

Aftercooler for Efficiency Improvement of Decarbonizing Steam Generator

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The Energy Research Center in co-operation with Vitkovice Power Engineering Ltd. designed and tested a new device which can serve as an integral part of a zero emission combined cycle with the CES combustor. In the primary circuit of the decarbonizing steam generator condensation of steam and separation process take place at increased pressure (approx. 3-6 bar). The released heat is transferred to the secondary circuit where a pure low-pressure steam is produced.

The experimental runs proved that effective separation is possible even at low temperature gradient caused by high concentration of CO₂ which prevents steam from reaching the heat transfer surface. Nevertheless some additional upgrades were required in order to utilize relatively substantial amount of waste heat in exiting mixture. This is a possible way how to improve CO₂ purity and thermal efficiency of the separator, thus another supporting exchanger has been installed directly behind the separator for the purpose of feedwater preheating. This so-called aftercooler was made in two variations in order to investigate effect of flow regime and surface arrangement on intensity of heat transfer between the mixture and feedwater. The article presents results of performance of the separator with the aftercooler at various mixture compositions and pressure differences.

1. Introduction

Carbon dioxide capture and separation from large point sources, such as power plants, can be achieved through three main pathways: pre-combustion, post-combustion, and oxy-fuel combustion. Pre-combustion and post-combustion capture options use physical or chemical solvents to separate and capture CO₂, whereas in oxy-fuel combustion capture and compression are achieved using a physical separation process.

Post-combustion method offers great opportunity to reduce CO₂ emissions because it can be built in to existing power plants without considerable modification. The most common solvents are amines which adsorb CO₂ from the flue gas. To drive off the CO₂ from the solvent it is necessary to deliver heat which increases energy cost about 30 % in comparison with a plant with no capture (Harkin et al. 2009). The process works well at atmospheric pressure and relatively low CO₂ concentrations (5-15 % by vol.) but degrades with presence of impurities (e.g. NO_x, SO₂).

Oxy-fuel combustion represents a suitable solution to this issue because oxygen instead of air is used, thus eliminating nitrogen from the flue gas stream. Currently, there is third generation of oxy-fuel systems, where the gaseous or liquid fossil fuel is combusted without flue gas recycling. The temperature moderator employed is either water or steam which results in a working fluid consisting mainly of water vapour and CO₂ (approx. 15 % by weight). Typical representatives of this concept are the CES cycle (Anderson and Viteri 2003) and the Graz cycle (Jericha and Fesharaki 1995) with CO₂ separation taking place in a condenser. Extra energy is needed in order to evacuate the condenser and compress CO₂ to transport pressure. This alone requires the equivalent of 2 per cent of the generation efficiency of the power plant (Damen et al. 2006).

The paper presents a novel component suitable for above mentioned cycles in which separation by condensation process takes place at increased pressure. This so-called decarbonizing steam generator (DSG) has been designed and tested at the Energy Research Center, Technical University of Ostrava.

2. Experimental work

2.1 Test facility

The intensity of heat and mass transfer during the condensation of steam from the steam-CO₂ mixture (SGM) were investigated on the experimental apparatus schematically shown in Figure 1. The main parts are: steam generator, gas supply line, mixing chamber, test section, feed water supply and data acquisition system.

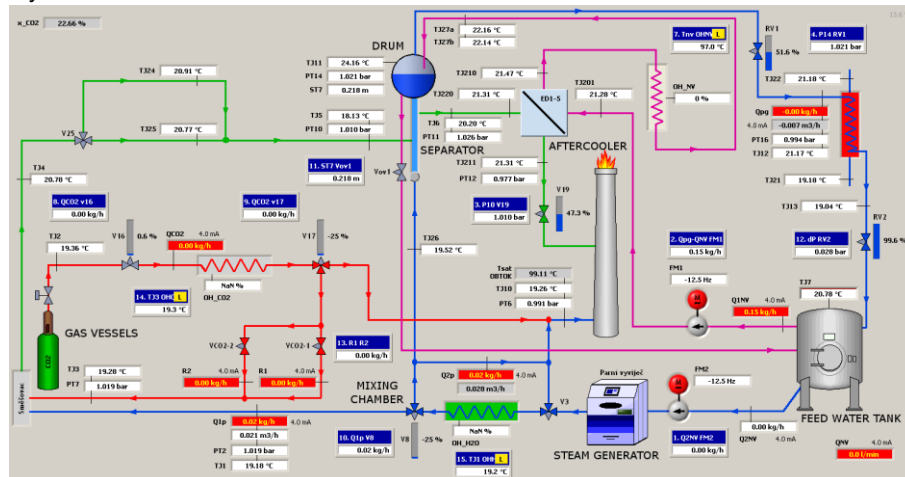


Figure 1: Test facility layout

The central element of the facility is the decarbonizing steam generator. The DSG was designed as a vertical tubular evaporator with natural circulation, surrounded by a steel shell defining the primary circuit. The SGM at the saturation temperature is introduced at the bottom of the primary circuit and then directed transversely towards the evaporation tubes by built-in barriers. In contact with the cooled surface the process of film-wise condensation begins. Drainage of condensate from the tube surface provides built-in baffles, which also prevent the growth of the condensate film thickness, which significantly reduces the intensity of heat transfer. The latent heat released during condensation is transferred through tube walls of the evaporator to the secondary circuit where boiling of saturated feed water takes place. The resulting steam-water mixture (SWM) is guided to a drum located outside the exchanger, where low-pressure steam is accumulated.

