Open Access Journal

Journal of Power Technologies 92 (1) (2012) 48–54

journal homepage:papers.itc.pw.edu.pl

Performance analysis of a gas turbine air heat recovery unit using GateCycle® software

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Abstract

The following article concerns the results of an analysis of a gas turbine (GT) with an air heat recovery turbine unit (AHRTU) using General Electric GateCycle® software. The analysis was conducted for five different variants of air heat recovery turbine units: (i) simple AHRTU, (ii) with air cooling by one intercooler, (iii) with air cooling by two intercoolers, (iv) with variable humidity before the compressor, and (v) with water injection into the compressor. Each variant was tested for four different air temperatures before air turbine (ATBAT): 573 K, 673 K, 773 K, and 873 K. For each air temperature before air turbine, computations were run for increasing compression ratios (CR): from 3 to 6.5 for variants 1 and 4 and from 3 to 12 for variants 2,3 and 5. The results were shown as graphs of specific power (SP) of the AHRTU versus compression ratio in the AHRTU.

Keywords: gas turbine, Brayton cycle, mathematical modelling

1. Introduction

The ideal cycle for gas turbine, operating in simple cycle (with internal combustion), is called the Brayton cycle. The cycle consists of two isobaric processes – delivering and giving up heat and two isentropic processes – compression and expansion. The efficiency of the ideal Brayton cycle is:

$$\eta = 1 - \frac{1}{\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}}} \tag{1}$$

Where index 1 refers to air before the compressor and index 2 refers to air after the compressor, and κ is the isentropic exponent [1]. The efficiency of the ideal Brayton cycle increases in tandem with higher compression ratios.

The real thermal process for a gas turbine differs from the ideal one. Compression and expansion are not isentropic processes (due to irreversibility), there are also pressure losses in the suction manifold, combustor chamber and exhaust manifold. Pressure losses result in a higher compression ratio than expansion ratio. Additionally, the highest temperature of gases (after combustion) is restricted by the permissible working temperature of the material from which the turbine blades are made [2].

Gas turbines (GT) working in simple cycle achieve efficiency levels of 30% to 40%. Exhaust gases have high temperatures and energy and they may be re-used in the cycle, boosting efficiency and

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power. The most common approach is to use exhaust gases to produce steam (combined cycle). Exhaust gas energy is used in a recovery boiler to produce steam. The steam, working in the classic Rankine cycle, provides additional power and efficiency. A cycle of this type may achieve efficiency levels of up to 60% for large power gas turbines. For low power gas turbines (20–50 MW) the benefits coming from a combined cycle are not meaningful. One way to increase efficiency and output power for low energy gas turbines is to use an air heat recovery turbine unit (AHRTU). This may be done using a high temperature air-exhaust gases heat exchanger (HE). The idea is to replace the combustion chamber in one gas turbine by an HE. Hot exhaust gases exiting the regular gas turbine enter the HE, where they provide energy for the second cycle. Using an HE enables air to be used as the working medium in the second cycle. This installation is called the Brayton-Brayton cycle [1] because each working medium works in the Brayton cycle.

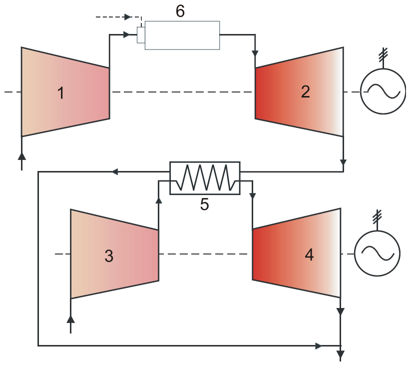

Figure 1: Simple AHRTU

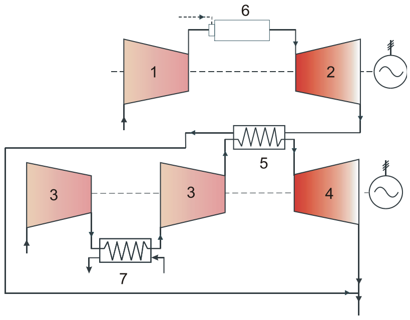

Figure 2: AHRTU with air cooling by one intercooler

2. Analyzed Brayton-Brayton cycles

The Brayton-Brayton cycle consists of two cycles in which a regular gas turbine (RGS) and AHRTU are working. The regular gas turbine and AHRTU are connected to a high temperature air-exhaust gases heat exchanger. Since the goal of this article was to study the performances of AHRTU the regular gas turbine was kept constant (the same in all analyzed variants).

