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Otto Cycle Analysis

by

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Course Category: Engineers

Course Level: Intermediate

Credit: 1 Hour

Otto Cycle Analysis

Course Description

The ideal cycle for a simple gasoline engine is the Otto Cycle. In this one hour course, the open, simple Otto Cycle used for stationary power generation is considered.

The Otto Cycle thermal efficiency is presented only for the air as the working fluid. The thermal efficiency derivation is presented with a simple mathematical approach. The Otto Cycle is presented in the p - V and T - s diagrams and its major performance trends (thermal efficiency and power output) are plotted in a few figures as a function of compression ratio, combustion temperature for fixed cylinder geometry. It should be noted that this online course does not deal with costs (capital, operational or maintenance).

In this course, the student gets familiar with the Otto Cycle, its components, p - V and T - s diagrams, operation and major performance trends.

This course includes a multiple choice quiz at the end.

Otto Cycle Analysis

Performance Objectives

At the conclusion of this course, the student will:

- Understand basic energy conversion engineering assumptions and equations
- Know basic components of the Otto Cycle and its p - V and T - s diagrams
- Be familiar with the Otto Cycle operation
- Understand general Otto Cycle performance trends

Otto Cycle Analysis

Introduction

Over the years, gasoline engine has become the premier transportation system for low loads. Gasoline engines are compact, lightweight, easy to operate and come in sizes ranging from several kilowatts to a few megawatts. Gasoline engines require relatively low capital investment, have high operating flexibility, high thermal efficiency and can be used for various transportation and industrial applications. Gasoline engines can help provide reliable power to meet the future demand using both high and low heat content fuels, with low emissions.

Otto Cycle Analysis

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Otto Cycle

This section provides an Otto Cycle analysis when the working fluid is air.

Analysis

In the presented Otto Cycle analysis, only air is considered as the working fluid behaving as a perfect gas -- specific heat has a constant value. Ideal gas state equation is valid -- pv = RT.

Air enters a cylinder at point 1 when compression starts and it ends at point 2. Isentropic compression is considered with no entropy change. Heat addition starts at point 2 and it ends at point 3. At a constant volume, combustion takes place (fuel is added to the cylinder and the air temperature raises) and/or heat gets added to air. Expansion starts at point 3 and it ends at point 4. Isentropic expansion is considered with no entropy change. Air heat rejection starts at point 4 and it ends at point 1. At a constant volume, air gets cooled and the working fluid temperature decreases. It should be mentioned that air at point 1 enters the compression process again and the cycle is repeated.

Figure 1 presents an Otto Cycle pressure vs volume diagram.

