New IC Cycle for Low NO_x at High Efficiency

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Summary

Introduction

Engineers and consumers around the world are always looking for a simpler, more fuel efficient, less polluting and more powerful I.C. engine. In 1816, Robert Stirling (1790-1878) patented the low-pressure Stirling cycle. In 1833, John Ericsson (1803-1889) developed the Ericsson cycle. In 1860 Jean Lenoir (1822-1900) developed the Lenoir cycle last used in the V-1 buzz bomb. In 1873 George Brayton (1830-1892) developed the Brayton cycle, better known as the gas-turbine cycle. In 1876 Nikolaus August Otto (1832-1891) developed the spark ignition Otto cycle. In 1893 Rudolf Diesel (1858-1913) ran a compression ignition engine on the Diesel cycle. Of all known reciprocating I.C. engine cycles, only the "spark ignition" Otto cycle, and the "compression ignition by fuel injection" Diesel cycle have been improved over the past century and are widely used. The modern Diesel cycle engine is more efficient and durable than the Otto cycle based engine, but is more costly, has low power to weight ratio and cannot be scaled down to small engine size due to the inability of fuel injectors to meter small quantities of fuel.

Recently, the authors applied for patents on a new cycle named "Compression Ignition by Air Injection", the "CIBAI" cycle, which application includes 2-stroke and 4-stroke engine configurations requiring only standard I.C. engine components. Engines operating on the CIBAI cycle are simpler and more reliable then current engines because they do not require a spark ignition system nor a high-pressure fuel pump with its cylinder fuel injectors. Half the air mass used in the CIBAI cycle is compressed separately to induce ignition by shock wave compression. This supplies enormous ignition energy, which allows igniting very lean mixtures, thus a throttle valve is not needed. This new engine is a stratified charge engine in its purest form. Shock wave compression resulting in ignition at top dead center increases the effective compression ratio without worry about pre-ignition and enjoying the increased efficiency. Because of the engine's simplicity it can be scaled way down. It tolerates a wide range of fuels even at low octane or cetane numbers and very lean mixtures. Both the rapid shock wave induced ignition and the ability to ignite very lean mixtures is to be credited for its low NO_x potential. Unlike the diesel engine CIBAI does not have cold starting problem and it can be scaled down to small engines.

CIBAI cycle engine operation

To operate an I.C. engine on the CIBAI cycle requires at least one or more pairs of cylinders or rotors to work together in phase. Their minimum Compression Volume (V_c) at top dead center must be located near one another, such as side by side, on top of one another, either in line or in V formation. Only one of the two compression volumes contains an ignitable, usually rich air-fuel mixture ratio. Its compression ratio (r_{vaf}) is limited to prevent pre-ignition knock. The other compresses only air to (r_{va}) at least double the air-fuel mixture pressure. This pressure must be high enough to assure: detonation type ignition followed by constant volume heat addition, when the two minimum compression volumes are connected to one another by means of a "Compression Volume Connecting Valve" (CVCV). This CVCV is designed so as not to alter their combined compression volumes. It can be a conventional stem-seat type valve or any other type such as: ball, butterfly or cylinder type valve and be actuated mechanical, hydraulic, pneumatic or electrical means. When the displacement volumes of the pair are equal then without turbo charging the air containing compression volume is so much smaller than the air-fuel containing volume so that most of the air transfers into the air-fuel containing volume for thorough mixing during ignition.

The CVCV remains open during the subsequent expansion stroke, and for 2-stroke engines also during scavenging. This allows exhausting near bottom dead center of the air displacement volume and intake on opposite end first with air, followed by an air-fuel mixture. This minimizes the chance for fuel to enter the air displacement volume. During the following compression the CVCV remains closed.

Thermodynamic Cycle Analysis

To compar efficiency with Otto- and Diesel cycles the mass ratio between the air fuel mixture and the compressed air are kept about the same by setting their displacements volumes equal. Polytropic compression and expansion coefficient n =1.4 has been assumed. Air-fuel mixture volumetric compression ratio r_{vaf} equal that in Otto cycle, and air-only volumetric compression ratio r_{va} equal that in the Diesel cycle. Further combustion induced temperature ratio T_3/T_2 same as in Otto and Diesel cycle where it is called cut-off ratio.
The cycle efficiency for the Otto an d Diesel cycles:

$$\eta_{th\,Otto} = \frac{W_{out} - W_{in}}{Q_{in}} = 1 - \frac{1}{r_v^{n-1}} \text{ and } \eta_{th\,Diesel} = \frac{W_{out} - W_{in}}{Q_{in}} = 1 - \left(\frac{1}{r_v^{n-1}}\right)\left(\frac{r_c^n - 1}{n(r_c - 1)}\right)$$

For the compression ignition CIBAI cycle find the air to air-fuel mixture mass ratio to be:

$$r_m = \frac{r_{va}/(r_{va} - 1)}{r_{vaf}/(r_{vaf} - 1)}$$

. This mass ratio is needed together with the volume ratio of the combined two cylinder compression volume V_2, divided by the displacement volume V_o of one of them.

$$\frac{V_2}{V_o} = \frac{1}{(r_{vaf} - 1)} + \frac{1}{(r_{va} - 1)}$$

. Inserted below gives the CIBAI cycle efficiency as:

$$\eta_{th\,CIBAI} = \left[\frac{W_{out}}{Q_{in}} = \frac{r_c * (1 - ((V_2/V_o)/(V_2/V_o + 2))^{(n-1)})}{(r_c - 1)}\right] - \left[\frac{W_{in}}{Q_{in}} = \frac{r_{vaf}^{(n-1)} - 1 + (r_{va}^{(n-1)} - 1) * \mathrm{r_m}}{(\mathrm{r_{vaf}}^{(n-1)} + \mathrm{r_{va}}^{(n-1)} * \mathrm{r_m}) * (r_c - 1)}\right]$$

Conclusions

The results of this analysis are for a cold air standard cycle. It indicates that the CIBAI cycle has a substantially higher thermal efficiency then the Otto or Diesel cycles for the same air-fuel mixture and air only compression ratios. The CIBAI cycle peak temperature ranges from 10% to 20% below that obtained in the Diesel cycle and the duration of this high temperature is much shorter then in the Diesel cycle. This promises a substantial reduction in exhaust nitrous oxide pollution. At top dead center the ideal CIBAI cycle pressure peaks momentarily rises to a substantially higher value than in the Diesel cycle. Due to its short duration, one can expect that in an actual cycle, this peak pressure will not be higher. The CIBAI cycle rate of gain in thermal efficiency with air-compression ratio is much smaller than in the Diesel cycle. An air compression ratio more than twice that of the air-fuel mixture is probably not needed in the CIBAI cycle.

The CIBAI cycle engine can tolerate a wide range of cheaper and safer fuels, eliminating the need for high lubricity to minimize Diesel fuel-injector wear and high cetane number to promote rapid combustion. General aviation 100 Low-Lead avgas could be taken off the market if general aviation engines where operated on an efficient CIBAI cycle using jet-fuel. A stratified charge engine operating its lean and rich mixture at different compression ratios is found only in one other patent # 5,239,959, dated Aug. 31, 1993.