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Brayton Cycle (Gas Turbine) for Propulsion Application Analysis

by

Engineering Software

Course Category: Engineers

Course Level: Intermediate

Credit: 1 Hour

Brayton Cycle (Gas Turbine) for Propulsion Application Analysis

Course Description

The ideal cycle for a simple gas turbine is the Brayton Cycle, also called the Joule Cycle. In this one hour course, the open, simple Brayton Cycle used for stationary power generation is considered providing thrust instead of power output. In order to keep the scope of the thrust analysis simple, the working fluid exiting gas turbine expands to the atmospheric conditions -- final working fluid exit pressure is equal to the ambient pressure.

The Brayton 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 Brayton Cycle is presented in a T - s diagram and its major performance trends (specific propulsion output and propulsion output) are plotted in a few figures as a function of compression ratio, gas turbine inlet temperature and working fluid mass flow rate. 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 Brayton Cycle, its components, T - s diagram, operation and major performance trends.

This course includes a multiple choice quiz at the end.

Brayton Cycle (Gas Turbine) for Propulsion Application 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 Brayton Cycle (Gas Turbine) and its T - s diagram
- Be familiar with the Brayton Cycle operation
- Understand general Brayton Cycle performance trends

Brayton Cycle (Gas Turbine) for Propulsion Application Analysis

Introduction

Over the years, gas turbine has become the premier propulsion generation system. Gas turbines are compact, lightweight, easy to operate and come in sizes ranging from several hundred kilowatts to hundreds of megawatts. Gas turbines require relatively low capital investment, have high operating flexibility, high thermal efficiency and can be used for various industrial applications. Gas turbines can help provide reliable propulsion to meet the future demand using both high and low heat content fuels, with low emissions.

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Brayton Cycle (Gas Turbine) for Propulsion Application

This section provides a Brayton Cycle analysis when the working fluid is air.

Analysis

In the presented Brayton 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.

A gas turbine is a heat engine that uses a high temperature, high pressure gas as the working fluid. Combustion of a fuel in air is usually used to produce the needed temperatures and pressures in the gas turbine, which is why gas turbines are often referred to as combustion turbines. Expansion of the high temperature, high pressure working fluid takes place in the gas turbine. The gas turbine shaft rotation drives an electric generator and a compressor for the working fluid, air, used in the gas turbine combustor. Many gas turbines also use a heat exchanger called a recouperator to impart turbine exhaust heat into the combustor's air/fuel mixture. Gas turbines produce high quality heat that can be used to generate steam for combined heat and power and combined-cycle applications, significantly enhancing efficiency.

Air is compressed, isentropically, along line 1-2 by a compressor and it enters a combustor. At a constant pressure, combustion takes place (fuel is added to the combustor and the air temperature raises) and/or heat gets added to air. High temperature air exits the combustor at point 3. Then air enters a gas turbine where an isentropic expansion occurs, producing power. Air exits the gas turbine at point 4. It should be mentioned that air at point 1 enters the compressor and the cycle is repeated.

Figure 1 presents a Brayton Cycle schematic layout.

