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PARAMETRIC STUDY OF GAS TURBINES OPERATION AT OFF-DESING CONDITIONS

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Abstract.

Gas turbines operate mostly at off-design conditions. To know how a gas turbine operates at off-design conditions performance curves are required, which are difficult to access. Thus with a commercial software, which has gas turbine operation curves, a parametric study of the gas turbines operating in off-design conditions was made. In the parametric study the influence of some gas turbine operating conditions (ambient temperature, relative humidity, altitude, fuel and gas turbine inlet and outlet pressure drop) on some performance parameters of the gas turbines (power, heat rate, exhaust mass flow rate and exhaust temperature) was studied. Correction polynomials were created that generate correction factors of the performance parameters as a function of the operating conditions and by multiplying the correction factors for the different operating conditions it is possible to predict the performance parameters for the turbines in off-design conditions. The method of predicting the performance parameters using correction factors was compared with simulations in the commercial software and correction curves found in the literature. An error below 1.5% was reached in most of the cases when the correction polynomials were compared with correction curves found in the literature. When compared with simulations in the commercial software an average error below 3% was obtained.

Keywords: gas turbine, off-design point, correction polynomials, performance prediction

1. INTRODUCTION

In the analysis of thermal power systems, it is important to know the behavior of the equipment operating in the design condition (operating condition for which the equipment was built) and in the off-design condition (operating condition in which the equipment operates most of the time). The knowledge of these operating conditions makes it possible to identify, in more detail, the real influence of an equipment in the operation of thermodynamic cycles, allowing to identify the most appropriate operating range or which equipment or technology is most suitable for a thermal power system.

One way of predicting the performance of an equipment is from the characteristics curves of this equipment, but the characteristics curves are difficult to access or even restricted, as an example is the case of gas turbines that are seldom provided by the manufacturer. There are specialized softwares capable of predicting the performance of several gas turbines, but these softwares are usually expensive, which makes it difficult to access the information.

Thus, from the availability of access to a software, that has characteristic curves of gas turbines, several gas turbines were analyzed operating at off-design condition, the behavior was observed and parametric performance equations were created with the objective of predicting the behavior of gas turbines operating at off-design conditions.

2. METHODOLOGY

In a similar way that Carvalho et al. (2011) did to predict the performance of a GE 7FA gas turbine, it is intended to create correction polynomials that generate correction factors capable of predicting some performance parameters of the gas turbines operating at off-design conditions. The performance parameter can be corrected by Eq. (1).

$$Ycor = Yref \prod FC \qquad (1)$$

Where: Y_{cor} is the corrected value of the performance parameter at off-design point (Power Output, Heat Rate, Exhaust Flow, Exhaust Temperature); Y_{ref} is the value of the performance parameter at design point (Power Output, Heat Rate,

Exhaust Flow, Exhaust Temperature), FC are the correction factors obtained through correction polynomials for each operating condition (Altitude, Fuel LHV, Exhaust Loss, Inlet Loss, Inlet Air Temperature, Relative Humidity).

2.1 Gas turbines selection and division in groups

Initially the gas turbines were divided in 7 groups according to the gas turbines type (aeroderivative or industrial) and rated power output as shown in Tab.1. One less group was defined for aeroderivative gas turbines because the power output of aeroderivative gas turbines is limited approximately to 50 MW (Kehlhofer et al., 2009).

Table 1. Gas turbines groups.

Group	Rated Power Output (P) [MW]	Type
1	P ≤ 15	Industrial
2	15 < P ≤50	Industrial
3	50 < P ≤ 100	Industrial
4	P > 100	Industrial
5	P ≤ 15	Aeroderivative
6	15 < P ≤50	Aeroderivative
7	P > 50	Aeroderivative

The gas turbines selected for each group are shown in Tab.2. The gas turbine data was taken from the Thermoflex version 25 (2015), which is the software used for the gas turbine simulation in this paper. As can be seen in Tab. 2, three turbines were chosen for each group. The criterion of choice of gas turbines was the ease and availability of information, since even in Therrmoflex there are some turbines that do not have all the desired information. For group 7 only one gas turbine was chosen because of the shortage of aeroderivative turbines with power above 50MW in the Thermoflex version 25 (2015) library.

Table 2. Chosen gas turbines.

	Gas Turbine	Power output [kW]	Heat Rate [kJ/ kWh]	Shafts	Pressure Ratio (PR)	Air Flow [kg/s]	Exhaust Temperature [°C]
Group 1	Siemens SGT-100-1S	5247	11948	1	14,8	20	537
	Mitsubishi MF111A	12826	11783	1	12,8	48	543
	GE 10	10218	11489	2	14,1	41	523
Group 2	Alstom GT9D	32776	12818	1	8,9	159	517
	Siemens SGT-600	24630	10513	2	14	78	542
	GE 6541B	39615	11067	1	11,8	138	534
Group 3	Alstom GT8C	52600	10526	1	15,7	176	517
	GE 7101	77110	11025	1	11,8	280	520
	Siemens SGT-3000E	60170	12396	1	10,5	322	424
Group 4	Siemens SGT5-2000E	159410	10397	1	11,4	500	547
	GE 9331 FA	245065	9775	1	14,6	636	591
	GE 9001H	331000	9115	1	23,2	685	621
Group 5	RR 501-KB7	4942	12414	1	13,4	20	536
	Solar Taurus 70	7250	10972	1	15	26	493
	GE LM500	3880	12059	2	14,5	16	513
Group 6	GE LM6000 PA	41020	9200	2	29,5	122	478
	GE LM2000	17639	10324	2	16	63	479
	P+W FT8 Swift Pac 30	27555	9437	3	20,2	82	480
Group 7	RR TRENT	51930	8714	3	35	152	448

2.2 Gas turbines simulation

The gas turbines were simulated with the Thermoflex version 25 (2015), varying the ambient temperature, altitude, relative humidity, gas turbine inlet pressure drop, exhaust duct load loss, and fuel. The standard operating conditions of the gas turbines used in the simulations were: ambient temperature 15 °C; ambient pressure 101,3 kPa (sea level);

relative humidity 60%; inlet pressure loss 0,87 kPa; exhaust pressure loss 0,63 kPa; and 100% load and the fuel used as standard is Methane (CH₄) (GTW, 2017). A fuel inlet temperature of 15 °C was adopted and the fuel inlet pressure was adjusted as a function of the pressure ratio (PR) of each turbine analyzed, as shown in Eq. 2.

$$Pfuel = 101,3 * PR \tag{2}$$

The variation used for each operating condition is shown in Tab.3. The simulations were made with the values set in the standard operating conditions and each condition being individually varied. For example, the ambient temperature was varied from 0 ° C (initial value) and the temperature was increased by 2 ° C until 40 ° C (final value), resulting in 21 cases of ambient temperature. While varying the ambient temperature the other operating conditions of the gas turbine remained fixed under the standard operating conditions.

Table 3. Operating conditions variation

	Initial Value	Increment	Final Value	Cases
Ambient Temperature [°C]	0	2	40	21
Altitude [m]	0	50	1000	21
Relative Humidity [%]	20	4	100	21
Inlet Pressure Loss [kPa]	0,63	0,0625	1,49	21
Exhaust Pressure Loss[kPa]	0,5	0,175	4	21

The fuel analysis was made varying the quantity of methane and air in the fuel as shown in Tab.4. The fuel composition variation represents a variation in the fuel lower heating value from 50025 kJ/kg (initial composition) to 28229 kJ/kg (final composition). Overall 6 operating conditions were analyzed for each turbine with 21 cases, as soon as the number of turbines analyzed were 19, this represented a total of 2394 cases.

