INCREASE OF THERMAL EFFICIENCY OF COGENERATION PLANT BY WASTE HEAT UTILISATION WITH ABSORPTION HEAT PUMP

by

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The very rapid growth of share of electricity generation from renewable sources is observed recent years. However, even if that share reaches about 50% in 2050, almost 50% of electricity will still be generated based on fossil fuels combustion rather than on nuclear energy. That means, energy generated from coal will still be important for the next decades. The largest sources of energy loses within the steam power plant is the steam cooling system. The energy dissipated to the atmosphere in that system is very difficult to be utilized mainly due to the relatively low temperature, and its direct utilization without additional equipment is rather impossible. The large amount of energy lost to the environment leads to low overall thermal efficiency of the plant, therefore, utilization of this energy should be of primary importance.

The paper shows concept of increasing efficiency of cogeneration plant thermal cycle by utilisation of waste heat from flue gas with absorption heat pump, for the purpose of system heat generation. Calculations of combined system of power plant fuelled with biomass fuel with implemented waste heat utilisation system were performed for one heating season and different moisture content in the fuel. Results show, that owing to waste heat utilization instead of conventional heat exchanger, additional electricity generation during the heating season at even 46864 MWh may be achieved which is over 18% more for the moisture content in the biomass fuel at 0.5 kg/kg, the same ambient conditions and heat generation.

Key words: *heat pumps, waste heat utilization, cogeneration power plant*

Introduction

The very rapid growth of share of electricity generation from renewable sources is observed in Europe recent years. However, even if that share reaches about 50% in 2050, almost 50% of electricity will still be generated based on fossil fuels combustion rather than on nuclear energy. That means, energy generated from coal will still be important for the next decades. Since processes of generation of electricity and system heat represents a substantial source of pollutants emission to the environment, it is necessary to continuously develop and improve these processes in order to enhance their overall efficiencies [1, 2]. Since the post

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combustion technologies for CO_2 capture [3, 4] are highly energy consuming [5, 6], and leading to significant decrease of power plant (PP) efficiency, the less costly way of emission reduction (especially of CO_2) from energy sector seems to be waste heat utilisation. There are two largest sources of energy loses within the conventional or cogeneration plant (CHP). One is the cooling system of steam leaving the turbine, where the low temperature heat is dissipated to the environment in cooling tower, and the second one is boiler generating hot (about 120 °C for hard coal and 170 °C for lignite) flue gas. The water in a cooling system and the flue gas are both sources of low temperature heat, however, the temperature of flue gas is much greater than of cooling water (which is less than 30 °C). The energy lost to the atmosphere with these two carriers is very difficult to be utilized mainly due to the relatively low temperature, and its direct utilization without additional equipment is rather impossible. However, the large amount of energy lost to the environment leads to low overall thermal efficiency of the plant, therefore, utilization of this energy should be of primary importance, and its lost amount should be minimized if only possible.

One of possible solutions leading to significant increase of conventional steam PP efficiency is implementation of a system for useful heat generation, *i. e*. for district heating system (DHS) purposes, in simultaneous production of electricity and heat in the CHP [7-9]. However, since the conversion from conventional PP into CHP, or additional generation of heat in CHP plant affects negatively electricity generation, the potential increase of efficiency and especially potential incomes depend on configuration of heat generation system and its implementation into PP. The conventional useful heat generation within CHP plant makes use of steam taken from the steam bleeding for feeding heat exchanger (HE), where hot water for DHS system is produced. This reduces the significant amount of heat released in the condenser cooling system, but strongly affects the amount of electricity generated. This negative impact may be limited by waste heat utilization such as recuperation of heat carried by the wet flu gas or condenser cooling water.

There are many known ideas for waste heat utilization [10-14] from both: flue gas and cooling water, depending mostly on the type of heat carrier, amount of heat available and its temperature. While applying special equipment, waste heat may be utilized for electricity generation either production of cooling or heating media. Among the others, ORC [15] for electricity generation, adsorption [16] and absorption chillers (ACH) [17] for cold generation or absorption heat pumps (AHP) [17] for heating purposes are worth to be distinguished.

