An Optimized Low Heat Rejection Engine for Automotive Use - An Inceptive Study

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ABSTRACT

An unconventional low heat rejection (LHR) engine design is described. Previous research efforts into LHR concepts, including high temperature materials and tribology, are reviewed. The continued reliance on conventional compression ignition designs is identified as a significant roadblock. Therefore, a set of design criteria is established, and an original design is formulated. The powerplant consists of an independent positive displacement compressor and expander, a high pressure combustor, and a compressed air accumulator. Compatibility with ceramic materials and high temperature combustion were primary goals. Inherent characteristics include full torque from zero RPM, enhanced combustion, improved efficiency under part load operation, and increased volumetric and thermodynamic efficiencies. These potential improvements warrant the design and construction of a prototype for further study.

INTRODUCTION

This paper describes the initial, inceptive design of an optimized low heat rejection engine. Included are a discussion of past LHR engine research, a brief description of the deficiencies and roadblocks which were uncovered, and a discussion of an avenue toward progress in LHR design. A set of basic criteria is established which supports the original design of an unconventional powerplant. Next, some relevant advances in material science are discussed, including ceramics and high temperature tribology. Lastly, the structure of the design is presented and described.

This design will more fully utilize the potential of the LHR concept and advanced ceramic materials. Additionally, the design provides for maximum torque from rest, efficient part load operation, enhanced volumetric efficiency, and improved combustion.

A follow-up to this inceptive study would include detailed computer modeling of the thermodynamic and gas flow process. Specific materials should be selected, and a more detailed design should be developed to aid in the construction of a working prototype.

BACKGROUND

THE LOW HEAT REJECTION ENGINE CONCEPT is not new. Engine designers have long been aware that both maximizing the temperature of combustion and minimizing the losses of combustion energy prior to the expansion cycle will increase thermodynamic efficiency. However, material limitations have restrained the development of such interests. The development and introduction of advanced ceramic materials in the past few decades has enabled low heat rejection research to progress, principally in the field of compression ignition engines.

In 1975, the U.S. Army Tank-Automotive Command (TACOM) and Cummins Engine Company began an "adiabatic" engine program [1], and significant progress has been made. [2,3] In addition, Isuzu Motors [4,5], Ford Motor Company [6,7], General Motors Corporation [8], NKG Insulators/Mitsubishi Motors Corporation [9], Integral Technologies [10,11], Massachusetts Institute of Technology [12], and others have conducted LHR engine experimentation. Most of these studies investigated modified conventional direct injection diesel engines.

Although promising, the results of the above investigations have been somewhat mixed. While most have concluded that insulation reduces heat transfer, none have produced exceptional gains in efficiency or performance. In fact, a few have shown that the addition of insulation and the elimination of cylinder coolant flow, degrades performance and increases cylinder wall heat flux. [12,13] A helpful discussion of several of these studies, which also included several numerical simulations not discussed here, was done by Union College and Oak Ridge National Laboratory. [14]

An observational study of LHR combustion using a high speed camera was done by Tiajin University. It was found that ignition delay following fuel injection was reduced, impairing air-fuel mixing, and ultimately prolonging combustion duration. [15] A reduced fuel injector nozzle orifice diameter or the employment of special impingement plates to enhance air-fuel mixing was suggested.

THE SHORTCOMINGS OF LHR RESEARCH are mainly the result of the improvisation of conventional engines to LHR designs. The mere substitution of ceramic components or the addition of insulating coatings fails to account for increased combustion temperatures and an altered combustion process. [14] There is no inherent utilization of the resulting retained heat energy. Consequently, complex turbocompounding devices or bottoming cycles must be employed to capture some portion of the retained heat energy from the exhaust stream.

In addition, conventional piston-crank designs produce piston side-wall stresses which make the direct substitution of ceramic for metallic materials troublesome. New designs which reduce piston side forces, or slapping forces, would be more compatible with ceramics. In a LHR review done by West Virginia University it was concluded that, "It may be helpful to return to the basics of engine design in formulating models of LHR engines." [16] This is the fundamental principle which this paper will address.