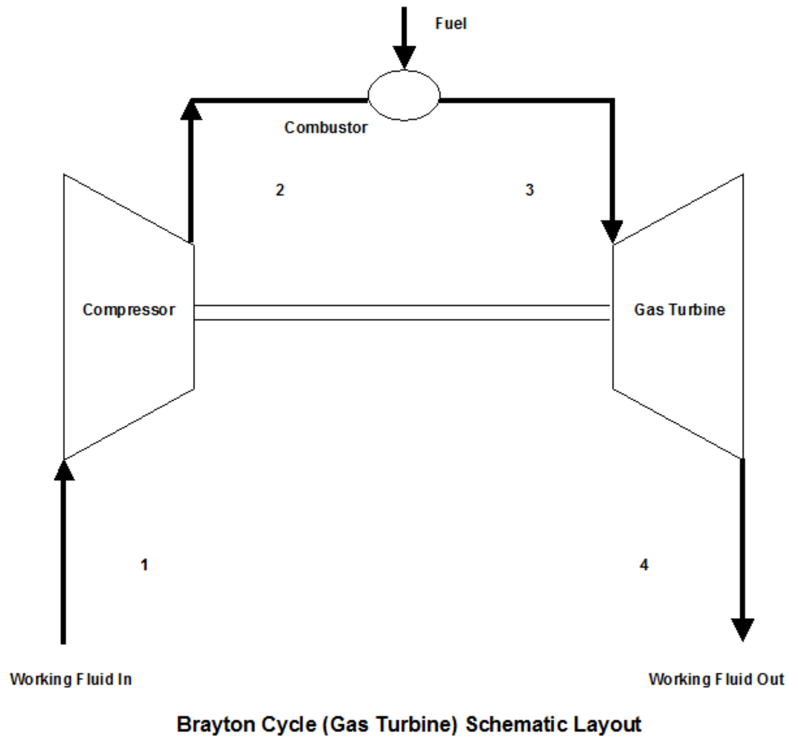

Figure 1 - Brayton Cycle Schematic Layout

Figure 2 presents a Brayton Cycle temperature vs entropy diagram.

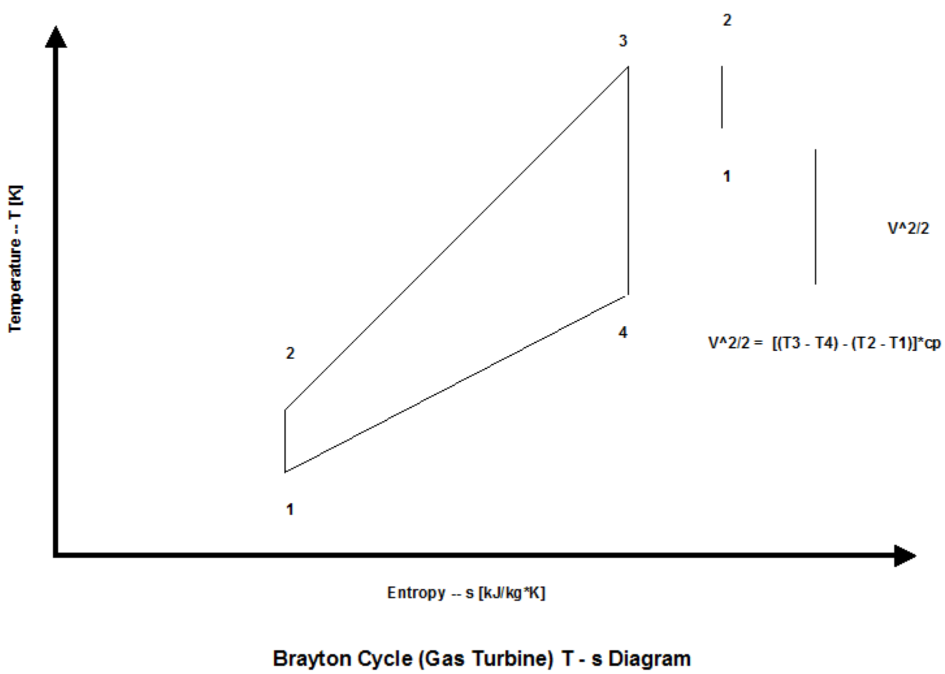

Figure 2 - Brayton Cycle Temperature vs Entropy Diagram

In order to keep the scope of thrust analysis simple, air exiting turbine expands to the atmospheric conditions - exit pressure is equal to the ambient pressure ($p_1 = p_4$).

It should be pointed out that this material deals with the open Brayton Cycle. The way how the T - s diagram is presented, it describes a closed Brayton Cycle -- this would require a heat exchanger after point 4 where the working fluid would be cooled down to point 1 and the cycle repeats. Therefore, the T - s diagram is presented as a closed Brayton Cycle to allow easier understanding and derivation of the Brayton Cycle thermal efficiency -- heat addition and heat rejection.

The gas turbine and compressor are connected by shaft so the considerable amount of work done on the gas turbine is used to power the compressor.

Propulsion is provided by the difference of gas turbine expansion minus the compressor power requirements:

Thrust = vm

where

Thrust - propulsion force [N]

$v = (2c_p((T_3 - T_4) - (T_2 - T_1)))^{1/2}$

v - working fluid velocity [m/s]

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

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

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

It can be noticed from the T - s diagram that the work done on the gas turbine is greater than the work necessary to power the compressor -- constant pressure lines in the T - s diagram diverge by going to the right side (entropy wise).

