PERFORMANCE OF GAS TURBINE WITH CARBON DIOXIDE AS THE WORKING FLUID

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Abstract. *The fulfillment of the increasing demand of electrical power associated with the endless search for new power-plants that are environmentally friendly places a huge burden on the professionals to develop new electricity sources. In the case of thermal power-plants, the elimination of emissions that contribute to greenhouse effect, namely carbon dioxide, has received special attention during the past few years. The actual development of the thermal power-plants technology cannot eliminate the use of gas turbines as prime movers, because the best thermal efficiencies are only achieved with those engines, especially when used in combined cycles. Therefore, the elimination of the carbon dioxide generated by a thermal power-plant requires the elimination of the carbon dioxide generated by the gas turbine. From several means to reduce the carbon dioxide emissions from a gas turbine, most require the use of the carbon dioxide as working fluid, that is, the carbon dioxide would replace the air, the usual working fluid. This work analyses gas turbine performance when carbon dioxide is used as working fluid both in a gas turbine that has been designed to work with air and would work on carbon dioxide and in a gas turbine especially designed to work with carbon dioxide. The conclusion is that carbon dioxide always causes performance degradation, so that the mitigation of the performance decrease requires higher pressure ratio. As a consequence of higher pressures new design paradigm is implied, mainly the related to the compressor design.*

Keywords*: Gas Turbine Performance, Carbon Dioxide, Power-plants Emissions, Working Fluid.*

1. Introduction

Storage of the CO_2 generated during the operation of a gas turbine requires relatively pure high pressure gas due to:

a. Concentrated CO_2 implies cheaper transportation;
b. The capacity of the storage tank is better utilized;
c. Impurities may be dangerous for the operation of the storage system or cause adverse environment effects.

For the production of CO_2 at the required conditions, the gas turbine cycles must be modified. Several configurations suit those requirements. Most of those configurations imply the utilization of semi-closed cycles, where the gas turbine working fluid is CO_2 (Ulizar, 1998).

Sketch of a gas turbine operating under a semi-close cycle is shown in Fig. 1. Heat addition (combustion) is achieved by the injection of oxygen and fuel in the combustion chamber. To keep the mass flow through the engine, water is extracted at the cooler exit and CO_2 is removed, at high pressure, at the compressor outlet. It is seen that both compressor and turbine run on a gas with very high CO_2 content.

In a semi-closed cycle as depictured in Fig. 1, two additional objectives may be attained (Ulizar and Pilidis, 1997): a) NO_x emission reduction, since the nitrogen is not introduced into the combustion chamber; and b) a fuel largely available as, for example, gas from coal, may be used.

The performance of a CO_2 cycle, as well as the performance of the engine components, mainly the compressor and turbine, must be analyzed in order to clarify the influence of such a working fluid in the overall cycle performance.

For the analysis that has been carried out in this study, the following steps were taken:

a. Analysis of the characteristics as far as CO_2 is concerned as a thermal machine working fluid ;
b. Ideal cycle analysis of a gas turbine working on CO_2 compared to the machine using dry air;
c. Components performance evaluation (compressor and turbine) that had been designed to run on dry air and would be running on CO_2;
d. Design point analysis of an actual gas turbine cycle using CO_2 as working fluid, compared with the same engine operating on dry air;
e. Off-design performance analysis of gas turbines that had been designed for dry air and would operate on CO_2.

The analyses of steps c, d and e have been carried out using the DESTUR Program (Alves, 1994 and Alves, 2003).