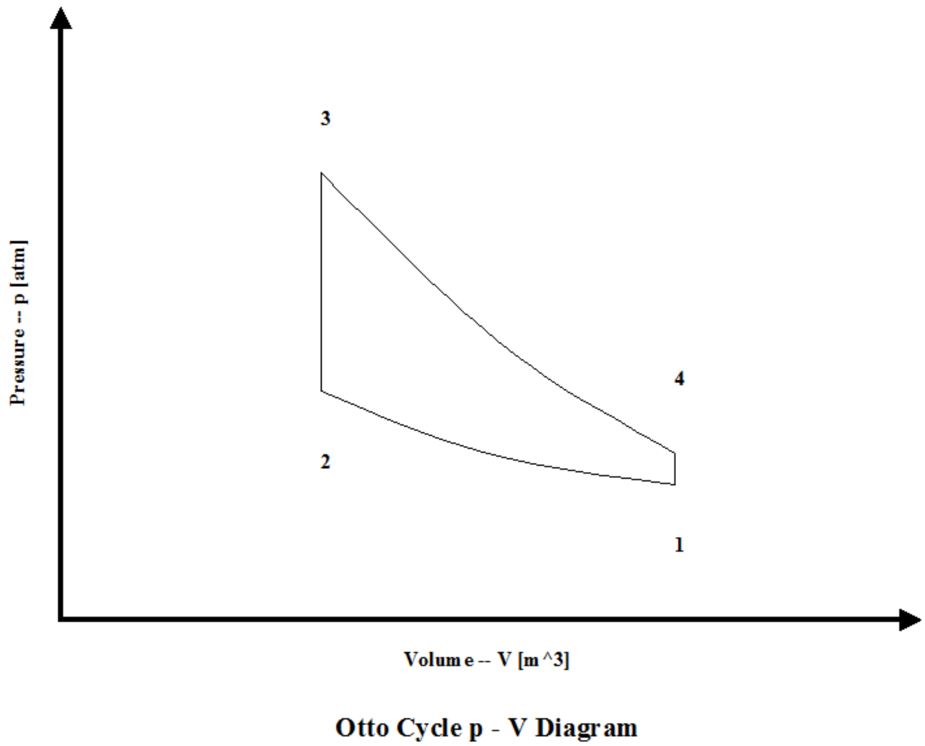

Figure 1 - Otto Cycle Pressure vs Volume Diagram

Figure 2 presents an Otto Cycle temperature vs entropy diagram.

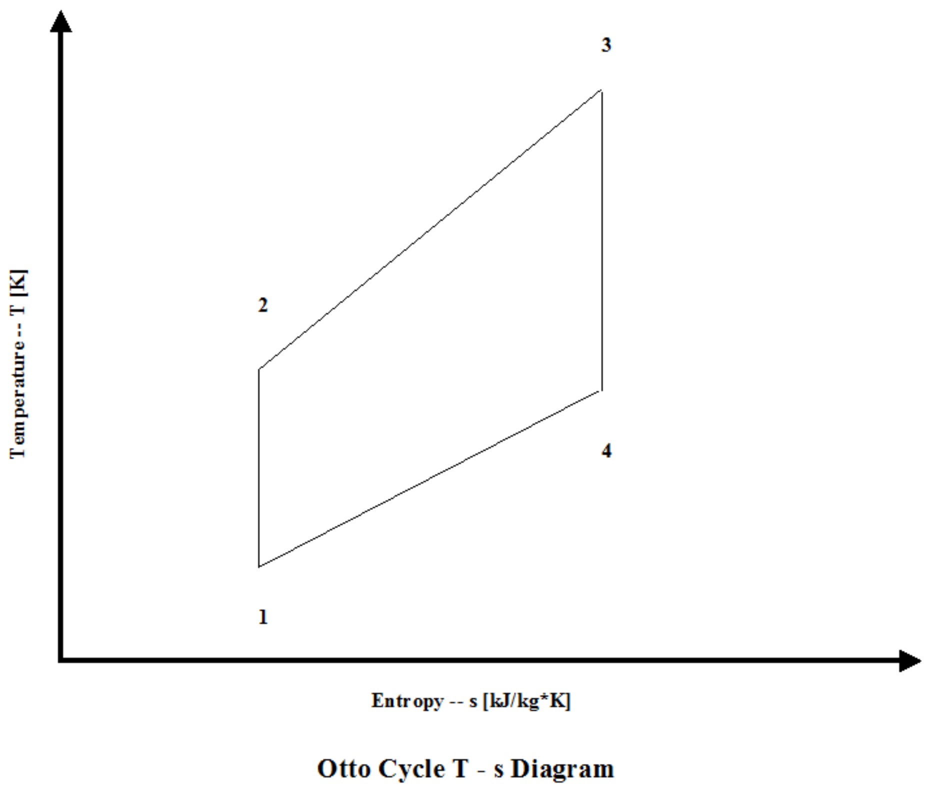

Figure 2 - Otto Cycle Temperature vs Entropy Diagram

The thermal cycle efficiency can be given as a function of specific external work (specific net power output) and heat added to the working fluid as follows:

$\eta = w/q_h = (w_e - w_c)/q_h = (q_h - q_l)/q_h$

or

$\eta = 1 - q_l/q_h = 1 - (c_v(T_4 - T_1))/(c_v(T_3 - T_2)) = 1 - (T_1(T_4/T_1 - 1))/(T_2(T_3/T_2 - 1))$

where

η - thermal efficiency [/]

w - specific external work (specific net power output) [kJ/kg]

w_e - expansion specific power output [kJ/kg]

w_c - compression specific power input [kJ/kg]

W - external work (net power output) [kW]

W_e - expansion power output [kW]

