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THE EFFECT OF ISOLATED AIR MASS AND FUEL/AIR RATIO ON THE EFFICIENCY OF ISOLATED COMBUSTION AND DILUTED EXPANNSION (ICADE) I. C. ENGINE CYCLE

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Abstract
The Isolated Combustion and Diluted Expansion (ICADE) internal combustion engine cycle combines the advantages of constant volume combustion of the Otto cycle with the high compression ratio of the Diesel cycle . In this work we studies the effect of Isolated air mass on the efficiency of the cycle, the analysis shown that the decrease of Isolated air mass will increase the efficiency of the cycle, the large dilution air mass will quenches all NO_x forming reactions and reduce unburned hydrocarbons . Furthermore, the effect of Fuel / Air ratio on the efficiency studies the analysis shown that the increase of Fuel / Air ratio will increase efficiency of the cycle.

NOMENCLATURE
B cofficient defined in text
D piston diameter
Dc combustion chamber diameter
DR combustion chamber to piston diameter ratio
m total cylinder intake air mass
mc isolated combustion chamber mass
mp isolated cylinder air mass
mr charge stratification, mr = mp/m
P( ) Otto cycle pressure at station ( )
P1 inlet reference pressure = Pi1
Pi( ) ICADE cycle pressure at station ( )
s piston stroke
rc max. combustion chamber compression ratio
riso compression ratio at point of isolation
T( ) Otto cycle temperature at station ( )
Ti( ) ICADE cycle temperature at station ( )
T1 inlet reference temperature = Ti1
TR maximum cycle temperature divided by T1
V1 maximum intake volume with piston at BDC
Vc combustion chamber volume
Vd piston displacemen volume
Vp cylinder clearance volume , piston at TDC
V( ) volume with piston at station ( )
γ specific heat ratio
ήth thermal efficiency
θ compression crank angle starting at BDC

Introduction
The steady of air standard cycles to obtain the performance of internal combustion engine has a great importance in spite of the actual engine works at different conditions rather than the supposed conditions in air standard cycles.
The actual cycle experienced by an internal combustion engine is not, in the true sense a thermodynamic cycle. An ideal air-standard thermodynamic cycle occurs in a closed system of constant composition. This is not what actually happens in an IC engine, and for this reason air-standard analysis gives, at best, only approximations to actual condition and outputs. Major difference include: [1]

1. Real engines operate on an open cycle with changing composition. Not only does the inlet gas composition differ from what exit, but often the mass flow rate is not the same. During combustion, total mass remains about the same but molar quantity changes. Finally, there is a loss of mass during

the cycle due to crevice flow and blow by past the pistons.

2. Air-standard analysis treats the fluid flow through the entire engine as air and approximates air as an ideal gas. In a real engine inlet flow may be all air, or it may be mixed with up to 7% fuel, either gaseous or as liquid droplets, or both. During combustion the composition is then changed to a gas mixture of mostly Co_2, H_2 O and N_2 , with lesser amounts of CO and hydrocarbon vapor. The lower pressures of inlet and exhaust, air can accurately be treated as an ideal gas, but at the higher pressures of during combustion, air will deviate from ideal gas behavior. A more serious error is introduced by assuming constant specific heats for the analysis. Specific heats of a gas have a fairly strong dependency on temperature and can vary as mush as 30% in the temperature range of an engine (for air, c_p= 1.004 kJ/kg-k at 300 k and c_p= 1.292 kJ/kg-k at 3000 k [2]).
3. There are heat losses during the cycle of a real engine which are neglected in air-standard analysis. Heat loss during combustion lowers actual peak temperature and pressure from what is protected. The actual power stroke, therefore starts at a lower pressure, and work output during expansion is decreased.
4. Combustion requires a short but finite time to occur, and heat addition is not instantaneous at TDC, as approximated in an Otto cycle. A fast but finite flame speed is described in an engine. This results in a finite rate of pressure rise in the cylinders, a steady force increase on the piston face, and a smooth engine cycle. Because of the finite time required , combustion is started before TDC and ends after IDC, not at constant volume as in air-standard analysis, By starting combustion TDC. Another loss in the combustion process of an actual engine occurs because combustion efficiency is less than 100%. This happens because of less than perfect mixing, local variations in temperature and air-fuel due to turbulence, flame quenching, etc. SI engines will generally about 98% efficient.
5. The blow down process requires a finite real time and a finite cycle time, and does not occur at constant volume as in air-standard analysis. For this reason, the exhaust valve must open 40^0 *to* 60^0 b BDC, and output work at the latter end of expansion is lost.
6. In an actual engine, the intake valve is not closed until after bottom-date center at the end of the intake stroke. Because of the flow restriction of the valve, air is still entering the cycle at BDC, and volumetric efficiency would be lower if the valve closed here. Because of this, however, actual compression does not start at BDC, but only after the inlet valve closes. With ignition then occurring before top dead center, temperature and pressure rise before combustion is less than predicted by air-standard analysis.
7. Engine valves require a finite time to actuate. Ideally, valves would open and close instantaneously, but this is not possible when using a cam follower, and this results in fast but finite valve actuation. Because of these differences which real air-fuel cycles have from the ideal cycles, result from air-standard analysis will have errors and will deviate from actual conditions. Interestingly, however, the errors are not great, and property values of temperature and pressure are very representative of actual engine values. Tayler[3] shows that over a large range of operating variables the indicated thermal efficiency of an actual SI four-stroke cycle engine can be approximated by .85 of Otto thermal efficiency .

