Available online at www.sciencedirect.com

ScienceDirect

Energy Procedia 148 (2018) 575–582

Energy Procedia

www.elsevier.com/locate/procedia

73rd Conference of the Italian Thermal Machines Engineering Association (ATI 2018), 12–14 September 2018, Pisa, Italy

Analysis of a Trigeneration Plant under Transient Operating Conditions

D. Perrone*, P. Morrone, T. Castiglione, A. Algieri and S. Bova

DIMEG - Dipartimento di Ingegneria Meccanica, Energetica e Gestionale-Università della Calabria, Via P. Bucci, Cubo 44 C, 87036 Rende, Italy

Abstract

A dynamic lumped-parameters model has been developed in order to analyse the performance of a combined cooling, heating and power (CCHP) plant during transient load variations. The plant allows the waste heat recovery from four Internal Combustion Engines (ICEs) to produce simultaneously refrigeration power for an absorption chiller, hot water for thermal user and electrical power. The heat recovery is realized through the exhaust gases, the jacket cooling water and the lubricant. The plant includes an auxiliary boiler, which maintains the water temperature levels to the values required by the absorption chiller, and a dry-cooler, which refrigerates the plant water before entering the internal combustion engines. Moreover, a three-way valve, which controls the water flow rate in order to satisfy both the refrigeration and the thermal loads, is considered. The simulations are carried out under thermal-drive and electric-drive strategy and the evaluation of the performance and time response of the CCHP apparatus are presented.

Keywords: Trigeneration; Internal Combustion Engines; CCHP; Performance Analysis; Time Response.

* Corresponding author. Tel.: +39 0984 49 4397;
E-mail address: diego.perrone@unical.it

10.1016/j.egypro.2018.08.144

1. Introduction

Trigeneration systems produce electricity, heating and cooling simultaneously with a higher sustainability and energy efficiency with respect to single-purpose conventional systems [1, 2] and are particularly attractive in households [3]. Various technologies for the prime mover have been investigated both numerically and experimentally in scientific literature for both grid-connected and stand alone applications: steam and Organic Rankine cycles [4, 5], gas- and micro-turbines, internal combustion engines [6, 7], Proton Exchange Membrane fuel cells [8, 9]. The cooling request is usually addressed with absorption and/or compression refrigeration systems [10, 11]. Researchers have been focusing their attention on the integration of renewable source technologies, like solar parabolic trough collectors [12-14], photovoltaic systems [7], biomass, geothermal energy [12] to increase the sustainability and global effectiveness. Furthermore, proper thermal energy storage systems and auxiliary boilers are common in trigeneration systems [15]. Numerical models have been proposed in literature for both steady-state and dynamic conditions [9, 13, 16]. Usually, TRNSYS software is used for dynamic simulations in order to emulate the real operating conditions [3, 16]. In this paper, a preliminary home-made numerical dynamic model of a micro-trigeneration system has been proposed in order to estimate the system performance under transient load variations and the time response of the CCHP unit. An internal combustion engine fueled with syngas obtained on-site from the gasification is the prime mover.

2. Trigeneration Power Plant Scheme and modelling

The core of the existing plant consists of four internal combustion engines, fueled with syngas obtained on-site from the gasification of solid wood chips, which deliver about 200 kW_{el} and 400kW_{th} electrical and thermal power, respectively. The electrical power is fed into the grid, while the thermal power is currently adopted to produce hot water for thermal usage. A better integration of distributed generation in the existing system can be obtained by the inclusion, in the plant, of an absorption chiller. A schematic of the power plant is reported in Fig.1.

