Conceptual Development of a LHR-Engines Based Trigeneration System and its Optimization for Enhanced Load-Matching Capability

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ABSTRACT

This paper presents a conceptual strategy for using LHR-Engine based trigeneration system. The system is optimized by implementing certain accessories like two stage turbo compounding with inter-cooling to send in cool and dense air in the combustion chamber and incorporation of water vapor in the intake air to raise the specific heat capacity and kinetic energy of exhaust gas, controlled pressure of the crank case or the other side of the piston to best regulate the power and heat requirement. A brief identification and survey of ceramic material used in this area is also presented with their operating and limiting parameters. Benefits and shortcoming in the present technological status has also been discussed.

Keywords: Adiabatic Engines, Low heat rejection engine (LHR engines), Combustion, Ceramic Materials, Cogeneration, Trigeneration, Insulation, Turbo-Compounding, Inter-cooling, Expansion cooling

1. INTRODUCTION.

The increase in the combustion chamber temperature increases the efficiency of the engines. The concept is well understood and defined by the thermodynamics. The question is why are we not raising the temperature of the combustion chamber, why this technology is not well established in commercial application till date. There are two reasons as pointed by [Randolph et. al., 4]**, but the priority is yet to be determined. According to them major obstacles is development of high temperature lubrication and ceramic material for construction of the engines. Generally it is seen that conventional lubricating oil start cracking at temperature above 350 ^oC [James, 6] and hence it cannot be used in a system where the temperature may reach to 800 ^oC or higher. Material sciences also evolved and presented some material, which can withstand higher temperature than ever before, SiC is one such material and now used for development of adiabatic engines on experimental basis. SiC provides some of the good feature required by a adiabatic engine like light in weight and tougher than other alloys for the same application, withstand higher temperature etc. other material and lubricating systems will be discussed in greater detail in next few pages.

The exhaust of the LHR engine has higher heat content than a conventional engine. Merely raising the power output from such engines is not the right direction of technological research. Since the exhaust contain higher heat value it can be utilized in system where there are heating or steam generation is required. A cogeneration system deals with only two components power and heat. Now requirements are far more and continue to expand there are systems where cooling is also accompanied by the heating and power generation. This system is termed as trigeneration system, which is specific to certain situation. This system is presented in detail here in this paper.

(Figure 1.a) show the typical heat and power balance of conventional diesel engine, turbo-charged diesel engine and LHR engine with turbo-compounding

**Numbers in parenthesis referred to the references in the last of the paper.

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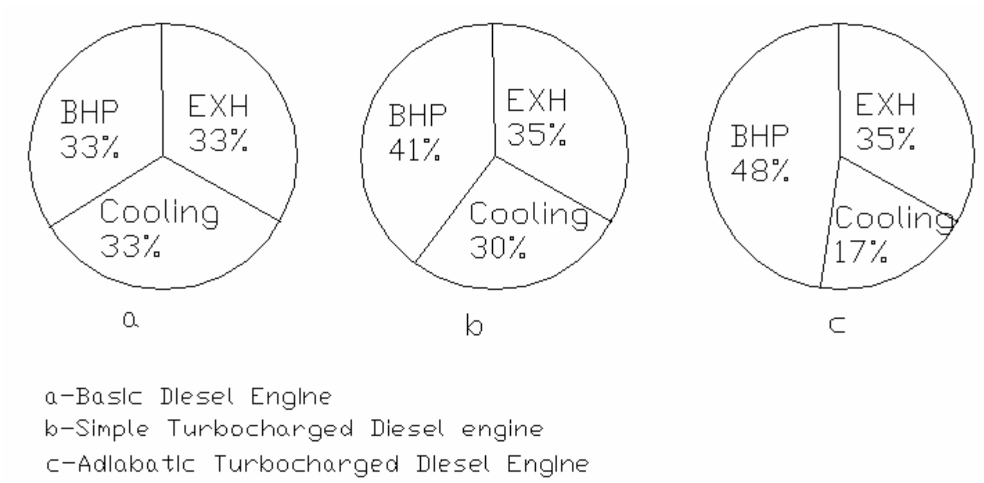

Figure 1.a: Heat and power balance of conventional diesel engine, turbo-charged diesel engine and LHR engine with turbo-charging. [Randolph et. al., 4]

