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EXERGETIC ANALYSIS OF A WET AIR TURBINE

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Abstract. *The exergetic analysis of a wet air turbine aims to calculate the unit exergetic cost of the produced power in design and off-design operating conditions. The thermal schematic of the cycle was simulated in the Gate Cycle™ software. The design operating condition was defined at ISO reference conditions. The turbine inlet temperature and compressor pressure ratio were studied to find the maximum performance at practical values. From the Gate Cycle™ mass, energy and entropy balances results, the specific and total exergy were calculated. The unit exergetic cost and the exergetic efficiency of the cycle were computed. The off-design Gate Cycle™ model and parametric studies were performed to study the performance due to ambient conditions and operational load variation. The maximum performance in a practical value of turbine inlet temperature was at 1200°C and a pressure ratio of 10, for a net power around 25 MW. In these conditions the thermal and exergetic efficiency were 51.78% and 50.51% respectively. In off-design ambient conditions parametric studies shown that the wet air turbine has relatively low influence on performance, in fact, the power variation is about ± 0.5 percentage points around the design condition value. The values of exhaust temperatures are very low and together with the unit exergetic cost follow the same behavior of the produced power. The thermal efficiency rises when the operating loads increase and falls when the ambient temperature rises. The wet air turbine operates more efficiently close to the nominal load. The behavior of the unit exergetic cost and the exergetic efficiency is inversely proportional. Close to the nominal load the wet air turbine tends to efficiency design condition. The high values of exergetic efficiency, around 50% (and lower unit exergetic costs, 1.98) show how the wet air gas turbine is suitable for power generation today*.

Keywords: *wet air turbine, gas turbine, exergy analysis, thermal schematic simulation.*

1. INTRODUCTION

Energy consumption expands throughout the world scene, being associated with great technological development and the increased level of global society quality of life in recent years. Technologies to help meet this consumption with a high efficiency are mandatory in the case of fossil fuels such as natural gas. The exergetic analysis of wet air gas turbine cycle aims, employing GateCycle™ software, to draw the cycle performance indicators curves in function of different input variables such as the ambient temperature and the load fraction.

2. LITERATURE REVIEW

Lee *et al*. 2010 noted that gas turbines with power generation capacity less than 300 kW could be used for electricity supply in big cities but they have a fall of performance with the increase of ambient temperature. In order to increase the performance the authors proposed to use the steam or water injection (wet air operation). Jesionek *et al*. 2012 showed that with the steam injection (STIG - Steam Injection Gas Turbine) the produced power rises significantly if compared with the conventional Brayton cycle. Another way to rise the performance is to increase the turbine inlet temperature, in this sense Rao (2006) said that it will be possible to operate with temperatures close to 1700°C in a near future. Hui *et al*. 2014 studied the wet air gas turbine cycle and verified that the air humidification could be used to control the produced power. Wang *et al*. 2007a executed an experiment to study the performance of a counter flow saturator. The authors revealed that the air exit temperature increases when more hot water is injected into the air, reducing the fuel consumption in the combustion chamber. Nyberg and Thern (2012) increased the air temperature at the outlet of the saturator and recommended the use of an economizer at the gas turbine exhaust producing hot water for the air umidification. Lazzaretto and Segato (2002) also concluded how the heating water increases the plant efficiency. Aronis and Leithner (2004) said that to obtain a high level of performance of the wet air turbine it is important to inject more water into the air and keep a high temperature at the turbine inlet. In this sense, Wei and Zang (2013) rose the produced power just with the water injection keeping constant the turbine inlet temperature. The fuel treatment could be another way to increase the performance of the wet air turbine. In this sense, Zhao e Yue (2011) studied the chemical decomposition of methanol reducing the exergy losses in 8% if compared with the classical wet air turbine cycle. The solar energy can be used to reduce the fuel consumption and increase the specific produced power. Zhao, Yue and Cao (2009) said that increasing the humidity from 12.44% to 17.35%, the specific power rises from 519.9 kJ/kg to 604.7 kJ/kg. Better performance results were also shown by Parente, Traverso and Massardo (2003) via experimental results and in a pilot plant of 50 MW of capacity. Wang *et al*. 2007b expressed that the wet air turbine has high level of performance and low cost and area for construction.

3. METHODOLOGY

The exergetic analysis of the wet air turbine was developed in the following main stages:

- Definition of the thermal schematic of the wet air turbine. This stage includes the selection of the cycle components, layout, operating parameters definition, specification of the design condition;
- Off-design parametric studies. This stage includes the estimation of performance of the wet air turbine with the variation of the ambient temperature and load.

