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Simulation of Integrated Biomass Gasification-Gas Turbine-Air Bottoming Cycle as an Energy Efficient System

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Abstract- Air Bottoming Cycle (ABC) is used to enhance total efficiency and output power in conventional gas turbine systems. An integrated biomass gasification-gas turbine-ABC combined cycle has been presented in this study. The proposed cycle has been used as a novel approach to alleviate restrictions on generated power in the biomass gasification-gas turbine systems. Additionally, a significant amount of heat can be produced in this combined cycle, which justifies its application as a combined heat and power system. Modeling and simulation of the cycle have been performed regarding the energy system. To generate syngas fuel from bagasse, a two equilibria gasifier system, integrated with a low-temperature gas cleaning system, has been used. Results show that delivered power from the proposed cycle has been increased about 44.2% compared to the conventional gas turbines, while the total energy efficiency of the combined cycle has been calculated about 58.9%. Moreover, results indicate that due to the higher opportunity of energy recovery in GT-ABC, the total efficiency and generated power reduction is less without ABC cycle because of pressure ratio changes. Additionally, wastage of heat in the proposed cycle was minimized by transferring waste heat to heat sinks, which resulted in the balance of energy in the cycle. Overall results show the suitability of the proposed cycle to attain high efficiency and power generation capacity in biomass gasification-gas turbine systems.unavoidable.

Keywords Air Bottoming Cycle, Gas Turbine, Biomass Gasification, Total Efficiency, Simulation.

1. Introduction

Reduction of greenhouse gas emissions and pollutants in the industrial sectors has been converted to principal goal concern for energy and environmental programs in recent years. Recovering the waste heat from power plants can lead to a major contribution for this purpose [1].

The combination of gas turbines with other power systems has been developed in recent decades, in regard to total energy efficiency increase. Also, biomass gasification is an alternative solution to supply required fuel of power generators in sustainable view point. Therefore, various types of GT system integrations along with biomass gasifiers have been proposed and implemented [2-7]. In order to increase power and efficiency of the hybrid power generators, integration of biomass gasification with a verity of combined cycles include a gas turbine, fuel cells or steam turbines have been proposed in recent researches [8-11]. It seems that complex or high cost presented cycles in several studies impede commercialization of these hybrid systems. So, feasible and efficient advanced cycles should be promoted to absorb investors for generating power with high efficiency and low emission.

On the other hand, developing conventional combined cycle conflicts with the purpose of water conservation and alternative approaches must be considered. Generally, a major portion of areas in the Middle East suffers from a severe scarcity of water resources, which has been reduced the number of sites that are suitable for deployment conventional power plants. Use of gas-turbines as an alternative to conventional Rankine steam cycles has been suggested, in order to facilitate the increased development of hybrid power plants in water scarce areas. Using air as working fluid cause to reduce water consumption and increase the flexibility of power generation by system integration. Also, replacing low temperature recuperated GT cycles with the conventional steam cycles can be a suggested solutions for the aforementioned objectives [12, 13].

One of the methods for increasing GT energy efficiency is a combination with air bottoming cycle. It is an accessible cycle and it is used in several industries as cogeneration system [14-33]. In an ABC, the combustion chamber is replaced by a gas-to-air heat exchanger, so ABC is an open Brayton cycle for extracting heat from the gas turbine exhausts. So, ABC might be a proper choice in different applications such as food, glass, oil and gas off-shore platforms and other industries which have high-temperature furnaces. In addition, not only GT and ABC integration causes higher total efficiency rather than simple GT cycles, but also it is a reasonable solution in dry areas in compare with wet bottom cycles [15, 16].

Regarding low water consumption target, compressed air is used as the working fluid in the bottoming cycle. The compressed air is then successively heated by the exhaust gasses of the topping cycle turbine.

At first, ABC integration with coal gasification plants was proposed in 1989 [17, 18], then most efforts have been focused on synchronizing this system for industrial cases ever since. Some of researches for ABC development have been shown in “Table 1”.

The effect of intercooler in ABC was studied in several studies. The results have shown that the efficiency of the cycle will be increased by using intercoolers [22]. Also, economic analysis of ABC has been performed in some researches and these estimations showed that the investment expenditure of ABC is much lower than conventional combined cycles [14, 15, and 22].

Moreover, since the area is a significant constraint in heat exchangers and basically ABC needs a large air heat exchanger (AHX); therefore area minimization of the air heat exchanger has been considered in various studies [1, 15, and 16].