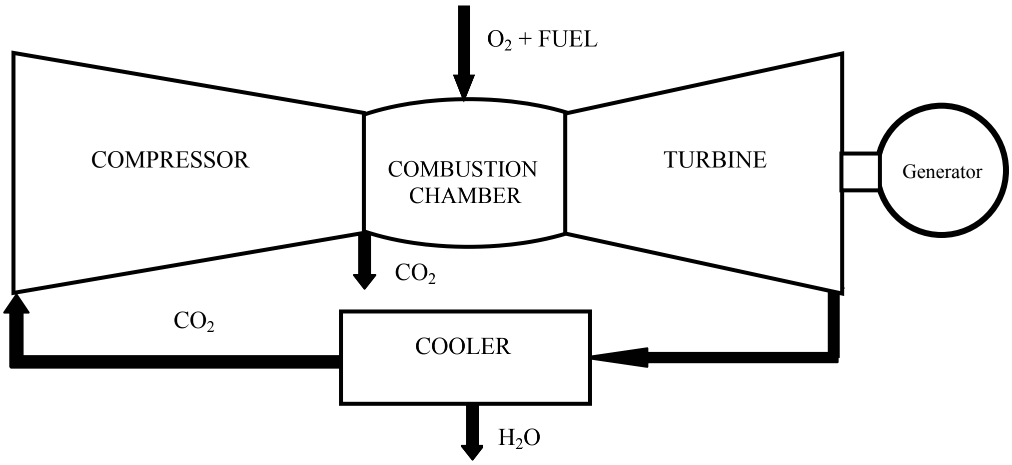

Figure 1- Sketch of a semi-closed cycle gas turbine

2. Working fluid characteristics

The working fluid is not, in fact, pure CO_2, since the working fluid expanding through the turbine contains water vapor generated in the combustion chamber, as well as a small amount of argon from the swallowed air. It is cheaper to keep the argon with the oxygen flow, which is used in the combustion chamber, than isolate in an air fraction process to isolate the oxygen. The amounts of water vapor and argon do not significantly alter the engine performance and do not modify the conclusions drawn from this study.

For the present study, the required working fluid properties are enthalpy, entropy, constant pressure specific heat and the specific heats ratio. It is assumed that the fluid is an ideal gas, so that these properties vary with temperature only; therefore, they are not influenced by pressure, as shown in Fig. 2: constant pressure specific heat (c_p), specific heats ratio (γ) for air and CO_2.

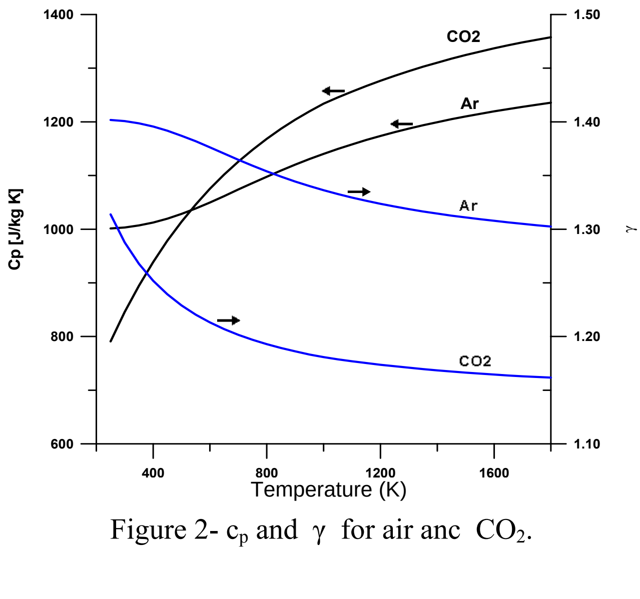

Figure 2- c_p and γ for air anc CO_2.

3. Ideal CO_2 Brayton Cycle

The detailed analysis of an ideal Brayton cycle is the subject of many textbooks (Cohen, Rogers and Saravanamuttoo, 2001). The relevant expressions for the calculation of cycle efficiency and specific work output are, respectively,

$$\eta = 1 - \left(\frac{1}{r}\right)^{\frac{\gamma-1}{\gamma}} \tag{1}$$

$$\frac{W}{c_p T_1} = t\left(1 - \frac{1}{r^{\frac{\gamma-1}{\gamma}}}\right) - \left(r^{\frac{\gamma-1}{\gamma}} - 1\right) \tag{2}$$

where:

η – cycle efficiency
r – compressor pressure ratio
t – maximum to ambient temperatures ratio (T_3 / T_1)
T_1 – ambient temperature
c_p – working fluid constant pressure specific heat
γ – specific heats ratio
W – useful work
$\dfrac{W}{c_p T_1}$ – specific work output

For the average cycle values of

$\gamma_{air} = 1.40$ and $\gamma_{CO_2} = 1.29$

Eq. (1) and Eq. (2) give the influence of pressure ratio and maximum cycle temperature on the cycle efficiency and specific work output, respectively. The cycle efficiency, as function of pressure ratio, is shown in Fig. 3; the specific work output, as function of pressure ratio and maximum cycle temperature, is shown in Fig. 4.

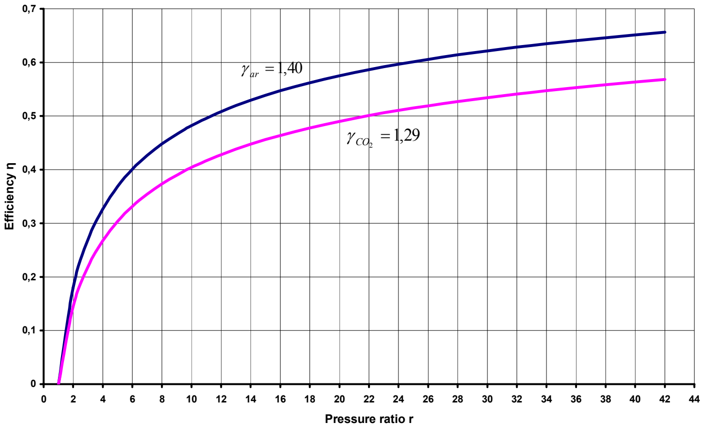

Figure 3- Influence of Pressure Ratio on cycle Efficiency

The following comments may be appropriate at this moment:

a. From the equation for the ideal cycle efficiency, given the pressure ratio it is possible to verify that the higher the fluid specific heats ratio the greater the efficiency. Since the CO_2 specific heat is lower than the specific heats ratio for the air, the CO_2 cycle is less efficient.
b. To achieve the same efficiency of an air cycle, the CO_2 cycle requires higher pressure ratio (Ulizar and Pilidis, 1997).

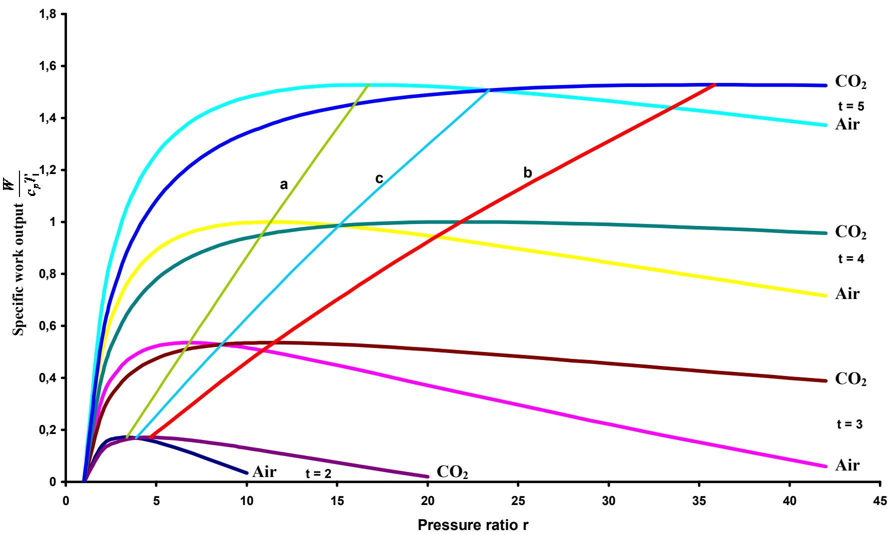

Figure 4- Influence of Pressure Ratio on the Specific work output

The following comments may also be appropriate at this moment:

a. Whether or not the specific work output for the CO2 cycle is higher than the air cycle will depend on the pressure ratio. Line c, superimposed to curves of Figure 4, divides the specific work output-pressure ratio domain into 2 regions: given the ratio t, to the right of c the specific work output is greatest for the CO2 cycle; to the left of c the opposite happens;

b. On line c, for a given t and at the chosen pressure ratio, the specific work outputs are equal both for CO_2 and air. The equation for line c is:

$$r = \sqrt[a]{t} \quad \text{and} \quad a = 2 - \frac{1}{\gamma_{CO_2}} - \frac{1}{\gamma_{Ar}} \therefore \frac{W}{c_p T_1} = \left(r^{\frac{\gamma_{CO_2}-1}{\gamma_{CO_2}}} - 1 \right) - \left(r^{\frac{\gamma_{Ar}-1}{\gamma_{Ar}}} - 1 \right) \qquad (3)$$

c. As a rule, the specific work output in a CO_2 gas turbine cycle will be higher than the specific work output of an air cycle at higher pressure ratios;

d. For the maximum specific work output, that is attained at the optimum pressure ratio $r_{optimum}$,

$$r_{optimum} = (t)^{\frac{\gamma}{2(\gamma-1)}} \quad \text{and} \quad \left(\frac{W}{c_p T_1} \right)_{máx} = \left[(r_{ótimo})^{\frac{\gamma}{(\gamma-1)}} - 1 \right]^2 = \left(\sqrt{t} - 1 \right)^2 \qquad (4)$$

Therefore, the value of $r_{optimum}$ is greatest with decreasing γ , but the value for the maximum specific work output is always the same for a fixed value of ***t***, independently of the working fluid, that is, independent of γ .

Line ***a*** on Fig. 4 pass through the points of maximum specific work output for the air cycle, whereas line ***b*** is drawn through the points of maximum specific work output for the CO_2 cycle.

4. Components performance

<u>Compressor</u>

Figure 5 e Figure 6 show the change of operating points of a compressor originally designed to pump air and is used to pump CO_2. It can be seen that, for a fixed compressor rotational speed, mass flow increases approximately 50%, pressure ratio 40% higher, but an important decrease of compressor isentropic efficiency, from 90% down to 66,4%. Due to such changes, the power to drive the compressor may go up 60%. As far as the compressor stability margin, it is seen that it decreases from 0,14 to 0,10, what is a disadvantage of working with CO_2.

