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Article

Modeling of a Combined Cycle Gas Turbine Integrated with an Adsorption Chiller

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Received: 29 November 2019; Accepted: 16 January 2020; Published: 21 January 2020

Abstract: Forecasts to 2030 indicate that demand for electricity will increase from 2% to 3% per year, and due to the observed high rate of development of the world economy, energy demand will continue to increase. More efficient use of primary energy has influence on reduction emissions and consumption of fuel. Besides, reducing the amount of fuel burned, it reveals a beneficial effect on the environment. Since extraction-back pressure turbines have some limitations, including the restriction of electricity production due to limited heat consumption in summer. The paper discusses the possibilities of integrating the adsorption aggregate with a combined cycle gas turbine and its impact on the operation of all devices. Simulations are performed on Sim tech IPSEPro software. The obtained results confirm that the adsorption aggregate, using a low grade of thermal energy, does not affect the operation of the gas and steam cycle and allows the production of electricity at a constant level. The calculated chemical fuel energy utilisation factor was 85.7% in cogeneration and 75.6% in trigeneration. These factors indicated a reduced utilisation of chemical fuel energy; however, this reduction is caused by a lower COP for adsorption chillers. Besides, the adsorption aggregate additionally generates chilled water for air conditioning or other technological processes, which stands for an added value of the innovative concept proposed in the paper.

Keywords: gas turbine; sorption chiller; increasing efficiency; steam cycle; recovery heat; polygeneration

1. Introduction

Refrigeration processes are widely used in many industry branches, such as the pharmaceutical industry, food storage and production, heavy industry and even power generation. In Poland, the HVAC market increased from 3.5% to 6.5% annually in the period between 2015 and 2019 [1]. In the European Union, there has been a continuous increase in the number of air-conditioning systems installed in buildings since the 1980s. The graph of electricity consumption for cooling can be seen in Figure 1. Power consumption has remained stable in recent years, at 155 TWh annually. It is not the result of a decreasing trend in the use of air conditioners but mainly improved efficiency and environmental performance of these devices. [2]. Annual global sales of air conditioning devices are approximately 135 million. Over 1.6 billion air conditioners are currently in use, half of which are in two countries, China and the United States.

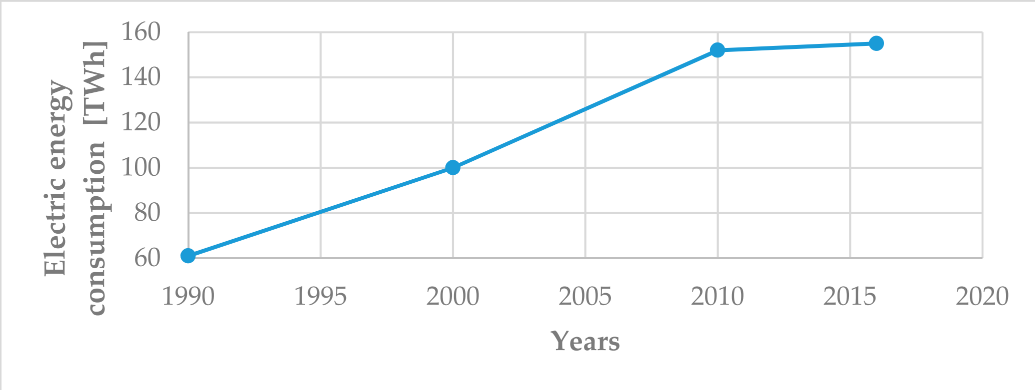

Figure 1. Consumption electricity for cooling buildings in the European Union [2].

Most of these air conditioners are compressor systems, which use substantial amounts of electricity. Indoor climate control systems are also increasingly contributing to electricity consumption. In 2016, these systems accounted for 10 per cent of the global energy requirement as assessed by the IEA.

In many countries, growing demands for cooling are observed. As an example, cooling devices accounted for approximately 14% of the peak electrical demand in 2016, but for some country in Middle East and the also some parts USA, electrical demand in the peak consuming consume about 70% of produced electrical. Due to reported expectations, power consumption heating will differ from the one for cooling. [3]. The growing demand for cooling is primarily caused by climate changes as well as people's increasing demand for comfort from the heat. In order to meet peak demands, the construction, maintenance and operation of electric power networks for electricity are very costly.

