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Research Article

Energy Conservation and CO_2 Emission Reduction Using Cogeneration Based on Gas Microturbine

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Abstract: Daily increasing propagation of environmental pollutants, such as CO_2 as the most prevailing greenhouse gas, has resulted in global warming and climate changes in the past decades. Therefore, essentiality of the optimum utilization of limited sources of energy which in turn leads to emission abatement in energy conversion process is being widely under consideration. Cogeneration, regarding energy conservation and efficiency enhancement, is known to be a noticeable and overriding strategy in substantiation of energy consumption management goal. This study deals with performance evaluation of a microturbine-based cogeneration plant and its effects on efficiency and environmental aspects by using a simulator code.

Keywords: Cogeneration, CO_2 emission reduction, microturbine

INTRODUCTION

Cogeneration, also known as Combined Heat and Power (CHP), as a natural method of Distributed Generation (DG) paradigm has major privileges like efficiency enhancement, fuel saving and emission reduction (Horlock, 1987; U.S. Environmental Protection Agency, 2002).

Pervasion of the liberalized electricity market over the past decades, following by a decline in the price of electricity, is considered to be an obstacle in widespread substitution of current large-scale separate heat and power production systems with cogeneration plants. On the other hand, this liberalization has reduced electricity price predictability in long term, thus neglecting tendencies towards conventional plants with massive investment. As a result, a great opportunity to utilize small-scale cogeneration plants is obtainable (Alanne and Saari, 2004).

The basis of cogeneration lies in thermal energy recovery in production cycles which had been carried out for large-scale conventional power plants in the past. However, one of the most promising objectives exists in small-scale residential and commercial applications like hospitals, hotels, service sectors or office buildings which are being extensively considerable for the present (Onovwiona and Ugursal, 2006).

Despite the fact that there is not a unique and comprehensive definition of small systems, generally the range of electrical power less than 200 kW is considered as small-scale cogeneration. Nowadays micro gas turbines, as scaled down versions of combustion turbines, are one of the competitors in the range, which are widely under investigations from the aspects of thermodynamic analysis, economic feasibility and environmental impacts.

In order to efficient exploitation of the microturbine-based cogeneration potentials, proper planning especially in terms of the prime mover capacity and load curve is essential, because sensitivity to deviations from design target in microturbines is significant. Therefore, if the system is overestimated, the feasibility reduces and if underestimated, the effectiveness decreases (Beihong and Weiding, 2006). Operating in part-load condition is one major deviation, leading to decline in efficiency along with an increase in pollution level, especially when running under the 50% of full load (Canova *et al.*, 2008). Hence, performance analysis of microturbines in part-load is crucial. For instance, study of part-load operation effects on the performance map of a microturbine-based cogeneration plant co-firing biomass and natural gas is carried out, revealing significant dependencies to the load changes (Riccio and Chiaramonti, 2009).

In addition to load, the effect of outdoor conditions such as inlet air pressure and temperature variation is investigated with Artificial Neural Networks (ANNs) by Bartolini *et al.* (2011) and commercial process simulators together with experimental data and empirical correlations by Vidal *et al*. (2007).

Investigation of fuel cell/gas microturbine combined system, as a novel technology, covers another aspect of cogeneration. In this cycle, the fuel

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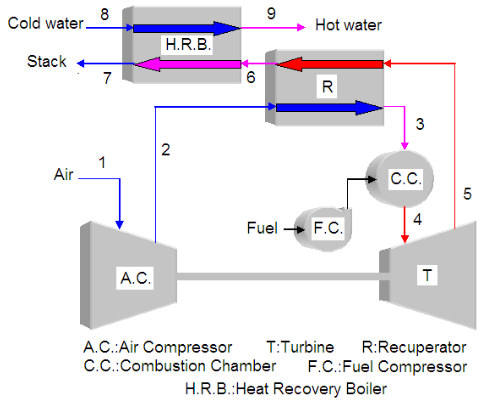

Fig. 1: Schematic diagram of a microturbine-based cogeneration plant

cell produces electricity in the electrochemical reaction processes at high operating temperatures. Afterwards, high quality exhaust gasses are used to run a gas microturbine. The resulting synergetic effect provides electrical power at very high efficiencies, around 60% (Akkaya *et al*., 2008).

Besides thermodynamic analysis, economic evaluation of microturbine relying on estimation of optimized capacity for specific load curves, has been carried out extensively (Beihong and Weiding, 2006; Sanaye and Ardali, 2009; Ehyaei and Mozafari, 2010). Study of the policies predominating energy market is also taken into consideration, since owning the right technology at the right price is not sufficient to guarantee that efficient solutions are embraced. Nevertheless, policy and market framework depending on subsidized tariffs can slow down the implementation and development of cogeneration systems, despite their approved thermodynamic and economic benefits (Tichi *et al*., 2010).

