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On the use of rotary gas/gas heat exchangers as a novel integration option for heat and water management in exhaust gas recycling gas turbine plants.

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Abstract

This work is a first-of-a-kind feasibility study investigating technology options with gas/gas rotary heat exchangers for the water management in the integration of Natural Gas Combined Cycle (NGCC) plants with post-combustion carbon capture, with and without exhaust gas recirculation (EGR). A range of configurations are examined for wet and dry cooling of the flue gas entering a post-combustion capture (PCC) absorption system, and regenerative heating of the CO_2-depleted flue gas prior to the power plant stack. First, this work examines the addition of a gas/gas rotary heat exchanger to transfer heat from the exhaust gas entering the absorber into the CO_2-depleted gas stream leaving the absorber. It then investigates the performance of a configuration with an additional air/gas rotary heater to further reduce exhaust flue gas temperature and water consumption, and, eventually, a more compact arrangement which combined the two heaters into a single gas/gas/air heater with a trisector configuration. A thermal performance analysis was conducted for each of the previous configurations, in order to evaluate the dimensions and the operational parameters of the heaters. By replacing the direct contact cooler traditionally used in PCC technology by a dry-cooling system, a significant reduction in the overall process water usage and cooling water consumption associated to the capture plant can be achieved. The second part of this work examines the use of a similar system for NGCC plant with EGR. This strategy increases CO_2 concentration in gas turbine exhaust gases and reduce O_2 induced solvent degradation. In addition to the heat and water balance around the absorber column of the PCC process, an important aspect of EGR is that recirculated gas stream temperature should be as low as possible so that the gas turbine performance is not compromised. The performance of the rotary heat exchanger configurations is analysed at different recirculation ratios.

Peer-review under responsibility of the Organizing Committee of GHGT-12

Keywords: Gas Turbine Combined Cycle; Post-combustion carbon capture; direct contact cooler; rotary heat exchanger.

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1. Introduction

The integration of the post combustion capture process using amine-based scrubbing technology with Natural Gas Combined Cycle (NGCC) power plants have been widely studied. Previously published studies on power plant integration have been mainly focused on options for steam extraction from the steam cycle, aiming to minimize the electricity output penalty and the effect on thermal efficiency reduction, omitting opportunities for integration and optimization of heat transfer in the flue gas pathway across the boundaries of the carbon capture plant.

In NGCC plants, flue gas typically leaves the heat recovery steam generator (HRSG) at a temperature range from 80 to 150 ºC to avoid acid gas condensation. In plants without CO_2 capture, the exhaust flue gas temperature is sufficiently high to rise through the stack by buoyancy effects. This temperature is, however, higher than the optimal temperature for the absorption process with amine based solvents. A low temperature in the column enhances the absorption process by increasing the solvent capacity and the driving force for mass transfer. The exhaust flue gas is therefore typically cooled down by means of a direct contact cooler until it reaches an optimal temperature, which has been reported to be around 35 ºC [1] and 40 ºC [2, 3, 4]. Temperatures as high as 50 ºC have also been presented in pilot plant data [5, 6]. A large amount of process and cooling water is, however, required and this fact might constitute a limitation for the full scale deployment of post-combustion capture, particularly in jurisdictions with an increasingly restricted access to cooling water. The application for gas/gas heaters, relying on ambient air for dry cooling, can therefore reduce the process water usage and cooling water consumption.

At the top of the absorber, the CO_2-depleted gas stream leaves at a temperature similar to the inlet flue gas stream. A water wash section at the top of the column is used to cool down the treated gas, in order to avoid solvent vaporization and solvent losses into the atmosphere. The treated gas is directly released into the atmosphere either through a wet stack design (e.g. in [7]), or through a dry stack design (e.g. in [1]). In the latter, the treated gas must be reheated in order to increase buoyancy forces and avoid plume visibility and corrosion due to water condensation in the saturated flue gas stream. A heat exchanger, using as heating fluid the condensed water coming from the reboiler of the stripper, has been used for this purpose in, for example, an IEAGHG study [1], increasing the CO_2-depleted gas temperature up to 60 ºC.

The application of gas/gas heater, relying on ambient air for dry cooling, can therefore reduce process water usage and cooling water consumption whilst ensuring that flue gas reaches an appropriate temperature prior to the stack. In this work, it is assumed that the reheated flue gas enters the stack at a temperature higher than 70 ºC for good buoyancy effects [8].

This work also examines the use of gas/gas heaters in plant configurations with exhaust gas recirculation (EGR) where a fraction of the flue gas is re-diverted from the outlet of the Heat Recovery Steam Generator to the compressor inlet. It has been widely studied in literature as a strategy to increase CO_2 concentration in the flue gas stream, in NGCC power plants with post-combustion amine based technology. Greater CO_2 partial pressure enhances the absorption process and the volume of the gas to be treated in the capture plant is reduced, leading to smaller capture plant dimensions. The recirculated stream is typically cooled down before it is mixed with ambient air, as lower inlet temperature increases the gas turbine power output. In previous work, little consideration has been given to optimizing the flue gas loop and the temperature of the recirculated gas stream is often assumed to be the same as that of the gas stream entering the absorber and, so the same cooling equipment is used for both streams [9, 10]. Recent studies have, however, proposed the recycling of exhaust gas at lower temperatures, and therefore two direct contact coolers of smaller size have been introduced in the process [1].