2.0 LITERATURE SURVEY

The literature survey revealed that the concept of LHR engine was well understood since the time of diesel but only recently the appreciable advancement takes place. In 1975 US army Tank automotive command (TACOM) and Cummins engine company began an adiabatic engine program, they are followed by Isuzu motors, Ford motor, general motors, NKG Insulators/Mitsubishi motors etc [James, 6] most of there study were carried out in a modified conventional direct injection diesel engine. It was observed that every one of then was successful in insulating the engine or making it near adiabatic but the results were somewhat of mixed nature. None of them have produced exceptional gain in efficiency or performance [James, 6]. The shortcomings of LHR research are mainly the result of the improvisation of conventional engine to LHR design. Mere substitution of ceramic component and effective lubrication systems and addition of good insulating layers do not account for increased combustion chamber temperature. Consequently the utilization of exhaust gas heat in cogeneration or some bottoming cycle has to be there for effective utilization of the fuel. Turbo compounding of LHR engines is a good area of research now a days.

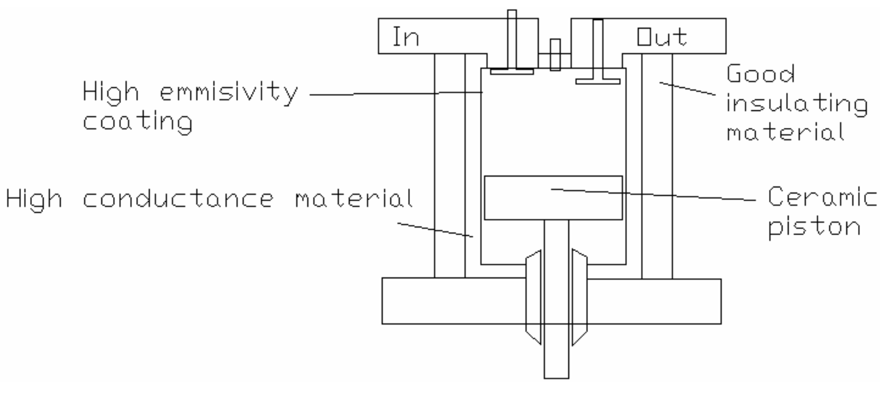

Figure 2.a: Typical construction schematic of LHR Engine [Randolph et. al., 4]

(Figure 2.a) shows a simple construction of an LHR engine, in which piston is of a ceramic material and cylinder is coated from inside with a high emissivity coating to contain the radiation emitted in the combustion, high emissivity coating is followed by a high thermally conductive material so as to reduce the thermal shock, since the TDC of the cylinder bear highest temperature shown in (Figure 2.b) that temperature has to be equalized as soon as possible to reduce the effect of thermal shock. Lastly the insulating material is bonded with the outer wall of the cylinder to make the engine adiabatic maximum of 70% of adiabacity can be achieved from 0.5 inches thick zirconia's insulation [Randolph, 4].

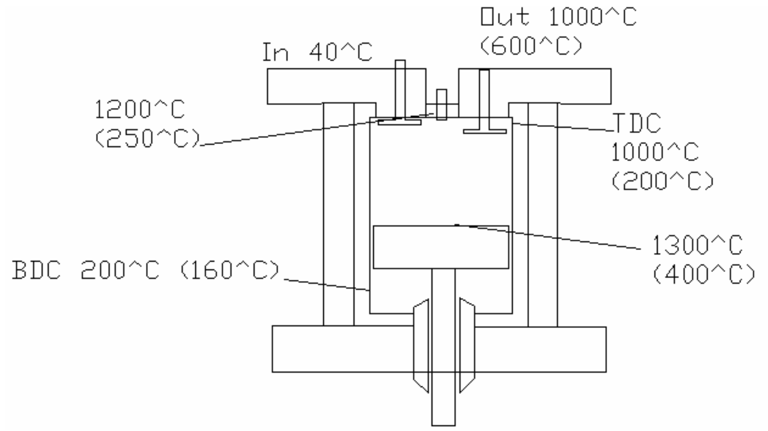

Figure 2.b: Typical temperature profile of basic diesel engine given in parenthesis and LHR engine temperature profile is shown without parenthesis [Randolph et. al., 4]