Figure 1 presents the wet air turbine schematic that was defined for the exergetic analysis. As we can see in this figure, the components of the cycle are: the compressor, the combustor, the expander, the recuperator, the economizer, the saturator, the collector and the pump. The last four components are responsible for the water injection and the air humidification. The pump pressurizing the water accordingly with the compressor discharge pressure. The economizer preheats the water before the injection. The saturator humidifies the air. The recuperator increases the air temperature for the combustion. The first three aforementioned components are the classical ones of the Brayton cycle.

The main data of each component of the cycle are shown in Fig. 1. In this figure, it is possible to see the molar composition of the natural gas and its lower heating value (LHV), 47450.63 kJ/kg, the combustion efficiency (0.995), the expander isentropic efficiency (0.9), the compressor isentropic efficiency (0.88), the pump isentropic efficiency (0.85), the recuperator effectiveness, NTU, global heat transfer coefficient (0.798, 3.62 and 0.05 kJ/(s m² K), respectively), the economizer effectiveness, NTU, global heat transfer coefficient (0.9, 2.74 and 0.05 kJ/(s m² K), respectively), the saturator stages (3) and the desired water fraction at the exit (0.15).

The definition of the wet air turbine operating parameters (pressure ratio and turbine inlet temperature) was done based of the graphs presented in Fig. 2. In this figure the thermal efficiency and the specific power output were plotted as function of the compressor pressure ratio and turbine inlet temperature. Figure 2 shows that when the turbine inlet temperature increases the thermal efficiency rises, and for each turbine inlet temperature there is a value of compressor pressure ratio in which the thermal efficiency is maximum. Figure 2 also shows that the specific power output always increases when the compressor pressure ratio and the turbine inlet temperature rise. Based on values of thermal efficiency and specific power output shown in Fig. 2, 1200°C and 10 where defined for the turbine inlet temperature and the compressor pressure ratio respectively. This definition was done by the fact that 1200°C is not a very high turbine inlet temperature nowadays, making long time operating hours possible without hot gas parts replacement. Using 10 as the compressor pressure ratio is enough to guarantee high values of thermal efficiency and specific power output without leaking in the gas turbine, mainly in the recuperator. With these parameters the thermal efficiency is about 51.8% as we can see in Fig. 1.

Once the design condition is defined, the wet air turbine GateCycle™ model was running in off-design to plot the performance curves as function of the ambient temperature and the load fraction. The relative variation respect to the design point was plotted for the specific power, the exhaust temperature, the thermal efficiency and the unit exergetic cost versus the ambient temperature ranged between 5 and 30°C. The specific power, the exhaust temperature, the thermal efficiency, the exergetic efficiency and the unit exergetic cost were plotted versus the load fraction for different values of ambient temperatures. The exhaust temperature is the temperature at the outlet of the economizer, named exhaust gas in Fig. 1. The other parameters aforementioned are defined as follows:

$$SP = \frac{\dot{W}}{\dot{m}_{air}} \qquad (1)$$

$$\eta = \frac{\dot{W}}{\dot{m}_{ng} \cdot LHV} \tag{2}$$

$$\eta_{ex} = \frac{\dot{W}}{\dot{m}_{ng} \cdot ex_{ng}} \tag{3}$$

$$k^{*} = \frac{1}{\eta_{ex}} \tag{4}$$

In the Eq. (1-4), SP is the specific power, $\dot{W}$ is the net cycle power, in kW, $\dot{m}_{air}$ is the air mass flow at the turbine inlet, in kg/s, $\dot{m}_{gn}$ is the natural gas mass flow, in kg/s, LHV is the Lower Heating Value of the natural gas, in kJ/kg, η is the thermal efficiency, η_{ex} is the exergetic efficiency, k* is the unit exergetic cost, ex_{gn} is the specific exergy of the natural gas, in kJ/kg, computed by the methodology presented by Lozano and Valero (1986).