2. Rotary heat exchanger technology

2.1. Description, components and performance

Gas/gas rotary heat exchangers rely on a technology widely used in coal fired power plants to pre-heat the primary and secondary combustion air streams using the flue gas exiting the boiler. The same technology is also used to recover heat from the inlet stream of the flue gas desulphurization unit into the outlet stream to increase temperature and buoyancy effect in the stack [11]. It can be easily adapted to NGCC with CO_2 capture applications.

Rotary-plate heaters are regenerative heat exchangers, where the heat is indirectly transferred by convection as a heat storage medium is periodically exposed to hot and cold flow streams, flowing in a counter current arrangement. The periodic exposure is accomplished by a rotary mechanism and steel elements are used as the heat storage medium. Regenerative heating surface elements are a compact arrangement of two specially formed metal plates. Each element pair consists of a combination of flat corrugated and undulated plate profiles [11]. The main components in the rotary heater design are illustrated in Fig.1. A bisector, trisector or quadsector configuration can be selected based on the number of streams involved in the heat transfer process and the total number of open sectors can be divided among the gas streams, proportionally to their mass flow rate, so that the gas velocity at either side of the sector plate is similar and does not result in a high pressure drop. Due to the rotation operation, gas flow leaks will occur for one gas side to the other of the sector plate. *Direct leakage* occurs through the radial, axial and other seals between rotating and stationary parts, and *entrained leakage* is the gas contained in a rotor sector and carried into the other streams by rotor rotation. Regenerative heaters are designed to meet thermal performance, low leakage level and pressure drop requirements.

2.2. Methodology followed for the selection of rotary heat exchangers for thermal performance analysis

The thermal performance analysis of the rotary heaters has been conducted using a proprietary software developed by Howden Group, a leading Original Equipment Manufacturer of rotary heat exchangers [12], based on a methodology specifically developed for this novel application. For each case of study, the objective is to select a feasible heater configuration, dimensional and operational parameters, which can achieve a desired outlet temperature for the exhausts flue gas and CO_2-depleted gas streams at the cold and hot ends of the rotary device respectively. Heater dimensions must be selected to minimize leakage level and pressure drop. The heater size and the element depth are directly related with the heating surface area and were varied in the analysis, with material specifications, metal thickness and rotor speed constant for all configurations. Due to the small temperature differential at the cold end in this particular application, there is a law of diminishing return for each incremental increase in heater size. Once a certain size is reached, a larger increase in heating surface is required to achieve a marginal decrease/increase of the outlet temperature of the hot/cold gas streams. Although larger heater size results in lower gas velocity and pressure drop, they operate with higher leakage level. A general criterion followed in his work is that the system operates with clean, dust depleted gas stream, unlike in coal plant applications. The final selection is based on a trade-off solution so that the desired outlet temperature in the treated and untreated gases can be achieved with minimum pressure drop and leakage levels and an acceptable heater size.

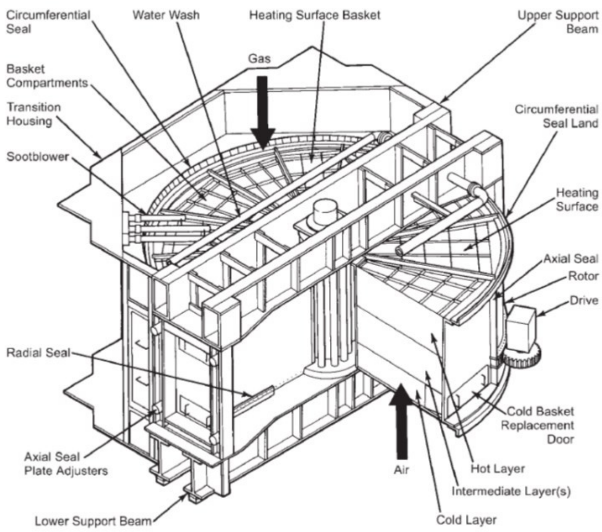

Fig.1. Example of a typical regenerative gas/gas rotary heater used in coal power plants [11].

3. Novel integration options for heat and water management in NGCC with post combustion capture

Three alternative configurations using rotary gas/gas heaters are compared to a standard amine-based scrubbing technology with a direct contact cooler.

- The addition of a gas/gas rotary heat exchanger upstream of the direct contact cooler to transfer heat from the exhaust gas entering the absorber into the CO_2-depleted gas stream leaving the absorber,
- A configuration with two rotary heat exchangers in series, which includes an air/gas rotary heater,
- A more compact arrangement which combines the two heaters into a single gas/gas/air heater with a trisector configuration.

The second part of this work examines the use of a similar system for NGCC plant with EGR. Block flow diagrams for each configuration are shown in Fig.2 and Fig.3 respectively.