3.0 COGENERATION IN LHR-ENGINES-REVIEW

During ordinary operation of any engine approximately 70% of the heat value is lost due to practical and physical limitation. The concept of cogeneration now a day is quite established and implemented almost in every industry, where power requirement is accompanied by the industrial process heating (IPH). The term heat to power ratio is some how a very interesting topics of research, as in every industry the load matching is very important for proper utilization of heat energy. Generally it is seen that the dynamic range to which Q/W ratio can operate is limited due to certain parameters in working of any power generation cycle, typical values for certain established systems are given in (Table 3). Range of Q/W can be raised by incorporating certain mechanisms in systems like steam bleed or supplementary firing of fuel to match the IPH requirements in steam turbine plant. The heat flux variation inside the cylinder of an LHR-Engine is depicted in the (Figure 3.a). The engine insulation posses some very obvious advantages, first is the removal of cooling system thereby better economy of the overall system. Now the gasses inside the cylinder posses more heat and temperature may reach up to 1500^{o}C and they tend to expand more to produce maximum thrust on the piston and thereby increasing the overall mechanical efficiency. Still the exhaust gases coming out of the exhaust manifold posses higher enthalpy, which can be utilized for cogeneration, or trigeneration purpose or for further optimizing the existing cycle by implementing turbo compounding [Bryzik, 2].
A comparison can be done for un-cooled diesel engine design with a 48% thermal efficiency in cogeneration in conjunction to a turbo-compounding, un-lubricated engine design with 55% thermal efficiency with significant heat present in the exhaust gases for bottoming cycle.

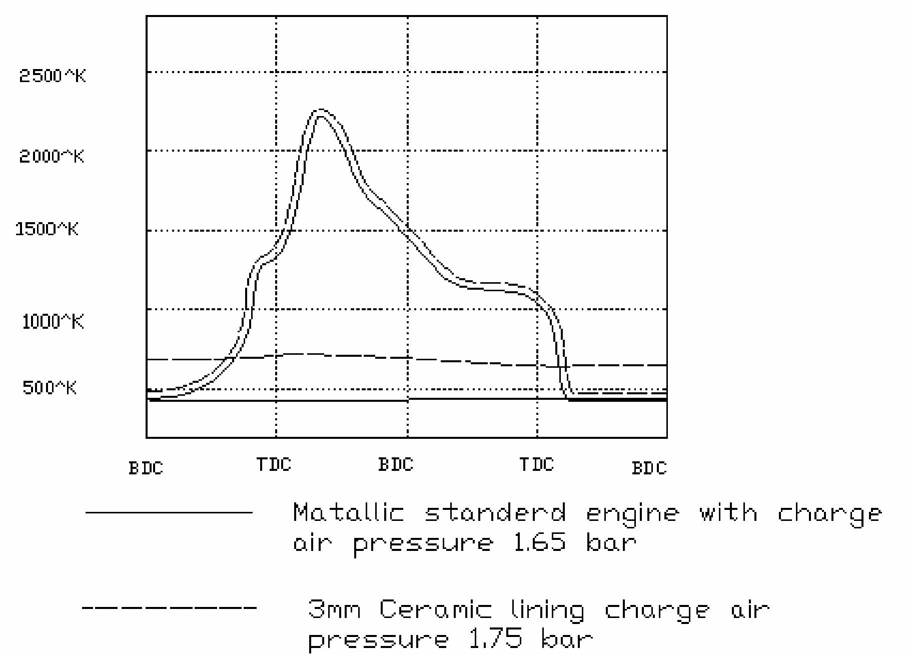

Figure 3.a: Typical gas and wall temperature profile of basic diesel engine and LHR-Engine [Randolph et. al., 4]

Cogeneration system	Q/W	Power Output
Back pressure Steam Turbine	4.0-14.3	14-22 %
Steam turbine	2.0-10.0	22.0-40.0 %
Gas turbine	1.3-2.0	24-35 %
Combined cycle	1.0-1.7	34-40 %
Ordinary reciprocating engine	1.1-2.5	33-53 %
Back Pressure LHR Engines.	------------	Up to 60%

Table 3. Efficiencies and dynamic power modulation of some established cogeneration technology.