There are three cycles have a great importance during the analysis of I.C. engine, as a whole they are:

1. Otto cycle (constant volume cycle)
2. Diesel cycle
3. Dual combustion cycle

Otto cycle represents the theoretical basis of spark ignition engine while the diesel cycle represents the theoretical basis of compression ignition engine. The modern high speed compression ignition engine works with dual combustion cycle.

Otto cycle is distinguished among the three cycles that it has the highest thermal efficiency when the three cycles work at the same compression ratio. Otto cycle efficiency is given by the equation

$$\eta = 1 - \frac{1}{r_c^{\gamma - 1}} \quad \text{...... ....(1)}$$

while the efficiency of diesel cycle is given by the equation

$$\eta = 1 - \frac{1}{r_c^{\gamma - 1}} \left(\frac{\rho^{\gamma - 1}}{\gamma(\rho - 1)} \right) \quad \text{......(2)}$$

but the engine works by Otto cycle is limited by certain compression ratio that is because of fuel octane number requirements, while diesel engine works at high compression ratio is nearly three times of Otto compression ratio, this makes it has the highest efficiency rather than the engine works by Otto cycle. The heat addition at constant volume in Otto cycle makes it more efficiency than the other cycle when they work at the same compression ratio, while the diesel cycle is distinguished by the ability of work at high compression ratio. From here, idea of Isolated Combustion and Diluted Expansion (ICADE) cycle was born. (ICADE) cycle was introduced by (Jone L. Loth & Eric Loth) (4) which include the two advantages [heat addition at constant volume, high compression ratio] , here there is a description of (ICADE) cycle was introduced by the two researchers.

ICADE CYCLE DESCRIPTION

A new stratified charge internal combustion engine named the “Isolated combustion and Diluted Expansion (ICADE)” engine is described here. It combines the advantage of constant volume combustion compression ratio of the Diesel cycle. Unlike most designs using an isolated combustion camber, the ICADE cycle does not require any external mechanical controls. At about 30^o crank angle before the piston reaches TDC, the cylinder is divided in two parts by an especially design dome mounted on top of the piston. Each part on contains roughly the same mass of air. The first part on top of the dome constitutes the combustion chamber. Its compression ratio is designed for the octane number of the fuel at hand. The second part is the remaining cylinder volume above the piston. That part is further compressed to about half the volume of the combustion chamber. This higher compression ratio is what improves the efficiency. Fuel is injected directly in to the isolated combustion chamber. A unique feature of this configuration is that the volume in the isolated combustion chamber varies little over about 30^o of crank angle. This allows even slow burning mixtures to burn at near constant volume thereby producing high combustion pressurization. As soon as the combustion chamber pressure rises above that in the cylinder , a ball type check valve in the dome opens and the combustion products rush into the cylinder to mix with the compressed air. This dilution quenches all No_x forming reactions and provides excess O_2 to reduce unburned hydrocarbons. The dilution of the combustion products prier to expansion simulates a stratified charge engine. Such a stratified engine produces less power per unit of displacement volume. For temporary increased power production additional fuel can be burned by admitting very lean fuel/air mixture instead of pure air. The mixture must be lean enough that compression ignition is not possible. A schematic of the engine geometry is shown in Fig. (1). Depending on the ratio of dome height to piston stroke, the dome starts to isolate the combustion chamber at about 30^o before TDC. Although the dome is actually a “leaky valve”, the mass above the dome undergoes very little volume change or change or compression and there for remains at near constant volume at about 30^o of crank angle. Near constant volume combustion has several advantages.