3.1. Wet cooling system: direct contact cooler

The gas is brought into direct contact with process water in a counter current configuration in a packed bed column. Water collected in the cooler sump is passed through a water-cooler heat exchanger before being returned to the top of the tower. Cooling water in the heat exchanger is provided by the primary plant cooling system.

3.2. Hybrid system: gas/gas heater and direct contact cooler

A gas/gas heater is introduced upstream of the direct contact cooler. Exhaust gas leaves the HRSG and flows counter current to the CO_2-depleted gas, exiting the water wash section at the top of the absorber, in a bisector arrangement. The elements contained in the gas/gas heater baskets are heated in contact with the untreated flue gas subsequently cooled in contact with the treated CO_2-depleted gas. Sensible heat is therefore transferred from the former gas stream to the later. Further cooling is, however, necessary for the untreated gas stream and a direct contact cooler is still required.

3.3. Dry cooling system: gas/gas and air/gas heaters in series

The direct contact cooler is replaced by two consecutive regenerative heaters in a dry cooling system. The first gas/gas heater is used to transfer sensible heat from the exhaust flue gas to the CO_2-depleted gas, heating the second stream until the desired temperature. The gas/gas heater design is the same as in the previous configuration. In order to further reduce exhaust flue gas temperature, an additional air/gas rotary heater is used with ambient air as cooling fluid.

3.4. Dry cooling system: gas/gas/air heater in a tri-sector configuration

The two consecutive rotary heat exchangers in the previous configurations can be replaced by a single heater with a tri-sector arrangement. Exhaust flue gas coming from the HRSG flows in a counter current manner to the CO_2-depleted gas and air streams. It is important to select the direction of rotation of the heater so that the baskets turn from the exhaust flue gas section into the absorber outlet gas section and then the air section, in order to optimize the heat transfer and achieve a smooth temperature gradient of the elements before they enter into contact with the hot exhaust flue gas stream.

The analysis of these configurations in a NGCC plant with EGR has been limited to one cooling device, reducing therefore the flue gas temperature upstream of the recirculation, instead of having an additional cooling device in the recycling stream. The heater size is selected for the air-fired NGCC plant case and the analysis is then performed for a range of recirculation ratios.

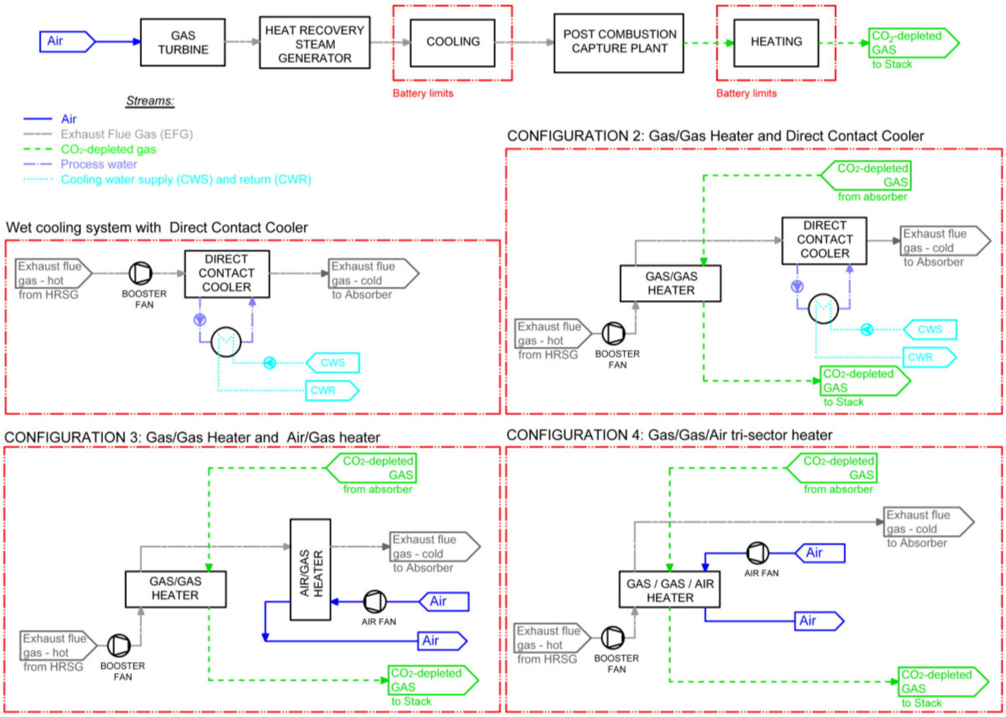

Fig.2. Block flow diagram of the different configurations in an air-fired natural gas combined cycle plant with post-combustion capture technology.