The ORC systems allow the use of waste heat at a temperature of up to 300 °C. The efficiency of ORC systems depends on the temperature of waste heat and the working medium used the size of the system, and ranges from 6 to 24% [18, 19]. The working fluids used in ORC systems in many cases have a negative impact on the environment and the system subassemblies [20]. The use of thermal oil and some low-boiling agents in ORC systems may result in a risk of fire, explosion or contamination in the event of system failure.

Adsorption and absorption technologies are well known and widely applied for different applications, mostly for separation of industrial gaseous mixtures [21-24], but also for cooling and heating purposes [25-29]. However, their application for cold or heat generation require appropriate recipient to be available. Therefore, ACH systems may be applied rather for small scale purposes like for stand-alone public buildings, hospitals, *etc*., and since the amount of waste heat available from even relatively small CHP is quite large and the demand for cold is rather small in that industry, adsorption or ACH are not the appropriate solution for energy sector applications. The most suitable solution of waste heat utilization for large scale applications such as CHP seems to be AHP technology. This technology is widely known and already applied worldwide in small as well as large scale [30, 31], however it was not applied in the power sector yet.

The important advantage of AHP is their very low demand for electricity, which is required for working fluid circulation only. It is because they are driven by heat not electricity, and require heat source at two different temperature levels: the heat source at relatively high temperature as an AHP driving force and the source of low temperature waste heat. If the AHP is going to be implemented into the conventional PP or CHP plant, the high temperature heat may be derived from the plant with steam, hot water or flue gas, which in different way affects amount of electricity generated within the plant. The highest affection is caused by deriving the steam, while the lowest if flue gas is taken as driving force.

Waste heat utilization concept

Electricity is the most valuable and precious energy form. Therefore, if heat production is required from conventional PP or additional heat generation from CHP plant is necessary, it must be realized with minimum impact on the electricity generation and the least interference into the PP infrastructure. The conventional heat generation in CHP plant relies on implementation of condensing heat exchangers (CHX) which are fed with steam taken from the turbine steam bleeding. If such a solution is applied to conventional PP, it affects not only electricity generation but also exploitation of a low pressure (LP) part of turbine. Especially at low PP loads, when the stream of steam flowing through turbine is low as well, additional portion of steam taken from turbine through steam bleeding may cause surplus longitudinal stresses which may be unacceptable from turbine's LP part exploitation point of view. Such a case takes place at wintertime at nights, when the demand for heat is the highest while for the electricity is the lowest. Therefore, conversion of PP into CHP plant must be carefully studied, and other then CHX solution should be considered.

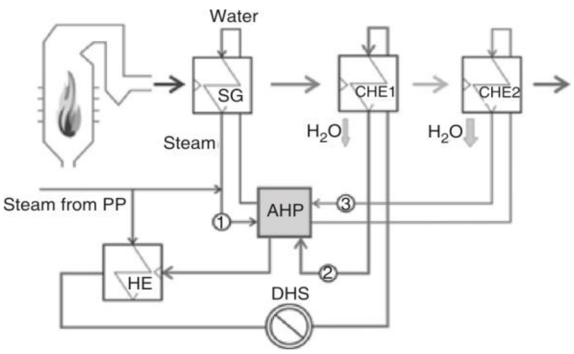

Figure 1. Schematic concept of a system for waste heat utilisation

Utilisation of waste heat carried by flue gas through application of AHP may be the solution in that case. It may fulfil all requirements by limiting the steam consumption for heat generation, while similar interference into the PP infrastructure like in CHX case is must be made. The schematic concept of the solution proposed is shown in the fig. 1.