While "returning to the basics" of engine design for the purpose of accommodating LHR concepts, this paper will next suggest factors which further optimize this powerplant with regard to its compatibility with its intended application, the passenger vehicle.

DESIGN CRITERIA

Below are several sets of design criteria which are the framework for the design process producing the engine described in this paper. While any engineering endeavor is fraught with compromises and undesirable practicalities, no individual criteria has been completely eliminated at the expense of another in this design.

CRITERIA SATISFYING TO THE VEHICLE OPERATOR which will produce a marketable product:
- Quiet operation.
- Smooth operation, lacking in vibration.
- Quick response to control input.
- Ample torque and power.
- High reliability and durability.
- Ease of operation and maintenance.

ECONOMIC CRITERIA pertaining to cost effective production and maintenance while in service:
- Simple in design.
- Manufactured from the minimum amount of materials by economical methods.
- Modular and/or compact in construction for ease of repair and ease of placement in compact engine compartments.
- Long service life.

PASSENGER VEHICLE COMPATIBILITY CRITERIA relating to typical automotive power requirements and driving cycles:
- High torque at low speeds and less at high speeds.

- Efficient part load operation.
- Operable at temperatures between -30 to 50 ^{o}C, and unaffected by altitude.

EFFICIENCY CRITERIA pertaining to fuel consumption and to the challenges we face with our environment:
- Multi-fuel capable.
- Highly fuel efficient.
- Low in emissions of incomplete combustion products.

These criteria bear upon the basic design of any automotive powerplant. However, the wealth of practical knowledge contained in the above cited references identifies several key pitfalls. These can be utilized as additional, invaluable criteria which must be avoided, or accounted for in the design process.
- Low tolerance of ceramic materials to mechanical stress and thermal shock.
- Failure of liquid lubricants at high temperatures.
- Degraded combustion process due to high temperatures.
- Reduced volumetric efficiency due to increased component temperatures encountered during induction.

CERAMIC MATERIALS

Two major obstacles of the LHR engine are component strength and tribology at high temperatures. Where conventional metals and lubricants fail to perform at elevated temperatures, advanced ceramic materials provide an alternative. These materials have provided the major impetus to LHR research and development in recent decades. High hardness, high elastic moduli, resistance to corrosion and wear, strength at high temperatures, and often low thermal conductivity are physical properties of ceramics. Principal substances of interest include nitrides and carbides of silicon (Si_3N_4 and SiC); oxides of chromium, aluminum, and iron (Cr_2O_3, Al_2O_3, and Fe_2O_3); and partially stabilized oxide of zirconium, (ZrO_2, or PSZ).

Low ductility, low tensile strength, and low bending strength have impeded the direct replacement of metals with ceramics in conventional engine designs. Conventional piston and cylinder stresses make the application of ceramics extremely challenging. Large piston ring loading forces produce large stresses and large friction forces. To reduce these forces, modifications to piston and connecting rod mechanics would decrease the demands which are currently placed upon tribological research.

Both monolithic ceramic components and ceramic coatings have been used by various LHR engine researchers. The work done by Adiabatics and the U.S. Army makes extensive use of titanium and ceramic coated steel components. Compared to monolithic ceramics, coatings "can be attributed to lower

cost, better reliability and durability, and the ease in design of the ceramic coated diesel engine." [17] A 100 hour endurance test of a partially cooled prototype was successfully completed. Liquid lubricant and a "self-cleaning" top piston ring were utilized. [3] Subsequent to this test, solid lubricant top piston rings are under development. [18]

Most experimental LHR diesel engines to date employ liquid lubricants. Although the performance of liquid lubricants in the above studies has been improved, their continued use will severely limit further increases in combustion temperatures. The design developed in this paper will utilize expander temperatures of 1200 to 1500 ^{o}C, precluding the use of any known liquid lubricant. In fact, one of the design goals is to develop a structure that could operate with ceramic triboical surfaces in the absence of liquid lubrication. Therefore, an investigation into other means of lubrication is essential.

HIGH TEMPERATURE TRIBOLOGY

The best liquid lubricants decompose at temperatures in excess of 350 ^{o}C. 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. Three alternatives are discussed below: solid lubricants, solids formed via gaseous dissociation, and gaseous lubricants.