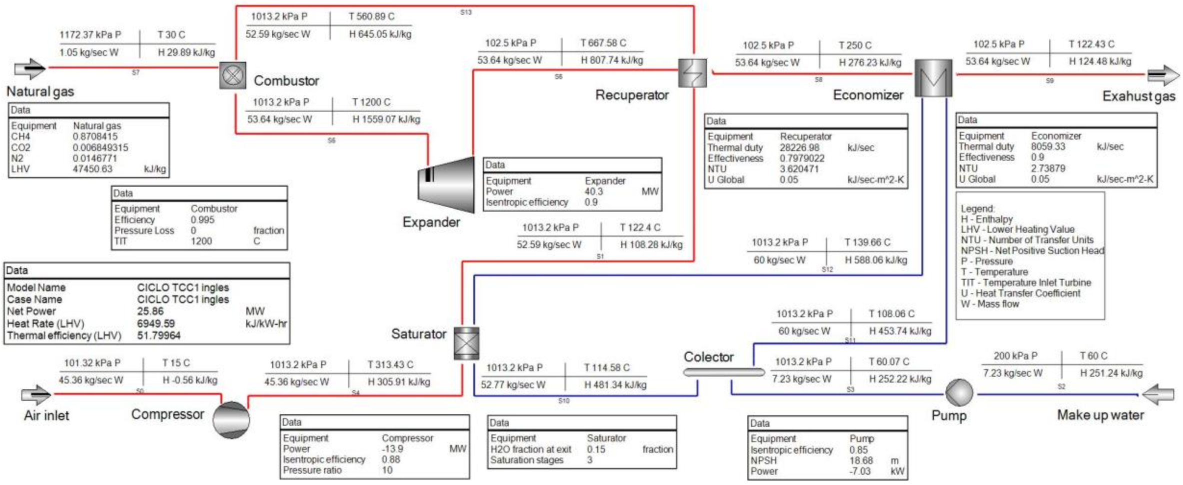

Figure 1. The wet air turbine schematic at design condition.

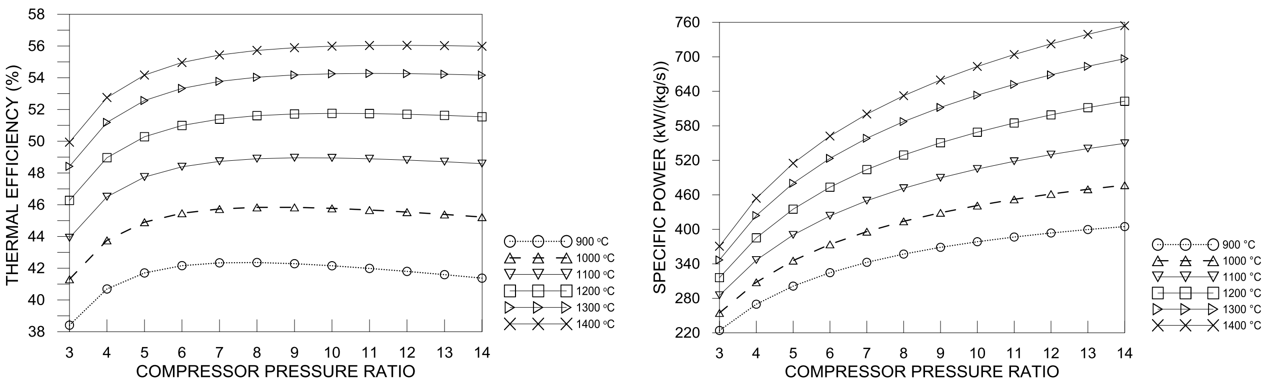

Figure 2. Variation of thermal efficiency and the specific power in the wet air turbine.

4. RESULTS AND DISCUSSIONS

The results of the calculations at design point condition are presented in Fig. 1. In this figure the values of pressure, temperature, enthalpy and mass flow are shown for each stream of the wet air turbine, also characteristic values for the different components of the cycle can be seen. A summary of results at the design condition are illustrated in Tab. 1.

Table 1. Results at design point.

Parameter	Value
Net cycle power (MW)	25.86
Specific power (kW/(kg/s))	570.11
Thermal efficiency (%)	51.80
Exergetic Efficiency (%)	50.51
Unit exergetic cost (-)	1.98

The estimation of performance of the wet air turbine was summarized in Fig. 2. The relative variation of several performance parameters function of the ambient temperature is presented on the left side of the Fig. 2. As we can see in this figure, the produced power is close to constant for the whole range of ambient temperature variation, in fact, the power variation is about ± 0.5 percentage points around the design condition value. This is the differential of the wet air turbine with respect to the conventional Brayton cycle. This behavior is explained by the effect of the injected water for the air saturation keeping constant the turbine inlet temperature. The addition of mass flow with the water injection increases the generated power in the expander attenuating the variation of the compressor consumed power with the variation of the ambient temperature. This behavior causes a decrease in the thermal efficiency at high ambient temperatures, which means that the increase in the produced power is lower than the increase in the fuel energy consumption. At low ambient temperatures the water injection is diminished reducing the fuel energy consumption and raising the thermal efficiency. The reduction in the fuel energy consumption causes a fall in the produced power. The exhaust temperature and the unit exergetic cost follow the same behavior of the produced power, which is caused by the variation in the fuel energy consumption mentioned before, for example, an increase in the fuel energy consumption at high ambient temperatures rises the exergy fuel consumption to produce the power. On the right side of the Fig. 2 it is possible to see that the specific power keep constant for any ambient temperature at partial load operation, which means that with the water injection for air saturation the effect of the ambient temperature variation on the specific power is abrogated.

