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EVALUATION OF A TRIGENERATION SYSTEM USING MICROTURBINE, AMMONIA-WATER ABSORPTION CHILLER, AND A HEAT RECOVERY BOILER

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Abstract*. In this work, a CCHP or trigeneration system has been projected, mounted, and tested in laboratory, combining a microturbine for power generation, a heat recovery boiler for hot water production, and an ammonia-water absorption chiller for chilled water production. The project was motivated by the large practical applications of this kind of energy recovery system in commerce, and industry, and, in general, more than 85% of the energy source is used as power, hot water, and cold water. In the first part, the trigeneration system theoretical model is detailed, and in the second part, experimental results are presented for different operation conditions.*

Keywords*: Cogeneration, Trigeneration, Absorption Cycle, Microturbine.*

1. INTRODUTION

In a competitive market scenario, energy has been an important input regarding to commercial and industrial production cost as well as a strategic production polices. In this way, distributed energy systems have been largely investigated as an economical way of electrical and thermal energy supply system, mainly for special applications in which reliability is a key point (Horlock, 1997).

Distributed energy has many definitions as presented in Ackermann et al. (2001), being characterized by the power generation of few kilowatts to dozens of megawatts (50 kW to 100 MW), generally near to the end user, without large energy transportation lines, which reduces the energy loss amount. The small power systems available for distributed energy systems use regular fossil fuel as primary energy source, commonly natural gas and diesel. Distributed energy technology for power generation has been largely developed and its implementation is ease to be made in large and medium urban centers, but as the same way of large power plants, those systems reject about 60% of total energy as hot gases to the atmosphere.

The heat recovery from hot gases produced in such power systems by a heat recovery system like a boiler allowed the emergence of a new concept in terms of energy recovery system, and with technological development of absorption chillers for heat and cooled water production, the heat recovery systems became extended including power, heat, and cooling production from a unique primary energy source. Those systems are named Combined Cooling, Heat and Power (CCHP) or Trigeneration.

Combined cooling, heat, and power (CCHP) or trigeneration systems became an economically available way to be applied for such necessities, saving energy, money and make environmental intelligent use regular fuels (Wu and Wang, 2006). The potential for energy savings by using the CCHP systems in Brazil have been increasing in the last years as a function of infrastructure increasing of natural gas network distribution in medium and large urban centers, and fuel tax incentive as well as energy regulations by federal government concerning distributed energy systems. Actually, the distributed energy represents less than 10% of total energy produced, but a trigeneration system has great potential to reduce carbon and air pollutant emissions beyond to increase resource energy efficiency of plants, office buildings, medical centers, supermarkets, airports, and shopping centers (Babus'Haq et al. 1990, Bassols et al. 2002, and Cardona et al. 2006). As it has been showed, trigeneration systems development and application needs to be largely studied and evaluated as a way to available secure and reliable data to the energy market.

In this way, a trigeneration system has been projected, mounted, and tested in the SISEA - Alternative Energy System Laboratory at University of São Paulo. The trigeneration system combines a microturbine for power generation, a heat recovery boiler for hot water production, and an ammonia-water absorption chiller for chilled water production. This project was motivated by the large practical applications of this kind of energy production systems in which, generally, more than 85% of combustible energy can be used for electrical and thermal energy production.

In this paper it is presented the conceptual, theoretical, and experimental aspects of that project. Experimental results were compared with a theoretical modeling developed based on energy and mass balances.

A comparative evaluation of many design options of trigeneration systems was made as a way of establishing a decision planning strategy before the selection of the actual most convenient alternative for a given application. The comparison was carried out by performing mainly technical analyses and a basic economic aspect of trigeneration systems. A theoretical modeling was developed to calculate the trigeneration cycle theoretical and energy balance, and results were compared with experimental data.

2. TRIGENERATION SYSTEM DESCRIPTION

The combined cooling, heating, and power system developed in the laboratory was originally composed of two different systems: a system with a microturbine, and a system with an internal combustion motor. This paper presents results from the first part, the system formed by a natural gas powered microturbine, a heat recovery boiler, and a 17 kW_{th} ammonia-water absorption chiller, as can be seen in Fig.1.

