# Analysis of a Cogeneration System Based on Thermodynamic Parameters Using Object-oriented Mathematical Modeling

Dawing Guette[a]

[a]*Facultad de Ingeniería, Universidad Tecnológica de Bolívar, Cartagena de Indias D.T y C.*

**Abstract**

In this paper are presented a cogeneration system with a gas turbine using mathematical modelling object-oriented with the help of program OpenModelica and the library ThermoSysPro, the purpose is get a model able show performance parameters as, heat rate, thermal and cogeneration efficiency, varying entree parameters as, air temperture, humidity, mass flow of air and fuel.

*Keywords:* Cogeneration System, Efficiency, Gas Turbine, Modelling Object-oriented, OpenModelica, ThermoSysPro

## 1. Introduction

The demand of electrical energy grow and agree with the UPME projection [1] until 2033 in Colombia, the demand will grow around of 2.39% annually, a other projection made by UPME is about the demand of natural gas [2] which will be grow 3.66% annually for the same period.

The biggest industries can generated his own electrical energy, they use fuels how coal, petroleum and natural gas, the last is the most used due the increment of the installation of turbine and motors gas [3], because it's think that they can reduce the pollution and dioxide of carbon emissions [4], also they can unite to heat recovery steam generator and form what is known how cogeneration system due that can produce two forms of energy (thermal and electrical), for this reason is important that this systems works with your best efficiency and for this, the manufacturers design your equipment based on the ISO conditions

(15C and 60% of humity) but in many cities how Cartagena this conditions are not comply (32C and 70% of humidity), for solution this problem, technologies must be implemented for take the ambient conditions and carry them to the ISO conditions.

The technologies that can be implemented to supply the problem is a not approach of this paper, the optimal range of the compressor inlet air is shows in [5] and the variation of the mass flow by the air and fuel will be taken of 11.5% , the model is elaborated used OpenModelica what is a program of mathematical modelling object-oriented which Mattson in [6] describes approach builds on non-causal modeling with true ordinary differential and algebraic equations that allow the use of object-oriented constructs facilitating your reuse compared with the mathematical modelling equation-oriented. OpenModelica has many libraries that can be used for model of cogeneration system, in this case was used ThermoSysPro librarie because provides the most used model's for the static and dynamic modelling of system, also allow modelling to other types of energy systems such as industrial processes, energy conversion systems, buildings [7].

For complete the objective of this paper, will be created mathematical model of everyone of components, they should have balances of mass and energy, for each one is defined the boundary conditions and the controls of variable how the themperature and mass flow of air and fuel managers of charged with making these vary, the other considerations that is take in count is that the water of alimentation i entree to 25 C and 15 bar of pressure, the fuel entree to 85C and 34 bar of pressure and the pressure of the inlet of compressor is 1 atm or 1.01 bar, the tempertue is variated of 15C to 5C, the humidity of aire is take to 60%.

The purpose of this first model is to obtain graphs that allow the different thermodynamic parameters to be compared as a function of time or other variables that may be relevant. In the future, the model can continue to be improved by introducing more elements to the system and incorporating more advanced performance parameters such as exergetics.

## 2. Modelling

The variables of entry is entered to boundary conditions, the connectors take this variables and carries to the connectors of system of destination through connection lines, in these system associated calculations are performed and the results is take by the outlet conectors to the other system or boundary conditions of sump, these metodology is represented in the figure 1.

