[1,2]Václav NOVOTNÝ, [1]Michal KOLOVRATNÍK

EXPANSION COOLING WITH POWER RECOVERY FOR DEWATERING OF CO_2 STREAMS FROM OXYFUEL CCS SYSTEMS

[1] Faculty of Mechanical Engineering, Czech Technical University in Prague, Prague, CZECH REPUBLIC
[2] University Centre for Energy Efficient Buildings, Czech Technical University in Prague, Bustehrad, CZECH REPUBLIC

Abstract: Carbon capture and storage (CCS) is one of the concepts some put hopes into for mitigation of climate change by separating CO_2 from power plant's flue gases and disposing (or utilizing) it. In the CCS systems with oxyfuel combustion the major advantage is considered to be fact, that the CO_2 stream contains only very few admixtures of other gases. This fluid however still contains significant amount of water which has its origin mainly in combustion of hydrogen content of fuels. This water needs to get separated from the mixture before CO_2 transport and storage. Typical concept for dewatering of the fluid is collection of the condensed liquid phase during cooling after each compression stage. The method for this collection is then use of flash tanks. Alternative method to obtain the liquid phase of the water so that it can be separated from the CO_2 stream is cooling, which can be well realized by the fluid expansion. This concept is still very new and hasn't been properly explored yet. In this work will be analysed one of possible configurations in which a stream CO_2-water mixture in vapour phase (simplified state of the oxyfuel flue gas) is expanded to a lower pressure, condensed phase is separated and CO_2 at higher purity is compressed back to previous near-ambient state. For this configuration there are presented results of separation effectiveness and power consumption as a function of inlet water fraction, expansion method (valve or expander with varying efficiency) and various methods for evaluation of the fluid properties. These results find its place in future and more rigorous analyses of these systems.
Keywords: CCS, two phase, expansion cooling, fluid property formulation

INTRODUCTION

The world is facing climate change in which the anthropogenic contribution has been linked primarily to CO_2 emissions as these can be easily quantified and tied with large producers as is a power production sector. Regardless the clear answer of the anthropogenic contribution in comparison to natural ones, large part of the world with many countries have signed the Paris agreement in hopes to fight the climate change and have committed to reduce greenhouse gas emissions. [1] Ultimate goal is to keep the average global temperature rise below 2°C when compared to the pre-industrial era [2].

Carbon capture and storage (CCS) is one of the concepts for decarbonisation. CCS technologies greatly reduce efficiency of power plants by consuming electricity in number of auxiliary systems and converting useful heat into a waste heat. [3] Regardless the fact that these systems actually use higher amounts of fuels, CCS systems enjoy large funding throughout the countries and many believe that it has a potential to play a significant role in the future of power generation in Europe, at least in a short to intermediate term. Reason is that it enables continuing of using mainly fossil fuels, which are to remain an important source for fuel and electricity production. In attempts to reduce amounts of CO_2 from the atmosphere there are also concepts of bio-CCS where biomass (relatively renewable) fuel is used and the CO_2 as a combustion product is captured and disposed underground so that it doesn't return into the atmosphere.

CCS systems are typically distinguished into three main principles of capture – precombustion (captures CO_2 before combustion via gasification and typically absorption), post-combustion (separates CO_2 from the flue gases) and oxyfuel combustion, which by combustion with pure oxygen the flue gas consists mostly of CO_2 with only very few admixtures of other gases. This fluid however still contains significant amount of water which has its origin mainly in combustion of hydrogen as a part of the fuel composition and especially in case of biomass. Extraction of water from the CO_2 stream is important not only to limit ballast carried in the stream for sequestration but also from more practical reasons. The most important aspect is that the water content causes serious corrosion of the transport and sequestration piping and equipment. Therefore, excluding water from the system is beneficial as soon as possible. [4]–[7]

Typically for the dewatering of the CO_2 are considered two methods. First one is collection of the condensed liquid phase during cooling after each compression stage. The method for this collection is using of flash tanks at the outlet of the cooling heat exchangers. Alternative method to obtain the liquid phase of the water so that it can be separated from the CO_2 stream is cooling. Refrigeration system is then a typical approach.

