

A Six-Stroke, High-Efficiency Quasiturbine Concept Engine With Distinct, Thermally-Insulated Compression and Expansion Components

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Abstract: One of the most difficult challenges in engine technology today is the urgent need to increase engine thermal efficiency. This paper presents a Quasiturbine thermal management strategy in the development of high-efficiency engines for the 21st century. In the concept engine, high-octane fuels are preferred because higher engine efficiencies can be attained with these fuels. Higher efficiencies mean less fuel consumption and lower atmospheric emissions per unit of work produced by the engine. While the concept engine only takes a step closer to the efficiency principles of Beau de Rochas (Otto), it is readily feasible and constitutes the most efficient alternative to the ideal efficiencies awaiting the development of the Quasiturbine photo-detonation engine, in which compression pressure and rapidity of ignition are maximized.

One of the most difficult challenges in engine technology today is the urgent need to increase engine thermal efficiency. Thermal management strategies and the choice of fuels will play crucial roles in the development of high-efficiency engines for the 21st century. However, it was during the 19th century that the fundamental principles governing the efficiency of internal combustion engines were first posited.

In 1862, Alphonse Beau de Rochas published his theory regarding the ideal operating cycle of the internal combustion engine. He stated that the conditions necessary for maximum efficiency were: (1) maximum cylinder volume with minimum cooling surface; (2) maximum rapidity of expansion; (3) maximum pressure of the ignited charge and (4) maximum ratio of expansion. Beau de Rochas' engine theory was first applied by Nikolaus Otto in 1876 to a four-stroke engine of Otto's own design. The four-stroke combustion cycle later became known as the "Otto cycle". In the Otto cycle, the piston descends on the intake stroke, during which the inlet valve is held open. The valves in the cylinder head are usually of the poppet type. The fresh fuel/air charge is inducted into the cylinder by the partial vacuum created by the descent of the piston. The piston then ascends on the compression stroke with both valves closed and the charge is ignited by an electric spark as the end of the stroke is approached. The power stroke follows, with both valves still closed and gas pressure acting on the piston crown because of the expansion of the burned charge. The exhaust stroke then completes the cycle with the ascending piston forcing the spent products of combustion past the open exhaust valve. The cycle then repeats itself. Each Otto cycle thereby requires four strokes of the piston- intake, compression, power and exhaust- and two revolutions of the crankshaft. The disadvantage of the four-stroke cycle is that only half as many power strokes are

completed per revolution of the crankshaft as in the two-stroke cycle and only half as much power would be expected from an engine of given size at a given operating speed. The four-stroke cycle, however, provides more positive scavenging and charging of the cylinders with less loss of fresh charge to the exhaust than the two-stroke cycle.

Modern Otto cycle engines, such as the standard gasoline engine, deviate from the Beau de Rochas principles in many respects, based in large part upon practical considerations related to engine materials and the low-octane fuel used by the engine. The six-stroke Quasiturbine concept engine described in this monograph is designed to overcome many of the limitations inherent in the Otto cycle and bring the engine's operating cycle closer to Beau de Rochas' ideal efficiency conditions. The preferred fuel for the concept engine is methanol because of its high-octane rating and its ability to cool the fuel/air charge during the intake stroke.

Maximum Volume / Minimum Cooling Surface

The first Beau de Rochas principle teaches that the engine should have a minimum cooling surface area while still allowing for maximum charge volume during intake ("volumetric charge efficiency"). Otto cycle engines generally have cooling systems.¹ The cooling system represents an engineering compromise. Without a cooling system, the pre-mixed fuel/air charge could prematurely ignite (or "knock") during the compression stroke, especially with low-octane fuels like gasoline. Knock reduces the engine's power because the pressure of the combustion event is not properly synchronized with the engine's power stroke. Knock can also seriously damage engine parts. A cooling system also serves to maximize volumetric charge efficiency by reducing the temperature of the charge during intake.

Targeting high-efficiency, the proposed concept engine eliminates the engine cooling system. Instead, cooling of the inducted fuel/air charge is achieved through the use of methanol, a liquid with a high latent heat of vaporization, which is injected into the intake port (port fuel injection or "PFI") during the intake stroke.² The compressor can then be thermally insulated in order to minimize the cooling surface, while still maintaining volumetric charge efficiency. Similarly, the expander can be thermally insulated to minimize the cooling surface and to maximize the pressure of the combusted gases during the power stroke, as discussed below.

Maximum Rapidity of Expansion

Rapidity of expansion in a spark-ignition engine can be achieved by increasing the engine's compression ratio. A higher compression ratio brings the fuel and oxygen molecules in closer proximity during ignition and facilitates rapid expansion. In order to increase engine compression ratio, a high-octane fuel is used. A high-octane fuel is a fuel that has a high autoignition temperature in air. Because the fuel/air mixture is heated during the engine's compression stroke (especially in the thermally insulated compressor cylinder of the concept engine), it is critical to avoid premature ignition or knock during that stroke. With high-octane fuels, such as methanol, premature ignition can be prevented while still increasing the engine's compression ratio. Thus, in order to achieve high compression ratios, lower octane fuels like gasoline (despite anti-knock additives)

should be avoided. High-octane fuels are most compatible with the high compression temperatures of the present concept engine.