The General Electric LM2500 gas turbine was chosen as the regular gas turbine. As the planned computations were to be run at four air temperatures before air turbine (573 K, 673 K, 773 K, 873 K) the temperature of the exhaust gases from the regular gas turbine had to be higher than 873 K. Since the temperature of the LM2500 gas turbine exhaust gases is normally 796 K, additional fuel had to be burned in the combustion chamber to increase the temperature of the exhaust gases. An additional 0.25 kg/s of fuel was given to the combustion chamber. This resulted in an exhaust gases temperature of 900 K, moreover, due to the higher ratio between the combustion gases before turbine and the air temperature before the compressor, the power produced by LM2500 gas turbine rose from 22.8 MW to 26.5 MW. The higher exhaust gases temperature caused efficiency to fall from 37.5% to 35.4%.

Five AHRTU variants were tested [3]:

1. Simple AHRTU (Fig. 1)
2. AHRTU with air cooling by one intercooler (Fig. 2)
3. AHRTU with air cooling by two intercoolers (Fig. 3)
4. AHRTU with variable air humidity (Fig. 4)

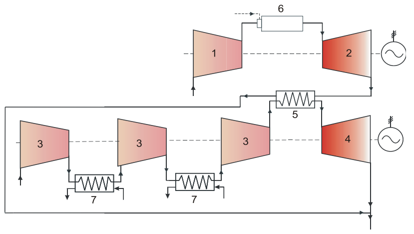

Figure 3: AHRTU with air cooling by two intercoolers

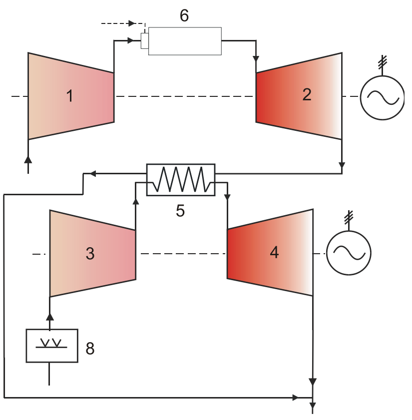

Figure 4: AHRTU with variable air humidity

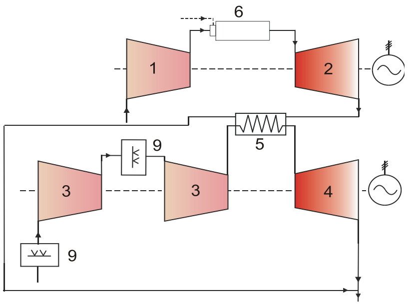

Figure 5: AHRTU with water injection into the compressor, components of LM2500 gas turbine: 1 – compressor, 2 – gas turbine, 6 – combustion chamber; components of AHRTU: 3 – air compressor, 4 – air turbine, 5 – high temperature air – exhaust gases heat exchanger, 7 – air cooler, 8 – air humidifier, 9 – components of water injection system

5. AHRTU with water injection into the compressor (Fig. 5)

3. Assumptions

Each AHRTU variant was tested at four different air temperatures before air turbine: 573 K, 673 K, 773 K, and 873 K. For each air temperature before air turbine, computations were run for increasing compression ratios of the AHRTU compressor:

1. For AHRTU from variants 1 and 4 the compression ratio rose in intervals of 0.5 from 3 to 6.5
2. For AHRTU from variants 2,3 and 5 the compression ratio rose in intervals of 1 from 3 to 12

The range of compression ratios differs across the variants due to an increase in air temperature during the compression. For a compression ratio of ca. 7 the air temperature after compression exceeds 573 K and simulations could not be run for the air temperature of 573 K before the air turbine. In variants 2, 3 and 5 the heat of compression is abstracted from the air (thereby reducing its temperature) so the range of analyzed compression ratios could be extended.

The input data for AHRTU were as follows [3]:

1. Air temperature: 288 K, air pressure: 101.3 kPa
2. Adiabatic efficiency of compressor: 90%
3. Mechanical efficiency of compressor: 95.5%
4. Total pressure loss coefficient of air intake: 0.015
5. Total pressure loss coefficient of heater for air: 0.064
6. Adiabatic efficiency of air turbine: 92%
7. Total pressure loss coefficient in exhaust duct: 0.045
8. Total pressure loss coefficient of heater for exhaust gases: 0.05
9. Injected water temperature: 293 K.