W_c - compression power input [kW]

q_h - heat added to the working fluid [kJ/kg]

q_l - heat rejected from the working fluid [kJ/kg]

c_p - specific heat at constant pressure [kJ/kg*K]

c_v - specific heat at constant volume [kJ/kg*K]

m - working fluid mass flow rate [kg/s]

ε - compression ratio [/]

For isentropic compression and expansion:

$T_2/T_1 = (p_2/p_1)^{(\varkappa-1)/\varkappa} = (V_1/V_2)^{(\varkappa-1)}$

$T_4/T_3 = (p_4/p_3)^{(\varkappa-1)/\varkappa} = (V_3/V_4)^{(\varkappa-1)}$

Knowing that

$V_3/V_4 = V_2/V_1$

where

$\varkappa = c_p/c_v$ - for air $\varkappa = 1.4$ [/]

V_1, V_2, V_3, V_4 - volume values at points 1, 2, 3 and 4 [m^3]

p_1, p_2, p_3, p_4 - pressure values at points 1, 2, 3 and 4 [atm]

T_1, T_2, T_3, T_4 - temperature values at points 1, 2, 3 and 4 [K]

It follows that

$T_3/T_4 = T_2/T_1 = (V_1/V_2)^{(\varkappa-1)} = \varepsilon^{(\varkappa-1)}$

where

$\varepsilon = V_1/V_2$

Therefore, after some mathematical operations the thermal efficiency is:

$\eta = 1 - T_1/T_2 = 1 - 1/(V_1/V_2)^{(\varkappa-1)}$

If the temperature ratio is substituted in terms of the volume/compression ratio:

$\eta = 1 - 1/\varepsilon^{(\varkappa-1)}$

Figure 3 presents the Otto Cycle efficiency as a function of the compression ratio. It should be noted that the inlet conditions are standard ambient conditions: temperature of 298 [K] and absolute pressure of 1 [atm].

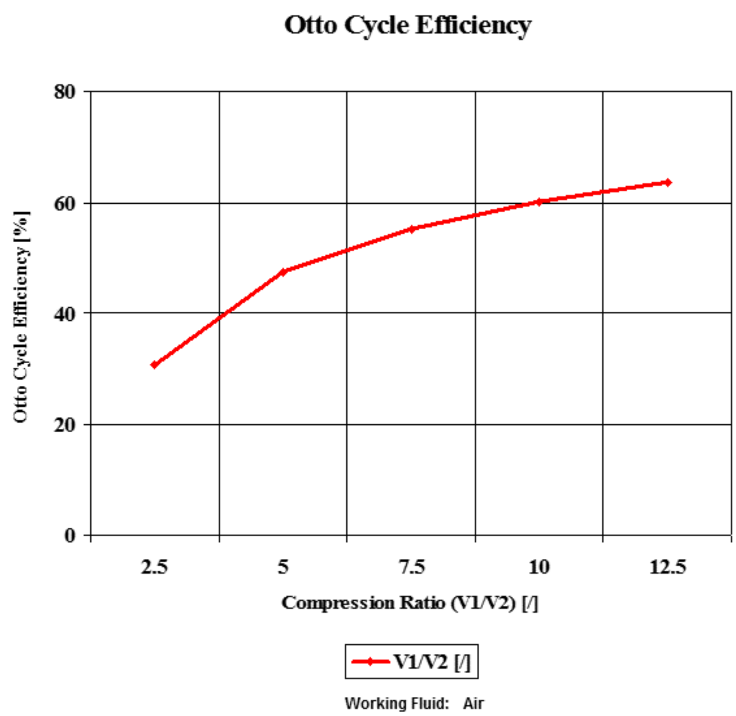

Figure 3 - Otto Cycle Efficiency

Figure 4 presents the Otto Cycle power output as a function of the combustion temperature and compression ratio. It should be noted that the number of revolutions is 60 [1/s] for given geometry of the four cylinder and four stroke Otto engine.