One solution is the use of air conditioning devices, which produce chilled water using waste heat from various energy processes characterised by very low electricity consumption. This type of devices includes absorption and adsorption chillers. This paper focuses on an analysis of the possibility to apply adsorption chillers for chilled water production mainly air conditioning sector by which chilling systems are integrated with gas turbines.

The demand for electricity in Poland in 2017 was 168,139 GWh while the domestic production was 168,852 GWh. Over 48% of Poland's energy was generated from coal-fired utility power plants. The increasing power consumption in Poland means that its domestic production also increases each year. This confirms the necessity of searching for new and more effective sources to generate power. Heat generation during 2017 in Poland was 395,596.9 TJ, of which 241,614.8 TJ was from cogeneration. The amount of heat supplied to consumers connected to the network was 242,527.3 TJ in 2017. In Poland, both power and heat generation are based on coal. Coal fuels account for over 73% of fuels that are used at heat sources. Nevertheless, the diversification of energy carriers used for the generation of heat is greater for the enterprises that produce heat by cogeneration; in this case, almost 31% are fuels such as diesel, natural gas and biomass. It is expected that power consumption for cooling will be different in comparison to the trend concerning heating. The growing demand for cooling is primarily caused by the changing climate as well as the increasing desire for people to be comfortable.

Facilities in both commercial and residential buildings generate an increasing need for cooling. It is estimated that by 2020 the share of commercial buildings equipped with cooling devices will rise by at least 60% in Europe [3–5]. Fossil fuel exploitation implies many harmful impacts on the environment. Therefore, looking for effective methods of converting fuels to electric energy and heat or replacing the existing fuels with those which are more environmentally friendly are indispensable. One of the promising methods, leading to an increase in fuel consumption efficiency, is polygeneration system. Waste heat can be used to generate cooling, vapour or hot water with higher parameters by utilising heat pumps, adsorption chillers and heat recovery boilers. The utilisation of waste heat reaps financial savings as well as a reduction in greenhouse gas emissions, reducing the adverse impact on the environment.

Gas turbines working in the Brayton–Joule cycle have a relatively low electrical efficiency power of 20% to 35%. To increase the efficiency of the gas turbine, various modifications can be proposed:

- Using interstage—cooling the compressor reduces the compression work. To compress air in the compressor, about 60% of the power generated by the turbine is used.
- Using a split combustion chamber on the main part and afterburner provides an increase in expansion work and gas temperature after the turbine.
- Injecting water before and after compressed air in compressor gas turbine. Data in article [6] shows that using the method of injecting water before and after compress air has an influence on fluctuation intensity between total pressure and total temperature ratio.
- Regeneration—using exhaust gases from the turbine for heating in the heat exchanger. After heating, process air is directed to the combustion chamber.
- Steam injection into the combustion chamber STIG turbine Steam Injection Gas Turbine. Injection steam causes an increase in the flue gas stream, which leads to an increase in power generation.
- Construction of a HAT Humidified Air Turbine is based on a combination of the concept of regenerative air heating before the combustion and water injection to air after the compressor. Water injection into the air before the regenerative heat exchanger causes a decrease in temperature compressed medium and leads to increases in heat regeneration efficiency [7].
- Wet compression technique—the advantage of the method is the ability to inject enough water to evaporate, and cooling the air is conducted in stable conditions. In this process, we obtained independence from the temperature and humidity of the air, causing a reduction of energy use for the compressor.
- The integration of gas turbine with Rankine Cycles (RCs) or the organic Rankine cycles (ORCs). Exhaust gases from the gas turbines have very high energy generation potential. They can be used for increasing the temperature of air and fuel before the combustion chamber or for producing steam in a heat recovery boiler [7].
- Transformation of the exhaust gases enthalpy to a new synthetic fuel. This method of waste-heat recovery is called thermochemical recuperation (TCR). TCR can influence energy efficiency of gas turbines and different devices using fossil fuels. This method can be implemented for steam methane and ethanol reforming. The idea of TCR method is to use waste heat from flue gas for producing a new fuel used in gas turbine [8,9].