The Fig.2 shows the system in which a Capstone Microturbine of 30 kW_{el} electrical power capacity uses compressed natural gas to generate electricity. The compressed natural gas was supplied by a pellet gas compressor, which furnishes the required natural gas volumetric flow rate of 10 m^3/h at 500 kPa (for 30 kW_{el}). The major part of the thermal energy of exhaust gases from microturbine is driven to the Robur ammonia-water absorption cycle to produce chilled water. The maximum refrigeration capacity of the absorption cycle used in this work is about 17 kW, as one can see in Table 1. The chilled water produced is reheated by a water heating circuit, where a certain thermal charge is applied, and the water is pumped back to the absorption n cycle. Ina practical installation, chilled water should be used to chilled water air conditioning system.

The lasting part of the thermal energy of exhaust gases is recovered by the Micogen heat recovery boiler unit that is used to produce hot water. A hot water refrigeration circuit retires the thermal charge from the boiler to ambient. In a practical installation, the hot water should be used for comfort space heating or used for some specific plant usage.

Some modifications were performed in the absorption chiller originally constructed to work with natural gas fire powered to the use of hot gases derived from the microturbine, including a hot gas flow adjustment system driving part of hot gases to the heat recovery boiler.

The electrical operating used was in Grid Connect (GC) mode, in which the electrical power produced by microturbine is used to supplement the electric power provided by local electrical power company. In this mode of operation, protective relays and an electrical transformer was installed as part of the necessary equipments for exporting electric power to the local grid, as can be seen in Fig1. Table 1 shows the trigeneration system equipments characteristics.

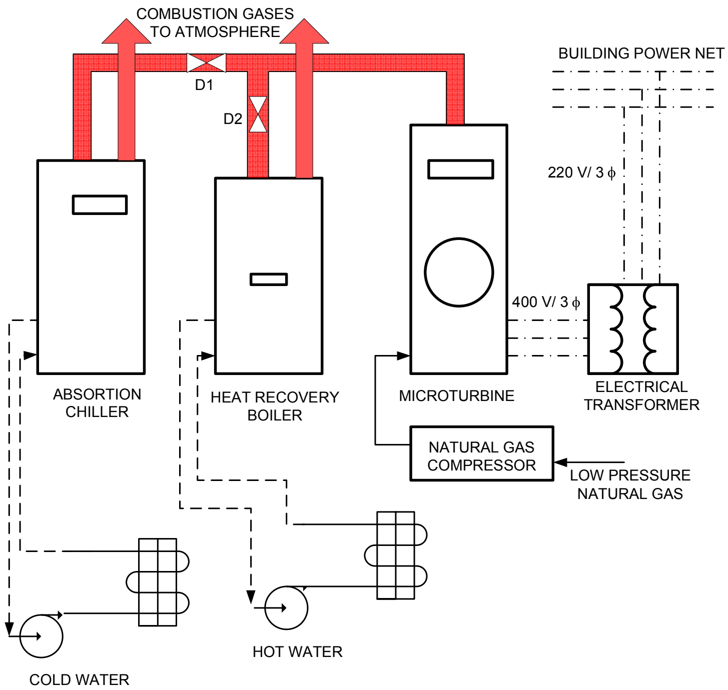

Figure 1. *Schematics of the trigeneration system.*

Figure 2. *Trigeneration system view.*

Table 1. *The trigeneration system equipment characteristics.*

Equipment	Model	Characteristics
Microturbine	Capstone C30	Power = 30 kWh_e, 400 V/ 3 phase Natural Gas *
Heat Recovery Boiler	Unifin MICOGEN MG1-C1	Max Heat Recovery = 41-73 kW_{th}
Ammonia-Water Absorption Chiller	Robur GAHP-AR	Cooling Capacity = 17 kW_{th} Natural Gas

* *Data from Capstone Microturbine Corporation.*

2.1 Theoretical Model

The theoretical model in development can, actually, determine only some parameters of microturbine operation corrected to the ISO conditions (Atmospheric Pressure of 101.325 kPa, Ambient Temperature of 288.15 K and Relative Humidity of 60%) , as follows:

- Electrical efficiency;
- Exhaust gas temperature;
- Exhaust gas mass flow rate;
- Exhaust gas energy;
- Combustible energy flux;
- Heat Rate.

All parameters from theoretical model were obtained from cures fitting of microturbine fabrication catalogue. Data from catalogues are presented for ISO conditions so, for any other operational conditions corrections must be made. The model can furnish all related parameters, basically, for the entire São Paulo state, the goal of the research project.

