engine. They have also carried out performance tests using the LHR engine

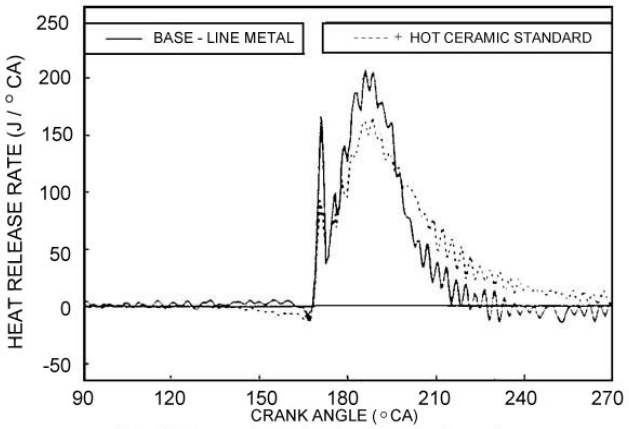


Fig. 7. Comparison of rate of heat release in LHR Engine and Water Cooled Engine. [Courtesy of S. Kabori et al (38)]

insulated only at the exhaust port and found that the excess air ratio increased by 2 to 4.2%. The investigation of Moore and Hoehne (33) indicates a similar result. The results of Miyairi et al (22) on the other hand, show that cooling the liner with water even in the case of a naturally aspirated insulated engine can moderate the deterioration in volumetric efficiency.

The results of many past investigations on combustion show decrease in the proportion of premixed combustion due to the shortening of the ignition delay and an increase in the proportion of diffusion combustion. The rate of heat release in the diffusion combustion phase shows a decreasing trend from the early to middle period and lengthening of the subsequent after-burning period. Fig. 7 shows a comparison of the rate of heat release in the LHR engine and the water-cooled engine.

The decrease in volumetric efficiency and shortening of ignition delay seem to be two of the reasons for the slow and deteriorating combustion. The investigation of Alkidas (36) indicates that poor air-fuel mixing is one of the reasons for degraded combustion in the case of LHR engine.

The Investigation of No et al (37) has clearly shown that the increase in viscosity of the burning gases as one of the major causes for the poor mixing rate, which is responsible for the degraded combustion.

EFFECT OF INSULATION ON ENGINE PERFORMANCE

Volumetric efficiency

Volumetric efficiency is an indication of breathing ability of the engine. It depends on the ambient conditions and operating conditions of the engine. Reducing heat rejection with the addition of ceramic insulation causes an increase in the temperature of the combustion chamber walls of an LHR engine. The volumetric efficiency should drop, as the hotter walls and residual gas decrease the density of the inducted air. As expected all the investigations [D.Assanis et al (28), J.A.Gatowski (27), R.H.Thring (20), Miyairi et al (22), Suzuki et al (35) and others] on LHR engine show decreased volumetric efficiency. The deterioration in volumetric efficiency of the LHR engine can be prevented by turbocharging, and that there can be more effective utilization of the exhaust gas energy.

Thermal efficiency

Thermal efficiency is the true indication of the efficiency with which the chemical energy input in the form of fuel is converted into useful work. Improvement in engine thermal efficiency by reduction of in-cylinder heat transfer is the key objective of LHR engine research. Much work has been done at many research institutes to examine the potential of LHR engines for reducing heat rejection and achieving high thermal efficiency. Researchers such as P.H.Havstad et al (10), C.H.Moore et al (33), A.C.Alkidas (39), R.H.Thring (20), T.Morel et al (21), and many others have reported improvement in thermal efficiency with LHR engine. They attribute this to in-cylinder heat transfer reduction and lower heat flux. However investigations of others such as W.K.Cheng et al (23), G.Woschni et al (24), S.Furuhama et al (43), D.W.Dickey (26) and some others report that thermal efficiency reduces with insulation. They all attribute this to an increase in the convective heat transfer coefficient, higher heat flux (increase in in-cylinder heat transfer) and deteriorated combustion. The in-cylinder heat transfer characteristics of LHR engine is still not clearly understood. Thus the effect of combustion chamber insulation on reducing heat rejection and hence on thermal efficiency is not clearly understood as on date.