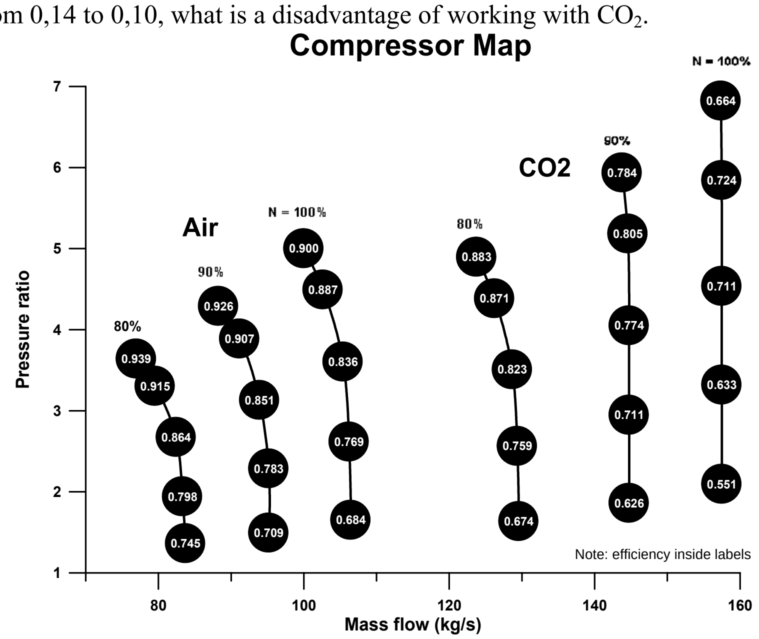

Figure 5 – Compressor Performance curves – Pressure ratio X Mass flow

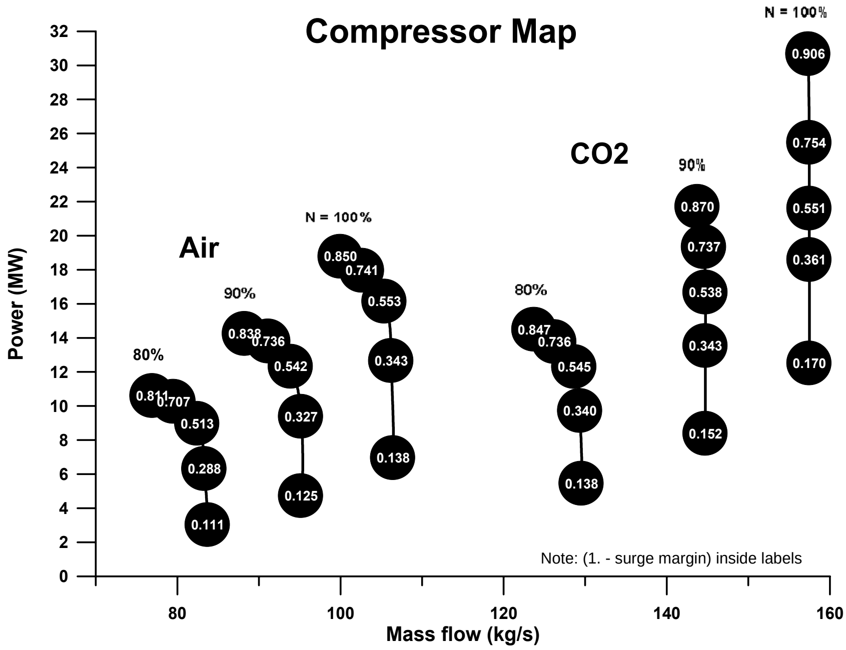

Figure 6 – Compressor Performance curves - Power X Mass flow.

Turbine

Figure 7 e Figure 8 show performance curves of air and CO_2 working fluids being used in a turbine designed to work on air. It is seen that, for the same expansion ratio, the power decreases when the working fluid is CO_2. Increase in the turbine efficiency may be as high as 10%. Such changes occur together with increase in the mass flow of about 20%. Decrease in the power produced by the turbine, despite higher mass flow and efficiency, is due to the fact that, for a specified expansion ratio, the temperature difference across the turbine decreases as γ_{CO_2} is lower.