Table 4. Fuel Composition

	Initial Fuel Composition [%]	Increment [%]	Final Fuel Composition [%]
Methane (CH₄)	100	-1,50	70
Nitrogen (N₂)	0	1,17	23,4
Oxygen (O₂)	0	0,33	6,6

2.3 Obtainment of the correction polynomials

Correction polynomials were created for the following performance parameters: power; heat rate, exhaust temperature; exhaust mass flow. The correction polynomials were extracted from correction curves, the correction polynomials are four-degree polynomials (Eq. 3). The performance parameters were normalized through Eq. 4. Then, a correction factor was obtained for the gas turbine groups from the average of the normalized performance factors of each gas turbine within a group. The correction factors created for the groups were used to plot curves on the Microsoft Excel, from these curves, correction polynomials (Eq. 3) were extracted.

$$FC(x) = a_4 x^4 + a_3 x^3 + a_2 x^2 + a_1 x^1 + a_0 \tag{3}$$

$$X_n = \frac{X}{X_0} \tag{4}$$

Where: X_n is the normalized performance parameter; X_0 the performance parameter in the standard conditions; X the performance parameter at off-design conditions.

2.4 Validation

In order to validate the simulations performed in Thermoflex and the methodology presented in the previous sections, correction polynomials created by Carvalho et al. (2011) were used. These correction polynomials created by Carvalho et al. (2011) can be applied to predict the performance of a GE7 FA (industrial gas turbine with 146.89 MW) at off-design conditions. The reference conditions utilized by Carvalho et al. (2011) are shown in Tab.5.

Table 5. Reference conditions utilized by Carvalho et al. (2011)

Ambient Temperature	22 °C
Ambient Pressure	91,84 kPa
Relative Humidity	67 %
Exhaust Loss	2,9890670 kPa
Inlet Loss	0,6220995 kPa
Fuel Inlet Temperature	30 °C
Fuel Inlet Pressure	2500 kPa
Fuel LHV	48334 kJ/kg

For a comparison between Carvalho et al. (2011) correction polynomials and correction polynomials obtained from the methodology described in the sections 2.1, 2.2 and 2.3 the gas turbines from Group 4 were used to create correction polynomials in the reference conditions presented in Tab.5.

Correction polynomials for power output, heat rate and mass flow as a function of inlet loss, exhaust loss, relative humidity and ambient temperature were compared with Carvalho et al. (2011) polynomials trough Eq. 5.

$$Relative\ Error = \frac{FC_{Carvalho} - FC_{methodology}}{FC_{Carvalho}} * 100\% \tag{5}$$

The largest relative error obtained by comparing the correction factors obtained by Carvalho et al. (2011) polynomials and the corrections factors obtained by the polynomials for the Group 4 turbines was 2.54%, which occurred for the power output correction factor with an exhaust loss of 3.98 kPa. Then it is concluded that the results obtained by the Thermoflex simulations and the proposed methodology can provide satisfactory results. Table 6 shows the corrections factor and relative error obtained while varying the ambient temperature for power output and heat rate.

Table 6. Values obtained for ambient temperature

Ambient Temperature (°C)	Heat Rate			Power Output		
	Methodology	Carvalho et al. (2011)	Relative Error %	Methodology	Carvalho et al. (2011)	Relative Error %
22	0.999790	1.000072	0.028%	1.000390	0.999686	0.070%
15	0.986905	0.985984	-0.093%	1.046019	1.055514	-0.908%
16.05	0.988793	0.988052	-0.075%	1.038833	1.046801	-0.767%
17.11	0.990694	0.990148	-0.055%	1.031772	1.038161	-0.619%
19.21	0.994504	0.994348	-0.016%	1.018164	1.021431	-0.321%
21.32	0.998470	0.998657	0.019%	1.004720	1.004960	-0.024%
22.37	1.000518	1.000848	0.033%	0.998030	0.996818	0.121%
23.42	1.002626	1.003075	0.045%	0.991303	0.988675	0.265%
24.47	1.004799	1.005344	0.054%	0.984520	0.980508	0.408%
25.53	1.007062	1.007680	0.061%	0.977597	0.972217	0.550%
26.58	1.009375	1.010044	0.066%	0.970656	0.963944	0.692%
27.63	1.011760	1.012460	0.069%	0.963624	0.955603	0.832%
29.74	1.016763	1.017471	0.070%	0.949219	0.938638	1.115%
30.79	1.019351	1.020040	0.068%	0.941926	0.930116	1.254%
31.84	1.021999	1.022652	0.064%	0.934566	0.921569	1.391%
32.89	1.024698	1.025299	0.059%	0.927157	0.913028	1.524%
33.95	1.027468	1.027993	0.051%	0.919652	0.904454	1.653%
35	1.030245	1.030667	0.041%	0.912219	0.896057	1.772%

3. RESULTS

Initially in tables 7 to 13 are presented the FC factors. FC are the correction factors obtained through correction polynomials for each operating condition Altitude, Fuel LHV, Exhaust Loss, Inlet Loss, Inlet Air Temperature, Relative Humidity, when gas turbine operates in off-design conditions.

The correction polynomials obtained for the group 1 are shown in Tab.7. The group 1 represents industrial gas turbines with rated power output greater than 0 MW and less than 15MW. To create the correction polynomials presented in Tab.7 the gas turbines Siemens SGT-100-1S, Mitsubishi MF111A and GE 10 were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 1 correction polynomials.

Table 7. Correction polynomials obtained for the Group 1.

		Correction Polynomials
Power Output	Altitude (m)	$FC = -6,0367E\text{-}16x^4 + 1,1574E\text{-}12x^3 + 4,6280E\text{-}09x^2 - 1,2552E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -5,4991E\text{-}21x^4 + 7,2945E\text{-}16x^3 - 1,4601E\text{-}11x^2 - 2,2166E\text{-}06x + 1,0906E\text{+}00$
	Exhaust Loss (kPa)	$FC = -5,3010E\text{-}06x^4 + 5,0700E\text{-}05x^3 - 1,5084E\text{-}04x^2 - 7,0201E\text{-}03x + 1,0044E\text{+}00$
	Inlet Loss (kPa)	$FC = -5,2031E\text{-}04x^4 + 1,7560E\text{-}03x^3 - 2,0080E\text{-}03x^2 - 1,6825E\text{-}02x + 1,0152E\text{+}00$
	Inlet Temperature (°C)	$FC = -4,6481E\text{-}08x^4 + 4,3269E\text{-}06x^3 - 1,1781E\text{-}04x^2 - 6,0180E\text{-}03x + 1,1044E\text{+}00$
	Relative Humidity (%)	$FC = 3,2237E\text{-}11x^4 - 4,5544E\text{-}09x^3 - 1,3340E\text{-}07x^2 + 7,9782E\text{-}05x + 9,9631E\text{-}01$
Heat Rate	Altitude (m)	$FC = 6,8693E\text{-}16x^4 - 1,2176E\text{-}12x^3 + 1,4030E\text{-}09x^2 + 6,9293E\text{-}06x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -1,3997E\text{-}21x^4 + 3,0215E\text{-}16x^3 - 3,1780E\text{-}11x^2 + 2,0682E\text{-}06x + 9,4698E\text{-}01$
	Exhaust Loss (kPa)	$FC = 3,6347E\text{-}08x^4 - 9,7385E\text{-}07x^3 + 3,3471E\text{-}05x^2 + 7,4041E\text{-}03x + 9,9552E\text{-}01$
	Inlet Loss (kPa)	$FC = 1,2790E\text{-}04x4 - 6,0550E\text{-}04x^3 + 1,0758E\text{-}03x^2 + 7,2193E\text{-}03x + 9,9322E\text{-}01$
	Inlet Temperature (°C)	$FC = 2,5229E\text{-}08x^4 - 2,1515E\text{-}06x^3 + 8,1089E\text{-}05x^2 + 1,0671E\text{-}03x + 9,7149E\text{-}01$
	Relative Humidity (%)	$FC = 9,7249E\text{-}13x^4 - 5,0941E\text{-}10x^3 + 9,2469E\text{-}08x^2 + 1,5867E\text{-}05x + 9,9882E\text{-}01$
Exhaust Flow	Altitude (m)	$FC = 5,0441E\text{-}16x^4 - 6,8937E\text{-}14x^3 + 4,2711E\text{-}09x^2 - 1,1893E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = 6,7883E\text{-}21x^4 - 1,3484E\text{-}15x^3 + 1,0474E\text{-}10x^2 - 4,2085E\text{-}06x + 1,0747E\text{+}00$
	Exhaust Loss (kPa)	$FC = 2,1316E\text{-}14x^4 - 2,1316E\text{-}13x^3 + 8,5620E\text{-}13x^2 + 6,5725E\text{-}13x + 1,0000E\text{+}00$
	Inlet Loss (kPa)	$FC = -2,2944E\text{-}04x^4 + 8,7705E\text{-}04x^3 - 1,0861E\text{-}03x^2 - 9,4635E\text{-}03x + 1,0089E\text{+}00$
	Inlet Temperature (°C)	$FC = 2,2114E\text{-}08x^4 - 1,2421E\text{-}06x^3 - 1,3086E\text{-}06x^2 - 3,4874E\text{-}03x + 1,0541E\text{+}00$
	Relative Humidity (%)	$FC = 1,7287E\text{-}11x^4 - 3,2785E\text{-}09x^3 + 1,5768E\text{-}07x^2 - 6,1670E\text{-}05x + 1,0037E\text{+}00$
Exhaust Temperature	Altitude (m)	$FC = 9,6593E\text{-}16x^4 - 2,0495E\text{-}12x^3 + 1,5430E\text{-}09x^2 + 4,0616E\text{-}07x + 9,9998E\text{-}01$
	Fuel LHV (kJ/kg)	$FC = 2,0167E\text{-}21x^4 - 1,2625E\text{-}16x^3 - 9,1495E\text{-}12x^2 + 1,0026E\text{-}06x + 9,7588E\text{-}01$
	Exhaust Loss (kPa)	$FC = -1,7429E\text{-}06x^4 + 1,1597E\text{-}05x^3 - 3,0405E\text{-}05x^2 + 3,3763E\text{-}03x + 9,9900E\text{-}01$
	Inlet Loss (kPa)	$FC = -4,1549E\text{-}04x^4 + 1,3109E\text{-}03x^3 - 1,3697E\text{-}03x^2 + 4,0040E\text{-}03x + 9,9691E\text{-}01$
	Inlet Temperature (°C)	$FC = -3,1789E\text{-}08x^4 + 3,3195E\text{-}06x^3 - 1,1813E\text{-}04x^2 + 3,3001E\text{-}03x + 9,6812E\text{-}01$
	Relative Humidity (%)	$FC = 2,0469E\text{-}11x^4 - 5,3217E\text{-}09x^3 + 4,4658E\text{-}07x^2 + 1,7690E\text{-}05x + 9,8819E\text{-}01$

