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Design of Steam Cycles for Oxy-Combustion Coal based Power Plants with emphasis on Heat Integration

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Abstract

The Oxy-combustion method of CO_2 capture is considered to have several advantages over other methods for CO_2 capture from coal based power plants. The capture process is energy intensive and hence expensive. Heat integration is often recommended to recover part of the energy expended in the capture process. In this study, pinch analysis is used as a tool to integrate heat from the CO_2 capture process into the steam cycle of the power plant. This way of heat integration provides an opportunity to make better use of the available low grade heat at the power plant premises by approaching the minimum allowable temperature difference between the hot and the cold streams. This ultimately results in a better overall efficiency by generating additional power for the same fuel input and also by reducing the consumption of cooling required in the capture process. The resulting steam cycle will be a custom design for oxy-combustion coal based power plants and will be tightly integrated with the capture process. As this method brings a lot of changes to the steam cycle configuration, this is best suited for new power plants rather than retrofit of existing plants. Results show that the Pinch method of heat integration achieves better overall thermal efficiency compared to the conventional method of steam cycle design and heat integration. A techno-economic is however required to justify the efficiency gains achieved. Further work will be done later to optimize some of the simulation assumptions and to arrive at the network design.

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Key words: Steam cycle; Pinch analysis; Heat integration; Oxy combustion; CO_2 capture; Energy penalty;

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1. Introduction

The oxy-combustion method is one of the three main methods considered for capturing CO_2 from power plants and other large industrial sources. This method is expected to have a competitive cost of capture [1] and a reduced environmental impact [2] compared to the other methods of capture. An oxy-combustion coal based power plant shares a large portion of its major equipment with a state-of-the-art pulverized coal (PC) based power plant and hence the technology is well suited for retrofit applications. Major equipment such as the boiler, steam turbine generator set, cooling systems and coal handling systems in an oxy-combustion power plant are essentially the same as in a modern pulverized coal based power plant. Additionally, two main units are required to enable the capturing and compression of CO_2. An Air Separation Unit (ASU) that produces oxygen for combustion and a CO_2 Compression and Purification Unit (CPU) downstream the boiler that further processes the captured CO_2 to pipeline purity and pressure levels. The necessity for a downstream purification unit arises due to the impurities present in the oxygen stream as well as due to the leakage of atmospheric air into the boiler. Addition of this equipment not only requires

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capital investment, but also an operating cost mainly in terms of energy consumed in order to operate these units. The efficiency penalty for capture is in the order of ten percentage points [3].

Several studies in the past have focused on improving the overall efficiency of an oxy-combustion coal based power plant by employing various methods. The methods include improvement of ASU, improvement of CPU, low grade heat recovery from the boiler flue gases, heat integration of CPU and the steam cycle, and other novel concepts to name a few. Some of the noteworthy results include the improvement of the cryogenic ASU [4], and optimization and heat integration of the CPU with the steam cycle [5]. However, the steam cycle that forms the core of the power plant largely remains unaltered. The design of the steam cycle follows an established method that has not been changed for several decades. The efficiency of the steam cycle has been improved by the advent of new materials that enable supercritical main steam parameters with increased pressures and temperatures. The above trend of increasing main steam pressures and temperatures is expected to last and result in even further improvements in performance of the steam cycles in the future. Other features of a modern steam cycle that are responsible for improved efficiency are the reheat and the regenerative feedwater preheating.