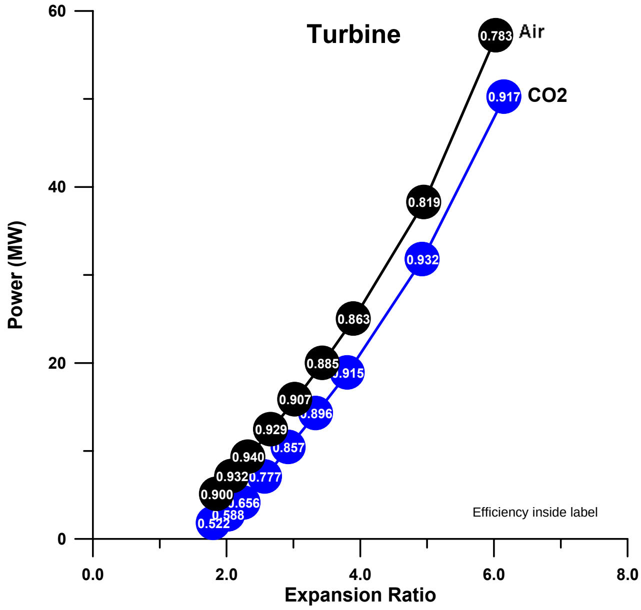

Figure 7 Turbine Performance curves – Power X Expansion ratio

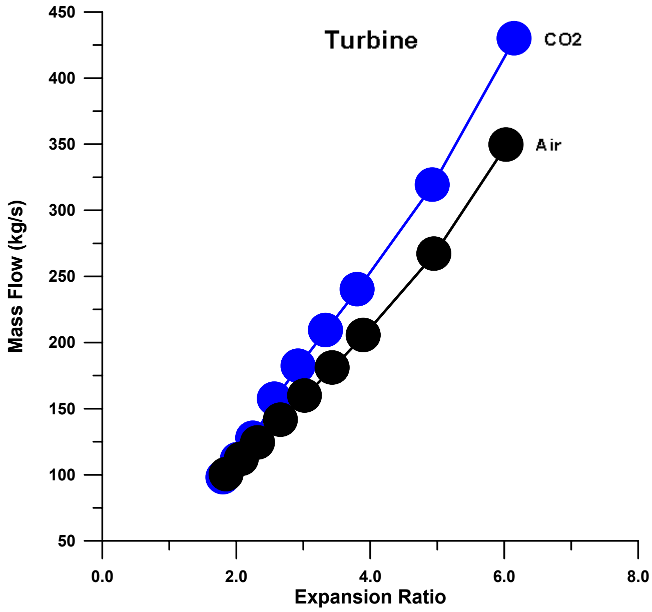

Figure 8 – Turbine Performance curves – Mass flow X Expansion ratio

Combustion Chamber

Although not simulated in this work, problems due to radiation will be present and even more complex (Ulizar ,1998); this is due to the higher flame tube temperature. It is expected that the combustion chamber life will diminish.

5. Actual CO_2 Brayton Cycle

If the component efficiencies are taken into account, simple cycle efficiency becomes also dependent on turbine entry temperature (TET), that is, the maximum cycle temperature and pressure ratio, as shown in Fig. 9.

The conclusion drawn for the ideal cycle that, to achieve the same efficiency as the air cycle the CO_2 cycle requires higher pressure ratios, is still valid for the actual cycle. It may be observed, in addition, that if the two cycles worked at the same pressure ratio and same TET, the air cycle would be more efficient and would produce higher specific work output than the CO_2 cycle. For example, a cycle with TET = 1500 K and pressure ratio = 16, if the working fluid were air the efficiency would be 36,5% and specific thrust 340 kW.s/kg, whereas a CO_2 cycle the efficiency would be 27% and the specific work output 310 kW.s/kg.