The basic principle of a biomass gasification power plant is to convert agriculture and forestry products and wood processing remains into combustible gasses. It can be used as fuel in the gas turbine to generate electricity. Biomass gasification successfully conquers the disadvantages of biomass, such as low flammability and wide diversity. Biomass gasification system is characteristic of small land requirement and environment-friendly. It’s one of the most effective ways of biomass utilization according to sustainable energy purposes [4, 9].

Furthermore, output power enhancement of conventional IBG-GT systems at reasonable total efficiencies and costs has always been a substantial constraint for the development of combined gasification and GT systems. This is mainly due to lower biomass fuels’ heating values in compare with conventional fossil fuels. Therefore, integration of air bottoming cycle and GT systems can be considered as an effective approach for this purpose.

In this paper, a novel and efficient configuration called IBG-GT-ABC system, containing biomass gasification (bagasse) unit, a gas turbine system in conjunction with an air bottoming cycle, has been investigated for increasing output power at an acceptable range of efficiencies.

The proposed cycle has been modeled, simulated and analyzed to present its advantages in comparison with other reported combined GT-ABC systems. In addition, some parametric studies have been carried out to consider cycle behaviors under different conditions.

2. System Configuration

The block diagram and streamlines of the conceptual design of the proposed IBG-GT-ABC system have been depicted in “Figure 1”.

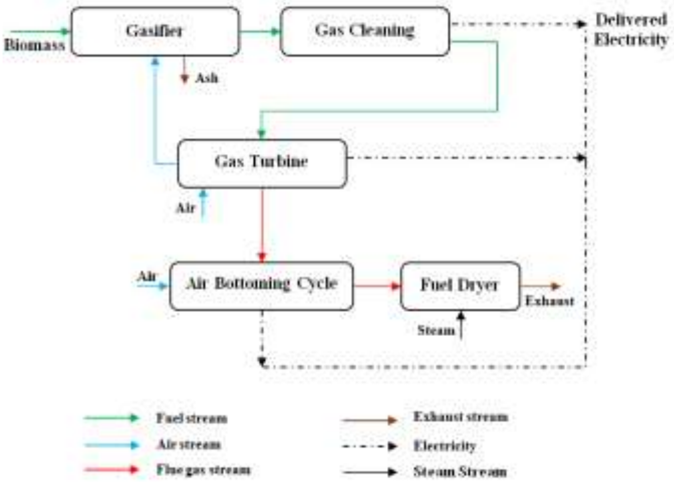

Fig. 1. Conceptual design of the proposed hybrid cycle.

According to “Figure 2”, the proposed system is comprised of different sections which have been pinpointed by the sections’ names. These sections include biomass gasifier and gas cleaning systems, GT and air bottoming systems, booster compressor and fuel dryer unit.

Gasification of the biomass is usually preformed in the gasification system. Impurities within the components of the bed are separated from the gasses by a C, SiO_2 separator. The gas which is exhausted from gasification unit cannot be directly used within GT combustion chamber. Therefore, components such as H_2S, SO_2, COS and NH_3 are effectively removed from the exhaust gas. Since performing gas treatment within the higher temperature ranges might causes structural and operational restrictions, the hot syngas needs to be appropriately cooled down before being treated.

The cooled exhaust gas from cooling and cleaning units is then mixed with compressed air in the GT combustor. The expanded flue gas has been used to heat transfer in air heat exchanger.

3. Model Development

The characteristics of the entered biomass fuel and bio-syngas from the gasification unit are shown in “Table 2”. Also, the calculations related to the performance of the cycle were conducted based on the initial values and the input data presented in “Table 3”. The proposed cycle has been designed and simulated using Cycle-Tempo software [34].

Table 1. Delivered power and total efficiency of some GT-ABC systems.

GT Type	Delivered Power	Total Efficiency	Reference
SGT-500 twin-spool/ABC	19.8 MW	37.0%	[1]
LM2500PE/ABC	29 MW	46.21%	[14]
Titan 130/ABC	17.5 MW	39.0%	[15]
ABB GT10/2IC ABC	31.2 MW	44.03%	[16]
SGT-500/1IC ABC	19.3 MW	36.5%	[19]
SGT-500 twin-spool/ABC	19 MW	35.5%	[20]
Simple GT/1IC ABC	41.1 MW	43.63%	[21]
Simple GT/1IC ABC	50 MW	43.17%	[22]
Simple GT/ABC-SI	50 MW	55.39%	[23]
Simple GT/ABC	594 kJ/kg	43.3%	[24]
Simple GT/ABC	484.1 kJ/kg	49.0%	[25]
Simple GT/2IC ABC	7.55 MW	43.0%	[26]
LM2500/2IC ABC	18 MW	41.9%	[27]
GE10/ABC	13.76 MW	39.0%	[28]