The AHP is driven by the steam which is generated in the steam generator (SG) by waste heat recuperated from wet flue gas. It is the first stage of recuperation of waste heat from flu gas. The flue gas temperature before SG is high enough thus there is no water condensation in SG at all, and the flue gas is cooled down only. Next the flue gas is fed into the dual section HE (CHE1-section one and CHE2-section two) where moisture condensation occurs, and the heat of condensation and from flue gas cooling is transferred to district heating water (in CHE1) and, as a low temperature waste heat, into the AHP (in CHE2). However, in case of insufficient thermal power of SG and/or of AHP according to heat demanded by recipient, additional energy may be complemented by supplying the steam from turbine steam bleeding to feed AHP or directly the pick HE. The pick HE is necessary here, because the thermal power of AHP is strongly dependent on external conditions (especially of temperature of water returning from the recipient's installation or DHS), and is some inconvenient conditions AHP thermal power may be insufficient, or it may be unable to heat up water to temperatures required by DHS. In such cases, the steam taken from the turbine steam bleeding may be supplied to the AHP to increase of its power or directly to HE for increasing the temperature of hot water produced.

As mentioned before, the temperature of water returning from the recipient's installation and also temperature of waste heat (low temperature energy source) have a significant influence on the AHP thermal power. Therefore, from the AHP point of view, it is very important to ensure the appropriate parameters of a low temperature source (parameters of utilized waste heat). Especially, possibly high and constant temperature of the heat source is required. From the other hand, AHP should utilize waste heat of relatively low parameters. These two contradictory requirements leaded to division of condensing HE into two sections (CHE1 and CHE2), which fulfils these requirements, and constitutes the second stage of waste heat recuperation from flue gas.

The proposed solution is almost zero-electricity demand, and for all conditions when the heat demand for DHS is smaller or equal AHP thermal power, as well as if the temperature of hot water required by the DHS is lower than maximum allowable temperature of water heated by AHP, the heat production from the proposed concept does not affect electricity generation within the PP at all, because it is fully driven by flue gas only.

Assumptions and conditions

The flue gas leaving PP carries a large amount of energy resulting not only from its temperature, but from the significant amount of moisture as well. The moisture concentration is especially high if lignite or biomass is combusted in the boiler. Since the heat of evaporisation and condensation of water is very large, the amount of energy consumed in the boiler for water evaporisation is also huge, and therefore, its utilisation through recuperation of heat from condensation of moisture from flue gas may significantly improve overall plant efficiency.

According to mentioned before and concept presented in fig. 1, the steam PP with fluidized bed boiler fed with biomass fuel was taken into account and analysed. The fuel composition in dry state combusted in the fluidized boiler of 100 MW_t nominal thermal power and efficiency $\eta_b = 0.88$ is shown in tab. 1. The composition of flue gas leaving the boiler is shown in tab. 2, and due to a high concentration of moisture, its temperature at the outlet from the boiler was assumed at about 180 °C. The nominal gross efficiency of PP was $\eta_{pp} = 0.4567$, while its electric power at that state was 40 MW_e.

For the analyzed case, the pick heat demand required by recipient and delivered to the DHS system was 45 MW_t. However, the heat delivered to DHS system is not constant along the year, and moreover, varies along a day as well.

It is because the heat demand and required temperature of water supplied into the DHS system depend on instantaneous value of ambient temperature. Parameters and the amount of heat required by DHS system are established by the agreement between the DHS operator and CHP plant. Therefore,

Table 1. Fuel characteristic in a dry state

Parameter	Operational state	
C	0.5091	kg/kg
H	0.0632	kg/kg
N	0.0017	kg/kg
S	0.0010	kg/kg
O	0.4110	kg/kg
Ash	0.0140	kg/kg
VM	0.8403	kg/kg
FC	0.1456	kg/kg
LHV	18.7	MJ/kg

Table 2. Flue gas composition

Parameter	Mole fraction	
CO_2	0.127	mol/mol
SO_2	0.001	mol/mol
N_2	0.614	mol/mol
O_2	0.027	mol/mol
H_2O	0.231	mol/mol

so called regulation table for heat delivery specifies such parameters as DHS feed water temperature and temperature of water returning from DHS system depending on ambient conditions (mainly temperature and wind speed), and for the analyzed case such a table is shown in tab. 3.