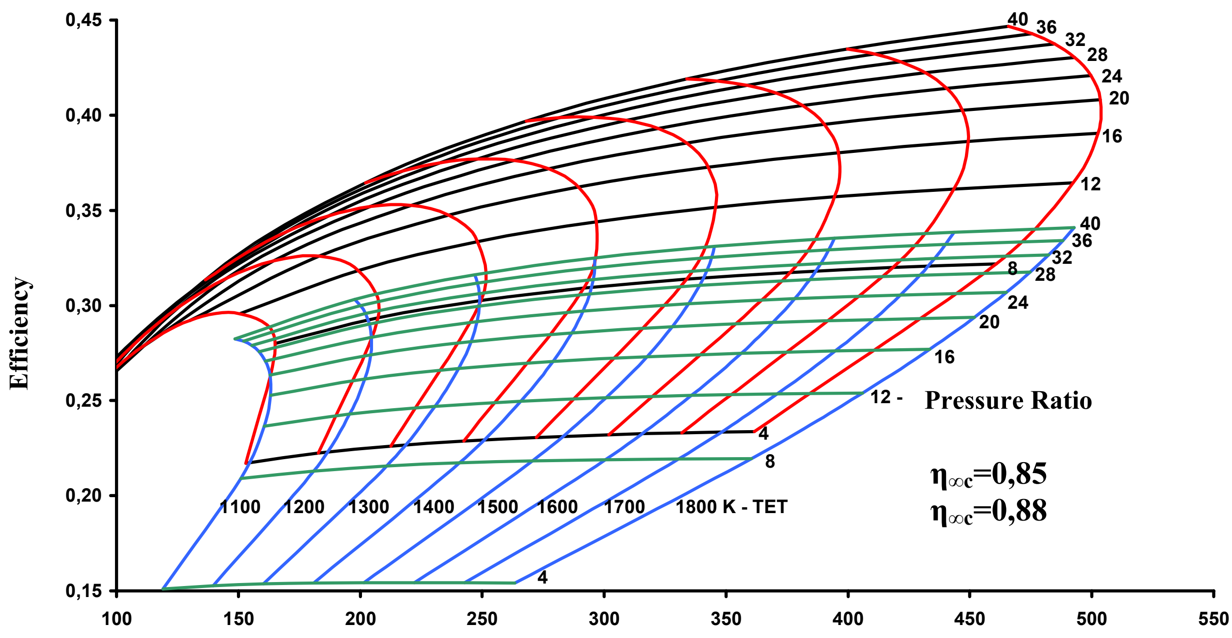

Figure 9 – Actual Brayton Cycle

6. Off-design Performance

Figures 10, 11 and 12 show the off-design performance of gas turbine designed for air, whose working fluids aree air and CO_2. As a comparison basis, the CO_2-operated gas turbine parameters were used at maximum TET of 1450K.

Figure 10 show that, increasing the percentage of CO_2 of the working fluid, engine efficiency would decrease drastically, down to near zero. In other words, the engine would stop working because the turbine would not produce enough power to drive the compressor. As it was shown for the ideal cycle, for higher efficiencies, the pressure ratio of a compressor for CO_2 would be much higher than the pressure ratio for the air cycle, thus making the engine designed for air inadequate to operate with CO_2 as working fluid. The exhaust gas temperature (EGT) would also significantly increase due to the fall of the engine efficiency.

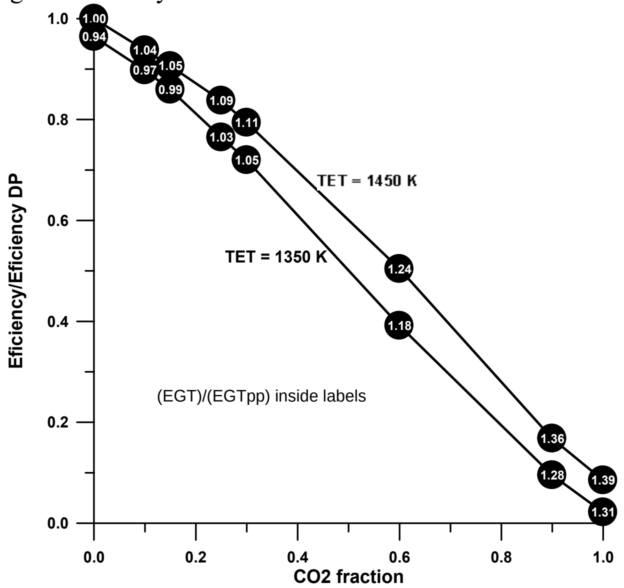

Figure 10 – Variation of efficiency as function of the increase of % of CO_2

Figure 11 show that when the percentage of CO_2 is increased, the engine power decreases and may reach very low levels when pure CO_2 is used. It may also be observed that with the increase of the CO_2 percentage the surge margin decreases significantly. A small increase in power may be possible if the percentage of CO_2 is not greater than 20%.

