Numerical analysis of a turbocompounded Diesel – Brayton combined cycle

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Abstract

This paper presents the numerical analysis of a proposed turbocompounded diesel Brayton cycle, where the Brayton cycle is the bottoming cycle. The energy from exhaust gases of diesel engines is used to drive the compressor in the proposed cycle thereby improving the efficiency of the gas turbine used in the bottoming cycle. Numerical analysis was carried out using basic thermodynamic equations with the the help of a MATLAB. The results show that overall efficiency of the cycle drops with increasing turbine inlet temperature and increases with increasing pressure ratios and Compression ratios. The advantages of using the proposed cycle with supercharged engines is also illustrated.

1 Introduction

Diesel engines have become very popular over the past decade because of their superior thermal efficiency. However Diesel engines remain heavy in spite of significant headway made in power augmentation technologies like supercharging and turbo charging. Micro gas turbines are also becoming candidates for future power plants because of their superior power to weight ratio. Micro GT efficiencies however remain very low because of low pressure ratios. The availability of large amounts of exhaust gas energy from a diesel engine presents an opportunity wherein it can be utilized to perform the compression operation for a Micro gas turbine. This can improve the thermal efficiency of the gas turbine significantly because a majority of the work extracted by the turbine in a gas turbine is spent to compress air. The combined turbocompounded Diesel –Brayton reheated cycle can result in increased power output of without significant increase in weight.

2 Nomenclature

C_p/C_v	Specific heat (KJ.Kg^{-1}K^{-1}
GT	Gas turbine
T	Temperature (K)
m	Mass flow rate (Kg/s)
W_d	Work (KW)
Q	Heat added/removed (KW)
η	Efficiency (%)
TIT	Turbine Inlet temperature
PR	Pressure ratio
CR	Compression ratio

Subscripts

c	compressor
t	turbine
d	diesel cycle
g	gas turbine cycle

in	input
out	output
sc	Supercharger

3 Trends

Trends in increasing Gas turbine thermal efficiencies have leaned heavily towards increasing operating temperatures and pressure ratios as both have been achievable with advanced materials and axial compressors respectively. Micro GTs commonly employ single stage centrifugal compressors and are hence not capable of achieving very high pressure ratios. Thermal efficiencies of non-recuperated Micro gas turbines are hence in the region of 15-16 % [2]. This makes them unattractive for power generation. Also, the Compressor work Wc exceeds 50% of the work generated by the turbine Wt. Energy from exhaust gases of reciprocating engines are commonly used to compress charge air. Hence it is quite clear that there is existing technology to harness exhaust gas energy for compressing air. A combined cycle arrangement as proposed presents even greater advantages for mechanically supercharged engines wherein the exhaust energy is wasted.

4 Cycle configuration

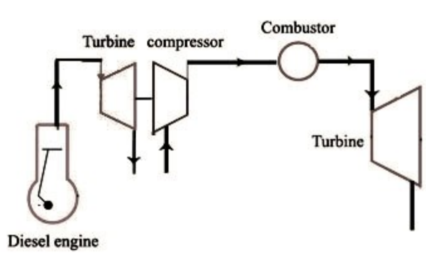

Fig. 1 Schematic diagram

The configuration of the turbocompounded Diesel Brayton cycle is illustrated in the sketch below. The arrangements comprises of a turbine which is assumed to be placed close enough to the cylinders of the diesel engine so as to eliminate any energy losses. A combustor is provided for burning fuel and a turbine is placed downstream of the combustor.

The diesel engine's exhaust as shown is made to flow through a turbine which is coupled to a compressor. This assembly is similar to a turbocharger found on most diesel engines. The hot gases form the combustor flow through a second turbine which is coupled to the load through a gearbox.

The energy available from exhaust gases is illustrated in figure 2. The shaded region denotes the blow down energy available for extraction by the turbine. The work available is given by the area under 4-5-1 in the P-v diagram and is equal to compression work of the turbine. It is given by

$$W_c = m.C_p(T_4 - T_5) = W_t \qquad (1)$$

5 Cycle analysis

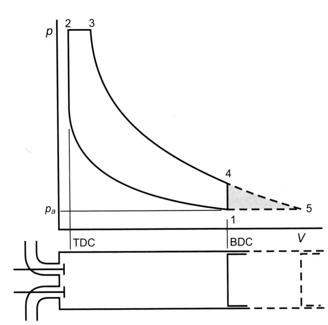

Fig. 2 Available energy from exhaust

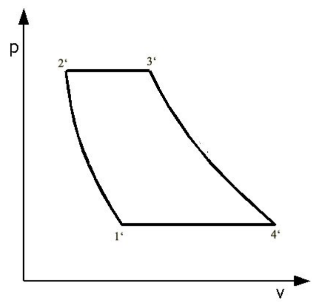

Fig. 3 P-V diagram of Brayton cycle

The work done in the diesel cycle is given by the equation

$$Q_{ind} - Q_{outd} = W_{dd} \qquad (2)$$

where

$$Q_{outd} = m.C_v(T_4 - T_1) \qquad (3)$$

$$Q_{ind} = m.C_p(T_3 - T_2) \qquad (4)$$

The work done by the gas turbine is given by the equation

$$W_{dg} = m'.C_p(T'_3 - T'_4) \qquad (5)$$

And heat input in the combustor is given by

$$Q_{ing} = m'.C_p(T'_3 - T'_2) \qquad (6)$$

The overall efficiency is hence given by

$$\eta = \frac{W_{dt} - W_{dc} + W_{dd} + W_{dg}}{Q_{ind} + Q_{ing}} \qquad (7)$$