The option of producing chilled water from waste heat [10–13] also involves another advantage for the traditional CHP plants. A big problem for this type of plants is the reduced demand for heat in the summer season; some facilities scale down their operations during this time and only supply hot water and generate electricity, while others shut down for July and August. Trigeneration solves this problem because of the increased demand for cooling during the summer period. Therefore, the trigeneration [10,11] system would be an ideal solution for heat generating plants that face a serious hindrance to their operation during the summer months. The systemic generation of cooling would also reduce power consumption for air conditioning, which would have a favourable effect on the entire power system and would relieve the demand for power during the summer months [14–17]. Advantages of the generation of district cooling include increased power safety as a result of increased generation of electricity during the summers' peak electricity demand and by improved effectiveness of the utilisation of the heat generation systems (generation sources as well as heat networks) will result in more effective use of primary energy resources as well as elimination of CFCs used in compressors, which are harmful to the environment. This paper presents some possibilities of improving the efficiency of CHP plants fuelled with natural gas and operating in a gas-vapour system by the use of adsorption chillers. The article analyses a new solution to ensure constant electricity production in the combined cycle gas turbine, using heat that would not be used during the summer. Simulation calculations were performed as shown in the article, which analysed the possibilities of using adsorption chiller for heat utilization from extraction-back pressure turbines. This type of solution was not used on a large industrial scale for high-power gas turbine cycle. This calculation is very important for checking the applicability of use adsorption chiller on industrial scale.

2. Analysis and Modelling

2.1. Adsorption Chillers

A basic adsorption unit (Figure 2) consists of three components, evaporator, condenser, adsorption bed. A single operational cycle consists of four stages, i.e., (1) adsorption, (2) heating of the adsorption bed, (3) regeneration of the adsorption bed (also called desorption) and (4) cooling of the bed. During the first stage, the adsorbent bed is heated by an external heat source, e.g., solar or waste process heat, which leads to an increase in temperature and pressure. This stage continues until the condensing pressure is reached. Adsorbate vapour generated in this process flows into the condenser where it releases its heat and changes its state to a liquid. This enables proper regeneration of the bed before the cycle is repeated. Then the adsorber is cooled, which causes a drop in temperature and pressure in the bed. This pressure drops until it reaches the value of evaporation pressure, which initiates the adsorption process, while at the same time heat is generated. In the course of this process, adsorbate vapour from the evaporator is transported to the adsorption bed while absorbing heat in the process, which leads to lowering the temperature of the liquid that is to be cooled down. The bed saturated in this way is heated again by an external source, which causes the refrigeration cycle to begin once again [16,18–20].

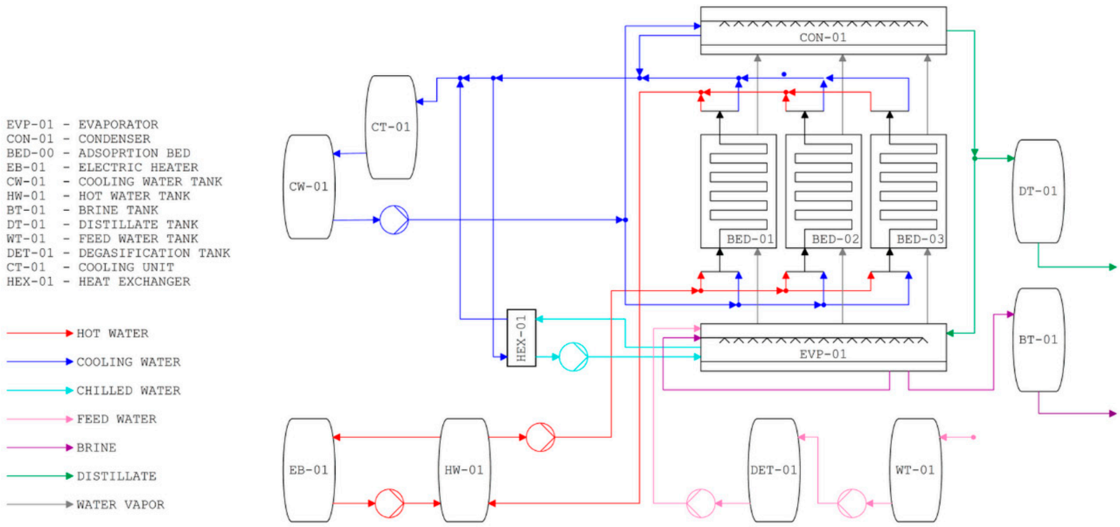

Figure 2. Scheme of adsorption chiller with desalination function at the Center of Energy AGH.