The correction polynomials obtained for the group 2 are shown in Tab.8. The group 2 represents industrial gas turbines with rated power output greater than 15MW and less than 50MW. To create the correction polynomials presented in Tab.8 the gas turbines Siemens SGT-600, Alstom GT9D and GE 6541B were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 2 correction polynomials.

Table 8. Correction polynomials obtained for the Group 2.

		Correction Polynomials
Power Output	Altitude (m)	$FC = -3{,}7123E{-}17x^4 + 7{,}2322E{-}14x^3 + 5{,}3049E{-}09x^2 - 1{,}2540E{-}04x + 1{,}0000E{+}00$
	Fuel LHV (kJ/kg)	$FC = -4{,}3953E{-}21x^4 + 4{,}1963E{-}16x^3 + 1{,}2898E{-}11x^2 - 3{,}1733E{-}06x + 1{,}1015E{+}00$
	Exhaust Loss (kPa)	$FC = -2{,}0959E{-}06x^4 + 1{,}9979E{-}05x^3 + 5{,}1610E{-}06x^2 - 8{,}4729E{-}03x + 1{,}0053E{+}00$
	Inlet Loss (kPa)	$FC = -9{,}1273E{-}05x^4 + 3{,}2093E{-}04x^3 - 2{,}9892E{-}04x^2 - 1{,}8994E{-}02x + 1{,}0166E{+}00$
	Inlet Temperature (°C)	$FC = -3{,}8805E{-}08x^4 + 4{,}3698E{-}06x^3 - 1{,}7292E{-}04x^2 - 4{,}3842E{-}03x + 1{,}0910E{+}00$
	Relative Humidity (%)	$FC = 3{,}2455E{-}11x^4 - 9{,}9131E{-}09x^3 + 8{,}7636E{-}07x^2 - 2{,}0117E{-}05x + 9{,}9979E{-}01$
Heat Rate	Altitude (m)	$FC = -1{,}9963E{-}16x^4 + 4{,}5571E{-}13x^3 + 3{,}8986E{-}10x^2 + 7{,}1608E{-}06x + 1{,}0000E{+}00$
	Fuel LHV (kJ/kg)	$FC = 4{,}6975E{-}21x^4 - 6{,}6620E{-}16x^3 + 2{,}5439E{-}11x^2 + 5{,}4945E{-}07x + 9{,}6282E{-}01$
	Exhaust Loss (kPa)	$FC = 1{,}7607E{-}06x^4 - 1{,}2821E{-}05x^3 + 4{,}0566E{-}05x^2 + 8{,}4994E{-}03x + 9{,}9464E{-}01$
	Inlet Loss (kPa)	$FC = -2{,}1899E{-}05x^4 + 1{,}3575E{-}04x^3 - 1{,}5527E{-}04x^2 + 9{,}1362E{-}03x + 9{,}9210E{-}01$
	Inlet Temperature (°C)	$FC = 4{,}6381E{-}08x^4 - 4{,}3247E{-}06x^3 + 1{,}7478E{-}04x^2 - 4{,}8133E{-}04x + 9{,}8014E{-}01$
	Relative Humidity (%)	$FC = -1{,}7435E{-}11x^4 + 4{,}8710E{-}09x^3 - 4{,}4713E{-}07x^2 + 6{,}2392E{-}05x + 9{,}9704E{-}01$
Exhaust Flow	Altitude (m)	$FC = 5{,}4733E{-}15x^4 - 1{,}1914E{-}11x^3 + 1{,}3366E{-}08x^2 - 1{,}2110E{-}04x + 1{,}0001E{+}00$
	Fuel LHV (kJ/kg)	$FC = 1{,}3178E{-}20x^4 - 2{,}0807E{-}15x^3 + 1{,}3187E{-}10x^2 - 4{,}5342E{-}06x + 1{,}0748E{+}00$
	Exhaust Loss (kPa)	$FC = 2{,}8422E{-}14x^4 - 3{,}9790E{-}13x^3 + 1{,}1227E{-}12x^2 - 1{,}9753E{-}12x + 1{,}0000E{+}00$
	Inlet Loss (kPa)	$FC = 1{,}3263E{-}04x^4 - 1{,}3962E{-}03x^3 + 2{,}8924E{-}03x^2 - 1{,}2032E{-}02x + 1{,}0092E{+}00$
	Inlet Temperature (°C)	$FC = 3{,}9531E{-}09x^4 - 2{,}6289E{-}07x^3 + 5{,}0618E{-}06x^2 - 3{,}2058E{-}03x + 1{,}0469E{+}00$
	Relative Humidity (%)	$FC = -6{,}2638E{-}11x^4 + 1{,}3769E{-}08x^3 - 1{,}0557E{-}06x^2 - 2{,}9140E{-}05x + 1{,}0034E{+}00$
Exhaust Temperature	Altitude (m)	$FC = 1{,}9542E{-}15x^4 - 3{,}5171E{-}12x^3 + 1{,}9261E{-}09x^2 + 8{,}5891E{-}07x + 1{,}0000E{+}00$
	Fuel LHV (kJ/kg)	$FC = 1{,}3993E{-}20x^4 - 2{,}1804E{-}15x^3 + 1{,}2231E{-}10x^2 - 2{,}7180E{-}06x + 1{,}0152E{+}00$
	Exhaust Loss (kPa)	$FC = 9{,}8688E{-}06x^4 - 9{,}5845E{-}05x^3 + 2{,}8743E{-}04x^2 + 3{,}0747E{-}03x + 9{,}9799E{-}01$
	Inlet Loss (kPa)	$FC = -1{,}1943E{-}03x^4 + 4{,}5641E{-}03x^3 - 5{,}9975E{-}03x^2 + 6{,}5256E{-}03x + 9{,}9653E{-}01$
	Inlet Temperature (°C)	$FC = 2{,}0182E{-}09x^4 - 3{,}2230E{-}07x^3 + 1{,}6508E{-}05x^2 + 1{,}1302E{-}04x + 9{,}9560E{-}01$
	Relative Humidity (%)	$FC = -3{,}2262E{-}12x^4 + 1{,}4720E{-}09x^3 - 2{,}5955E{-}07x^2 + 5{,}7882E{-}05x + 9{,}9714E{-}01$