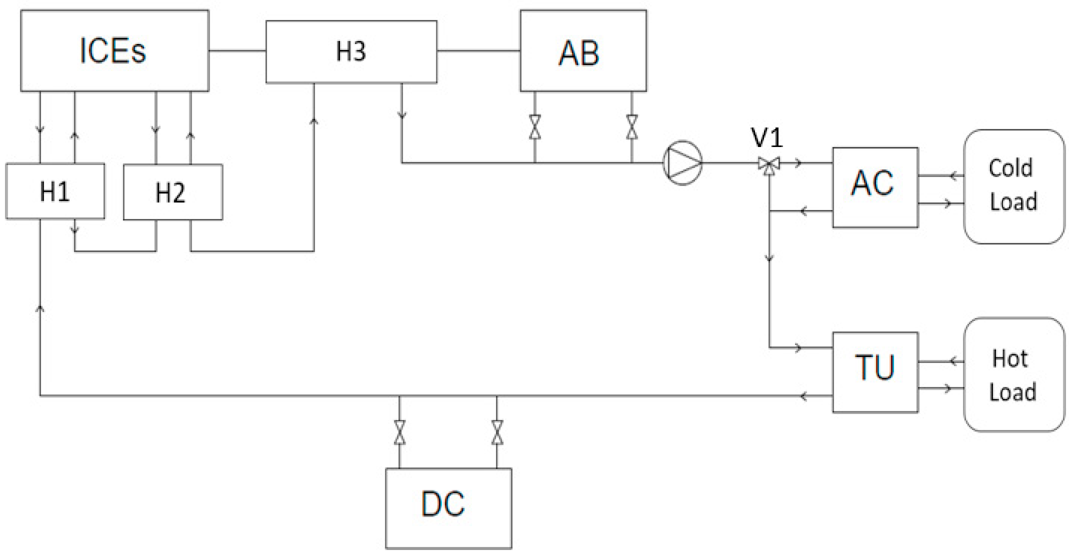

Fig. 1. Schematic of the CCHP plant.

The heat recovery from the ICEs is realized through the lubricant oil, the jacket cooling water and the exhaust gases, by means of heat exchangers (H1, H2 and H3). After this warm-up phase, the plant supply water feeds the absorption chiller, which requires prescribed water temperature levels for an efficient operation; an auxiliary boiler (AB), which maintains the level temperature to the target values, is therefore included. A three-way valve (V1) is used for the management of the water flow rate in order to satisfy the refrigeration load, which is satisfied by an absorption chiller (AC). The hot water flows through a heat exchanger for a thermal user (TU); finally, a dry-cooler (DC) refrigerates the plant water before entering the internal combustion engines.

The plant operating ranges are summarized in Table 1:

Table 1. Plant operating ranges

	Rated Thermal Power [kW_{th}]
ICEs	400
Auxiliary Boiler	400
Absorption Chiller	503
Thermal User	200
Dry – Cooler	200

The development of a simulation model allows a preliminary analysis of the energetic performance of the combined cooling, heating and power plant for transient thermal and refrigerating loads. A lumped-parameters model of the described power plant was developed in Matlab-Simulink.

The heat recovery from the ICEs is modeled by considering that 15% of the engine thermal power is rejected to the oil, an amount of 30% is transferred to the cooling medium and the remaining 55% is lost with the exhaust gases. These percentages are given as inputs to the model in order to calculate the temperatures of lubricant oil, coolant and exhaust gases at the engine exit. The heat exchangers adopted for heating the primary water flow rate, are modeled through the ε-NTU method [17], which permits the sizing of the heat exchangers and gives as an output the water temperature at the exit of each heat exchanger.

The auxiliary boiler has the main purpose to supply the thermal power required by the thermal and refrigerating loads in all those cases for which the one available from the engines is unable to satisfy the request; furthermore, the adsorption chiller requires prescribed temperature levels, which are reached with the activation of the auxiliary boiler. Therefore, this component is modeled by considering that, if no additional power is needed and the primary water temperature satisfies the level required by the adsorption chiller, the component is by-passed; otherwise, the amount of fuel needed to satisfy the thermal load and water temperature level, as well as the water temperature at the exit of the boiler are computed.

The absorption and refrigeration powers of chiller are calculated with the implementation of look-up tables obtained from the data-sheet of a commercial device. The absorption power depends on the inlet temperature and water mass flow rate, which is managed by a 3-way valve. The management is based on the refrigeration load and on the water temperature difference between the inlet and outlet of the chiller.

