AL-MAMON UNIVERSITY COLLAGE

DEPARTMENT OF ELECTRICAL POWER ENGINEERING TECHNIQUES

Part 2

Lecture notes 6

THERMODYNAMIC

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Thermodynamic Cycles

This lecture notes consist the following topics:

- Introduction.
- Processes & Cycles.
- Major Types of Thermodynamic Processes
- Thermodynamic cycles.
- Brayton Cycle.
- Otto Cycle.
- Diesel Cycle.

Thermodynamic Cycles

6.1 Introduction

An important application of thermodynamics is the analysis of power cycles through which the energy absorbed as heat can be continuously converted into mechanical work.

6.2 Processes & Cycles

Sections throughout this lecture will discuss different types of processes and different types of cycles, therefore it is important to understand the difference between a process and a cycle.

A process, as shown in Figure 1, is a change in the system from one equilibrium state to another.

الاجراء(العملية) هو تغيير في النظام من حالة توازن إلى أخرى

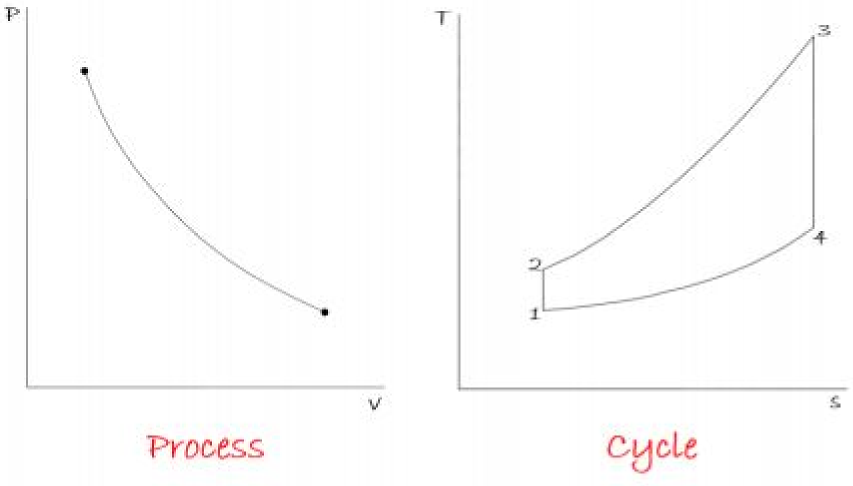

Figure 1 Processes and cycles

In a cycle, as shown, the system returns to the initial state at the end of the set of processes.

الدورة وهي ان يعود النظام إلى الحالة الأولية في نهاية مجموعة العمليات الحرارية (الاجراءات)

6.2.1 Major Types of Thermodynamic Processes

There are several specific types of thermodynamic processes that happen frequently where the properties of substance like (Temperature, Pressure and Specific volume). Each has a unique trait that identifies it, and which is useful in analyzing the energy and work changes related to the process.

هناك عدة أنواع محددة من العمليات (الاجراءات) الديناميكية الحرارية التي تحدث بشكل متكرر حيث تتغيربها الخصائص الرئيسية للمادة مثل (درجة الحرارة والضغط والحجم النوعي)، وهي مفيدة في تحليل الحراري للطاقة وتغييرات الشغل المتعلقة بالعملية.

- **Adiabatic process** - a process with no heat transfer into or out of the system.
  عملية بدون انتقال للحرارة داخل أو خارج النظام
- **Isochoric process** - a process with no change in volume, in which case the system does no work.
  عملية بدون تغيير في الحجم ، وفي هذه الحالة لايوجد شغل منجز في النظام
- **Isobaric process** - a process with no change in pressure.
  عملية بدون تغيير في الضغط
- **Isothermal process** - a process with no change in temperature.
  عملية بدون تغيير في درجة الحرارة

It is possible to have multiple processes within a single process. The most obvious example would be a case where volume and pressure change, resulting in no change in temperature or heat transfer - such a process would be both adiabatic & isothermal.

من الممكن أن تتغير خاصيتان للمادة في عملية واحدة اي حدوث اكثر من عملية او اجراء في ان واحد. المثال الأكثر وضوحًا هو الحالة التي يتغير فيها الحجم والضغط ، مما يؤدي إلى عدم حدوث تغيير في درجة الحرارة أو انتقال الحرارة.