The correction polynomials obtained for the group 3 are shown in Tab.9. The group 3 represents industrial gas turbines with rated power output greater than 50MW and less than 100MW. To create the correction polynomials presented in Tab.9 the gas turbines Siemens SGT-3000E, Alstom GT8C and GE 7101 were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 3 correction polynomials.

Table 9. Correction polynomials obtained for the Group 3.

		Correction Polynomials
Power Output	Altitude (m)	$FC = 4,3437E\text{-}17x^4 - 7,3051E\text{-}14x^3 + 5,2461E\text{-}09x^2 - 1,2194E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = 5,1222E\text{-}21x^4 - 1,1040E\text{-}15x^3 + 1,0011E\text{-}10x^2 - 5,0935E\text{-}06x + 1,1104E\text{+}00$
	Exhaust Loss (kPa)	$FC = 7,5135E\text{-}07x^4 - 6,9317E\text{-}06x^3 + 6,6305E\text{-}05x^2 - 6,4309E\text{-}03x + 1,0040E\text{+}00$
	Inlet Loss (kPa)	$FC = 8,5562E\text{-}06x^4 - 1,9201E\text{-}05x^3 + 6,2833E\text{-}05x^2 - 1,6740E\text{-}02x + 1,0145E\text{+}00$
	Inlet Temperature (°C)	$FC = 6,9378E\text{-}08x^4 - 6,1207E\text{-}06x^3 + 1,4681E\text{-}04x^2 - 8,3215E\text{-}03x + 1,1094E\text{+}00$
	Relative Humidity (%)	$FC = -8,7547E\text{-}13x^4 + 2,9917E\text{-}10x^3 - 4,1003E\text{-}08x^2 + 4,5490E\text{-}06x + 9,9982E\text{-}01$
Heat Rate	Altitude (m)	$FC = -1,3190E\text{-}16x^4 + 3,7468E\text{-}13x^3 + 1,9701E\text{-}11x^2 + 3,4047E\text{-}06x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -4,2125E\text{-}22x^4 + 1,6807E\text{-}16x^3 - 2,2672E\text{-}11x^2 + 1,5637E\text{-}06x + 9,6011E\text{-}01$
	Exhaust Loss (kPa)	$FC = -2,1432E\text{-}06x^4 + 2,5680E\text{-}05x^3 - 9,1728E\text{-}05x^2 + 6,8613E\text{-}03x + 9,9572E\text{-}01$
	Inlet Loss (kPa)	$FC = 1,4851E\text{-}04x^4 - 4,8594E\text{-}04x^3 + 6,0673E\text{-}04x^2 + 6,7226E\text{-}03x + 9,9395E\text{-}01$
	Inlet Temperature (°C)	$FC = -3,6161E\text{-}08x^4 + 3,8717E\text{-}06x^3 - 7,9226E\text{-}05x^2 + 2,2599E\text{-}03x + 9,7208E\text{-}01$
	Relative Humidity (%)	$FC = -9,0761E\text{-}12x^4 + 2,4179E\text{-}09x^3 - 2,1286E\text{-}07x^2 + 4,1170E\text{-}05x + 9,9790E\text{-}01$
Exhaust Flow	Altitude (m)	$FC = -1,8676E\text{-}15x^4 + 4,9860E\text{-}12x^3 + 7,6630E\text{-}10x^2 - 1,1808E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -9,2775E\text{-}21x^4 + 1,1637E\text{-}15x^3 - 4,0507E\text{-}11x^2 - 4,9194E\text{-}07x + 1,0385E\text{+}00$
	Exhaust Loss (kPa)	$FC = 2,1316E\text{-}14x^4 - 2,1316E\text{-}13x^3 + 8,5620E\text{-}13x^2 + 6,5725E\text{-}13x + 1,0000E\text{+}00$
	Inlet Loss (kPa)	$FC = -6,8260E\text{-}04x^4 + 2,3167E\text{-}03x^3 - 2,9999E\text{-}03x^2 - 8,2451E\text{-}03x + 1,0085E\text{+}00$
	Inlet Temperature (°C)	$FC = -8,7167E\text{-}10x^4 + 1,0387E\text{-}07x^3 - 9,2197E\text{-}06x^2 - 3,9104E\text{-}03x + 1,0602E\text{+}00$
	Relative Humidity (%)	$FC = -3,5514E\text{-}11x^4 + 7,9580E\text{-}09x^3 - 6,2472E\text{-}07x^2 - 4,1683E\text{-}05x + 1,0036E\text{+}00$
Exhaust Temperature	Altitude (m)	$FC = 5,4980E\text{-}16x^4 - 1,6319E\text{-}12x^3 + 1,6260E\text{-}09x^2 + 1,4604E\text{-}07x + 9,9999E\text{-}01$
	Fuel LHV (kJ/kg)	$FC = -5,1252E\text{-}21x^4 + 8,5040E\text{-}16x^3 - 5,3861E\text{-}11x^2 + 1,6640E\text{-}06x + 9,7718E\text{-}01$
	Exhaust Loss (kPa)	$FC = 5,1653E\text{-}06x^4 - 4,4428E\text{-}05x^3 + 1,2602E\text{-}04x^2 + 2,9084E\text{-}03x + 9,9814E\text{-}01$
	Inlet Loss (kPa)	$FC = -6,2344E\text{-}04x^4 + 2,4276E\text{-}03x^3 - 3,1785E\text{-}03x^2 + 4,6803E\text{-}03x + 9,9708E\text{-}01$
	Inlet Temperature (°C)	$FC = 1,1630E\text{-}09x^4 - 1,0063E\text{-}07x^3 + 8,9463E\text{-}06x^2 + 1,2390E\text{-}03x + 9,7985E\text{-}01$
	Relative Humidity (%)	$FC = 1,8643E\text{-}11x^4 - 5,2650E\text{-}09x^3 + 5,1890E\text{-}07x^2 - 5,7571E\text{-}08x + 9,9902E\text{-}01$

The correction polynomials obtained for the group 4 are shown in Tab.10. The group 4 represents industrial gas turbines with rated power output greater than 100MW. To create the correction polynomials presented in Tab.10 the gas turbines Siemens SGT5-2000E, GE9331 FA and GE 9001H were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 4 correction polynomials.

Table 10. Correction polynomials obtained for the Group 4.