The main purpose of the dry-cooler is to maintain the temperature level compatible with the ICEs in all those cases for which the thermal power provided by the ICEs is higher than the refrigeration and thermal loads

3. Results and discussion

In order to evaluate the performance and the time response of the CCHP, a preliminary analysis was carried out. This section presents the results in terms of thermal power, plant water temperature and fuel consumption for the FTL (Following Thermal Load) and FEL (Following Electric Load) strategies. Fig. 2 shows a typical hourly thermal (TU), refrigeration (RU) and electric load profile.

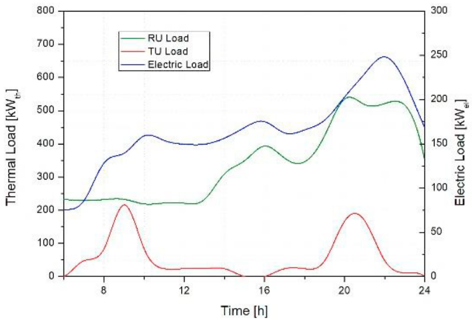

Fig. 2. Refrigeration, thermal and electric loads

The AC absorbs the minimum power during the morning and reaches higher thermal power during the evening. On the contrary, the thermal user (TU) presents two peaks, in the morning and in the evening. The electric load increases during the day and reaches a maximum value in the evening. When the system operates under FTL strategy, the thermal power generated by the ICEs follows the total thermal loads at any time. Fig 3 (a) shows the thermal power provided by the ICEs and the AB, and the total thermal load required during the day.

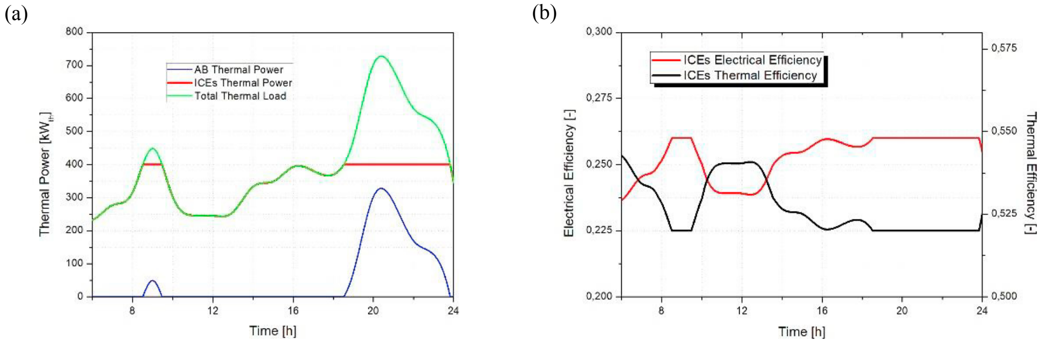

Fig. 3. Thermal power profiles (a) and (b) Electrical and thermal efficiencies of ICEs under FTL condition

When the total thermal demand is higher than the ICEs thermal power, the AB provides the surplus thermal power. During this period, the ICEs work at maximum power with the highest electrical efficiency, as shown in Fig 3 (b). On the contrary, when the ICEs work at minimum partial load, the thermal and electrical efficiency are at their maximum and minimum respectively. Fig. 4 (a) shows the corresponding electric generation profile of the ICEs.

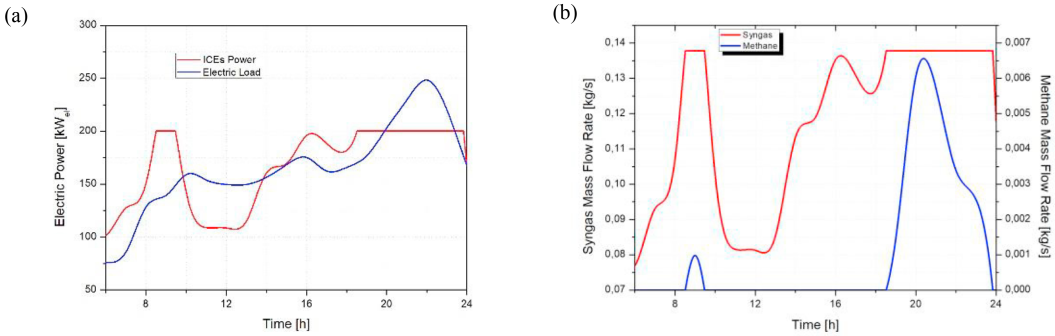

Fig. 4. Electric power and electric load profiles (a) and (b) Syngas – Methane consumption under FTL condition