6.3 Thermodynamic cycles

Thermodynamic cycle is a series of processes where the properties of the system are the same after the cycle as they were prior.

الدورة الديناميكية الحرارية هي سلسلة من العمليات (الاجراءات) حيث تتغير خصائص النظام خلالها ثم تعود نفسها بعد الدورة.

To be considered a cycle, all properties need to be the same at their initial state and at the end. One property could remain the same throughout any of the processes; the cycle is considered isothermal if temperature is constant, isobaric if pressure is constant, and isochoric or isometric if specific volume is constant. The most efficient type of cycle is one that has only reversible processes, such as the Carnot cycle, which is made up of four reversible processes. There are two classes of cycles and they are:

1. Power Cycles.

2. Heat Pump Cycles.

Power cycles are used when there exists some way of converging some heat energy input into mechanical work output. while heat pump cycles transfer heat from low to high temperature stages by using mechanical work as the input source.

تُستخدم دورات الطاقة لتحويل الطاقة الحرارية الى شغل ميكانيكي. بينما تقوم دورات المضخات الحرارية بنقل الحرارة من مراحل درجات الحرارة المنخفضة إلى درجات الحرارة العالية باستخدام الشغل الميكانيكي.

A thermodynamic cycle in respect to net mechanical work by input from heat energy in a closed loop on the (P-V diagram) mathematically can be presented as:

$$W = \oint P\mathrm{d}V \qquad \text{Eq (6-1)}$$

The net work presented by Eq. (6.1) is equal to the balance of heat Q transferred into the system and mathematically is presented by Eq. (6.2) in the following form:

$$W = Q = Q_{\mathrm{in}} - Q_{\mathrm{out}} \qquad \text{Eq (6-2)}$$

The main interest lies in the thermodynamic analysis of power cycles is estimating the energy conversion efficiency or the thermal efficiency. The thermal efficiency is defined as the ratio of the net work output (W) delivered to the energy absorbed as heat (Q) and mathematically is presented by symbol (η) and can be written as:

$$\boxed{\eta = \frac{W}{Q}} \qquad \text{Eq (6-3)}$$

6.3.1 Brayton Cycle

Gas turbine power plants, both stationary and those for jet engines operate on the Brayton cycle. The cycle is named after George Brayton, an American mechanical engineer Brayton.

This cycle differs from the Otto and Diesel cycles in that the processes making the cycle occur in open systems or control volumes. Therefore, an open system, steady-flow analysis is used to determine the heat transfer and work for the cycle. We assume the working fluid is air and the specific heats are constant and will consider the cold-air-standard cycle.

تختلف Brayton Cycle عن دورات أوتو او الديزل من حيث أن العمليات التي تتكون منها الدورة تحدث في أنظمة مفتوحة أو حجم ثابت. لذلك ، يتم استخدام تحليل التدفق الثابت للنظام المفتوح لتحديد انتقال الحرارة والشغل في الدورة. نفترض أن المائع المشغل للدورة هو الهواء وأن درجات الحرارة النوعية ثابتة .