		Correction Polynomials
Power Output	Altitude (m)	$FC = 1{,}1455E\text{-}18x^4 - 1{,}0993E\text{-}14x^3 + 5{,}1787E\text{-}09x^2 - 1{,}2094E\text{-}04x + 1{,}0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -3{,}3828E\text{-}20x^4 + 5{,}5253E\text{-}15x^3 - 3{,}2022E\text{-}10x^2 + 6{,}4989E\text{-}06x + 9{,}9639E\text{-}01$
	Exhaust Loss (kPa)	$FC = -2{,}5080E\text{-}07x^4 + 2{,}7749E\text{-}06x^3 - 2{,}3429E\text{-}05x^2 - 3{,}2434E\text{-}03x + 1{,}0021E\text{+}00$
	Inlet Loss (kPa)	$FC = -1{,}0956E\text{-}06x^4 + 3{,}8454E\text{-}06x^3 - 2{,}0092E\text{-}05x^2 - 1{,}3300E\text{-}02x + 1{,}0116E\text{+}00$
	Inlet Temperature (°C)	$FC = -4{,}3810E\text{-}08x^4 + 4{,}3714E\text{-}06x^3 - 1{,}6692E\text{-}04x^2 - 3{,}2813E\text{-}03x + 1{,}0731E\text{+}00$
	Relative Humidity (%)	$FC = 3{,}7756E\text{-}11x^4 - 1{,}1293E\text{-}08x^3 + 1{,}0064E\text{-}06x^2 - 1{,}6646E\text{-}05x + 9{,}9933E\text{-}01$
Heat Rate	Altitude (m)	$FC = 1{,}3360E\text{-}15x^4 - 3{,}0305E\text{-}12x^3 + 2{,}6060E\text{-}09x^2 + 3{,}0266E\text{-}06x + 1{,}0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = 4{,}4960E\text{-}21x^4 - 6{,}6804E\text{-}16x^3 + 2{,}9741E\text{-}11x^2 + 1{,}7161E\text{-}07x + 9{,}7246E\text{-}01$
	Exhaust Loss (kPa)	$FC = 1{,}6199E\text{-}06x^4 - 1{,}5859E\text{-}05x^3 + 5{,}4543E\text{-}05x^2 + 4{,}8903E\text{-}03x + 9{,}9687E\text{-}01$
	Inlet Loss (kPa)	$FC = -1{,}2199E\text{-}04x^4 + 5{,}9777E\text{-}04x^3 - 8{,}8935E\text{-}04x^2 + 5{,}7439E\text{-}03x + 9{,}9531E\text{-}01$
	Inlet Temperature (°C)	$FC = 2{,}3732E\text{-}08x^4 - 2{,}1528E\text{-}06x^3 + 8{,}9060E\text{-}05x^2 + 1{,}8964E\text{-}04x + 9{,}8335E\text{-}01$
	Relative Humidity (%)	$FC = -9{,}2898E\text{-}14x^4 + 3{,}5493E\text{-}12x^3 + 3{,}0127E\text{-}08x^2 + 3{,}2062E\text{-}05x + 9{,}9796E\text{-}01$
Exhaust Flow	Altitude (m)	$FC = -1{,}6227E\text{-}15x^4 + 3{,}2942E\text{-}12x^3 + 3{,}1726E\text{-}09x^2 - 1{,}1911E\text{-}04x + 1{,}0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = 7{,}0201E\text{-}21x^4 - 1{,}2564E\text{-}15x^3 + 9{,}5135E\text{-}11x^2 - 4{,}1022E\text{-}06x + 1{,}0805E\text{+}00$
	Exhaust Loss (kPa)	$FC = 1{,}2941E\text{-}05x^4 - 1{,}1750E\text{-}04x^3 + 3{,}4413E\text{-}04x^2 - 3{,}1960E\text{-}04x + 1{,}0001E\text{+}00$
	Inlet Loss (kPa)	$FC = 1{,}2296E\text{-}04x^4 - 6{,}5872E\text{-}04x^3 + 1{,}1659E\text{-}03x^2 - 1{,}0739E\text{-}02x + 1{,}0088E\text{+}00$
	Inlet Temperature (°C)	$FC = 2{,}2718E\text{-}08x^4 - 1{,}2754E\text{-}06x^3 - 4{,}0839E\text{-}06x^2 - 3{,}0250E\text{-}03x + 1{,}0479E\text{+}00$
	Relative Humidity (%)	$FC = 1{,}7129E\text{-}11x^4 - 4{,}2177E\text{-}09x^3 + 3{,}6848E\text{-}07x^2 - 7{,}4804E\text{-}05x + 1{,}0039E\text{+}00$
Exhaust Temperature	Altitude (m)	$FC = -7{,}8875E\text{-}16x^4 + 1{,}6642E\text{-}12x^3 - 1{,}0768E\text{-}09x^2 + 1{,}1843E\text{-}06x + 1{,}0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -2{,}6624E\text{-}20x^4 + 4{,}6601E\text{-}15x^3 - 3{,}0882E\text{-}10x^2 + 9{,}3926E\text{-}06x + 8{,}8626E\text{-}01$
	Exhaust Loss (kPa)	$FC = 1{,}8900E\text{-}06x^4 - 2{,}5812E\text{-}05x^3 + 8{,}5672E\text{-}05x^2 + 4{,}2707E\text{-}03x + 9{,}9724E\text{-}01$
	Inlet Loss (kPa)	$FC = -2{,}5264E\text{-}04x^4 + 6{,}8315E\text{-}04x^3 - 5{,}4330E\text{-}04x^2 + 4{,}6069E\text{-}03x + 9{,}9604E\text{-}01$
	Inlet Temperature (°C)	$FC = -2{,}9086E\text{-}08x^4 + 1{,}8398E\text{-}06x^3 - 2{,}8981E\text{-}05x^2 + 1{,}5830E\text{-}03x + 9{,}7860E\text{-}01$
	Relative Humidity (%)	$FC = 6{,}2904E\text{-}11x^4 - 1{,}6346E\text{-}08x^3 + 1{,}4028E\text{-}06x^2 - 1{,}1775E\text{-}05x + 9{,}9834E\text{-}01$

The correction polynomials obtained for the group 5 are shown in Tab.11. The group 5 represents aeroderivative gas turbines with rated power output greater than 0MW and less than 15MW. To create the correction polynomials presented in Tab.11 the gas turbines Solar Taurus 70, GE LM500 and Rolls-Royce 501-KB7 were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 5 correction polynomials.

Table 11. Correction polynomials obtained for the Group 5.