The condenser is divided into six sections, each with an identical surface area in order to experimentally investigate heat transfer coefficients and the rate of condensation in various parts of the condenser (Nevriva et al., 2009). For this purpose the DSG was equipped with a measurement system, including a platinum resistance thermometer at the beginning of each section, a set of thermocouples under and over the insulation surface for heat loss calculation and an ultrasonic flow meter for estimation of circulation ratio of the steam-water mixture.

For better waste heat utilization and higher purity of CO₂, an aftercooler was installed directly behind the DSG, serving as feed water preheater. The aftercooler was made in two variations in order to investigate the effect of flow regime and surface arrangement on intensity of heat transfer between the working fluids.

3. Performance testing

The experimental work included 120 runs with steam-CO₂ mixture at test conditions listed in Table 1, which were determined by expected parameters of the mixture expanded in HP (IP) turbine of the CES cycle. The range of inlet CO₂ mass fraction was chosen to cover possible composition of the mixture generated in the CES combustor. To obtain reliable data, the SGM flow rate, composition and pressure on the primary side and the SWM pressure and feed water temperature on the secondary side were kept constant during each test.

At these conditions, the complete condensation never occurred and outlet CO₂ mass fraction was specified by the following methods: 1) mass balance, 2) temperature measurement of the outlet mixture, 3) infrared spectroscopy.

Table 1: Test conditions

Parameter	Range
Primary side (steam-gas mixture) pressure [bar]	3-6
Mixture inlet flow rate [kg/h]	73
NC inlet mass fraction [%]	5-15
Secondary side (steam-water mixture) pressure [bar]	2.1-4.9
Steam production [kg/h]	28-54

4. Results and discussion

On the basis of the known quantity of condensed steam in each section of the DSG, it is possible to carry out an analysis involving energy balance which is needed in order to calculate the amount of heat transferred to the secondary circuit for low-pressure steam production. As condensation progresses, the mass fraction of CO₂ in the mixture rises and the partial pressure of steam and its corresponding saturation temperature decreases (Figure 2).

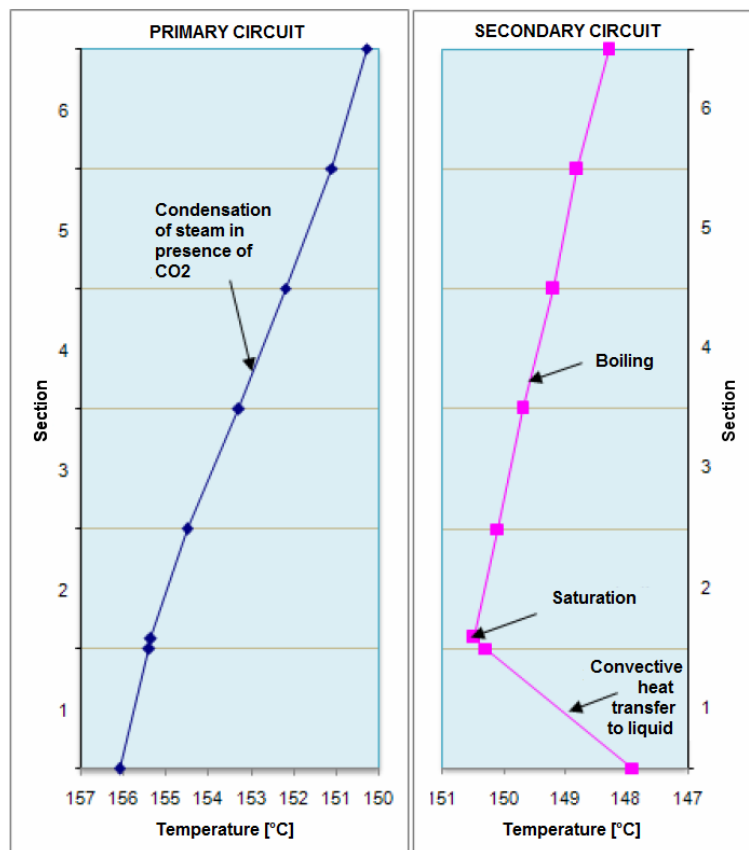


Figure 2: Temperature profile in the DSG

Since the temperature at which boiling occurs varies very slightly only because of hydrostatic pressure, the temperature difference representing heat transfer driving force is reduced along the surface of the DSG (divided into 6 sections, Figure 3).