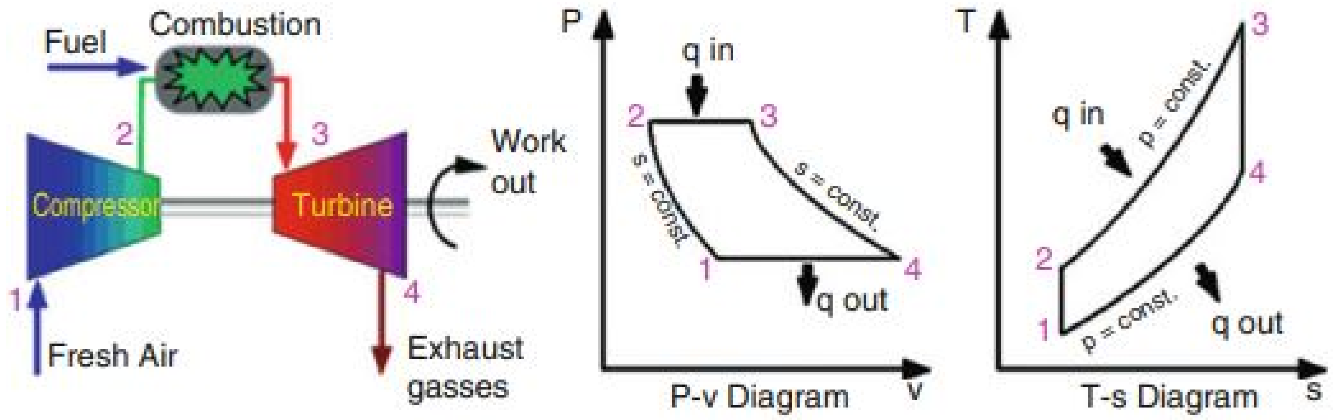

Figure 2 Schematic of Brayton cycle along with P – v and T – s diagrams

in Fig. 2. A schematic of T –s and P – v for the Brayton cycle for a power plant are illustrated.

The Brayton cycle is outlined as follows:

1 → 2: isentropic compression (W added),

2 → 3: isobaric heat addition (Q added),

3 → 4: isentropic expansion (W extracted), and

4 → 1: isobaric heat rejection (passive exhaust).

Note, the work extracted is greater than the work added.

Thermal efficiency of the Brayton cycle

$$\boxed{\eta_{\text{th, Brayton}} = \frac{W_{\text{net}}}{Q_{\text{in}}} = 1 - \frac{Q_{\text{out}}}{Q_{\text{in}}}} \qquad \text{Eq } (6 - 4)$$

As mentioned above: -

$Q_{\text{in}} = \textit{the heat transfer to the system}$

$Q_{\text{out}} = \textit{the heat rejected from the system}$

$W_{\text{net}} = \textit{the net work}$

Now to find Q_{in} and Q_{out} depend on T −s and P − v diagrams as shown in figure 2.

Apply the conservation of energy to process 2-3 (at P-v diagram) for P is constant (no work), steady-flow, and neglect changes in kinetic and potential energies.

Conservation equation:

$$E_{in} = E_{out}$$
$$\dot{m}_2 h_{2min} + Q_{in} = \dot{m}_3 h_3$$

The conservation of mass gives:

$$\dot{m}_{in} = \dot{m}_{out}$$
$$\dot{m}_2 = \dot{m}_3 = \dot{m}$$

For constant specific heats, the heat added per unit mass flow is:

$$Q_{in} = \dot{m}(h_3 - h_2)$$
$$Q_{in} = \dot{m}C_p(T_3 - T_2)$$
$$\boxed{q_{in} = \frac{Q_{in}}{\dot{m}} = C_p(T_3 - T_2)}$$

Q = is heat transfer

q = heat transfer to unit of mass

Sub in Eq (6-4) the thermal efficiency becomes:

$$\eta_{th,\ Brayton} = 1 - \frac{Q_{out}}{Q_{in}} = 1 - \frac{q_{out}}{q_{in}}$$
$$= 1 - \frac{C_p(T_4 - T_1)}{C_p(T_3 - T_2)}$$
$$\eta_{th,\ Brayton} = 1 - \frac{(T_4 - T_1)}{(T_3 - T_2)}$$
$$= 1 - \frac{T_1(T_4/T_1 - 1)}{T_2(T_3/T_2 - 1)}$$

Recall processes 1-2 and 3-4 are isentropic at T-s diagram, so

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \quad and \quad \frac{T_3}{T_4} = \left(\frac{P_3}{P_4}\right)^{(k-1)/k}$$

An isentropic process is a thermodynamic process, in which the entropy of the fluid or gas remains constant. It means isentropic the isentropic process is a special case of an adiabatic process in which there is no transfer of heat or matter. It is a reversible adiabatic process.

العملية الايزوتروبك هي عملية ديناميكية حرارية ، حيث تظل إنتروبيا المائع أو الغاز ثابتة. هذا يعني أن العملية الايزوتروبك هي حالة خاصة لعملية (الاديباتيكية) ثابت الحرارة لا يوجد فيها انتقال للحرارة أو الكتلة.