As a coal based power plant with CO_2 capture consists of many additional sub-systems, a systems oriented approach to the design of future coal based power plants is necessary. This systems oriented approach would guide us in building power plants that are much more efficient compared to a similar power plant designed using conventional design methods [6]. In a modern large scale steam power plant, as many as nine feedwater heaters are used to preheat the boiler feedwater in stages. This results in improved overall efficiency of the power plant. Also, air preheating is employed to recover heat from the flue gases exiting the boiler. In an oxy-combustion power plant, most of the flue gases are recycled for temperature control and oxygen from the ASU is used for combustion. This eliminates the need for air preheating. A small amount of oxygen preheating is done to avoid condensation of moisture available in the flue gases when the flue gases are mixed with oxygen before combustion. The above design feature of an oxy-combustion power plant results in a fairly high temperature of the flue gases exiting the boiler that has to be cooled down before the downstream processing in CPU. This presents an opportunity for heat recovery. Also a large portion of the power consumed by the CPU is for compression of gases and hence a large amount of cooling is required in order to reduce the CPU energy requirements. This also provides an opportunity for heat integration. One of the ways of integrating this large amount of heat is to use it to preheat the boiler feedwater in the steam cycle. The traditional way of steam cycle design is not adapted to integrate a large amount of external process heat. This makes the systems approach to the design of the steam cycle more important. Pinch analysis is used as a tool in this study to design a steam cycle with heat integration in mind. This design is then compared with the traditional method of steam cycle design in order to evaluate the relative improvement in efficiency brought by the Pinch based systems approach. The pinch based systems approach would result in a tightly integrated system that will use the available energy much more efficiently albeit at an increased investment in the heat exchange area and increased network complexity. The economic feasibility of this approach will be studied subsequently to add more value to the thermodynamic results obtained in this study. The challenges related to increased complexity and the associated operability and control related issues are out of scope for the study.

Nomenclature

ASU	Air Separation Unit
BFP	Boiler Feed Pump
BFW	Boiler Feed Water
CPU	Compression and Purification Unit
D/A	Deaerator
DCA	Drain Cooler Approach temperature
ESP	Electrostatic Precipitator
G	Generator
H/I/LPT	High/Intermediate/Low Pressure Turbine
H/LP-FWH	High/Low Pressure-Feed Water Heaters
TTD	Terminal Temperature Difference

2. Methodology

An oxy-combustion coal based power plant is simulated in Aspen Plus®. The simulated sub-systems include the boiler island, steam cycle and the CPU. The ASU itself is not simulated, but the energy required to produce the oxygen is taken from the literature. The simulation parameters including the coal composition, ambient conditions, steam turbine parameters, CO_2 pipeline specifications and the CPU operating parameters are taken from the literature and can be found in the authors previous publication [7]. This gives a baseline coal based power plant with CO_2 capture. The baseline power plant has a supercritical steam cycle designed by using the traditional methodology. The baseline power plant also has a double flash type CPU that removes the volatiles and compresses the final product to pipeline specifications. The Aspen Plus® simulations provide the heat and mass balances from which the overall performance is calculated. Various heat integration cases are designed around the baseline case in order to assess the heat integration potential and the role of the Pinch method [8] in improving the overall efficiency of the power plant. The fuel flow is kept constant between the various cases for comparison purposes.

2.1. Base case process description

The schematic of the base case is shown in Fig. 1. The boiler island has a pulverized coal boiler to which coal and the oxygen stream from the ASU are fed into. After combustion and steam production, the flue gas is taken to an Electrostatic Precipitator (ESP) to remove the fly ash. Ash is also removed from the furnace bottom. The majority of the flue gas is then returned back to the combustor to control the furnace temperature. A recirculation fan is used to overcome the pressure drop in the gas circulation path. The boiler operates at a pressure slightly lower than the atmospheric pressure for operational and safety reasons. Because of this, atmospheric air leaks into the boiler. One of the main design parameters for the boiler is the excess oxygen at the combustor exit and it is set at 2.2% dry. For low sulphur coals, there is no need to remove oxides of sulphur from the flue gases before recirculation [9]. This enables the utilization of the sensible heat available in the flue gases to reduce combustion related irreversibility in the boiler. Due to a high degree of feedwater preheating in modern day power plants using steam extraction, the flue gases cannot be cooled down substantially in the boiler and hence they contain considerable amount of sensible and latent heat when they leave the boiler. This heat must either be removed using coolers or be recovered to generate additional power in the steam cycle. This step is necessary as the downstream processing requires the flue gases to be cooled down for compression. A special heat exchanger called *Acid Condenser* [10] made with corrosion resistant materials is used to recover the sensible and latent heat available in the flue gases before the CPU. The recovered heat is used to substitute steam extraction from the turbines for feedwater preheating.