In this work will be explored and alternative method of CO_2 separation by cooling, where this cooling would be achieved by the fluid expansion. This concept is still very new and hasn't been properly explored yet. In this work will be analysed a configuration in which a stream CO_2-water mixture in vapour phase (simplified state of the oxyfuel flue gas) is expanded to a lower pressure, condensed phase is separated in a flash tank and CO_2 at higher purity is compressed back to previous near-ambient state. It needs to be noted that this is only a first analysis putting some first light into this concept and its results will be used in future analyses.

METHODS

The whole concept is depicted in Figure 1. The CO_2 rich fluid at approximately ambient pressure will most likely be in a state of saturation with water or in case of oversaturation the liquid phase is assumed to be separated before inlet into the considered system. Therefore the inlet stream is considered to be in a saturation state and as so is routed into the expander. Expansion takes place to a pressure so that the temperature of the mixture is at 3°C (not lower to limit possible freezing issues). By the temperature decrease the water condenses and is separated from the CO_2 in a subsequent flash drum. Separated liquid is pumped to a pressure required for its treatment. Finally the CO_2 is compressed, in this illustrational case back to ambient pressure in a single stage of compression.

Boundary conditions common to all explored configurations are inlet and outlet pressures (100 kPa), unit mass flow (1 kg/s) of the inlet flue gas and temperature after the expander of 3°C. Pressure drop across the flash drums is neglected. No dynamic effects are assumed the fluid in all processes is assumed to be in thermodynamic equilibrium.

The process was modelled in AspenPLUS software with isentropic efficiency specification for both, expander and the compressor. Baseline case assumes a 2% H_2O content in CO_2 (by mass) and at saturation state (35°C flue gas temperature). Here the baseline concentration was chosen with respect to temperature around 35°C to which the flue gas can be cooled without needs for refrigeration.

Further baseline parameters include 80% isentropic efficiency of both expander and the compressor and Peng-Robinson (PR) equation of state for determination of fluid properties. The other equations of state were chosen as potentially suitable for given system and these are Soave-Redlich-Kwong (SRK, note that here vapour-liquid-liquid equilibrium was necessary at turbine outlet for proper operation), non-random two-liquid model (NRTL), Peng-Robinson-Wong-Sandler (PRWS), Predictive Soave-Redlich-Kwong (PSRK) and Schwarzentruber and Renon (SR-POLAR).

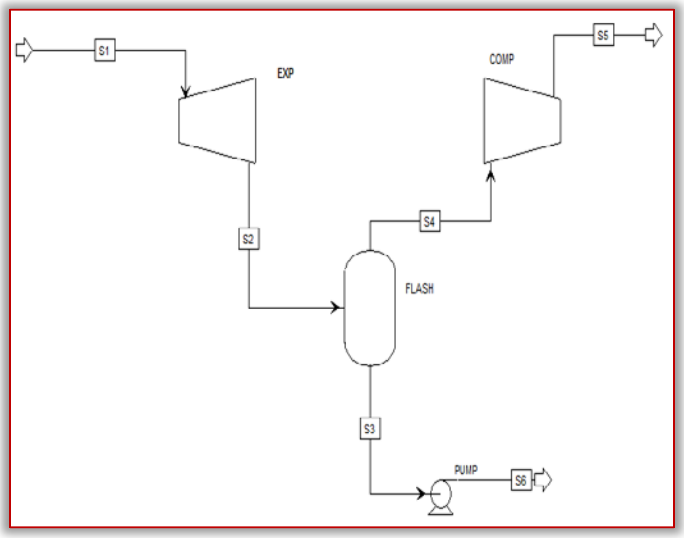

Figure 1: A process diagram of the proposed dewatering concept for CCS systems

RESULTS AND DISCUSSION

Table 1 shows a whole set of explored varieties of the parameters. The m stands for mass fraction, x for quality, T for temperature, p for pressure, and W for work. The rate of power consumption increase can be observed from decreasing in isentropic efficiency of expander and compressor. More detailed design is necessary to validate actually achievable efficiency. Another issue that can be seen from the results is a discrepancy between various fluid property definitions while some are in decent agreement. This is a recognized issue in the CCS community where certain effort is being focused to specifications of CO_2 mixture properties which would provide required accuracy.

Graphically is in Figure 2 shown a dependency of outlet water fraction as a function of inlet water fraction from which is seen only slightly nonlinear dependency, where the decrease of water content is approximately to half in low H_2O contents but reaches almost 90% for the highest considered concentration.

