OPERATIONAL PAPER

COUNTER-FLOW AIR HEATER FOR INDUSTRIAL WATERTUBE BOILERS

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Abstract

Air heaters in industrial watertube boilers are typically tubular heat exchangers that preheat air before it is used in combustion. Located near the end of the boiler flue gas path, the air heater serves to extract excess heat from the flue gases and transfers it to cold air that is pumped into the boiler by the forced draft fan.

The feeding of hot air into the furnace increases combustion efficiency by assisting the fuel to reach its ignition temperature faster, as well as by reducing the relative humidity of the combustion air. This, in turn, reduces unburnt carbon in the fly ash and results in more stable combustion, both of which result in increased boiler efficiency.

In this study, it was shown that by utilising an air heater design where heat exchange is performed in a counter-flow arrangement, rather than the parallel-flow arrangement that is more traditionally used in bagasse-fired boilers, it is possible to achieve an increase of more than 10% in combustion air pre-heating, which results in increased combustion stability and efficiency, particularly when firing bagasse with a high moisture content.

Keywords: boiler, water tube, air heater, boiler efficiency, bagasse

Introduction

Air heaters in industrial watertube boilers are typically tubular heat exchangers that preheat air before it is used in combustion. Located near the end of the boiler flue gas path, the air heater serves to extract excess heat from the flue gases and transfers it to cold air that is pumped into the boiler by the forced draft fan.

The feeding of hot air into the furnace increases combustion efficiency by reducing the relative humidity of the combustion air and assists the fuel to reach its ignition temperature. This, in turn, reduces the unburnt carbon in the fly ash and results in more stable combustion, both of which result in increased boiler efficiency. The typical increase of boiler efficiency due to air heaters is around 2-3%.

By utilising an air heater design where heat exchange is performed in a counter-flow arrangement, rather than the parallel-flow arrangement that is more traditionally used in bagasse-fired boilers, it is possible to further increase the efficiency gain of air heaters within an industrial watertube boiler. When the air is flowing in a counter-flow direction relative to the flue gas, the temperature difference is larger, in comparison to a parallel-flow direction, which results in a larger amount of heat transfer within the exchanger. In addition, the temperature difference distribution is much more uniform along the heat transfer area, which results in reduced thermal stresses within the exchanger.

The aim of this study is to develop a mathematical model to contrast the performance of parallel-flow and counter-flow air heaters and, in particular, the heat transfer and tube metal temperatures, and to compare it with the results of a recent project undertaken by John Thompson, who converted an existing parallel-flow air heater to a counter-flow arrangement.

Materials and Methods

Site

The boiler on which this modification was performed is a typical bagasse-fired bi-drum watertube boiler, operating at 31 bar(g). The boiler was originally fitted with a vertical two-pass tubular air heater, with flue gas travelling vertically down inside the tubes and air travelling across the tubes, first over an upper pass and then over a lower pass.

Thermal modelling

Theoretical models of the boiler operating with both the original parallel-flow air heater, as well as the updated counter-flow air heater, were developed by using proprietary software. A discretised calculation on the air heater was also prepared by using the methods set out by Gnielinski in the VDI Heat Atlas [1-3], in order to obtain the localised air and gas temperatures, as well as the tube metal temperatures.

Modification to the existing air heater

The modification to the ducting, casings and dampers to convert the air heater from a parallel-flow configuration to a counter-flow configuration was done by John Thompson during the 2022/23 off-crop period.

The design of the air heater tube bank remained unchanged, with the total number of tubes in both the transverse and longitudinal directions, as well as the staggered tube arrangement, remaining as-is.

After the modification, the air first travels across the lower pass, after which it travels across the upper pass, with the flue gas flow remaining unchanged. Figure 1 shows the air flow in blue and the gas flow in red, for both configurations.

