Thermodynamics: Discussion on Power Consuming Cycles

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Abstract: ***The aim is to discuss about the power consuming cycles involved in different types of engines in the broad spectrum of "Thermodynamics". Thermodynamic cycles which engines use for generation of net power output are referred to as "Power Cycles." It is well known that the efficiency of various engines varies depending on the kind of power cycle used. Internal combustion engines, also known as IC engines, gas turbines, and steam turbines are the primary devices that use power cycles. The traditional, antiquated power cycles found in internal combustion engines, such as Otto, Diesel, and Dual cycles, are the primary areas briefly presented in this paper.***

Keywords: Thermodynamics, Power Cycles, IC engines, Otto cycle, Diesel cycle, Dual cycle

1. Introduction

Thermodynamic cycles can be categorized into two as power cycles and refrigeration cycles, depending on the type of working fluid. Power cycles use gas as their working fluid while refrigeration cycles use vapor as their fluid. There are also other thermodynamic cycles which use liquids as working fluids. There is another categorization in thermodynamic cycles which is based on recirculation of the working fluid, in this there are two types, open and closed cycles. In open cycles the working fluid does not get recirculated, instead gets renewed at the end of the cycle, whereas in closed cycle the working fluid gets recirculated at the end of every cycle. There are many different cycles used in different machinery, here we discussed about the following:

1.1. Power cycles used in IC engines:
1.1.1. Otto cycle
1.1.2. Diesel cycle
1.1.3. Dual cycle
1.1.4. Atkinson cycle
1.1.5. Miller cycle
1.2. Power cycles used in steam turbines:
1.2.1. Rankine cycle
1.3. Power cycles used in gas turbines:
1.3.1. Brayton cycle

The above listed power cycles are the fundamental principles used for the running any machine which converts thermal energy to useful mechanical work. The internal combustion engines use petrol as a fueling agent. i.e. SI engines run on "Otto cycle". Whereas the IC engines use diesel as fuel. i.e. CI engines run on "Diesel cycle", these are the most commonly used engines across the globe. There are few more specialized and customized engines which are manufactured to meet the requirements of costumers. The modern high-speed and turbocharged diesel engines such as Mahindra XUV, Tata safari, run on "Dual cycle". The very recently innovated hybrid vehicles such as Toyota hybrid, have an internal combustion engine which charges a battery with power generation mainly runs on "Atkinson cycle". There are even more complex engines which mainly focus on performance over efficiency known as supercharged engines (Audi A6 2.0L turbo, Volkswagen EA211 1.5L TSI evo), these engines function using "Miller cycle", which is just a modification of either otto or diesel cycles. On the tech front there are also few non-piston engines which generate power known as turbines. The working fluid for turbines is mainly gas and steam. Steam turbines use "Rankine cycle" as their functioning power cycle. Whereas gas turbines use "Brayton cycle" for generating power.

The focus of this paper is to enlighten knowledge about the traditional thermodynamic power cycles of internal combustion engines constituting Otto, Diesel and Dual cycles. In summary, thermodynamic power cycles like the Otto, Diesel, Dual, Atkinson, and Miller cycles drive internal combustion engines, while the Rankine cycle powers steam turbines and the Brayton cycle underpins gas turbines. These fundamental cycles, adapting for efficiency and specific applications across open and closed systems, are the bedrock of global power generation and transportation.

2. Literature Review and Discussion

2.1 Otto cycle

The Otto cycle is the ideal cycle for spark-ignition reciprocating engines. It is named after Nikolaus A. Otto, who built a successful four-stroke engine in 1876 in Germany. In most spark-ignition engines, the piston executes four complete strokes within the cylinder, and the crankshaft completes two revolutions for each thermodynamic cycle. These engines are called four-stroke internal combustion engines. The thermodynamic analysis of the actual four-stroke or two-stroke cycles described is not a simple task. The analysis can be simplified significantly if the air-standard assumptions are utilized. The resulting cycle, which resembles the actual operating conditions, is the ideal Otto cycle. (1)It consists of four internally reversible processes:

(i) Isentropic Compression (1→2)
(ii) Isochoric Heat Addition (Combustion) (2→3)
(iii) Isentropic Expansion (Power Stroke) (3→4)
(iv) Isohoric Heat Rejection (Exhaust Blowdown) (4→1)

$$n_{th,Otto} = w_{net}/q_{in} = 1 - q_{out}/q_{in} = 1 - (T_4 - T_1/T_3 - T_2) = 1 - T_1 (T_4 / T_1 - 1) / T_2 (T_3 / T_2 - 1)$$

The paper (2) presented the estimated pollutant gas emissions in vehicles with otto cycle engines. They developed a parametric model which accurately estimated the emissions of CO_2, CO, and NOx from M1 Otto cycle vehicles. With R-values of 0.91 for CO_2, 0.75 for CO, 0.77 for THC, and 0.92 for NOx, it demonstrated a strong correlation with actual values. The model's dependability was confirmed by the low mean errors, which ranged from 0.0016 to 0.34. Highway results showed some deviation, but THC estimation was accurate in both urban and rural areas, hence concluding that there are higher emissions in urban zones when compared to rural areas.