Fuel consumption

Numerous investigators have modeled and analyzed the effects of in-cylinder thermal insulation on fuel consumption. Researchers such as R.Kamo et al (1), V.Sudhakar (44), T.Yoshimitsu et al (45), W.R.Wade et al (40), K.L.Hoag et al (4) and T.Morel et al (9) have reported improvement in the reduction of fuel consumption in LHR engine. The level of improvement that has been predicted ranged from 2 to 12 %. They attribute this to insulation of in-cylinder components. It has been predicted that insulation of in-cylinder components is a more effective means of reducing heat rejection and reducing fuel consumption. The investigation of R.H.Thring (20) indicates reduction in fuel consumption, and attributes this to reduced friction due to increased wall temperature. He also states that there is no measurable improvement in fuel consumption based on the thermodynamics involved. Investigation of Miyairi et al (22) indicates higher fuel consumption of LHR engine. They attribute this to the increase in reciprocating mass. Investigation of J.A.Gatowski (27) shows that LHR engine has roughly 25% greater fuel consumption than the baseline engine. R.H.Thring (20) states that comparison of SFC between baseline and LHR engine should be done carefully, because reducing the heat rejection affects other engine operating parameters such as volumetric efficiency, air-fuel mixing etc, which in turn affect fuel consumption. Hence it is felt that, comparison between the two engines should be made at same engine operating conditions and same engine operating parameters. In general, it has been reported that fuel consumption of, naturally aspirated LHR engine is in the range of 0 to 10% higher, turbocharged LHR engine in the order of 0 to 10% lower and turbocompounded LHR engine in the order of 0 to 15% lower, when compared with the conventional cooled engine.

Effect of injection characteristics on LHRE performance

In heavy-duty diesel engines, rather than air motion - the momentum and energy of the injected fuel are the major physical factors, which control the air fuel mixing process. Accordingly it is necessary to optimize the fuel injection system of the heavy-duty uncooled LHR diesel engines (38).

The investigation of Alkidas (39) has shown that the fuel economy of the LHR engine is of the same level as that of water cooled engine at the medium load, but deteriorated significantly at the high load condition. He attributed this to increased temperature of the combustion chamber walls, thus also increasing the temperature of the fuel issuing from the heated nozzle orifice resulting in the reduced fuel viscosity. This caused a heavy leakage fuel inside the nozzle and extended injection duration as well. Admitting the need for tuning of the fuel injection system for LHR engine operation, he optimized an injector tip configuration and achieved equal or superior fuel consumption.

Dickey's (26) experimental data show that higher insulated temperature in the insulated engine alters both the needle lift and line pressure. Assanis et al (28) have shown that with proper adjustment of the injection timing it is possible to partially offset the adverse effect of insulation on heat release rate. Their data have shown that reducing heat rejection from the cylinder, shift the combustion from pre-mixed towards diffusion. They have shown that by advancing the timing, the LHR engine achieves the same pre-mixed heat release rate.

Injection pressure and rate can also offset the adverse effect of insulation. Sun et al (30) have shown that decrease in pre-mixed combustion by about 75% in an insulated engine increases the BSFC by about 9%.

EFFECT OF INSULATION ON EMISSION

Unburned hydrocarbon

The emission of unburned Hydrocarbon from the LHR engines is more likely to be reduced because of the decreased quenching distance and the increased lean flammability limit. The higher temperatures both in the gases and at the combustion chamber walls of the LHR engine assist in permitting the oxidation reactions to proceed close to completion. Most of the investigations show reduction in HC level. However investigations of Wade et al (40) and S.Henningsen (41) indicate increased level of HC emissions. They attribute this to deterioration in diffusion combustion. The burning of lubricating oil due to high wall temperature is believed to be the other reason for increased UBHC level.

Carbon monoxide

It might be expected that LHR engines would produce less Carbon monoxides, for reasons similar to those for unburned Hydrocarbon. In fact many investigations indicate lower level of CO emissions. They attribute this to high gas temperature and combustion chamber walls. The reduced level of pre-mixed combustion in the insulated engine decreases the initial production of CO and the higher temperatures during diffusion combustion accelerate the oxidation of CO.