The total cycle efficiency is obtained from the sum of electrical and thermal efficiencies which has been shown in “equation (1)”. The electrical efficiency of the system is achieved from GT and ABC electrical efficiency using the general “equation (1)”. The total efficiency of the system is calculated by “equation (1)”.

$$\eta_{total} = \eta_{electrical} + \eta_{heat} \tag{1}$$

$$\eta_{electrical} = \frac{W_{net}}{LHV\ \dot{m}_f} \tag{2}$$

Where,

$$\dot{W}_{net} = \dot{m}_g W_{t,T} + \dot{m}_{a,B} W_{t,B} - \dot{m}_{a,T} W_{c,T} - \dot{m}_{a,B} W_{c,B} \tag{3}$$

Then,

$$\eta_{total} = \frac{\sum Electricity_{gen} + \sum heat_{gen} - \sum Electricity_{con}}{LHV_f} \tag{4}$$

As the same way, the average energy conversion efficiency of agricultural fuel gasifiers is about 60-70% and is defined as:

$$\eta_{gas} = \frac{\dot{m}_{syngas}\ LHV_{syngas}}{\dot{m}_f\ LHV_f} \tag{5}$$

In the present study bagasse which is a common agricultural waste has been considered. The main reasons for selecting this type of biomass are the followings:

Regarding the proportion and the percentage of the present elements in different types of common agricultural biomass applied for energy production purposes, bagasse has an appropriate LHV [35]. Properties of the bagasse and produced syngas have presented in “Table 2”.

There are vast sugar cane plantations in the south of Iran where a huge amount of bagasse is produced and is available. The total amount of the energy which could be generated from the regions where the bagasse utilization is feasible is 152.4 PJ [36]. Thus, a remarkable potential for local and regional power generation exists from this resource.

4. Results and Discussion

The main energy generation and consumption results of the cycle modeling have been indicated in “Table 4”. Additionally in “Table 5”, various indicated efficiencies of the system have been shown. According to Table 5, the total energy efficiency of the cycle is about 58.9% which is higher than other studies explained in Table 1.

