USING ADSORPTION CHILLERS FOR UTILISING WASTE HEAT FROM POWER PLANTS

by

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At present, energy efficiency is a very important issue and it is power generation facilities, among others, that have to confront this challenge. The simultaneous production of electricity, heat and cooling, the so-called trigeneration, allows for substantial savings in the chemical energy of fuels. More efficient use of the primary energy contained in fuels translates into tangible earnings for power plants while reductions in the amounts of fuel burned, and of non-renewable resources in particular, certainly have a favorable impact on the natural environment. The main aim of the paper was to investigate the contribution of the use of adsorption chillers to improve the energy efficiency of a conventional power plant through the utilization of combined heat and power waste heat, involving the use of adsorption chillers. An adsorption chiller is an item of industrial equipment that is driven by low grade heat and intended to produce chilled water and desalinated water. Nowadays, adsorption chillers exhibit a low coefficient of performance. This type of plant is designed to increase the efficiency of the primary energy use. This objective as well as the conservation of non-renewable energy resources is becoming an increasingly important aspect of the operation of power generation facilities. As part of their project, the authors have modelled the cycle of a conventional heat power plant integrated with an adsorption chiller-based plant. Multi-variant simulation calculations were performed using IPSEpro simulation software.

Key words: *adsorption chiller, adsorption cooling, combined heat and power, combined cooling, heating and power, polygeneration*

Introduction

Polish electricity production is mainly based on conventional fuels, particularly hard coal and lignite (jointly 79%), sources with smaller shares in electricity production include: RES 13%, gaseous fuels 5%, and biomass and others 3%. In 2016, electricity power production in Poland was 166.6 TWh while its consumption was 159.1 TWh. In 2016, the total thermal capacity installed at the licensed heat producers was 54259.8 MW, and the generation

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capacity was 53434.7 MW of which heat supplied to consumers connected to the network was 235545.9 TJ. With regard to heat production, the predominant fuel utilized for this purpose is coal 75%, followed by gaseous fuels 7.2% and RES 7.6%. Production of heat in cogeneration units used 2 230 263 334 PJ energy from coal fuels [1, 2].

The use of fossil fuels implies a lot of adverse effects on the environment, such as global warming, acid rain, smog as well as soil and water pollution. Furthermore, global energy resources are dwindling. Counteracting this phenomenon involves increasing the efficiency of electricity production and searching for more efficient methods of conversion of the chemical energy of a fuel to electricity or replacing existing fuels with ones that are more environmentally friendly. In accordance with Poland's Energy Policy Until 2050, coal is going to remain the predominant fuel utilized for the production of electricity and heat, tab. 1, hence, all of the kinds of actions aimed at reducing the adverse effects of combustion products on the natural environment are fully justified.

Table 1. Forecast of electricity and district heat production in 2050 [1]

Fuels	Electricity production [TWh]	Heat production [PJ]
Coal	74.5	221.4
Lignite	10.3	0.1
Natural gas	20.4	44.3
Renewable energy	73.2	27.1
Nuclear power	43.2	–
Petroleum products	-	5.3
Other	1.4	11.5
Total	74.5	309.8

One of the ways to increase the efficiency of the use of chemical energy from fuels with simultaneous reduction of the negative effect on the environment is generation through combined heat and power (CHP) or through polygeneration, *i. e*. generation of an extra utility beside heat and electricity, *e. g*. cooling or compressed air. Then, not just one but several products are obtained from the same amount of fuel and all of them can be usefully exploited, and the efficiency of the combined production of electricity and heat is higher than 80%. In order to raise the awareness of the savings resulting from the economical use of fuels in industrial manufacturing processes, a system of Energy Efficiency Certificates, so-called White Certificates, has been introduced, and also, the EU Emissions Trading System (EU ETS). The term *energy effectiveness* is understood as the ratio of the value of the effective output of a particular installation, equipment or the entire facility to the amount of energy that was used by this facility in order to achieve this result. Pursuant to the Act of April 15th, 2011 on Energy Efficiency, actions aimed at improving energy efficiency include the use of RES, the use of heat from high efficiency cogeneration as well as utilization of waste heat from power plants and industrial processes. Waste heat is produced as a result of energy conversion processes and is released into the ambient environment even though it can be utilized for a beneficial purpose. Possible applications of this recovered heat are varied and depend on the type and characteristics of the plant and on its thermodynamic properties. Depending on the type of carrier, waste heat can be recovered from combustion exhaust gases, cooling liquids or exhaust steam. Waste heat can be used to produce cooling, steam or hot water with higher parameters through the use of heat pumps, adsorption and absorption chillers, and heat recovery boilers. Utilization of waste heat also implies huge financial savings as well as a reduction of the emissions of GHG into the atmosphere, which significantly reduces the negative effect on the environment.