1. Fuel injected in the combustion chamber can be ignored early with out power loss associated with compression of the combustion product.
2. Fuel cannot leak into the cylinder because the pressure there is higher.
3. Even slow burning fuels have adequate time for combustion thereby producing significant combustion pressurization.
4. Only after combustion pressurization, will the ball be forced of its seat to allow rapid mixing of the combustion products with compressed air above the piston expansion.

No external mechanisms are needed to control the opening and closing of the ball valve. At the start of the compression stroke the inertia of the ball forces it into the piston. There it accelerates with the piston velocity to reach a maximum velocity at midpoint of the stoke.

From there on the piston slows down but the ball continues at constant velocity and thus floats away from the piston to seal off the dome outlet. This occurs just before the dome type isolation valves closes. As the air in the cylinder is further compressed, the resulting pressure differential maintains the check valve in the closed piston. Not until the pressure above the ball exceeds the cylinder pressure by 35 psi will the ball unseat itself and allow the combustion products to rush into the cylinder and mix with the air. The resulting dilution and temperature reduction terminates any No4 forming reactions and reduces the heat losses to the cylinder walls during expansion. To further reduce heat loss the combustion chamber could be insulated as direct fuel injection is used and the walls there need not support any piston skirt force.

The advantage of the ICADE cycle over the Otto cycle are :

1. The cylinder compression ratio r_p is higher than the combustion chamber compression ratio r_c. Thus the average compression ratio is higher than for the Otto cycle, which explains the higher ICADE cycle efficiency.
2. The ICADE cycle has the combustion products quench from T_{i4} down to T_{i6} immediately after combustion to halt the formation of No_x . This is unlike the Otto cycle where the temperature drops slowly and No_x formation can continue during piston expansion.
3. The ICADE engine can be lighter for the same volume V_1 because the maximum cylinder pressure P_{i6} is lower than P_3 in the Otto cycle. However for the same power rating the structure weight will be about the same.
4. If the isolation valve closure could be modulated or the combustion chamber volume be reduced at part power operation, then the need for an engine throttle valve and associated efficiency loss would be eliminated. The reduced mixture temperature T_{i6} would further lower cycle wall heat losses. But for the configuration shown in Fig.(1) these schemes are not possible as the valve opens and closes automatically under the action of inertia and pressure.

The disadvantage of the ICADE cycle over the Otto cycle are :

1. Required direct combustion chamber fuel injection. But this can be done slowly during about 30^o of crank angle.
2. Additional mechanical complexity such as a combustion chamber isolation valve, like a dome on the piston with ball type check valve, is needed.
3. Although for a given engine volume V_1 the ICADE cycle engine weight is lower and the efficiency is higher than for the Otto cycle, the power output per unit volume is reduced. For example if the ICADE cycle combustion camber volume V_c is half that of the Otto cycle volume V_2 , then the fuel burned per cycle is half as much and the engine power output is reduced accordingly.

ANALYSIS OF THE ICADE CYCLE

For a comparative analysis between the ICADE and the Otto cycle, Both cycles are operated at Identical conditions such as [Fuel – Air ratio , combustion compression ratio (r_c) intake conditions (V_1 , P_1 , T_1 and intake mass m)] The ICADE cycles different in that the air remaining in the cylinder [mp = m-m_c] is compressed Further by the cylinder compression ratio (r_p) With Limitation $P_{i5} < P_{i4}$ as shown in Fig (2) which is shown the pressure as a function of crank angle for both Otto and ICADE cycles .