During some hours of the day, the electric generation is less than the electric demand, therefore, the grid electricity will be purchased; otherwise, when the generation is higher than the load, the surplus electricity will be sold to the grid. The syngas and methane consumption profiles in the ICEs and AB, respectively, are displayed in Fig. 4 (b). As expected, the syngas consumption is maximum at ICEs maximum power and the methane is consumed when the AB is active. Differently from a stationary model, the current dynamic-lumped parameters model allows providing the temperature profiles of the system. In particular, the ICEs inlet/outlet water temperatures, the AB outlet water temperature, the TU inlet/outlet water temperatures are shown in Fig 5. It is worth noting that ICEs outlet water temperature and AB outlet one correspond to the case when the AB is off. Similarly, because the CCHP works under FTL condition, the air-cooler is off, therefore the TU inlet water temperature and ICEs inlet water temperature match. When the thermal demand is higher than engine thermal power the AB is on, therefore the water temperature of plant increases. The maximum water temperature drop occurs in the maximum thermal and refrigeration load phases due to the thermal absorption by users.

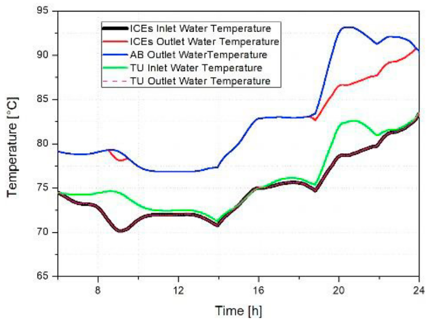

Fig. 5. Plant water temperature profiles under FTL condition

Fig. 6 (a) and Fig 6 (b) show the water mass flow rate in the AC and the temperature difference between the hot water inlet temperature and outlet one. It is interesting to note that when the refrigeration load increases, the hot water flows through the absorption chiller due to a 3-way control valve provided with a thermal actuator. In fact, in order to satisfy the refrigeration load, when the temperature difference decreases the water mass flow rate increases. On the contrary, when all water mass flow rate flows in the absorption chiller the difference temperature increases.

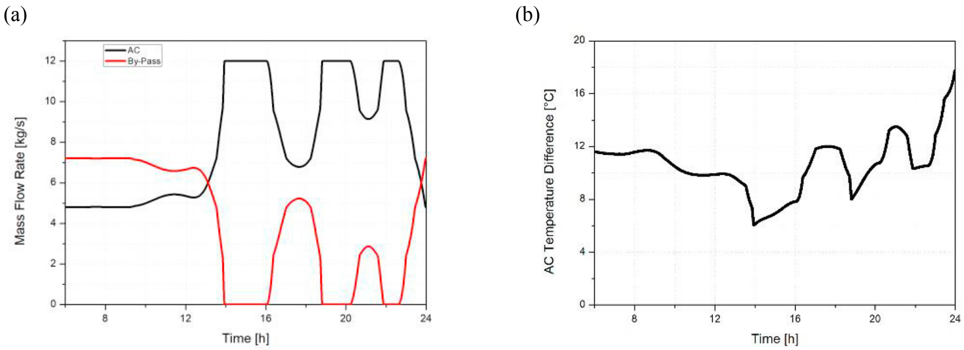

Fig. 6. By-pass and effective water mass flow rate to the AC (a); (b) Water temperature difference at AC under FTL condition

If the CCHP works under FEL operating condition, the electric power profile of the ICEs completely follows the electric load as shown in Fig. 7 (a). The syngas and methane consumptions are displayed in Fig. 7 (b).