4. Software used

The computations were run using General Electric GateCycle® software. The GateCycle® application is a PC-based software application used for design and performance evaluation of thermal power plant systems. The GateCycle® application combines an intuitive, graphical user interface with detailed analytical models for the thermodynamic, heat-transfer and fluid-mechanical processes within power plants, allowing design and simulation studies of any complexity [4]. The GateCycle® application contains a rich gas turbine library from which the LM2500 gas turbine was chosen. As mentioned above, the LM2500 gas turbine was stationary and the AHRTU cycle was built in each variant. The computations were managed from the MS Excel application using the CycleLink application, which is part of the GateCycle® software.

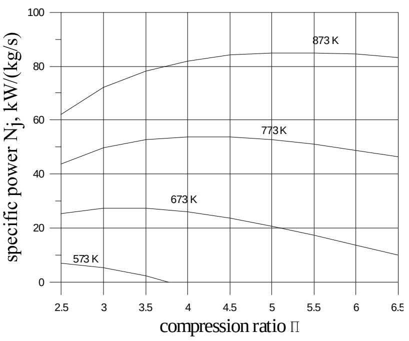

Figure 6: Specific power versus compression ratio of Simple AHRTU

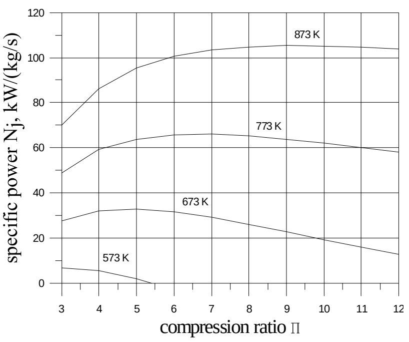

Figure 7: Specific power versus compression ratio of AHRTU with intercooling

5. Computations results

The results of the computations are shown below as graphs of specific power (N_j) of AHRTU versus compression ratio (Π) in AHRTU (Figures 6 – 10):

5.1. Simple AHRTU

For the Brayton-Brayton cycle with simple AHRTU (Fig. 6) significant power boost were noticed. For air temperature before air turbine 873 K the highest power boost was 6.46 MW (compression ratio 5.5) which gave 24% growth with LM2500 gas turbine working alone. The efficiency of the Brayton-Brayton cycle in this configuration varied between 36.38% and 44.09%. The first value was achieved for air temperature before air turbine 573 K and compression ratio 3, and the second value was achieved for air temperature before air turbine 873 K and compression ratio 5.5. Those values gave absolute efficiency growth: 1.02% and 6.98%.

5.2. AHRTU with intercooling by one intercooler

The Brayton-Brayton cycle with air cooling by intercooler in AHRTU (Fig. 7) gave an additional power and efficiency boost (compared to the simple AHRTU). The highest values for each air temperature before air turbine were (compared to the LM2500 gas turbine working alone):

1. 0.81 MW power and 1.06% efficiency boost for compression ratio 4 (air temperature before air turbine 573 K)
2. 2.78 MW power and 3.37% efficiency boost for compression ratio 5 (air temperature before air turbine 673 K)
3. 5.20 MW power and 5.82% efficiency boost for compression ratio 7 (air temperature before air turbine 773 K)
4. 8.03 MW power and 8.25% efficiency boost for compression ratio 11 (air temperature before air turbine 873 K).

Adding an intercooler to the AHRTU makes it more complicated and causes additional pressure losses. For low compression ratios (2 and 3) those losses cause reductions in specific power compared to the simple AHRTU. For example, for compression ratio 3 and for air temperature before air turbine 773 K and 873 K the specific power drop was 1.61% and 2.54%. However, a significant specific power boost occurred for the highest compression ratio. For air temperature before air turbine 673 K the absolute growth of specific power was 130%. As the air temperature before air turbine increases, the absolute growth of specific power decreases and for 873 K it is 18%.

5.3. AHRTU with intercooling by two intercoolers

For AHRTU with double intercooling (Fig. 8), the layout of the system became very complicated (2 intercoolers, 3 compressors) which would probably increase the investment costs significantly. Moreover, as in the case of the single intercooler, the second intercooler results in additional pressure losses which with a low compression ratio range causes a drop in specific power. For example, for air temperature before air turbine 873 K and compression ratio 3, the specific power of

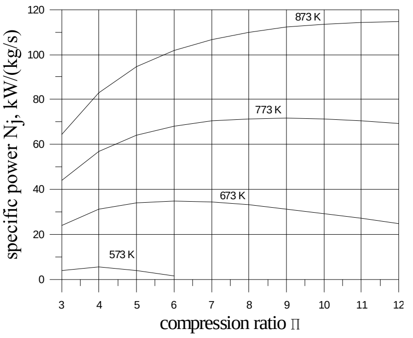

Figure 8: Specific power versus compression ratio of AHRTU with double intercooling