Both cycles have the same maximum temperature ratio

$$\left[TR = \frac{T_3}{T_1} = \frac{T_{i4}}{T_{i1}} \right].$$

At TDC after combustion the ball type check valve opens and the combustion products mix with the lower air inside the cylinder .

$$m_R = \frac{m_P}{m} = \quad 1 - \frac{m_c}{m}$$

Station 1 :- Otto cycle ICADE cycle

With volume V_1 , at start of compression stroke , with crank angle $\theta = 0$ degrees to combustion chamber at compression ratio (r_c) .

$$m = \frac{P_1 V_1}{R T_{1i}} \qquad \text{…………(3) .}$$

$$r_c = \frac{V_1}{V_2} \qquad \text{……(Otto cycle)…… ….(4).}$$

$$r_c = \left(\frac{V_1}{V_{3i}}\right) \times (1-mr) \quad \text{(ICADE cycle)...(5).}$$

Station 2:- (Otto cycle only)

At $\theta = 180$ degrees with volume V_2

$$\frac{P_2}{P_1} = \left(\frac{T_2}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left[(r_c)^{\gamma-1}\right]^{\frac{\gamma}{\gamma-1}} \quad \text{……(6).}$$

Station 2i : - [ICADE cycle only]

At $\theta = 150$ degrees

Compression ratio at point of isolation is

$$r_{iso} = \frac{V_1}{V_{iso}} \quad \text{……………………..…..(7).}$$

$$\frac{P_{i2}}{P_1} = \left(\frac{T_{i2}}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left[(r_{iso})^{\gamma-1}\right]^{\frac{\gamma}{\gamma-1}} \quad \text{……..(8).}$$

Station 3i :- [ICADE cycle only]

With volume v_{i3} at $\theta = 180 \deg ress$

$$\frac{P_{i3}}{P_1} = \left(\frac{T_{i3}}{T_1}\right)^{\frac{\gamma}{\gamma-1}} = \left[(r_c)^{\gamma-1}\right]^{\frac{\gamma}{\gamma-1}} \quad \text{………(9).}$$

Note that

$T_{i\,3} = T_2$

$P_{i\,3} = P_2$

But with mass mc instead of m and volume v_c .

Station 3 :- [Otto cycle only]

At $\theta = 180$ degrees with mass = m

$$V_3 = V_2$$

Combustion at constant volume with temperature ratio $TR = \frac{T_3}{T_1}$ which depended on Fuel / Air ratio .

$$\frac{P_3}{P_2} = \frac{T_3}{T_2} = (TR) \left(\frac{T_1}{T_2}\right) = (TR)\left(\frac{1}{r_c}\right)^{\gamma-1} \quad \text{…(10).}$$

Station 4i :- [ICADE cycle only]

At $\theta = 180$ degrees with mass = mc

$V_{4\,i} = V_{3\,i}$

combustion at constant volume with temperature ratio

$$\left(TR = \frac{T_{i\,4}}{T_i}\right)$$

$$\therefore \; T_{i\,4} = T_3 \quad \text{…………..…..…(11).}$$

$$\frac{P_{i\,4}}{P_{i\,3}} = \frac{T_{i4}}{T_{i3}} (TR) . \left(\frac{T_1}{T_{i3}}\right) = (TR)\left(\frac{1}{r_c}\right)^{\gamma-1} \quad \text{…..(12).}$$

$$\therefore \; \frac{P_{i\,4}}{P_{i\,3}} = \frac{P_3}{P_2} \quad \text{. ………..(13).}$$

but

$$P_{i3} = P_2$$

$$\therefore \; P_{i\,4} = P_3 \quad \text{………..…….. (14).}$$

Station 5i :- [Icade cycle]

At $\theta = 180$ degrees , Icade cycle isolated cylinder clearance volume V_P .

$$\frac{V_P}{V_1} = \frac{mr}{r_P} \quad \text{……………….……..(15).}$$

$$\frac{V_c}{V_1} = \frac{(1-mr)}{r_c} \quad \text{……………….(16).}$$

$$\therefore \frac{T_{5\,i}}{T_1} = (r_p)^{\gamma-1} \quad \text{……………..…….(17).}$$

$$\frac{P_{5i}}{P_1} = \left(\frac{T_{5i}}{T_1}\right)^{\frac{\gamma-1}{\gamma}} = \left[(r_p)^{\gamma-1}\right]^{\frac{\gamma-1}{\gamma}} \quad \text{……….(18).}$$

Station 6i :- [Icade cycle]

At $\theta = 180$ digress, at this point the piston is still at TDC and the ball type check valve is open which allows the high pressure combustion products at p_{i4} to mix with the air in the cylinder at pressure P_{5i} .