		Correction Polynomials
Power Output	Altitude (m)	$FC = 1,7901E\text{-}15x^4 - 3,5994E\text{-}12x^3 + 7,7447E\text{-}09x^2 - 1,2753E\text{-}04x + 9,9999E\text{-}01$
	Fuel LHV (kJ/kg)	$FC = 6,7646E\text{-}21x^4 - 1,2651E\text{-}15x^3 + 1,0660E\text{-}10x^2 - 5,5131E\text{-}06x + 1,1251E+00$
	Exhaust Loss (kPa)	$FC = -8,5977E\text{-}06x^4 + 7,8558E\text{-}05x^3 - 2,1390E\text{-}04x^2 - 7,2792E\text{-}03x + 1,0047E+00$
	Inlet Loss (kPa)	$FC = 2,9579E\text{-}04x^4 - 1,0417E\text{-}03x^3 + 1,3033E\text{-}03x^2 - 1,9928E\text{-}02x + 1,0176E+00$
	Inlet Temperature (°C)	$FC = -2,8559E\text{-}08x^4 + 2,3912E\text{-}06x^3 - 8,1105E\text{-}05x^2 - 6,1921E\text{-}03x + 1,1032E+00$
	Relative Humidity (%)	$FC = 2,4886E\text{-}11x^4 - 6,5013E\text{-}09x^3 + 3,7675E\text{-}07x^2 + 3,2827E\text{-}05x + 9,9777E\text{-}01$
Heat Rate	Altitude (m)	$FC = 1,0346E\text{-}15x^4 - 1,9664E\text{-}12x^3 + 2,0560E\text{-}09x^2 + 8,0774E\text{-}06x + 1,0000E+00$
	Fuel LHV (kJ/kg)	$FC = 5,0249E\text{-}21x^4 - 7,2152E\text{-}16x^3 + 2,9985E\text{-}11x^2 + 3,5127E\text{-}07x + 9,6624E\text{-}01$
	Exhaust Loss (kPa)	$FC = -3,3977E\text{-}06x^4 + 3,2784E\text{-}05x^3 - 7,8139E\text{-}05x^2 + 7,5985E\text{-}03x + 9,9511E\text{-}01$
	Inlet Loss (kPa)	$FC = -5,3997E\text{-}04x^4 + 1,9588E\text{-}03x^3 - 2,3409E\text{-}03x^2 + 9,7037E\text{-}03x + 9,9201E\text{-}01$
	Inlet Temperature (°C)	$FC = 5,0287E\text{-}08x^4 - 3,3817E\text{-}06x^3 + 1,0149E\text{-}04x^2 + 9,2764E\text{-}04x + 9,7193E\text{-}01$
	Relative Humidity (%)	$FC = 1,2528E\text{-}11x^4 - 1,8431E\text{-}09x^3 + 1,0514E\text{-}07x^2 + 2,7539E\text{-}05x + 9,9820E\text{-}01$
Exhaust Flow	Altitude (m)	$FC = 3,5392E\text{-}15x^4 - 6,1123E\text{-}12x^3 + 8,3818E\text{-}09x^2 - 1,1999E\text{-}04x + 1,0000E+00$
	Fuel LHV (kJ/kg)	$FC = -1,0116E\text{-}20x^4 + 1,4212E\text{-}15x^3 - 6,2264E\text{-}11x^2 + 1,9279E\text{-}07x + 1,0315E+00$
	Exhaust Loss (kPa)	$FC = -1,4211E\text{-}14x^4 + 1,7053E\text{-}13x^3 - 3,4106E\text{-}13x^2 - 6,8212E\text{-}13x + 1,0000E+00$
	Inlet Loss (kPa)	$FC = -9,5849E\text{-}04x^4 + 3,5432E\text{-}03x^3 - 4,5919E\text{-}03x^2 - 8,2030E\text{-}03x + 1,0091E+00$
	Inlet Temperature (°C)	$FC = 3,9768E\text{-}08x^4 - 2,2228E\text{-}06x^3 - 4,4583E\text{-}06x^2 - 2,9986E\text{-}03x + 1,0487E+00$
	Relative Humidity (%)	$FC = 2,5915E\text{-}11x^4 - 7,4946E\text{-}09x^3 + 7,5886E\text{-}07x^2 - 9,3944E\text{-}05x + 1,0042E+00$
Exhaust Temperature	Altitude (m)	$FC = 2,0356E\text{-}15x^4 - 4,0719E\text{-}12x^3 + 2,7241E\text{-}09x^2 + 2,0812E\text{-}07x + 1,0000E+00$
	Fuel LHV (kJ/kg)	$FC = 4,3618E\text{-}21x^4 - 5,9166E\text{-}16x^3 + 2,4727E\text{-}11x^2 - 9,5403E\text{-}08x + 9,8962E\text{-}01$
	Exhaust Loss (kPa)	$FC = 4,1697E\text{-}06x^4 - 3,9249E\text{-}05x^3 + 1,1314E\text{-}04x^2 + 3,0439E\text{-}03x + 9,9799$
	Inlet Loss (kPa)	$FC = 1,2882E\text{-}03x^4 - 4,1557E\text{-}03x^3 + 4,5107E\text{-}03x^2 + 1,5981E\text{-}03x + 9,9703E\text{-}01$
	Inlet Temperature (°C)	$FC = -8,2670E\text{-}09x^4 + 1,1779E\text{-}07x^3 + 3,3972E\text{-}05x^2 + 4,4721E\text{-}04x + 9,8640E\text{-}01$
	Relative Humidity (%)	$FC = 5,9511E\text{-}11x^4 - 1,5308E\text{-}08x^3 + 1,2528E\text{-}06x^2 + 3,8199E\text{-}05x + 9,9575E\text{-}01$

   The correction polynomials obtained for the group 6 are shown in Tab.12. The group 6 represents aeroderivative gas turbines with rated power output greater than 15MW and less than 50MW. To create the correction polynomials presented in Tab.12 the gas turbines GE LM6000 PA, GE LM200 and Pratt & Whitney FT8 Swift Pac 30 were simulated in Thermoflex version 25 (2015). For each gas turbine 126 simulations were made, resulting in a total of 378 simulations to obtain Group 6 correction polynomials.

Table 12. Correction polynomials obtained for the Group 6.

		Correction Polynomials
Power Output	Altitude (m)	$FC = 2,9011E\text{-}17x^4 - 8,6648E\text{-}14x^3 + 5,3151E\text{-}09x^2 - 1,2234E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = 7,5757E\text{-}21x^4 - 1,5907E\text{-}15x^3 + 1,4018E\text{-}10x^2 - 6,8590E\text{-}06x + 1,1440E\text{+}00$
	Exhaust Loss (kPa)	$FC = -1,2828E\text{-}06x^4 + 1,3364E\text{-}05x^3 - 5,3442E\text{-}05x^2 - 3,2801E\text{-}03x + 1,0021E\text{+}00$
	Inlet Loss (kPa)	$FC = 1,3262E\text{-}04x^4 - 4,4554E\text{-}04x^3 + 5,4592E\text{-}04x^2 - 1,5612E\text{-}02x + 1,0134E\text{+}00$
	Inlet Temperature (°C)	$FC = -7,8916E\text{-}08x^4 + 9,6312E\text{-}06x^3 - 4,6652E\text{-}04x^2 - 4,5668E\text{-}04x + 1,0845E\text{+}00$
	Relative Humidity (%)	$FC = 5,0495E\text{-}11x^4 - 1,1039E\text{-}08x^3 + 7,1003E\text{-}07x^2 + 2,0462E\text{-}05x + 9,9795E\text{-}01$
Heat Rate	Altitude (m)	$FC = -6,0357E\text{-}17x4 - 8,0742E\text{-}15x^3 + 3,9571E\text{-}10x^2 + 3,7810E\text{-}06x + 1,000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -1,9790E\text{-}21x^4 + 4,4185E\text{-}16x^3 - 4,2299E\text{-}11x^2 + 2,3098E\text{-}06x + 9,4736E\text{-}01$
	Exhaust Loss (kPa)	$FC = -4,0086E\text{-}07x^4 + 4,7494E\text{-}06x^3 - 1,1867E\text{-}05x^2 + 4,2112E\text{-}03x + 9,9732E\text{-}01$
	Inlet Loss (kPa)	$FC = -2,9286E\text{-}04x^4 + 1,0560E\text{-}03x^3 - 1,2475E\text{-}03x^2 + 5,8591E\text{-}03x + 9,9530E\text{-}01$
	Inlet Temperature (°C)	$FC = 5,6581E\text{-}09x^4 + 7,1999E\text{-}08x^3 + 3,3840E\text{-}05x^2 + 7,5760E\text{-}04x + 9,7996E\text{-}01$
	Relative Humidity (%)	$FC = -6,3810E\text{-}12x^4 + 1,4317E\text{-}09x^3 - 8,9040E\text{-}08x^2 + 3,3278E\text{-}05x + 9,9809E\text{-}01$
Exhaust Flow	Altitude (m)	$FC = 7,9593E\text{-}16x^4 - 1,5505E\text{-}12x^3 + 5,8443E\text{-}09x^2 - 1,1939E\text{-}04x + 1,0000E\text{+}00$
	Fuel LHV (kJ/kg)	$FC = -3,2210E\text{-}20x^4 + 4,8741E\text{-}15x^3 - 2,6265E\text{-}10x^2 + 5,2968E\text{-}06x + 9,8390E\text{-}01$
	Exhaust Loss (kPa)	$FC = 2,1316E\text{-}14x^4 - 2,1316E\text{-}13x^3 + 8,5620E\text{-}13x^2 + 6,5725E\text{-}13x + 1,0000E\text{+}00$
	Inlet Loss (kPa)	$FC = 3,5659E\text{-}04x^4 - 8,1858E\text{-}04x^3 + 3,2776E\text{-}04x^2 - 9,7150E\text{-}03x + 1,0087E\text{+}00$
	Inlet Temperature (°C)	$FC = 3,6075E\text{-}09x^4 + 1,3933E\text{-}06x^3 - 1,2412E\text{-}04x^2 - 3,1838E\text{-}03x + 1,0682E\text{+}00$
	Relative Humidity (%)	$FC = -1,2946E\text{-}10x^4 + 3,0662E\text{-}08x^3 - 2,5698E\text{-}06x^2 + 2,8032E\text{-}05x + 1,0027E\text{+}00$
Exhaust Temperature	Altitude (m)	$FC = -1,3506E\text{-}15x^4 + 2,5050E\text{-}12x^3 - 1,3664E\text{-}09x^2 + 1,0974E\text{-}06x + 9,9997E\text{-}01$
	Fuel LHV (kJ/kg)	$FC = -6,4772E\text{-}22x^4 + 8,5175E\text{-}17x^3 - 5,7974E\text{-}12x^2 + 3,2644E\text{-}07x + 9,9159E\text{-}01$
	Exhaust Loss (kPa)	$FC = 3,8465E\text{-}06x^4 - 2,7355E\text{-}05x^3 + 4,8994E\text{-}05x^2 + 2,4049E\text{-}03x + 9,9961E\text{-}01$
	Inlet Loss (kPa)	$FC = -1,2806E\text{-}03x^4 + 4,3953E\text{-}03x^3 - 5,2515E\text{-}03x^2 + 5,3614E\text{-}03x + 9,9715E\text{-}01$
	Inlet Temperature (°C)	$FC = -7,6270E\text{-}08x^4 + 6,7007E\text{-}06x^3 - 2,4185E\text{-}04x^2 + 5,2001E\text{-}03x + 9,6031E\text{-}01$
	Relative Humidity (%)	$FC = 9,8521E\text{-}11x^4 - 2,2186E\text{-}08x^3 + 1,6378E\text{-}06x^2 + 4,7841E\text{-}06x + 9,9733E\text{-}01$