3. RESULTS

The first experiments made with the trigeneration system are presented and data for the inlet and outlet temperatures, inlet and outlet flow rates of gases and water of each component (equipment) of the trigeneration system can be seen in Table 2.

All temperatures were measured with K type thermocouples previously calibrated, pressures were measured with bourdon manometers in each pressure measurement sections, and all data were acquired by a National Instrument NI cDAQ-9172 data acquisition device. A standard Pitot tube of 100 x 3 mm was used for exhaust gases velocities measurement at the outlet exhaust gases section of microturbine. The exhaust gases mass flow rate was calculated according to the EPA 02, 02A and 03 methods.

Chilled and hot water flows was measured using turbine type water flow meters with uncertainties of ± 0.001 m^3 installed in each water circuit as showed in Fig 1.

The ammonia-water absorption chiller model ROBUR (GAHP-AR), was setup for specified cooling capacity 17 kW at ambient temperature of 293K and cooling water delivery temperature of 283 K with a differential temperature of 10 K (difference between delivery and return). The average water flow rate measured was 2.0 m^3/h.

The heat recovery boiler model Unifin MICOGEN MG1-C1 was setup for gas temperature limits of 533 K to 644 K, and water temperature limits of 293 K to 353 K. The hot water average flow rate was 1.86 m^3/h

Tests were made with the Capstone C30 microturbine setup for theoretical 50% of electrical power capacity or 15 kW_{el}, and for the maximum local electrical power delivered by microturbine or 24 kW_{el}. Results measured and calculated by the theoretical model are presented for the local condition (São Paulo) in Table 2. The local condition observed was: atmospheric pressure of 93.325 kPa, ambient temperature of 293.15 K, and relative humidity of 66%.

For simple comprehension, the pieces of equipment nomenclatures were established as follows: Microturbine (MT), Heat Recovery Boiler (HRB), and Absorption Chiller (ABS). Temperatures nomenclatures are indicated as follows: T_{GIHRB} is the gas temperature (microturbine´s outlet gas temperature) at heat recovery boiler inlet; T_{GOHRB} is the gas temperature at heat recovery boiler outlet; T_{WIHRB} is water temperature at heat recovery boiler inlet; T_{WOHRB} is the water temperature at heat recovery boiler outlet; T_{GIABS} is the gas temperature at absorption chiller inlet (generator); T_{GOABS} is the gas temperature at absorption chiller outlet; T_{WIABS} is water temperature at absorption chiller inlet; T_{WOABS} is the water temperature at absorption chiller outlet;

Table 2. *The main measured and calculated parameters in the trigeneration system.*

Parameter	Electrical Power Delivered (kW_{el})			
	15		24	
	Measured	**Calculated**	**Measured**	**Calculated**
Natural Gas Flow Rate (m^3/h)	8.0	---	10.5	---
Exhaust Gas Mass Flow (kg/s)	0.186	0.212	0.289	0.274
Exhaust Gas Temperature from MT (K)	568.2	510.8	615.6	536.7
Differential gas temperature in CALD (K)	57.2	---	26.27	---
Differential gas temperature in ABS (K)	86.1	---	138.8	---
Electrical efficiency (%)	---	22.55	---	25.6
Exhaust gas energy (kW)	---	51.77	---	73.27
Heat Rate (kWt/kWe)	---	7.29	---	5.67

Tests were carried out with the dumper D1 fully opened and the dumper D2 partially opened (90%), which permitted the higher exhaustion gases flew direct to the absorption chiller, and a small parcel of exhaustion gases flew to heat recovery system. This operational condition was imposed to guarantee that the total absorption chiller's cooling capacity was attended.

The total exhaust gas energy calculated is 51.77 kW when microturbine is producing 15 kW_{el}, and 73.77 when it is producing 24 kW_{el} (or at maximum local power capacity). The maximum cooling capacity of the absorption chiller is 17 kW which means that, for a specified COP of 0.6, the minimum exhaust gas energy necessary to supply that cooling capacity is about 28 kW. In both cases the existing minimum exhaust gas energy can supply the total absorption chiller cooling capacity and there is sufficient exhaust gas energy to attend the water heating demand of the heat recovery boiler.

In the first case (MT producing 15 kW_{el}), for the total exhaust gas energy delivered of 51.77 kW, about 54% of that energy can supply 100% of the absorption chiller energy demand, and about 46% of total energy can supply the water heating demand. In second case (MT producing 24 kW_{el}), about 38% of total exhaust gas energy is necessary to supply the total absorption chiller demand, and about 62% can supply the water heating demand.