As this process is adiabatic and at constant volume , the internal energy does not change and the final mixture temperature as given by :

$$\frac{T_{6i}}{T_1} = (1-mr)\frac{T_{4i}}{T_1} + (mr)\frac{T_{5i}}{T_1} \quad \text{……..….(19).}$$

$$V_{6i} = Vp + V_c = V_1 \left[\frac{mr}{r_p} + \frac{(1-mr)}{r_c}\right] \quad \text{…….(20).}$$

From the equation of state

$$\frac{P_{6i}}{P_1} = \frac{V_1}{T_1} * \frac{T_{i6}}{V_{i6}} = \frac{\left(\frac{T_{i6}}{T_1}\right)}{\frac{mr}{r_p} + \frac{1-mr}{r_c}} \quad \text{……….(21).}$$

Station 4 :- [Otto cycle]

At $\theta = 360$ digress, the Final expansion of the Otto cycle ends up at $V_4 = V_1$, with temperature T_4

$$\frac{P_4}{P_3} = \left(\frac{1}{r_c}\right)^{\gamma} \text{ ……………(22).}$$

$$\therefore \quad \frac{P_4}{P_1} = \frac{P_3}{P_1}\left(\frac{1}{r_c}\right)^{r} \text{ ……..(23).}$$

$$\therefore \frac{T_4}{T_1} = \frac{T_3}{T_1}\left[\left(\frac{1}{r_c}\right)^{\gamma}\right]^{\frac{\gamma-1}{\gamma}} \text{ …………..(24).}$$

$$\therefore \quad \frac{T_4}{T_1} = TR\left[\left(\frac{1}{r_c}\right)^{\gamma}\right]^{\frac{\gamma-1}{\gamma}} \text{ …………..(25).}$$

Station 7i :- [Icade cycle]

The final expansion of the ICADE cycle ends up at $V_{7i} = V_1$ with temperature T_{7i}

$$\frac{T_{7i}}{T_1} = \frac{T_{6i}}{T_1}\left(\frac{V_{6i}}{V_{7i}}\right)^{\gamma-1} = \frac{T_{6i}}{T_1}\left(\frac{mr}{r_p} + \frac{1-mr}{r_c}\right)^{\gamma-1} \text{ ..(26).}$$

For the ICADE cycle :

The expansion work

$$= mc_v\left(T_{i6} - T_{i7}\right) \text{ ….(27).}$$

The compression work

$$= m_p\, c_V\, \left(T_{5i} - T_{1i}\right) + m_c\, C_v\left(T_{3i} - T_{1i}\right) \text{….(28).}$$

The heat supplied

$$= m_c\, c_v\left(T_{4i} - T_{3i}\right) \text{ ……..……(29).}$$

$$\therefore \quad \eta_{i_{th}} = \frac{\left[mc_v\left(T_{6i} - T_{7i}\right)\right] - \left[m_p\, c_V\left(T_{5i} - T_{1i}\right) + m_c\, c_V\left(T_{3i} - T_{1i}\right)\right]}{m_c \quad C_V\left(T_{4i} - T_{3i}\right)}$$

…...….(30).

$$\therefore \eta_{ith} = \frac{\left(T_{6i} - T_{7i}\right) - \frac{m_p}{m}\left(T_{5i} - T_{1i}\right) - \frac{m_c}{m}\left(T_{3i} - T_{1i}\right)}{\frac{m_c}{m}\left(T_{4i} - T_{3i}\right)}$$

……………... (31)

By substituting the temperatures from the above equations this expression reduces to :

$$\therefore \quad \eta_{ith} ICADE = 1 - \frac{B}{r_c^{(\gamma-1)}} \text{ ………(32).}$$

Where B is given by :

$$B = \frac{\left[mr + \frac{r_P}{r_C}(1-mr)\right]^{\gamma-1}\left[\frac{(1-mr)TR}{(r_p)^{\gamma-1}} + mr\right] - 1}{\frac{(1-mr) \quad TR}{r_c^{\gamma-1}} + mr \quad -1}$$

………..…(33).

The cycle efficiency improvement is shown in Fig (3) as a function of the added piston compression after isolation as given by (r_p / r_c).

The ICADE cycle reduces to the Otto cycle for the case when (m_p) go to zero , or if the mass (m_p) has no extra compression or $r_p = r_c$ in either case coefficient B reduces to 1.

Isolated air mass effect :

Both cycles are based on the same intake mass m, P, T, and combustion compression ratio r_c .

m_c Is the mass isolated in the combustion chamber which compressed by r_c and mixed with fuel to ignite.

when we reduces m_c, m_p will be increase , thus m_r will be increase , this means the a mount of mass compressed by r_p will increase and the cycle efficiency will approach to diesel cycle efficiency, but this will decreases the power generation from an engine .