Reduced electricity demands, simple design (no moving parts, pumps or compressors), quiet and vibrationless operation and low maintenance requirements are the main features of adsorption chillers. Resultingly, adsorption chillers are independent of the power supply and have a long lifetime. On the other hand, bulkiness (large dimensions and mass) and high design requirements due to low pressures are the main disadvantages of adsorption chillers [21–25].

The main parameter determining the possibility of using adsorption chiller for production of chilled water is temperature regeneration of sorbent such as silica gel, activated carbon and zeolite.

Adsorption chiller for operating temperature below 90 °C can use hot water produced in solar collectors and water from the district heat installation. According to data from [12], adsorption chiller with silica-gel can by operating from 43 °C with double stage cycle, from 62 °C for single stage cycle device. Due to the low regeneration temperature, adsorption chillers can be used in systems in which other devices cannot work.

2.2. Gas and Steam Cycle

The discussed analysis is focused on the influence of an adsorption cooler on a gas and steam cycle with a gas turbine. The subject of the investigation was a gas and steam system with a triple-pressure boiler. Useful heat was hot process water. It was assumed that demand is stable over time.

The basis for the systems in the analysis was a gas turbine model Siemens SGT5-4000F Table 1. The following are the turbine's performance parameters:

Table 1. Siemens SGT5-4000F turbine parameters [26].

Electric power output	292 MW
Exhaust mass flow	692 kg/s
Exhaust temperature	577 °C

A model of the turbine was built using separate elements available in the program library, based on data provided by the manufacturer. The analysis concerned a system with a gas turbine and a triple-pressure recovery boiler integrated with an extraction-back pressure turbine. The initial parameters were consistent with the assumptions. Deaerator pressure in the systems with superheating was set at 2 bars. The analysed system was a serial arrangement with a live steam superheater, HP superheater, HP evaporator, IP superheater, HP heater, LP superheater, IP evaporator, IP heater, LP evaporator and total flow heater as well as heat exchangers XA and XB (Figure 3).

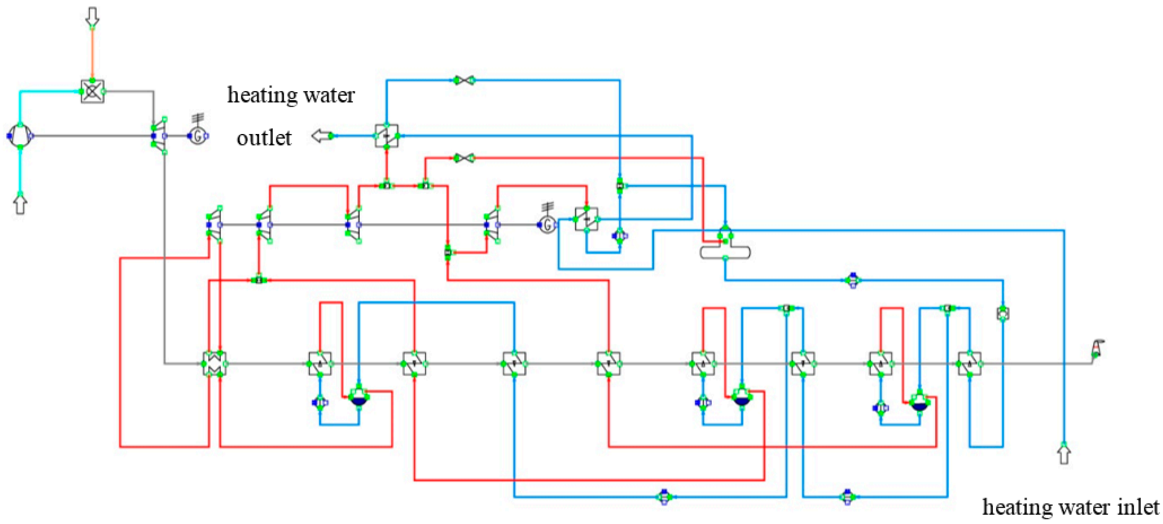

Figure 3. Schematic diagram of the gas and steam cycle.

The main parameters of the CHP system are depicted in Table 2.

Table 2. The main parameters of the cooling, heating and power (CHP) system.