Since $P_3 = P_2$ and $P_4 = P_1$ as shown P-s diagram, we see that:

$$\frac{T_2}{T_1} = \frac{T_3}{T_4} \quad or \quad \frac{T_4}{T_1} = \frac{T_3}{T_2}$$

The Brayton cycle thermal efficiency $\eta_{th,\ Brayton}$ becomes:

$$\boxed{\eta_{th,\ Brayton} = 1 - \frac{T_1}{T_2}}$$

Since process 1-2 is isentropic

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} = r_p^{(k-1)/k}$$

$$\frac{T_1}{T_2} = \frac{1}{r_p^{(k-1)/k}}$$

where the pressure ratio is $r_p = P_2/P_1$ and $k = Cp/Cv$ is the specific heat ratio

$$\boxed{\eta_{th,\ Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}}$$

k* = *Cp* /*Cv *is the specific heat ratio*

Cp = Heat capacity (isobaric)

السعة الحرارية بثبوت الضغط

Cv = Heat capacity (isochoric/volumetric)

السعة الحرارية بثبوت الحجم

Example 6-1: The ideal air-standard Brayton cycle operates with air entering the compressor at 95 kPa, 22ºC. The pressure ratio $\boldsymbol{r_p}$ is 6:1 and the air leave Combustion Chamber at 1100ºk and (*k = 1.4, Cp = 1.005 kJ/kg. K*). Determine:

1- The thermal efficiency of cycle.

2- The temperature inters the Combustion Chamber.

3- The heat added to the cycle.

Solution: -

$$r_p = \frac{P_2}{P_1}$$

$$r_p = \frac{6}{1} = 6$$

$$\eta_{th,\ Brayton} = 1 - \frac{1}{r_p^{(k-1)/k}}$$

$$\eta_{th,\ Brayton} = 1 - \frac{1}{6^{\frac{(1.4-1)}{1.4}}} = 0.40$$

$$\eta_{th,\ Brayton} = 40\ \%$$

The temperature inters the Combustion Chamber is (T_2) in ideal Brayton cycle

$$\frac{T_1}{T_2} = \frac{1}{r_p^{\frac{k-1}{k}}} \quad \text{or} \quad \eta_{th,\ Brayton} = 1 - \frac{T_1}{T_2}$$

$$\frac{22}{T_2} = \frac{1}{6^{\frac{1.4-1}{1.4}}}$$

$$T_2 = 37℃ \; or \; 310 \; k$$

The heat added to the cycle is (q_{in})

The conservation of mass gives:

$$\dot{m}_{in} = \dot{m}_{out}$$
$$\dot{m}_2 = \dot{m}_3 = \dot{m}$$

$$Q_{in} = \dot{m}(h_3 - h_2)$$
$$Q_{in} = \dot{m}C_p(T_3 - T_2)$$
$$q_{in} = \frac{Q_{in}}{\dot{m}} = C_p(T_3 - T_2)$$

$$q_{in} = 1.005\,(1100 - 310)$$

$$q_{in} = 794\,\frac{kJ}{kg}$$

Example 6-2: Consider an air standard Brayton cycle with fixed inlet conditions (***P_1= 101 kPa***), and (***T_1= 26 ºC***). We also measured outlet temperature from compressor at (***T_2= 35 ºC***). Find the pressure ratio (***r_p***). Then find the thermal efficiency. (***C_p*** =100.5, ***C_v*** = 0.718 kJ/kg. K)

Solution: -

$$\frac{T_2}{T_1} = \left(\frac{P_2}{P_1}\right)^{(k-1)/k} \quad = r_p^{(k-1)/k}$$

$$\frac{T_1}{T_2} = \frac{1}{r_p^{(k-1)/k}}$$

$$k = Cp\,/Cv$$

$$k = \frac{1.005}{0.718} = 1.4$$

$$\frac{26}{35} = \frac{1}{r_p^{\frac{1.4-1}{1.4}}}$$

$$r_p = 4$$

$$\eta_{th,\ Brayton} \quad = 1 - \frac{T_1}{T_2}$$

$$\eta_{th,\ Brayton} \quad = 1 - \frac{26}{35}$$

$$\eta_{th,\ Brayton} \quad = 0.25 \ or\ 25\%$$

Introduction to Internal Combustion Engines

Before explaining the Otto cycle, it is helpful to discuss some terminology associated with internal combustion engines. Figure 3 shows a cross-section looking at a cylinder in an engine illustrate the piston and valves.

قبل شرح دورة أوتو ، من المفيد التعرف على بعض المعلومات والمصطلحات الخاص بمحركات الاحتراق الداخلي. يوضح الشكل ٣ مقطعًا عرضيًا ينظر إلى أسطوانة في يوضح المكبس والصمامات.