The effect of isolated air mass is shown in fig. (4) , the ICADE cycle efficiency increases with decreases of isolated air mass[increases of m_r] , the improvement over the Otto cycle efficiency is about 10% when (mr = 0.6) Increases of mr means that the stratification portion of the mass m_p will increases , this will quenches all No_x forming reactions and provides excess O_2 to reduce unburned hydrocarbons .

More decreases in isolated air mass are not practical because of power losses.

Fuel / Air Ratio effect:

At increase F/A ratio inside the combustion chamber, this will lead to the increase of release energy, so the increase to the maximum temperature inside the combustion TR

The effect of $\frac{F}{A}$ ratio on the efficiency of (ICADE) cycle is shown in fig .(5)

We can notice the efficiency increase with TR increasing so as to the improvement over the Otto cycles thermal efficiency reaches to 9% at

TR = 8 , with the increasing of power generation at the cycle .

But in other side the increasing of F/ A ratio will lead to increasing of unburned hydrocarbons.

The fig. (6) is shown the improvement of efficiency over the efficiency of Otto cycle at different F/ A values and different values of mr .

We can notice that the increasing of efficiency of cycle with the increasing mr and TR .

In fact to obtain the best performance it is advised to work at high F/ A and high mr but according to the power requirement limitation.

The use of great mr it means the existence of great amount of air outside combustion chamber , so reducing the unburned hydrocarbons .

The fig. (7) is shown the improvement of cycle efficiency over Otto efficiency at (mr= 0.6 , TR= 8) comparatively the efficiency at (mr= 0.5 , TR= 7), the use of (mr= 0.6 , TR= 8) means the highest efficiency, the greatest power and little unburned hydrocarbons , but this will be a companied with the increase of heat transfer to the cylinder wall in expansion stroke , that is because of raising of T_{6i} value .

CONCLUSIONS:

1- Conversion to the ICADE cycle benefits the efficiency of spark ignition engines because the compression ratio is about doubled and combustion pressurization is improved, even with slowly burning fuels .
2- It will be able to improvement the cycle efficiency through control by F/A ratio and amount of isolated air .
3- With the decreasing of the isolated air in combustion chamber , the efficiency of cycle will increase but power generation requirement will limited the decreasing of isolated air amount.
4- During the increase F/A ratio which it means highest the maximum temperature of the cycle TR , the cycle efficiency will increase.
5- The combustion product dilution provides the excess air needed to minimize emissions of unburned hydrocarbons and reduce NOx formation .
6- Detonation is not expected to be too harmful as only the relatively small piston dome is subjected to the shock wave . Also the combustion product compression by the piston will be small [5] .

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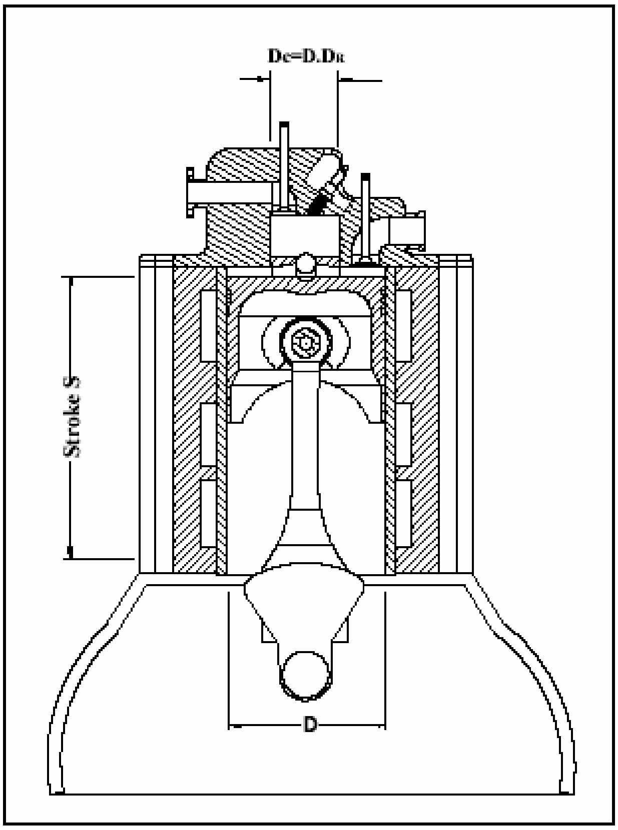