Electric power output	383.7 MWe
Thermal power output	343.93 MWt
Useful heat Q_{un}	251.44 MWt
Electrical efficiency	51.7%
Heat-to-power ratio	1.14
Fresh steam pressure	160 bar
Fresh steam temperature	540 °C
Steam mass flow	70 kg/s
Superheated steam temperature	565 °C
Feed water temperature—summer mode	75 °C
Return water temperature—summer mode	45 °C
Cogeneration water mass flow rate	2000 kg/s

Modelled system uses back pressure turbine, which has some limitations. One of them is the dependence of the production of electric on heat received from the heat exchangers, which in this cycle are working as a condenser. Reduced demand for heat electricity generation influences the operation of the whole generation system. According to data [27], during summer, total consumption of heat for heating purposes is reduced to 80% compared to winter season. In winter season, temperature of district heat in hot water is from 130–150 °C. It depends on the type of heating system and the outside temperature; in summer, temperature of hot water is about 70 °C. However, district waste heat may also be applied for cooling production in adsorption chillers [7]. In such a way, cogeneration turns into trigeneration system.

Simulation calculations were performed using IPSEpro software by SimTech. IPSEpro is an advanced environment for modelling, simulating and analysing energy processes. It enables creating conventional steam cycle power plants as well as integrated gasification combined cycle (IGCC) and also cooling processes. IPSEpro is a program is for modelling and analysing processes in energy engineering and chemical engineering areas. The program can be used for modelling conventional power plants, IGCC integrated gasification combined cycle, gas turbine and other industrial processes. For creation of energy installation, components from IPSEpro library can be used. All components are described by the mass and energy balance equation [28].

In addition to generating electricity, a CHP unit also provides end consumers with heat in the form of hot water for domestic purposes (in summer) and for heating purposes. In summer, the heat generated can also be used to generate cooling while the same level of electricity generation is maintained.

2.3. *Type of Chiller*

For the considered case, the optimal solution seems to be an adsorption chiller with the bed made of silica-gel/water working pair, e.g., a chiller made of New Energy Transfer (Table 3) have cooling capacity of 1070 kW and production of 100 t/d of desalinated water. The cooler can be supplied by water at 60 °C–84 °C and produce chilled water of 11 °C. The decrease in the temperature level of the water fed to the chiller (the difference between the temperature of water at the inlet and at the outlet of the adsorption device) is about $\Delta Tz = 7$ [29].

Table 3. Technical specification of the New Energy Transfer chiller [29].

Model ADC		**Source of Heat for Regeneration**	
Cooling capacity	1.070 kW	Temperature range	60–84 °C
Refrigerant	Water	Chilled water	
Dimensions		Temperature range	16–11 °C
Width	3500 mm	Cooling water	
Length	4500 mm	Temperature range 3–38 °C	
Height	5000 mm		
Weight	20,000 kg		

2.4. COP Values

The value of the COP of adsorption chiller with silica-gel it strongly depends on the temperature of feed water. Based on the data made available by the company New Energy Transfer, the COP value for hot water temperature equal to 75 °C is $COP_{75\,°C} = 0.6$. Absorption chillers can also be used to utilise waste heat; however, devices of this type reach the highest efficiency above 95 °C, and their efficiency below 75 °C is lower in comparison to adsorption chillers, see Figure 4.