As may be seen from tab. 3, the lower ambient temperatures require higher DHS feed water temperatures and vice versa. The DHS system considered is supplied with hot water at the range of 50 °C to 135 °C, while the temperature of water returning from the DHS varies from 38 °C to even 70 °C. Since the correlation of ambient air temperature and heat parameters is very strong, the distribution of ambient temperature along the year for plant localization was determined, and is shown in figs. 2 and 3. As may be seen from figs. 2 and 3, most operating hours of CHP plant during the heating season concern air temperatures roughly between –10-12 °C. Lower ambient temperatures are rather rare, and for higher temperatures heat delivery to DHS system is stopped. As it was mentioned, the pick heat demand required was assessed at 45 MW_t level, and therefore, taking into account ambient temperature distribution, an appropriate AHP with 35 MW_t of nominal thermal power and of COP = 1.8 was selected, which fully fulfils the heat recipients demand in the range of air temperatures greater than –10 °C.

Table 3. Regulation table

Air temperature	Feed water temperature	Return water temperature	Air temperature	Feed water temperature	Return water temperature	Air temperature	Feed water temperature	Return water temperature
[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]	[°C]
–20	135	70	–9	108	59	2	81	48
–19	133	69	–8	105	58	3	79	47
–18	130	68	–7	102	57	4	76	46
–17	128	67	–6	99	56	5	72	45
–16	125	66	–5	97	55	6	69	44
–15	123	65	–4	95	54	7	66	43
–14	121	64	–3	93	53	8	63	42
–13	118	63	–2	91	52	9	59	41
–12	115	62	–1	88	51	10	56	40
–11	113	61	0	86	50	11	53	39
–10	111	60	1	84	49	12	50	38

Operating characteristics of selected (from manufacturer's product catalogue) AHP showing the potential thermal power (heating capacity) in respect to pressure of saturated steam feeding AHP (point 1 in fig. 1), DHS returning water temperature (point 2 in fig. 1) and waste heat source temperature (point 3 in fig. 1) are shown in figs. 4 and 5, respectively. All characteristics are relative, related to their nominal values.

As may be seen from characteristics shown in fig. 6. The AHP heating capacity is strongly related to thermodynamic parameters of streams feeding into the AHP. For less favourable temperatures, this means temperatures lower than nominal ones, heating capacity decreases significantly. However, for temperatures higher than nominal, AHP heating capacity increases beyond the nominal value. Moreover, these characteristics may be extrapolated

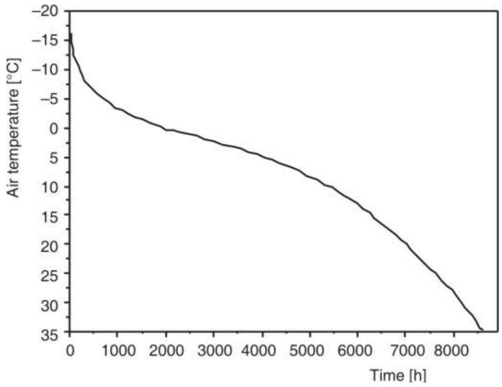

Figure 2. The structured graph of outer air temperature [24]

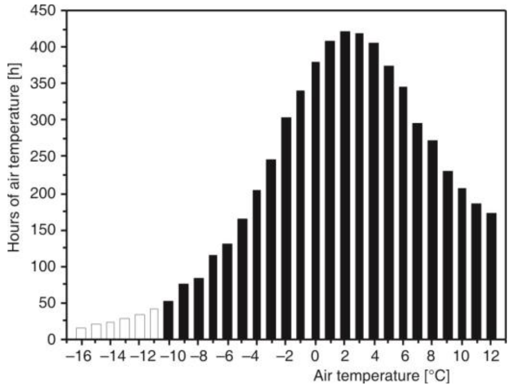

Figure 3. Hours of presence of ambient air temperature during heating season [24]