Fig.1
ICADE Engine Layout

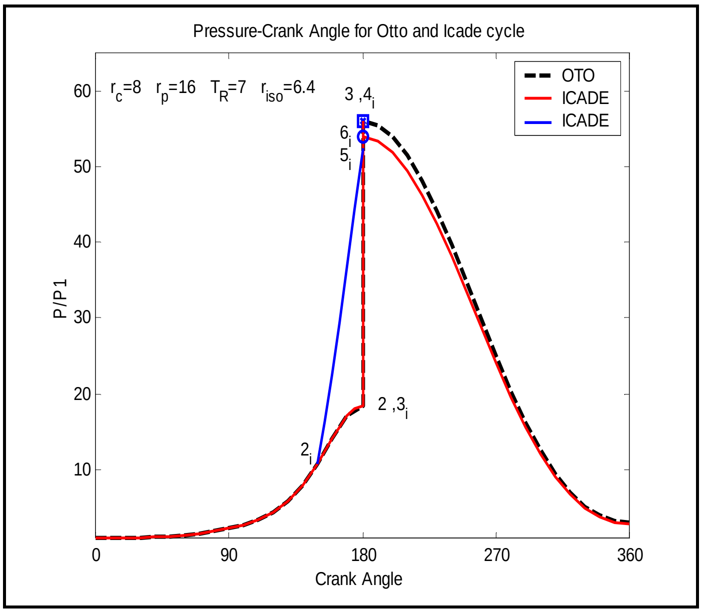


Fig.2 Pressure as afunction of crank angle for both Otto and ICADE cycle .

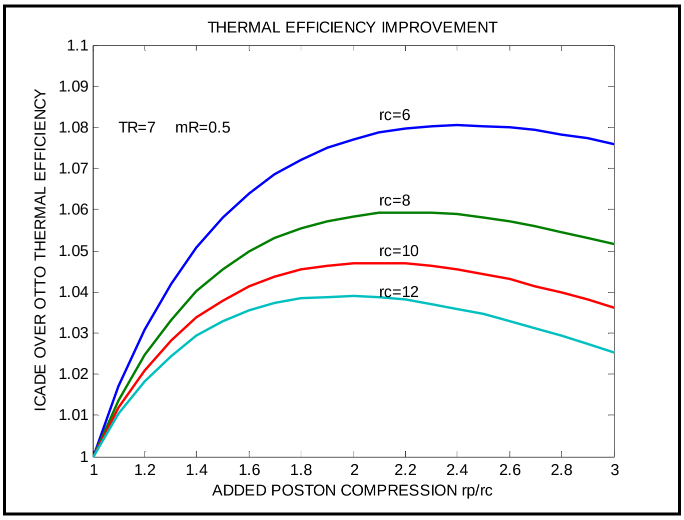


Fig.3 Comparison of ICADE and Otto cycle efficiency.