The correction polynomials obtained for the group 7 are shown in Tab.11. The group 7 represents aeroderivative gas turbines with rated power output greater than 50MW. To create the correction polynomials presented in Tab.13 the gas turbine Rolls-Royce TRENT were simulated in Thermoflex version 25 (2015). The gas turbine was simulated 126 times to obtain Group 7 correction polynomials.

Table 13. Correction polynomials obtained for the Group 7.

		Correction Polynomials
Power Output	Altitude (m)	$FC = -2,1425E-16x^4 + 4,2135E-13x^3 + 4,9099E-09x^2 - 1,2118E-04x + 1,0000E+00$
	Fuel LHV (kJ/kg)	$FC = 4,4244E-21x^4 - 1,0639E-15x^3 + 1,0663E-10x^2 - 5,8351E-06x + 1,1305E+00$
	Exhaust Loss (kPa)	$FC = -1,3681E-06x^4 + 1,1926E-05x^3 - 6,3470E-05x^2 - 3,6162E-03x + 1,0023E+00$
	Inlet Loss (kPa)	$FC = -6,0056E-05x^4 + 1,9667E-04x^3 - 2,6270E-04x^2 - 1,3660E-02x + 1,0120E+00$
	Inlet Temperature (°C)	$FC = 5,9936E-08x^4 - 3,4352E-06x^3 + 2,6680E-05x^2 - 8,7184E-03x + 1,1313E+00$
	Relative Humidity (%)	$FC= -5,4789E-12x^4 + 1,5529E-09x^3 - 1,5010E-07x^2 + 1,0420E-05x + 9,9966E-01$
Heat Rate	Altitude (m)	$FC = -5,9379E-09x^4 + 3,0457E-07x^3 - 4,3542E-06x^2 + 1,5925E-04x + 9,9984E-01$
	Fuel LHV (kJ/kg)	$FC = 8,7074E-21x^4 - 1,1976E-15x^3 + 5,0001E-11x^2 + 1,0137E-07x + 9,6519E-01$
	Exhaust Loss (kPa)	$FC = -2,6211E-06x^4 + 2,0908E-05x^3 - 3,4459E-05x^2 + 4,8137E-03x + 9,9701E-01$
	Inlet Loss (kPa)	$FC = -3,1953E-04x^4 + 1,1103E-03x^3 - 1,2848E-03x^2 + 5,5610E-03x + 9,9559E-01$
	Inlet Temperature (°C)	$FC = -1,2777E-08x^4 + 9,0559E-07x^3 + 1,1522E-05x^2 + 1,5252E-03x + 9,7210E-01$
	Relative Humidity (%)	$FC = -5,1360E-11x^4 + 1,2013E-08x^3 - 9,8635E-07x^2 + 5,8314E-05x + 9,9813E-01$
Exhaust Flow	Altitude (m)	$FC = -2,3009E-15x^4 + 6,8938E-12x^3 - 1,5939E-09x^2 - 1,1719E-04x + 1,0001E+00$
	Fuel LHV (kJ/kg)	$FC = 7,9790E-20x^4 - 1,2326E-14x^3 + 7,1277E-10x^2 - 1,8867E-05x + 1,2035E+00$
	Exhaust Loss (kPa)	$FC = 3,8465E-21x^4 - 5,6843E-14x^3 + 9,9476E-13x^2 - 4,0217E-12x + 1,0000E+00$
	Inlet Loss (kPa)	$FC = 6,0685E-03x^4 - 2,1994E-02x^3 + 2,6754E-02x^2 - 2,2012E-02x + 1,0099E+00$
	Inlet Temperature (°C)	$FC = 7,5717E-08x^4 - 4,1056E-06x^3 + 1,6410E-06x^2 - 4,8825E-03x + 1,0788E+00$
	Relative Humidity (%)	$FC = -6,6568E-10x^4 + 1,4554E-07x^3 - 1,1195E-05x^2 + 2,9414E-04x + 9,9949E-01$
Exhaust Temperature	Altitude (m)	$FC = 3,2754E-15x^4 - 6,9105E-12x^3 + 4,8252E-09x^2 - 3,1138E-07x + 9,9999E-01$
	Fuel LHV (kJ/kg)	$FC = -2,4347E-20x^4 + 3,8061E-15x^3 - 2,2494E-10x^2 + 6,2266E-06x + 9,2748E-01$
	Exhaust Loss (kPa)	$FC = 8,4369E-06x^4 - 7,7528E-05x^3 + 1,7483E-04x^2 + 4,1561E-03x + 9,9738E-01$
	Inlet Loss (kPa)	$FC = 1,1088E-03x^4 - 3,7737E-03x^3 + 4,4746E-03x^2 + 2,1703E-03x + 9,9669E-01$
	Inlet Temperature (°C)	$FC = -3,2445E-08x^4 + 1,4268E-06x^3 + 2,7835E-05x^2 + 1,3824E-03x + 9,7177E-01$
	Relative Humidity (%)	$FC = 1,5625E-11x^4 - 3,1597E-09x^3 + 2,0937E-07x^2 + 1,4512E-05x + 9,9894E-01$

In order to verify if the obtained polynomials present satisfactory results for the gas turbines operating in off-design conditions, a comparison was made between results obtained through simulation in Thermoflex and results obtained using the correction factors generated by the correction polynomials. Seven gas turbines were chosen for the comparison, one of each group. The gas turbines were tested at five different operating points as shown in Tab.14.

Table 14. Operating points used for the correction polynomials test.

