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Experimental Investigation of the Heat Transfer in a Feedwater Preheater for the Decarbonizing Steam Generator

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The paper presents a feedwater preheater for a zero-emission steam cycle used for electricity generation from fossil fuels. The objective was to study an effectiveness of the preheater to separate a steam-gas mixture by condensation and utilize the latent heat for regenerative heating of the feedwater. Set of experimental regimes was carried out for three different modifications of the preheater. Experiments were conducted in order to investigate an impact of the presence of a non-condensable gas in the mixture on the intensity of heat transfer in the preheater.

1. Introduction

Over the past few years a multitude of different power cycles with CO_2 capture have been presented in the literature. The various concepts differ in technological maturity and operational challenges. One of the most promising concepts is the CES variation of an oxy-fuel combined cycle known as Water cycle (Figure 1). This cycle basically consists of high and low temperature Rankine cycles. The integral part is a recovery steam generator (HRSG). The other fundamental components are an air separation unit, a gas generator, a high (HP) and low (LP) pressure turbine, a CO_2 compressor and a condenser.
The fuel (natural gas) together with the nearly stoichiometric mass flow of oxygen is fed to the combustion chamber where two combustion products CO_2 (15 %) and H_2O (85 %) are generated. The mixture serves as a working fluid which is expanded in the HP turbine (Hollis et al.-2012). The hot exhaust gas is cooled in the following HRSG to vaporize and superheat pure steam for the LP turbine.
Energy Research Center (ERC) is currently developing a novel component called decarbonizing steam generator (DSG or simply separator) which is intended to substitute the HRSG and allow an easy and cost-effective CO_2 separation by condensation (Kupka and Kolonicny- 2013).

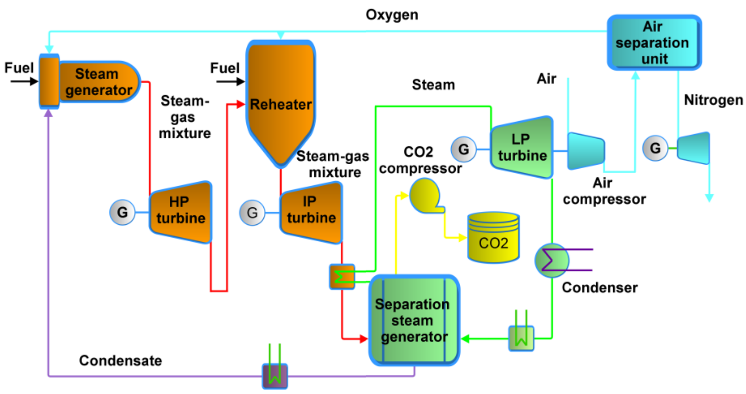

Figure 1: Decarbonizing steam generator incorporated in the CES oxy-fuel combined cycle

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Vítkovice Power Engineering Company (VPE) designed and constructed a 50 kW experimental unit, which has been tested in operation since 2010. The experimental runs proved that an effective separation is possible even at low temperature differences caused by a high concentration of CO_2 which prevents water vapor from reaching the heat transfer surface. However, the test runs revealed a high potential for better utilization of waste heat in the residual mixture. Thus a new exchanger has been designed and installed directly behind the DSG. The exchanger operates as a feedwater preheater which purpose is to rise overall thermal efficiency and improve CO_2 purity.
Non-condensable gases' effect on steam condensation has been extensively studied by many authors. Theoretical models involve either boundary layer solution or the heat and mass transfer analogy with a relatively good prediction. Despite comprehensive validations of the models by experimental investigations with gases like air, helium or nitrogen (Lee and Kim- 2008), there is lack of data for carbon dioxide. The presented experimental effort was made to understand mostly the primary variables such as mass fraction, temperature difference and pressure in wide ranges of operating conditions. The work also focuses on determination of empirical correction factors for the analogy-based models which are underestimating experimental results due to neglecting rippling on the liquid surface of the condensing film.

