THERMODYNAMIC MODELING of an IBG-CHAT-ST POWER SYSTEM

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Abstract—Cascaded Humidification Advanced Turbine (CHAT) cycles have been proposed to increase delivered power of simple gas turbine systems. In this paper, an Integrated Biomass Gasification (IBG)-HAT-Steam Turbine (ST) combined cycle has been presented as a novel approach to consider the restrictions of power generation in gas turbine (GT) systems using biomass gasification. Additionally, significant amount of heat which is produced in proposed cycle generates power in steam turbine to justify its application as a combined heat and power (CHP) cycle. Based on the energy point of view, modeling and simulation of the cycle have been performed and results show more than 2.2 times increase in electrical power generation compared to a simple gas turbine cycle. However, the total energy efficiency of the proposed cycle is in the acceptable range of combined cycles. Moreover, results indicate stability of the output power against ambient temperature variations. Additionally, delivered power and electrical efficiency of the presented cycle will be decreased when moisture content of biomass, gasification temperature and inlet temperature of high pressure turbine increase.

Keywords—Biomass Gasification, Fluidized Bed, Gas Turbine, Steam Turbine, Combined Cycle.

I. INTRODUCTION

Gas turbines with air–water mixtures as the working fluid promise high electrical efficiencies and high specific power outputs to specific investment costs below that of combined cycles [1], [2].

- Humidified gas turbines have a thermodynamic potential of electrical efficiencies similar to, or higher than, combined cycle efficiencies.
- The evaporative gas turbine including a humidification tower has the highest efficiency of the humidified gas turbine cycles.
- Humidified gas turbines have higher specific power outputs than dry gas turbine cycles.
- Humidification of the gas turbine working fluid results in a volumetric flow rate mismatch between the compressor and expander. Gas turbines that can accommodate the increased flow rate are still to be developed.
CHP, cogeneration of power and district heating seems to be a promising application for humidified gas turbines. It has been estimated that the specific investment costs and costs of electricity and heat should be significantly lower than for combined cycles [3]-[7]. In the 1980s, the interest in gas turbine cycles with humidification towers increased and a research program on the Humid Air Turbine (HAT), the evaporative cycle patented by Rao [8], was commenced in the USA. The humid air gas turbine cycle is used as working fluid system “water-air”, which can significantly improve the capacity and efficiency compared to the simple gas turbine cycle. EPRI [9] presented a report on HAT and combined cycles IGHAT or fired with natural gas. Two gas turbine manufacturers, GE and Asea Brown Boveri(ABB), supplied data for the gas turbines used in the study. For natural gas, the GE HAT cycle had an efficiency of 53.5% while the triple-pressure reheat combined cycle efficiency was 49.5% and the ABB HAT cycle efficiency was 57.4% while the combined cycle efficiency was 53.4%. Various novel cycles such as HAT [9], Cascaded Humidified Advanced Turbine (CHAT) [10], REgenerative EVAPoration cycle (REVAP) [11], and Top Humidified Air Turbine (TopHAT) [12] have been proposed for highly effective operation by combining the regenerative cycle with humid air. It is thought to be suitable for distributed power supply to a combined cycle because of high efficiency, simplicity of the system, and applicability to cogeneration. It is suitable for a typical gas turbine, which is widely used for industrial small-size to large-size machines. Nakhamkin [13] calculated that in case of existence of 55% output of the CHAT cycle and turbine inlet temperature increase to 1500 and pressure ratio to 80, with 500 MW power is between 63% and 65%. The CHAT (cascaded humidified advanced turbine) was proposed to solve the problem of flow mismatch between the compressor and turbine in the HAT. The CHAT cycle demonstrates a combination of the best characteristics of Combustion Turbine (CT) and Combined Cycle (CC) plants:

- Startup characteristics, operating flexibility, and load following are similar to or better than CT.
- Efficiency and part-load characteristics are better than CC plants based on the same CT.
- The performance characteristics of each of the three CHAT plants (35, 95, and 145 MW) are significantly better than for the base CT [14]:
  - Power is approximately double that of the base CT.
  - Heat rate improved by approximately 35% relative to base CT.
  - Better part-load efficiency, constant power over a wide range of temperatures, lower NOx.
- CHAT cycle shows improved life cycle costs relative to combined cycle based on same core engine; can get even better with optimized components
- Results do not account for other CHAT cycle advantages, which would improve the comparison in real applications (better hot day and part-load performance, better altitude performance, etc.). [14],[15].