The primary limitations on the compression ratio in the concept engine are (1) the autoignition temperature of the selected high-octane fuel and (2) the temperature tolerance of the oil-free lubricant which is used to coat the piston rings of the compressor. Lubricating graphite surface coatings have a maximum temperature tolerance of about 1000F / 540C / 810K.³ Methanol has an autoignition temperature in air of 470C / 740K. Thus, in principle, high compression ratios can be achieved with high-octane fuels while still maintaining the temperature in the cylinder during the compression stroke at less than the maximum temperature tolerance of the oil-free lubricant.

Maximum Pressure of the Ignited Charge

The pressure of the ignited charge is subject to several conditions: the compression pressure of the fuel/air charge prior to ignition, the ratio of fuel to air in the charge itself and the temperature of the combusted gases after ignition. While ideal, maximum pressure cannot be achieved in the concept engine⁴, the concept engine does improve on the Otto cycle engine by eliminating the cooling system and by allowing high compression pressures with high-octane fuels. The Otto cycle cooling system reduces pressure both during the compression stroke and during the expansion stroke. By using thermal insulation for both the compression function and for the expansion function and by using a near stoichiometric ratio of high-octane fuel and air, the concept engine takes a significant step closer to Beau de Rochas ideal cycle efficiency.

Maximum Expansion

The fourth Beau de Rochas efficiency principle teaches that the expansion volume of the combusted fuel/air charge should be maximized. In Otto cycle engines, the compression volume and the expansion volume are equal because the cylinder volume swept by the piston is the same for both the compression stroke and for the power stroke. For maximum efficiency, the expansion volume should always exceed the compression volume. The constant-volume Atkinson cycle has this characteristic.

The Atkinson cycle engine is a type of internal combustion engine invented by James Atkinson in 1882. The Atkinson cycle is designed to provide efficiency at the expense of power. The Atkinson cycle allows the intake, compression, power and exhaust strokes of the four-stroke cycle to occur in a single turn of the crankshaft. Because of the engine's novel linkage, the expansion ratio is greater than the compression ratio, which results in greater efficiency than a comparable engine operating in the Otto cycle.⁵

Another way to achieve the Atkinson cycle effect is to separate the engine's compression function, its combustion function and the expansion function. That approach is the one used in the present Quasiturbine concept engine. The stand-alone compressor has its own set compression volume. Fuel and air would be pre-mixed and compressed in the compressor. The pre-mixed fuel and air would be combusted in engine combustion chambers. The stand-alone expander would have an expansion volume that is greater than the compressor's volume. This can readily be achieved because of the separation of functions. Unlike an Otto cycle engine, the volume of the expander's expansion chamber

does not have to equal the compression chamber volume, if the compression and expansion functions are separated. Instead, the volume of the expansion chamber may be sized to exceed the compressor's compression chamber volume. The expansion volume thereby exceeds the compression volume by design.⁶

Engine Components

There are four principal engine components necessary to perform the engine's three functions. The first component is a thermally-insulated, piston-type air compressor. The air compressor shares a common shaft (or is linked by a belt drive or chain drive) with the Quasiturbine expander. The expander provides the necessary power for compression work. The second component is a Holzwarth combustion chamber, which is described in more detail below. The third component is the Quasiturbine expander, which is also comprised of thermally insulating materials. The fourth component is a compressed fuel/air line, which delivers the fuel/air charge under pressure to the combustion chambers. The engine is a six-stroke engine. The six strokes occur during each 90 degrees of shaft rotation. The six strokes are: one intake stroke, one compression stroke, two power strokes and two exhaust strokes. A special linkage, not unlike the Atkinson engine linkage, allows the compressor to complete eight strokes (four intake strokes and four compression strokes) during each 360 degrees of shaft rotation, which results in one complete compression cycle over each 90 degrees.

There are eight power strokes per each 360 degrees of Quasiturbine revolution as compared to one power stroke per two revolutions of the Otto cycle engine. Each of the engine components and their operation are described in more detail in the following sections.

Piston-type Compressor

The concept engine's compressor is a thermally-insulated, positive-displacement, piston-type compressor. The piston crown is a "pancake" or "flat aspect" crown. The compressor shares a common shaft with the Quasiturbine expander. See, Figure 1. The maximum temperature in the compressor is limited by the temperature tolerance of the oil-free piston ring lubricant and by the autoignition temperature of the fuel. The compressor temperature, however, can be moderated by port injection of a liquid with a high latent heat of vaporization. The liquid in this case is the methanol fuel itself. The operation of the compressor must be considered over 90 degrees of shaft rotation, which represents one complete compression cycle.

Compressor Materials

The Beau de Rochas principles teach that a minimum cooling surface is necessary for high-efficiency engine operation. Thus, the heat of compression should be retained and should not be rejected to a cooling system if possible. The separation of functions in the concept engine makes thermal insulation of the compressor practical. The piston, cylinder and cylinder head can either be coated with a thermally insulating material like zirconia or they can be comprised of a thermally insulating ceramic like silicon nitride.⁷

In either case, by retaining the heat of compression in the compressor, the compression pressure of the fuel/air charge will be maximized at ignition.

The separation of functions yields another benefit as well. Oil-free lubrication of the compressor piston rings is now possible because the internal compressor temperature can be maintained at less than the temperature tolerance limit of the graphite coating on the piston rings. This is not possible in an Otto cycle engine where the cylinder alternates between the compression function and the high-temperature, combustion/expansion function.