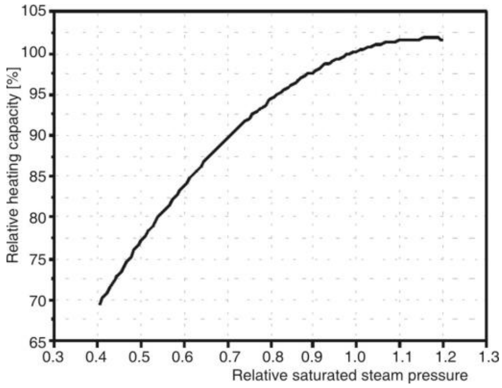

Figure 4. Relative steam pressure

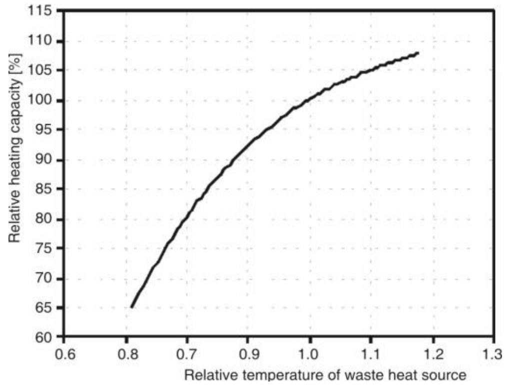

Figure 5. Relative DHS returning water temperature

for the wider range, but it must be mentioned that for the selected AHP there are two parameters that restrict this extrapolation. One of them is the maximum increase of heated stream (DHS water) temperature done with eq. (1).

$$\Delta t_{\mathrm{hs}} = t_{\mathrm{hs\_out}} - t_{\mathrm{hs\_in}} \tag{1}$$

where Δt_{hs} is the increase of heated stream temperature, $t_{\mathrm{hs\_out}}$ – the temperature of heated stream at outlet from AHP, and $t_{\mathrm{hs\_in}}$ – the temperature of heated stream at inlet to AHP.

For temperatures of heated stream at the outlet from AHP $t_{\mathrm{hs\_out}} \le 95$ °C the increase of heated stream temperatures is almost constant and $\Delta t_{\mathrm{hs}} \approx 35$ °C. The second parameter restricting extrapolation of characteristics results from the LiBr-H_2O type of selected AHP. For that type of AHP, maximum allowable temperature of hot water produced is about 95 °C. That is due to necessity of adding to LiBr-H_2O mixture some additives which prevent corrosion.

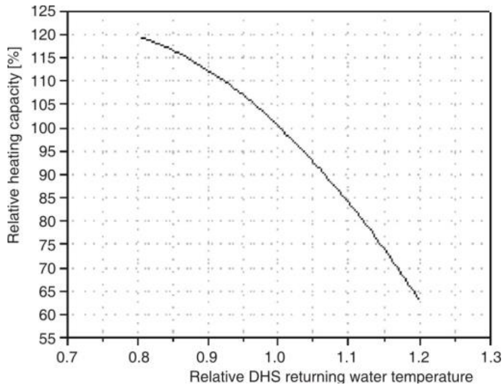

Figure 6. Relative waste heat source temperature

These additives are not high temperature resistant and are degraded in temperatures higher than 185 °C. That condition limits the highest allowable temperature of steam feeding AHP, and therefore, the maximum allowable temperature t_{hs_out} do not exceeds 95 °C. Due to that reason, while the air temperature is higher than –4 °C and corresponding DHS feed water temperature is 95 °C or lower, AHP may produce hot water which may be directly supplied to the DHS, because it fulfils DHS requirements. However, for ambient air temperatures lower than –4 °C, and corresponding DHS feed water temperatures higher than 95 °C, production of heat by AHP must be supported by pick HE, see fig. 1, through heating up water to temperatures required by DHS system, according to regulation table. Of course, in some inconvenient conditions AHP may produce hot water of appropriate temperature but its heat capacity may be insufficient in these conditions. Therefore, the pick HE must also support AHP operation in such cases.

