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Heat integration and heat exchanger network design for oxyfuel cement plants

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Abstract

The cement sector needs to reduce its CO_2 emissions. An oxyfuel CO_2 capture technology allows to considerably reduce the emission. However, heat recovery and energy efficiency measures are essential to make the technology economically feasible. An approach to design heat exchanger networks applied to a 1st generation oxyfuel cement plant is described in this article. The approach consists of two steps: preliminary targeting and heat exchanger network design. For the studied cement plant, the steam Rankine cycle was identified to be superior to organic Rankine cycles. In the ideal case about 10.5 MW of power can be recovered. However, in a cost-efficient simple heat exchanger network recovery of only about 8.7 MW is economically reasonable.

Keywords: Heat integration, Heat exchanger network design, Oxyfuel cement plants.

1. Introduction

The cement sector is responsible for about 7% global anthropogenic CO_2 emissions (IEA, 2018). Two-third of the CO_2 emission originate from calcination of limestone while one-third come from the combustion of fuel. It is, therefore, impossible to reach CO2 emission targets with fuel switching alone. CO_2 capture and storage is essential to become carbon neutral. An oxyfuel-based capture process is a promising candidate for capturing CO_2 from a cement plant (Voldsund et al., 2019). In the oxyfuel process the combustion is performed with oxygen mixed with recycled CO_2. The CO_2 enriched flue gas allows a relatively cost-efficient purification and separation. Nevertheless, CO_2 purification consumes additional power and process heat must be transferred to air streams to dry the raw material energy-efficiently. The temperature levels in an oxyfuel plant are higher than in conventional plants because of the increased oxygen concentration in the combustion, and flue gas has to be cooled before it is recirculated. Waste heat recovery and heat integration are important for an economic implementation of oxyfuel technology in cement plants.

An existing cement plants was investigated for retrofit of the 1st generation oxyfuel process. The process simulations are performed with VDZs in-house cement process model. Afterwards, the heat integration is performed using a two-step methodology.

This article focusses on a systematic approach to heat integration and applies it to an oxyfuel cement plant. In the following, a brief description of the model setup is given

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followed by the introduction of the two-step methodology for heat integration and its application the oxyfuel cement plant is described.

2. Methodology

2.1. Modelling approach

The retrofit of the 1st generation oxyfuel process to cement plant was performed with several models. The clinker burning process was accessed by a kiln process model. The model described the process from the kiln meal feed to the outlet of the clinker from the cooler. It is made up by individual linked models of preheater, calciner, bypass, kiln and cooler, where material and energy balances are calculated (Koring, 2013). The process model outputs are performance data, thermal energy demand, clinker quality and available excess heat. Input data about the process design and some plant specific data to make the process model representative was provided by the cement producer and equipment supplier.

A second model, the heat integration model, access the waste heat recovery and the heat integration of the CO_2 Processing Unit (CPU). Data was iteratively exchanged between the two models.

2.2. Heat integration

Stream data from the process engineering model by VDZ was used to create the heat integration model in Aspen HYSYS. In addition, a CPU model was created in Aspen HYSYS. These models were used to access the energy streams of the 1st generation oxyfuel cement plant. In the following the two-step methodology consisting of a preliminary targeting step and a Heat Exchanger Network (HEN) design step, is presented.

2.2.1. Preliminary targeting of the heat exchanger network design

The goal of the preliminary targeting is to identify the most promising heat to power cycles for the HEN design. A pinch analysis is performed which identifies the bottle neck of the plant regarding heat integration and allows to estimate an upper bound on the power production of the heat to power cycles. This step is also used to dimension the heat to power cycles. The stream data from this analysis is used in the HEN design phase.