Compressor Operation

From 1 degree to 45 degrees, the piston is moving upward and is compressing the fuel/air charge. From 46 degrees to 90 degrees, the piston is moving downward and is inducting the next fuel/air charge. If a high-octane, liquid fuel is used, the fuel is injected into the air intake port prior to the intake valve. See, Figure 2.

The pressure in the Quasiturbine expander is at its maximum when the power stroke begins at 1 degree after top dead center. See, Figure 1. The pressure in the expander chamber of the Quasiturbine diminishes as expansion occurs. Minimum pressure in the expander chamber is reached at 90 degrees after top dead center. At 45 degrees, the pressure remaining in the expander should ideally exceed the maximum pressure in the compressor to prevent the engine from stalling. Of course, if the ideal cannot be attained, two Quasiturbines 45 degrees out of phase or a flywheel can be used to prevent stalling.⁸

Port injection of methanol may provide some assistance here. The compression chamber is thermally insulated; however, since a liquid with a high latent heat of vaporization is injected, the temperature and pressure of the compressed fuel/air charge in the compressor will be reduced. The latent heat of vaporization of the liquid allows the compression stroke to proceed isothermally during the intake stroke and during the first portion of the compression stroke. Later in the compression stroke, the compression function proceeds adiabatically as methanol's latent heat of vaporization is reduced to zero and the it phase-shifts from liquid to a vapor.

The final temperature and pressure of the compressed fuel/air charge at maximum compression is thereby reduced in proportion to the injected methanol's volume and the latent heat of vaporization associated with methanol (i.e., 1100 J/g). Reduction of the maximum compression pressure may prove sufficient to prevent engine stalling without a flywheel. Reduction of the temperature during the intake stroke also benefits volumetric charge efficiency and reduction of the temperature prevents premature ignition of the fuel/air charge in the compressor during the compression stroke.

Compressor Strokes

As previously stated, from 1 to 45 degrees, the compression stroke is occurring. The intake valve is closed and the compressor outlet valve is closed during the beginning of the stroke. The compressor outlet valve opens when the pressure of the fuel/air charge in the cylinder exceeds the pressure in the compressed fuel/air line, which leads to the combustion chambers. As the piston begins to descend at 46 degrees, the compressor

outlet valve closes and the intake valve opens. A fresh charge is drawn into the cylinder by partial vacuum suction. The fresh charge includes air and atomized methanol droplets with a high latent heat of vaporization. Heat is transferred to the droplets as the charge is drawn past the intake valve and into the thermally insulated compression chamber. At 90 degrees, the intake stroke ends and the piston begins to ascend. The intake valve closes and the compression cycle repeats.

Compressed Fuel/Air Line

The compressed fuel/air line interconnects the compressor with the combustion chambers of the concept engine. The compressed fuel/air line is thermally insulated. At one end of the compressed fuel/air line, there is a connection with the compressor's outlet port. The compressed fuel/air charge enters the line at that point. See, Figure 2. At the other end of the compressed fuel/air line, the line splits into four separate "feeder" lines. Each feeder line connects with the compressed fuel/air inlet valve of one of the four combustion chambers. The purpose of the compressed fuel/air line is to convey the compressed fuel/air charge from the compressor to the combustion chambers with a minimum of heat and pressure loss.

Holzwarth Combustion Chambers

There are a total of four combustion chambers in the concept engine design. Each combustion chamber has two valves: a compressed fuel/air inlet valve and a combusted gas outlet valve. The fuel/air charge is ignited by spark ignition. The combustion chambers are "Holzwarth-type" combustion chambers.

In 1905 Hans Holzwarth of Germany began a long series of experiments with respect to the "explosion" turbine. His turbine consisted of a constant-volume combustion chamber into which a charge of fuel and air was introduced under pressure. Following ignition, the pressure was increased to about 4 1/2 times the original value. The pressure increase caused a spring-loaded valve to open, admitting gases to a nozzle directed against the blades of the turbine. The engine was arranged so that the valve remained open until the combustion chamber pressure equalized with atmospheric pressure, after which the valve would close and a new fuel/air charge was introduced. Although an air compressor was employed in the Holzwarth turbine, the efficiency of the compressor was not extremely important because the air could be supplied at a pressure only about one-fourth that ultimately achieved during combustion and also because only enough air was supplied to furnish the oxygen necessary for combustion. The concept engine follows the Holzwarth combustion chamber model. See, Figure 3.

In the concept engine, the fuel/air charge is first compressed in the compressor. The compressor's outlet valve opens when the pressure in the cylinder exceeds the pressure in the compressed fuel/air line. Simultaneously, the compressed fuel/air inlet valves of two of the combustion chambers open. The fresh compressed fuel/air charge is delivered to the two combustion chambers through the compressed fuel/air line. The pressures equalize and the fresh fuel/air charge is thereby delivered to the combustion chambers. The compressor outlet valve and the combustion chambers' inlet valves close

at about 46 degrees of the shaft's rotation. The two combustion chambers are thereby fully charged and ready for ignition.

The charges in the two combustion chambers are spark-ignited. As combustion is completed, the combusted gas outlet valve in each of the combustion chambers opens (at about 91 degrees of the shaft's rotation) and the high-temperature, high-pressure combusted gases are delivered to two opposed Quasiturbine's expansion chambers. Thus, combustion chamber charging occurs during the first 45 degrees of rotation and combustion chamber discharging occurs at the end of 90 degrees of rotation. This charge/discharge cycle matches the Quasiturbine's four-chamber rotation.