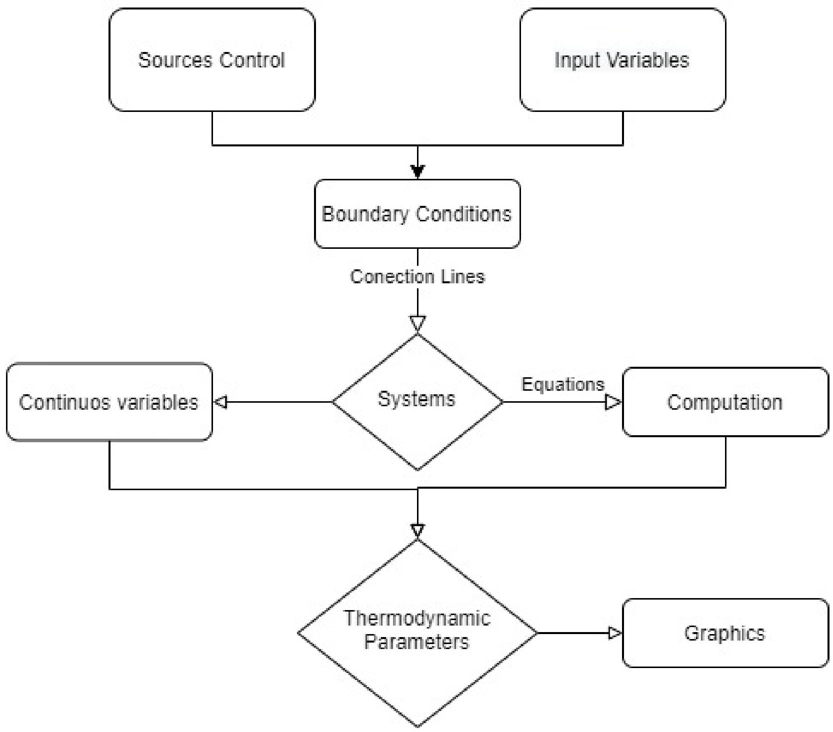


Figure 1: Methodology

For modelling the system was used differents elements of the library of ThermoSyspro and others that are combination of this library and creation of the author, the figure 2 is the diagram view in OpenModelica.

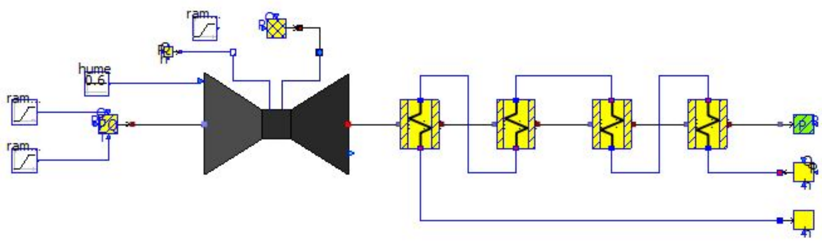

Figure 2: Diagram View

*2.1. Gas Turbine*

The gas turbine is compound for the compressor of air, combustion chamber and the turbine, in the compresor are read data of the conectors for the air an caclulate the work of entree that is need to compress this air according whit the relation of compression, the combustion chamber is conected to boundary of fuel that contain everyone parameters temperature, composition and pressure, for other part is conected to the outlet of the compressor, is calculated the power of fuel and the heat that is loss, the turbine is conected to the outlet of the chamber combustion and take the flue gases and expand according to the expand relation, is caculated the work is produced, net work and electric power.

**Compressor**

The object that represent compressor is show in the figure 3, the equations used in the compressor model are described, the equation that use to calculated the temperature of exit is presented in [8].

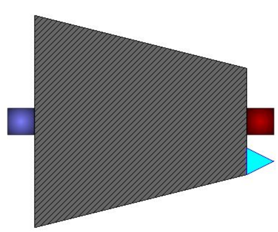

Figure 3: Compressor

$$Wcp = \frac{Q * (H_s - H_e)}{Nmec}$$

$$T_s = T_e + \frac{T_e}{Ncomp} * (RPcomp^{RCpv} - 1)$$

$$RCpv = \frac{Kc - 1}{Kc}$$

$$Kc = \frac{\frac{Cp_e + Cp_s}{2}}{\frac{Cv_e + Cv_s}{2}}$$

**Combustion Chamber**

The combustion chamber used is completely of Thermo Syspro, count with the entree of air and fuel also other entree for water or steam by if the cycle need steam or water injection, the outlet is the flue gases of combustion, the equations and objects for component is presented next.

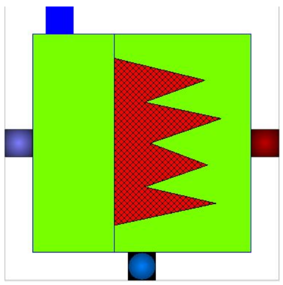

Figure 4: Combustion Chamber

$$Q_{ews} * H_{ews} + Q_{ea} * H_{ea} + Wfuel - Q_{sf} * H_{sf} - Wcc = 0$$

$$Wfuel = Q_{fuel} * LHV_{fuel}$$

$$Q_{sf} = Q_{ea} + Q_{ews} + Q_{fuel}$$

**Turbine**

The turbine take the flue gases and expand producing mechanic work and electric power, is calculated net work and electric power depending of the efficiency of generator, the flue gases outlet go to the heat recovery steam generator, the object and equation is presented next.