2.2.2. Heat Exchanger Network design

In the second step after the preliminary targeting the HEN is designed which allows cost-efficient design of the heat recovery in the cement plant. The best HEN involves optimizing the trade-off between capital costs determined by the number of heat exchanger units and their areas and the operating costs determined by the amount of hot and cold utilities required by the process. The software tool termed SeqHENS (Sequential Framework for HEN Synthesis) developed at the Norwegian University of Science and Technology and SINTEF Energy was used to design the optimal HEN (Anantharaman, 2011). An overview of the four-step methodology in the toolbox is given next:

1) Given stream data on the relevant hot and cold streams given by the preliminary targeting the minimum amount of hot and cold utility required is determined. The Linear Programming (LP) transhipment model is used to solve the optimization (Papoulias et al., 1983).
2) The absolute minimum number of heat exchanger units is determined where the heuristic is used that the optimal number is close to the minimum number of

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units. This problem is solved with the Mixed-Integer Linear programming formulation (Papoulias et al., 1983).

3) Given the numbers of units and using engineering judgement the correct matches between hot and cold streams is determined. This “Steam Match Generator” problem is formulated using the vertical MILP transportation model (Anantharaman, 2011). The result is a Heat Load Distribution which gives the amount of heat exchanged between hot and cold stream.
4) Finally, the optimal topology of the HEN is determined. This problem is solved with a nonconvex Nonlinear Program (Floudas et al., 1986). The objective is to minimize the total cost of the HEN, where engineering judgment is used to get a simple HEN.

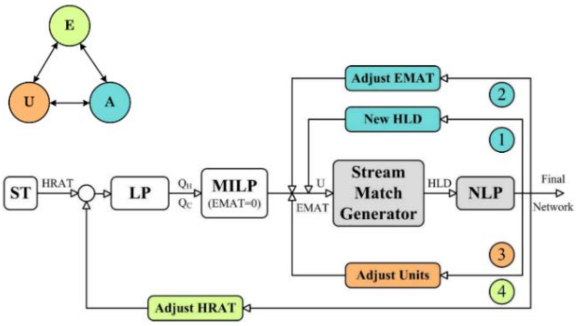

Figure 1. Overview of SeqHENS framework.

3. Case Study

The 1st generation oxyfuel cement plant consists of a preheater, pre-calciner, rotary kiln and cooler (Figure 2). The preheater exhaust is recirculated to the cooler, where a part of the recirculated stream is extracted and sent to the CPU. The Air Separation Unit (ASU) provides purified oxygen. An air stream is heated and used to dry the raw material.

The studied cement plant has an average annual clinker production of about 5600 t/d. The kiln line is a common dry process, and the raw material moisture is about 2-3%. The estimated drying demand for the raw material is about 300 $kJ/kg_{clinker}$. This heat must be supplied by the excess heat of the process before additional excess heat can be used in a heat to power cycle.

The hot streams in the oxyfuel cement plant are the preheater exhaust stream at a temperature of about 450℃, cooler exhaust stream at a temperature of about 180℃, and the bypass stream, which is pinched with parts of the recycling stream, after which the combined stream has a temperature of 400℃. Additional heat streams are available from the CPU at a temperature of about 120℃. The cold streams are the heat required for drying the raw material, heat required in the CPU and heat for the heat to power cycle.

It is necessary that the recirculated stream is cooled down to about 50℃ to remove chlorine, sulfure and water. Moreover, bag filters are used to remove dust. In addition, the air stream existing the raw mill should have required heat left for evaporate water. Therefore, a minimum temperature of 120℃ was chosen for this stream.

3.1. Preliminary targeting of 1st generation oxyfuel cement plant case study

The preliminary targeting phase was used to 1) find an optimal flue gas recirculation rate, 2) evaluate if heat from the Bypass should be used and 3) compare different heat to power cycles. The first and second step required iterations between the heat integration and