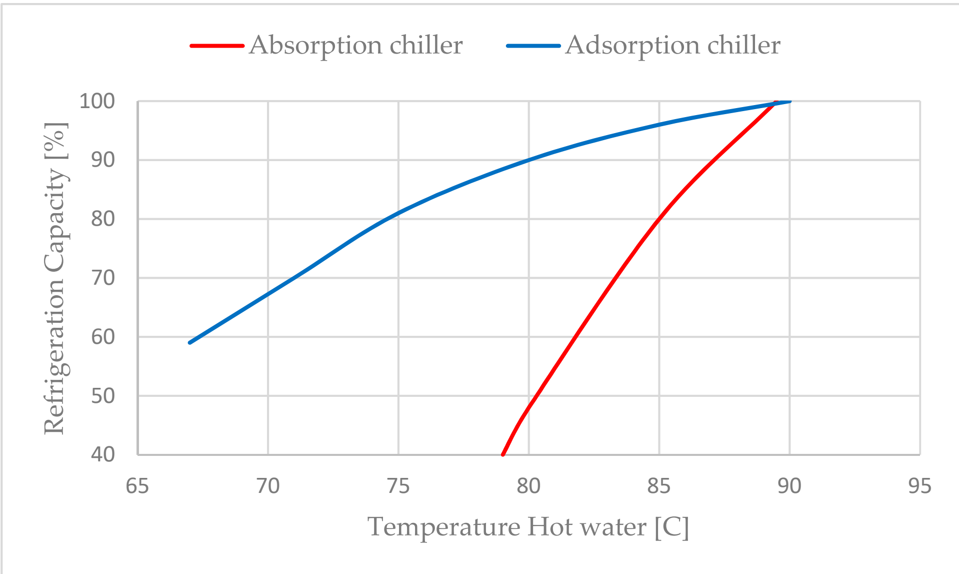

Figure 4. Cooling efficiency of adsorption and absorption chillers depending on the feed temperature [21].

Adsorption chillers can be utilised in systems producing water with a temperature over 43 °C, which can be used to generate cooling in order to feed adsorption chillers. In the analysed gas-steam system, it was assumed that the CHP unit operates in the summer mode, i.e., the temperature of feed water at the inlet of the district heat network is 75 °C while return water temperature is 45 °C. The temperature range is consistent with the literature data [7,27,30]. It was assumed that during the summer season 20% of the total heat generated in the heat exchangers will be used as domestic hot water while 80% of the total heat production will be used to generate cooling. The modelled gas and steam cycle will be combined with a cycle with an adsorption chiller modelled according to the mass and energy balance equations formulated based on the publication [3,8] and the data provided by the manufacturer, New Energy Transfer. Standard libraries, IpsePro program does not have an adsorption chiller model. A new chiller model was implemented in the IPSEpro program and integrated with combined gas cycle. The model uses data from real objects New Energy Transfer and from the adsorption chiller located at the AGH energy centre [19]. Based on actual data, it was assumed that the drop in temperature during regeneration at the beds was at the level of $\Delta Tz = 7\ ^\circ C$. Figure 5 shows a schematic diagram of the gas-steam cycle combined with an adsorption chiller. It was assumed that the adsorption chiller produces chilled water at 11 °C. Water cooling the adsorption chiller works in a closed cycle with a fan chiller. Figure 5 below shows a schematic diagram of the gas-steam cycle combined with an adsorption chiller.

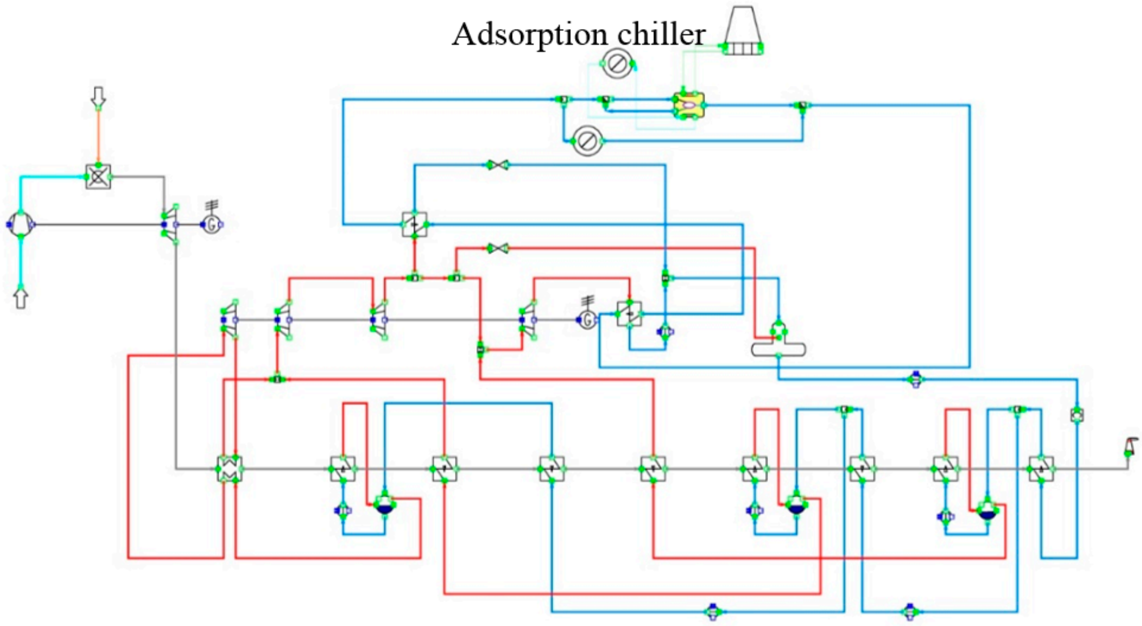

Figure 5. Schematic diagram of a CHP unit cycle with chillers installed, modelled in IPSEpro.