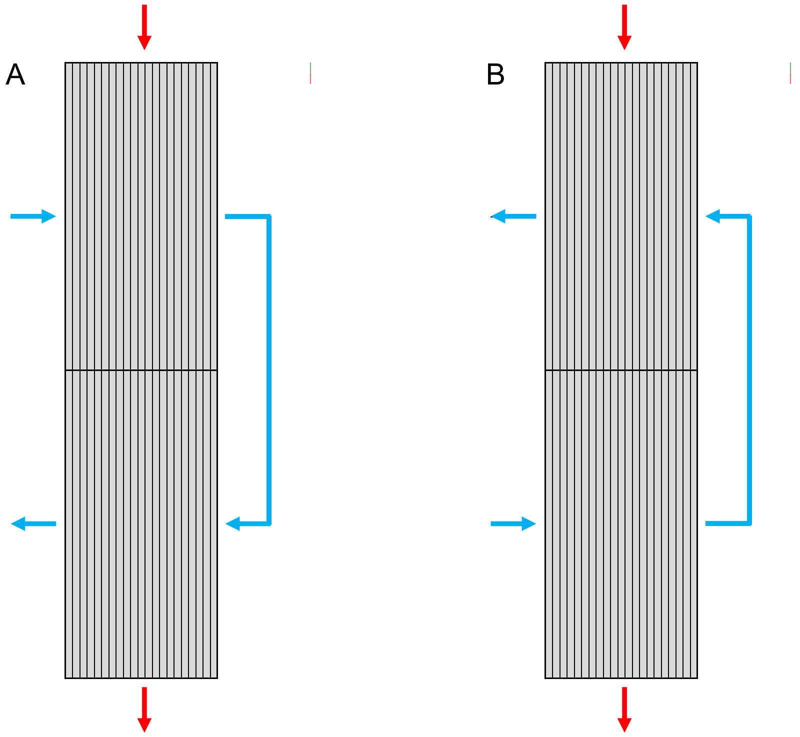

Figure 1. Air heater configuration for parallel-flow (A) and counter-flow (B)

Testing

Operational data were collected from the boiler control system by using the existing instrumentation. All the relevant data from the boiler operation during the 2022 crop were collected to study the operation prior to the modification, and all the data from the 2023 crop (to date) were collected to study the current operation.

Results and Discussion

Log mean temperature difference

The total heat transfer $\dot{Q}$ through any heat exchanger can be calculated as follows: [4]

$$\dot{Q} = UA\Delta T_{LM}$$

where U is the overall heat transfer coefficient, A is the total heat transfer surface area, and ΔT_{LM} is the logarithmic mean temperature difference (LMTD) between the two fluids.

Since the overall heat transfer coefficient for any two-pass air heater - be it a parallel- or counter-flow air heater - stays relatively constant throughout the tube banks, the only way to increase the efficiency of an air heater of a constant size is to increase the LMTD.

In the case of a parallel-flow air heater, the LMTD is calculated as follows:

$$\Delta T_{LM} = \frac{(T_{Gas.In} - T_{Air.In}) - (T_{Gas.Out} - T_{Air.Out})}{\ln\left((T_{Gas.In} - T_{Air.In})/(T_{Gas.Out} - T_{Air.Out})\right)}$$

In the case of a counter-flow air heater, the LMTD is calculated as follows:

$$\Delta T_{LM} = \frac{(T_{Gas.In} - T_{Air.Out}) - (T_{Gas.Out} - T_{Air.In})}{\ln\left((T_{Gas.In} - T_{Air.Out})/(T_{Gas.Out} - T_{Air.In})\right)}$$

Plots of the differences between the gas and air temperatures for the air heater in question can be seen in Figure 2.