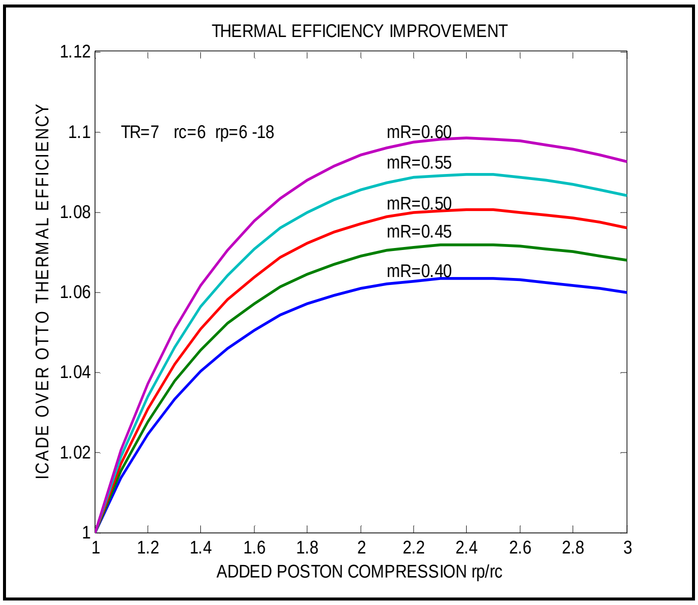


Fig.4 Effect of isolated air mass on ICADE efficiency improvement

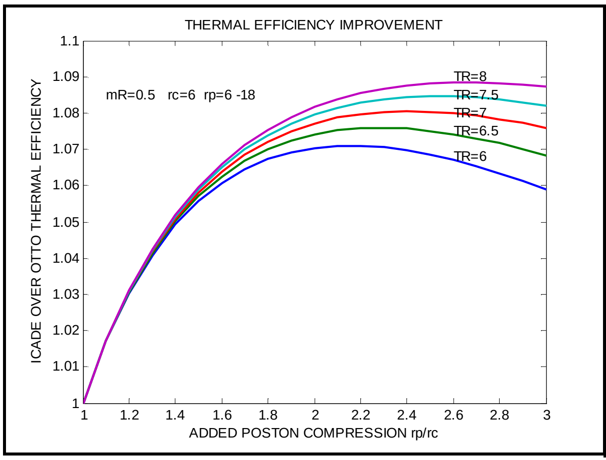


Fig.5 Effect of Fuel / Air ratio on ICADE efficiency improvement

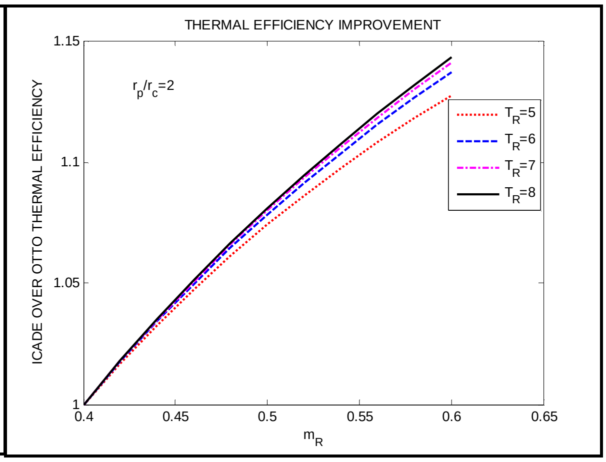
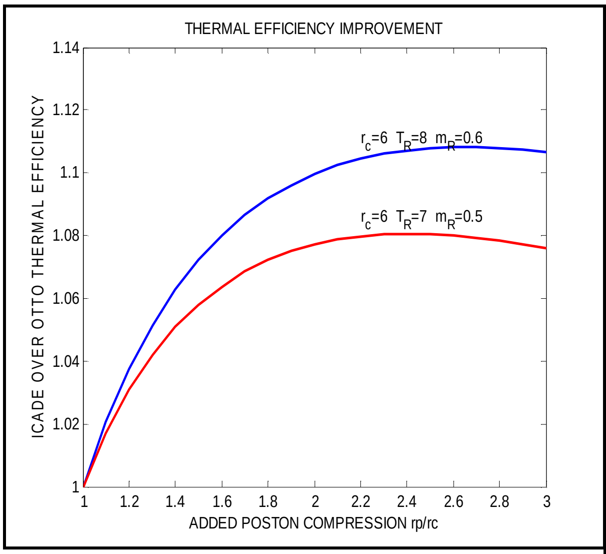


Fig.6 Combind effect of isolated air mass and Fuel/Airr atio



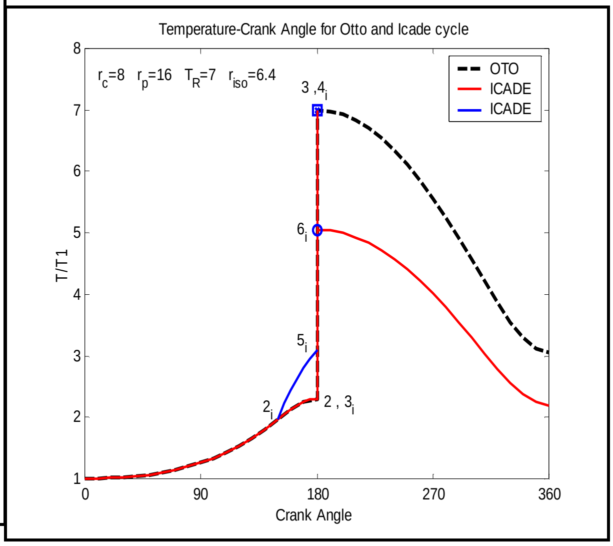


Fig.7 Comparison of ICADE efficiency at different values of TR and m_R.

Fig.8 Temerature as function of crank angle for both ICADE and Otto cycles