LHR-Engines with turbo compounding can be the next significant step in improvement of advanced diesel based power generation system. A system network for trigeneration with such LHR-Turbo compounding Engine has been proposed here in this paper. Aspects of system optimization were also discussed for better load matching capability.

3.2 DEVELOPMENT OF LHR-ENGINE BASED TRIGENERATION SYSTEM.

Insulating the engine and using its exhaust heat in turbo compounding or in other bottoming cycle would not complete the chapter. Still the exhaust gasses contain good amount of high-grade heat, which can be further utilized cogeneration or trigeneration in power plant, District heating etc. the basic advantage of this system is it compactness and economy compared to other system like gas turbine and steam turbine cogeneration system.

A trigeneration Network has been developed using LHR-engine as a core component for simultaneous production of heat, power and cooling the network has been shown in (figure 3.2.a). This trigeneration network with LHR-engine has been optimized to facilitate maximum and minimum requirements of heating cooling and power simultaneously. Auxiliaries were suggested to meet the shock loading, its feasibility study and implementation is still a subject matter of the requirements of the facility.

An attempt has been made to identify the regulation points but it is yet to conceive that how much they would affect in the ratio of cooling heating and power or dynamic cooling heating and power (CHP) modulation for varying CHP ratio’s for load matching at different load condition at different period of time. A complete thermodynamic and mathematical model and simulation has to be worked out.

The trigeneration network contains four distinct components for heating, cooling, power and core LHR-based engine with two-stage turbo-compounding, inter-cooling and water vapor injection

3.2.1 TRIGENERATION SYSTEM OPTIMIZATIONS.

To achieve higher pressure and temperature of the exhaust gas, the inlet air must be dense and cooled to achieve this aspect a positive displacer screw expander based on Atkinson cycle or a turbine is used. Positive displacement is achieved by cyclic volume changes bounded by lobs of two rotors in continuous mesh, the screw rotates at 20000 rpm as compared to 50000 to 100000 rpm of a turbine, this used because it is easy to couple it to the main out put shaft of the engine [Randolph et. al., 4], at higher speed reduction gearing posses problems the selection of either one of them is completely defined by the facility requirements. The exhaust gases power this screw expander or turbine, and it is driving a two-stage compressor with inter-cooling to densify the intake air before sending it to combustion chamber. Another optimization can be incorporating the water vapors or steam in to the intake air; this will lead raised specific heat capacity and specific weight of the exhaust gases and hence kinetic energy. Pressure regulation is done via Pressure regulation valve (PRV) at exhaust manifold the crankcase or the other side of the piston is such that the connecting rod is making a sealed sliding link. So as to avoid leakage of hot gases, which are maintaining desirable pressure at the other side of the piston, in (fig 3.2a), the accumulator is connected with an insulated pipe to BDC of the cylinders. The function of this modification is to regulate the amount of shaft work or power from the engine, as the pressure is increased at other side of the piston or BDC side the shaft work gets reduced proportionally due to lesser pressure differential and lead to higher temperature and pressure exhaust going to accumulator. Arrangements have been done to compensate the shock loading requirements. Electrical immersion heating element has been provided to maintain temperature in thermal storage device.