The mathematical modeling of various components of the cycle was done with standard equations found in [1]. Results are obtained for input data tabulated below using MATLAB.

Ambient conditions	T_1, T_1' =303K $P_1, P_{1'}$ =1.013 bar
Compressor	75% Isentropic efficiency
Turbine	85% Isentropic efficiency
Cut off ratio V_3/V_2	2.5

5 Results

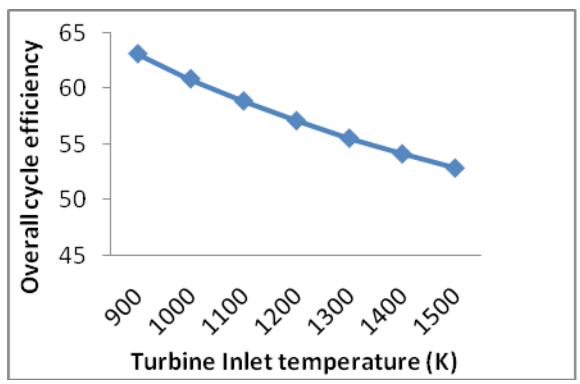

Figure 4 TIT Vs overall efficiency, PR = 4, CR=14

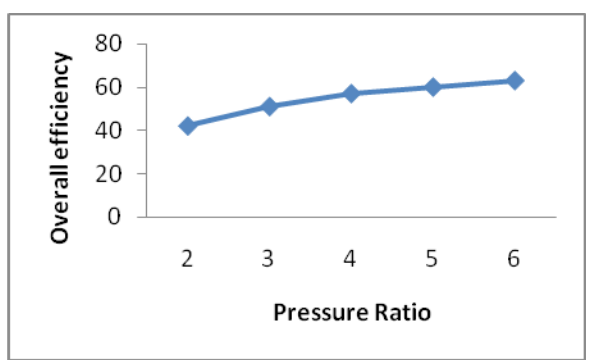

Figure 5 PR Vs Overall efficiency, CR=14 and TIT = 1200K

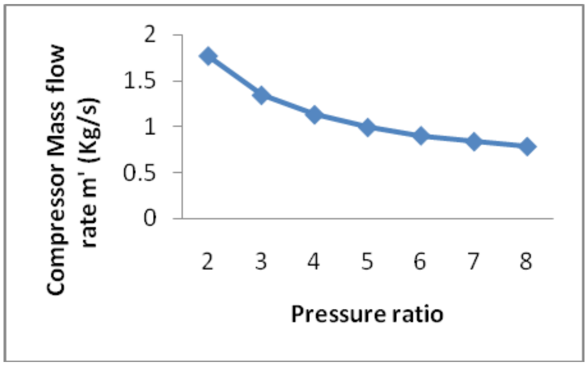

Figure 6 PR vs Mass flow rate, CR=14 and TIT = 1200K

Results show that the efficiency of the cycle increases with increase in pressure ratio of the gas turbine. However an increase in pressure ratio results in a decrease in the mass flow rate of the compressor, this is shown in fig 5 and 6. Increase in the Turbine inlet temperature however results in a decrease in overall efficiency.

6 Supercharged diesel engines

Supercharged diesel engines use a mechanically driven compressor to compress air supplied to the diesel engine. This improves power output and consumes power to compress air from the engine.

Hence the overall efficiency for supercharged engines is given by

$$\eta = \frac{W_{dt} - W_{dc} + W_{dd} - W_{sc} + W_{dg}}{Q_{ind} + Q_{ing}}$$

Though the efficiencies achieved are lower, the power output of both the diesel engine and gas turbine are increase as a consequence of increased mass flow. Results showed that for a boost pressure of 300 Kpa, the power output was 1759 KW for 1Kg/s mass flow through the diesel engine as against 1137 KW for a normally aspirated engine.

7 Conclusion

Hence the turbocompounded diesel Brayton cycle presents an attractive option for normally aspirated and supercharged diesel engines to recover waste energy from exhaust gases and augment power with the help of a gas turbine without major additions in weight due to the light weight characteristics of a gas turbine.

References

[1] Van Wylen, Sonntag and Borgnakke. *'Fundamentals of classical thermodynamics'* , Fourth edition, John Wiley and sons, 1994.

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[3] Claire Soares, *'Micro gas turbines'* ,Elsevier, 2007