Another aspect of cogeneration is fossil fuel emission abatement which has been taken into interests in recent years (Chicco and Mancarella, 2008a, b; Mancarella and Chicco, 2008). Despite the usefulness of these studies, detailed description of the machine and its internal characteristics has been avoided, while performance characteristics such as efficiencies are established on pre-assumed relations. Therefore, study of such performance parameters through thermodynamic calculation for each component of the whole system and investigation of interactions between emission indicators and working in part-load condition, is a necessity.

The main objective of this study is performance evaluation, thermodynamic simulation and environmental assessment of a microturbine-based cogeneration plant. The effects of off-design parameters such as ambient temperature changes and part-load behaviors are studied.

Gas microturbine modeling: In order to simulate mentioned cogeneration system, it seems necessary to investigate the performance parameters of gas microturbines.

Microturbines are small-scale gas turbines, which consist of an air compressor, a turbine, a combustion chamber, a fuel compressor, a recuperator and an electric generator.

As shown in Fig. 1, a heat recovery boiler should be used on exhaust gas path to make this system applicable for cogeneration.

In this study, to increase accuracy, enthalpies have been acquired directly through gas tables of Keenan and Kaye (2002), instead of thermo-physical properties estimation at mean temperatures.

The input parameters, which should be introduced to simulator program, are the followings:

- Pressure ratio of rotating parts
- Maximum allowed turbine inlet temperature
- Compressor inlet pressure and temperature
- Minimum permissible exhaust temperature
- Isentropic efficiencies of turbine and compressor

System performance analysis for part-load operation is particularly important. In partial load conditions, the output power can be controlled by decreasing the compressor rotational speed and therefore its pressure ratio along with turbine inlet temperature.

Problem formulation: To analyze cogeneration systems, it is essential to redefine some indicators. In this section, Thermodynamic indicators and relevant emission factors are introduced.

Thermodynamic indicators: Characteristics of cogeneration prime movers can be described by means of the electrical efficiency η_e and thermal efficiency η_q which are ratio of electrical and thermal output to fuel input, respectively (Horlock, 1987):

$$\eta_e = \frac{W}{F} = \frac{W}{\dot{m}_f LHV} \quad (1)$$

where W is obtained power, F is released fuel energy, LHV is fuel lower heating value and $\dot{m}_f$ shows fuel mass flow rate. In addition, assuming Q_u as useful recovered heat, we have:

$$\eta_q = \frac{Q_u}{F} \quad (2)$$

Energy Utilization Factor (EUF) or overall efficiency of a cogeneration plant is:

$$EUF = \frac{W + Q_u}{F} = \eta_e + \eta_q \quad (3)$$

Fuel Energy Saving Ratio (FESR) is another useful criterion which can be determined through:

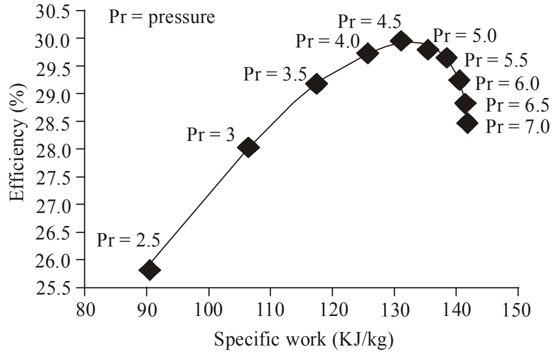

Fig. 2: Performance characteristic curve of microturbine

$$FESR = 1 - \frac{F}{W/\eta_{e,sp} + Q_u/\eta_B} = 1 - \frac{\eta_{e,sp}/\eta_{e,cg}}{\left(1 + \left(\lambda\eta_{e,sp}/\eta_B\right)\right)} \quad (4)$$

where λ is recovered heat to power ratio and η_B represents boiler efficiency. The indices cg and sp are referred to cogeneration and separate generation of heat and power, respectively.

