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Carnot Cycle Analysis

by

Engineering Software

Course Category: Engineers

Course Level: Intermediate

Credit: 1 Hour

Course Description

The Carnot Cycle is an ideal simple cycle consisting of isentropic compression and expansion and isothermal heat addition and heat rejection. The Carnot Cycle thermal efficiency determines the highest thermal efficiency that a heat engine can achieve. In this one hour course, the closed, simple Carnot Cycle used for stationary power generation is considered.

The Carnot 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 Carnot Cycle is presented in a T - s diagram and its major performance trends are plotted in a few figures as a function of heat addition and heat rejection temperature values.

In this course, the student gets familiar with the Carnot Cycle, its components, T - s diagram, operation and major performance trends.

This course includes a multiple choice quiz at the end.

Carnot 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 Carnot Cycle and its T - s diagram
- Be familiar with the Carnot Cycle operation
- Understand general Carnot Cycle performance trends

Carnot Cycle Analysis

Introduction

The Carnot Cycle is an ideal simple cycle consisting of isentropic compression and expansion and isothermal heat addition and heat rejection. The Carnot Cycle thermal efficiency determines the highest thermal efficiency that a heat engine can achieve.

Therefore, for a heat engine, the maximum thermal efficiency is determined by the Carnot Cycle efficiency and it is not dependent on the physical properties of the working fluid.

The Carnot Cycle efficiency can be very helpful in when studying the impact of ambient temperature, on the installed power generation capacity and available electric power generation -- what happens with the amount of available electric power generation capacity when the ambient temperature changes one way or the other.

Carnot Cycle Analysis

Table of Contents

Carnot Cycle

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

Analysis

In the presented Carnot 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 compressor at point 1 and it exits the compressor at point 2. Isentropic compression is considered with no entropy change. Air enters a heat exchanger -- heat addition -- at point 2 and it exits the heat exchanger at point 3. At a constant temperature, heat addition takes place. Air enters a turbine at point 3 and it exits the turbine at point 4. Isentropic expansion is considered with no entropy change. Air enters a heat exchanger -- heat rejection -- at point 4, and exits the heat exchanger at point 1. At a constant temperature, heat rejection takes place. It should be mentioned that air at point 1 enters the compressor and the cycle is repeated.

Figure 1 presents a Carnot Cycle schematic layout.

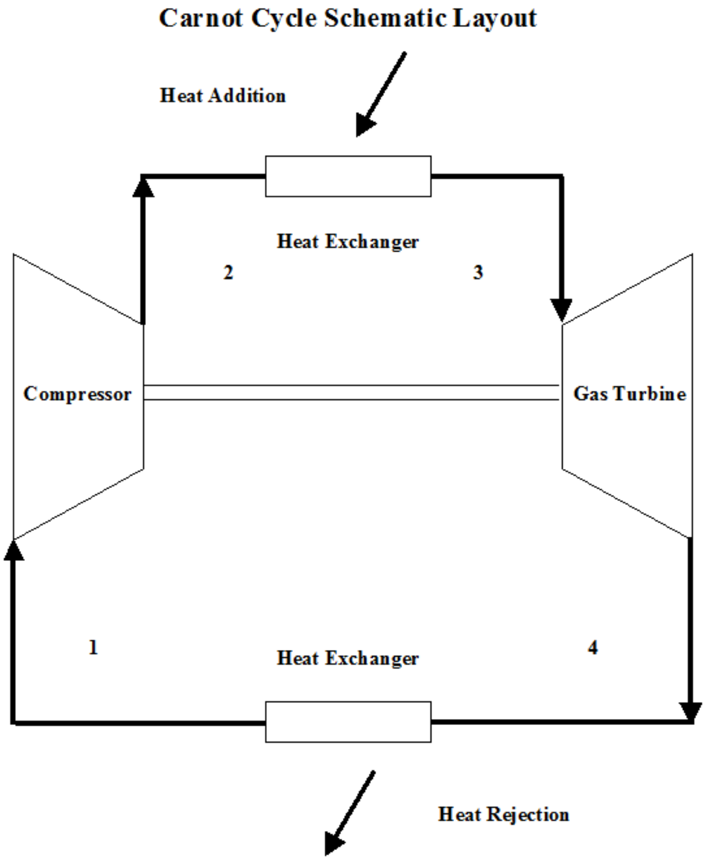

Figure 1 - Carnot Cycle Schematic Layout

Figure 2 presents a Carnot Cycle temperature vs entropy diagram.