Another important aspect contributing to a more efficient use of primary energy, which includes the increased efficiency of CHP generation, is the use of cooling systems based on adsorption chillers, which are supplied with water from heat network terminal units. In the case of CHP plants, equipped with back-pressure turbine systems, there is a strong interrelationship between electricity generation and heat consumption by external users. During the summer period, when demand for heat is low and heat is only produced for heating utility water, such systems operate with a reduced efficiency. Operation of the unit with a minimum load is problematic and inefficient, therefore, in order to increase electricity production, two possible solutions are applied. The first involves discharging excess heat and transferring it to accumulator hot water tanks. The second consists of utilizing so-called *pseudo-condensation i. e*. chilling return water from a heating system (using cooling radiators or taking advantage of adsorption chillers) to the heat exchangers of the back-pressure turbine, which causes an increased absorption of heat, which contributes to the increased flow of steam through the turbine thereby causing an increase in electricity production. The advantages of the production of district cold are the increased safety of electricity production during the summer peak load of the energy system and the improved efficiency of the utilization of the heating systems (both the generation sources and the heat networks), the increased efficiency of primary energy use, and also elimination of environmentally harmful chlorofluorocarbons used in compressor units. This paper presents the possibility of increasing the effectiveness of cogeneration units through the application of adsorption chillers fed by heat from the terminal unit of the district heating network. The greater quantity of heat generated from combusting fuels will be effectively utilized to, inter alia, feed chillers and the cold produced will be used for example for air conditioning. This will contribute to a reduction in energy consumption for cooling purposes while at the same time reducing the amount of heat that remains unused in the process of generating electricity at conventional power plants, and consequently to savings in fossil fuels and improving the condition of the environment we live in [3-5].

Analysis and modelling

Adsorption chillers

The operating principle of an adsorption cooling system, fig. 1, consists of evaporating the refrigerant in the evaporator under reduced pressure. The process takes place without the use of a mechanical compressor but takes advantage of the thermal effect of adsorption and desorption. The system operates on a cyclical basis and the process of adsorption and desorption (bed regeneration) takes place alternately. Refrigerant vapours discharged from the evaporator are adsorbed in an adsorption bed, which is accompanied by the generation of heat which is absorbed by the cooling water. In order to enable further operation of the bed, it is necessary to remove the adsorbate from the adsorbent (desorption). This process requires the application of heat from an external source. Refrigerant vapours released in the desorption process are discharged into

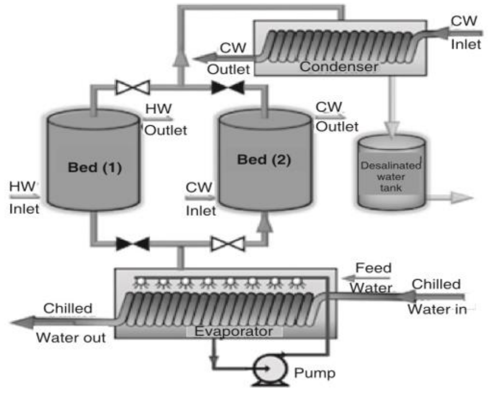

Figure 1 Two-bed adsorption cooling-desalination system [5]; CW – cooling water, HW – hot water

the evaporator. In a closed system, the condensate from the condenser is fed back to the evaporator. It is possible to apply an adsorption chiller with an open system and using water as the refrigerant. The constant feeding of water from an external source results in producing condensate that is devoid of the substances dissolved in the feed water. Where the system is fed by saline water, an extra product apart from the cooling effect is desalinated water [6-8]. The first hybrid systems using adsorption cooling systems provided both heating and cooling effect. Adsorption chillers do not need electricity to operate and they are powered by heat being delivered to them.

Therefore, they can be used in the utilisation of waste heat in power plants and in CHP plants or steelworks: They can also be used at terminal units of district heating networks in the summer periods for the production of coolant and utilising it for air conditioning or technological processes thus contributing to primary energy savings. Adsorption chillers have a simple design without any moving parts, pumps or compressors, which implies that they are very reliable. Furthermore, they are quiet, do not generate vibrations and are resistant to corrosion. Their running costs are much lower compared with other types of chillers and they have a long service life and are not dependent on a power supply. Adsorption chillers also do have some disadvantages including their large dimensions and mass, the considerable investment costs or high design requirements due to the necessity of maintaining very low pressures. Moreover, adsorption chillers have low values of the COP as compared with other types of chillers [9-11]. The thermodynamic cycle of a cogeneration system considered based on the example of the CHP plant in Czestochowa with a power of 64 MW was defined numerically in the IPSEpro software based on the design parameters.