Analyses of the experimental results compared with the theoretical values obtained by the model revealed some discrepancies between them, as it is clear in exhaust gas temperature and mass flow rate. Adjusts must be implemented in theoretical model and experimental measurements must be revised to establish the real differences between them, which will permit to obtain a reliable theoretical model to simulate trigeneration systems in different operational conditions.

Temperatures of exhaustion gases delivered by microturbine reaches 568 K according to the experimental results and can touch 540 K at absorption chiller inlet, showing a 5% in terms of gas temperature.

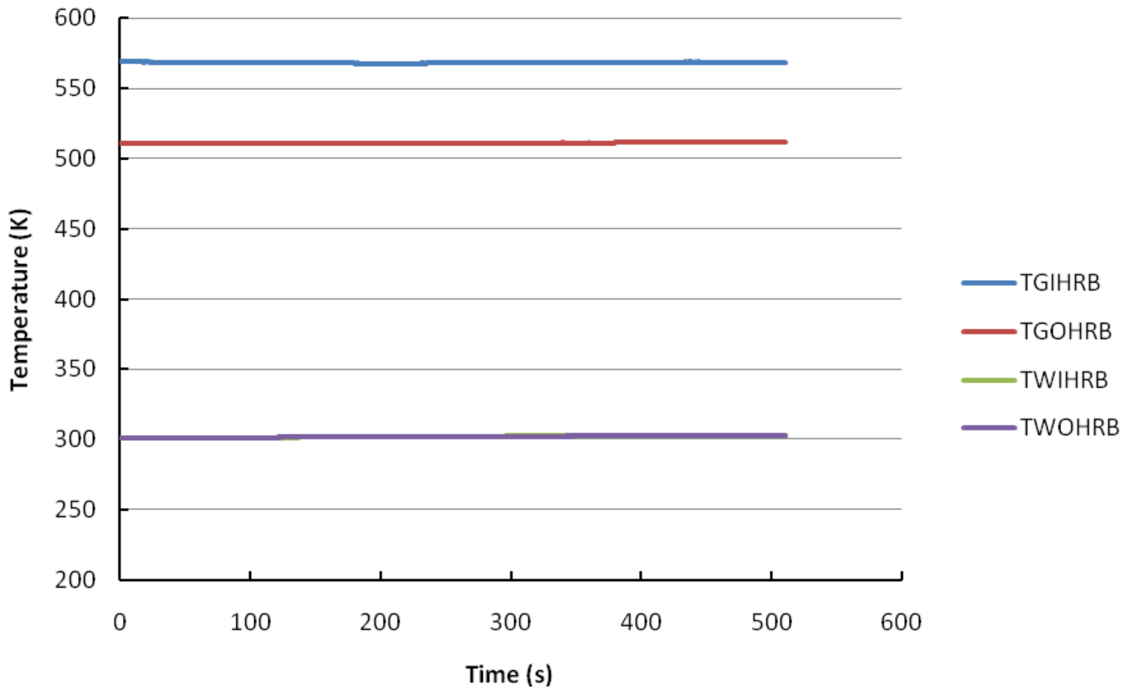

Figure 3. *Temperature measurement historical at Heat Recovery Boiler (HRB) for 15 kW$_{el}$ electrical power setup.*