Nakhamkin and Gulen [16] presented a transient analysis of the first CHAT cycle design. It was found that the CHAT cycle was comparable to a simple cycle gas turbine in operation flexibility at startup. Further studies of the CHAT have shown higher power outputs and electrical efficiencies than combined cycles based on commercially available gas turbines for midsize power generation (30–150 MWe). For a GE Frame 6FA core engine, a combined cycle had a power output of 107.4 MWe and an efficiency of 53.0%, while a CHAT cycle had a power output of 143.5 MWe and an efficiency of 54.9% [17]. A CHAT demonstration plant based on the Rolls-Royce Allison 501-KB7 gas turbine, with a power output of 12.1 MWe and a net efficiency of 46.4 has been proposed for distributed generation [18]. Gaul [19] proposed an 11 MWe CHAT design, also based on the 501-KB7, for distributed generation. In this CHAT cycle, the second shaft was not power-balanced to avoid
costly modifications to the gas turbine compressor. EPRI [9] presented a report on HAT cycles fueled with gasified coal or natural gas. The IGHAT was predicted to have about 2–3% (1% point) higher efficiency, about 20% lower specific investment cost, decreased operation and fixed maintenance costs and a 15% lower cost of electricity compared with a IGCC. The cycle electrical efficiencies were slightly above 40% and the power outputs were in the range of 460–600 MWe. EPRI [20] presented a report on a 410 MWe IGHAT based on two FT 4000 HAT gas turbines. The design calculations showed that the IGHAT had approximately the same efficiency (about 42.5%) as a 502 MWe IGCC based on two industrial gas turbines, although the specific investment cost was 11% lower and the cost of electricity was 8% lower. A CHAT cycle integrated with coal gasification (IGCHAT) has also been proposed. Compared with an IGCC, the exclusion of the steam bottoming cycle reduced the investment cost in the order of 100 USD/kWe. In addition, the IGCHAT could use low-temperature energy; hence, it could use a low-cost quench gasifier that further reduced the investment cost [21]. IGCHAT plants have the potential for significant investment savings and performance improvements for coal gasification based power plants. Delivered power reduction has been one of substantial constraints for development of integrated biomass gasification and GT systems. This is mainly due to different heating value of bio fuels and fossil fuels in conventional combined cycle. Therefore, delivered power enhancement using humidified cycles at acceptable total efficiencies will be proposed to cover this defect. Moreover, integration of advanced GT cycles and conventional steam cycle can be considered as an effective approach for this purpose. In this paper, a novel and efficient configuration called IBGCHAT-ST cycle, which includes integrated biomass gasification (IBG) unit, a cascaded humidified advanced turbine (CHAT) cycle in conjunction with a conventional steam turbine (ST) system, has been investigated for increasing output power at acceptable range of efficiencies. The proposed cycle has been modeled, simulated and analyzed to present its advantages in comparison with other reported combined CHAT systems.

SYSTEM CONFIGURATION
This intercooled, humidified, recuperated and reheated cycle has two shafts: one power-generation shaft with a low-pressure compressor and expander and one power balanced shaft with intermediate-pressure and high-pressure compressors and expanders. The plant diagram and streamlines of the proposed IBGCHAT-ST system have been depicted in Fig. 1. As shown, CHAT and ST cycles are the two power generators of the proposed hybrid system. Accordingly, the cycle can be divided into three sections: At first, biomass gasification unit, which has been considered to generate and purify syngas. In this unit the air enters to air separation unit, while the gained oxygen of separation unit enters the gasifier along with biomass and steam or water. Syngas is the output of the gasifier which must be passed from several stages of purification unit. In the second part, the air enters into the LP compressor, then the exhausting air from the LP compressor enters to sequential intercoolers in the CHAT cycle section. Also, the exhausting air from IP compressor enters the third and fourth intercoolers before it enters the HP compressor. Likewise, the outlet air from HP compressor enters the humidification tower which increases humidity and temperature of air. Third part of the proposed cycle is related to cogeneration system. Hot exhaust gasses from the fluidized bed gasifier produce pressurized steam in a heat recovery steam generator (HRSG). Then, superheated steam pass through a steam turbine and generates power. The best installation of elements for integrating biomass gasification, CHAT and steam turbine has been carried out in this model. HP combustion chamber has been designed so that the HP turbine matches with LP turbine and the
power generation capacity of this turbine is about 12.5 MW. Furthermore, LP turbine generator will deliver 15.7 MW electrical power.