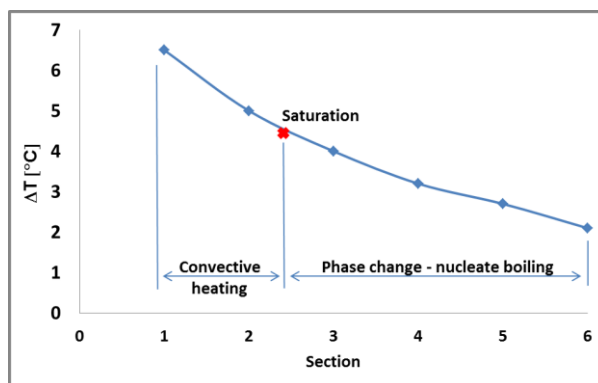


Figure 3: Temperature difference between fluids

About 98 % of heat load comes from the latent heat of steam, whereas a minor portion comes from the sensible heat of the mixture. Its distribution along the DSG is depicted in Figure 4. Although all the sections have an equally large heat transfer surface area, the last two sections work considerably inefficiently, which is in addition to the above-mentioned reasons, caused by a significant decrease in flow rate resulting in a substantial reduction in velocity and attenuation of the intensity of heat transfer.

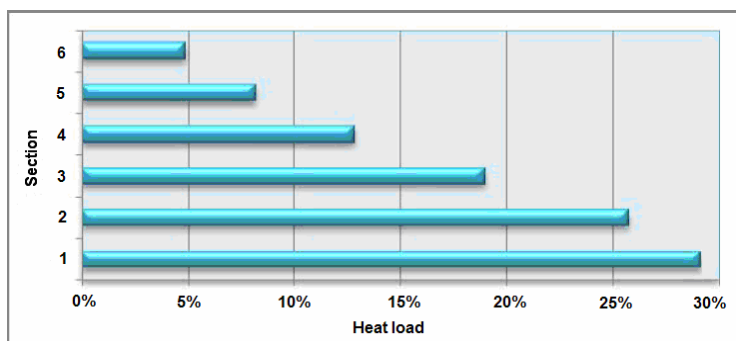


Figure 4: Heat load distribution in the DSG

The impact of the pressure on efficiency of utilization of heat released during the separation process and used for pure low-pressure steam production for a case of 15 % inlet CO₂ mass fraction is shown in Figure 5. The low pressure of the SGM has a positive influence on the utilization of heat which is most obvious at 1 bar pressure differences between working fluids where the recovery efficiency differs almost by 30 %.

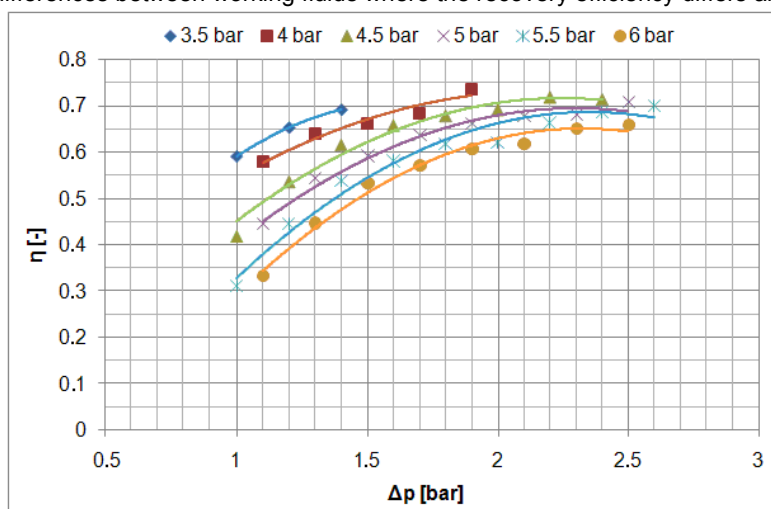


Figure 5: Heat recovery efficiency (15 % inlet CO₂)

To evaluate the performance of the DSG, the term condensation efficiency was defined as the ratio of total mass flow rate of condensed water to the incoming mass flow rate of water vapour in the mixture on the DSG inlet. The effect of CO₂ on the condensation efficiency is shown in Figure 6, which confirms theoretical assumptions referring to the deterioration of the heat transfer coefficients due to resistance for steam to diffuse from the bulk to the condensate film adjacent to vertical tubes of the DSG.