The pressure and temperature of the combusted gases remaining in the combustion chamber at the end of the discharge will be equal to the pressure and temperature of the combusted gases in the expansion chamber at the end of the Quasiturbine power stroke, discussed below. When the combusted gas outlet valve closes (at the end of the power stroke), some of the combusted gases will remain in the chamber. The remaining combusted gases will have an "exhaust gas recirculation" effect, i.e., the combustion temperature of the next, fresh fuel/air charge will be lowered somewhat. However, the lower combustion temperature will serve to reduce NO_x formation during the combustion event.

Valves

The compressor intake valve may be a standard poppet valve. However, the compressor outlet valve and the combustion chamber valves should be rugged, rapid-response solenoid valves. The combustion chamber's compressed fuel/air inlet valve must be timed to close at 45 degrees of rotation, when the combustion chamber is fully charged. The combustion chamber's combusted gas outlet valve must be timed to open at 91 degrees of rotation and close at 180 degrees, when the power stroke ends. Solenoid valves allow this type of precise timing to occur. Because of the sudden pressure rise in the combustion chambers during the combustion event, the valves also must be extremely rugged in order to withstand the shock of high pressure/high temperature combustion events.

The solenoid valve for the compressor outlet serves a somewhat different function with methanol as the fuel. Methanol has a cold-starting problem, in part due to its high latent heat of vaporization. In cold weather, it tends to remain in a liquid state and does not fully vaporize as required for ignition. The concept engine eliminates the cold-starting problem. At start-up, the compressor outlet valve is held open and the piston in the compressor is cranked by the starter motor. As the piston moves up and down (4 complete compression cycles per revolution of the shaft), the methanol/air mixture is heated in the thermally insulated compression cylinder and compressed fuel/air line. The process is sufficient to vaporize the methanol in the cylinder and the line for ignition.

Quasiturbine Expander

The Quasiturbine is a static pressure expansion engine. See, Figure 1. It differs from an aerodynamic pressure expansion engine, like a gas turbine, in that the pressure of the combusted gases acts directly on the rotor segments rather than first having to be

converted to kinetic energy in order to activate the rotary motion by turbine blades. In essence, the Quasiturbine is a direct expansion engine. The QT operates like a uniflow engine in that the combustion/expansion area of the engine occupies a different region of the stator than the cooler exhaust area. In conventional piston engines, the same cylinder head and cylinder walls are cooled due to engine exhaust and have to be reheated by combustion. The ceramic QT engine can operate at higher thermodynamic efficiency since the temperature of the combustion/expansion area of the engine remains hotter and has less temperature fluctuation during operation. These characteristics make the Quasiturbine the ideal expander for the constant-volume Atkinson cycle. Like other rotary engines, there are relatively few parts to the engine itself. The Quasiturbine consists of four rotor segments, two face plates, a stator and differential.⁹

The present engine concept would not be as efficient with a conventional turbine as the expander because a conventional turbine cannot be adapted for the thermal retention strategies discussed below.

Expander Materials

In the concept engine, the Quasiturbine expander is comprised of a thermally insulating material like silicon nitride. The reason for the selection of this material is twofold. First, under the first Beau de Rochas principle, the engine should have a minimum cooling surface to allow for maximum pressure during the entire combustion cycle. Thermal insulation minimizes the cooling surface for both the compressor and the expander in the concept engine. Second, the Quasiturbine model used in the concept engine is the QT-SC. The QT-SC is a free-spinning turbine. Consequently, there is a very slight air gap between the rotor segments and both the stator and the face plates. Lubrication of the rotor segments is therefore not required. As the QT-SC heats up during operation, there will be expansion of the rotor segments, the stator and the face plates, which will reduce the width of the air gap. By choosing a material for the expander that has a low coefficient of thermal expansion, such as silicon nitride, the change in the width of the air gap can be minimized as the expander heats up from ambient temperature to maximum operating temperature. In addition, silicon nitride has a high temperature tolerance, which should allow the use of near-stoichiometric ratios of fuels such as methanol.

Quasiturbine Expander Operation

Because the QT-SC has four rotor segments, during each 90 degrees of shaft rotation, there are four strokes occurring simultaneously: two power strokes and two exhaust strokes. For illustrative purposes, the operation of one power stroke and one exhaust stroke during 180 degrees of rotation will be discussed below. However, it should be noted that the same two strokes are also occurring in the other half of the QT-SC.

At 1 degree of rotation, the combusted gas outlet valve of one of the two Holzwarth combustion chambers tributary to the QT-SC's combusted gas inlet port is open. The second combustion chamber is beginning charging mode. The high-temperature, high-pressure combusted gases released from the combustion chamber push

the QT-SC rotor segment in the direction of rotation and the volume of the chamber increases. Ideally, at 45 degrees of rotation, the pressure in the expander chamber will exceed the pressure in the compressor, as discussed above. The chamber reaches maximum volume at 90 degrees after top dead center. Because the engine is operating in the Atkinson cycle, the expansion volume of the expander is engineered to exceed the compression volume of the compressor. Consequently, the pressure in the expander at the end of the power stroke can be reduced to approximately 1.25 atmospheres.¹⁰ By reducing the pressure at the end of the power stroke to 1.25 atmospheres, the exhaust temperature and pressure will be minimized and overall engine thermal efficiency will be maximized. At 91 degrees the chamber begins the exhaust stroke. The exhaust stroke is completed at 180 degrees. The minimal power necessary for the exhaust stroke is provided by the next chamber, which is engaged in its own power stroke during this rotational period.