The CHP plant, launched in 2010, is one of the most environmentally friendly and modern facilities of its type in Central and Eastern Europe, and provides 86% of the city's demand for heat. The main parameters of the system have been presented in tab. 2.

Table 2. Main parameters of the CHP plant [12]

CHP operating parameters	
Nominal output of superheated steam	280 t/h
Fresh steam temperature	515 °C
Primary steam pressure in the boiler	111 Bar
Feed water temperature	230 °C
Electrical power of the generator	64 MWe
Heating capacity	120 MW
Boiler efficiency	91%
CHP overall efficiency	90%
Supply water temperature	86 °C
Return water temperature	57 °C

Simulation calculations were performed using the IPSEpro software by SimTech. The IPSEpro is an advanced environment for modelling, simulating and analysis of energy processes. It allows for the creation of conventional systems of steam thermal power plants as well as gas and gas-steam systems, IGCC and cooling processes. It also enables the modelling of single power generating units and whole systems. Apart from generating power, a CHP plant provides end users with large amounts of heat that can also be effectively utilised for coolant production. In order to increase the energy efficiency of the power plant, a proportion of the heat generated in the cogeneration process will be used to generate coolant through the use of adsorption chillers for this purpose. A potential place that is the source of supply heat for the chiller is the return flow of district water, which is characterised by a relatively low temperature albeit sufficient for the adsorption cooling unit, T_z = 57 °C and by a high water mass-flow rate, $\dot{m}$ = 999 kg/s [13-15].

Choice of chiller type

The optimal solution in this particular case will be the application of an adsorption chiller based on the silica gel/water pairing. In the aim of this paper the exemplary adsorption chiller is the unit with a power of 1180 kW. It is capable of operating in a hot water temperature range between 52 °C and 93 °C, producing chilled water with a temperature of 7.2 °C. The drop in temperature of the water supplying the refrigerator (the difference between inlet temperature and outlet temperature) as specified in the data sheet for this model is $\Delta T_z = 6.6$ °C. Electricity consumption is very low: 1.3-2.4 kW [16, 17]. Operation parameters of the adsorption chiller are included in tab. 3.

Table 3. Technical specification of the adsorption chiller [16]

Main parameters		Source of heat for regeneration	
Cooling capacity	1180 kW	Temperature range	52-93°C
Electricity consumption	1.3-2.4 kW	Volume flow rate	5072 L/min
Refrigerant type	Water	Chilled water	
Dimensions		Temperature range	3-20°C
Height	3505 mm	Volume flow rate	3043 L/min
Width	3658 mm	Condenser water	
Length	5334 mm	Temperature range	10-39°C
Weight	21319 kg	Volume flow rate	9167 L/min

The COP value

The value of the COP of a chiller working based on the silica gel/water pairing is variable and strongly dependent on the hot water inlet temperature. Based on the graph in fig. 2, the COP for hot water temperature of 57 °C is $COP_{57\,°C} = 0.29$.

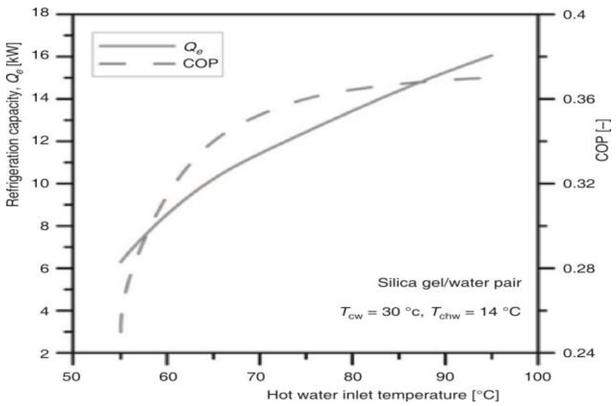

Figure 2. The COP values for silica gel/water chiller depending on the supply water temperature [17]

The adsorption chillers in the case concerned are fed by the district heating water network, as a result of which its outlet temperature is reduced, fig. 3. After installing adsorption chillers fed by return water from the district heating network the drop in its temperature will be