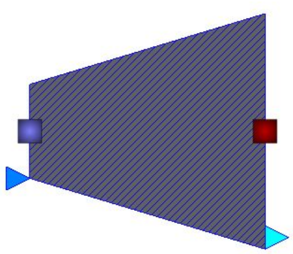

Figure 5: Turbine

$$T_s = T_e - T_e * Nexp * (1 - (1 - ((\frac{1}{RPexpand})^{RCpv})))$$

$$RCpv = \frac{Kc - 1}{Kc} \qquad Kc = \frac{\frac{Cp_e + Cp_s}{2}}{\frac{Cv_e + Cv_s}{2}}$$

$$Wturb = Q * (H_e - H_s)$$

$$Wnet = Wturb - Wcp$$

$$Pelec = Wnet * Ngen$$

*2.2. HRSG*

The recovery steam generator use the flue gases of turbine and convert the water of alimentation in superheated steam that after will be used in the steam turbines for electric generation and production of steam of less pressure and condensate, HRSG is compound for four exchanger used like this two superheaters, a evaporator and a economizer.

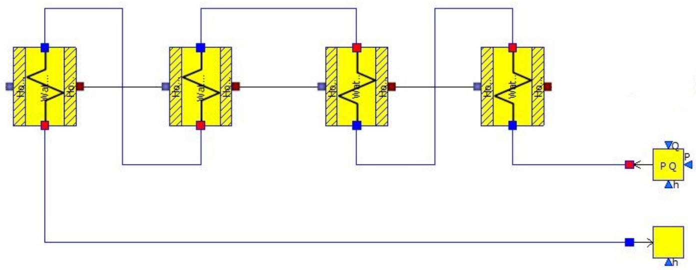


Figure 6: Heat Recovery Steam Generator

**Exchanger**

The exchanger uses the heat of flue gases to heating the current of water or steam, is a counter current exchanger and the total heat lost by one is the gain for the other, is considerate as adiabatic due that not exist losses of heat to the ambient, the model has this equations and is represented by this figure.

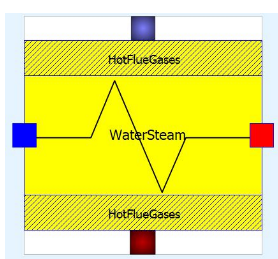


Figure 7: Exchanger

$$W = (Q_e * Cp_e, Q_f * Cp_f) * Ef * (T_{ef} - T_{ee})$$

$$W = Q_f * (H_{ef} - H_{sf}) \qquad \textit{flue gases current}$$

$$W = Q_e * (H_{se} - H_{ee}) \quad \textit{water / steam current}$$

## 3. Thermodynamic Parameters

The indicators that allow meet and evaluating the behavior of the plant on based of mass and energy balances according to first law of thermodynamic are:

### *3.1. Thermal Efficiency*

Is the ratio of the net electrical energy generated to the total energy of the fuel, is calculated as:

$$N_{th} = \frac{Pelec}{Wfuel} \tag{1}$$

### *3.2. Heat Rate*

It is a performance measurement of a thermoelectric power station, and expresses the thermal energy supplied by the fuel necessary to produce one kWh of electrical energy., is calculated as:

$$HR = \frac{3600 * Wfuel}{Pelec} \tag{2}$$

### *3.3. Cogeneration Efficiency*

As shown in [9], it is a measure of how well all the power of the fuel is being used for the production of electrical energy and the generation of heat in the boiler and it's can calculate as:

$$N_{cogeneration} = \frac{Wnet + W_{HRSG}}{Wfuel} \tag{3}$$

### *3.4. Specific Fuel Consumption*

Is defineted by [10] as the fuel saved over that required for the separate production of electricity and thermal energy per unit of useful thermal energy produced and the equation is:

$$SFC = \frac{3600 * Qfuel}{Pelec} \tag{4}$$

## 4. Case Study

For validate the functionality of the model, is need use real data that allow know that fine the model ajust to the reality, for this was used the next data that was used by [5] in your study, finally the results are compared and find the error.

| Data | | | |
|---|---|---|---|
| Ncomp=85% | Nexpand=88% | RPcomp=31.25 | RPexpand=29 |
| Nmec=98.5% | Ngen=98% | Ef=95% | LHV=48446 $\frac{KJ}{Kg*K}$ |
| $Q_{air} = 86.5\ to\ 76.5\ Kg/s$ | $Q_{fuel} = 1.85\ kg/s$ | $T_{fuel} = 86\ C$ | $T_{air} = 5\ to\ 32\ C$ |
| $Q_{water} = 63\ kg/s$ | $P_{water} = 15.2\ bar$ | $P_{fuel} = 34\ bar$ | $P_{air} = 1\ atm$ |

### *4.1. Results*

Comparing the results obtained by this model with the reference data, was obtain in average a 7% of error for everyone of the parameters which it's acceptable for this first model, the graphs obtained is presente to continuation.