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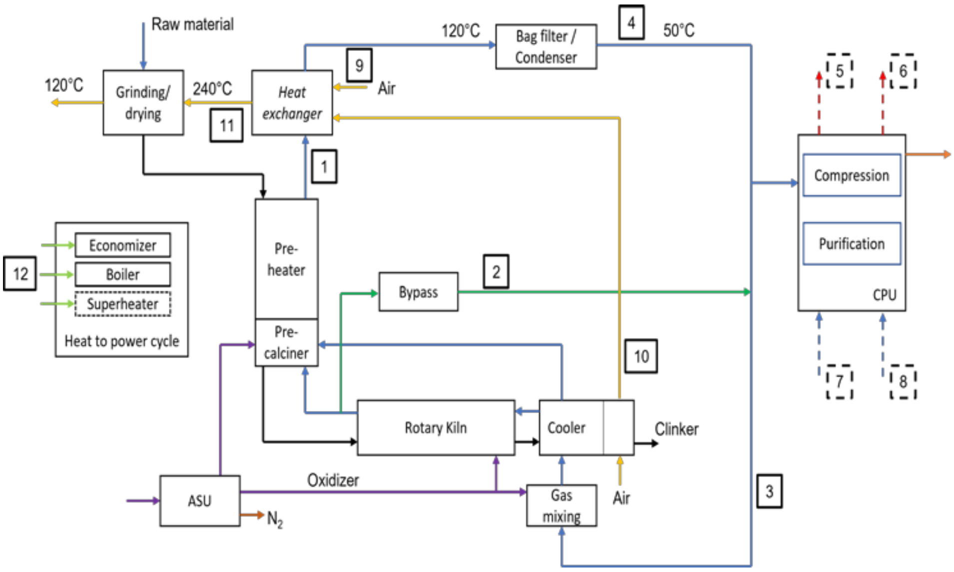

Figure 2. 1st generation oxyfuel cement plant. The numbers indicate hot and cold streams. Temperature constraints are displayed.

updating the process engineering model. It was concluded that no heat should be extracted from the Bypass since it increased the overall fuel use.

Organic Ranking cycles using Benzene or Butane and a steam Ranking cycle with different pressure levels were compared. The best performing Ranking cycle was the steam Rankine cycle at a pressure level of 15 bar, which was used for the HEN design (Table 1).

Table 1. Performance of different Rankine cycles.

Rankine cycle	**Power production**	**Recirculation rate**
Steam Rankine cycle (15 bar)	10.5 MW	0.49
ORC – Benzene	10.0 MW	0.49
ORC – Butane	8.4 MW	0.49

3.2. Heat exchanger network design of 1st generation oxyfuel cement plant case study

The preliminary targeting phase concluded that in the ideal case 10.4 MW power can be produced. However, this performance can only be reached with a complicated and expensive HEN. In the HEN design phase using SeqHENS stream splits and small heat exchangers which are not cost efficient were avoided. This resulted in a HEN which allows the required heat recovery and a power production in the steam Rankine cycle of about 8.7 MW (Figure 3). This is a 15% reduction compared to the ideal case.

In this study a retrofit is investigated, and the CPU will be located several hundred meters away from the kiln line. In the HEN obtained long pipelines are required between the CPU and the kiln line for only a small heat recovery. It was therefore decided to also investigate a case with the CPU excluded from the HEN design to create a simpler

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network. The design of the simpler network (Figure 4) increases the overall heat exchanger area but reduces complexity and piping, which is not included in the objective function of SeqHENS. The same amount of power as before (8.7 MW) can be produced.