**MODEL DESCRIPTION**

A. Biomass gasification unit

Since biomass has been used to produce syngas in the proposed system, wood chips has been considered as the utilized type in this study. The fuel is converted to syngas by a Fast Internal Circulated Fluidized Bed (FICFB) gasification unit [22], [23]. The major advantage of this technology is the possibility to carry out the process in two interconnected vessels, the first operating under gasification conditions, while the second one allows for partial combustion of the fuel and char burn-off [24], [25].

The fast internal circulating fluidized bed gasifier is an indirect gasifier, where the gasification zone (operating at a temperature of 800°C, and a pressure of 4 bar) and the combustion zone (operating at: 1100°C, 1 bar) are separated. Some parts of the gasses, liquid and biomass fuel start to reaction in gasification section. While in gasification process various reactions occur, most principals have been presented in following relations. At these equations biomass has been shown with Cs and also $a$, $b$ and $c$ are the stoichiometric amounts related to gas waste [26], [27].

\[
\begin{align*}
C(s) + O_2 &\leftrightarrow CO_2 \quad \Delta h= -394 \text{ kJ mol}^{-1} \\
C(s) + H_2O &\leftrightarrow CO + H_2 \quad \Delta h= +131 \text{ kJ mol}^{-1} \\
C(s) + CO_2 &\leftrightarrow 2CO \quad \Delta h= +173 \text{ kJ mol}^{-1} \\
C(s) + 2H_2 &\leftrightarrow CH_4 \quad \Delta h= -75 \text{ kJ mol}^{-1} \\
CO + H_2O &\leftrightarrow CO_2 + H_2 \quad \Delta h= -41 \text{ kJ mol}^{-1} \\
CH_4 + H_2O &\leftrightarrow CO + 3H_2 \quad \Delta h= +206 \text{ kJ mol}^{-1}
\end{align*}
\]

B. Low temperature gas cleaning

The produced gasses from biomass gasification should not directly be used in combustion chamber of gas turbine, because it contains various impurities, which are harmful for equipment. Gas purification in high temperature has restrictions in chemical reactions so it is carried out in lower temperature. The impurities in the bio syngas and the assumed tolerances of the gas turbine are listed in Table 2

<table>
<thead>
<tr>
<th>Component</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>C (wt. %)</td>
<td>39.92</td>
</tr>
<tr>
<td>H (wt. %)</td>
<td>4.80</td>
</tr>
<tr>
<td>N (wt. %)</td>
<td>0.44</td>
</tr>
<tr>
<td>O (wt. %)</td>
<td>33.94</td>
</tr>
<tr>
<td>S (wt. %)</td>
<td>0.05</td>
</tr>
<tr>
<td>Cl (wt. %)</td>
<td>-</td>
</tr>
<tr>
<td>Ash (wt. %)</td>
<td>0.64</td>
</tr>
<tr>
<td>H2O (wt. %)</td>
<td>20.13</td>
</tr>
<tr>
<td>LHV (kJ/kg)</td>
<td>14,869</td>
</tr>
</tbody>
</table>

**TABLE I** Characteristics of wood chips

Syngas losses heat in a heat sink and is cooled to 110°C. The released heat in a heat sink has been used in a steam cycle for cogeneration purpose. During cooling...
process a series of alkaline metals are condensed and separated from the bag filter so that some other particles can be separated. The next process is passing the gas through a water scrubber which decreases the syngas temperature to 74°C. Also, it causes descendants and omissions of halogens, tars and residual alkalis from gas the emitting syngas in compressed to 4.6 bar by compressor. The compressed gas is led through a packed bed with ZnO. This is supposed to be necessary to remove any Sulphur compounds from the gas. To make sure that also the last particles in the gas will be removed, the gas is finally passed through a ceramic filter. The syngas temperature is increased to 119°C.