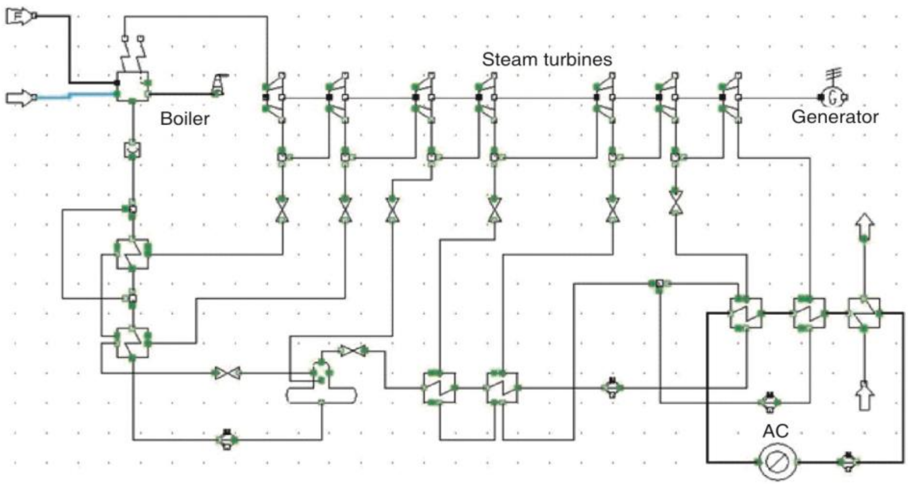

Figure 3. The CHP diagram with chillers installed, modelled in IPSEpro

$\Delta T_{s.\mathrm{chilled}}$ = 35.6 °C. In order for the generator power output to remain unchanged (N_{el} = 63.974 MW) at times of increased network load, the fuel chemical energy flux delivered to the boiler, with chillers installed, is: $E_{\mathrm{ch\ z}}$ = 184073 MW. Calculations were carried out on the basis of data included in tab. 4.

Table 4. Summary of the most important data needed for the calculations

Name of parameter	Symbol	Value	Unit
CHP electrical capacity	N_{el}	63.973	MW
CHP heat capacity	$\dot{Q}_{\mathrm{s}}$	121.388	MW
CHP overall efficiency	η_{ec}	91	%
Maximum heat influx into the adsorption chiller	$\dot{Q}_{\mathrm{s}}$	27.626	MW
Maximum cooling capacity	$\dot{Q}_{\mathrm{ch}}$	8.011	MW
Coefficient of cooling performance	COP_{57}°C	0.29	–
District water temperature drop in the chiller	ΔT_{s}	6.6	°C
District water mass-flow	$\dot{m}$	999	kg/s
Fuel chemical energy delivered to the boiler	$\dot{E}_{\mathrm{ch\ c}}$	186.054	MW
CHP annual operating time	τ_0	8400	h
Adsorption chillers operating time	τ_{chi}	1800	h

Fuel chemical energy savings ratio

In order to evaluate the energy efficiency of the cogeneration system, the ratio of fuel chemical saving is calculated. It serves the function of an energy efficiency indicator, like the primary energy savings (PES) indicator. The fuel chemical energy saving ratio for electricity, heat, and cooling production is defined:

$$\left(\frac{\left|-\Delta \dot{E}_{\mathrm{ch}}\right|}{\dot{Q}_{\mathrm{uc}}}\right)_{\mathrm{p\ chi}} \frac{\mathrm{MW}}{\mathrm{MW}} \tag{1}$$

where $\dot{Q}_{\rm uc}$ is the demand for useful heat covered by the unit with heat generation added, $\left|-\Delta\dot{E}_{\rm ch}\right|$ – the energy effect, which in the case of additional production of cooling is a saving in chemical energy of the fuel used for cogeneration of electricity, useful heat and cooling as compared with electricity and heat generation with separate cooling generation:

$$\dot{Q}_{\rm uc} = \dot{Q}_s = \dot{m}\Delta T_s c_p = 121.388 \text{ MW} \tag{2}$$

Energy effect $\left|-\Delta\dot{E}_{\rm ch}\right|$ can be expressed:

$$\left|-\Delta\dot{E}_{\rm ch}\right| = \left(\dot{E}_{\rm ch\,c} + \dot{Q}_s\right) - \dot{E}_{\rm ch\,s} = 29.607 \text{ MW} \tag{3}$$

By substituting expression (1) with results of eqs. (2) and (3) we can calculate the value of the chemical fuel energy saving ratio:

$$\left(\frac{\left|-\Delta\dot{E}_{\rm ch}\right|}{\dot{Q}_{\rm uc}}\right)_{\rm p\,chi} = \frac{29.607}{121.3885} = 0.2439\frac{\rm MW}{\rm MW} \tag{4}$$