Table 4 present results of analysis. After giving off heat, the fluxes are mixed in a mixer and the outlet temperature of water is 66.2 °C. In this kind of analysis, 20% of the total amount of heat generated for heating purposes was used as domestic water; with a temperature drop, it was 30 °C. The rest of the heat generated in the form of hot water could be used for the purpose of feeding the adsorption chiller. In the case of using an adsorption chiller, the assumed temperature drop was 7 °C, which corresponds to 188 MWt. Such an amount of heat makes it possible to generate 113 MW, which may be applied for air conditioning purposes. An essential indicator that enables assessment of the performance of the system is the chemical fuel energy utilisation factor in the trigeneration system (Figure 6).

Table 4. Operating parameters of a CHP unit with an adsorption chiller.

Parameter	Symbol	Value	Unit
CHP electric power	N_{en}	383.7	MW
Factor of chemical energy utilisation in CHP system	EUF_t	85.7	%
Factor of chemical energy utilisation in polygeneration system [12]	EUF_t	75.6	%
Heat flux fed to the adsorption chiller	Q_N	188	MW
Cooling capacity	Qch	113	MW
Temperature drop of district water in the chiller	ΔT_z	7	°C
District water temperature at feed side—summer mode	-	75	°C
District water temperature at return side—summer mode	-	66.2	°C

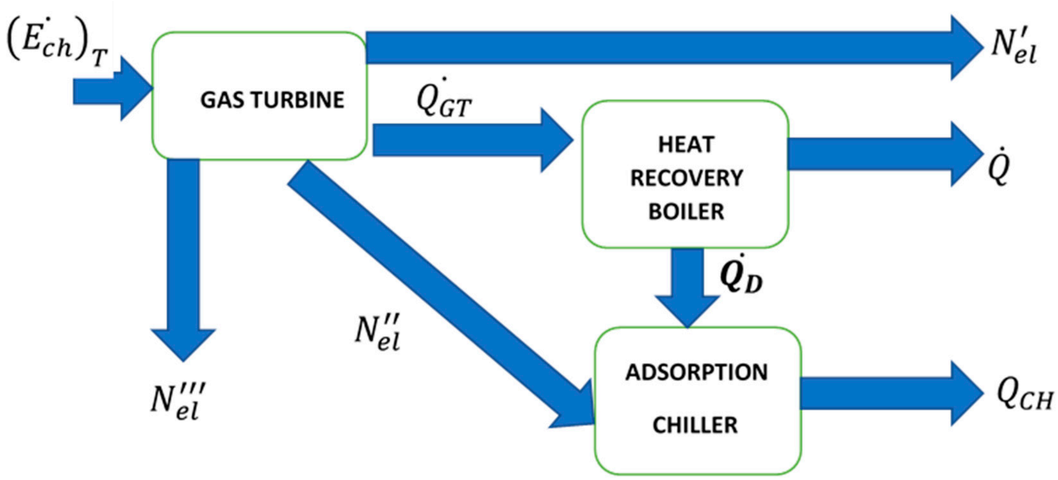

Figure 6. Simplified schematic diagram of a trigeneration-polygeneration system with a gas turbine, recovery boiler and adsorption chiller [7].

Calculations of the factor were made based on the formula:

$$\eta_{cT} = EUF_T = \frac{N_{en} + Q_{un} + Q_{CH}}{G_p \cdot W_d} \tag{1}$$

$$N_{en} = N_{en} - \left(N_p + N_w\right) \tag{2}$$

$$Q_{un} = Q_u - Q_N \tag{3}$$

where:

N_{en}—net electric power output generated;
N_e—electricity generated by the system;
N_p—power rating of the pump drive of the adsorption chiller, p·N;
N_w—auxiliary electricity consumption of the system;
Q_{un}—useful heat output from the system;
Q_N—thermal power required to drive the adsorption chiller;
Q_{ch}—cooling power generated;
G_p—fuel flux;
Qu—useable heat output from cogeneration;
w_d—calorific value of the fuel.