The oxygen stream supplied from the ASU is not 100% pure and contains impurities such as nitrogen and argon. The air leakage into the boiler is an operational condition that also brings in additional atmospheric air into the system. Due to the above reasons, downstream processing is required to remove volatile components from the flue gases before compression. A flue gas desulphurization unit (FGD) is also required before the CPU to remove oxides of sulphur and nitrogen formed during the combustion of coal. Although wet FGD can be used to remove SO_x, a novel system of removing SO_x as sulfuric acid in high pressure water wash columns [11] is considered for this study. This is mainly due to the fact that the flue gases need to be compressed to higher pressures by the CPU and the above method for removing SO_x and NO_x in a water wash column at higher pressure is better suited for oxy-combustion coal based power plants. After the removal of SO_x and NO_x, the flue gases are compressed and cooled for removal of volatiles using the double flash method. Finally, the resulting CO_2 stream is cooled and condensed into liquid state before pumping to pipeline pressures for transport. Selected simulation assumptions used in the baseline case are shown in Table 1.

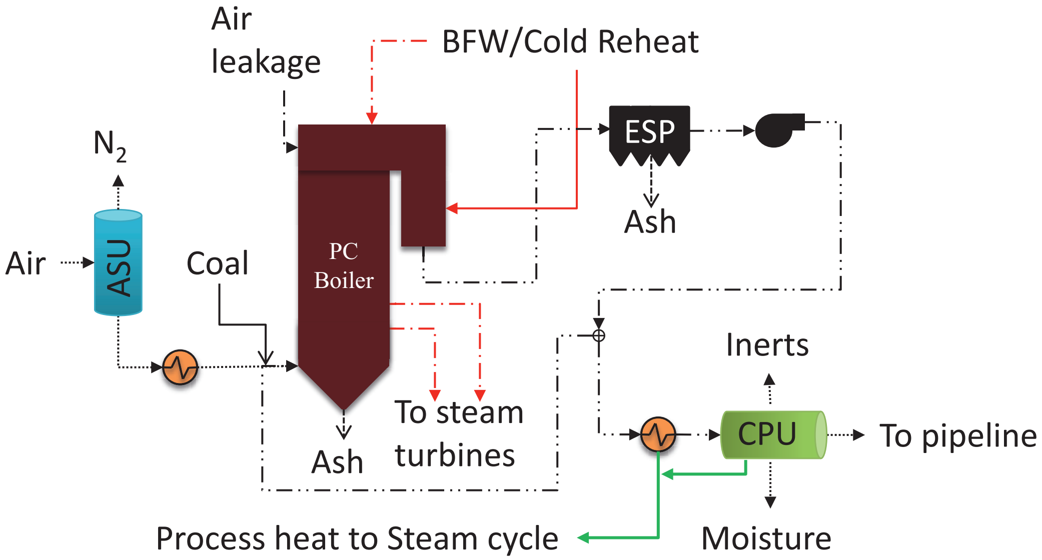

Fig. 1 Schematic of the oxy-combustion boiler and CPU with potential heat integration options

Table 1. Selected simulation parameters

Parameter	Value	Units
Steam Cycle		
Main steam pressure	280	bar
Main steam temperature	600	^oC
Reheat temperature	610	^oC
Condenser pressure	0.048	bar
Feedwater heaters	7	
Feedwater final temperature	315	^oC
Deaerator pressure	18	bar
Boiler island		
Evaporator pressure drop	15	bar
Boiler minimum design pinch	20	^oC
Boiler operating pressure	1.0124	bar
Excess oxygen@ combustor outlet	3	% (dry)
Combustor exit temperature	1850	^oC
Oxygen purity	95	%
Fan pressure ratio	1.04	-
Recycle ratio	71	wt %
CO_2 Purification Unit		
Stage 1 temp/pressure	-30/33	^oC /bar
Stage 2 temp/pressure	-54/31	^oC /bar
Final product pressure	110	bar

2.2. The Pinch method of heat integration

The baseline case described in the previous sub-section is designed using the established steam cycle design principles. The established design method helps build a stand-alone steam cycle with no heat integration. Heat is only added into the cycle in the main boiler by producing main steam and by reheating. Feedwater preheating is done regeneratively by extracting steam from the steam turbines at several extraction pressures. The following steps are involved in designing the steam cycle by using the conventional method:

- The main steam parameters and the reheat parameters are selected
- The structure and arrangement of the feedwater heating train is fixed
- The number of steam extractions are decided depending on the economics of the power plant
- Each heater in the train is allocated a heating duty either in terms of equal enthalpy rise or equal temperature rise
- The extraction pressure is determined by the saturation temperature of the steam and the pipeline pressure drop
- Minimum temperature differences such as TTD and DCA dictate the steam extraction mass flows
- A deaerator is required to remove dissolved gases such as oxygen from the feedwater and also to act as a direct contact heater

The above design procedure results in a steam cycle design that is stand alone. In order to integrate external process heat into the feedwater preheating, part of the feedwater to be preheated is extracted after the condensate forwarding pump or the boiler feed pump and heated in parallel to the existing heater train. This substitutes some of the steam extractions from the turbine and hence generates additional power in the generators. Although individual heaters in the feedwater heating train are restricted at both ends by TTD and DCA of 3^oC and 5^oC respectively, the overall system is not even close to the optimal utilization of the extracted steam. This is shown by constructing a composite heating/cooling curve of the feedwater heating network. Fig. 4 (a, c) shows that the allowable minimum temperature difference of 3^oC between the condensing steam and the feedwater is not fully exploited at the hot side of the feedwater heating train.

The Pinch design method [8] recognizes the significance of the process pinch or the heat recovery pinch and starts the design at the pinch moving away. This ensures that the minimum energy target is achieved by the resulting heat exchanger network. The composite heating and cooling curves are separated at the pinch by ΔT_{min}. The allowable ΔT_{min} is match-specific. It is 3^oC, 10^oC and 20^oC between the feedwater and the condensing steam, boiler flue gases and the gases from CPU respectively. ΔT_{min} contributions are allocated to various streams accordingly. The steam extractions act as hot utilities. The steam extraction mass flows are adjusted until various minimum temperature differences between the hot and the cold composite curves are close to the allowable ΔT_{min}. The mass flows of the main steam and the reheat steam are adjusted accordingly to maintain constant fuel flow into the boiler. The steam extraction pressures and other steam cycle assumptions are kept the same between various cases to highlight the efficiency improvement potential of the Pinch method for heat integration. A new feedwater heating network is required to realize the new composite curve which will better utilize both the extracted steam as well as the external heat integrated into the steam cycle by proper placement of various heaters and by means of stream splits. In the Aspen Plus® simulation of the steam cycle, multiple individual heaters are replaced with a single multi-stream heat exchanger. The heat integration results in a reduced temperature of the boiler flue gases. Sensible heat available in the flue gas and part of the latent heat in the form of water vapor condensation are recovered in the *acid condenser* which is now represented by a multi-stream heat exchanger. After adjusting the steam extraction mass flows, the system has multiple pinches with one for each steam extraction and one after each of the two feedwater pumps.

The overall feedwater heating network is split into two halves by the deaerator, referred to as the low and high pressure sections. The Pinch method is applied to either side of the deaerator separately for simplicity of convergence. The heat recovery pinch occurs at the inlet of the feedwater heating train, both at the low pressure and the high pressure sections of the feedwater heating network. All other pinches caused by steam extractions are considered to be utility pinch points. Hence, there are two threshold problems on either side of the deaerator both requiring only hot utilities i.e. steam extraction from the turbines. Fig. 4 (b, d) shows that the composite curves are closer after the adjustment of the steam extraction mass flows and also the final feedwater temperature is increased for the same steam extraction pressures.