1.1 Experimental setup

The DSG is conceived as a vertical tubular evaporator inserted in a surrounding shell which forms primary circuit. The steam-gas mixture 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. The latent heat of the mixture is transferred through tube walls to the secondary circuit where pure low-pressure steam is generated. The stream of CO_2 and remaining vapor flow to the feedwater preheater, where residual heat is utilized for bringing the feedwater up to the saturation temperature. The feedwater is subsequently delivered to the evaporator where boiling takes place.
The preheater was made in three modifications in order to investigate the effect of flow regime and surface arrangement on the intensity of heat transfer between the working fluids. The inner longitudinal tubes (Figure 2) of the counter-flow design were fabricated in three different variations – besides smooth tubes also the ones with enhanced surface were included in the experimental program.

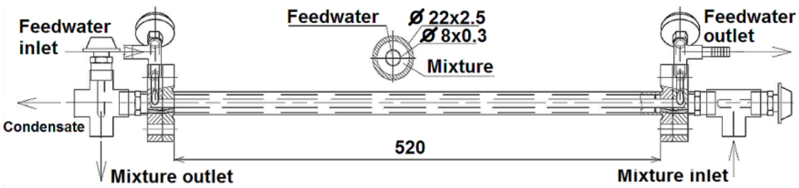

Figure 2: Single pass preheater with interchangeable middle section (installed in a vertical position)

The separator and the preheater are incorporated in an experimental apparatus schematically shown in Figure 3. The main parts are a steam generator, a gas supply line, a mixing chamber, a test section (DSG with preheater), a condensate collecting system, a water supply line and a data acquisition system. The apparatus allows variety of configurations defining the mixture composition, flow rates and pressure levels.

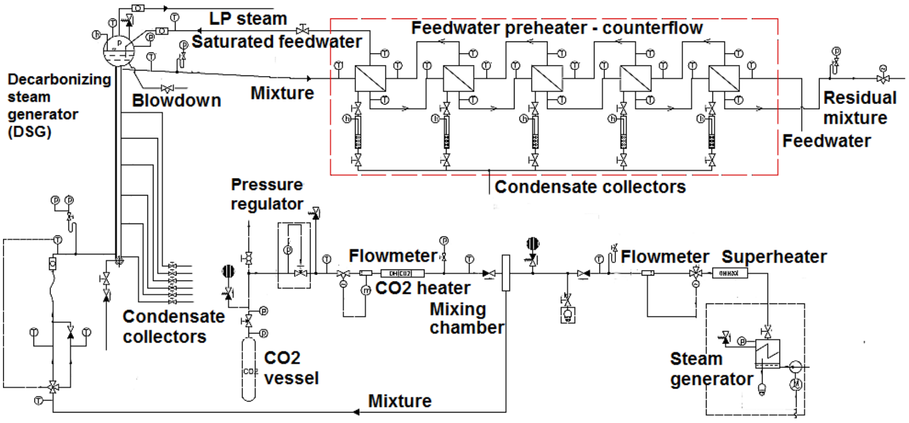

Figure 3: Schematic of experimental setup

Around 250 configurations in total were included in the experimental work with 84 different regimes for each type of the heat transfer surface (smooth, finned and twisted tubes) in the counter-flow arrangement. Depending on test conditions the heat transfer intensity influences the scale of the separation in the DSG which determines amount of the mixture flowing to the preheater. In some cases almost complete condensation occurred in the DSG alone which means that the preheater was only cooling down the CO_2 stream.

Table 1: Test conditions for counter-flow arrangement

Parameter	Range
Primary side (mixture) pressure [bar]	3 - 6
Mixture inlet flow rate [kg/h]	65 - 73
CO_2 inlet mass fraction [%]	15 - 91
Secondary side (feedwater) pressure [bar]	2.1 - 4.9

1.2 Data processing

For each section of the preheater the heat gained by the feedwater is calculated directly from its flow rate, the specific heat capacity and the inlet and outlet temperatures by the expression:

$$Q_i = \dot{m}_{FW} \cdot c_{p,FW} \cdot \left(T_{FW,i}^{out} - T_{FW,i}^{in}\right) \quad (1)$$

This value must be in balance with the energy transferred from the mixture side which is given by the measured condensation flow rate and the latent heat of vaporization of the mixture, corrected by the sensible heat changes of the mixture and the condensate (Al-Shammari et al.- 2004).
The heat flux can be obtained from the following formula using the area of heat transfer surface which is specified by known geometry of the preheater (Table 2).

$$q_i = \frac{Q_i}{A_i} \quad (2)$$

Table 2: Preheater geometry and dimensions

Parameter	Value
Inner diameter [mm]	7.4
Outer diameter [mm]	8
Tube length [mm]	560
Inner cross-section [mm^2]	43
Internal surface [mm^2]	12 089
External surface [mm^2]	13 069

The calculated heat flux and the logarithmic mean temperature difference allows the overall heat transfer coefficient to be evaluated:

$$U = \frac{q_i}{LMTD_i} \quad (3)$$

Once the total heat flux is determined, the heat transfer coefficients for the mixture and the feedwater can be evaluated. The Gnielinski correlation has been employed for the prediction of the feedwater HTC.