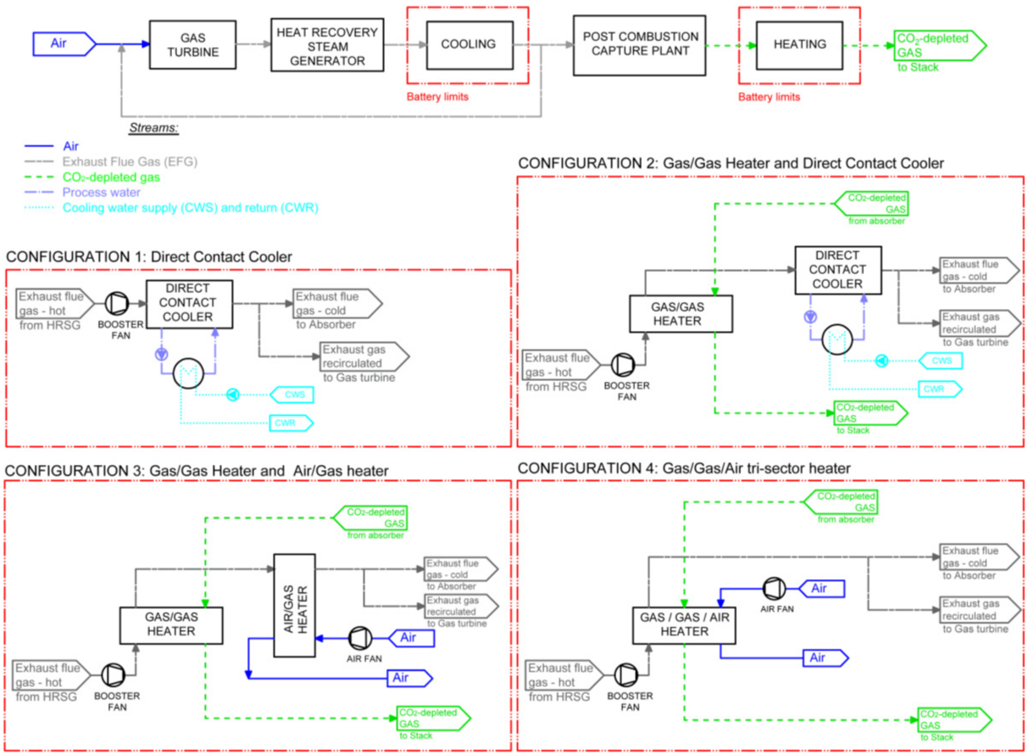

Fig.3. Block flow diagram of the different configurations in a natural gas combined cycle plant with exhaust gas recycling and post-combustion capture technology.

4. Booster fan and air fan

The integration of the post-combustion capture plant in a NGCC plant requires a booster fan to overcome the additional pressure drop in the gas pathway and, thus, avoid any negative effect of increasing the back pressure on the gas turbine exhaust. An increase in the gas turbine back pressure would limit the mechanical work achieved through the expansion of the gas and would lead to a reduction in the power output.

In a configuration with a direct contact cooler, the booster fan can be located upstream of the cooling device for a more accurate control of the temperature at the absorber inlet. Locating the booster fan downstream of the cooling device offers the advantage of a lower temperature and volumetric flow rate at the inlet of the fan, which results in lower fan power consumption [1].

In the configurations with rotary heat exchangers, the leakage level and the direction of the leaked flow in the rotary device play an important role in the selection of the booster fan position, in addition to the power consumption and temperature rise due to compression. In this work, the booster fan is located upstream of the regenerative heat exchanger (See Fig.2 and Fig.3). This position results in a higher pressure differential between the untreated gas and the treated gas side and, thus, larger leakage levels compared to the configuration in which the fan is located downstream of the cooling device. The temperature rise due to compression, however, occurs before the cooling process and the temperature at the cold end of the rotary heater can be higher. The larger the temperature difference at the cold end, the smaller the heating surface, which results in lower pressure drop and booster fan power consumption. Therefore, this location of the fan is preferable from the point of view of power consumption. Leakage can be mitigated with strategies relying on purge and scavenging gas streams. The purge and scavenge flows are tapped off from the treated gas outlet ducting and via a low leakage fan passes back, under positive pressure, to the purge and scavenge slots [13]. In configurations in which ambient air is used to further reduce the flue gas temperature, an air fan is required, with the purpose of overcoming the pressure drop through the rotary heater and pressure losses in the air ducts.

5. Engineering assessment

A thermal performance analysis of the rotary heat exchangers is conducted whilst dimensional and operational parameters are evaluated in order to assess the feasibility of each configuration. The results are compared with the traditional wet cooling system using a direct contact cooler and reported for one train consisting of one gas turbine, one heat recovery steam generation and one post combustion capture unit, of the reference NGCC plant with a 2-on-1configuration. Particular attention is paid to the reduction in process water usage and cooling water consumption and the booster and air fans power requirements. Key values are summarised in Appendix A and key findings are discussed below.

5.1. Reference plant and boundary limits

In the reference NGCC plant, the exhaust flue gas leaves the HRSG at 86 ºC and 101.3 kPa (see Appendix A). The booster fan, located upstream of the cooling device, increases the flue gas pressure by 10 kPa, resulting in a temperature rise of around 11 ºC. The exhaust flue gas is then cooled down until it reaches the dew point temperature. With EGR, the partial pressure of water vapor in the exhaust flue gas increases with the recirculation ratio and so does the dew point temperature. The CO_2-depleted gas leaves the water wash section at the top of the absorber saturated in moisture at a temperature of 45 ºC, in order to maintain the water balance in the column.