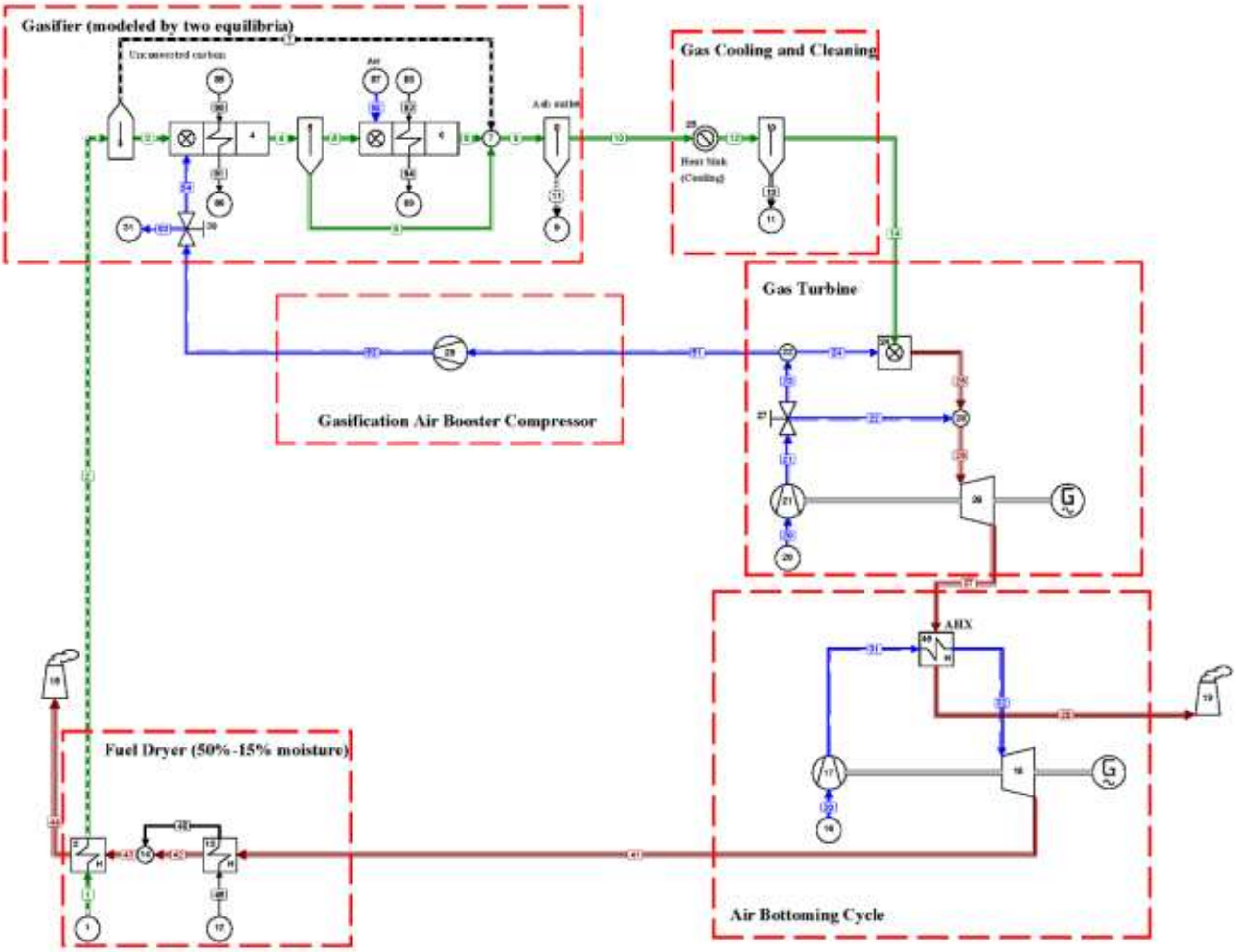

Fig. 2. Simulated IBG-GT-ABC cycle.

On the other hand, the desirability of biomass gasification performance was verified in this new system integration.

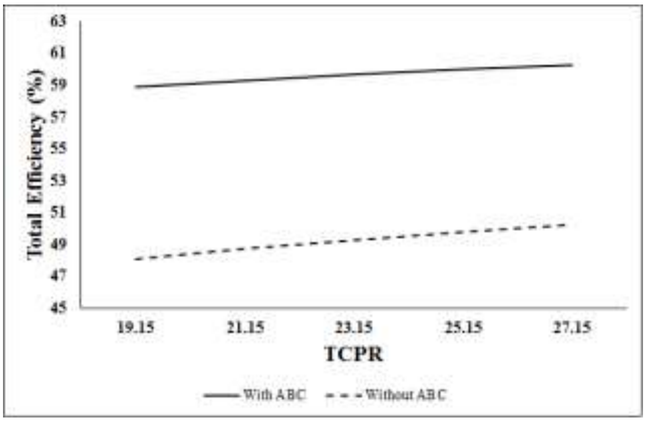

Fig. 3. Total efficiency changes based on different TCPR amounts with and without ABC.

“Figure 3”, compares the total efficiency of the proposed model in cases with and without ABC, based on TCPR. These curves demonstrate that the total efficiency will increase if the amount of the pressure ratio intensifies in the topping cycle. The discrepancy between the two curves is significant, so positive effect of ABC application on the cycle efficiency is perceptible. It means that by using ABC instead of simple GT cycle, higher values of the total efficiency are achievable.

Pressure drop in the AHX has a remarkable effect on the performance of ABC [16]. Due to the requirement of applying large surface area in the air heat exchanger, some portion of pressure drop might be inevitable in the mentioned cycle. Hence, investigation of pressure drop impact in the proposed cycle shows the importance of the convenient design of this apparatus.

The results of energy efficiency and output power change for different pressure drops in the AHX, based on TCPR variation are presented in “Figure 4”, and “Figure 5”.

Since energy efficiency is linearly dependent on the output power, the maximum points of power generation and energy efficiency are in the same pressure ratio. Also, considerable decreases in both mentioned factors have been observed when pressure drop of AHX is increased.

Table 2. Bio fuel and main dry bio-syngas characteristics.

Sugarcane Bagasse Parameter (unit)	Value
Bagasse fuel	
C (wt. %)	43.6
H (wt. %)	5.3
N (wt. %)	0.14
O (wt. %)	38.4
S (wt. %)	0.04
Cl (wt. %)	0.03
Ash (wt. %)	2.09
H_2O (wt. %)	10.4
LHV (kJ/kg)	15,619
Bio syngas	
H_2 (mol %)	10.31
N_2 (mol %)	43.12
CO_2 (mol %)	12.96
CH_4 (mol %)	5.41
CO (mol %)	15.21
H2O (mol. %)	12.46
Ar (mol. %)	0.51