1.3 Test performance

The fluid used for experimental work is the mixture consisting of water vapor and carbon dioxide. The mass flow rate of vapor is given by the nominal output of the steam generator which is 63 kg/h. The mass flow rate of CO_2 varied from 3.4 to 11.3 kg/h depending on desired mass concentration of the gas in the mixture. The 5 %, 10 % or 15 % mixture prepared in the mixing chamber is led to the DSG where the first stage of separation process takes place. Its effectiveness is based on the condensation rate which is determined by a pressure difference between the working fluids in the DSG. It also determines how much mixture is transported to the preheater for further processing (second stage of separation).
The preheater is divided into five individual sections. Each section is equipped with temperature measurement instruments on both sides (mixture and feedwater) and the condensate collection system. Data from these measurements together with known flow rate of the feedwater are used for the evaluation of condensation rate and heat transfer between the working fluids.

A separation efficiency is expressed as a ratio between condensed vapor and its inlet mass flow. This parameter for the whole separation process which includes condensation in the DSG and the preheater (with twisted tubes in this case) is shown in Figure 4. It clearly illustrates negative effects of lower pressure difference between working fluids and higher concentration of CO_2 in the mixture introduced to the DSG (i.e. inlet mass fraction).

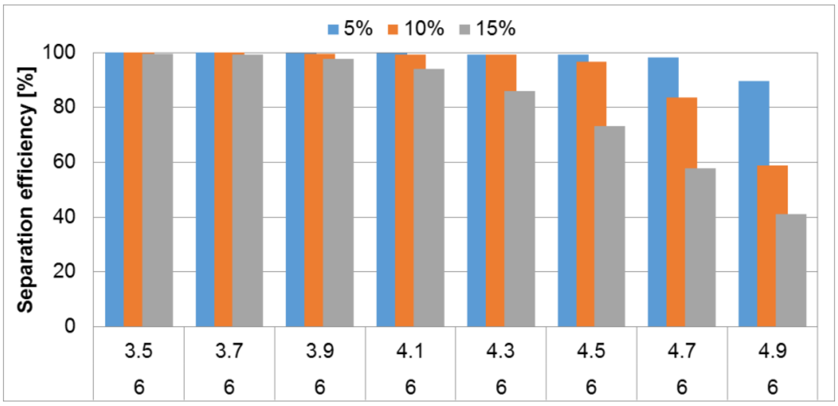

Figure 4: Effect of CO_2 presence in the mixture on the intensity of condensation (twisted tubes)

The heat extracted from the mixture in the preheater is determined by the amount of vapor unprocessed in the DSG. Lower pressure differences in the DSG provoke less intensive condensation resulting in a higher flow rate of vapor through the preheater in addition to lower concentration of CO_2 which acts as a barrier for vapor diffusion to the heat transfer surface. These factors have great impact on the heat distribution between the DSG and the preheater and its contribution to the separation process (Figure 5).

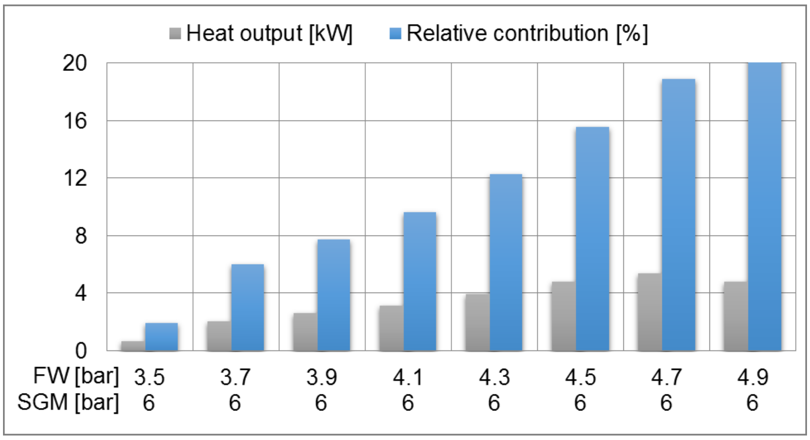

Figure 5: Heat output of the preheater and its contribution to the total heat output (10% CO_2)