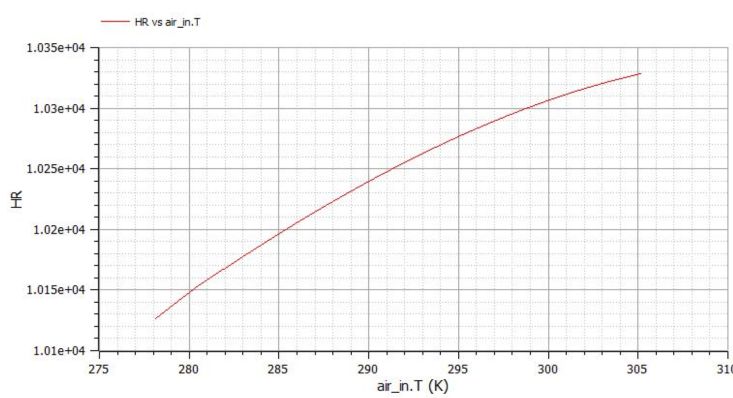


Figure 8: Heat Rate Vs. Temperatura inlet of Compressor

In the graph it is shown that the heat rate increases as the temperature increases, this can be summarized in that more thermal energy is needed to generate one kWh, for ISO conditions the heat rate is 9852 kJ / kWh and in our model it was obtained 10424 kJ / kWh which represents an error of 5.5%.

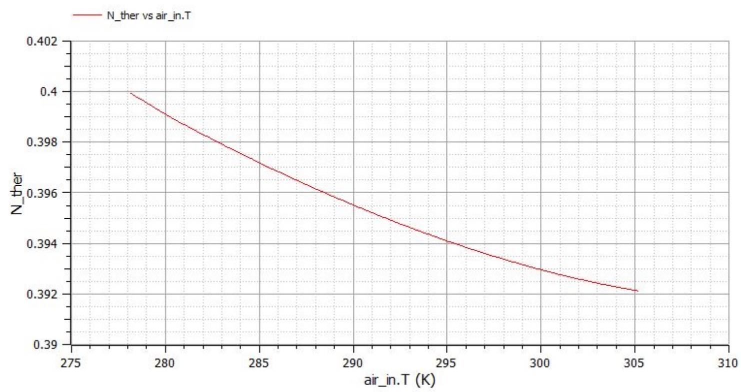


Figure 9: Thermal Efficiency Vs. Temperatura inlet of Compressor

The thermal efficiency decreases on average 0.5% due to the 5 degree increase in temperature, for ISO conditions it must be 36.57% and the model gets 39.6% giving an error of 7.3%.

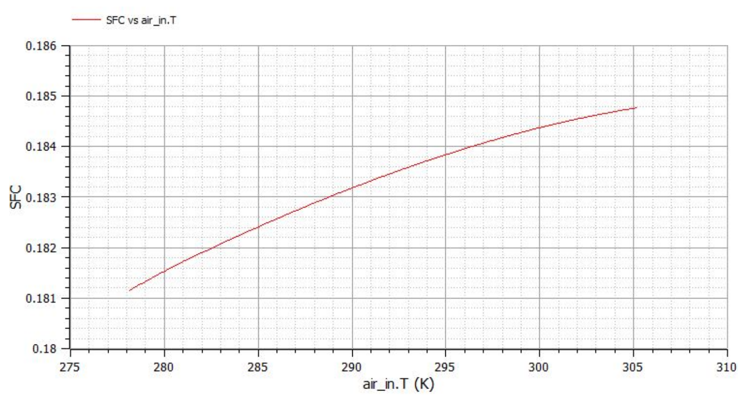


Figure 10: Specific Fuel Consumption Vs. Temperatura inlet of Compressor

It is evident that the specific consumption increases as the temperature increases, this means that more fuel is needed to generate the same amount of electrical power, for ISO conditions the SFC value should be 0.2031 kg / kWh and with the model it is obtained 0.183 kg / kWh, which leaves us with an error of 9.8%.