In order to compare cogeneration with separate heat and power (SHP), it is necessary to compare similar parameters. The total fuel energy required in SHP is regarded as reference and can be calculated through:

$$F_{ref} = \frac{1}{\eta_e, sp} + \frac{\lambda}{\eta_B} = \frac{\eta_B + \lambda\eta_{e,sp}}{\eta_B \cdot \eta_{e,sp}} \quad (5)$$

The thermal efficiency of the two separated plants in producing heat and power is:

$$\eta_{ref} = \frac{1}{F_{ref}} = \frac{\eta_B \cdot \eta_{e,sp}}{\eta_B + \lambda . \eta_{e,sp}} \quad (6)$$

This reference case (η_{ref}) will be compared with $\eta_{e,cg}$. Finally, Energy Utilization Factor of a SHP plant is:

$$EUF_{ref} = \frac{(1+\lambda)\eta_{e,sp}}{1 + \lambda . \eta_{e,sp}} \quad (7)$$

Emission reduction factor: The amount of any pollutant emission from a combustion device can be assessed through an energy output-based emission factor approach (Chicco and Mancarella, 2008a, b; Mancarella and Chicco, 2008). According to this approach, the mass $m^X_{co_2}$ of co_2 emitted while producing the energy output X can be calculated as:

$$m^X_{CO_2} = \mu^X_{CO_2} X \quad (8)$$

where $\mu^X_{co_2}$ is specific emissions of CO_2 per unit of X, in (g/kWh). The output X can be electrical energy (W), useful thermal energy (Q) or fuel energy (F), all in (kWh).

The indicator for CO_2 emission reduction evaluation is generally defined as:

$$CO_2ER = \left[\left(m_{CO_2}\right)_{sp} - \left(m_{CO_2}\right)_{cg}\right] / \left(m_{CO_2}\right)_{sp} \quad (9)$$

Now, it is possible to define the CO_2 emission characteristic ratio (CO_2ECR) as a meaningful indicator for the successive analyses:

$$CO_2ECR = \left(\mu^F_{CO_2}\right)_{cg} / \left(\mu^W_{CO_2}\right)_{sp} \quad (10)$$

$\mu^F_{co_2}$ depends on fuel properties, so with natural gas as system fuel, one can calculate $\mu^F_{co_2} = 202(\frac{g}{kWh_t})$ on a LHV basis (Mancarella and Chicco, 2008).

CO_2 specific emissions ($\mu^W_{co_2}$), depends upon electricity production substructure and renewable energy sources adopted in the country which can be acquired from statistical studies. For Iran, $\mu^W_{co_2} = 678(\frac{g}{KWh_e})$ is derived from energy balance annual report of ministry of energy. The value is rather high due to the great reliance on fossil fuels.

Equation (9) can be re-formulated in more applicable form to show reduction of CO_2 emissions from cogeneration systems in percentage:

$$CO_2ER = 1 - \frac{\eta_B \times CO_2ECR}{\eta_B\eta_{e,cg} + \eta_{q,cg}CO_2ECR} \quad (11)$$

NUMERICAL RESULTS AND DISCUSSION

The case study of current research is based on micro gas turbine Turbec-T100. The unit is fired with natural gas and generates 100 kW of electrical power with an electrical efficiency of 30% at standard condition. The unit utilizes centrifugal compressor with nominal pressure ratio of 4.5. Turbine Input Temperature (TIT) is reported 950°C which is about the maximum temperature which can be tolerated by microturbine blades (Turbec, 2005).

At first, Thermodynamic analysis of the cycle with different pressure ratios has been performed through simulator software code produced in MATLAB environment at standard conditions (inlet temperature: 15°C and inlet pressure: 1*bar*) and performance characteristic curve of microturbine has been presented in Fig. 2.

As illustrated in the figure, efficiency reached to its peak at pressure ratio of 4.5. It is necessary to remind that in microturbines, single-stage centrifugal compressors are used which rarely produce pressure ratios higher than 4.5.

The mentioned microturbine has been analyzed in nominal load based on input data published by Riccio and Chiaramonti (2009) and Turbec (2005). Table 1 shows results in nominal load and compares them with ones presented in other references.

Table 1: Comparison of T100 microturbine performance parameters in current research and available literature (Riccio and Chiaramonti, 2009; Turbec, 2005)

Computed value (current research)	Computed value (Riccio and Chiramonti, 2009)	Nominal value (Turbec, 2005)	Unit	Parameter
105.8	104	100 (+3)	KW	Electrical power
154	159.8	155 (+5)	KW	Thermal power
277	264	270	°C	Exhaust gas temperature
30	31.1	30 (+1)	-	Electrical efficiency
799	780	800	g/s	Exhaust gas mass flow rate
7.3	6.7	6.6	g/s	Fuel mass flow rate

Table 2: Comparison of performance indicators between cogeneration and SHP plants

Percentage of growth (%)	Cogeneration (%)	SHP (reference value)	Parameter
37	30	21.9%	η_e
30	74	56.9%	EUF
27	27	-	FESR
34	34	-	CO_2ER