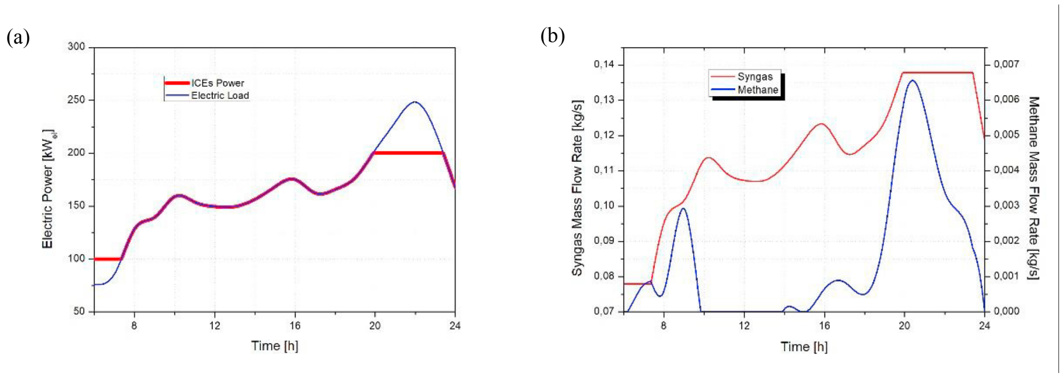

Fig. 7. Electric power and electric load profiles (a) and (b) Syngas – Methane consumption under FEL condition

In this condition the AB provides a thermal energy and therefore a methane consumption higher than the previous case (FTL). In fact, the corresponding thermal power of the ICEs is lower than the total thermal load for more time during the day as shown in Fig. 8 (a). Furthermore, when the ICEs thermal power is higher than the total thermal load, the DC is on and subtracts the requirement thermal power in order to cool down the water temperature before entering the ICEs.

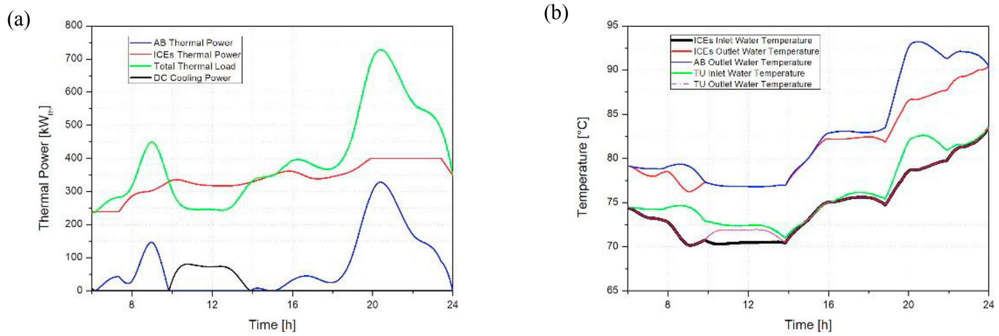

Fig. 8. Thermal power profiles (a) and (b) Plant water temperature profiles under FEL condition

The plant water temperature range is between 70-95 °C both for FEL and FTL operating condition as shown in Fig. 8 (b) and Fig. 5. It is worth noting that the AB outlet water temperature, which corresponds to the AC inlet water temperature, is in accordance with the prescribed hot water temperature levels of AC both for the FEL and FTL cases.

Table 2. Syngas and Methane Consumption under FTL and FEL condition

Fuel	FTL [kg/day]	FEL [kg/day]
Syngas Consumption (ICEs)	7745	7615
Methane Consumption (AB)	71.5	96.5

Table 2 summarizes the syngas and methane consumption for FTL and FEL strategies. The FTL strategy allows obtaining higher syngas consumption, but lower methane consumption than the FEL strategy. In order to define the best strategy, these preliminary results require an optimization of the model and future environmental - economic study.

4. Summary and conclusion

In this work, a preliminary study of the possibility to convert an existing plant in a CCHP system was carried out. A dynamic model was developed in order to analyze the performance and the time response of the plant for transient thermal and refrigeration loads. Preliminary results show that the model predicts the plant water temperature in accordance with the prescribed temperature ranges by the components for both FTL and FEL strategies. A FTL strategy allows obtaining a higher syngas consumption, but a lower methane consumption than FEL one. This study is the first part of a project, which requires the development of optimal dynamic model, an environmental-economic analysis, as well as a measurement campaigns on order to validate the model.