5.2. Thermal performance analysis and water management

5.2.1 Air fired NGCC plants

In the hybrid cooling system with a rotating heat exchanger and a direct contact cooler a treated gas outlet temperature above 80 ºC is achieved. The untreated gas leaving the gas/gas heater is further cooled down in a smaller direct contact cooler to reach a temperature of 43 ºC at the cold end. The lower amount of heat that needs to be removed from the exhaust gas results in a reduction of the cooling and process water consumption of 60% and 20% respectively, compared to the traditional configuration with a single direct contact cooler.

In the dry cooling system, where air cooling replaces the direct contact cooler, a further reduction of the overall process and cooling water used in the post-combustion capture plant is achieved. The two rotary heaters in series, a gas/gas heater and an air/gas heater using ambient air as cooling fluid, operates with an air mass flow rate of 350 kg/s to reach the desired flue gas outlet temperature of 43 ºC. The air temperature at the hot end reaches 54 ºC. The second configuration for the dry cooling system where the two heaters are combined into a single gas/gas/air heater with a trisector arrangement has the potential for large reduction in the overall size, heater footprint and capital cost. An air mass flow rate of 300 kg/s is required to reach an exhaust flue gas temperature of 43 ºC and a CO_2-depleted gas temperature of 77 ºC. The air stream is heated from ambient temperature, 15 ºC, up to around 70 ºC.

It is important to highlight that water condensation will occur on the heating elements of the rotary heaters when ambient is used for further cooling, if the exhaust flue gas outlet temperature becomes lower than the dew point, for a given pressure and water content. This would happen if, for instance, the system was operated with an ambient air temperature lower than 15 ºC. Appropriate material selection can mitigate possible long-term corrosion issues in the heating elements with the use of CORTEN steel and enameled elements.

5.2.1 NGCC with Exhaust Gas Recirculation

With EGR, the design of the cooling device is the same as the corresponding configuration with air firing. The results are shown in Fig.4 and Fig.5 for EGR ratio of 40%. This is the maximum recirculation ratio reported to be feasible with minor modifications in the combustor for the current state-of-the-art turbine technology [14]. As the EGR ratio is gradually increased from 0 to 40%, the water content in the exhaust flue gas leaving the HRSG increases since the absolute humidity of the recirculated stream is greater than that of the inlet air. The flue gas temperature at the outlet of the cooling device is closer to the dew point. For the wet cooling configuration with a direct contact cooler, the process and cooling water requirements thus decrease for increasing recirculation ratio.

In addition, the fraction of the gas to be treated in the capture plant becomes lower and the mass flow rate of the CO_2-depleted gas leaving the absorber decreases accordingly. Given that the latter stream takes heat from the exhaust flue gas, this has implications on the configurations with a gas/gas heater.

In the hybrid cooling system, the exhaust flue gas temperature at the cold end of the gas/gas heater increases, which leads to higher water flow rate requirements in the direct contact cooler. The CO_2-depleted gas outlet temperature however increases.

In the dry cooling system with a gas/gas heater and an air/gas heater in series, the temperature of the exhaust flue gas entering the air/gas heater increases and so does the temperature at the outlet of the air/gas heater for the same cooling air mass flow rate. For an air mass flow rate of 350 kg/s, the flue gas temperature at the inlet of the absorber remains, however, close to the dew point, which is the desired operating condition in this study. The saturation temperature is 49 ºC for a 40% recirculation ratio, compared to 43 ºC for the air fired cases. An increase of the recirculation ratio has the same effect in the trisector gas/gas/air heater configuration. The increment of the exhaust flue gas temperature at the cold end with the recirculation ratio, compared with the air fired NGCC plant, is lower than in the previous configuration, and becomes less significant at larger cooling air flow rates. For an air mass flow rate of 300 kg/s, the EFG temperature at the cold end remains close to the dew point. The CO_2-depleted gas outlet temperature and the air outlet temperature increase at large recirculation ratios, providing a positive effect to enhance stack buoyancy.

The process water usage, the cooling water consumption and the cooling air requirements for both an air-fired NGCC plant and a NGCC plant with exhaust gas recirculation at 40% recirculation ratio are summarized for comparison in Fig. 4. The heater dimensions, gas streams temperatures and operational parameters are included in Table 1.

One important consideration for this application is the management of untreated gas leaked flow into the treated gas stream, which has an impact on the overall CO_2 removal of the capture system. Leaked flow rate obtained in these configurations of around 3.5% of the inlet untreated gas mass flow can be significantly mitigated with strategies relying on purge and scavenger flows. Leakage levels as low as 0.5% would result in a marginal reduction of the overall CO_2 removal rate, e.g. by 0.45% point for an absorber designed for 90% capture.