Calculation results

The calculations presented in figs. 7-10 were performed for moisture content in the fuel at 0.45 kg/kg and for two cases. Case one as a reference case, where heat for DHS was produced by conventional HE only, and case two, where heat for DHS was produced by AHP with the support of pick HE. Both cases were calculated for one heating season and the most common air temperature within the range of –10-12 °C. First, the potential of heat recuperation from flue gas, assuming nominal temperatures of media transferring energy from CHE2 to AHP was assessed. Therefore, the amount of heat available for utilization was assessed at more than 35 MW_t which shows that the thermal power potential of the flue gas is enough for implementation of concept shown in fig. 1 into cogeneration PP considered. Moreover, since the solution proposed utilizes the waste heat for AHP feeding, there is also enough energy in the steam taken from PP.

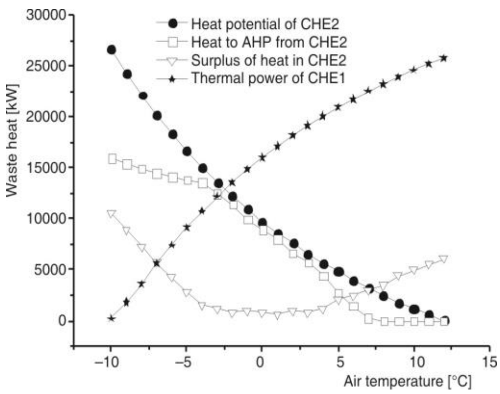

Figure 7. The structured graph of outer air temperature

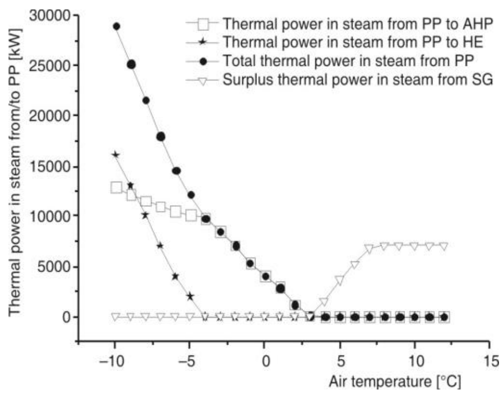

Figure 8. Thermal power derived from PP for feeding AHP and HE

Since the amount of heat available for recuperation, especially low temperature heat recuperated in CHE2, depends on ambient air temperature, the fig. 7 shows the distribution of the amount of heat available for recuperation from CHE2, heat utilized by AHP from CHE2 and surplus heat still available to be recuperated from that HE for the range of air temperature considered.

The decreasing with temperature heat potential results from the impact of the CHE1. The higher ambient air temperature leads to the lower temperature of the water returning from