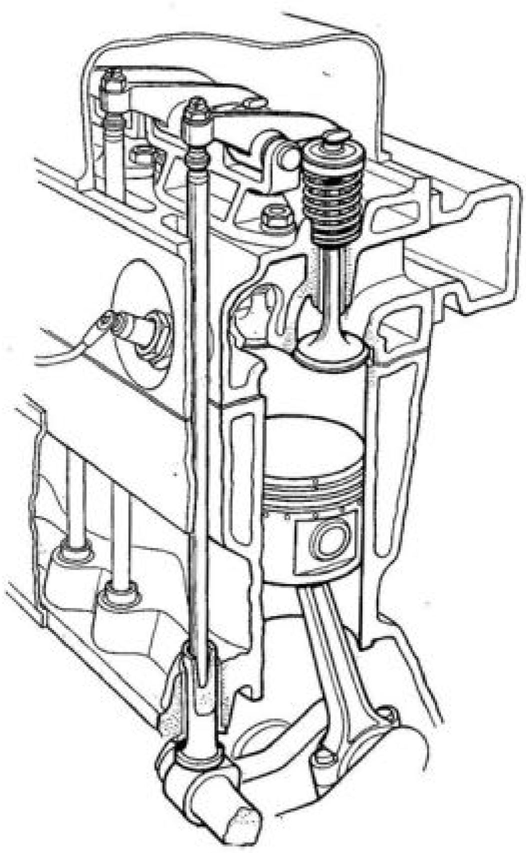

Figure 3 Engine cross-sectional view showing piston and valves

Figure 4 (a) shows a simplified piston figure with some important terms for the reciprocating piston. The extreme positions of the piston are called top dead center (TDC) and bottom dead center (BDC). The distance between TDC and BDC is the stroke. Figure 4 (b) illustrates a typical four-stroke engine cycle. The four-stroke combustion cycle consists of the compression stroke, combustion stroke, exhaust stroke, and the intake stroke.

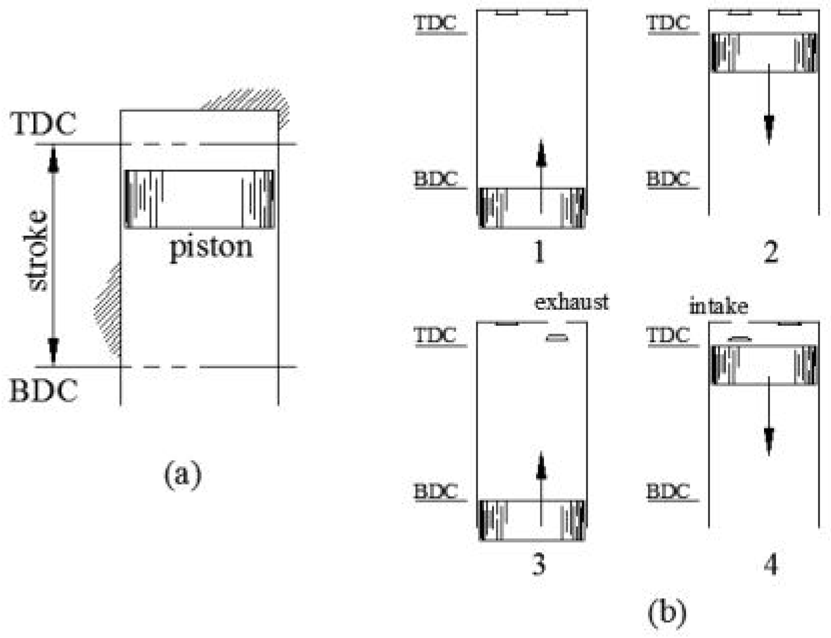

Figure 4 (a) Piston stroke and terminology

(b) Four-stroke combustion cycle.

يوضح الشكل ٤ (*a*) المكبس بشكل مبسط مع بعض المصطلحات المهمة للمكبس الترددي. تسمى المواضع القصوى للمكبس المركز الميت العلوي (*TDC*) والمركز الميت السفلي (*BDC*)، و المسافة بين *TDC* و *BDC* هي الشوط. أما الشكل ٤ (*b*) يوضح دورة محرك رباعي الأشواط النموذجي. تتكون دورة الاحتراق رباعية الأشواط من شوط الانضغاط وشوط الاحتراق وشزط العادم وشوط السحب.