AHRTU decreased by 8.3% (compared to AHRTU with single cooling). But as air pressure increases, so does specific power and for compression ratio 12 the specific power growth is significant. For air temperature before air turbine 673 K – 97.7%, for 773 K – 19.8% and for 873 K – 10.4%. Adding a second intercooler caused a growth in efficiency. Efficiency increases in tandem with compression ratio growth, and for the highest tested compression ratio (12) the absolute growths in efficiency were (compared to AHRTU with simple cooling):

1. 2.8% for air temperature before air turbine 673 K
2. 2.4% for air temperature before air turbine 773 K
3. 2% for air temperature before air turbine 873 K

Those increases almost allowed the Brayton-Brayton cycle to reach the 50% efficiency level (47.05% for air temperature before air turbine 873 K).

5.4. AHRTU with variable air humidity

The goal of this AHRTU was to check how the variable humidity of air effects the performances of AHRTU. The air humidity was changed only before the compressor of AHRTU to allow comparison of variant 1 to the AHRTU. For all previous and following variants air humidity was taken as 60%. In this variant the following humidity levels were tested: 70%, 80%, 90% and 95%. For each air humidity computations were run for each air temperature before air turbine and for each compression ratio. Only one diagram is presented in this paper (for air temperature before air turbine 873 K – Fig. 9). The results were compared to the Brayton-Brayton cycle with simple AHRTU. As air humidity increases, its density and specific volume decrease, resulting in less power required to compress it. As the compressor takes less power, more power may be transferred to the generator. The power reduction increases with air humidity and compression ratio growth. The highest power reduction was achieved for air humidity 95% and compression ratio 6 – 129.5 kW. The impact of air humidity falls as the air temperature before air turbine rises. For example, for compression ratio 3 and for air temperature 573 K specific power growth was 26.1%, whereas for 873 K it was only 2%.

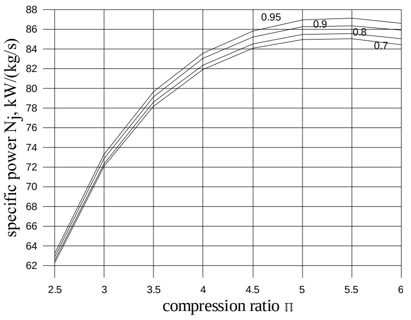

Figure 9: Specific power versus compression ratio of simple AHRTU with variable air humidity for air temperature before air turbine 873 K

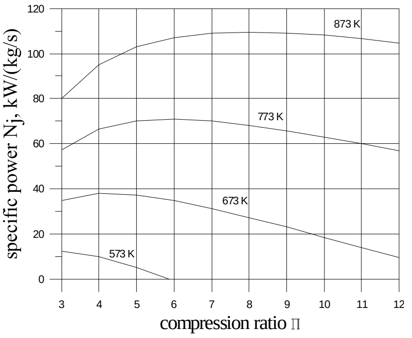

Figure 10: Specific power versus compression ratio of AHRTU with water injection

5.5. AHRTU with water injection

The water injection into the AHRTU was achieved through humidification of air to the value of 95% before low and high pressure compressor in AHRTU. The computations show that such AHRTU (Fig. 10) has a similar performance to AHRTU with air cooling by one intercooler. Compared to AHRTU with air cooling by one intercooler, the benefits from water injection are relatively small. The biggest power increase (for the Brayton-Brayton cycle) was 1.9% (0.64 MW) at compression ratio 3 and air temperature before air turbine 873 K. As the compression ratio increases, the performances of AHRTU with water injection achieve values closer to AHRTU with air cooling by one intercooler. For each CR the amount of water injecting to reach 95% humidity of air before low pressure compressor was constant, but before high pressure compressor it was not. The amount of water injected into the AHRTU changed from 1.96% for CR 3 to 4.38% for CR 12 referring to the air flow rate. According to [1] analyses of AHRTU with water injection were conducted for 3 variants. In each variant a constant amount of water was injected into the compressor for the whole range of compression ratios (2%, 4% and 6% of water, referring to the air flow rate). Although the computations were not conducted in the same way, some conclusions may be drawn. In paper [1] for water injection of 2% by air flow rate and CR 3, specific powers were approximately: 20 kW/(kg/s) for ATBAT 573 K, 42 kW/(kg/s) for 673 K, 68 kW/(kg/s) for 773 K and 89 kW/(kg/s) for 873 K. In this paper for CR 3 the water injection was nearly 2% (1.96%) by air flow rate, so those points are comparable. The results are: 12.3 kW/(kg/s) for 573 K, 34.7 kW/(kg/s) for 673 K, 57.3 kW/(kg/s) for 773 K and 80 kW/(kg/s) for 873 K, which gave results that were lower by about 62%, 21%, 18% and 11% respectively. For CR 10 the water injection by air flow rate was roughly 4% (4.03%) so this point was comparable with the corresponding variant from paper [1] – water injection by air flow rate of 4% and CR 10. The results in paper [1] were higher than in this paper by approximately: 122% for 673 K, 42% for 773 K and 25% for 873 K.