2.3. Heat integration cases

Five heat integration cases are constructed based on various levels of heat integration with and without the Pinch method. The cases are chosen in order to highlight the efficiency improvements brought by the Pinch methodology. The cases are described as follows:

Case 1: Supercritical coal based power plant w/o CPU integration by conventional design (baseline case)
Case 2: Subcritical coal based power plant w/o CPU integration by conventional design
Case 3: Case 2 implemented by using the Pinch method
Case 4: Subcritical coal based power plant w/ CPU integration
Case 5: Case 4 implemented using the Pinch method
Case 6: Supercritical coal based power plant w/ CPU integration by the Pinch method

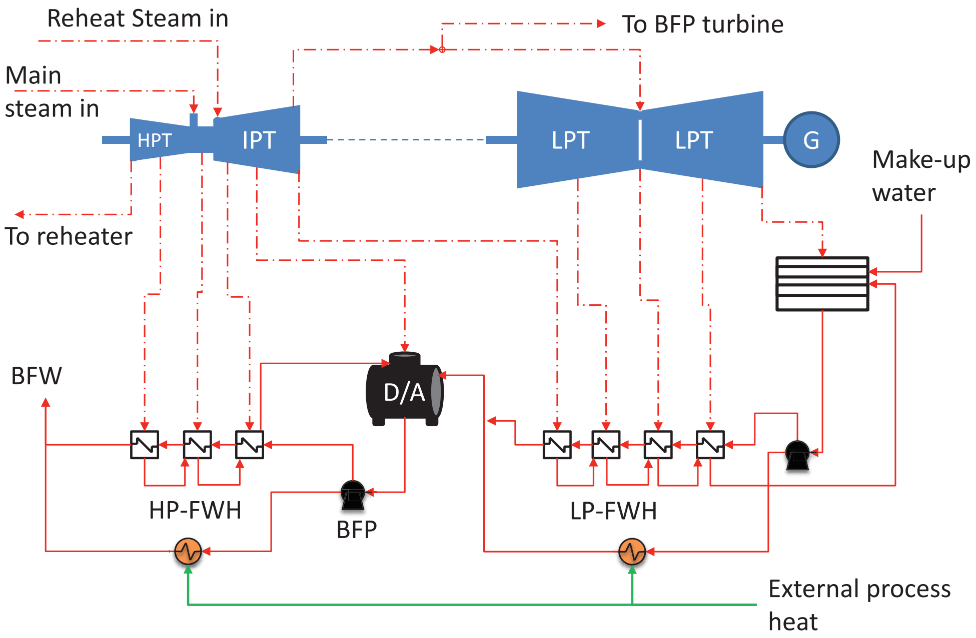

Fig. 2 Schematic of the steam cycle designed by using a conventional method

Supercritical technology for steam based power plants are considered to be state-of-the-art for large commercial installations offering improved efficiency and reduced emissions. Although the subcritical technology is less efficient, it is reliable, proven and suitable for small scale power plants and low grade coals. Because of the above features, the subcritical technology is still considered for construction of new power plants around the world [12]. Fig. 2 and Fig. 3 show the steam cycles used in conventional and Pinch design cases.