2. Results and discussion

The mass flow rate of feedwater must be equal to the amount of low-pressure steam generated in the secondary circuit of the DSG in order to keep water level in a drum at a stable value. This is significant factor influencing heat transfer in the preheater since the heat transfer coefficient (HTC) of feedwater depends on its velocity. The feedwater velocity is within a range of 0.22 to 0.32 m/s which means there is also a certain variation in the HTC of feedwater at the preheater inlet. However, a much higher variation can be seen in individual sections of the preheater caused by different temperature gradients (Figure 6).
The dependence of the heat transfer coefficient of feedwater on the Reynolds number is illustrated in Figure 7. The highest HTC are achieved in terminal sections of the preheater where the feedwater temperature is near the saturation point and a flow pattern fully developed into the turbulent regime. This is obvious especially in experiments with low pressure (temperature) differences between the fluids.

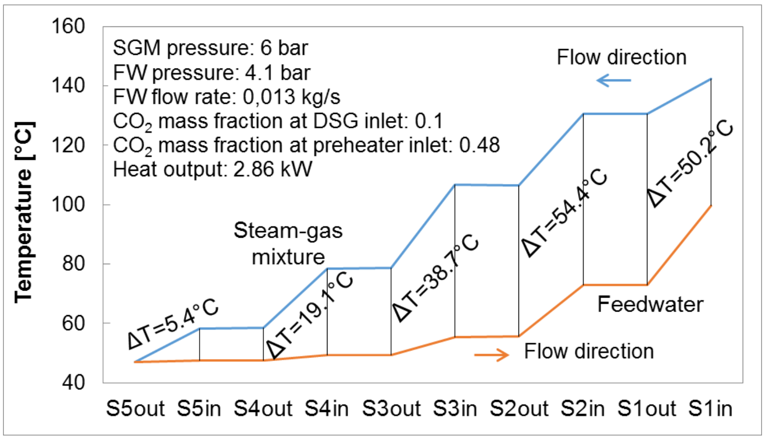

Figure 6: Typical temperature differences in preheater

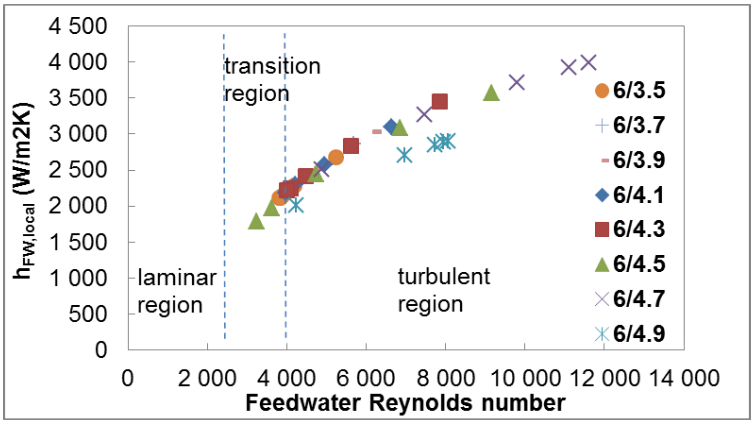

Figure 7: Heat transfer coefficients of feedwater in preheater (pressure in bar, mixture/feedwater)

Whereas the HTC of feedwater is relatively uniform, there is a huge range of heat transfer coefficients of the mixture which is caused by rising concentration of CO_2. The non-condensable gas inhibits the condensation process and reduces the intensity of heat transfer. The result in the form of heat fluxes in the preheater is shown in Figure 8.