Nitrogen oxides

NO_x is formed by chain reactions involving Nitrogen and Oxygen in the air. These reactions are highly temperature dependent. Since diesel engines always operate with excess air, NO_x emissions are mainly a function of gas temperature and residence time. Most of the earlier investigations show that NO_x emission from LHR engines is generally higher than that in water-cooled engines. They say this is due to higher combustion temperature and longer combustion duration.

The Investigation of Alkidas (42) reports an increase in the LHR engine NO_x emissions and concluded that diffusion burning is the controlling factor for the production of NO_x. Almost equal number of

investigations report declining trend in the level of emission of NO_x. For example the investigations of Wade et al (40) indicate reduction in NO_x level. They reason this to the shortening of the ignition delay that decreases the proportion of the premixed combustion

Smoke and particulates

It might be expected that LHR engines would produce less smoke and particulates than standard engines for reasons such as high temperature gas and high temperature combustion chamber wall. Earlier investigations show that smoke and particulates emission level increased in some cases and decreased in a few others. The results obtained by Wade et al (40) show significant reduction in smoke emission. They attribute this to enhanced soot oxidation, which was made possible by both the high combustion temperature and the intense turbulence created by the reversed squish. However investigations carried out at SwRI show increased level of smoke. They attribute it to increased oil consumption resulting from the loss of oil control at the higher temperatures. Factors such as short ignition delay, poor air-fuel mixing are also responsible for the formation of smoke and particulates.

THERMAL BARRIER COATINGS

Thermal barrier coatings are becoming increasingly important in providing thermal insulation for LHR engine components. For such an engine the insulating material must possess low thermal conductivity, low specific heat, high strength, high fracture toughness, high thermal shock resistance, low friction and wear resistance, high temperature capability, high expansion coefficient and chemical inertness for high resistance to erosion and corrosion.

In the mid 1970's materials such as silicon carbide (SiC) and silicon nitride (Si_3N_4) were first used as materials in engine cylinder construction (46). Silicon carbide in granular form possess good wear resistance, high temperature capabilities, low coefficient of friction, good corrosion resistance, half the density of steel. But they are more brittle and shrinking to about 18% during sintering. Even though it was successful in some high temperature engine application more advanced materials were developed then for Low Heat Rejection Engines.

The other substances of interest include Silicon Nitride (Si_3N_4), Aluminium Titanate (Al_20_3 TiO_2), Aluminium Magnesium Silicate (AMS). The Table.3 shows a list of ceramic materials and their properties (47).

Zirconia, a ceramic material that has very low thermal conductivity values, good strength, thermal expansion coefficients similar to metals and is able to withstand much higher temperatures than metals. However one disadvantageous trait is its characteristic of changing phases with increase in temperature. Eliminating this phase change would ease the burdens of construction and use of the material in an engine (46).

TABLE – 3 **Properties of Ceramic Materials**

Material	Ultimate flexure strength MPa	Den g/cc	Young's modulus at 1260°C GPa	Coeff.of therm Exp. 300-1260°k 10^{-6}/°k	Coeff.of therm Cond W/m°k
Si_3N_4	300	3.1	300	3.2	12
SiC	450	3.15	400	4.5	40
AMS	20	2.2	12	0.6	1
ZrO_2	300	5.7	200	9.8	2.5
Al_20_3 TiO_2	20	3.2	23	3.0	2

Partially Stabilized Zirconia (PSZ) has been developed that decreases the magnitude of these changes. At present Partially Stabilized Zirconia has been found to be quite desirable for adiabatic engine application because of its excellent insulating characteristics, adequate strength characteristics and thermal expansion characteristics, which are relatively close to some metals.