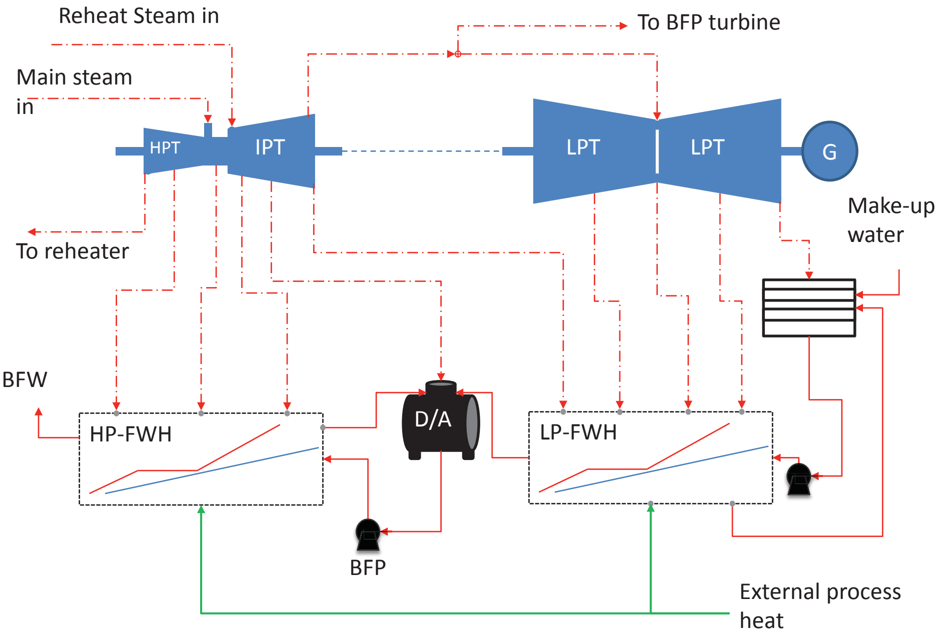

Fig. 3 Schematic of the steam cycle designed by the Pinch method

3. Results and discussion

The composite curves of the subcritical cases are presented in Fig. 4. The ΔT_{min} between the extracted steam and the boiler feedwater in case of conventional design increases as the pressure level increases. This is despite the fact that each heater in the feedwater heating train is designed with a ΔT_{min} of 3^oC at the hot end. This shows that although individual heaters are constrained at both ends, the system as a whole deviates from the allowable ΔT_{min}. This can be attributed to the selection of steam extraction pressures in the conventional design methodology. The steam extraction pressure is based on the saturation temperature of the steam rather than the actual temperature of the steam. As the pressure level increases, the degree of superheat available in the extracted steam is very high and this leads to the deviation from the designed ΔT_{min} for the system. The Pinch based design requires a new arrangement for the feedwater heaters which makes better use of this available superheat in the extracted steam, and this result in increased steam extraction mass flows and a corresponding increase in the final feedwater temperature for the same extraction pressures. Despite the increase in steam extraction mass flows, the Pinch method of design results in higher power output from the turbines for the same fuel input. In the Pinch method, the external process heat is integrated in such a way that it substitutes the steam extraction of the highest pressure levels and hence allows the most expensive steam to generate power while using the best of both steam extraction and external process heat to preheat the feedwater. This leads to a systems approach in designing the steam cycle that is tightly integrated with other sub-systems in the power plant. As this systems approach requires a whole new arrangement of heaters, the method is best suitable for new plants rather than retrofit applications. The systems approach results in a more complicated and integrated feedwater heating network for an oxy-combustion coal based power plant. If needed, simpler heat exchanger network designs can be derived at the expense of thermal efficiency by using the same Pinch method. For instance, a steam cycle designed by using a systems approach achieves the same thermal efficiency with fewer number of steam extractions from the turbines [6].

Fig. 5 shows the overall thermal efficiency achieved by the various design cases. The improvement brought by heat integration of the CPU and the steam cycle by the conventional design method amounts to 1.1 percentage points (Cases 2 and 4 or 3 and 5). The Pinch method adds 0.4 percentage points (cases 2 and 3 or 4 and 5) in net LHV efficiency improvement over the conventional design method. The overall efficiency improvement achieved both in the subcritical and supercritical cases are 1.5 percentage points respectively.