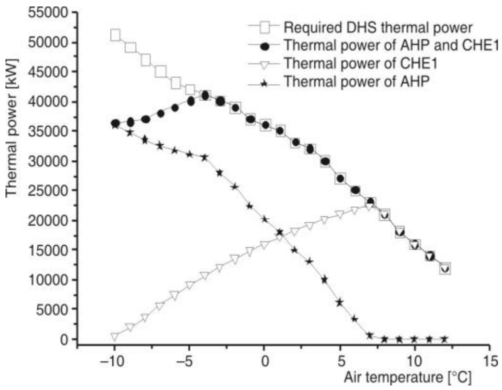

Figure 9. Thermal power of waste heat utilisation system *vs*. DHS system demand

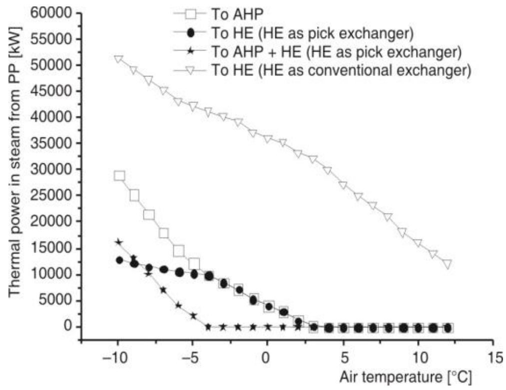

Figure 10. Thermal power in steam from PP

the DHS system which causes the more energy to be recuperated in the CHE1, and therefore, less energy remains to be recuperated in CHE2. Moreover, at higher air temperatures, especially higher than 7 ^{o}C, the amount of heat recuperated in CHE1 and the temperature of DHS water at its outlet are enough to directly feed the DHS system. In these conditions, AHP may be switched off. It may also be seen that for temperatures between –4 ^{o}C and 7 ^{o}C almost all heat potential is utilized, while for lower temperatures it is not. That situation (air temperature <–4 ^{o}C) is caused by the requirement of DHS feeding water temperature being higher than 95 ^{o}C. That causes the pick HE must be used to heat up water from 95 ^{o}C (produced by AHP) to desired temperature (see regulation table in tab. 3), which requires some amount of steam taken from PP. Thermal power derived from PP for supplementing the lack of energy required for feeding AHP (SG HE thermal power is insufficient) and for feeding the pick HE are shown in fig. 8.

It may be seen from fig. 8 that for air temperatures lower than 3 ^{o}C thermal power of SG is insufficient for utilization of heat from CHE2 by AHP, and therefore, some amount of steam must be taken from PP to supplement the lack of energy required by AHP. Increase of SG thermal power is possible, but it would lead to limiting the amount of heat available in CHE1 and CHE2. However, from the amount of waste energy utilized point of view, it is meaningless where this energy is recuperated (in SG or in CHE1). Therefore, to utilize as much energy as possible form flue gas, AHP requires additional energy which is derived from PP in this case. Figure 8 also shows the heat required by the pick HE while DHS feeding water temperatures are greater than 95 ^{o}C (outside air temperatures <–4 ^{o}C). Since AHP is not able to fulfil the DHS system requirements, steam must be taken from PP to feed HE.

It is also worth noting, that for outside air temperatures greater than 3 ^{o}C the amount of energy (heat) which may be recuperated from flue gas is larger than required by DHS system. Since the steam at 170 ^{o}C may still be produced in SG, this unnecessary (from DHS point of view) heat may be utilized by the PP thermal cycle *i. e*. in the condensate regeneration system. If so, less steam is derived from turbine steam bleeding for feeding the condensate regeneration system leading to increase of electricity generation within PP. The potential of heat generation in respect to DHS system demand is shown in fig. 9.

It must be pointed out that for the outside air temperature greater than –4 ^{o}C the total heat demand required by DHS may be covered by production from AHP and CHE1, what may be seen from fig. 9. That is because the AHP and CHE1 works well in different conditions and supplements each other. While CHE1 working conditions do not allow for heat recuperation at low air temperatures, most of heat is generated by AHP. From the other hand, in the range of higher air temperatures, working conditions of AHP are poor but in that range the CHE1 takes the lead in heat generation. As mentioned before, for ambient air temperatures lower than –4°C only pick HE is required due to the necessity of fulfiling the DHS requirements concerning feeding water temperature.

Figure 10 shows the energy in steam derived from PP which is needed by absorption heat pump, by HE working as a pick HE and by HE while heat for DHS is generated by conventional operation of HE only. It may be seen, that in the whole range of outside air temperatures considered, production of useful heat for DHS system with AHP and CHE1 requires significantly less energy than production of the same heat with conventional HE.

The less energy derived from PP directly means the more electricity is generated. The comparison of electric power of the cogeneration PP for heat generation with conventional system with HE only and for generation by implementation of concept proposed is shown in fig. 11. Calculations which results are shown in fig. 11 were also performed for different values of moisture content in the fuel, and the exemplary results for moisture content at 0.4, 0.45, and 0.5 kg/kg are shown. It may be seen form fig. 11 that for the whole range of ambient air temperatures and moisture content in the fuel at 0.45 kg/kg, increase of electric power of PP varies from about 4.7 MW_e to almost 8 MW_e, which means the relative increase from 9.6% to 18.8% while the same heat for DHS system is produced. Moreover, the analysis of electric power distribution for different moisture content in the fuel leads to interesting conclusions. From the PP efficiency point of view, the higher moisture content in the fuel, the lower PP efficiency, since more fuel bust be combusted in the boiler to achieve the same energy transfer to the PP working fluid. However, in the same time it leads to larger potential and amount of heat available for recuperation from flue gas, and therefore, less energy derived with steam from PP is required for heat generation. Finally, increased amount of source energy in the fuel delivered to the boiler is less than decreased amount of energy derived in steam from PP, and since more heat is recuperated from flue gas it leads to more electricity being generated within the PP.