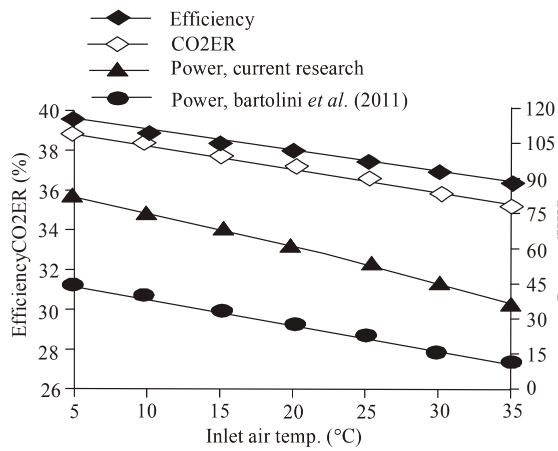

Fig. 3: Ambient temperature effects on system

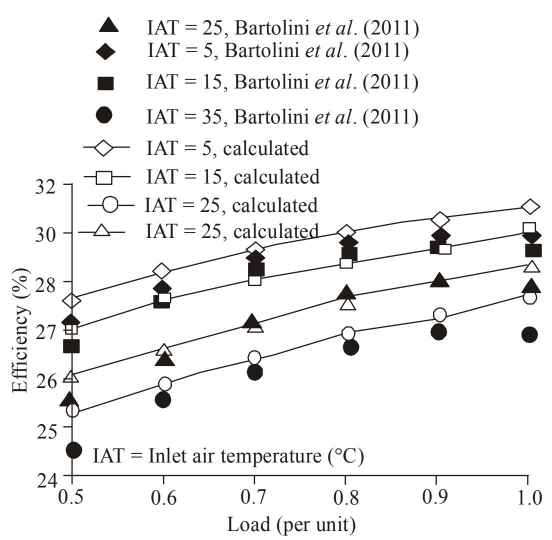

Fig. 4: Part-load efficiency in various ambient temperatures

Proper correlation between results computed by software and other references verifies correct performance of simulator code and makes it eligible for other related calculations.

Thermodynamic comparison of cogeneration and SHP plants: Table 2 presents performance indicators in nominal condition for mentioned cogeneration system. SHP Boiler efficiency and network electrical efficiency are assumed 85% and 35%, respectively.

As shown in the table, cogeneration can increase electrical efficiency and EUF around 37% and 30%, respectively. Furthermore, fuel consumption decreases 27% and CO_2 emission reduction is 34%.

Ambient temperature impact: As mentioned before, nominal values are presented at standard condition where ambient temperature is 15°C.

The diagram in Fig. 3 shows the impact of ambient temperature as air inlet, on efficiency, power and CO2ER. With the rise in ambient temperature, the electrical power output, efficiency and CO2ER show a decline. A negligible difference can be seen in the figure between current research calculated power and the values reported by Bartolini *et al.* (2011).

Part-load effects: Figure 4 compares the impact of working in part-load conditions in various ambient temperatures, with the available data from Bartolini *et al.* (2011). Despite the similar trends, the results start to deviate near nominal load. In fact, in the results of Bartolini *et al.* (2011), efficiency reached its peak at 90% of the nominal load and then a plateau appears.

Part-load effects on fuel consumption, CO_2 emission and efficiency are simulated in standard condition and compared in Fig. 5. In order to simulate partial load behavior, following three different methods have been used:

- **Model A:** In this model which is derived from Sanaye and Ardali (2009), cycle is analyzed at nominal load and following empirical equations are applied to relate the part-load efficiency and microturbine exit temperature to their nominal values.

$$\eta_{pl} = \eta_{nom}\left(0.236Ln\left(100pl\right) - 0.082\right)$$
$$T_{ex,pl} = T_{ex,nom}\left(0.387Ln\left(100pl\right) - 0.779\right) \tag{12}$$

where, η represents efficiency, pl and T_{ex} show partial to nominal load ratio and microturbine exit temperature, respectively.