CHAT cycle
The inlet air is first enters to the LP compressor, which its pressure ratio is 4. After passing this air through two intercoolers, the air enters IP compressor and then after being cooled to 74°C in two other intercoolers, is led to HP compressor and its pressure gets up to 14 bar. The compressed air enters the saturator after exhausting the HP compressor. At this unit, the inlet input water enters the team recycling cycle and mixes with it after pressure increase. Then the saturated steam inlets the humid tower with 8 bar pressure and 130°C temperature. The inlet compressed air mixes with the water steam at the humid tower. The water to inlet air ratio is 0.13 while exhausting the humid tower. It must be considered that the inlet water temperature must be more than the inlet air temperature [31]. The humid air enters the HP combustion chamber after passing through the heat exchanger whilst its temperature has been increased and its pressure is less than 14 bar. Then the mixture of humid air and produced syngas will be combusted. The flue gas of HP turbine enters the LP combustion chamber and mix with the syngas fuel to generate power. Generally, CHAT cycle efficiency is presented as in Eq. 3:

$$\eta_{CHAT} = \frac{WT - W_{Comp}}{Q} \text{(3)}$$

Since WT is gained by total generated power in LP and HP turbines:

$$WT = W_{Turb(HP)} + W_{Turb(LP)} \text{ (4)}$$

Then considering the distribution methods of fuel and air in LP and HP turbines.

Also, WComp is the result of total work of LP, IP and HP compressors.

Steam cycle
Steam turbine bottoming cycle has been modeled based on Rankine cycle methodology. For modeling this cycle, the primary energy absorbed by the HRSG boiler, the power produced by the generator, the electricity consumption of the pumps and the net supplied power have been indicated. It should be mentioned that the pumps electricity consumptions considered as auxiliary power consumers, which subtracted from gross electricity generated to estimate net power delivered. To examine the efficiency of the Rankine cycle, input and output works have been defined, so the thermal efficiency can be written Eq. 5 [32]:

$$\eta_{(thermal,ST)} = \frac{W_{out} - W_{in}}{Q_{in}} \text{ (5)}$$

Where, Wout and Win are generated power and pumps work, respectively. Also, Qin is the input heat to the cycle.

IV. MODEL SIMULATION
A. Model constraints
recommended cycle.

B. Model assumptions
Some assumptions in the simulated model are considered as follow:

- System works in steady state condition.
- Problems in system due to created tars by alkali metals, gasifier and other fouling components have been eliminated.
- Fluid pressure drop in different equipment has been considered based on functional conditions.

C. Simulation purposes
Simulation of the process has been completed by creating connection among selected sections in system, combining power generation, environmental condition definition, inlet primary amounts, assumptions determination in each
section and then model execution. The Cycle-Tempo software has been used in order to simulate this system [33]. The main purposes of model implementation are as follow: Increase power generated from conventional IBG-GT combined cycle, simulate heat and power generation in form of a comprehensive cycle, and finally heat waste decrease and efficiency increase by creating a logical connection between consuming and energy generating units. In order to simulate the system and gaining the mass and energy balance of the cycle has been used in constant condition [34]. Gaining coverage in sub-systems has been the most important goal at this model.

V. RESULTS & DISCUSSIONS

Electrical efficiency in IBG-CHAT-ST combined cycle has been shown in Eq. 6, which expresses the heat to power ratio of the comprehensive cycle. $\eta_{el} = \frac{\text{Total heat input}}{\text{Total electricity output}}$ (6) The main results of the simulation have been presented in Table 3. Generated power has been gained based on inlet fuel rate and syngas distribution in efficient parts of the combined cycle. Inlet fuel flow rate is 4 kg/s. in addition, total steam rate in gasification unit is about 1.275 kg/s, according to achieved result. Also, the air mass flow rate in the gasifier is about 7.63 kg/s.