(3) in their study examined a novel spark ignition engine design that increases the piston's dwell time close to top dead center (TDC) through an unusual piston mechanism, resulting in a quasi-constant volume (QCV) combustion process. The effects of changing engine speed, compression ratio, and piston motion on power and efficiency are investigated using a zero-dimensional thermodynamic model. In comparison to conventional engines, the results indicate that a moderate dwell near TDC increases power, fuel consumption, and combustion efficiency, while an excessive dwell decreases efficiency and increases heat loss. (6) reveals real spark-ignition engines are susceptible to several irreversibility's, including friction, heat transfer losses, and incomplete combustion, whereas the ideal Otto cycle assumes internally reversible processes. A finite-time thermodynamics method was presented by Joseph and Thampi (2022) that uses a single heat leak term applied at discrete time steps in the compression and expansion processes to represent all of these irreversibility's. This simplified model is a useful tool for realistic cycle analysis because it closely resembles actual brake thermal efficiency trends for SI engines, with deviations as small as 0–15% from experimental data.

Here are some popular otto cycle engines which use petrol (gasoline) as a fuel available in the market, across different segments:

2.1.1 Hatchbacks
(a) Maruti Suzuki Swift
(b) Hyundai i20
(c) Tata Altroz (Petrol variants)
(d) Volkswagen Polo (Petrol)

2.1.2 Sedans
(a) Honda City (Petrol variant)
(b) Hyundai Verna (Petrol)
(c) Maruti Suzuki Ciaz
(d) Skoda Slavia (Petrol)

2.1.3SUVs
(a) Hyundai Creta (Petrol variant)
(b) Kia Seltos (Petrol)
(c) Toyota Urban Cruiser Hyryder (Petrol hybrid)
(d) MG Hector (Petrol)

2.1.4Luxury Cars
(a) BMW 3 Series (Petrol variants)
(b) Mercedes-Benz C-Class
(c) Audi A4
(d) Jaguar XE (Petrol)

(10) discussed Mozurkewich and Berry (1981) applied finite-time thermodynamic optimization to the Otto cycle, incorporating friction and heat leakage effects. They identified an optimized piston motion profile that improves work output and second-law efficiency by approximately 10% compared to conventional sinusoidal motion. This pioneering study demonstrates how modifying engine kinematics can enhance performance under realistic operating constraints.

2.2 Diesel cycle

(4) in their study found the Diesel cycle is the ideal cycle for CI reciprocating engines. The CI engine, first proposed by Rudolph Diesel in the 1890s, is very similar to the SI engine discussed in the last section, differing mainly in the method of initiating combustion. In spark-ignition engines, the air–fuel mixture is compressed to a temperature that is below the auto-ignition temperature of the fuel, and the combustion process is initiated by firing a spark plug. In CI engines, the air is compressed to a temperature that is above the auto-ignition temperature of the fuel, and combustion starts on contact as the fuel is injected into this hot air. Therefore, the spark plug is replaced by a fuel injector in diesel engines. The remaining three processes are the same for both ideal cycles. That is,
(a) Isentropic compression (1-2)
(b) Isobaric heat addition (2-3)
(c) Isentropic expansion (3-4)
(d) Isochoric heat rejection (4-1)

The thermal efficiency of a diesel cycle is slightly different from otto cycle and is given as
$\eta_{Diesel}=1-1/r\gamma-1.[\gamma(\rho-1)/\rho\gamma-1]$

Where:
r = Compression ratio = V1/V2
ρ = Cut-off ratio = V3/V2
γ = Ratio of specific heats (Cp/Cv)

(5) in their study used a different irreversible heat-transfer method that takes into consideration more realistic engine losses. They also provided a performance analysis of the air-standard Diesel cycle in this paper. The cycle model in the study takes into account variables like finite heat-transfer rates, combustion inefficiencies, and heat losses to the environment. The authors use this method to examine how the air-fuel ratio and fuel mass flow rate affect maximum power output and thermal efficiency. The findings indicate that while increasing the fuel mass flow rate increases power output with only slight changes in efficiency, decreasing the air–fuel ratio increases both efficiency and power.