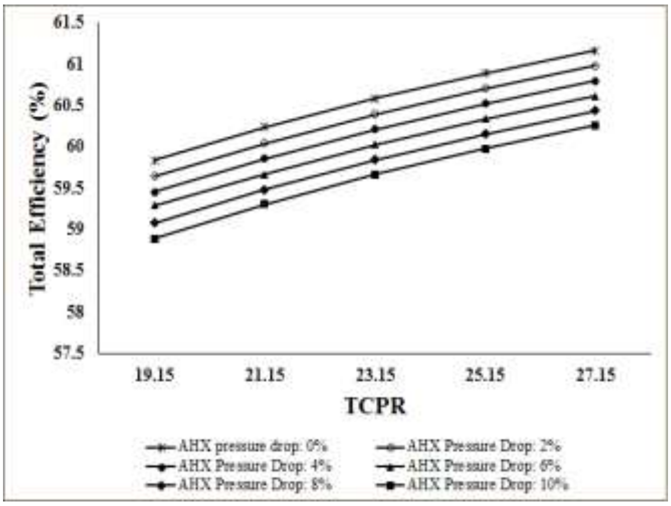

Fig. 4. Total efficiency changes based on different TCPR and AHX pressure drop amounts.

Based on gas turbine fundamentals, topping and bottoming cycles' pressure ratios in the ABC might have significant effects on the results of presented hybrid cycle. However, these changes are not ascending in all ranges and also mutual effects of both pressure ratios might make other restrictions in the comprehensive cycle.

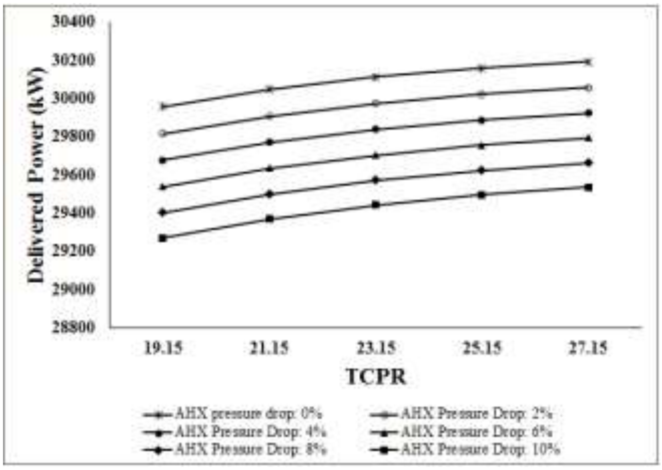

Fig. 5. Delivered power changes based on different TCPR and AHX pressure drop amounts.

Furthermore, results of the pertained effect of BCPR in contribution with the different TCPR values on total efficiency have been indicated in "Figure 6".

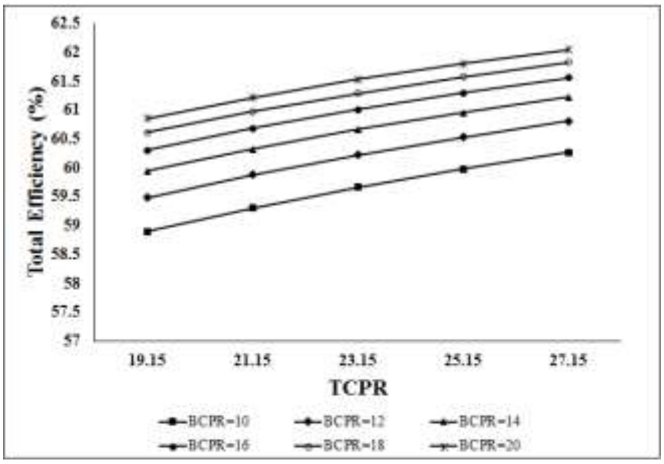

Fig. 6. Total efficiency changes based on different TCPR and BCPR amounts.

Outcomes of cycle simulation have been illustrated that energy efficiencies in the greater TCPRs are more sensitive to variation of BCPR. This is the main reason behind the reduction of the total energy efficiency. Output power changes for different combinations of TCPR and BCPR is depicted in "Figure 7".

According to these results, increasing the rate of total efficiency and total delivered power in lower BCPRs is greater than higher BCPRs. Therefore, rising up of the BCPR caused to intensify restriction against pressure ratio effects in the GT-ABC combined system.

Ambient temperature changes might have serious consequences on the gas turbine performance [37]. Moreover, in Iran, a major portion of sugarcane bagasse produces in the south provinces which have high-temperature difference during summer and winter seasons [38].

Table 3. Assumptions and input data in the analysis model.