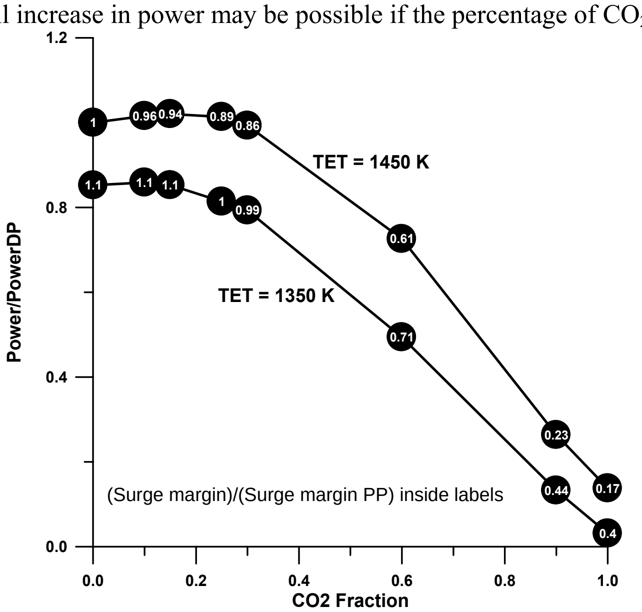

Figure 11 – Variation of power as function of the increase of % of CO_2

Figure 12 show that increasing the percentage of CO_2, the engine compressor pressure ratio increases. Despite this increase in pressure ratio, the engine efficiency does not increase, but decreases. It may also be observed from the figure that the decrease of compressor efficiency causes the decrease of the engine useful power.

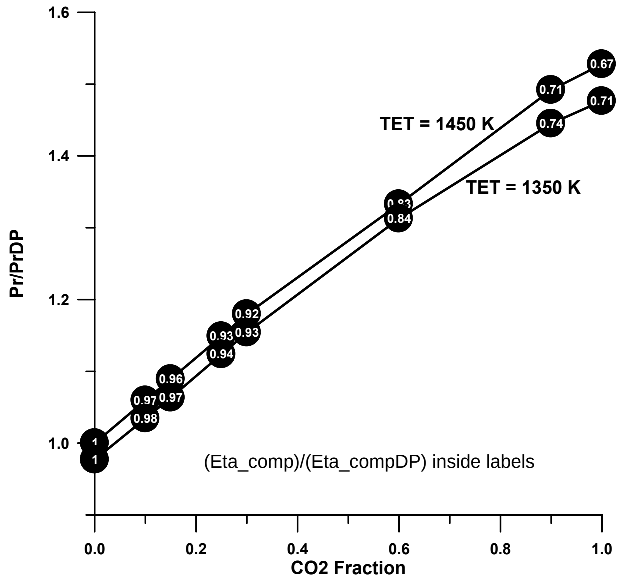

Figure 12 – Variation of pressure ratio as function of the increase of % of CO_2

7. Conclusions

This study confirms the conclusions drawn for the ideal cycle: as far as shaft power and efficiency are concerned it is not recommended to operate an air working fluid gas turbine with CO_2 as a new working fluid.

A gas turbine specially designed to use CO_2 as working fluid would:

- operate on high compressor pressure ratio.
- have a compressor especially designed to pump CO_2.
- have a turbine especially designed to expand CO_2.

For the components design (compressor e turbine), especially the ones operating on CO_2, it is required to adapt the theory developed for air as working fluid, therefore new human resources development is necessary. Rig-testing these components is also necessary, so that they may achieve the same levels of efficiency of those that operate on air and/or combustion products resulting from combustion of fossil fuels used in gas turbines.

Concerning the compressor pressure ratios for the CO_2 compressor, a 20:1 pressure ratio of an engine that uses air will translate into a pressure ratio of 45 if it is to pump CO_2, requiring additional development of the technology for compressor design.

Therefore, the operation of a gas turbine using CO_2 as working fluid sets a new level for the technological development. In terms of the actual technological development, the use of gas turbines, operating with CO_2, to reduce emissions from the thermal power plants may not be an acceptable solution.

8. Acknowledgements

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9. References

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