At 181 degrees, the chamber again receives a combusted gas charge, but this time from one of the Holzwarth combustion chambers tributary to the QT-SC's second expansion port. Identical power and exhaust strokes then occur in this half of the QT-SC. Because the QT-SC performs 8 power strokes per revolution, as opposed to the Otto cycle engine's 1 power stroke per 2 revolutions (a 16:1 ratio), the concept engine may be far more compact, in terms of both size and weight, than a comparable Otto cycle engine even while operating in the more efficient Atkinson cycle.¹¹

The following table tracks the operation of the compressor, the Holzwarth combustion chambers and the Quasiturbine expansion chambers over 360 degrees of shaft rotation.

Degree of Shaft Rotation	Compressor Stroke	Combustion Chambers 1&3	Combustion Chambers 2&4	QT Chambers 1&3/Stroke	QT Chambers 2&4/Stroke
1	Compression	Discharge	Charge	Power	Exhaust
46	Intake	Discharge	Ignition	Power	Exhaust
91	Compression	Charge	Discharge	Exhaust	Power
136	Intake	Ignition	Discharge	Exhaust	Power
181	Compression	Discharge	Charge	Power	Exhaust
226	Intake	Discharge	Ignition	Power	Exhaust
271	Compression	Charge	Discharge	Exhaust	Power
316	Intake	Ignition	Discharge	Exhaust	Power

Methanol and Efficiency

Methanol is a high-octane fuel that can be derived from natural gas (currently the most common method), coal or biomass charcoal. With respect to the concept engine, methanol's primary application would be as a vehicle fuel because it can be easily dispensed at a fuel station and can be stored in the vehicle's fuel tank. Methanol's energy density is about half that of gasoline, i.e., about 55,000 BTUs per gallon. Methanol's autoignition temperature in air is 470C/740K. Because of methanol's high latent heat of vaporization (1100 J/g), the compression ratio can be 12:1 without premature ignition even with thermal insulation. At a 12:1 compression ratio, the theoretical thermal

efficiency of the Atkinson cycle is above 60%. Because heat has been absorbed by the methanol adiabatically prior to ignition, bringing the methanol close to its autoignition temperature, ignition lag, which is a second problem often associated with methanol in Otto cycle engines, may be eliminated in the concept engine.

In a recent EPA study, methanol was used in a high compression ratio, Otto cycle engine (19.5:1 ratio).¹² Although the engine had a cooling system, efficiencies of 43% were reported. With heat retention strategies and operation in the efficient Atkinson cycle, it is believed that the six-stroke Quasiturbine should be capable of higher thermal efficiencies. It should be noted that, despite the concept engine's lower compression ratio, its expansion ratio can equal, or exceed, 19.5:1 because of the separation of the compression and expansion functions. The fourth Beau de Rochas principle teaches that maximum expansion is required for high engine thermal efficiencies. By increasing the efficiency of the engine, methanol's lower energy density can be compensated for and the vehicle's fuel tank need not be much larger than a comparable gasoline-powered vehicle's tank.

Emissions

The EPA study referred to above indicates that with exhaust gas recirculation (which naturally occurs in the concept engine) and with the slower heat release rate of methanol, levels of NO_x are reduced to 0.1 to 0.2 g/kWh. Hydrocarbon and carbon monoxide emissions were about 0.2 g/kWh respectively with an oxidation catalyst after-treatment system. It would be anticipated that the concept engine's emission levels would be comparable to those reported in the EPA study.

Conclusion

The concept engine is intended to follow Beau de Rochas principles with methanol as the preferred fuel. In the concept engine, high-octane fuels are preferred because higher engine efficiencies can be attained with these fuels. Higher efficiencies mean less fuel consumption and lower atmospheric emissions per unit of work produced by the engine.

Unfortunately, present engine technologies are primarily¹³ the result of the century-long development of the petroleum-fueled, Otto cycle engine.¹⁴ These engines were designed for low-octane fuels and are not well-suited to high efficiency operation with high-octane fuels. The six-stroke Quasiturbine concept engine is an engine, which, by design, operates most efficiently with high-octane fuels like methanol.

By separating the engine functions, the concept Quasiturbine engine permits the efficient utilization of methanol by:

- Maximizing volumetric charge efficiency through the latent heat of vaporization of the methanol, which, in turn, reduces the temperature of the fuel/air charge during intake
- Minimizing the loss of compression heat by thermally insulating the compressor
- Minimizing the negative work associated with compression by reducing the final compression temperature of the compressed fuel/air charge

- Maximizing the rapidity of ignition by means of a high charge compression ratio and by eliminating much of the ignition lag associated with methanol
- Maximizing the engine pressure during the power stroke by means of thermally insulating expander materials and by means of the Quasiturbine's unique "static pressure" expansion characteristics
- Maximizing the volume of the power stroke by means of the Atkinson cycle, as adapted for the concept engine
- Maximizing the power/weight and power/volume engine ratio by means of 8 power strokes per revolution in the Quasiturbine

It is believed by the authors that when methanol enters the market¹⁵ as an alternative vehicle fuel, the six-stroke Quasiturbine will be the choice as the engine which can fully utilize this high-octane fuel's unique efficiency potential. While the concept engine only takes a step closer to the efficiency principles of Beau de Rochas, it is readily feasible and constitutes the most efficient alternative to the ideal efficiencies awaiting the development of the Quasiturbine photodetonation engine, in which compression pressure and rapidity of ignition are maximized. A subsequent paper will discuss applications of the Quasiturbine concept engine to high-octane gaseous fuels.