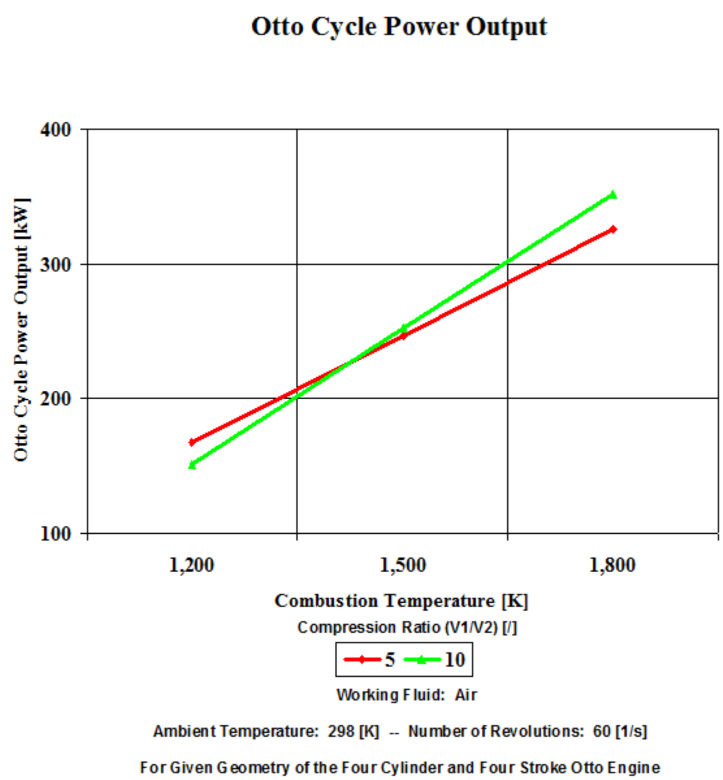

Figure 4 - Otto Cycle Power Output

One can notice that the Otto Cycle efficiency increases with an increase in the compression ratio values. One can notice that the Otto Cycle power output increases with an increase in the combustion temperature. The Otto Cycle power output is greater for the higher compression ratio values.

Assumptions

Working fluid is air. There is no friction. Compression and expansion are isentropic -- there is no entropy change. Ideal gas state equation is valid -- pv = RT. Air behaves as a perfect gas -- specific heat has a constant value.

Otto Cycle Analysis

Governing Equations

$$T_2/T_1 = (V_1/V_2)^{(\varkappa-1)}$$

$$V_1/V_2 = (T_2/T_1)^{1/(\varkappa-1)}$$

$$T_3/T_4 = (V_4/V_3)^{(\varkappa-1)}$$

$$V_4/V_3 = (T_3/T_4)^{1/(\varkappa-1)}$$

$$\varkappa = c_p/c_v$$

$$c_p - c_v = R$$

$$pv = RT$$

$$w = q_h - q_l$$

$$q_h = c_v(T_3 - T_2)$$

$$q_l = c_v(T_4 - T_1)$$

$$w = c_v(T_3 - T_2) - c_v(T_4 - T_1)$$

$$W = (c_v(T_3 - T_2) - c_v(T_4 - T_1))m$$

$$\eta = 1 - 1/\varepsilon^{(\varkappa-1)}$$

$$\varepsilon = V_1/V_2$$

Input Data

T_1 = 298 [K]

p_1 = 1 [atm]

T_3 = 1,200, 1,500 and 1,800 [K]

ε = 2.5, 5, 7.5, 10 and 12.5 [/]

R = 0.2867 [kJ/kg*K]

c_p = 1.004 [kJ/kg*K]

$\varkappa$ = 1.4 [/]

Results

Otto Cycle Efficiency vs Compression Ratio

Compression Ratio [/]	**Otto Cycle Efficiency [%]**
2.5	30.69
5	47.47
7.5	55.33
10	60.19
12.5	63.59

Otto Cycle Power Output

Power Output [kW]	**Combustion Temperature [K]**		
Compression Ratio [/]	1,200	1,500	1,800
5	167	246	326
10	151	252	352

Conclusions

The Otto Cycle efficiency increases with an increase in the compression ratio values. Also, the Otto Cycle power output increases with an increase in the combustion temperature. Tthe Otto Cycle power output is greater for the higher compression ratio values.

Please use the material you just read to answer the quiz questions at the end of this course.

When you get a chance, please visit the following URL:
http://www.engineering-4e.com

The above URL provides lots of free online and downloadable e-material and e-solutions on energy conversion.