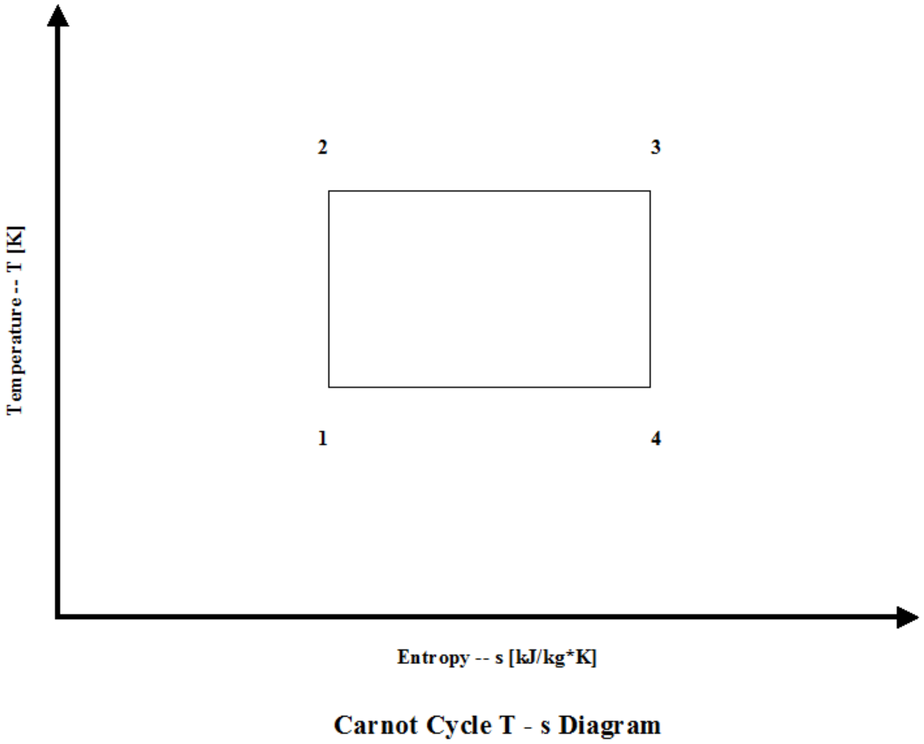

Figure 2 - Carnot Cycle Temperature vs Entropy Diagram

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:

$\eta = w/q_h = (w_t - w_c)/q_h = (q_h - q_l)/q_h = 1 - q_l/q_h = 1 - T_1\Delta s/T_2\Delta s = 1 - T_1/T_2 = 1 - T_R/T_A$

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]

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

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

Δs - entropy change during heat addition and heat rejection

T_A - temperature during heat addition

T_R - temperature during heat rejection

T_1 - compressor inlet temperature

T_2 - compressor outlet temperature

T_3 - turbine inlet temperature

T_4 - turbine outlet temperature

For isentropic compressor and turbine

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

and

For isentropic compression and expansion:

$T_2/T_1 = (p_2/p_1)^{(\varkappa-1)/\varkappa} = T_3/T_4 = (p_3/p_4)^{(\varkappa-1)/\varkappa}$

and

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

Again, it follows that

$\eta = 1 - T_1/T_2 = 1 - T_R/T_A$

The Carnot Cycle efficiency is not dependent on the working fluid properties.