	Inlet Temperature (°C)	Altitude (m)	Exhaust Loss (kPa)	Inlet Loss (kPa)	Relative Humidity (%)	Fuel LHV (kJ/kg)
Point 1	35	870	1,34	1,39	90	38257
Point 2	27	500	3,7	0,3	0	28624
Point 3	0	250	2,5	0,47	50	34837
Point 4	10	110	1,7	0,75	25	41919
Point 5	40	1000	4	1,49	100	45834

Confronting the power output simulated by Thermoflex and with the correction polynomials combined with Eq.1, an average difference of 1.89% was obtained for the power output tests, the largest difference obtained was 5.48% for a GE 5 gas turbine (industrial with 5.2MW rated power) operating at point 1. For heat rate the average difference was 1.21% and the maximum difference was 4.38%, which occurred for a GE 5 turbine at the operating point 5. In the mass flow tests an average difference of 2.48% was obtained, the largest difference obtained was 5.53%, which occurred for the P + W FT8 Swiftpac 60 (aeroderivative with 50.3 MW rated power) turbine at the operating point 5. For the exhaust temperature, an average difference of 1.16% and a maximum difference of 4.48% were obtained for the Siemens SGT-700 (industrial with 50.3 MW rated power) at the operating point 5.

The biggest differences were observed at points where most of the operating conditions were far from the reference conditions (operating points 1 and 5), this means that when distancing from the reference conditions the polynomials lose part of their accuracy when compared to the Thermoflex simulations.

Cloyd and Harris Jr. (1995) have developed correction curves for power output and exhaust flow as a function of altitude, power output as a function of relative humidity and heat rate and power output as a function of ambient temperature. These curves were compared with the obtained correction polynomials reaching a difference of less than 1,5% for most of the cases.

Comparing the correction factor obtained through the correction polynomial of power output as a function of the relative humidity of all groups with Cloyd and Harris Jr. (1995) correction curve, a relative error of less than 1% was obtained in all cases, which indicates that the correction factors obtained have a similar behavior than the correction curve presented by (Cloyd and Harris Jr, 1995). Table 15 shows the correction factor extracted from Cloyd and Harris Jr. (1995) correction curve, the correction factors calculate through the obtained correction polynomials for the groups 1-4 and the relative error between Cloyd and Harris Jr. (1995) and the groups.

Table 15. Corrections factors and relative error for power output as a function of relative humidity.

Cloyd and Harris Jr. (1995)		Group 1		Group 2		Group 3		Group 4	
Relative Humidity %	Correction Factor	Correction Factor	Relative Error %	Correction Factor	Relative Error %	Correction Factor	Relative Error %	Correction Factor	Relative Error %
0	0.9910	0.9963	0.53%	0.9998	0.89%	0.9998	0.89%	0.9993	0.84%
20	0.9940	0.9978	0.38%	0.9997	0.57%	0.9999	0.59%	0.9993	0.53%
40	0.9970	0.9991	0.21%	0.9998	0.28%	1.0000	0.30%	0.9996	0.27%
60	1.0000	1.0001	0.01%	1.0000	0.00%	1.0000	0.00%	1.0000	0.00%
80	1.0030	1.0008	0.22%	1.0000	0.29%	1.0000	0.30%	1.0002	0.28%
100	1.0055	1.0016	0.39%	0.9999	0.56%	1.0001	0.54%	1.0002	0.53%

The correction curves for power and heat rate as a function of ambient temperature presented by Cloyd and Harris Jr. (1995), use a temperature range of -10 ° C to 40 ° C. A temperature range of 0 ° C to 40 ° C was used in the correction polynomials generated from the simulations in Thermoflex. For most of the groups, when using the correction polynomials for the operating range of -10 ° C to 0 ° C, a relatively high difference was observed for most groups of turbines when compared to the correction curves of Cloyd and Harris Jr. (1995). In the operating range between 0 ° C and 35 ° C, the correction polynomials of most groups showed a very close behavior to the correction curves of Cloyd and Harris Jr. (1995) for heat rate and power output. The comparison between the correction factors extracted from Cloyd and Harris Jr. (1995) ambient temperature curve and the correction factors obtained through the correction polynomials of group 4 is shown in Tab.16.

Table 16. Corrections factors and relative error for power output and heat rate as a function of ambient temperature.

Cloyd and Harris Jr. (1995)			Group 4			
Ambient Temperature(°C)	Correction Factor Power	Correction Factor Heat Rate	Correction Factor Power	Correction Factor Heat Rate	Relative error Power	Relative error Heat Rate
-10	1.150	0.965	1.0844	0.9927	5.70%	-2.88%
-5	1.120	0.970	1.0848	0.9849	3.15%	-1.54%
0	1.090	0.975	1.0731	0.9834	1.55%	-0.86%
5	1.065	0.985	1.0530	0.9863	1.12%	-0.13%
10	1.035	0.990	1.0275	0.9922	0.72%	-0.23%
15	1.000	1.000	0.9989	1.0002	0.11%	-0.02%
20	0.970	1.010	0.9687	1.0093	0.14%	0.07%
25	0.935	1.020	0.9379	1.0194	-0.31%	0.06%
30	0.905	1.030	0.9070	1.0303	-0.22%	-0.03%
35	0.870	1.045	0.8755	1.0424	-0.63%	0.25%

The correction curve of Cloyd and Harris Jr. (1995) for power output and exhaust flow as a function of altitude utilizes an altitude range of 0 to 2500m, the power output and mass flow correction polynomials were generated using an operating range between 0 and 1000m. Comparing the correction polynomials of power output and mass flow of all groups in the range between 0 and 2250m with the correction curve of Cloyd and Harris Jr. (1995), a relatively small difference is observed for most of the polynomials. Then concluded that the altitude correction polynomials provide good results outside the operating range, in which the turbines were simulated. The comparison between the correction factors extracted from Cloyd and Harris Jr. (1995) altitude curve and the correction factors obtained through the correction polynomials of group 7 is shown in Tab.17.

Table 17. Corrections factors and relative error for power output and mass flow as a function of altitude.

Cloyd and Harris Jr. (1995)			Group 7			
Altitude (m)	Correction Factor Power	Correction Factor Mass Flow	Correction Factor Power	Correction Factor Mass Flow	Relative error Power	Relative error Mass Flow
0	1	1	1.0000	1.0001	0.00%	-0.01%
250	0.97	0.97	0.9700	0.9708	0.00%	-0.08%
500	0.94	0.94	0.9407	0.9418	-0.07%	-0.19%
750	0.91	0.91	0.9120	0.9135	-0.22%	-0.38%
1000	0.88	0.88	0.8839	0.8859	-0.45%	-0.67%
1250	0.86	0.86	0.8565	0.8590	0.41%	0.12%
1500	0.83	0.83	0.8296	0.8323	0.05%	-0.28%
1750	0.81	0.81	0.8032	0.8055	0.84%	0.56%
2000	0.785	0.785	0.7772	0.7777	0.99%	0.93%
2250	0.76	0.76	0.7515	0.7479	1.12%	1.59%

4. CONCLUSIONS

From the tests performed with the correction polynomials in combination with Eq.1, it is concluded that they are able to represent the behavior of the gas turbines operating in off-design point presenting results close to those of the commercial software simulations. It has also been observed that the correction polynomials lose some of their accuracy when the operating conditions are far from the design point.

It should be noted that the correction polynomials for the fuel are valid only for methane as fuel in combination with dry air because other fuel compositions may show different behavior. In the case of the addition of dry air to the methane, the power output increases by decreasing the fuel LHV (increasing the concentration of air in the fuel). In some cases, as in the case of the combination of methane and propane the power output of the gas turbine decreases when the fuel LHV is decreased (addition of propane in the fuel).

No comparison was made between the polynomials of each turbine group to determine the similarity between the various gas turbine groups, which could decrease the number of groups and consequently the number of polynomials. For example, it was observed through the simulations that the turbine exhaust loss has no influence on the exhaust flow

for almost all gas turbines, so a polynomial could be defined that encompasses several groups of turbines for this operation condition.

For future studies is highlighted the importance of a more detailed study of the influence of fuel on the performance of gas turbines using various natural gas and fuel oil compositions and the study of other operating conditions that affect the performance of the gas turbines, such as the extraction of air and the injection of diluents. It is also relevant to study the performance of other thermal machines operating in off-design point, such as internal combustion engines, heat recovery steam generators and steam turbines.

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