<table>
<thead>
<tr>
<th>Parameter (unit)</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>HP Generator electricity generation (kW)</td>
<td>12,497.13</td>
</tr>
<tr>
<td>LP Generator electricity generation (kW)</td>
<td>15,721.31</td>
</tr>
<tr>
<td>Steam Turbine electricity generation (kW)</td>
<td>5411.80</td>
</tr>
<tr>
<td>HP Turbine outlet temperature (K)</td>
<td>1088.28</td>
</tr>
<tr>
<td>LP Turbine outlet temperature (K)</td>
<td>957.92</td>
</tr>
<tr>
<td>FICFB syngas outlet temperature (K)</td>
<td>1094.55</td>
</tr>
<tr>
<td>FICFB syngas outlet flow rate (kg/s)</td>
<td>4.15</td>
</tr>
<tr>
<td>Inlet air flow rate (kg/s)</td>
<td>39.15</td>
</tr>
<tr>
<td>Gasifier cold gas efficiency (%)</td>
<td>80.71</td>
</tr>
<tr>
<td>Gasifier hot gas efficiency (%)</td>
<td>89.22</td>
</tr>
<tr>
<td>Gasifier thermal efficiency (%)</td>
<td>79.62</td>
</tr>
<tr>
<td>Hydrogen production potential (%)</td>
<td>83.79</td>
</tr>
<tr>
<td>Electrical energy efficiency (%)</td>
<td>56.54</td>
</tr>
<tr>
<td>Net energy efficiency (%)</td>
<td>50.33</td>
</tr>
<tr>
<td>Heat energy efficiency (%)</td>
<td>6.12</td>
</tr>
<tr>
<td>Total energy efficiency (%)</td>
<td>56.45</td>
</tr>
</tbody>
</table>

Total plant energy efficiency has been has been resulted more than 56%, whilst electrical efficiency of the proposed plant is 56.54%. This efficiency value is completely comparable with previous studies on CHAT cycles. On the other hand, electrical efficiency of an IBG-SGT cycle is about 24.7%. Therefore, electrical efficiency of the proposed cycle has increased more than 2.2 times rather than IBG-SGT cycle. Since the IBG-CHAT-ST cycle is ultimately considered as a combined cycle to generate power and heat, it has been attempted to prevent heat loss, in this study. As can be observed, since the presented combined cycle is a generating power and heat cycle, the total cycle efficiency is 56.45% with heat efficiency consideration. This amount is reasonable for a GT-ST combined cycle. One of the advantages of the proposed cycle is its low sensitivity to ambient temperature changes. Output power of gas turbines decrease between 0.05 to 0.09% by each 1 degree ambient temperature change [34]. While in the recommended cycle, as mentioned in Fig. 2, there are no significant changes in inlet and outlet system power due to temperature changes in compare with simple GT cycles. It has only 2% decrease in delivered power for 25 degree ambient temperature increase. The power production by proposed cycle decreases with increasing moisture content of biomass fuel.
This is also true for auxiliary components in which power consumption decreases; particularly the syngas blower and the compressor which are due to reduction of syngas mass flow and consequently the required air. Plant efficiency and total delivered power changes due to changing of the moisture contents of biomass has been shown in Fig. 3. In any case it is better to have low moisture content, approximately 10%, mainly because the output net power production will be reduced otherwise.

In this study, an IBG-CHAT-ST novel combined cycle was proposed for attaining high power generation capacity in conventional gas turbine and CHAT cycles, while maintaining reasonable total plant efficiency. The following conclusions can be drawn from this study:

- Compared to a conventional simple GT cycle integrated with same biomass gasification system, electrical power generation from the proposed IBGCHAT-ST cycle has been increased by about 2.28 times.
- Despite the presented cycle uses biomass fuel, the total energy efficiency of the comprehensive cycle is about 56.5%, which is still within the acceptable range of combined cycles.
- The output power from the proposed cycle is stable against ambient temperature variations: for change in ambient temperature from 15 to 40°C, the generated power decreases by about 2%.
- Additionally, the effects of moisture content of biomass have been studied, which resulted significant changes in the balance of energy in the cycle.
- The proposed cycle is suitable to generate power from wastes of several kinds of industries along with high value of energy efficiency.

REFERENCES