5.3. Fans power consumption

The power consumption associated with the booster fan, air fan and water pumps is shown in Fig. 5 for an air-fired NGCC plant and a NGCC plant with EGR. Results are reported for one single train gas turbine – HRSG – carbon capture unit in the NGCC plant. The pressure drop through the absorber column with structured packing and through gas ducts was assumed around 5 kPa and 2.5 kPa respectively [1]. These values are reported in literature for a system to treat the exhaust flue gas stream from a NGCC plant similar to the reference plant in this study and are fixed for all configurations. It is important to highlight that a dry cooling system with a trisector gas/gas/air heater replaces the direct contact cooler with minimum pressure drop and, thus, it has lower power consumption, compared to a configuration with two rotary heaters in series. As the recirculation ratio is increased, the CO_2-depleted gas flow rate is reduced and so is the pressure drop through the rotary heaters, which results in lower booster fan power consumption. In the wet and hybrid cooling configurations, the power consumption associated to the cooling water pumps was also calculated, with the assumptions shown in Appendix B, Table B.1. The resulting value was of similar order of magnitude as the power consumption associated to the air fans in the dry-cooling configuration.

Table 1. Summary of the results: Rotary heaters basic design and operational parameters (per GT-HRSG-absorber train).

	Heating surface area	**Inlet / Outlet temperature**	**Hot End Velocity**	**Pressure drop**	**Cooling air mass flow rate**
	m^2	**ºC**	**m/s**	**kPa**	**kg/s**
CONFIGURATION 1: air firing natural gas combined cycle					
Gas/gas heater and direct contact cooler	GGH 33019	UTG [1] 97.5 / 62.6 TG [2] 45 / 82.3	UTG 13.5 TG 12.9	UTG 1.19 TG 1.15	N/A
Gas/gas heater and air/gas heater	GGH 33019 AGH 22985	UTG 62.6 / 43.6 AIR 15 / 54	UTG 14.63 AIR 7.61	UTG 1.32 AIR 0.75	350
Gas/gas/air trisector heater	77046	UTG 97.5 / 43.6 TG 45 / 77 AIR 15 / 71.1	UTG 11.8 TG 11.87 AIR 8.45	UTG 1.32 TG 1.47 AIR 0.88	300
CONFIGURATION 2: natural gas combined cycle with exhaust gas recirculation (EGR ratio 40%)					
Gas/gas heater and direct contact cooler	GGH 33019	UTG [1] 97.5 / 73.7 TG [2] 45 / 91.6	UTG 13 TG 7.1	UTG 1.32 TG 0.37	N/A
Gas/gas heater and air/gas heater	GGH 33019 AGH 22985	UTG 73.7 / 49.55 AIR 15 / 62.9	UTG 14.63 AIR 10.72	UTG 1.55 AIR 0.95	350
Gas/gas/air trisector heater	77046	UTG 97.5 / 47.5 TG 45 / 85.5 AIR 15 / 82.4	UTG 11.34 TG 6.57 AIR 8.68	UTG 1.26 TG 0.475 AIR 0.902	300

Note 1: Exhaust flue gas and untreated gas (UTG) are used indistinctly here.

Note 2: CO_2-depleted gas and treated gas (TG) are used indistinctly here

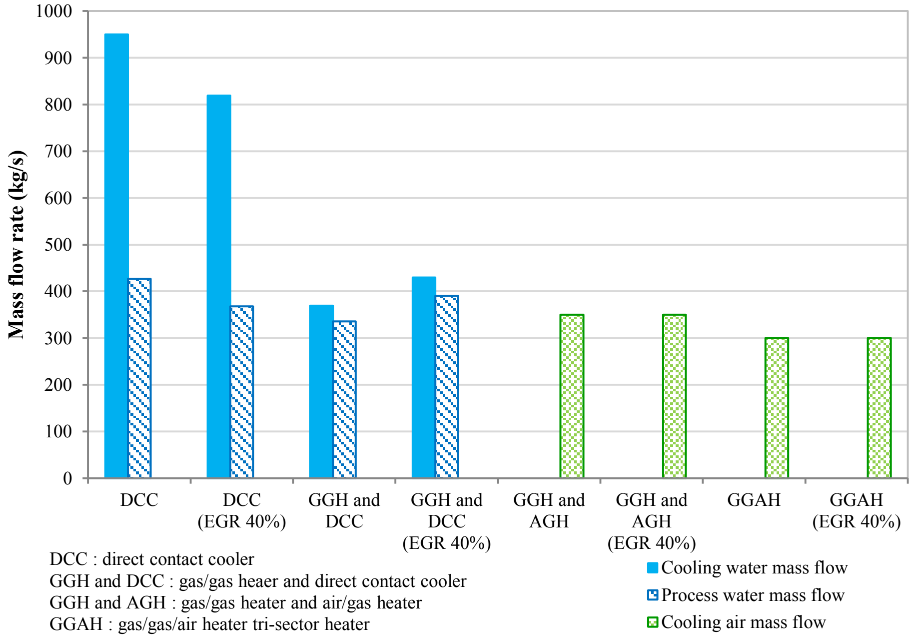

Fig.4. Cooling water, process water and cooling air mass flow per net power output required for each configuration, within the boundary limits, in an air-fired natural gas combined cycle plant and a natural gas combined cycle plant with exhaust flue gas recirculation (40% recirculation ratio), both with post-combustion capture technology (per GT-HRSG-absorber train).