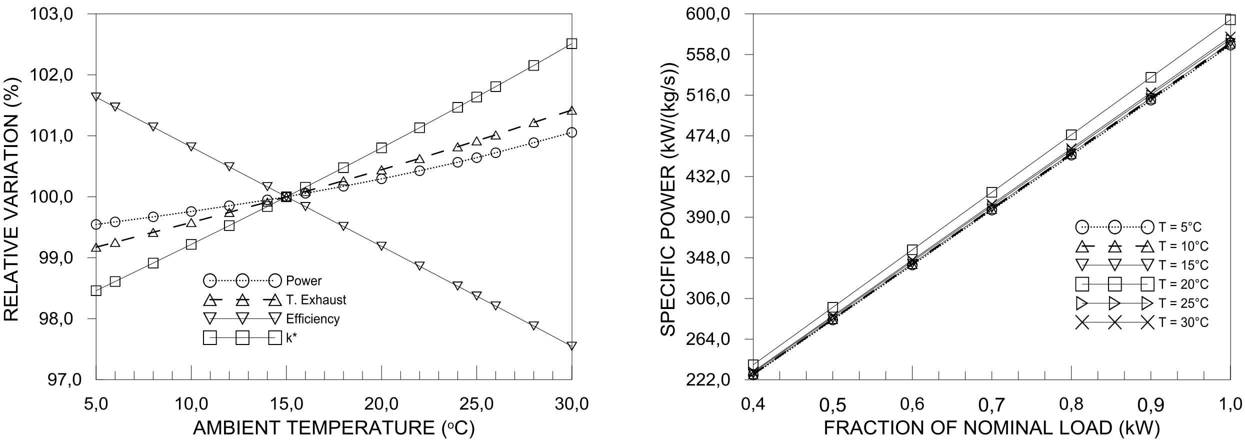

Figure 2. The wet air turbine performance at off design condition.

Figure 3 shows the influence of the ambient temperature and the load fraction on the exhaust and the thermal efficiency. At higher ambient temperatures and operation load, the higher values of exhaust temperature are observed. On these conditions more water is injected for humidification and more energy is consumed from fuel causing an increase in the exhaust temperature, but it is interesting to note that the values of exhaust temperatures are very low, which are given by using the economizer to preheat the water for humidification. As we can see on the right side of Fig. 3, the thermal efficiency rises when the operation load increases, and falls when the ambient temperature rises. The wet air turbine operates more efficiently close to the nominal load, as expected for thermal systems in which the better operating condition is at design point. At high ambient temperatures more energy with fuel is necessary to keep constant turbine inlet temperature when more water for humidification is injected to compensate the diminishing in the produced power.

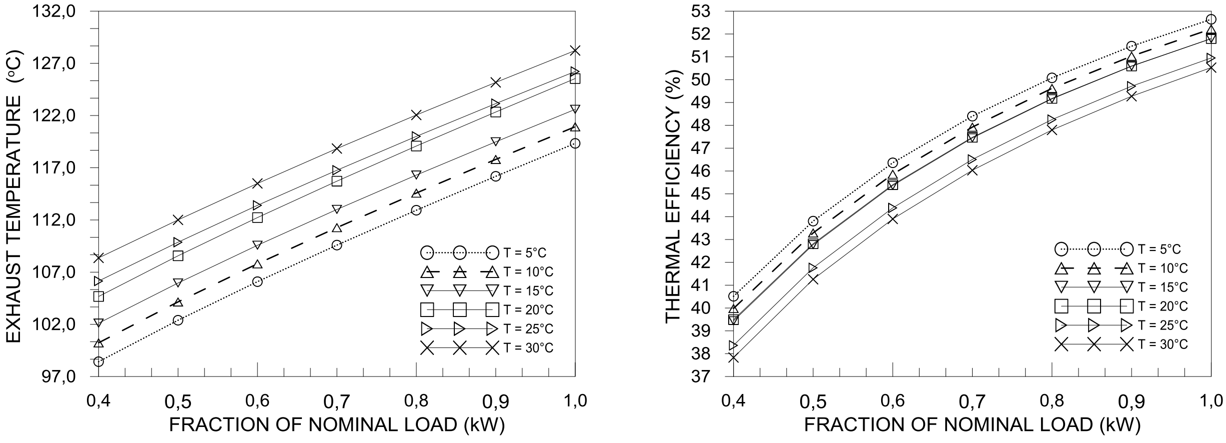

Figure 3. Exhaust temperature and thermal efficiency at off design condition.