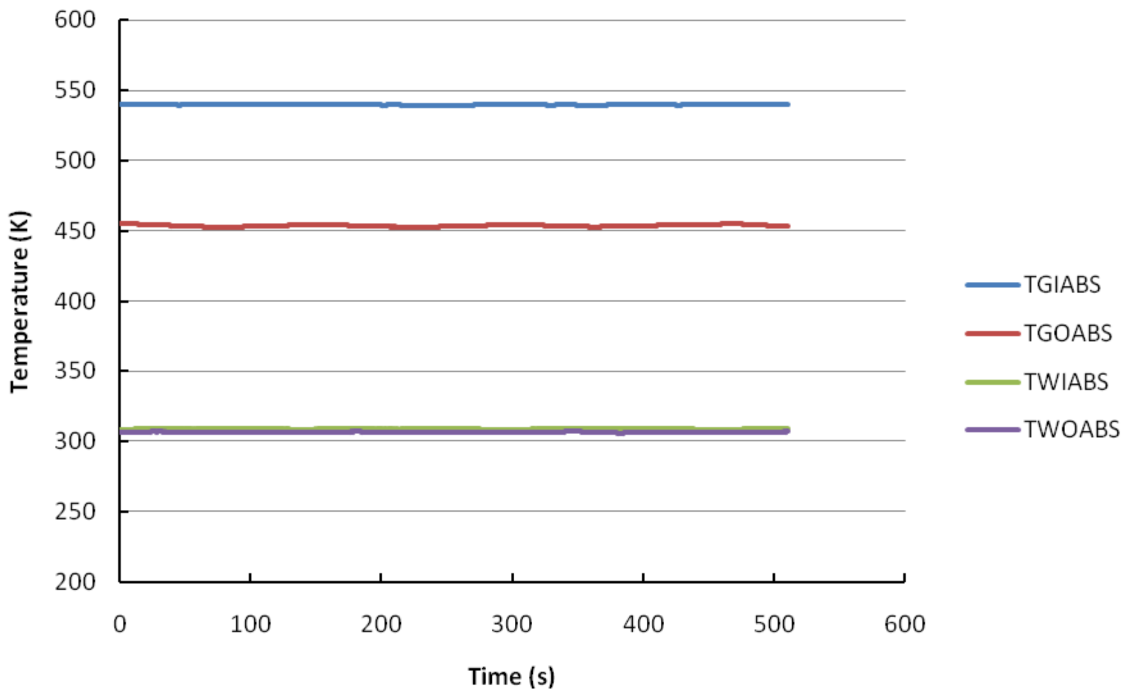

Figure 4. *Temperature measurements at Absorption Chiller (ABS) for a 15 kW$_{el}$ electrical power setup.*

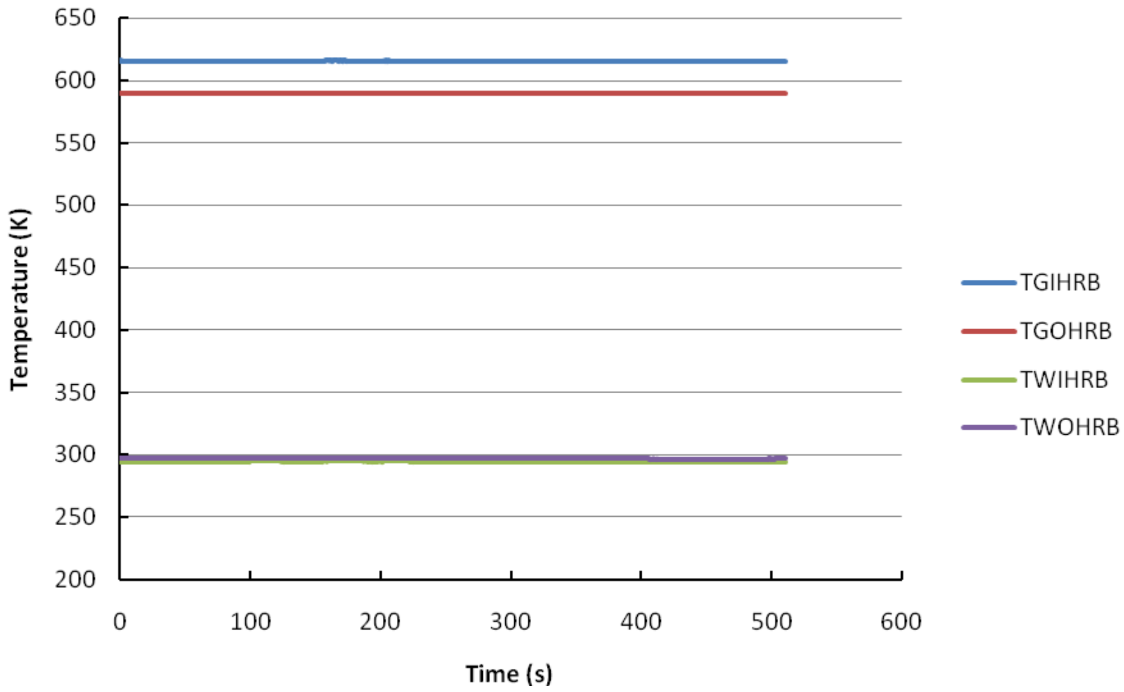

Figure 5. *Temperature measurements at Heat Recovery Boiler (HRB) for 24 kW_{el} electrical power setup.*