(*) Author Biographies

George Marchetti is vice-president of the Chicago chapter of the Electrochemical Society. He has several issued patents in the area of fuel cell technology and has followed with interest the development of high-efficiency combustion engines, especially the Quasiturbine.

Gilles Saint-Hilaire is a thermonuclear physicist, who leads the Quasiturbine development team in Montreal, Canada. He has been involved in government renewable energy projects and has served as a gas pipeline and nuclear energy advisor. His interest in perfecting rotary engines has resulted in the invention of the patented rotary engine known as the Quasiturbine.

Footnotes

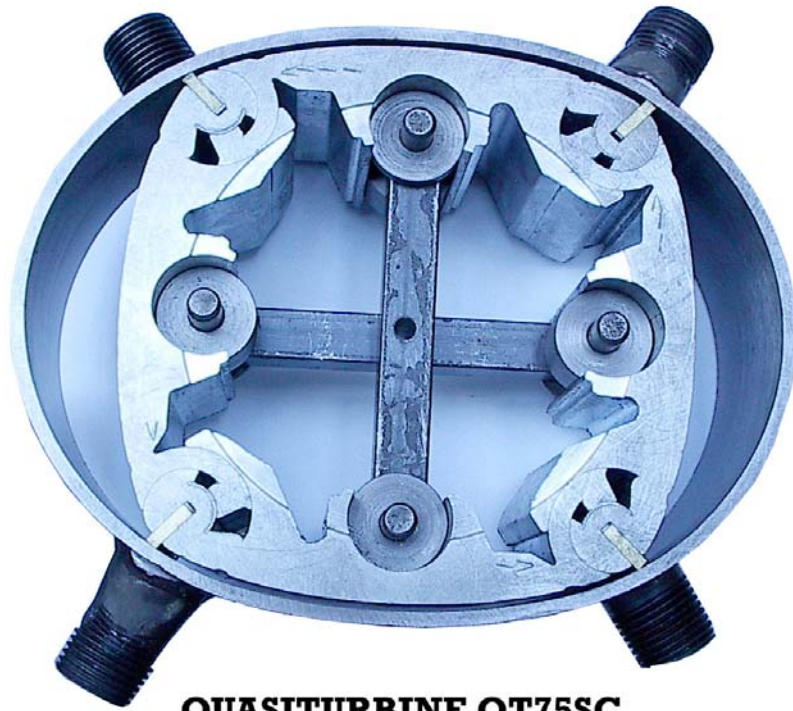
1. The Otto cycle engine cooling system generally consists of a water-jacket apertures in the engine block, a coolant pump, a radiator and a fan. Some Otto cycle engines may be air-cooled. Adiabatics, Inc. has developed an Otto cycle engine that eliminates the liquid coolant system. See, www.adiabatics.com.
2. While it is assumed that neat methanol is the fuel for the concept engine, it should be noted that a mixture of methanol and another high-octane liquid fuel, such as ethanol, is also possible. Mixture of methanol with a low-octane fuel, however, could result in knock because of the lower autoignition temperature of the low-octane fuel and the high temperatures associated with the target compression ratios of the concept engine. Low octane fuels with a cooling substance, such as gasoline with atomized water injection, could be another fuel option with the concept engine.

3. One such oil-free, graphite coating is SureCoat, manufactured by Superior Graphite, Inc. See, www.superiorgraphite.com. Its reported temperature tolerance is 1000⁰F.
4. The most rapid ignition possible, and the most efficient form of ignition to maximize the pressure of the ignited charge, is photodetonation ignition. See, www.quasiturbine.com. The concept engine uses less efficient spark ignition.
5. The Toyota Prius and the Ford Escape hybrid electric vehicles use a variant of the Atkinson cycle to increase fuel efficiency.
6. The engine is not a Brayton cycle engine, even though it employs an expander and a compressor. The constant-pressure Brayton cycle relies on the compressor to supply the necessary combustion pressure for the fuel/air charge. The present concept engine follows the constant-volume Atkinson cycle, in which combustion pressure is supplied by both the compressor and by the burning of the fuel/air charge in the combustion chamber.
7. While not as thermally efficient, it should be noted that, even without a thermal barrier coating, ambient air could act as an effective compressor insulator. The only cooling would be by air convection at the outer surface of the cylinder.
8. A rotary compressor will require a flywheel if such a compressor were used.
9. See, www.quasiturbine.com.
10. The Quasiturbine will continue to turn with an internal pressures differential of 2-3 psig or about 1.25 atmospheres.
11. A detailed presentation of the Quasiturbine's characteristics, including a comparison of power/weight ratios to other engines, may be found at www.quasiturbine.com.
12. Brusstar, et al., "High Efficiency and Low Emissions from a Port-Injected Engine with Neat Alcohol Fuels", Society of Automotive Engineers, No. 2002-01-2743 (2002). <http://www.epa.gov/otaq/presentations/sae-2002-01-2743.pdf#search='brusstar%20neat%20alcohol'>.
13. The Brayton cycle gas turbine is a notable exception.
14. Some of the concepts in this article will seem counterintuitive to those trained in Otto cycle technology. The Beau de Rochas principles apply to all constant-volume engines, of which the Otto cycle is only a subset. In particular, there are two Otto cycle fundamentals that do not apply to the concept engine. First, increasing the compression ratio does not increase the concept engine's expansion volume. The expansion volume is independent of the compression ratio because the expander is separated from the compressor. Separation of functions allows for optimum scaling between both units. Increasing compression ratio increases the rapidity of ignition. Second, in the standard Otto cycle engine, the cooling system limits the temperature rise in the fuel/air charge during compression so that compression proceeds in a generally isothermal manner. Under the ideal gas law ($PV = nRT$), pressure increases as (1) volume decreases and/or (2) temperature increases. If there is no temperature increase during compression, the process is isothermal. If there is a temperature increase during compression, accompanied by no heat loss from the system, the process is adiabatic. Because of heat loss to the cooling system during compression, Otto cycle engines are non-adiabatic and more nearly isothermal. By comparison, compression in the Quasiturbine concept engine proceeds isothermally during the intake stroke and for the first portion of the compression stroke because of methanol's latent heat of vaporization. During the second portion of the compression stroke, however, compression proceeds adiabatically due to the compressor insulation and the reduction of the latent heat of vaporization to zero. When the latent