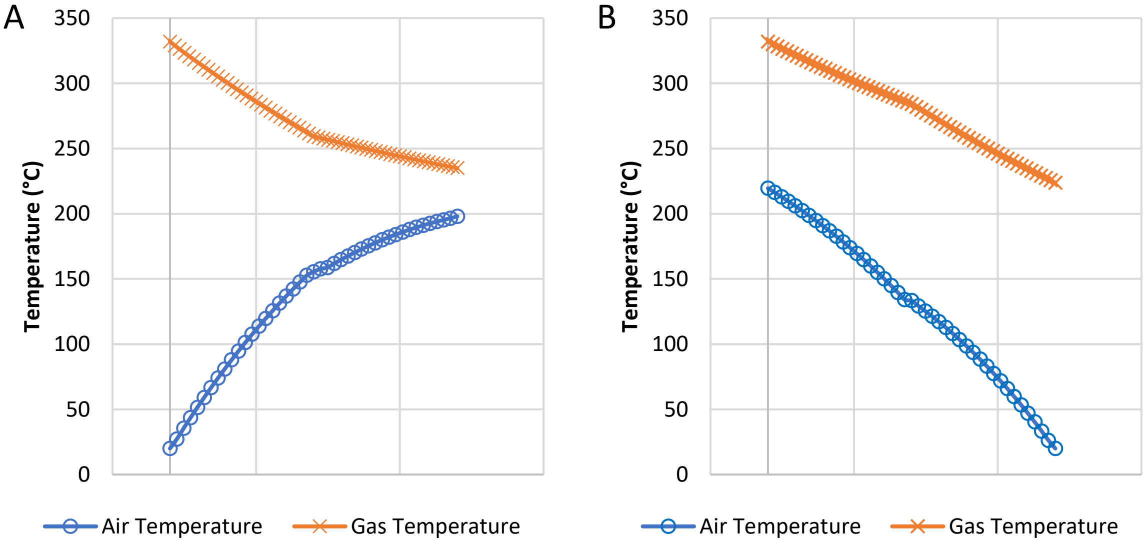

Figure 2. Difference between the gas and air temperatures for the parallel-flow (A) and counter-flow (B) configurations

These graphs show that the temperature difference between the flue gas and air in the original parallel-flow configuration is initially very large, but it rapidly decreases as the air and gas flows through the air heater. In the counter-flow arrangement, however, the difference in temperature between the flue gas and air remains relatively large throughout the air heater.

Performance increase in the counter-flow arrangement

The LMTD for the air heater in question, in its original parallel-flow configuration, with the boiler operating at its maximum continuous rating (MCR), was calculated from a theoretical model (which was correlated with the site data) as 133°C.

In the revised counter-flow arrangement, the temperature difference between the gas and air is more constant throughout the air heater. The LMTD in this revised configuration was calculated as 149°C, which is an increase of more than 12%.

The increase in the overall heat transfer through the counter-flow configuration is also significant at more than 10%, being up from 9 580 kW to 10 600 kW, with no change to the tube bank.

The air outlet temperature of the air heater increased from 198°C in the parallel-flow configuration to 219°C in the counter-flow configuration, which is an increase of more than 20°C and which greatly assists the combustion stability in the boiler, particularly during periods when the bagasse moisture content is high.

The effect of this additional heat transfer on the overall boiler efficiency is somewhat tempered by an economiser downstream of the air heater, which results in only a 7°C decrease in the final gas temperature, or roughly a 0.3% increase in efficiency when operating at full capacity. Had the boiler not been fitted with an economiser, the increase in the overall efficiency would have been significant.

Dew point corrosion and fouling

The dew point temperature of the flue gas in a bagasse-fired boiler is typically around 65°C, due to the large quantity of moisture that is normally present in bagasse. As a result, the moisture in the flue gas will tend to condense on any surface with a temperature that is lower than this.

Figure 3 shows the differences in inside metal temperatures in the air heater tubes between a counter-flow and parallel-flow configurations, with the green hues indicating lower temperatures and the red hues indicating higher temperatures. The flow of air through the air heater is indicated by blue arrows, while the gas flow is indicated by red arrows. It is worth noting that the lowest metal temperature on a counter-flow air heater is lower than that of a parallel-flow unit (in this case, 151°C vs 135°C with the boiler running at full capacity), and also that the area of low metal temperatures on a counter-flow unit is significantly larger than on a parallel-flow unit (20% of the air heater inside the tube area is less than 180°C in the counter-flow arrangement, compared to only 5% in the parallel-flow arrangement.)

The risk of condensation in a counter-flow air heater is subsequently higher than in a parallel-flow air heater, which also brings with it the risk of corrosion and fouling in the air heater tubes.