Figure 4 shows the influence of the ambient temperature and the load fraction on the unit exergetic cost and the exergetic efficiency. The behavior of these two parameters is inversely proportional, according to Eq. (4). As we can see on the left side of Fig. 4, the unit exergetic cost rises when the ambient temperature increases and the operation load decreases. At high values of ambient temperatures more water injected for humidification and more energy are consumed from fuel, so it needed more input exergy to produce the same amount of power. Close to the nominal load the wet air turbine tends to efficiency design condition which is also where the better values of exergetic efficiency and lowest unit exergetic cost are registered. The high values of exergetic efficiency (and lower unit exergetic costs) show how the wet air gas turbine is suitable for power generation today.

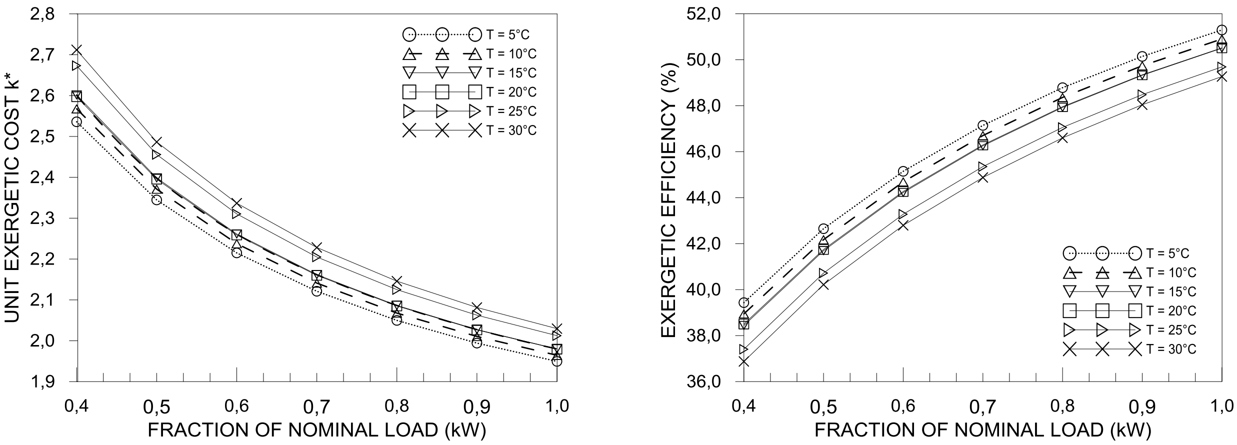

Figure 4. Unit exergetic cost and exergetic efficiency at off design condition.

5. CONCLUSIONS

The exergetic analysis of the wet air turbine makes it possible to express the following conclusions:

- For the whole range of ambient temperature variation, in fact, the power variation is about ± 0,5 percentage points around the design condition value. This is the differential of the wet air turbine with respect to the conventional Brayton cycle;
- The exhaust temperature and the unit exergetic cost follow the same behavior of the produced power as function of the ambient temperature variation;
- The thermal efficiency decreases at high ambient temperatures, which means that the increase in the produced power is lower than the increase in the fuel energy consumption;
- At higher ambient temperatures and operation load, the higher values of exhaust temperature are observed, but the values of exhaust temperatures are very low;
- The thermal efficiency rises when the operation load increases, and falls when the ambient temperature rises;
- The wet air turbine operates more efficiently close to the nominal load;
- The behavior of the unit exergetic cost and the exergetic efficiency is inversely proportional;
- The unit exergetic cost rises when the ambient temperature increases and the operation load decreases;
- Close to the nominal load the wet air turbine tends to efficiency design condition which is also where the better values of exergetic efficiency and lowest unit exergetic cost are registered;
- The high values of exergetic efficiency, around 50% (and lower unit exergetic costs, 1.98) show how the wet air gas turbine is suitable for power generation today.

6. ACKNOWLEDGEMENTS

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