Parameter	Value (unit)	Parameter	Value (unit)
GT		Reaction temperature	773.15 K
GT and Compressor mechanical efficiency	0.99	Chemical equilibrium temperature	773.15 K
GT isentropic efficiency	0.89	Gasifier outlet gas pressure	4 bar
Compressor isentropic efficiency	0.83	Oxidant to fuel ratio	1.67
Compressor pressure ratio	19.15	Fuel dryer	
ABC		Biomass outlet temperature	365.15 K
Turbine and Compressor mechanical efficiency	0.99	Gas cleaning system	
Turbine isentropic efficiency	0.89	Bio syngas outlet temperature	773.15 K
Compressor isentropic efficiency	0.83	Fuel and Air inlets	
Compressor pressure ratio	10	Biomass inlet temperature	288.15 K
AHX hot stream outlet temperature	393.15 K	Air inlet temperature	293.15 K
Fluidized bed gasifier		Biomass inlet pressure	1.3 bar
Reaction pressure	4 bar	Air inlet pressure	1.013bar

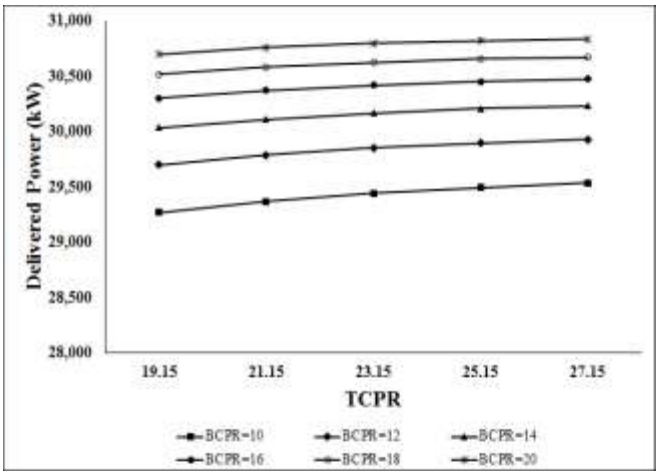

Fig. 7. Delivered power changes based on different TCPR and BCPR amounts.

Table 4. Absorbed and delivered the energy of the proposed IBG-GT-ABC cycle.

		Energy (kW)
Absorbed	Biomass Source	72,850.00
Delivered	GT Generator	20,252.09
	ABC Generator	9018.21
Auxiliary Power Consumption	Compressor (No. 29)	1094.29
Net Power Delivered		28,176.01
Delivered Heat	Heat Sink (No. 25)	14,726.67
Total Delivered		42,902.68

Table 5. Energy efficiencies of the proposed cycle.

Efficiencies	Value (%)
Gross	40.18
Net	38.67
Heat	20.21
Total	58.89

Therefore, consideration of this variation influences is useful to determine off-design operations of the proposed cycle. Additionally, cogeneration provides more flexibility against surrounding changes [16, 37]. Therefore, the total efficiency and generated power reduction by increasing ambient temperature for cycles with and without using ABC are displayed in “Figure 8”, and “Figure 9”.

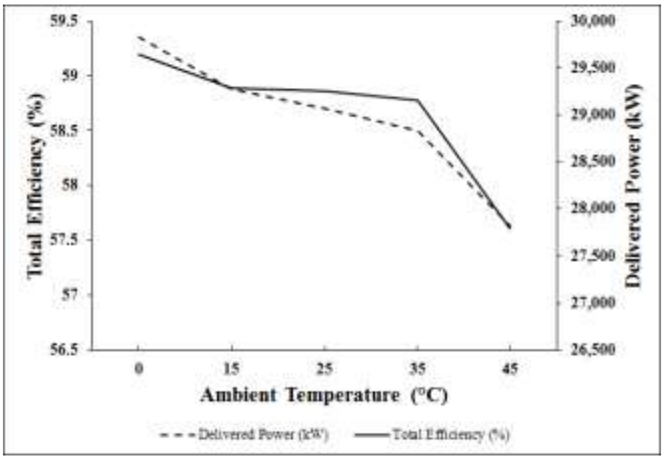

Fig. 8. Total efficiency and delivered power changes based on ambient temperature variation (with ABC).

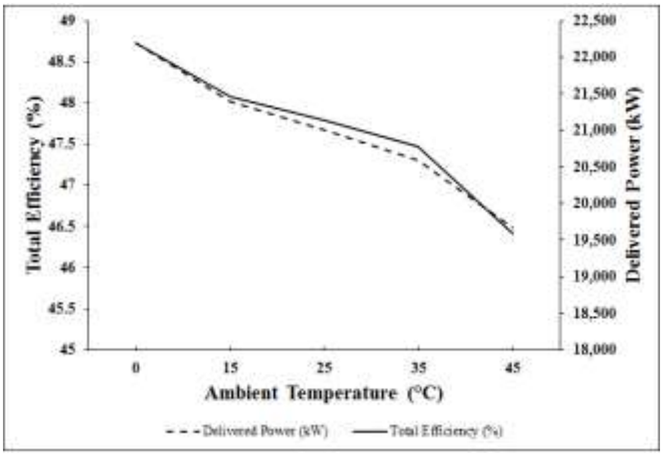

Fig. 9. Total efficiency and delivered power changes based on ambient temperature variation (without ABC).