6.3.2 Otto Cycle

The Otto cycle is the ideal cycle for spark ignition reciprocating engines. Because the cycle treats the working fluid as an ideal gas, tables for ideal gas properties of air will be used. The cycle is shown in Figure 4 on a P-v diagram along with a brief description of the four internally reversible processes. The combustion process is replaced with a heat addition process.

دورة أوتو هي الدورة المثالية لمحركات الاشتعال بالشرارة الترددية. يكون السائل المشغل (working fluid) غاز مثالي . تظهر الدورة في الشكل ٣ على مخطط *P-v* مع وصف موجز للعمليات الأربع القابلة للعكس داخليًا.

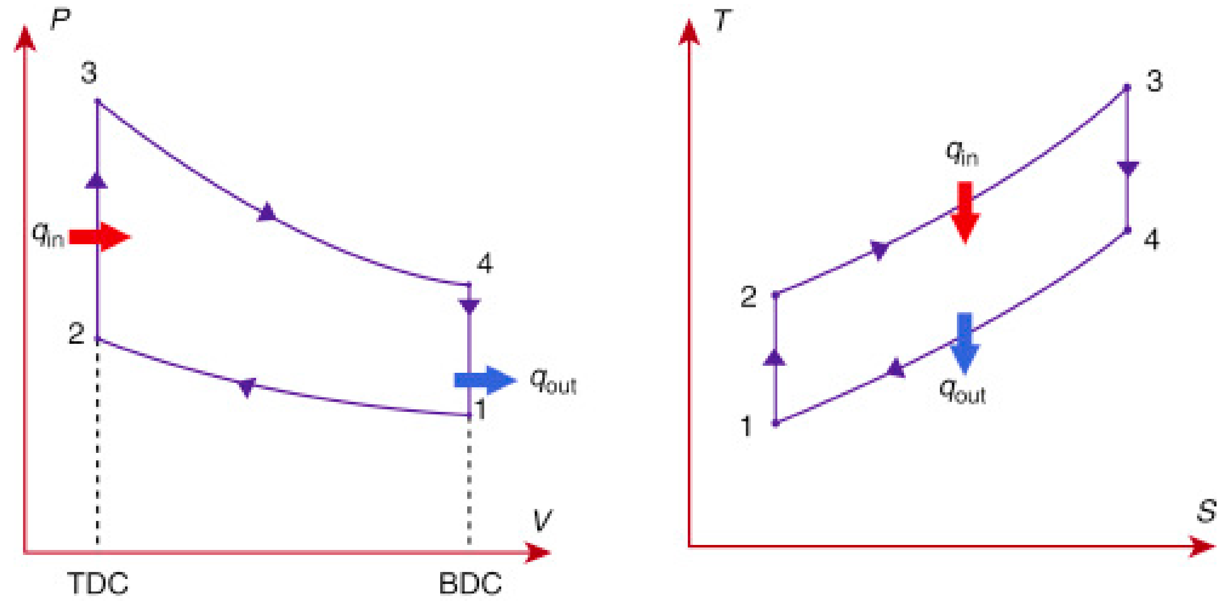

Figure 4: P − v and T − s diagrams for the Otto cycle.

1 → 2: **isentropic compression** in the compression stroke,

2 → 3: **isochoric heating** in the combustion stroke during spark ignition,

3 → 4: **isentropic expansion** in power stroke,

4 → 1: **isochoric rejection** of heat to the surroundings.

Thermodynamic analysis of the Otto cycle produces a simple relationship among the thermal efficiency of the Otto cycle $\eta_{th,\,Otto}$, compression ratio r_p, and specific-heat ratio k:

$$\boxed{\eta_{th,Otto} = 1 - \left(1/r_p^{(1-k)}\right)}$$

The influence of compression ratio and specific-heat ratio on the thermal efficiency of the Otto cycle. For a given specific-heat ratio, thermal efficiency increases dramatically with increasing compression ratio $\boldsymbol{r_p}$.