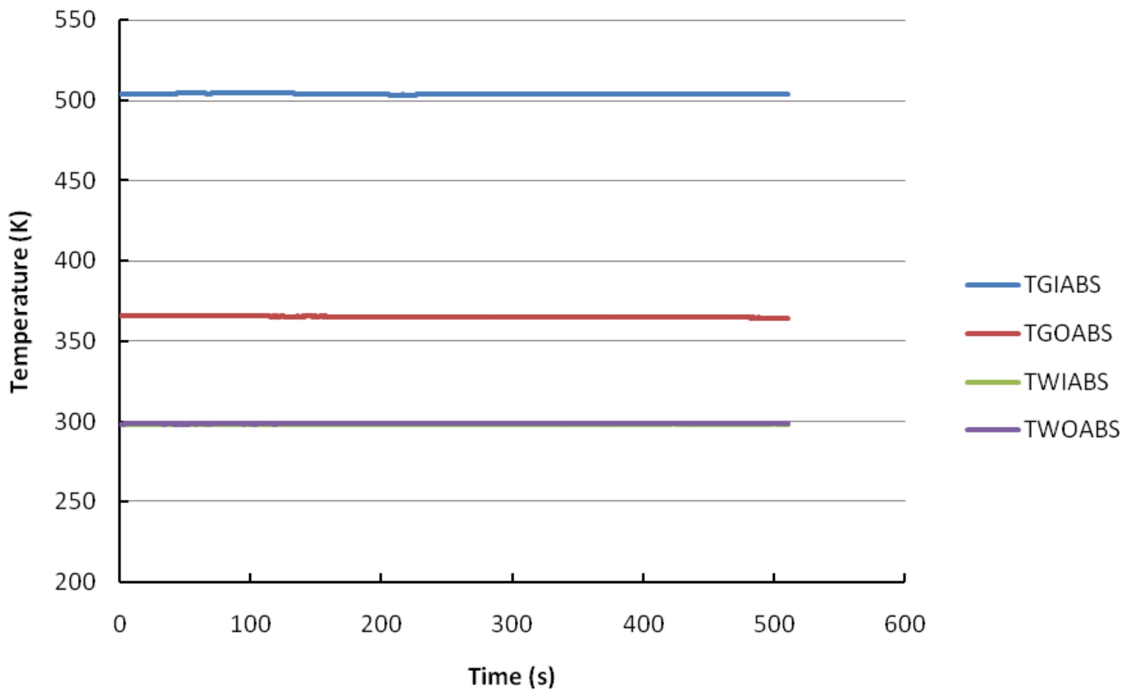

Figure 6. *Temperature measurements at Absorption Chiller (ABS) for a 24 kW_{el} electrical power setup.*

Table 3. Exhaustion gas heat parcels used by absorption chiller.

Absorption Chiller					
Electrical Power (kW_{el})	$\dot{m}_G$ (kg/s)		ΔT (K)	Q_G (kW)*	
	Measured	Calculated		Measured	Calculated
15	0,186	0,212	86	16,7	19
24	0,289	0,274	139	42	40

* *Assuming the Nitrogen Cp = 1,0416 kJ/kg.K.*

Table 3 shows the comparison between the exhaustion gas heat parcels driven to absorption chiller according to the gas mass flow rate measured and calculated. The temperature difference (ΔT) was measured for both situations. Exhaustion mass flow rate present strong difference for the two electrical power operational conditions, but one can observe that the absorption chiller heat demand can be attended just when the microturbine operates generating above 20 kW_{el}. In this way it is possible to determine the limit of operational condition of the trigeneration system designed to produce electrical energy as a primary source, chilled water (at 280 to 283 K) and hot water (at 313K).

4. CONCLUSIONS

Experimental and theoretical results are presented and they show all system adjustment parameter for appropriate operation including natural gas consumption, electrical power, hot and chilled water production over different operational conditions: partial load electrical power of 15 kW_{el} and maximum electrical power delivered of 24 kW_{el}. Theoretical model has been developed for the trigeneration system and results were compared with experimental ones showing the operational behavior of such cogeneration system and giving technical support for new theoretical model development and experimental specific studies necessary for the trigeneration system practical applications.

5. ACKNOWLEDGEMENTS

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