SOLID LUBRICATION has been widely investigated by material scientists and LHR diesel researchers. 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. [18,19], the Midwest Research Institute [20], and Battelle. [21,22,23] Recent work done by Battelle [24] describes the successful application of a well known "Boes" compact to temperatures of 850 ^{o}C. [25,26] The NASA Lewis Research Center has shown the effectiveness of coatings of some oxides and fluorides to 900 ^{o}C. [27,28] Nickel/molybdenum-bonded titanium carbide cermets [29] and nickel/molybdenum-bonded chromium carbide cermets [30] have also shown to be effective. Additional research must be directed toward the development of the most promising materials.

DISLOCATION OF CARBONACEOUS GASES has been presented as a means to continuously replenish a lubricating carbon on metallic or ceramic surfaces undergoing friction. [31,32] "Graphitic" carbon on nickel-containing and Sialon (Si_3N_4 +10% Al_2O_3) surfaces are produced in an ethylene gas atmosphere at 350 to 650 ^{o}C. Coefficients of friction well below 0.1 were observed. However, it is questionable whether such techniques could be applied to this design. The high temperature pre-combustion which is utilized would reduce any carbonaceous gases to carbon dioxide prior the expansion cylinders.

GASEOUS LUBRICATION offers the greatest potential for low friction at high temperatures. A ringless piston/cylinder with very small and precise clearances would allow small amounts of combustion gases to pass, forming a gaseous film. Although the low viscosity of such a film will not support large loads, significant reductions in friction are probable. Major impediments exist to implementation of gaseous lubrication in conventional piston/crank engines. However, due to its structure, this optimized LHR design is particularly suited to gas lubrication.

First, main piston side forces have been greatly reduced by the employment of a crosshead piston and cylinder. Second, the combustion products which blow-by the piston, producing the gaseous film, would not escape the main cylinder. There is no issue of contamination of a crankcase lubricant. Third, thermal cycling is reduced due to the pre-combustion, external to the cylinder. The expansion cylinder will only be exposed to products of combustion, and not to cool atmospheric air. Therefore, tight tolerances can me maintained.

A low friction, unlubricated diesel engine was investigated by S. Timoney at the University College of Dublin. [33] It consisted of a ringless, valveless, opposed piston, two stroke diesel engine constructed of silicon carbide. Although the study was rather limited, it successfully demonstrated the operation of a piston/cylinder lubricated by a gaseous film. A second investigation into this same design was conducted with similar results. [34]

Regardless of the type of in-cylinder lubrication, the crosshead shaft seal must utilize a solid lubricant. Refer to expander description below. It is a relatively small interface to seal, and will only experience linear sliding forces. Therefore, the application of a solid lubricant will be less involved.