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:

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

or

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

where

η - thermal efficiency [/]

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

w_t - expansion specific power output [kJ/kg]

w_c - compression specific power input [kJ/kg]

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

W_t - 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]

r_p - compression ratio [/]

For isentropic compression and expansion:

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

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

Knowing that

$p_3/p_4 = p_2/p_1$

where

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

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

$T_3/T_4 = T_2/T_1$

or

$T_3/T_2 = T_4/T_1$

Therefore, after some mathematical operations the thermal efficiency is:

$\eta = 1 - T_1/T_2 = 1 - T_4/T_3$

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

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

where

$r_p = p_2/p_1$

Figure 3 presents the Brayton 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].

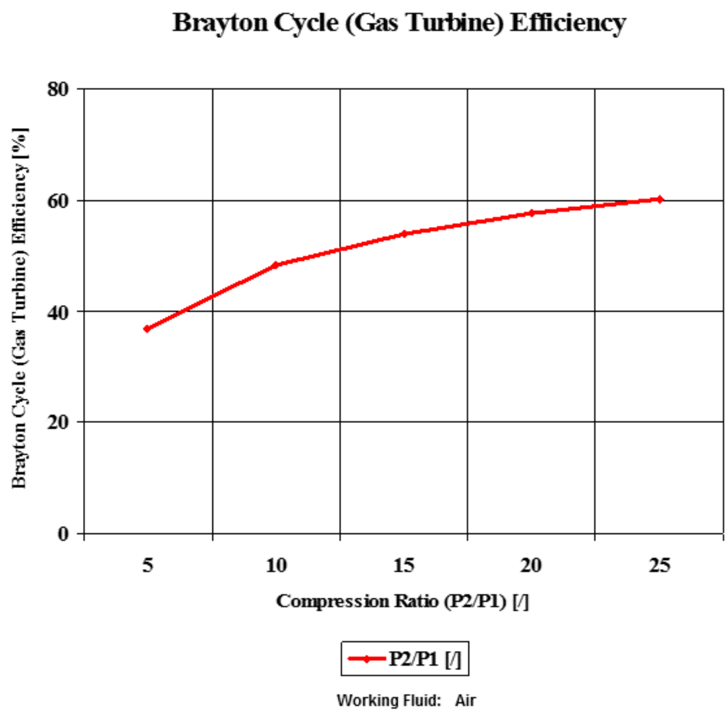

Figure 3 - Brayton Cycle Efficiency

Here, two general performance trends are considered. First, impact of the gas turbine inlet temperature and compression ratio on the Brayton Cycle specific propulsion output and second, impact of the working fluid mass flow rate for a fixed gas turbine inlet temperature on the Brayton Cycle propulsion output.

Figure 4 presents the results of the first performance trend, while Figure 5 presents the results of the second trend.