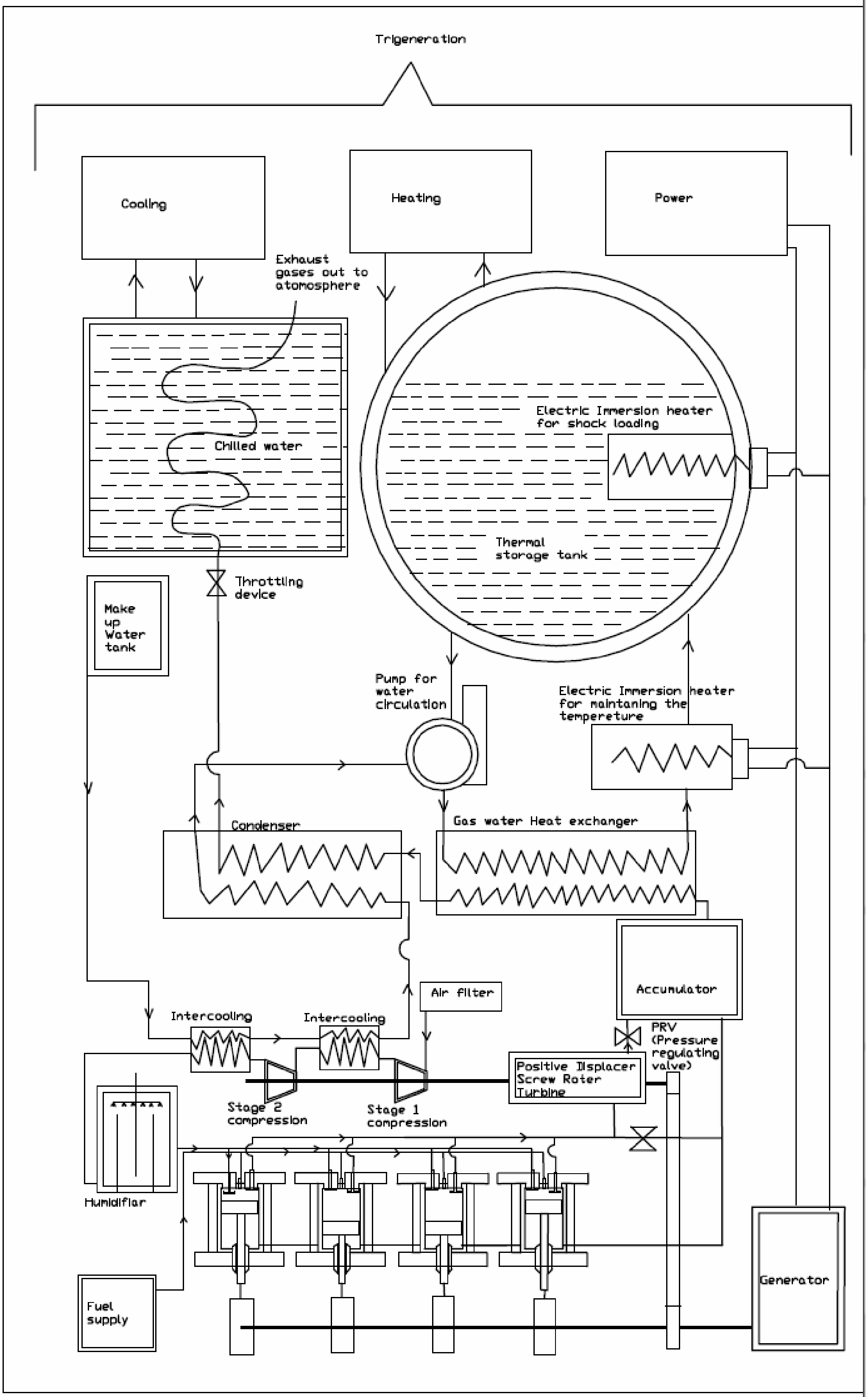

Figure 3.2a: Cycle network for LHR-engine based trigeneration system

3.2.2 COMPONENT DESCRIPTION AND WORKING

The network is presented in (Figure 3.2a). The line corresponds to insulated pipes except the line coming out of the generator. On the top of the network three boxes are shown in which heating cooling and power is finally utilized.

The cycle network start with air filter and fuel tank, the air send to a two-stage compressor with inter cooling to let the air become denser. Turbo-compounding results in higher quantities of fuel to be burnt in side the cylinder and higher temperatures and pressure can be achieved, after the turbo compounding the air is also humidified. Humidifier's, functionality is to humidify intake air; it is placed before the core engine system and after intake air multi stage compressor. The humidification increases the specific heat capacity and specific weight of the exhaust gases. Therefore the exhaust gases are capable more of retaining more heat and posses more kinetic energy.

The core component consist of four cylinder LHR-engines, all are capable of 70% adiabacity. They are well insulated from out side, high conductance liner material, which reduces the thermal shock damage to the liner. The inside of the cylinder is exposed to temperature difference of 500^{o}C and more, the conductance of liner quickly disperse out the heat through out the walls and reduces the probability of thermal shock. The inside of the cylinder is also coated with high emissivity coating to reflect and radiate maximum energy in the core combustion volume.