POWERPLANT STRUCTURE

The powerplant consists of a several separate subsystems. Figure 1 illustrates a schematic of the engine design, including a positive displacement compressor, a compressed air accumulator, a fuel combustor (or burner), and a positive displacement expander. It is similar in design to George Brayton's (1839-1892) "Ready Motor" gas engine. [35,36] Brayton's engines were commercially available gas or oil burning "hot air" designs from which the Brayton, or isobaric combustion, thermodynamic cycle originated. Various engines containing some of the features which will be described below may be found in numerous patents. Recent investigations into a coal burning engine by West Virginia University have produced a related design. [37] However, all of the above designs have lacked critical components or the materials required to become successful.
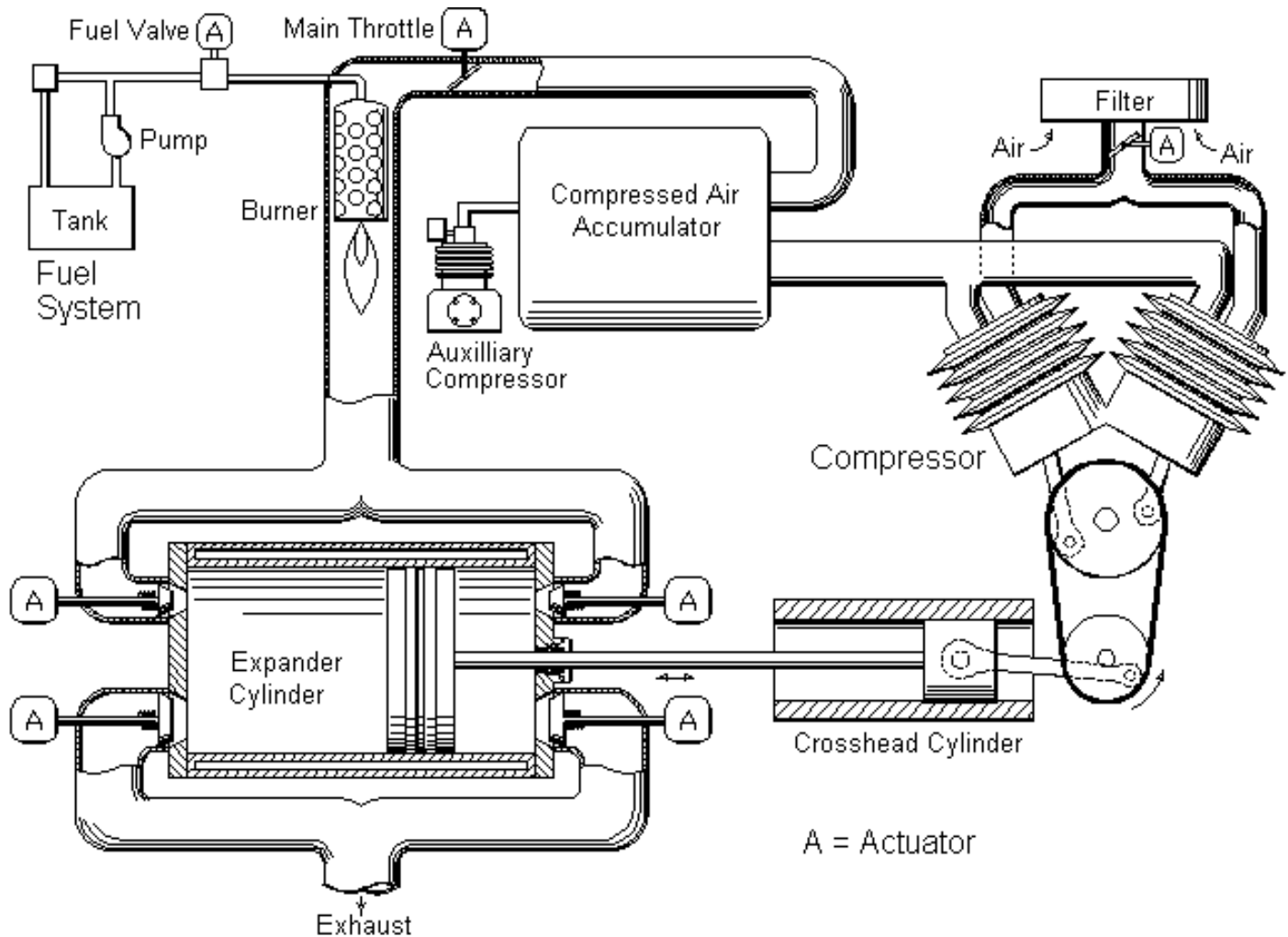
Figure 1 General Engine Schematic Showing Primary Components

THE COMPRESSOR is a conventional, positive displacement piston device. It is driven by the expander via a suitable fixed-ratio, power transmission, but is a separate device. Attention is given to isolate the compressor from the high temperatures present in the burner and expander. Actuated poppet type valves contribute to complexity and cost, but also reduce noise and improve air flow when compared to standard air compressor reed type valves. A conventional air or liquid cooling system will be employed to maintain low compressor temperatures and enhance volumetric efficiency. The amount of heat rejected will be significantly less than that rejected from an IC engine cooling system. For a prototype powerplant, a small motorcycle engine could be modified to operate as a compressor. The intake to the compressor may be throttled to vary induction air flow. Induced air flow will modulate to maintain the desired compressed air accumulator pressure. The additional work encountered during throttling, which is required to induce air at pressures below atmospheric, may be eliminated by eliminating the throttle. Alternatively, intake valve timing may be varied or individual cylinders may simply be idled. Any of the above techniques will significantly

reduce part load compressor work, increasing the overall, part load efficiency.