In the case of cogeneration systems, the chemical fuel energy utilisation factor during the cogeneration cycle is 85.7% while in the case of added cooling generation this factor is 75.6%. The calculation analyses suggest that simultaneous generation of heat, cooling and electricity in a system with a gas turbine, recovery boiler and adsorption chiller may also generate a saving of chemical energy of fuels. However, this is lower than in a combined heat and power system. The observed decrease in the factor is an effect of the low cooling capacity of absorption chillers. In spite of the fact that the reduced chemical efficiency indicator is reduced, the system still has the ability for electricity generation at a constant level with the simultaneous cooling and heat generation. As far as generation of heat for domestic purposes in the summer season is concerned, 20% of the total heat generation in the gas-steam cycle, the steam part of the cycle, would have to be completely taken out of operation, which would result in a reduction in electricity generation by 100 MWe.

3. Summary and Final Conclusions

The main objective of this paper was to analyse the influence of adsorption chillers on gas and steam cycle.

In steam cycles with a back-pressure turbine, it is important to ensure constant heat transfer from heat exchangers where they have function of condensers. During summer season, reduced demand for heat was observed, which has an influence on reduced heat production in heat exchangers, contributing to the decreasing of electricity production in the steam Rankine cycle. The idea considered allows for cooling generation using district water at a temperature below 85 °C. For the analysed case, the chiller was integrated with a gas-steam cycle, which enabled generation of electricity at a constant level with concurrent generation of heat and cooling. The calculated chemical fuel energy utilisation factor was 85.7% in cogeneration and 75.6% in trigeneration-polygeneration system. These factors indicated a reduced utilisation of chemical fuel energy; however, this reduction is caused by a lower COP for adsorption chillers in comparison to compressor chillers. In this case, the driving energy for the chiller is heat, which cannot by any means be utilised by compressor chillers. Due to the operation of the adsorption chiller, 113 MW of cooling can be generated for air conditioning or as process heat. The use of the trigeneration system allows for more effective use of the chemical energy of the fuel. However, some conditions must be fulfilled. The authors in literature show [7,31,32] how to supply absorption chillers with mainly used waste thermal energy from the electricity production processes, or produced as a result of structural changes in the steam cycle, replacing the condenser with a heat exchanger built in an adsorption chiller. The approach leads to an increase in the efficiency of the fuel's chemical energy use, up to 20% in some cases [32]. In the considered case, useful heat, which is usually exploited for heating purposes during the winter, is converted into the cooling power in the adsorption chiller in the summer. However, as the cooling capacity of an adsorption aggregate is about 0.6, cooling power produced is much lower compared to the supplied heating power, which means that the saving of chemical energy of fuel factor is lower compared to cogeneration systems for this circuit. The advantage of an adsorption chillers application is the possibility of using water at 75 °C, with higher efficiency production chilled water than in absorption chillers. This device can be connected to the central heating district system and produce chilled water for the air conditioning system. This type of system allows for constant production of electricity, heat and chilled water in conditions of reduced consumption of useful heat in summer seasons. The obtained results confirm also that in the case of producing only electric energy in the gas-steam cycle, the chemical energy utilization factor is 52% while for cogeneration and trigeneration-polygeneration the factor increases to 75.6%, which is confirmed by literature studies [7,31]. Polygeneration cycles equipped with adsorption chillers provide an optimal solution for stable electricity production during the summer season, lowering the use of the chemical fuel energy.

Author Contributions: The contribution of co-authors in creating article is: conceptualization, K.S., W.N.; methodology, J.K., K.S.; software, K.S., T.S.; validation, M.S. and K.G.; formal analysis, K.S.; investigation, L.M., K.S.; resources, M.S., K.G.; data curation, W.K., A.B.; writing—original draft preparation, K.S., J.K.; writing—review and editing, K.S., J.K., W.K.; visualization, W.K., A.B.; supervision, K.S.; project administration, L.M., W.N.; funding acquisition, L.M., W.N. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by subsidy Faculty of Energy and Fuels AGH University of Science and Technology number 16.16.210.476.

Conflicts of Interest: The author declares no conflicts of interest.

Nomenclature

AC	Adsorption Chiller
FIS	Fuzzy Inference System
CC	Cooling Capacity
CCHP	Combined Cooling, Heating and Power
COP	Coefficient of performance
SCP	Specific Cooling Power
HVAC	Heating, Ventilation, Air Conditioning

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