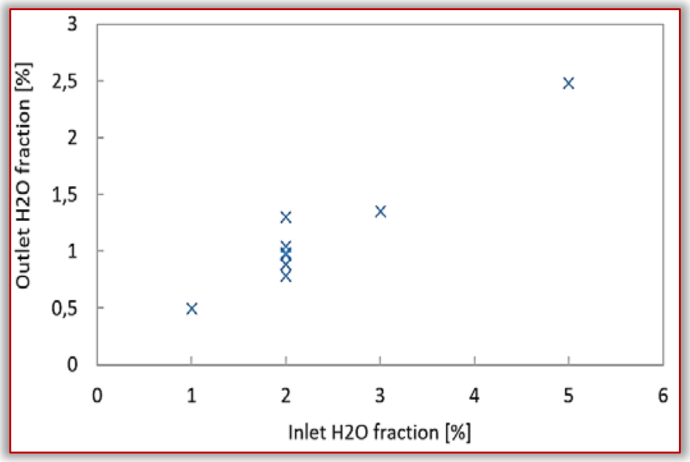

Figure 2: A dependency of outlet water fraction as a function of inlet water fraction for all explored cases

The net power consumption to separated amount of water should be compared in future work to the results of conventional systems (in separation after each stage of compression and cooling then with the whole compression line) to assess actual feasibility of this system.

Alternatively this system could be inserted also into a later stage of the compression line or if combustion would take place at significantly elevated pressures with perspective of better dewatering. It could also be suitable to use multiple stages of compression with intercooling to limit compression work. Numbers of possible modifications are large (e.g. final cleaning after upstream systems, multiple stages or multiple numbers of these systems across the plant) and for a feasible application a much of work with a careful optimization seems to be necessary. One specific aspect is an actual temperature and water content of the inlet, which is yet to specified to provide best performance with combination of flue gas treatment and heat rejection methods.

This concept seems also very suitable for smaller units as will be exactly for biomass as it is widely accessible but quantity related to specific location is significantly smaller than in case of fossil fuels. Typical issue with CO_2 systems is small volumetric flow, which on the one hand causes devices to be small, on the other hand expanders and compressors suffer from tip, aspect ratio and similar losses. Expansion into vacuum might provide better compressor and expander efficiency than at higher pressures.

Table 1: Explored cases of expansion-compression dewatering

$m_{H2O\ in}$	T_{in}	η_{exp}	η_{comp}	Method
[%]	[°C]	[%]	[%]	[-]
5	51	80	80	PR
3	42	80	80	PR
2	35	80	80	PR
1	24	80	80	PR
2	35	65	80	PR
2	35	50	80	PR
2	35	80	65	PR
2	35	80	50	PR
2	36	80	80	SRK
2	32	80	80	NRTL
2	32	80	80	PRWS
2	32	80	80	PSRK
2	32	80	80	SR-POLAR

$p_{exp\ out}$	$x_{exp\ out}$	$m_{H2O\ out}$	W_{exp}	W_{comp}	W_{net}
[kPa]	[%]	[%]	[kW]	[kW]	[kW]
9,5	94	2,48	105	-208	-103
18	96	1,35	74	-140	-66
28	97	0,88	54	-99	-45
50	99	0,49	29	-50	-21
23	98	1,04	50	-117	-67
19	98	1,3	43	-136	-93
28	97	0,88	54	-122	-68
28	97	0,88	54	-158	-104
26	97	0,78	59	-105	-46
32	98	0,98	49	-88	-39
32	98	0,97	48	-87	-39
32	98	0,97	49	-87	-38
32	98	0,97	49	-87	-38

In specifically considered expander concepts, separation of liquid phase could already take place within the expander, thus flash tank separator would be substituted by integrated rotation (or generally centrifugal) one.

CONCLUSIONS

This paper gives first theoretical results for a novel approach for water separation from CO_2 streams in CCS systems. The system is based on expansion cooling of the fluid for decreasing the temperature and thus condensing the water. Water separation in operation under the assumed condition takes place but still there is non-negligible amount of water remaining in the CO_2 streams. Even though this concept might be interesting for CCS systems after a careful optimization and placement into a specific points within the process. Energy and economic comparison of this system with regular ones is a subject of future work. Another concept worth exploring is placing this system into the areas of higher pressures with potential to separate more water from the CO_2 stream.

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