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

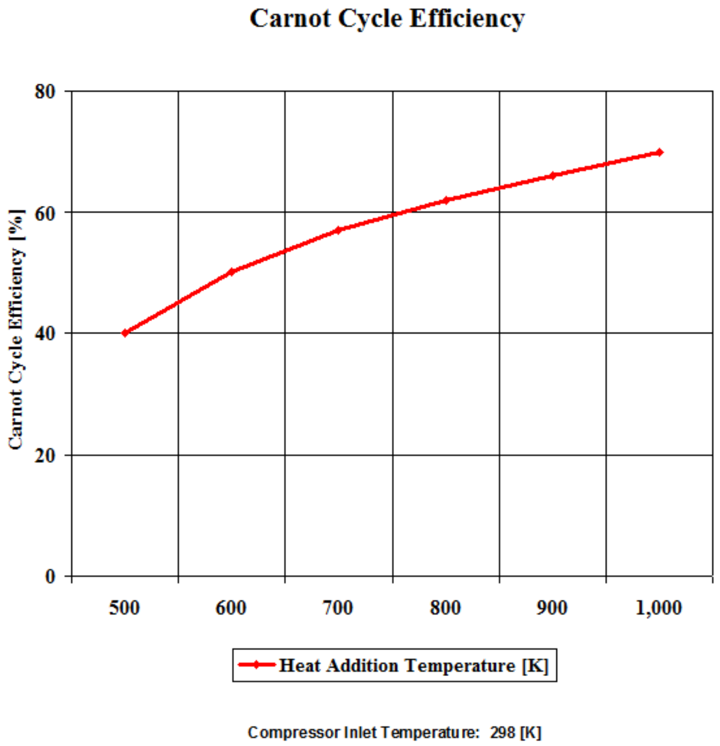

Figure 3 - Carnot Cycle Efficiency vs Heat Addition Temperature

Figure 4 presents the Carnot Cycle efficiency as a function of the heat rejection temperature. It should be noted that the turbine inlet temperature is at 800 [K].

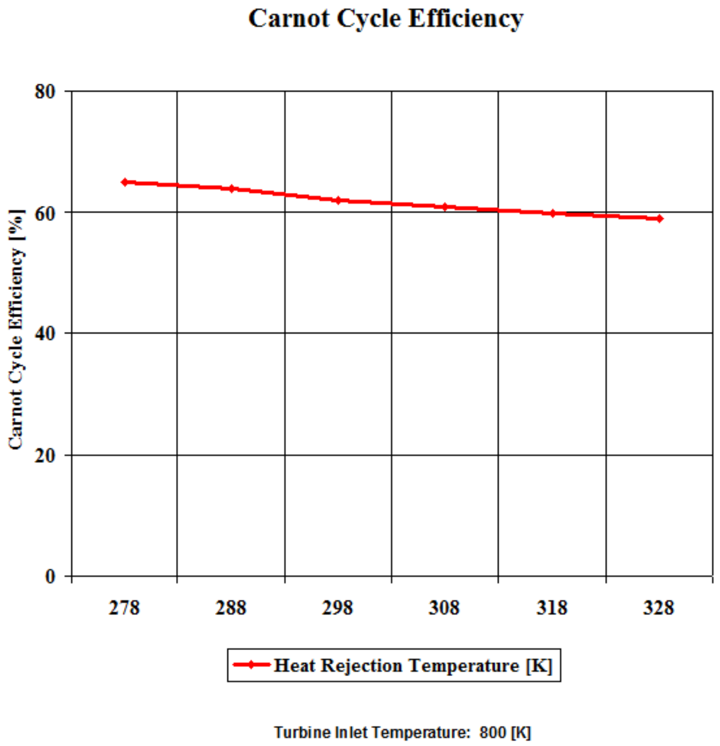

Figure 4 - Carnot Cycle Efficiency vs Heat Rejection Temperature

One can notice that the Carnot Cycle efficiency increases with an increase in the heat addition temperature when the heat rejection temperature does not change at all. One can notice that the Carnot Cycle efficiency decreases with an increase in the heat rejection temperature when the heat addition temperature does not change at all.

Assumptions

Working fluid is air. There is no friction. Compression and expansion are isentropic -- there is no entropy change. During heat addition and heat rejection, the air temperature does not change. Ideal gas state equation is valid -- pv = RT. Air behaves as a perfect gas -- specific heat has a constant value.

Governing Equations

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

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

$$\varkappa = c_p/c_v$$

$$pv = RT$$

$$\eta = 1 - T_1/T_2 = 1 - T_R/T_A$$

Input Data

$T_1 = 298$ [K]

$p_1 = 1$ [atm]

$c_p = 1.004$ [kJ/kg*K]

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

Results

Carnot Cycle Efficiency vs Heat Addition Temperature
Heat Rejection Temperature is 298 [K]

Heat Addition Temperature [K]	Carnot Cycle Efficiency [%]
500	40.40
600	50.33
700	57.43
800	62.75
900	66.89
1,000	70.22

Carnot Cycle Efficiency vs Heat Rejection Temperature
Heat Addition Temperature is 800 [K]

Heat Rejection Temperature [K]	Carnot Cycle Efficiency [%]
278	65.25
288	64.00
298	62.75
308	61.50
318	60.25
328	59.00

Conclusions

The Carnot Cycle efficiency increases with an increase in the heat addition temperature when the heat rejection temperature does not change at all. Furthermore, the Carnot Cycle efficiency decreases with an increase in the heat rejection temperature when the heat addition temperature does not change at all.

The Carnot Cycle efficiency is not dependent on the working fluid properties.

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.