Investigation of M.Marmach et al (48) indicates that Toughened Partially Stabilized Zirconia (PSZ) ceramics possess a number of advantageous properties for advanced engine components, in particular for adiabatic engine system. It has also been stated that Magnesia Partially Stabilized Zirconia (Mg-PSZ) is suitable for LHR engine components. Magnesium and Nickel have been added to PSZ to improve strength and ductility characteristics respectively. Magnesia Partially Stabilized Zirconia (Mg PSZ) has a thermal expansion coefficient and elastic modulus close to that of Iron and Steel and is suitable for liners, valve guides and seats, hot plates, tappet inserts, and piston caps in the engine cylinder. Mg PSZ is made of 20 to 24% Magnesia. This has the highest fracture toughness of all the PSZ materials.

Stabilization of Zirconia can be accomplished with the addition of CaO, MgO and Y_2O_3, but these formations tend to be coarse, lack strength and toughness and exhibit poor thermal shock resistances. Alloys with 20% Yttria or 5% Calcia create fully stabilized Zirconia and good thermal coefficients of expansion (49).

Another way to improve PSZ characteristics to impregnate the surface after forming of the part. Success has been shown with a Cr_2O_3 impregnation treatment(50). This is also referred as densification treatment. A coating of plasma sprayed Zirconia

densified with this treatment exhibits an 87% lower wear rate than a similar undensified coating. The Chromium Oxide fills the open pores between molecular structures and hardens the surface.

Another promising material is Syalon (Si-Al-O-N) ceramics. Silicon Nitride mentioned above is one derivative of this classification. The major advantage of the material is the low creep characteristics at high temperatures. The material also has low density and low coefficient of friction. This will be good for reciprocating parts such valves and bearings.

However, ceramic materials are not ductile in general and any small imperfection produces stress concentration, which develops crack. Other ceramic, composite and advanced materials are being developed for different engine applications. Research is continuing to obtain ceramics with greater ductility.

TRIBOLOGY

Tribology involves lubrication, friction and wear. Better Lubrication technology is essential to the success of the operation of LHR engine. LHR engine is usually operated at elevated temperature. For 60% adiabaticity, temperatures at the point of top ring reversal in the 550-600^{o}C range are anticipated (45). But the best automotive liquid lubricants decompose at temperatures in excess of 350^{o}C. The synthetic lubricant used in aircraft gas turbines can also be used for automotive purpose. This will sustain the engine operating temperature for another 200^{o}C. Even the more advanced synthetics, which promise another 150^{o}C, appear unable to cope. Some of these new synthetics are so viscous at winter time temperature that they can not be pumped by traditional means. In addition, current petroleum based oils contain upto 15 percent additives that include anti-oxidants, anti-wear agents, anti-foam agents, rust inhibitors, detergents, pour-point depressants et, Assuming such additives will be necessary in advanced lubricants as well, additives will have to be developed to extend their thermal stability to temperatures not previously experienced (51). Therefore a piston-cylinder tribological system operating in an environment in excess of 1000^{o}C will need to utilize some other form of lubrication.

Solid lubrication has been widely investigated by many researchers for use in LHR Engine. In the absence of a liquid transport medium, the solid lubricant must be included in the piston ring or cylinder liner materials. Such materials are often referred to as self-lubricating composites. Significant research efforts have been undertaken by Adiabatics Inc., et.al(52), the Midwest research institute(53) and Battelle(54). Recent work done by Battelle(55) describes the successful application of a well known 'Boes' compact to temperatures of 850^{o}C (56). The NASA Lewis Research center has shown the effectiveness of coatings of some oxides and fluorides to 900^{o}C (57).Nickel/Molybdenum-bonded Titanium Carbide Cermets and Nickel/Molybdenum-bonded Chromium Carbide Cermets have also found to be effective.

Gaseous lubrication offers the greatest potential for low friction at high temperatures. This is the practice of providing a film or layer of gas between operating engine parts-piston and cylinder. A ringless piston-cylinder with very small and precise clearances would allow small amounts of combustion gases to pass, forming a gaseous film. This may be viewed as controlled blowby or with proper design the gases may be trapped between piston and cylinder. This has drawbacks primarily in design complexity(46). Required tolerances would be difficult to reproduce in gross numbers. Piston sidewall forces would have to be eliminated because the lower viscosity of gases will not handle heavy loads. Air or other gases could also be introduced from external sources to supply the friction surface with lubrication.