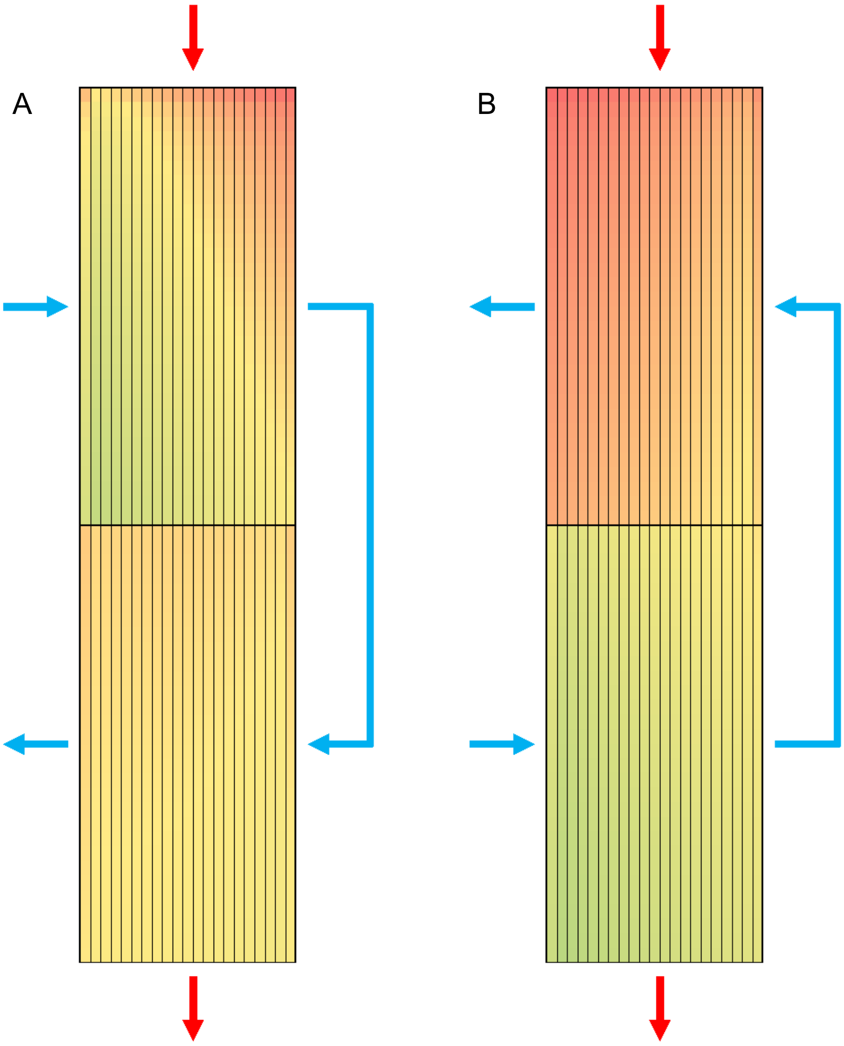

Figure 3. Air heater tube metal temperatures for the parallel-flow (A) counter-flow (B) configurations

John Thompson has recently successfully used less-traditional tube materials that better withstands corrosion caused by condensation in the air heater tubes than traditional low-cost carbon steel tubing. However, care should be taken when selecting corrosion-resistant air heater tubing; some materials might be susceptible to chlorine attack in bagasse-fired boilers or may offer a reduced thermal conductivity, which might negate any heat transfer benefits of a counter-flow arrangement.

Another way in which the risk of condensation in the air heater can be mitigated is by ensuring an even gas- and air-flow distribution through the air heater, which can be done by modelling and optimising the flow of gas from the boiler gas outlet duct through the air heater, using computational fluid dynamics (CFD). The CFD analysis is used in the redesign of ducting and/or guide vanes to ensure that no areas exist where localised low gas velocities, or high air velocities, will reduce the air heater tube metal temperatures.

Finally, it would also be possible to install a steam air heater to pre-heat the combustion air prior to the air heater, which would not only result in higher tube metal temperatures, but also an increased cycle efficiency when co-generating, due to reduced condenser losses.

Comparison of calculations with recorded site data

Following the modifications to the boiler in question, the initial indications are that the air outlet temperature from the air heater has increased by nearly 35°C. While this increase is certainly impressive, it is unlikely that this was solely a result of the reconfiguration of the air heater;

and that it was more likely, in part, due to general maintenance on the boiler that was carried out during the off-crop.

Figure 4 shows the calculated, as well as the measured air temperatures against the boiler load, from 55% to 100% MCR for the previous parallel-flow configuration, as well as the current counter-flow arrangement.