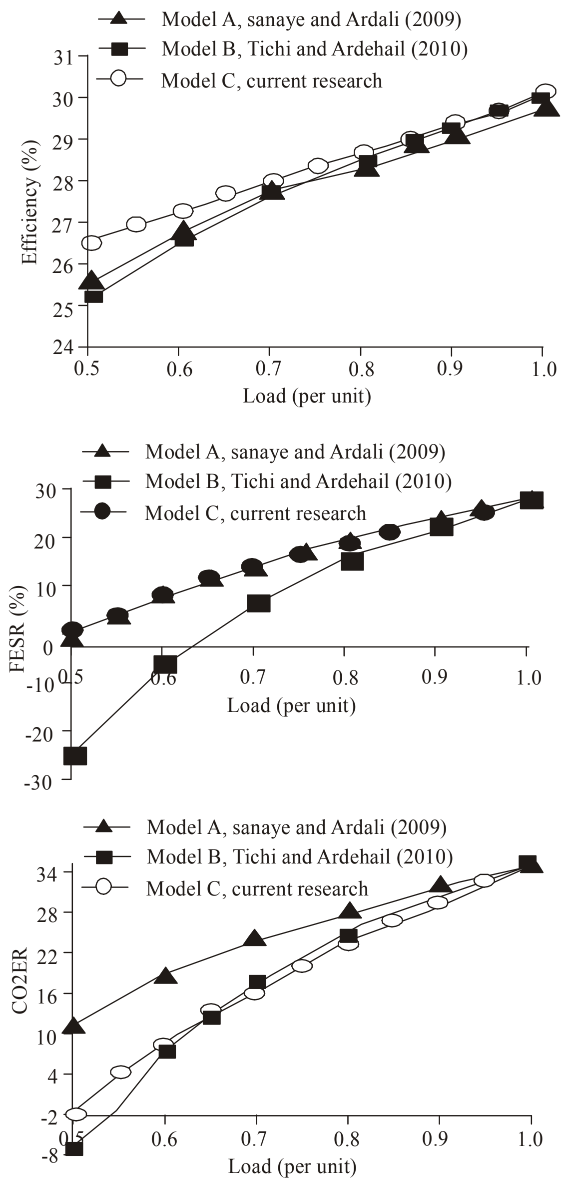

Fig. 5: Part-load effects on system

- **Model B:** In this model, cycle is analyzed at nominal load and following empirical equations are applied to relate the part-load efficiency and microturbine exit temperature to their nominal values, presented by Tichi *et al.* (2010):

$$\begin{aligned} \eta_{pl} &= \eta_{nom}\left(0.8838pl^3 - 2.182pl^2 + 2pl + 0.29\right) \\ Q_{u,pl} &= \left(W_{pl} / \eta_{pl}\right) \times \eta_{q,nom} \end{aligned} \quad (13)$$

where, $\eta_{q,\,nom}$ is thermal efficiency of microturbine and assumed to be 48%.

- **Model C:** In this model which is suggested by authors, deviation from nominal load results in decline in microturbine inlet and exit temperatures and compressor pressure ratio according to linear interpolations (19). Then, thermodynamic cycle analyzing is done again based on new computed values. Moreover, in this model, a linear correction for microturbine specific emission is applied.

$$\begin{aligned} TIT &= 250pl + 700 \\ T_{ex,pl} &= 152.8\left(pl - 0.5\right) + 0.75T_{ex,nom} \\ P_r &= 2.5pl + 2 \\ \mu^F_{CO_2,pl} &= -113pl + 315 \end{aligned} \quad (14)$$

where, TIT, T_{ex}, pl, P_r and $\mu^F_{\mu co_2,pl}$ are part-load microturbine inlet and exit temperatures in (°C), pressure ratio and specific emissions of fuel in (g/kWh), respectively.

As illustrated in the Fig. 5, the efficiency results presented for all models are almost the same. About Fuel Energy Saving Ratio (FESR), models B and C have a good coincidence but model A, experiences a relatively steep gradient toward negative values as in 50% of nominal load, so pessimistically predicts 24% increase in fuel consumption. In spite of this significant growth in fuel use, Model A demonstrates an 8% decrease in the field of CO_2 Emission Reduction (CO_2ER), which is incongruous. Finally, regarding CO_2ER, in both models of A and C, at 50% of nominal load and less, with emission indicator tending to negative values, ignoring the operation of such plant is expected. Meanwhile, unlike the other ones, model B shows 11% CO_2 emission reduction in half of full load, which seems quite optimistic. It can be elicited from the comparison that model C, proposed in the present study, is more consistent, thus its results are more compatible.

CONCLUSION

In this study, performance of a microturbine-based cogeneration plant is investigated in the form of thermodynamic and environmental evaluation by a simulator computer code. Part-load simulation is carried out and a model for emission and fuel saving calculation in such condition is proposed, which is more consistent than other models. Comparison of obtained results with the data in open literature, verifies the accuracy and authenticity of the approach, revealing the huge potential to conserve energy and environment due to the current energy generation substructure and framework in Iran.

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