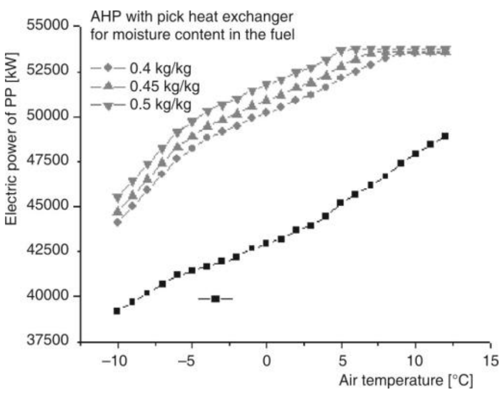

Figure 11. Electric power of PP for conventional HE and AHP + CHE1

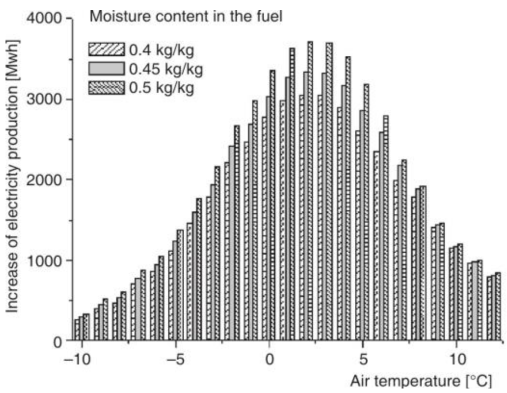

Figure 12. Additional electricity production due to the waste heat utilization by AHP + CHE1

The higher electric power of PP leads to more electricity production, while the same amount of heat is delivered to DHS system. If the number of hours during the heating season is taken into account, the total amount of additionally generated electricity may be calculated, and its distribution in respect to outside air temperature and total additional electricity production are shown in fig. 12 and tab. 4 respectively.

Table 4. Total additional electricity production

Total electricity production during heating season with conventional HE		257595	MWh
Moisture content in the fuel	Total increase of electricity production during heating season (AHP + PHE)	Total electricity production during heating season (AHP + PHE)	Relative increase of electricity production during heating season (AHP + PHE)
[kg/kg]	[MWh]	[MWh]	[%]
0.4	39482	297078	15.33
0.45	42880	300475	16.65
0.5	46864	304460	18.19

Results show that total additional electricity production during the heating season resulting from waste heat utilisation from flue gas instead of heat generation by conventional HE is about 39482 MWh for 0.4 kg/kg of moisture content in the fuel, which is about 15% more. That increase may be even greater if the fuel moisture content is higher, and in case of 0.5 kg/kg it reaches more than 18% increase.

Conclusion

The paper presents concept and calculations of additional heat production by utilisation of waste heat from flue gas leaving the PP boiler, with application of AHP. Calculations were performed for different weather conditions in two cases: generation of heat by conventional HE as a reference case and generation of heat by waste heat utilisation done with AHP. Results show, that implementation of AHP instead of conventional heat echcanger has lower impact on the PP thermal cycle which results from smaller amount of steam taken from turbine stem bleeding, owing to waste heat utilisation. Amount of waste heat allowable for recuperation, and therefore amount of additional electricity production depends mainly on ambient conditions and moisture content in the fuel. For the biomass fuel with 0.5 kg/kg moisture content additional electricity generation due to AHP implementation reaches almost 48000 MWh (for one heating season) wich means over 18% more, then if conventional heat echcanger is used.

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