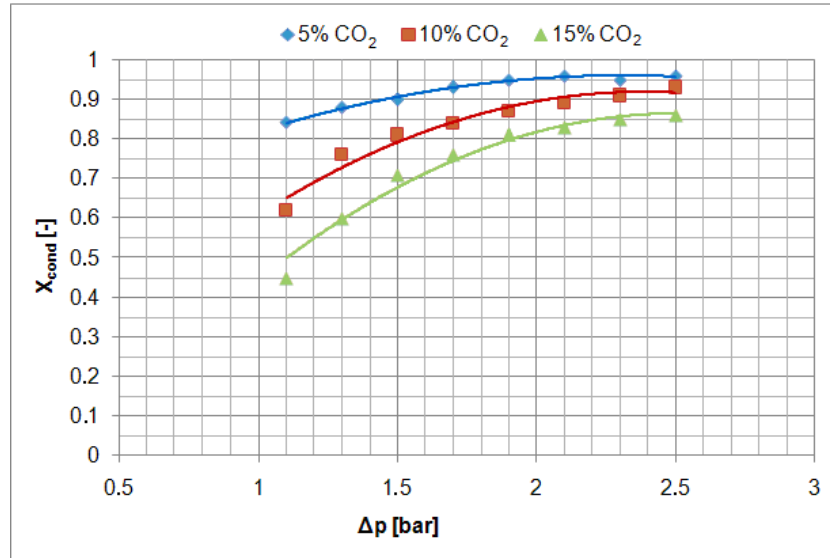


Figure 6: Condensation efficiency (15 % inlet CO₂)

The condensation efficiency of a mixture with 5 % CO₂ at 6 bar and 1 bar pressure gradient is 84.2%, whereas in case of a mixture with 15 % CO₂ it is only 44.8 %, which results in a nearly 50 % reduction in heat output. This dramatic decline is depressed with increasing pressure gradient and for Δp 1.9 bar difference in the heat output is only 17 %.

The outlet CO₂ mass fraction in the SGM has a weak dependence on the inlet composition of the mixture. An effect of higher inlet concentration of CO₂ is offset by a lower volume of condensed water vapour as illustrated in Figure 7.

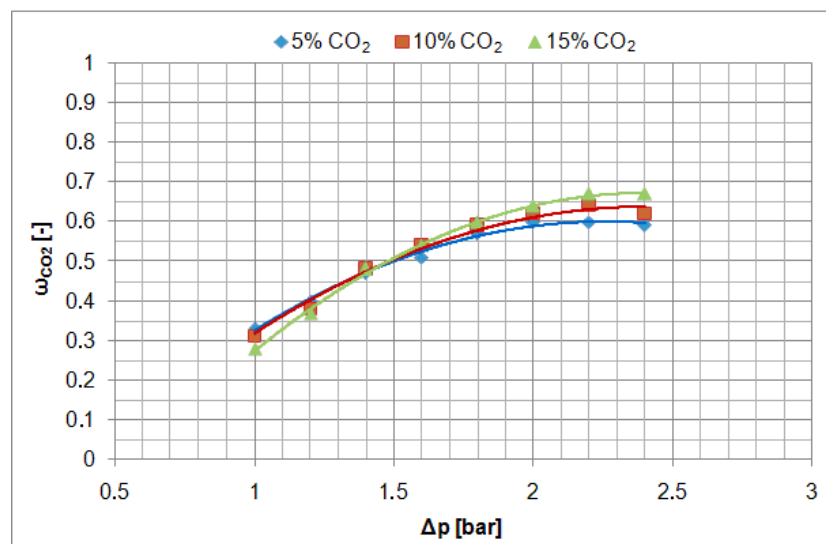


Figure 7: Outlet CO₂ mass fraction

5. Conclusions

The experimental results constitute a set of data for the condensation of steam from a mixture with composition corresponding to the working fluid produced in the CES gas generator. The mixture with pressure from 3.5 to 6 bar and CO₂ mass fraction from 5 to 15 % was separated into its constituents by a process of condensation on vertical tubes. Many tests were repeated to demonstrate the level of reproducibility of the experimental data.

The measurement of relevant parameters proved that the driving force for condensation of steam in the presence of the non-condensable gas is sufficient even at a very low temperature difference (2.5-5 °C) between the mixture and the low-pressure steam. The positive effect of pressure level and pressure difference on heat and mass transfer has been revealed. The limitation for effective condensation is a around pressure difference of 2 bar. Further condensation is possible at the cost of surface area extension which is not an economic solution. It was also found that higher inlet mass fraction of CO₂ affects the condensation efficiency and total heat load considerably; however composition of the mixture at outlet of the DSG is almost constant for various inlet concentrations of the non-condensable gas.

The rise of low-pressure steam from feedwater preheating in the aftercooler improved heat utilization of the DSG and increased outlet purity of CO₂ by about 12 % reaching 80 % mass fraction level, which helps to cut-down financial and energy demands for CO₂ compression and follow-up technologies.

References

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