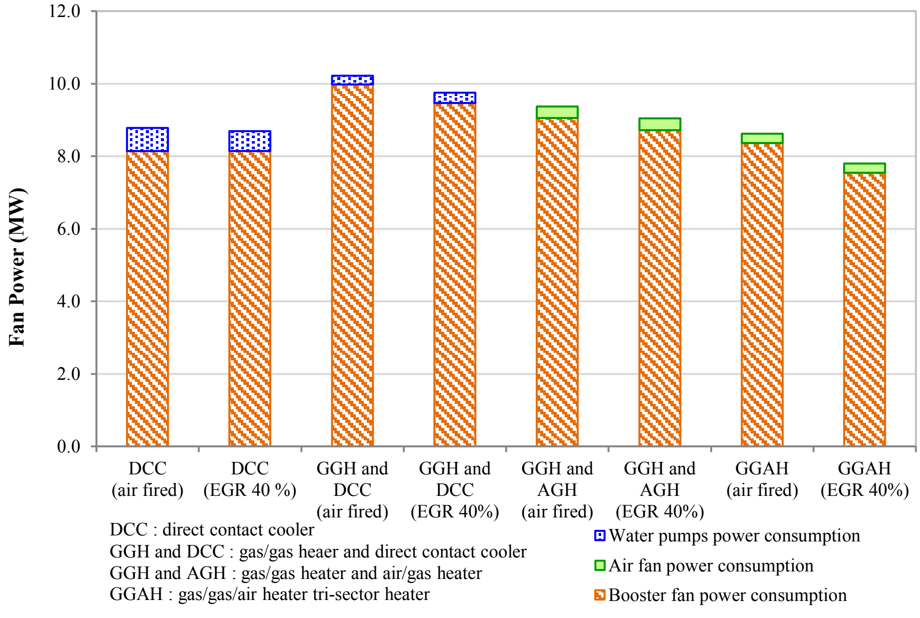

Fig.5. Booster fan, air fan, cooling and process water pumps power consumption, in an air-fired natural gas combined cycle plant and a natural gas combined cycle plant with exhaust flue gas recirculation (40% recirculation ratio), both with post-combustion capture technology (per GT-HRSG-absorber train).

6. Conclusions

This work investigated the feasibility of introducing a dry cooling system based on rotary wheel technology in order to meet the cooling requirements in the exhaust flue gas stream prior to the absorber and reheat the CO_2-depleted gas leaving the water wash section at the top of the absorber before it is released into the atmosphere through the stack of the plant. The aim was to replace the direct contact cooler typically used for amine based scrubbing technology, with a consequent reduction in the overall process water usage and cooling water consumption. For this purpose, three configurations using rotary heat exchangers were studied and compared with the wet cooling system taken as reference. Thermal performance analysis of the rotary heaters was conducted using a proprietary software developed by Howden Group (H-112).

A hybrid system with a gas/gas heater and a smaller direct contact cooler to transfer heat from the exhaust flue gas into the CO_2-depleted gas reduced cooling water consumption by 60% compared to a configuration with a single larger direct contact cooler. Stack temperature in excess of 70 ºC and a temperature around 43 ºC at the inlet of the absorber can be obtained.

A dry cooling system using ambient air instead of water as the cooling fluid shows good performance for a mass flow rate of air of respectively 350 kg/s and 300 kg/s when two rotary heaters are in series and when the two rotary heaters are replaced by a single gas/gas/air heater with a trisector arrangement. The fan power associated with the additional air flow rate is of the same order of magnitude as the water circulation pumps of a direct contact cooler (< 0.5 MW). Water savings with the removal of the direct contact cooler consists of water withdrawal used for process water and water consumption for cooling water. The latter is typically of the order of 30% of water consumption in the rest of the plant, mostly used for the power cycle condenser.

One important consideration for this application is the management of leakage levels, which have an impact on the overall CO_2 removal of the capture system. Leakage level can be mitigated with purge and scavenge gas techniques to levels as low as 0.5% of the total untreated mass flow entering the hot side of the heater. This would result in a marginal reduction of the overall CO_2 removal rate, e.g. by 0.45% point for an absorber designed for 90% capture.

A similar thermal performance analysis was also conducted for a NGCC plant with exhaust gas recirculation, for the same design of rotary heaters as in the air-fired case. As the recirculation ratio increases, the amount of flue gas to be treated in the absorber and the CO_2-depleted flow rate decrease, which results in a reduction of the overall cooling capacity at constant heating surface area in the rotary device. In addition, the buoyancy of the flue gas entering the stack is higher.

The dimensions of the rotary heat exchangers selected in each configuration did not significantly vary the pressure drop in the system, compared to the wet cooling system. A dry cooling system using a single gas/gas/air heater with a trisector arrangement resulted in a more compact design, with lower booster fan power consumption, smaller foot print and, potentially, lower capital cost compared with the configuration with two rotary heaters in series. Additionally, it allows for a more constant exhaust flue gas temperature at different recirculation ratios. The additional cooling air fan power consumption in the dry cooling system was relatively small and equivalent to the reduction in the overall water pumps power requirements when the direct contact cooler is replaced.