2.2.1 The benefits of diesel engines
Diesel engines are highly advantageous, especially for heavy-duty applications. Because of their higher energy density and compression ratios, they deliver 25–35% more fuel efficiency than gasoline engines. They are ideal for trucks, buses, and construction equipment because they generate more torque at lower RPMs. Additionally, due to their durable design, diesel engines have a longer service life

and require less maintenance. Their thermal efficiency has exceeded 50%, thanks to recent advances.

2.2.2 Diesel engines have certain drawbacks which are explained below

Diesel engines have disadvantages despite their benefits. Because they use stronger materials and have more sophisticated emissions controls, they are usually more expensive to manufacture. They can produce more vibration and be noisier, but they are generally more fuel-efficient. Environmental regulations are difficult to comply with because of issues like high nitrogen oxide (NOx) and particulate emissions. Additionally, diesels have lower peak horsepower, which limits their use in high-speed applications, and diesel fuel can be more expensive or harder to find.

2.2.3 Discontinued Diesel Hatchbacks in India

a) Maruti Suzuki Swift 1.3 DDiS
b) Ford Figo Diesel
c) Volkswagen Polo 1.5 TDI
d) Chevrolet Beat Diesel

2.2.4 Diesel Hatchbacks (Globally Available)

a) Volkswagen Golf TDI (Europe/UK)
b) Skoda Fabia TDI (Europe)
c) Peugeot 208 BlueHDi (Europe)
d) Renault Clio dCi (Europe)

2.2.5Sedans

a) Honda City
b) Hyundai Verna

2.2.6 Compact and Midsize SUVs

a) Hyundai VenueKia SonetTata Nexon
b) Mahindra XUV 3XO
c) Mahindra Scorpio N and Classic
d) Mahindra Bolero
e) Kia Seltos
f) Hyundai Creta

2.2.7 Large SUVs / Premium SUVs

a) Mahindra XUV700.
b) Tata Harrier.
c) Tata Safari.
d) Toyota Innova Crysta.
e) Toyota Fortuner.
f) Land Rover Defender.
g) Jeep Compass.

2.2.8 Luxury and Specialty Cars

a) Land Rover Defender.
b) Aston Martin DBX (diesel variant).
c) Kia Carnival.

2.3 Dual cycle

(4) discussed the dual cycle (sometimes referred to as the mixed, Seiliger, Sabathe, or Trinkler cycle) is a thermodynamic cycle that incorporates both the Otto and Diesel cycles. It is a theoretical cycle of heat, used to model and analyze an engine that has characteristics of constant volume (Otto) and constant pressure (Diesel) combustion processes.

(6) briefed the following five processes that comprise dual cycle:

a) Isentropic (adiabatic) compression (1→2): The working fluid (usually ideal air) is compressed without heat loss (or gain).
b) Constant-volume (isochoric) heat addition (2→3): Heat is added with no change in volume—this is a representation of spark ignition, as in Otto cycle.
c) Constant-pressure (isobaric) heat addition (3→4): Heat is added at constant pressure; this is representative of the fuel injection process that occurs in the Diesel cycle.
d) Isentropic expansion (4→5): The gas expands adiabatically, performing work on the piston.
e) Constant-volume heat rejection (5→1): Heat is rejected at a constant volume to complete the cycle.

2.3.1 Efficiency & Mathematical Formulation (10)

The thermal efficiency of the dual cycle (η_{dual}) is either between the efficiency of the Otto cycle and efficiency of the Diesel cycle with the same compression ratio:

$$\eta_{dual} = 1-(Q_{out}/\ Q_{in},1+Q_{in},2)$$

It can also be expressed in terms ratios temperature, pressure, and volume as follows:

$$\eta_{Dual}=1-((r_p r_c{}^k-1)+kr_p(r_c-1)/\ (r^k-1))$$

Where:
1. r = compression ratio
2. r_c = cutoff ratio
3. r_p = pressure ratio during constant-volume addition
4. k = specific-heat ratio (Cp/Cv)

(8) in their paper uses an irreversible thermodynamic model to examine the relationship between combustion efficiency and dual cycle engine performance. In order to account for incomplete fuel burning, the analysis incorporates a combustion efficiency factor and takes into account irreversibility's during compression and expansion. According to the findings, a lower combustion efficiency lowers the maximum usable compression ratio, which in turn lowers work output and thermal efficiency. It is shown that efficiency–work plots cannot form closed loops when realistic factors like heat loss and fuel energy limits are included, and mathematical expressions are given to quantify these effects. This study highlights how important combustion quality is to attaining the best dual cycle performance.

(7) in their study concluded that a realistic foundation for examining contemporary high-speed compression ignition engines is provided by the developed finite-time thermodynamic model for an irreversible air-standard dual cycle, which takes into consideration variable specific heats, friction losses, internal irreversibility, and heat transfer. According to numerical results, the ideal compression ratios and operating ranges are influenced by the pressure ratio and cut-off ratio, which have notable and unique effects on power output and thermal efficiency. Practical cycle analysis must take these effects into account because the results

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provide insightful advice for assessing and enhancing actual dual-cycle engine performance.