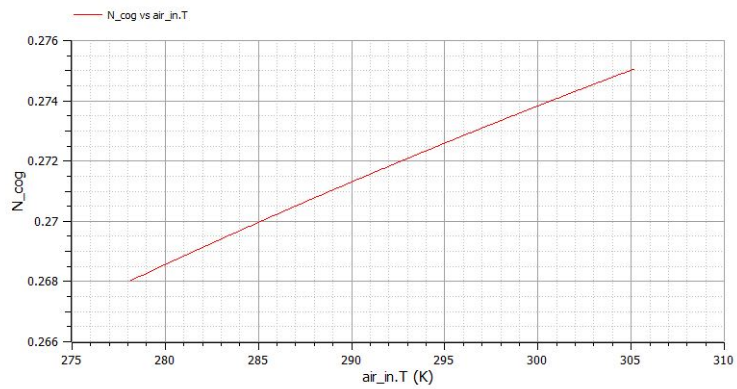


Figure 11: Cogeneration Efficiency Vs. Temperatura inlet of Compressor

With the increase in temperature the efficiency of cogeneration increases, this is because there will be an increase in the temperature of the gases leaving the boiler, for ISO conditions it is estimated that its efficiency should be around 29% and with the model 27.1% was obtained for an error of 6.5%.

## 5. Conclusions

The objective proposed at the beginning of the paper was achieved, the model adjusts to reality with an average error of 7 % which is acceptable, in the future it is proposed to continue including more advanced parameters that allow a better understanding of the operation and state of the system using exergy balances and exergical performance parameters, as well as reducing the error obtained in this first model.

| Nomenclature | | | |
|---|---|---|---|
| Nexp | expand efficiency | Ncomp | compress efficiency |
| Nmec | mechanic efficiency | Ngen | generator efficiency |
| Q | Mass Flow | Wcp | Compressor Power |
| Wturb | Turbine Power | Wnet | Net Power |
| Wfuel | Fuel Power | Wcc | Combustion Chamber Power |
| Pelec | Electrical Power | Rpcomp | Compression Ratio |
| Cp | Spechific Heat to Constant Pressure | T | Temperature |
| Cv | Specific Heat to Constant Volume | H | Enthalpy |
| Rpexpand | Expand Ratio | Ef | exchanger effectiveness |
| Subscripts | | | |
| e | inlet | s | outlet |
| ews | inlet water/steam | ea | inlet air |
| sf | outlet flue gases | ef | exchanger inlet flue gases |
| se | exchanger outlet water/steam | ee | exchanger inlet water/steam |

## References


[1] UPME, Proyeccion demanda energia.

[2] UPME, Proyeccion demanda GN.

[3] T. K. Ibrahim, M. K. Mohammed, O. I. Awad, A. N. Abdalla, F. Basrawi, M. N. Mohammed, G. Najafi, R. Mamat, A comprehensive review on the exergy analysis of combined cycle power plants 90 835–850. doi:10.1016/j.rser.2018.03.072.

[4] S. Iglesias Garcia, R. Ferreiro Garcia, J. Carbia Carril, D. Iglesias Garcia, Critical review of the first-law efficiency in different power combined cycle architectures 148 844–859. doi:10.1016/j.enconman.2017.06.037.

[5] D. Barreto, J. Fajardo, J. Campillo, Determination of the optimal range of the compressor inlet air temperature in a power plant with stig cycle through of advanced exergetic analysis.

[6] S. E. Mattsson, H. Elmqvist, M. Otter, Physical system modeling with modelica 6 (4) 501–510. doi:10.1016/S0967-0661(98)00047-1.

[7] B. El Hefni, D. Bouskela, G. Lebreton, Dynamic modelling of a combined cycle power plant with ThermoSysPro, pp. 365–375. doi:10.3384/ecp11063365.

[8] A. P. Santos, C. R. Andrade, Analysis of gas turbine performance with inlet air cooling techniques applied to brazilian sites 4 (3) 341–354. doi:10.5028/jatm.2012.04032012.

[9] F. A. Al-Sulaiman, F. Hamdullahpur, I. Dincer, Trigeneration: A comprehensive review based on prime movers 35 (3) 233–258. doi:10.1002/er.1687.

[10] ASME, Asme ptc 4.4 - gas turbine heat recovery steam generators.