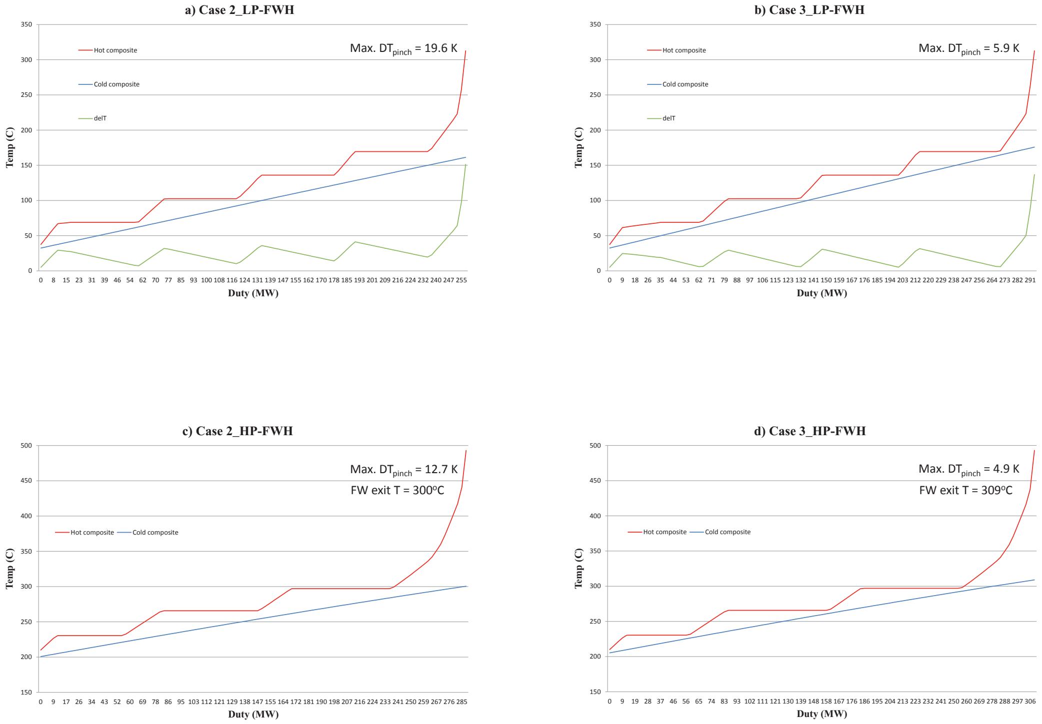

Fig. 4 Composite curves of the feedwater heating train (Case 2 and 3)

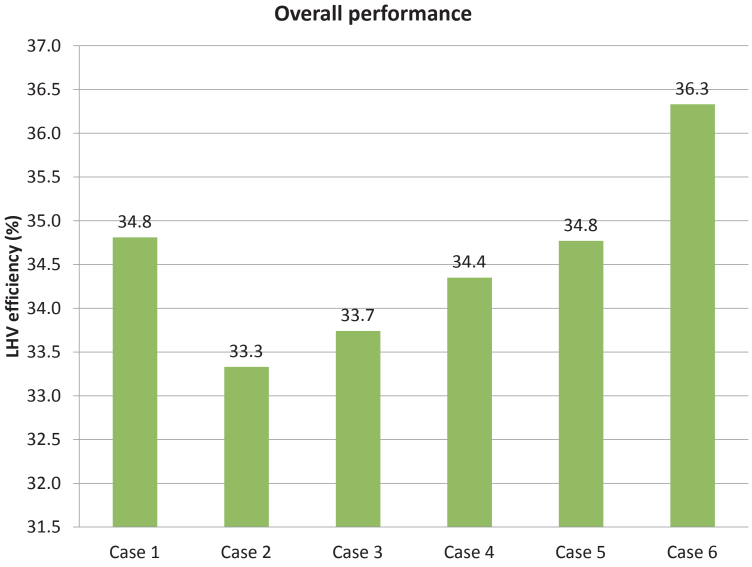

Fig. 5 Comparison of the overall efficiency of various integration cases

Integration of the compression heat from the CPU compressors into the steam cycle may result in some operational difficulties. The steam cycle becomes more complex and may face difficulties in changing the power output when required. Moreover, the startup and the shutdown procedures of such integrated systems may be complicated compared to conventional designs. But keeping in mind the energy penalty associated with CO_2 capture, such heat integration within the power plant is necessary to increase the overall efficiency of the power plant. Similar approach of using pinch analysis to reduce the capture penalty of post combustion CCS power plants also shows the promising potential of heat integration [13].

4. Conclusion

Pinch analysis is used as a tool to integrate the compression heat from the CPU compressors and low grade heat from the boiler flue gases into the feedwater heating train of a steam cycle. The study shows that the Pinch method can be used as an effective tool to design steam cycles for oxy-combustion power plants with considerable efficiency gains over the conventional design methods available. The study also shows the potential available in process heat integration to reduce the CO_2 capture penalty of an oxy-combustion coal based power plant. Recovering low grade heat and using the existing power cycle to generate more power can be one of the easiest ways to improve the reliable oxy-combustion technology for coal based power plants. Heat recovered from the CPU compressors improves the overall efficiency by 1.1 percentage points. The pinch method of heat integration helps utilize the recovered heat better and hence adds another 0.4 percentage points to the overall net efficiency of the power plant.

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