heat of vaporization has been reduced to zero during the second portion of the compression stroke, the entire quantity of liquid phase-shifts to a vapor state prior to ignition. The consequences of this process are as follows: (1) volumetric charge efficiency is maintained due to the isothermal nature of the intake stroke; (2) negative compression work is reduced due to the isothermal nature of the first portion of the compression stroke; (3) the pressure in the cylinder increases during the first portion of the compression stroke due to volumetric decrease only (i.e., little or no pressure rise due to increased temperature); (4) the heat of adiabatic compression is retained during the second portion of the compression stroke, during which period pressure rises due to both volumetric decrease and increasing temperature; and (5) the final compressed fuel/air charge pressure is less than would be indicated by the ideal gas law but higher than pure isothermal compression.

15. Recently, Nobel prize winner George A. Olah advocated a methanol-based energy economy in lieu of reliance on fossil fuels. See, http://en.wikipedia.org/wiki/Methanol_economy.

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QUASITURBINE QT75SC

Figure 1
Quasiturbine QT-SC Series

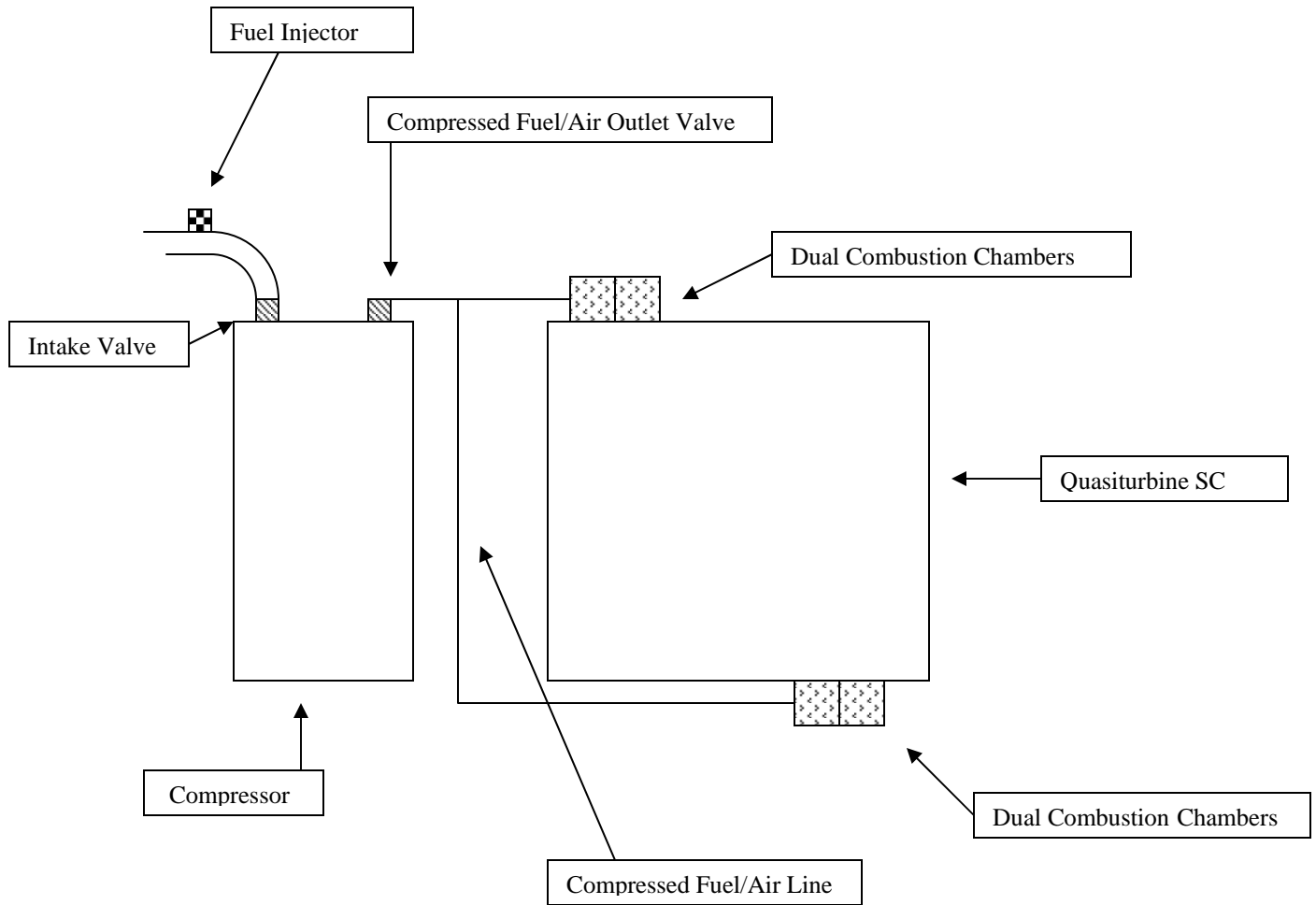


Figure 2
Schematic Diagram of Six-Stroke Quasiturbine
with a Distinct Compressor and Expander, Both Thermally Insulated

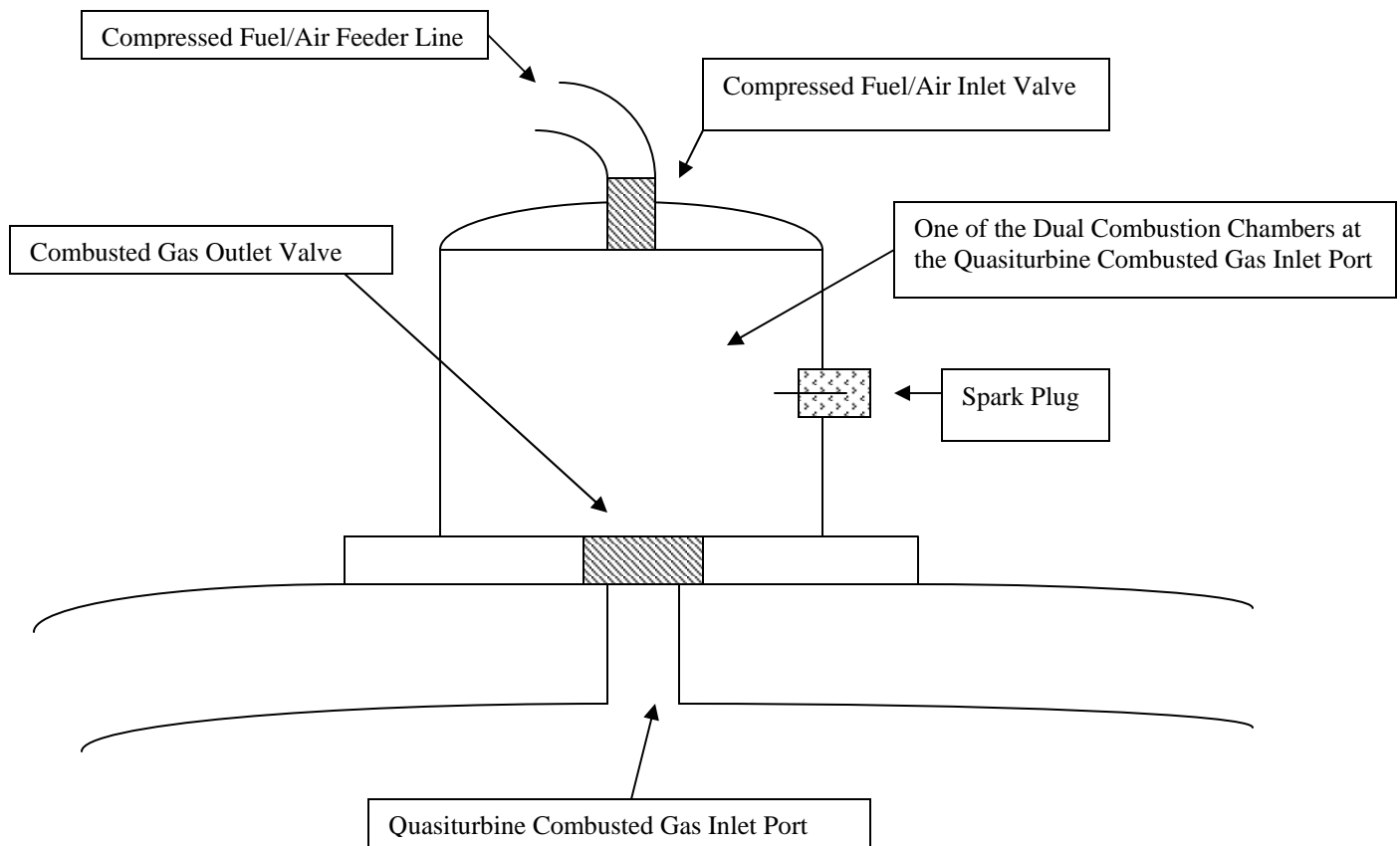


Figure 3
Schematic Holzwarth Combustion Chamber
for the Six-stroke Quasiturbine with a Distinct Compressor and Expander
Both Thermally Insulated