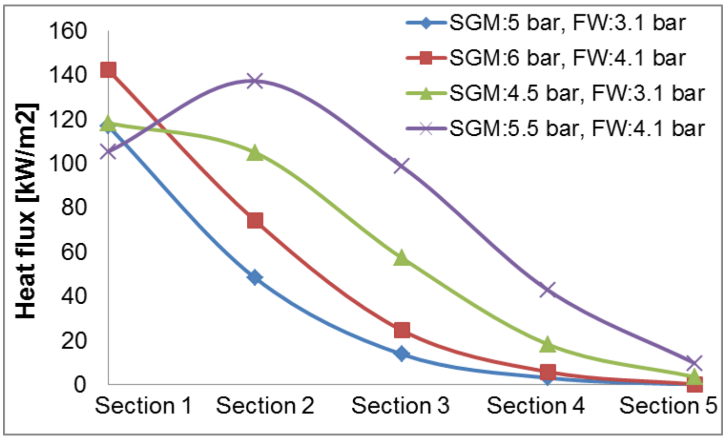

Figure 8: Heat fluxes in preheater (10 % CO_2 mass concentration at the DSG inlet)

Figure 9 depicts average values of the overall heat transfer coefficient in the preheater for examined heat transfer surfaces. The best preheater performance has been obtained with the twisted tubes which is in accordance with an assumption that surface enhancement has positive effect on creation of irregular fluctuations in the fluid flow (Kukulka and Smith, 2012). These continuous changes in both magnitude and direction increase heat transfer mainly on the mixture side where CO_2 boundary layer is disrupted and transport of water vapor to the surface is improved.

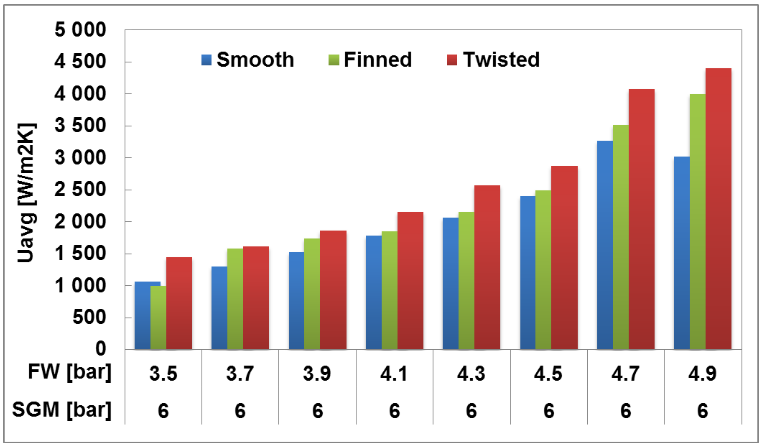

Figure 9: Average overall heat transfer coefficients

3. Conclusions

The aim of the experimental work was to achieve substantial energy savings in a mixture separation process by utilization of the heat released during condensation for regenerative heating of feedwater. The data obtained by measurement of relevant parameters show that the feedwater preheater can gain additional heat energy accounting for up to 20 % of the total heat load. The performance of the preheater is strongly dependent on mass fraction of CO_2 in the mixture which adversely influences the intensity of heat transfer due to reduced diffusion of vapor to the heat transfer surface. Thus three different variations of single pass tube exchanger were employed in order to investigate improvement in the heat and mass transfer by induced turbulences. A modification with twisted tubes proved to be the most efficient. An overall heat transfer coefficient is in average 10 % higher than in case of finned tubes and 27 % higher than in case of smooth tubes.

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References

Al-Shammari S.B., Webb D.R., Heggs P., 2004, Condensation of steam with and without the presence of non-condensable gases in a vertical tube, Desalination, 169, 151-160.

Hollis R., Skutley P., Ortiz C., Varkey V., LePage D., Brown B., Davies D., Harris M., 2012, Oxy-fuel turbomachinery development for energy intensive industrial applications, Proc. of the ASME Turbo Expo 2012, Copenhagen, Denmark, 3, 431-439, DOI: 10.1115/GT2012-69988.

Kukulka D., Smith R., 2012, Development and evaluation of enhanced heat transfer tubes for transitional Reynolds number flow, Chemical Engineering Transactions, 29, 1489-1494, DOI: 10.3303/CET1229249.

Kupka D., Kolonicny J., 2013, Aftercooler for efficiency improvement of decarbonizing steam generator, Chemical Engineering Transactions, 35, 733-738, DOI: 10.3303/CET1335122.

Lee K-Y, Kim M.H., 2008, Effect of an interfacial shear stress on steam condensation in the presence of a noncondensable gas in a vertical tube, International Journal of Heat and Mass Transfer, 51, 5333-5343.