Calculation of the β indicator value

The β indicator refers to the relative increase in relative fuel chemical energy savings as a result of the additional utilisation of heat for feeding the adsorption chillers compared to the amount of chemical energy that was saved as a result of generating useful heat in cogeneration. The relative energy effect described by the β indicator depends primarily on the energy COP of the adsorption chillers, the useful heat flux for heating, $\dot{Q}_z$, and the generated cooling flux, $\dot{Q}_{\rm ch}$. Assuming that auxiliary electricity consumption is negligible, the β indicator is described:

$$\beta = 1 + \frac{0.42\tau_{\rm chi}}{0.438\tau_0}\frac{\dot{Q}_{\rm ch}}{{\rm COP}_{57\,^\circ{\rm C}}\dot{Q}_s}\frac{\left(\dfrac{\left|-\Delta\dot{E}_{\rm ch}\right|}{\dot{Q}_{\rm uc}}\right)_{\rm p\,chi}}{\left(\dfrac{\left|-\Delta\dot{E}_{\rm ch}\right|}{\dot{Q}_{\rm uc}}\right)_{\rm p\,g}} \tag{5}$$

where $\tau_{\rm chi}$ is the length of the cooling season, assumed: 1800 hours, τ_0 – the annual CHP operating time, assumed: 8400 hours, and $(\left|-\Delta\dot{E}_{\rm ch}\right|/\dot{Q}_{\rm uc})_{\rm p\,g}$ – the fuel chemical energy saving ratio as an effect of adding heat generation to the power plant unit in relation to the amount of heat produced [18]

In this case, the $\left|-\Delta\dot{E}_{\rm ch}\right|$ can be defined as the amount of chemical energy saved in the course of the cogeneration process as compared to the separate production of electricity and heat:

$$\left|-\varDelta\dot{E}_{\rm ch}\right| = \left(\frac{N_{\rm el}}{\eta_{\rm ei}} + \frac{\dot{Q}_s}{\eta_{\rm ec}}\right) - \dot{E}_{\rm ch\,c} = 138.173 \text{ MW} \tag{6}$$

where $\eta_{\rm el}$ is the electricity generation efficiency at a substitute power plant, assumed: 33.52%, $\eta_{\rm ec}$ – the overall cogeneration efficiency in a substitute CHP plant, assumed at 91% [18].

Thus

$$\left(\frac{\left|-\Delta\dot{E}_{\rm ch}\right|}{\dot{Q}_{\rm uc}}\right)_{\rm p\,g} = \frac{138.173}{121.3885} = 1.1383\frac{\rm MW}{\rm MW} \tag{7}$$

Substituting the previously values into the eq. (5) we obtain:

$$\beta = 1.01002 \tag{8}$$

The calculated value of the β indicator is 1.01002. This point to the advantageous effect of the application of the trigeneration technology on the relative increase of savings in chemical fuel energy in the course of additional fuel consumption for the purpose of coolant production as compared to the amount of fuel that was saved through generating heat in cogeneration at the CHP plant [18].

Summary and final conclusions

The main objective of this paper was to examine the effect of the application of adsorption chillers on the improved energy efficiency of a conventional power plant. Actions aimed at increasing and improving it, as well as the savings in non-renewable energy resources, are becoming an increasingly important aspect of the operation of power plants. This brings tangible benefits both to the natural environment and the power company itself (profits from fuel savings or White Certificates). An indicator that clearly demonstrates the relative energy effect of the application of trigeneration technology, *i. e*. the utilisation of the heat capacity of the cogeneration unit for additional production of coolant, is the β indicator. The previous calculations demonstrate that its value in the above case is β = 1.01002. This means that the relative increase of savings in chemical fuel energy in the course of additional heat consumption for feeding adsorption chillers for the purpose of generating coolant in relation to the amount of fuel that was saved in the course of producing heat in cogeneration is 1.01002. In the case concerned, this indicator is rather low. However, the improvement in the efficiency of primary energy consumption is already noticeable, which also implies a lower consumption. The β indicator for the given value of the cooling COP displays a linear correlation with the relation between the maximum flux of the cold being generated and the maximum useful heat for heating. Therefore, the more coolant that is generated by the chillers installed, the higher the β indicator will be. Likewise, the β indicator rises when the COP is lower for the chillers under consideration. In the solution contained in this paper, *i. e*. feeding chillers by hot district water, the maximum cooling capacity was assessed at 8.011 MW. A higher production of coolants would be inefficient or impossible due to the too low temperature of the district water network and the lack of the opportunity to reduce the temperature of the water that reaches the district heat end users.

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