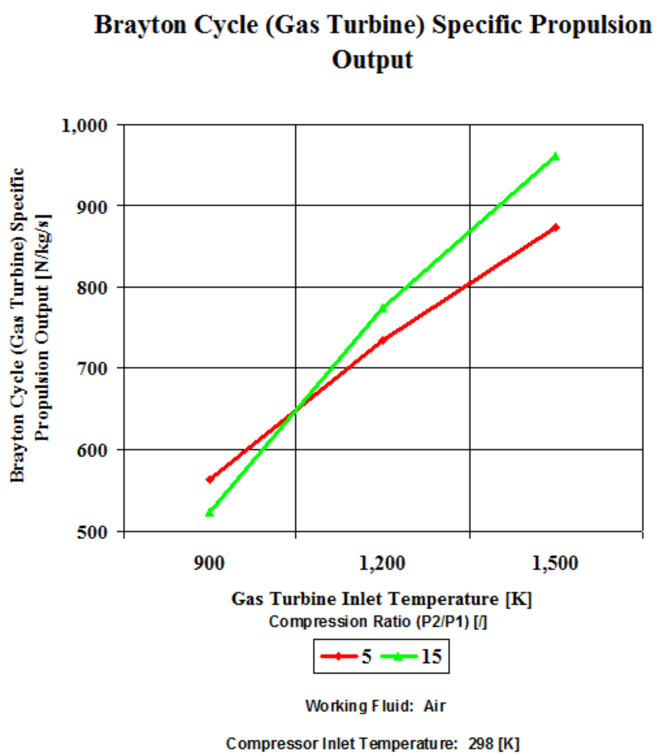

Figure 4 - Brayton Cycle Specific Propulsion Output

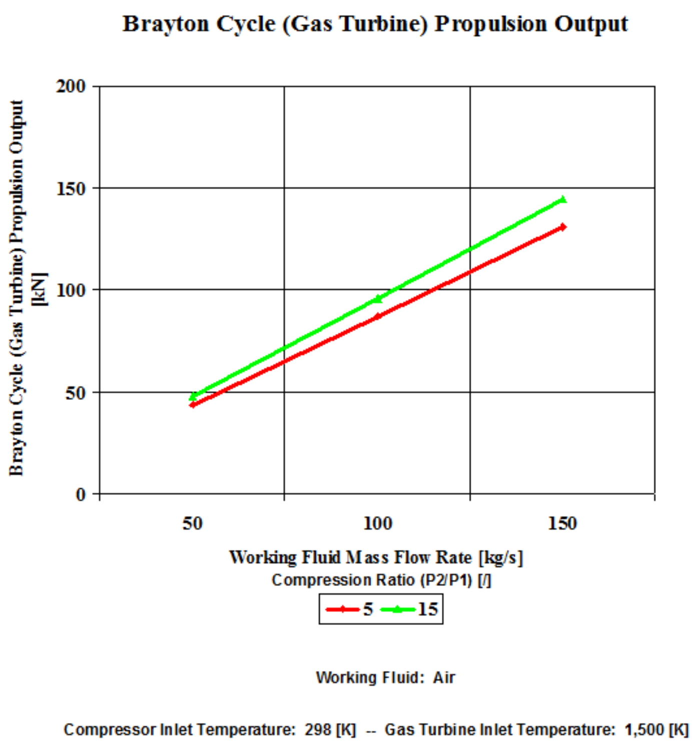

Figure 5 - Brayton Cycle Propulsion Output

One can notice that the Brayton Cycle efficiency increases with an increase in the compression ratio values. One can notice that the Brayton Cycle specific propulsion output increases with an increase in the gas turbine inlet temperature. Furthermore, the increase is greater for the higher compression ratio values.

One can notice that the Brayton Cycle propulsion output increases with an increase in the working fluid mass flow rate for a fixed gas turbine inlet temperature. The increase is greater for the higher compression ratio values.

Assumptions

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

Governing Equations

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

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

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

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

$$\varkappa = c_p/c_v$$

$$c_p - c_v = R$$

$$pv = RT$$

$$w = q_h - q_l$$

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

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

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

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

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

$$r_p = p_2/p_1$$

$$v^2/2 = c_p((T_3 - T_2) - (T_4 - T_1))$$

$$v = (2c_p((T_3 - T_2) - (T_4 - T_1)))^{1/2}$$

$$\text{Thrust} = vm$$

Brayton Cycle (Gas Turbine) for Propulsion Application Analysis

Input Data

T_1 = 298 [K]

p_1 = 1 [atm]

T_3 = 900, 1,200 and 1,500 [K]

p_3 = 5, 10, 15, 20 and 25 [atm]

R = 0.2867 [kJ/kg*K]

c_p = 1.004 [kJ/kg*K]

$\varkappa$ = 1.4 [/]

m = 50, 100 and 150 [kg/s]

Results

Brayton Cycle Efficiency vs Compression Ratio

Compression Ratio [/]	**Brayton Cycle Efficiency [%]**
5	36.92
10	48.22
15	53.87
20	57.53
25	60.16

Specific Propulsion Output vs Compression Ratio for a few Gas Turbine Inlet Temperature Values

Specific Propulsion [N/kg/s]	**Gas Turbine Inlet Temperature [K]**		
Compression Ratio [/]	900	1,200	1,500
5	563	734	872
15	524	774	961

Propulsion Output vs Compression Ratio
for a few Mass Flow Rates
Gas Turbine Inlet Temperature = 1,500 [K]

Propulsion [kN]	**Mass Flow Rate [kg/s]**		
Compression Ratio [/]	50	100	150
5	43.61	87.23	130.85
15	48.06	96.11	144.17

Conclusions

The Brayton Cycle efficiency depends on the compression ratio and working fluid properties. The efficiency increases with an increase in the compression ratio values. Also, the efficiency increases with the higher value for $\varkappa$, which is a ratio of gas specific heat values (c_p/c_v).

The Brayton Cycle specific propulsion output increases with an increase in the gas turbine inlet temperature. Furthermore, the increase is greater for the higher compression ratio values. The Brayton Cycle propulsion output increases with an increase in the working fluid mass flow rate for a fixed gas turbine inlet temperature. The increase 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:
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