After PRV the first component is positive displacer screw expander or a turbine to drive the turbo compounding compressor this is using the kinetic energy and pressure of the exhaust gas to run, it is also coupled to main generator shaft, so the remaining shaft work left form the turbo compounding is fed to generator via some suitable reduction gearing. there is a bypass line connecting engine exhaust to accumulator via one more PRV, this is to regulate the intensity of turbo-compounding. Followed by this there is a highly insulated accumulator to accumulate the exhaust gas and to reduce the pulsating exhaust characteristic. The function of this accumulator is to maintain certain desired pressure and temperature followed by this there is a Pressure regulation valve (PRV). This accumulator will be the source of heat and pressure to rest of the components.

After highly insulated accumulator the gases goes to a gas-water heat exchanger for the thermal storage system. Here the gas lose some of its heat at certain pressure, this thermal storage system is nothing but a highly insulated vessel contain large amount of water inside generally temperature kept from 96^{o}C to 104^{o}C. The estimation of heat content can be evaluated by the relation $Q=m\ c_p\ (T_2-T_1)$. This thermal storage vessel is also fitted with two electric immersion heaters. This is to meet shock load demand and maintaining the temperature [Reay, 7]. There is a makeup water tank, which continuously replenishes the water in the thermal storage vessel. First this water takes the heat rejected by two intercoolers then it goes to the condenser of the chilling system, take all the heat in the gasses at certain pressure then it goes to a pump and then to thermal vessel.

The chilling system incorporated here is based on gas expansion cooling. Compressed exhaust gases after rejecting heat to thermal storage vessel still contains some heat, which has to be rejected to achieve cooling effect. These gases are kept at certain pressure and allowed to pass through condenser, condenser is cooled by cooling water coming from water storage tank and continuously replenishing the thermal storage vessel water level. After rejecting the heat these compressed exhaust gasses are allowed to expand in throttling device which produce cooling and that is used to chill the water kept in the insulated tank.

For industrial process of heating cooling and power, network of insulated pipes is required which takes hot water or chilled water from these vessels and transport it to the place required via pumps.

4.0 MATERIALS USED FOR ADIABATIC ENGINES

Higher temperature of the combustion chamber was limited by two reasons as pointed out by researcher i.e. lubrication and materials to withstand such higher temperature during operation. Now at this stage materials have been developed for such application and intense research was started after 1970 different option were entertained glass was also experimented due to its high insulating properties but it require further work in strength to work at such elevated stresses. The (Table 4), is listing properties of some ceramic engine materials.

Material	Ultimate flexural strength (Mpa)	Density Gm/cc	Young's modulas 1260 ^{o}K (GPa)	Coefficient of thermal expansion 300-1260^{o}K $10^{-6}/^oK$	Coefficient of thermal conductance W/m^{o}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
$Al_2O_3.TiO_2$	20	3.2	23	3.0	2

Table 4: listing of properties of some ceramic engine materials

In summery there are other option in material selection depending upon the engine operation following are the few characteristic that the material have to posses

- Low thermal conductivity, <0.01^{o}K
- Low specific heat; <0.4J/Kg ^{o}K
- High flexure strength >800 MPa
- High fracture toughness K_{IC};>8.0 MPa/m
- High thermal shock resistance;>500 delta T ^{o}C
- Good wear resistance
- Chemical inertness
- Thermal expansion equal to iron and steel;>$10^{-6}/^oC$
- Temperature limit up to;>1800^{o}F

Other substances of interest are Cr_2O_3, Al_2O_3, Fe_2O_3 and Partially stabilized zirconium (PSZ),
For a trigeneration network the whole system has to be made adiabatic in the sense that the heat stored in the accumulator after the engine has to be transferred to different point with different pressure so the piping network in the system has to be properly insulated. And insulation material has to be such that least amount of heat should be lost because the transportation of hot gasses can be to far-off places where they are actually required.