2.3.2 (8) discussed benefits of the Dual Cycle

(a) Higher Thermal Efficiency:
- Offers benefits of both Otto and Diesel cycles.
- Provides greater similarity to actual combustion in an engine.

(b) More Complete Combustion:
- Rapid combustion followed by slow combustion provides better use of fuel.

(c) Lower Emissions:
- Flexible combustion phase can improve control over peak temperatures and pressures which helps lower NO_x and other emissions.

(d) Balance between Power and Efficiency:
- Applications for efficient heat addition strategies improves their work output while limiting fuel consumption.

2.3.3 (11) discussed disadvantages of the Dual Cycle

(a) Implementation Complexity:
- Realizing constant-volume and constant-pressure heat addition within the same engine cycle adds design difficulty.

(b) Engine Design Challenges:
- Requires precise fuel injection timing and potentially advanced control systems (e.g., ECU, variable valve timing).
- Increased mechanical complexity leads to higher production and maintenance costs.

(c) Less Common in Practice:
- Very few real engines operate exactly on a dual cycle.
- It remains a theoretical model used to approximate real combustion processes.

(12,13) in their study it has been discussed about The Relative efficiencies of traditional thermodynamic cycles:

1) For same compression ratio(r):

The Otto cycle is the most efficient for the same compression ratio, followed by the Dual cycle and the Diesel cycle. This is due to the Otto cycle's use of constant-volume heat addition, which maximizes work output by producing the highest temperature rise for a specific compression ratio. The Diesel cycle, on the other hand, uses constant-pressure heat addition, which lowers efficiency by producing a smaller average temperature rise at the same compression ratio. The Dual cycle has intermediate performance characteristics because it combines both constant-volume and constant-pressure heat addition phases.

Otto cycle efficiency > Dual cycle efficiency > Diesel cycle efficiency

2) For same maximum temperature and pressure (T and P):

The Diesel cycle, Dual cycle, and Otto cycle are the most efficient when they are running at the same maximum pressure and temperature limits. This happens because a longer expansion process helps the Diesel cycle extract more work from the high-temperature gases before rejecting heat. On the other hand, the Otto cycle has a shorter expansion stroke, which causes more heat loss during exhaust, even though it is subject to the same maximum pressure–temperature restrictions. The Dual cycle produces performance and efficiency values that fall between those of the Otto and Diesel cycles by combining constant-volume and constant-pressure heat addition.

Diesel cycle efficiency > Dual cycle efficiency > Otto cycle efficiency

(9) in their research examined the development of finite-time thermodynamic research applied to the Otto, Diesel, Dual, Atkinson, and Miller cycles of internal combustion engines. In addition to taking working fluid characteristics and heat transfer laws into account, the authors examined optimization techniques like maximum power, maximum efficiency, and ecological performance criteria. Their compilation provides a thorough guide for choosing the best FTT models to balance environmental impact, fuel efficiency, and performance.

3. Limitations of this Paper

1) Atkinson, Miller, Rankine, and Brayton cycles are not discussed in this paper, only the Otto, Diesel, and Dual cycles discussed with thorough thermodynamic analysis and performance evaluation, this restricted understanding about only selected power cycles. Future research will include a thorough examination of these other cycles.
2) The analysis in this paper ignored real-world losses like friction, heat transfer to the environment, pumping losses, and variations in specific heats in favour of air-standard assumptions and ideal thermodynamic processes.
3) Although there are a few real-world engine examples in the discussion, there aren't any in-depth case studies or simulations for particular vehicle or turbine applications.
4) Without taking into account the transient and dynamic behaviour of actual internal combustion engines, the focus is restricted to ideal cycle models.

4. Conclusion

This study examined the thermodynamic concepts and performance traits of the Otto, Diesel, and Dual cycles, which form the basis of majority of internal combustion engines. The Diesel cycle performs best under extreme pressure and temperature conditions. The Otto cycle offers the highest efficiency at equal compression ratios, and the Dual cycle offers a well-balanced trade-off between efficiency and power output. In real-world applications, operational needs, fuel type, and emission considerations influence the choice of cycle. The Atkinson, Miller, Rankine, and Brayton cycles were not the focus of this study, future research papers will be done to provide a thorough understanding of thermodynamic power cycles and how they improve engine performance, fuel economy, and emissions reduction. Finally concluding that thermodynamic power cycles ultimately should result in optimizing the cycles which remains the most important factor to meet the future demands of sustainable and efficient power generation.

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