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Appendix A. Reference natural gas combined cycle power plant

The reference plant is an 800 MWe air-fired natural gas combined cycle (NGCC) with a 2-on-1 configuration: two GE937IFB gas turbines with the flue gas exiting into two HRSGs, which jointly supply steam to a subcritical triple pressure steam cycle. The gas turbine operates at a turbine inlet temperature (TIT) of 1371 ºC and air fuel ratio (AFR) of 40.5 on mass basis, at ISO atmospheric conditions and 100% load, with a power output at coupling of 285 MWe. In a combined cycle, the remaining heat contained in the exhaust flue gas is partially recovered to generate steam at three pressure levels. In this work, the flue gas is assumed to leave the HRSG at a temperature of 86 ºC [1]. Flue gas is cooled down before entering the absorber. In the absorption column, the inlet and outlet temperature are typically kept close in order to maintain the water balance in the absorber column. The gas composition at outlet is then calculated assuming a removal ratio of CO_2 of 90% and that gas leaves the water wash section saturated at a temperature of 45ºC. Stream variables are shown in Table A.1 and Table A.2 for a single gas turbine – heat recovery steam generator – absorber unit train. The electricity output penalty of capture and compression in the air-fired NGCC and the NGCC with EGR is not considered in the scope of this work.

Table A.1. Exhaust flue gas stream information at HRSG outlet at different recirculation ratios (per GT-HSRG-absorber train).

EGR ratio		0	10	20	30	40	50
Temperature	ºC	86.00	86.00	86.00	86.00	86.00	86.00
Pressure (HRSG outlet)	kPa	101.30	101.30	101.30	101.30	101.30	101.30
Dew Temperature	ºC	41.48	43.34	45.03	46.61	48.08	49.47
Pressure (Fan outlet)	kPa	111.30	111.30	111.30	111.30	111.30	111.30
Dew Temperature	ºC	43.25	45.13	46.85	48.45	49.94	51.35
Mass flow rate	kg/s	660.17	652.94	646.27	640.23	635.01	630.92
Molar flow rate	mol/s	23177	22959	22751	22551	22361	22180
MW	g/mol	28.48	28.44	28.41	28.39	28.40	28.45
Composition							
CO_2	%vol	4.17%	4.64%	5.24%	6.02%	7.06%	8.55%
H_2O	%vol	7.85%	8.66%	9.46%	10.25%	11.05%	11.85%
N_2	%vol	75.01%	74.73%	74.55%	74.50%	74.65%	75.12%
O_2	%vol	12.07%	11.08%	9.86%	8.34%	6.35%	3.58%
Ar	%vol	0.90%	0.90%	0.89%	0.89%	0.89%	0.90%

Table A.2. CO_2-depleted gas stream information at absorber outlet, at different recirculation ratios (per GT-HSRG- absorber train).

EGR ratio		0	10	20	30	40	50
Temperature	ºC	45	45	45	45	45	45
Pressure	kPa	106.30	106.30	106.30	106.30	106.30	106.30
Mass flow rate	kg/s	618.31	603.57	588.43	572.51	555.14	535.17
Molar flow rate	mol/s	22108	21603	21089	20554	19978	19327
MW	g/mol	27.97	27.94	27.90	27.85	27.79	27.69
Composition							
CO_2	%vol	0.44%	0.49%	0.57%	0.66%	0.79%	0.98%
H_2O	%vol	7.33%	7.36%	7.41%	7.47%	7.55%	7.67%
N_2	%vol	78.64%	79.42%	80.42%	81.74%	83.55%	86.20%
O_2	%vol	12.66%	11.77%	10.64%	9.15%	7.11%	4.11%
Ar	%vol	0.94%	0.95%	0.96%	0.98%	1.00%	1.03%

Appendix B. Assumptions

Table B.1. Assumptions

AMBIENT AIR ISO CONDITIONS		
Temperature	ºC	15
Pressure	bar	1.013
Relative humidity	%	60
DIRECT CONTACT COOLER		
CWF Temperature [1]	º C	22
DCC Bottom temperature differential with air cooling [1]	º C	46
DCC Bottom temperature differential with EGR	º C	23
DCC Cooler temperature pinch [1]	º C	7
Cooling water temperature rise [1]	º C	10
PUMPS		
Efficiency [7]	%	75
Process water pump head [7, 15]	m	57
Cooling water pump head [7, 15]	m	26
Pump electric power to Cooling duty ratio	%	0.8
FANS		
Efficiency	%	85
Absorber pressure drop [1, 4]	kPa	5
Ducts pressure drop	kPa	2.5
Direct contact cooler pressure drop [1, 4]	kPa	3
ROTARY HEAT EXCHANGERS [12]		
Rotor speed	rpm	0.75 - 1
Element metal thickness	mm	0.75
Enamel metal thickness	mm	0.3

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