NOISE

Ceramics are light weight materials when compared with the common metals and alloys, because they are less dense in nature. So it is generally expected that use of such material for engine components would decrease the noise generated in an engine (58). The rotating and the reciprocating masses can be lighter, decreasing response time, noise and the required spring forces for successful operation. Lighter materials will decrease vibration created in the system. Friction would also be decreased as would the resultant friction or sustaining work required and decrease the noise at that interaction (46).

FUELS FOR LHRE

Increased cylinder temperatures will allow LHR Engines to use a wider range of fuels. The in-cylinder components temperatures greater than 600^{o} C will enable the use of less volatile fuels to auto ignite. The hot combustion wall temperatures of an adiabatic engine provide higher compression charge temperatures with consequent reduction in ignition delay. Short ignition delay is conducive to multifuel capability. Due to high operating temperature of an adiabatic engine low grade fuels such as alcohol, castor-oil, neem-oil, kerosene and fuels with low cetane number can also be used.

An idea that has received much interest is the burning of coal in engines. Low Heat Rejection Engines will reduce the burn time of coal with increased temperatures and promote more complete combustion (46). Adiabatics Inc. has successfully run an engine on 100% coal fuel without any external ignition sources (59). The main problem encountered has been the contamination of the lubricating medium by the particles of coal. Blowby past the pistons send solid particulates into the crankcase and are also encrusted on the cylinder walls. Scaring of the cylinder wall surface by large coal particles will increase blowby. This causes the contamination of the lubricating oil. Coal burning also requires improved

injection nozzles that will handle very large injection pressures and particle nature of coal.

CONCLUSION

An attempt has been made here to review the previous studies on Low Heat Rejection engine concept. Various researchers have carried out a number of simulation as well as experimental investigations. Although promising, the results of the above investigations have been somewhat mixed. Most of these studies investigated, modified conventional direct injection diesel engines. Most have concluded that insulation reduces heat transfer. None have produced exceptional gains in efficiency and performance. In fact, a few have shown that the addition of insulation, the elimination of cylinder coolant degrade, performance and increase cylinder wall heat flux. The question of whether insulation actually increases heat transfer at high temperatures as held by some must be settled. The conflicting results are probably due to the large number of possible LHR engine configurations, test conditions and the analysis techniques used.

Theoretical analysis capability necessary for engine development has been believed to be inadequate. Various theoretical analysis of LHR engines stress that an increase of adiabaticity directly resulted in an improvement in thermal efficiency. However the combustion model used in simulations cannot sufficiently simulate a stratified combustion process of a diesel engine.

It has been found that ignition delay following fuel injection reduced, impairing air-fuel mixing, and ultimately prolonging combustion duration. A reduced fuel injector nozzle orifice diameter or by blending diesel with 25% Gasoline is suggested to enhance air-fuel mixing. As like J.A.Leidel (60) and C.S.Reddy et al (2), we too feel that the shortcomings of LHR research are mainly the result of the improvisation of conventional engines to LHR design. The mere substitution of ceramic components or the addition of insulating coating fails to account for increased combustion temperatures and an altered combustion.

Conventional piston crank designs produce piston side wall stresses, which make the direct substitution of ceramic for metallic materials troublesome. It is felt that new mechanisms have to be developed, which will reduce piston side forces or slapping forces. Such mechanisms would be more compatible with ceramics.

The use of reduced heat rejection in diesel engines is least useful in naturally aspirated engines, more useful in Turbo-charged engines. In order to obtain better performance over a wide range of engine loads it becomes necessary to match the engine with a Turbo-charger.

The higher temperatures of the combustion chamber surfaces of LHR Engine deteriorate the properties of lubricating oil. Hence one of the main directions of the research in adiabatic engines should be development of lubricating oils capable of retaining satisfactory viscosity at the higher temperatures encountered in the engine.

The need to satisfy emission regulations must be addressed.

The objectives of improved thermal efficiency, improved fuel economy and reduced emissions are attainable, but much more investigations under proper operating constraints with improved engine design are required to explore the full potential of Low Heat Rejection engines.

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