Ambient temperature was changed from 0 to 45°C and its consequences have been considered. Due to a higher opportunity of energy recovery, the percentage of decrease in the total efficiency and delivered power for "with ABC" scenario is less than "without ABC".

Air mass flow rate (AMFR) of the bottoming cycle is able to have some influences on total efficiency and output power of combined cycle. In addition, the effects of varying this factor on total efficiency and delivered power have been presented in "Figure 10".

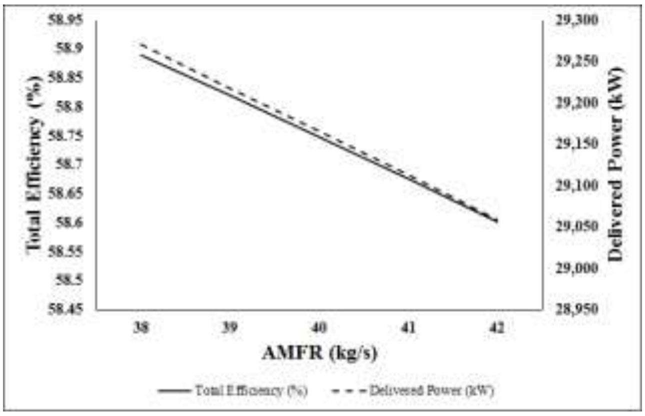

Fig. 10. Total efficiency and delivered power changes based on different AMFR amounts

Based on the variation of AHX characteristics, the main restriction for changing AMFR is the turbine inlet temperature (TIT). The increase of the AMFR causes degradation of mass flow temperature and accordingly, during AMFR changes, the TIT of bottoming cycle was preserved in a reasonable range. According to "Figure 11", results explain positive slopes in the plant efficiency and output power between TIT of 938 to 1000°C by reducing the amount of AMFR.

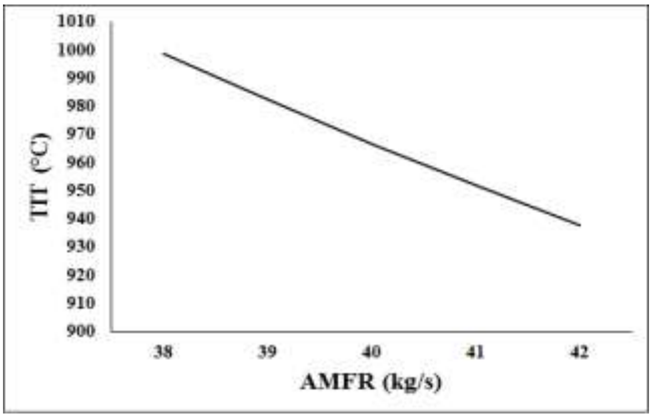

Fig. 11. TIT changes based on different AMFR amounts.

The total efficiency of the proposed power plant reached to about 58.9%, which in compare with pertained previous studies expressed in "Table 1", it is considerably high. It demonstrates that applying biomass fuel as a renewable energy source, in contribution with air bottoming cycle is an effective approach for increasing performance of conventional GT cycles. Furthermore, major energy streams have been shown as a Sankey diagram in the "Figure 12". As shown in "Figure 12", heat recovery for fuel drying and using pressurized biomass gasification can increase the energy content of produced syngas. In addition, absorbing the available heat of syngas before power generation has led to increasing the total efficiency.

Principal efficiency values which have been resulted from a simulation of the presented plant have been expressed in Table 5. These values are indicated for the 29.3 MW output power of cycle operation.

5. Conclusion

In this study, an IBG-GT-ABC novel combined cycle was proposed to attain high total efficiency in conventional gas turbine cycles. This cycle has been presented based on CHP concept, to increase delivered power and reduction of water consumption. Moreover, using biomass gasification as fuel producer mechanism caused to explain alternative fuel resources for sustainable energy purposes. Bagasse which is produced with a significant amount in the south of Iran has been considered as a renewable energy resource for this cycle. The following conclusions can be drawn from this study:

- Acts Compared to the conventional gas turbine cycles, electrical power generation from the proposed novel cycle has been increased by 44.2%.
- The total energy efficiency of the presented comprehensive cycle is about 58.9%, which is higher than related previous studies on air bottoming cycle.
- The total efficiency and delivered power from the proposed cycle are more stable against ambient temperature variations. According to the results, in ambient temperature changes from 0 to 45°C, the generated power decreases to about 6%, while it is about 11% in the simple IBG-GT cycle.