References

[1] N. Kabalina, M. Costa, W. Yang, A. Martin, M. Santarelli, Exergy analysis of a polygeneration-enabled district heating and cooling system based on gasification of refuse derived fuel, J. Clean. Prod. 141 (2017) 760–773.
[2] S. Sibilio, A. Rosato, G. Ciampi, M. Scorpio, A. Akisawa, Building-integrated tri- generation system: energy, environmental and economic dynamic performance assessment for Italian residential applications, Renewable Sustainable Energy Rev. 68 (2) (2017) 920–933.
[3] G, Cioccolanti L, Renzi M. Modelling the Italian household sector at the municipal scale: Micro-CHP, renewables and energy efficiency. Energy 2014;68:92–103. http://dx.doi.org/10.1016/j.energy.2014.02.055.
[4] F.A. Al-Sulaiman, F. Hamdullahpur, I. Dincer, Greenhouse gas emission and exergy assessments of an integrated organic Rankine cycle with a biomass combustor for combined cooling, heating and power production, Appl. Therm. Eng. 31 (4) (2011) 436–446
[5] L. Cioccolanti, R. Tascioni, E. Bocci, M. Villarini, Parametric analysis of a solar Organic Rankine Cycle trigeneration system for residentialapplications, Energy Conversion and Management. 163 (2018) 407–419.

[6] Gazda, W., and Stanek, W., 2016, “Energy and Environmental Assessment of Integrated Biogas Trigeneration and Photovoltaic Plant as More Sustainable Industrial System,” Appl. Energy, 169, pp. 138–149.
[7] International Energy Agency, 2016, “Co-Generation Trends. Tracking Clean Energy Progress,” OECD/IE, Paris, France.
[8] Al Moussawi, F. Fardoun, H. Louahlia, Selection based on differences between cogeneration and trigeneration in various prime mover technologies, Renewable Sustainable Energy Rev. 74 (2017) 491–511
[9] Chang H, Wan Z, Zheng Y, Chen X, Shu S, Tu Z, et al. Energy analysis of a hybrid PEMFC–solar energy residential micro-CCHP system combined with an organic Rankine cycle and vapor compression cycle. Energy Convers Manage 2017;142:374–84
[10] J. Deng, R.Z. Wang, G.Y. Han, A review of thermally activated cooling technologies for combined cooling, heating and power systems, Prog. Energy Combust. Sci. 37 (2) (2011) 172–203
[11] M.M. Ghafurian, H. Niazmand, New approach for estimating the cooling capacity of the absorption and compression chillers in a trigeneration system, International Journal of Refrigeration. 86 (2018) 89–106
[12] M. Al-Ali, I. Dincer, Energetic and exergetic studies of a multigenerational so- lar–geothermal system, Appl. Therm. Eng. 71 (1) (2014) 16–23.
[13] E. Bellos, C. Tzivanidis, Energetic and exergetic evaluation of a novel trigeneration system driven by parabolic trough solar collectors, Thermal Science and Engineering Progress. 6 (2018) 41–47. doi:10.1016/j.tsep.2018.03.008.
[14] A. Baghernejad, M. Yaghoubi, K. Jafarpur, Exergoeconomic optimization and en- vironmental analysis of a novel solar-trigeneration system for heating, cooling and power production purpose, Sol. Energy 134 (2016) 165–179.
[15] Rosato A, Sibilio S, Scorpio M. Dynamic performance assessment of a residential building-integrated cogeneration system under different boundary conditions. Part I: Energy analysis. Energy Convers Manag 2014;79:731–48.
[16] Caliano M, Bianco N, Graditi G, Mongibello L. Economic optimization of a re- sidential micro-CHP system considering different operation strategies. Appl Therm Eng 2016;101:592–600
[17] Cengel, Y.A., Heat and Mass Transfer: A Practical Approach, McGraw-Hill, 2006, New York.