AN INSULATED ACCUMULATOR will receive and briefly store the compressed air supply. All losses of heat energy from the compressed air stream will be minimized after exiting the compressor. The hot, compressed air will flow from the accumulator via a main throttle to the burner. The accumulator will be the largest component in the powerplant. It is not practical to construct an accumulator with sufficient volume to allow for prolonged operation without a functioning compressor or to allow for regenerative braking. However, it must be of sufficient volume to provide an energy reserve to the burner/expander during acceleration while the induction controls respond and maintain pressure. For example, a 5 second reserve serving an expander at 0.02 kg/sec would require 0.1 kg of compressed air. If a volumetric compression ratio of 6 and a compressor efficiency of 85% are assumed, an accumulator pressure of approximately 1300 kPa is produced. If the 5 second air flow is allowed to isothermally reduce the accumulator pressure by 20% to 1040 kPa, a volume of 0.065 m^3 is required. A 2.5 m

long cylinder with a diameter of 18 cm contains a similar volume. Higher compression ratios, reduced mass flow rates, or larger acceptable pressure drops will reduce accumulator size requirements. This is a substantial volume for an insulated, mobile pressure vessel. However, it is this energy reserve which will produce the favorable torque versus engine speed required of a typical passenger vehicle.   Full torque is instantly available at zero RPM, and less is produced at higher engine speeds. Relatively slower operating speeds will be seen, and idling requirements are reduced or eliminated.   Additionally, power transmission requirements are greatly reduced. This characteristic result of reserve power is common to electric motors and steam engines.

Possible locations for the large accumulator are the engine compartment, somewhere in the rear of the vehicle, or in an elongated form underneath the vehicle similar to a driveshaft. The independent compressor and expander arrangement make the use of an accumulator possible, and the torque/power requirements of the typical passenger vehicle make an accumulator essential.

THE BURNER AND FUEL INJECTION SYSTEM will combust a variable flow of compressed air with a high pressure fuel supply. The structure is similar in design to a small gas turbine combustor. For a prototype powerplant, it would be practical to modify and utilize a small gas turbine combustion system. However, the ignition system must be capable of reliable and repeated re-lighting. This is a condition not encountered by gas turbines. The final burner design will utilize ceramic materials throughout to allow exit temperatures of 1200 to 1500 $^{\circ}$C.

With the high combustion temperatures, the formation of nitrogen dioxide (NO_2) increases exponentially.   Increased residence time of the combustion products within the combustor provides complete combustion, but it also contributes to NO_2 formation. An effective after-treatment with a reducing catalyst or the limitation of maximum flame temperatures must be investigated.

THE EXPANDER consists of an insulated cylinder housing a double acting piston. The cylinder walls and heads are constructed to retain as much heat as possible. Insulating air gaps within the cylinder wall will provide additional insulation.   An appropriate tribolical system encompassing piston rings (if used), the cylinder wall, and crosshead shaft seal will provide dry, high temperature lubrication as discussed above. The absence of liquid lubricants has eliminated the need for an oil sump and accompanying vertical piston/cylinder arrangement.   This permits various cylinder arrangements which are not feasible with conventional piston over oil sump designs. Spatial efficiency may be improved, particularly in the flexibility of component placement.   As discussed above, hot gas blow-by passing the piston will be contained within the opposite end of the cylinder and not vented. A ventilation system,
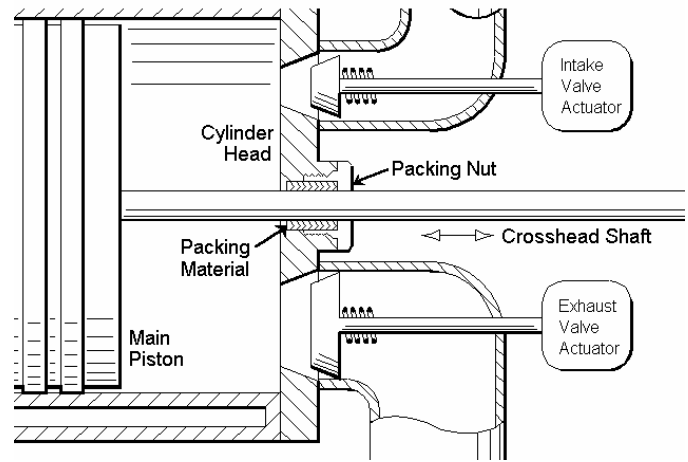
Figure 2 Crosshead Shaft Packing