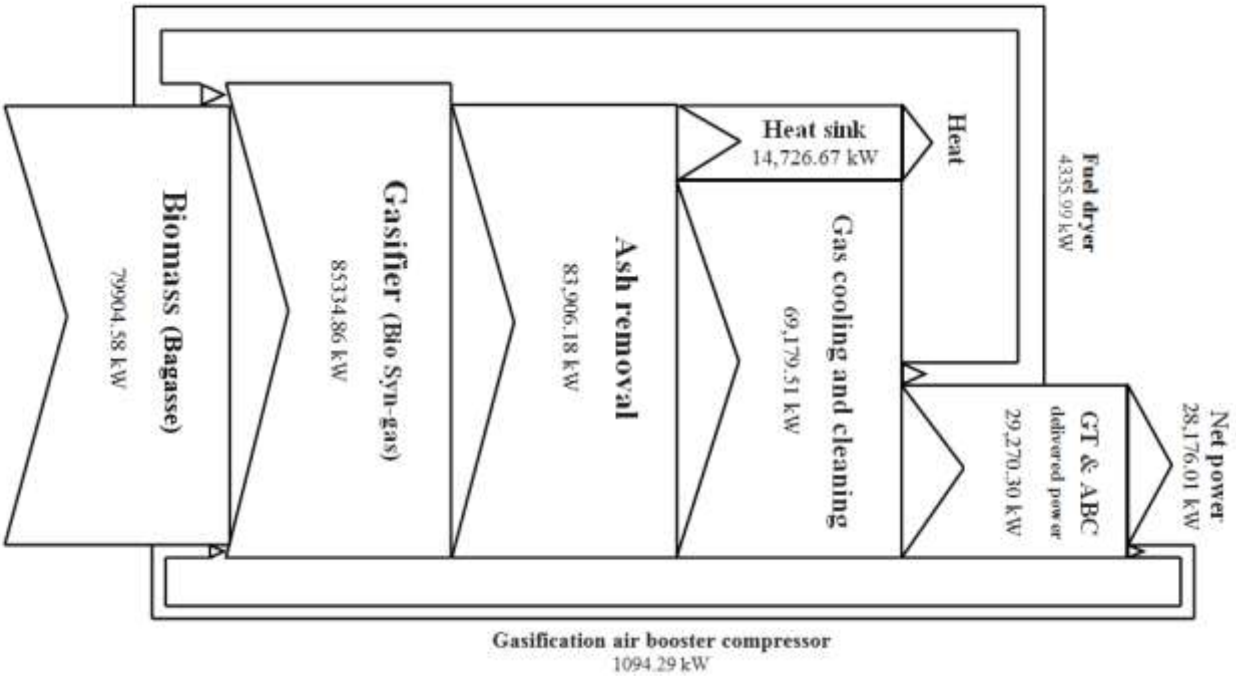

Fig. 12. Sankey diagram for the proposed system.

- Additionally, wastage of heat in the proposed cycle was minimized by transferring waste heat (about 14,726 kW) to heat sinks. It can be consumed at auxiliary processes and causes to increase the thermal efficiency of the cycle.

- The proposed cycle is suitable for attaining high power generation capacity in combined cycles, by reducing water consumption and using renewable energy resources.

Nomenclature	
LHV	Lower Heating value [kJ kg^{-1}]
$\dot{m}$	Flow rate [kg s^{-1}]
PR	Pressure ratio [-]
$\dot{W}$	Power [Watt]
Abbreviations	
ABC	Air Bottoming Cycle
AHX	Air Heat Exchanger
$AMFR$	Air Mass Flow Rate
$BCPR$	Bottom Cycle Pressure Ratio
CHP	Combined heat and Power
GT	Gas Turbine
IBG	Integrated Biomass Gasification
SI	Steam Injection
$Syn-gas$	Synthesis gas
$TCPR$	Top Cycle Pressure Ratio

TIT	Turbine Inlet Temperature
Greek	
η	Efficiency
Subscripts	
a	Air
B	Bottom cycle
c	Compressor
$electrical$	Electrical
f	Fuel
g	Gasifier
gen	Generated
$heat$	Heat
net	Net
$syngas$	Syngas
t	Turbine
T	Top cycle
$total$	Total
Greek	
η	Efficiency

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