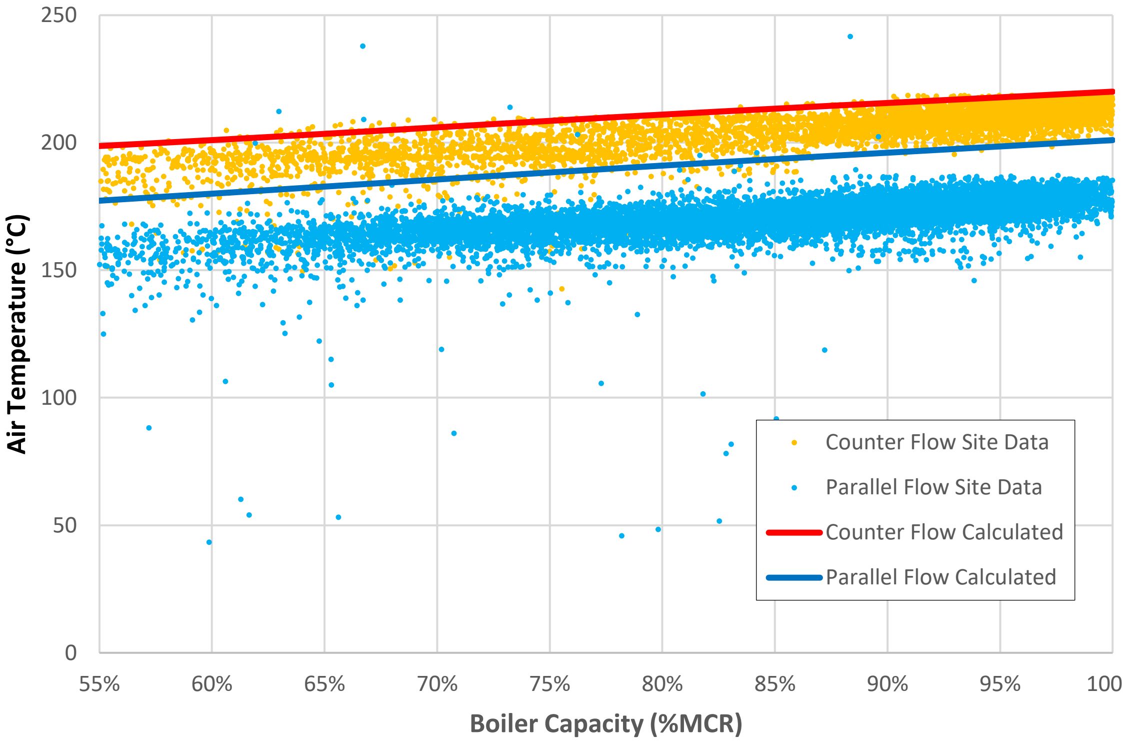

Figure 4. Calculated and measured air outlet temperatures from the air heater before and after reconfiguration

The predicted air outlet temperatures from the air heater in its original parallel-flow configuration were lower than expected, although this is likely the result of compromised air heater tubes and/or ducting. The predicted air outlet temperatures from the air heater for the new counter-flow arrangement correlate well with the actual measured site data across a wide range of operating loads.

The data show that the measured air temperatures have a roughly 20°C spread for any given boiler load and that the upper limit of this range coincides with the calculated air temperature. This spread is most likely the result of a combination of factors, including fuel quality, ambient conditions and boiler load variations.

Summary of relevant boiler parameters

The relevant gas and air temperatures for various boiler loads, as well as boiler efficiencies, are summarised in Table 1 below:

Table 1. Summary of relevant boiler parameters

		Counter-flow				Parallel-flow			
Operating capacity	% MCR	40%	60%	80%	100%	40%	60%	80%	100%
Boiler efficiency (GCV)	%	66.85	66.53	66.03	65.48	66.56	66.22	65.71	65.15
Air heater air outlet temperature	°C	192	201	211	220	169	180	191	201
Air heater gas inlet temperature	°C	264	288	311	332	264	288	311	332
Air heater gas outlet temperature	°C	170	190	209	227	183	202	220	237
Economiser gas outlet temperature	°C	131	144	157	170	136	149	163	176

Conclusions

A mathematical model was developed to calculate the localised heat transfer in both a parallel-flow and a counter-flow air heater, which compares favourably with the measured site data, following the conversion from a parallel-flow to a counter-flow unit on a bagasse-fired water-tube boiler.

The modification resulted in a more than 20°C increase in the combustion air temperature, which correlates well with the theoretical calculations and greatly assists both the combustion efficiency and stability. However, extreme care should be taken when performing such a modification to an existing boiler, as a counter-flow air heater is much more likely to experience dew-point corrosion and fouling. The ways in which this can be mitigated include CFD modelling of the air and gas flow through an air heater to ensure proper air and gas flow distribution, as well as the selection of a non-traditional material for the air heater tubing.

The overall boiler efficiency after the conversion also increased marginally (an increase of roughly 0.3%, when operating at full capacity). The increase would be much more significant on a boiler where the air heater is the last piece of heat recovery equipment, such as boilers with an economiser before an air heater in the gas path, or those without an economiser.

This study has shown that this conversion can be a cost-effective way of improving the operation of an existing bagasse-fired boiler.

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