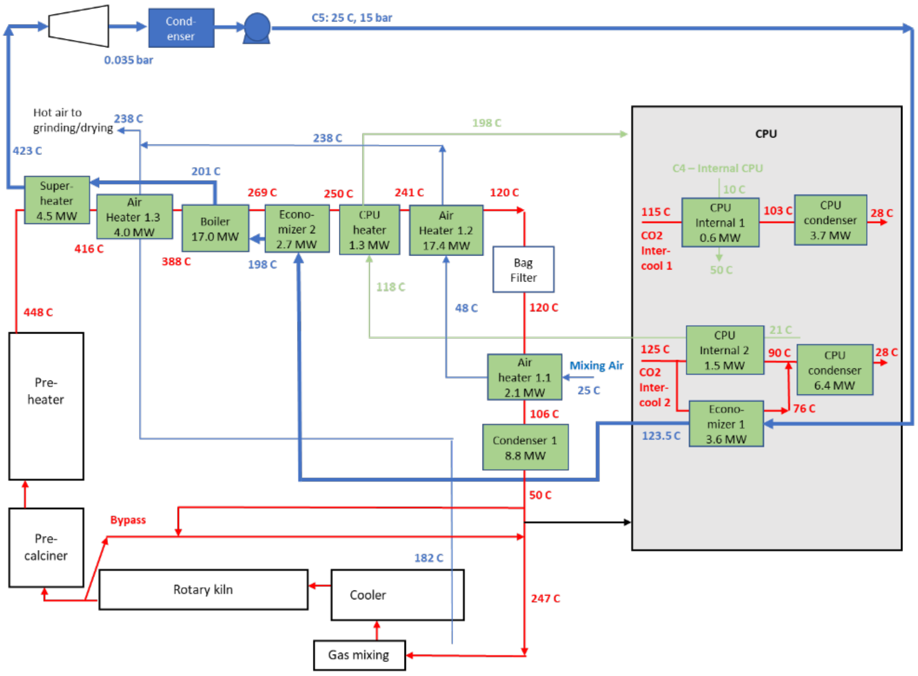

Figure 3. Heat exchanger network including heat integration of CPU.

In both HENs the Air Heater 1.2 is responsible for the majority of costs since it has a large duty, and it is a gas-gas heat exchanger with low heat transfer and large heat exchanger area.

4. Conclusion

This article shows how to apply heat integration and heat exchanger network design to a 1st generation oxyfuel cement plant. Heat integration is essential for economically implementation of the oxyfuel technologies to existing cement plants. required heat exchanger is a gas-gas heat exchanger which also is the largest cost driver. This heat exchanger is essential since air must be heated for drying the raw material. The direct use of the preheater exhaust as in conventional cement plants is impossible since it would emit CO_2. It is possible for this cement plant to recover about 8.7 MW of power which decreases the energy consumption of the plant. In future, a more detailed economic

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assessment of the steam Rankine cycle and required heat exchangers must be performed to evaluate the profitability.

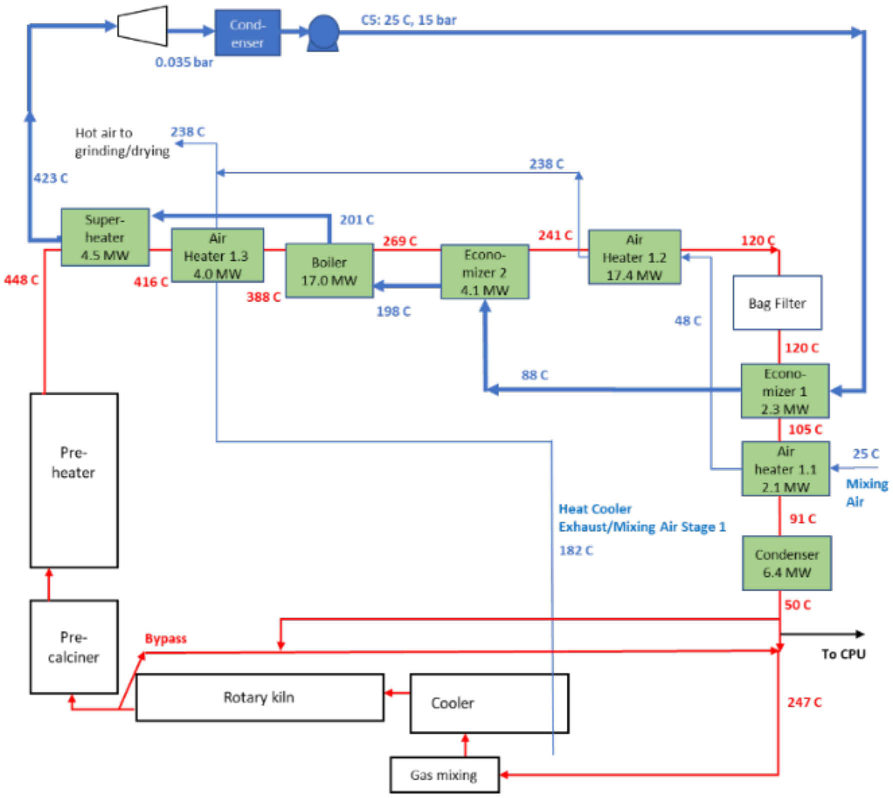

Figure 4. Heat exchanger network without heat integration of CPU.

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