5.0 BENEFITS AND SHORTCOMMINGS OF THE TECHNOLOGY

One interesting feature reported by [Randolph, 4] is of Noise reduction due to density they also reduce strength requirement for support, and lighter material respond quickly than that of cast iron and other high density-moving component. One of the major short coming of LHR engines is NOx emission as reported by [James, 6] that with high temperature, the formation of NOx increases exponentially although this can not be said as an obstacle to the development rather we have sufficient technological background to implement after treatment of exhaust gasses with reducing catalyst or limiting the maximum flame temperature. On the other hand the formation of CO is not the thing to be talked about here at such high temperature combustion, so it's an advantage of LHR engines.

At these elevated temperature lubrication is a problem generally above 350^oC the best lubricant available starts to crack down in lower component. There are two other alternatives available for LHR lubrication i.e. solid lubrication and gaseous lubrication. In gaseous lubrication Catalytic generation of lubrication from carbonaceous gasses have also been achieved [Lauer, 5] soot formation in the engine can be taken as an input to solid lubrication soot generally contains Hydrogen so present different lubricating properties and fall under the category of polymer now by introducing a catalyst the carbon in soot can be transformed to graphite or nascent carbon which can fulfill the necessities of lubrication, tribological surface reaction of generation of solid lubricant form gasses has been presented by [Lauer, 5]. Another benefit of this technology is the reduction in weight of the system, which is about 40% of conventional technology systems. This is due to elimination of cooling system and the ceramic material, which have generally lower density than conventional materials [Bryzik, 2].

$$\mathbf{4\ Air + 3CO_2 \rightarrow 2Au_2O_3 + 3C}$$

It was suggested graphite layer forms, when nickel containing or palladium surfaces at high temperature are exposed to atmosphere containing ethylene and thereby friction and wear is reduced [Lauer, 5]

Multi fuel capability of LHR engine makes it very interesting and useful area of research at such high temperature approximately complete combustion of any fuel can be achieved with slight modification in fuel system. Wall and piston temperature above 600^oC would allow less volatile fuel to burn off quickly and with ease [Randolph, 4]

The idea of burning coal slurry in LHR engines has gained much importance due to the fact of burning less volatile fuel. And availability of coal in specific cogeneration trigeneration and quad generation system such a cheap and handy heat and power source would be very useful. The only difficulties encountered in the research are injection of coal slurry and wear and tear of cylinder, piston due to the entrapment of abrasive ash particle between the moving parts.

6.0 CONCLUSIONS AND FUTURE WORK

A trigeneration network has been proposed. Different aspect, heating cooling and power were discussed in detail optimization were also suggested. Feasibility of such system in power generation is very good due to its compactness cheapness and high efficiency. System of the sizes of a large generator set can be developed and sold commercially. They will be having good demands in the market.

In the current work identification of the regulation point by which, one can regulate the requirement of the load matching has to be simulated. Author would continue this work in this direction, Placement of PRV's Pressure regulation valves is key feature to control the system and this aspect has to be dealt in greater detail. Mathematical models have to develop to practically justify the current work.

7.0 ACKNOWLEDGEMENT

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8.0 REFERENCES

1. W. Bryzik and R. Kamo, “TACOM/Cummins Adiabatic Engine Program”; SAE Paper 830314, Detroit, MI (1983)

2. W. Bryzik and R. Kamo, “Cummins-TARADCOM Adiabatic Turbo compound Engine Program”; SAE Paper 810070, Detroit, MI (1981)

3. G. Woschni, W. Spindler, and K. Kolesa, “Heat Insulation of Combustion Chamber Walls – A Measure to Decrease Fuel Consumption of I.C. Engines?”, SAE Paper 870339, Detroit, MI (1987)

4. R.A. Churchill, J.E. Smith, N.N. Clark, and R.A. Turton, “Low-Heat Rejection Engines – A Concept Review”; SAE Paper 880014, Detroit, MI (1988)

5. J.L. Lauer and B.G. Bunting, “Catalytic Generation of Lubricants from Carbonaceous Gases on Surface Undergoing Friction at High Temperatures”; SAE Paper 880019, Detroit, MI (1988)

6. James A. Leidel, “An Optimized Low Heat Rejection Engine for Automotive Use - An Inceptive Study”, SAE Paper 970068, Detroit Edison Company

7. D.A Reay,”Hand Book of Energy Management-Industrial Energy Conversion”, International Research and development Co. Ltd New Castle-Upon Tyne, England, Pergamon Press. (1997)