6. Computations results. Analysis

The performance of AHRTU depends on compressor work (compression ratio) and the temperature of the medium before air turbine. In each analyzed variant specific power increases as air temperature before air turbine increases – the air temperature before compressor is constant so as air temperature before air turbine increases, the ratio between those temperatures also increases.
For each air temperature before air turbine (573 K, 673 K 773 K, 873 K) only one maximum of specific power is achieved for only one specific value of compression ratio. As the air temperature before air turbine increases, the compression ratio for which specific power achieves the maximum value moves toward higher values.
In each AHRTU variant – for air temperature before air turbine 573 K – there is a value of the compression ratio for which specific power reaches zero and as the compression ratio increases it continues to decrease. For those compression ratios AHRTU cannot work alone. Unfortunately, the specific values of those compression ratios have not been found.
It would be reasonable to compare the results for variant 5 (AHRTU with water injection) to the results for variants 2 (AHRTU with intercooling) and 3 (AHRTU with double intercooling).
AHRTU with water injection achieved significant specific power growth – in the low compression ratio range – compared to variants with air cooling by one and two intercoolers. Compared to variant 2 for compression ratio 3 and air temperature before air turbine 873 K it was 9.8 kW/(kg/s), a 13.9% increase and for variant 3 for the same parameters as in variant 2 – 15.6 kW/(kg/s), which was a 24.3% increase. As the compression ratio increases, specific power growth decreases and may start to achieve negative values (AHRTU with intercooling starts to achieve better performances). For AHRTU with one intercooler this started to happen (the exact values were not determined):

1. After compression ratio 9 for air temperature before air turbine 673 K
2. After compression ratio 10 for air temperature before air turbine 773 K

3. For air temperature before air turbine 873 K the cycle with water injection achieved better performances in the whole compression ratio range. The lowest specific power growth was for compression ratio 12: 0.88 kW/(kg/s) giving growth of 0.85%.

Compared to AHRTU with air cooling by two intercoolers, the cycle with water injection achieved worse performances (the exact values were not determined):

1. After compression ratio 6 for air temperature before air turbine 673 K
2. After compression ratio 6 for air temperature before air turbine 773 K
3. After compression ratio 7 for air temperature before air turbine 873 K.

7. Summary

This article showed the possibility of creating an effective installation to re-use energy from gas turbine exhaust gases. Using an AHRTU may boost power by up to 32% and efficiency by up to 9%. The results presented above are comparable to other studies pertaining to the Brayton-Brayton cycle. For example, the exact same studies as above were performed in paper [1]. This paper shows only the graphs of specific power versus compression ratio, so an exact comparison is not possible. However, from the shape of those graphs the following conclusions may be drawn:

1. The results for simple AHRTU and for air cooling by one and two intercoolers were very close
2. The result for AHRTU with water injection differs significantly (at comparable points).

In this paper water injection into the compressor was divided into two parts: water injection before low pressure and before high pressure compressors. This approach was used as it was not possible to model directly the water injection into the compressor. In paper [1] it would appear that another approach was taken. This may provide one reason for the differences in the results (at comparable points).

References

[1] V. V. Romanov, V. V. Kuznetsov, V. N. Chobenko, S. N. Movchan, O. S. Kucherenko, A. P. Shevtsov, Performances and application perspectives of air heat recovery turbine units, in: ASME Turbo Expo 2010: Power for Land, Sea, and Air (GT2010) Paper no. GT2010-23129 pp. 121-133, 2010.

[2] K. Badyda, A. Miller, Energetyczne turbiny gazowe oraz układy z ich wykorzystaniem, Kaprint Lublin, 2011.

[3] M. Kowalski, Analysis of gas turbine with air heat recovery turbine unit using gatecycle software, Master's thesis, Warsaw University of Technology (2011).

[4] GateCycle version 6.0.0.4. Manual.

Nomenclature

AHRTU	air heat recovery turbine unit
ATBAT	air temperature before air turbine
CR	compression ratio of compressor working in AHRTU
GT	gas turbine
HE	high temperature air-exhaust gases heat exchanger
SP	specific power