such as crankcase ventilation, for emissions control is unnecessary, nor is there an issue of oil sump contamination of combustion products. The crosshead shaft passes through one cylinder head to a crosshead piston/cylinder via a packing gland as shown in Figure 2. The packing material will be a solid lubricant as discussed above. This arrangement will remove the majority of lateral piston/cylinder forces from the high temperature expander. The crosshead is removed from the high tribolic system and contain them at the crosshead temperature combustion products and may be conventionally lubricated in conjunction with a conventional crankarm and crankshaft power take-off.

Figures 1 and 2 illustrate poppet style valves on the expander intake and exhaust ports.   The wide apertures attainable via poppet valves make them a good choice, but the use of rotary or sliding type valves should not be overlooked.

As the maximum cycle temperature is increased, the powerplant thermodynamic efficiency will increase, as will the specific work output.   This temperature will be seen at the exit of the burner, throughout the expander intake manifold, at the intake valves and valve guides, and into the expander itself. The materials used for these components, and possibly NO_2 control, will dictate the maximum allowable temperature. Once selected, this temperature may then be used to find an appropriate volumetric compression ratio.   A computer simulation utilizing the standard Brayton cycle was performed by this author in order to maximize the specific work output of an engine with respect to the compression ratio. Utilizing a 1200 to 1500 $^{\circ}$C maximum cycle, assuming compressor and expander efficiencies of 85 percent, and neglecting heat rejection, a volumetric compression ratio of 6 to 8 was derived. Further increases in the compression ratio will incrementally increase the compressor to expander back-work ratio, decreasing overall specific work output. The simulation also assumed that the volumetric expansion ratio was equal to the compression ratio. In reality, this is not required. The ability to increase the expansion ratio independently of the compression ratio has the potential to more fully expand the products of

combustion. This concept is well known in conventional engine design, the Atkinson cycle, and has actually been used to improve efficiency. An engine made by James Atkinson (1846-1914) in England was first to utilize this concept.

Another consideration in the selection of compression ratio is the potential use of exhaust gas regeneration, and an accompanying potential for further increases in cycle efficiency. While the previously discussed improvements in efficiency without regeneration are sufficient to justify continued development of this design, a brief discussion of regeneration is warranted. As the compression ratio increases, the compressor exiting temperature also increases. It is this gas stream which must accept the heat energy from the hot exhaust gases. The higher the compressed air temperature, the lower the potential for heat transfer from exhaust gases. Therefore, for a given, fixed maximum cycle temperature, a lower compression ratio will facilitate regeneration. However, a reduction in compression ratio will reduce the specific work output. An increased mass flow rate, and hence increased cylinder volume, must be then be utilized to maintain an equivalent net work output. The added complexity and cost of a regenerator will be a major consideration as well.

Finally, one last option is an integral accumulator/regenerator design. A regenerator is a heat exchanger requiring large surface areas in order to be effective. An accumulator could be developed to contain an integral heat exchanging conduit through which exhaust gases could pass, providing a regenerative effect.

POWERPLANT CONTROL

Several control sequences will operate independently. Induction, power, and combustion control are briefly described below.

INDUCTION will vary as required to maintain the desired accumulator pressure. As the compressor operates via a fixed transmission ratio with the expander, the intake to the compressor will be throttled to modulate induction. Part load compressor work will be reduced in proportion.