6.3.3 Diesel Cycle

The diesel cycle is very similar to the Otto cycle, with the difference being the heat addition process. The Otto cycle has a constant volume heat addition process where the diesel cycle has a constant pressure heat addition process. The diesel cycle is shown on the P-v and T-s diagram in Figure 5

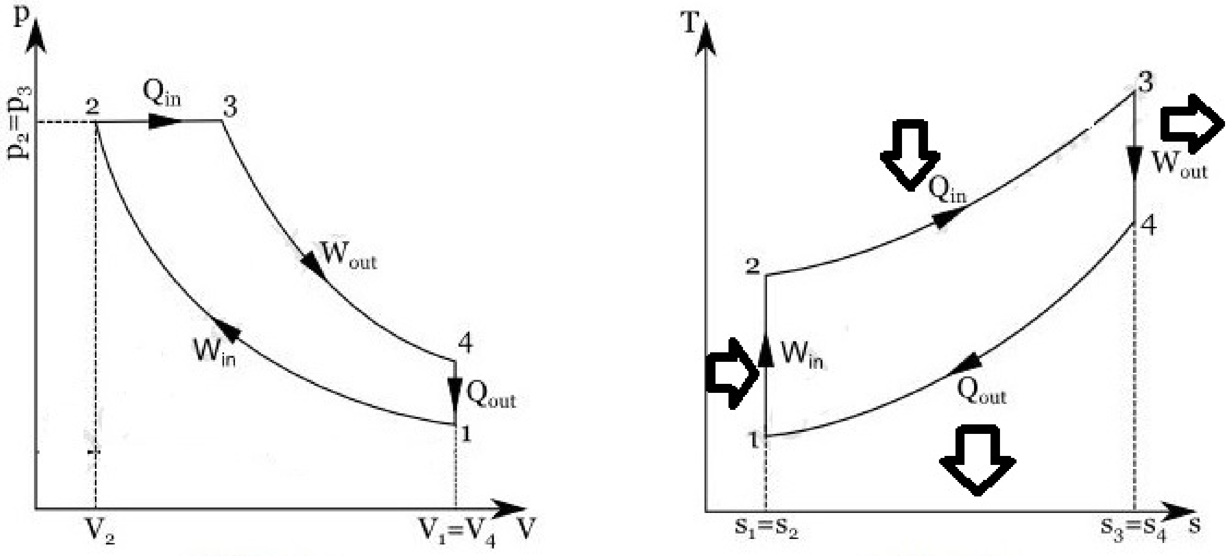

Figure 5: P − v and T − s diagrams for the Diesel cycle.

A diesel engine is also known as a compression ignition engine, where the Otto cycle was based on the spark ignition engine. In a diesel engine, the combustion starts by compressing the air to a temperature above the auto ignition temperature of the fuel and injecting fuel into the high temperature air. In the diesel cycle, only air is compressed during the compression process. The combustion process in the cycle is approximated as a constant pressure heat addition process. The diesel cycle is based on the air-standard assumptions.

يُعرف محرك الديزل أيضًا باسم محرك الإشعال بالضغط ، ليس كما في دورة أوتو يعتمد الاشعال في محرك على الشرارة الخارجية. في محرك الديزل ، يبدأ الاحتراق بضغط الهواء ورفع درجة حرارته الى درجة أعلى من درجة حرارة الاشتعال التلقائي للوقود ومن ثم حقن الوقود في الهواء ذو درجة الحرارة المرتفعة. يتم ضغط الهواء فقط أثناء عملية الضغط، وتكون عملية الاحتراق في الدورة الديزل كعملية إضافة حرارة بثبوت الضغط.

Thermodynamic analysis of the Diesel cycle produces a simple relationship between the thermal efficiency of the Diesel cycle ηth, with compression ratio r, cut-off ratio r_c and specific-heat ratio k:

$$\boxed{\eta_{th,\, diesel} = 1 - \frac{1}{r^{k-1}}\left[\frac{r_c^k - 1}{k(r_c - 1)}\right]}$$

Where:

$\eta_{th,\, diesel}$ = *is thermal efficiency of Diesel cycle,* هي الكفاءة الحرارية للدورة الديزل

r_c = *is the cut-off ratio* $\frac{V_3}{V_2}$ *(ratio between the end and start volume for the combustion phase),*

هي نسبة القطع (النسبة بين حجم النهاية وحجم البداية لمرحلة الاحتراق)

r = *is the compression ratio* $\frac{V_1}{V_2}$,

هي نسبة الانضغاط

k = *is ratio of specific heats* (c_p/c_v).

هي نسبة الحرارة النوعية