ENGINE POWER will be delivered in response to an operator input. Figure 1 illustrates a main throttle at the inlet to the burner for modulation of compressed air flow. Alternatively, the passage between the accumulator and the burner could be left unrestricted, and compressed air flow could be controlled via a variable intake valve period. This approach would provide the full accumulator pressure at the intake valves, and losses associated with throttling would be avoided. The art of steam engine design has dealt with this issue extensively. It was previously termed "variable cut-off". A good comparison of flow control methods was made by GM Research Labs with regard to the SE-101 steam powerplant [38].

IO = Intake opens   BDC = Bottom dead center
IC = Intake closes   TDC = Top dead center
EO = Exhaust opens   IC' = Intake closes
EC = Exhaust closes   light load

a. Throttle Control   b. Variable Intake Control
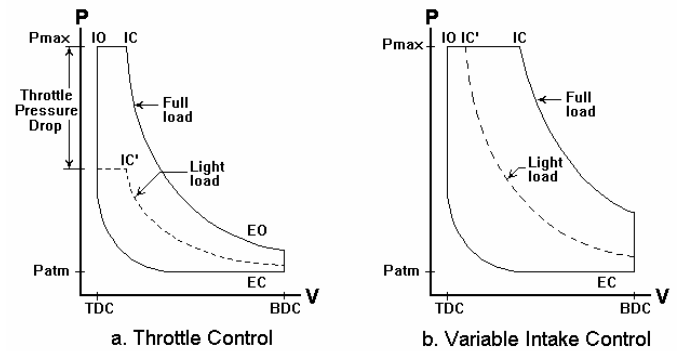
Figure 3 Ideal Pressure-Volume Diagrams for Throttle and Variable Intake Expander Control

A contrast between these two control methods can be seen via their ideal indicator diagrams. Figure 3a illustrates an ideal diagram of a throttled expander. Both full and part load conditions rather fully expand the combustion products. The associated throttling losses are not shown. Figure 3b illustrates an ideal diagram with variable intake period control (variable valve timing). During full load, a substantial portion of the expansion process is wasted, while during part load, expansion is more complete. Since the majority of automotive powerplant operation is part load, this is a significant concern. However, the added complexity of a variable valve mechanism may be the overriding factor.

COMBUSTION will be controlled by the modulation of fuel flow to the burner. Ideally, fuel would be delivered in direct proportion to the compressed air flow. Two methods for determining the compressed air flow rate are possible. First is the direct measurement of flow via a high temperature, high pressure mass flow sensor. The availability of such a sensor "off the shelf" is questionable. Therefore, the empirical calculation via more readily measurable operating parameters such as throttle position, accumulator pressure and temperature, and engine speed would be more practical.

With semi-continuous combustion, very lean air/fuel ratios are possible. The main limitation on excess air would be satisfactory ignition and re-ignition under all operating conditions. A wide variety of fuels could be utilized. The increased time allowed for combustion, in the confines of a high temperature burner and expander, allows for complete oxidation of the fuel. Although complete combustion of hydrocarbons is possible, the high temperatures will surely increase the formation of NO_2 . Attention must be given to maintaining acceptable levels in the exhaust products.

CONCLUSIONS

This exercise in engine design has contrived a powerplant design that takes advantage of continuous high temperature combustion and advances in ceramic materials. The potential of the LHR concept can be incorporated more readily if an adherence to conventional engine structures and designs is forgone.

A preliminary design has been developed with the "potential" for the following:

- Smooth and quiet power delivery due to non-impulsive combustion, relatively slower engine speeds, and a favorable torque response.
- Enhanced part load efficiency due to variable compressor induction.
- Reduced fuel consumption due to lean air/fuel ratios.
- Improved combustion efficiency due to a semi-continuous combustion prior to the expander.
- Increased volumetric efficiency due to reduced induction component temperatures.
- Increased thermodynamic efficiency due to more complete expansion of combustion products.
- Increased thermodynamic efficiency due to increased combustion temperatures.

Although many issues with the application of materials remain, this design merits further development. The combined effect of the above improvements could produce a powerplant with significant reductions in emissions of incomplete combustion products as well as significant improvements in fuel economy.

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