Efficient Combustion of Waste Fuel with Supercritical CFB Technology

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Presented to:
NTPC Global Energy Technology Summit 2014

Date:
November 7-9, 2014

Location:
New Delhi, India
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BR-1924

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Keywords: IR-CFB, Washery Rejects, IBHX, Supercritical, Once-Through

Abstract

With government authorities of India directing mines to wash coal to lower the ash content and increase the gross calorific value (GCV), reserves of high ash, low GCV washery rejects will remain behind at the site. The only technology capable of effectively burning this opportunity fuel economically is a circulating fluidized-bed (CFB) boiler. In India, two-stage internal recirculating (IR) CFB technology has been supplied and serviced for 18 CFB units to date using washery rejects as fuel for subcritical applications. Globally, CFB technology has gained recognition as being a viable technology for larger utility boilers as CFBs have now been successfully operated in commercial boilers as large as 600 MW. At this scale, CFB technology has transitioned from subcritical to supercritical circulation, and typically incorporate an additional fluidized-bed heat exchanger coupled with the lower furnace. This combines the benefits of a CFB, fuel flexibility and low emission without additional equipment, with the plant efficiency benefits of supercritical technology. By installing mine-mouth supercritical CFB power plants, fuel transportation costs are minimized. In addition, a reliable supply of washery rejects is available to keep the unit consistently supplied with fuel for generating electricity to the grid. The result is an efficient, economical and environmentally responsible way of disposing of waste coal.
Introduction

The directive on Ministry of Environment and Forests currently restricts the use of coal containing an ash content greater than 34% to power stations located less than 1000 km away from the pit heads. These regulations may even be further reduced to plants located within 500 km. In addition, based on fuel supply agreements, a minimum GCV of 3100 kcal/kg is to be maintained by Coal India Ltd. To improve the quality of Indian coal, coal is typically washed to decrease the ash content and increase the GCV. This results in a reserve of low GCV (approximately 1800 kcal/kg), high ash (>55%), washery rejects left behind at the washing site.

Figure 1 shows the growth in coal demand for utility power in India over the last six years. Also, coal imports in India have increased 18% year over year. Currently, the Ministry of Coal indicates there is about 103 t\textsubscript{m} per annum of installed washery capacity with a growth potential to 244 t\textsubscript{m} per annum over the next 5 years. Washery rejects can be considered a good alternative fuel to coal. Washing coal produces approximately 80% high GCV low ash fuel to the end user, and the remaining 20% low GCV high ash rejects remain at the site. Thus, of the 244 t\textsubscript{m} per annum washed, 48.8 t\textsubscript{m} per annum of washery rejects are generated. If the average GCV of these rejects is 1800 kcal/kg, then there is
enough capacity in rejects alone to consistently fuel over 3.5 GW of electricity – not considering the reserves of washery rejects established and currently being accumulated.

Rejects remaining at the site not only represent an opportunity fuel, as the cost to produce power is cheaper than conventional coal-based power, but also represent an environment friendly way to use the coal rejects. By locating plants close to mine-mouths, transportation costs are minimized and a constant supply of fuel is readily available. CFB technology, and even more so, supercritical CFB technology, represents an efficient, economical and environmentally responsible path forward in disposing of washery rejects.

The effort to scale industrial size CFBs to commercial scales has resulted in a blend of multiple technologies: CFB, BFB, and supercritical circulation. For improved efficiency at higher capacities, the typical subcritical circulation has been increased to supercritical steam conditions with superheat and reheat temperatures capable of 600C. For optimum heat transfer and reduced cost, bubbling fluidized-bed heat exchangers are typically coupled to the lower furnace for reheat and superheat surface.

**IR-Circulating Fluidized-Bed Technology**

IR-CFB boilers circulate solid particles within the combustion process to transfer heat from the chemical process to the boiler’s water-cooled tube enclosure and other heating surfaces as shown in Figure 2. A two-stage solids separation system is utilized where impact type separators (U-beams) located at the furnace exit internally recirculate about 95% of the solids, while multi-cyclone dust collectors (MDC), located after the convection pass, recycle the remaining solids to control furnace temperatures and improve limestone and carbon utilization. Furnace temperatures are typically controlled to 815 to 900C to optimize the sulfation reaction of calcium oxide resulting in low sulfur dioxide emissions. With MDC controllable solids, a wide turndown ratio (5:1) is achievable. Refractory use is 80 to 90% less compared to single-stage solids collection systems with hot cyclones.
Bubbling Fluidized-Bed Technology

The bubbling fluidized-bed (BFB) combustion process has been successfully applied to smaller industrial boiler applications as shown in Figure 3. In a smaller furnace, the coal can be fed over the
top of the bed, and the bed gas velocities can be lowered to minimize erosion rates. Heat transfer surface may be placed within the bed to achieve the desired bed operating temperature. In smaller, lower velocity beds, the surface can be arranged to eliminate the need for complicated tube supports. Because of the lessons learned from coal-fired applications, improvements provide smaller capacity BFB boilers capable of using a wide range of biomass fuels, and many BFB industrial projects have been successful for many years.

**Supercritical Technology**

Since Babcock & Wilcox introduced the first supercritical steam cycle in the 1950s, supercritical boilers have been built all over the world. Steam parameters continue to be increased with units today operating at steam temperatures as high as 600°C. See Figure 4. When comparing similar plant

![Figure 4. SWUP and VTUP Boiler](image-url)
steam flows, supercritical steam cycles typically generates about 4% more net power than subcritical steam cycle. Cycle thermodynamic efficiency is improved by increasing the temperature of the heat source for a constant sink temperature. This temperature can be increased when the feedwater pressure is increased because the boiler inlet pressure sets the saturation temperature in the Rankine cycle. If the pressure is increased above the critical point of 220 bar, the addition of heat no longer results in a typical boiling process in which there is defined interface between the steam and water. Rather, the fluid can be treated as a single phase. This is referred to as a supercritical steam cycle.

Supercritical Once-Through CFB Technology

Supercritical once-through CFB technology is based on the experience and expertise obtained from current CFB, BFB, and supercritical once-through boiler designs as shown in Figure 5. Figure 6 shows how Babcock & Wilcox Power Generation Group (B&W PGG) combined these technologies with its supercritical CFB with in-bed heat exchanger (IBHX). To optimize the boiler aspect ratio of the supercritical CFB design, the furnace features dual primary zones which share a common upper furnace shaft. This reduces the furnace enclosure perimeter by making it squarer as opposed to rectangular. In addition, an air plenum is introduced in the center of the furnace providing secondary air to each of the primary zones. This allows increased furnace depth while maintaining secondary air penetration within industry standards for emissions. Internal to the furnace between the dual primary
zones is a bubbling fluidized bed, or the IBHX. The BFB is fluidized at approximately 1 m/s compared to the CFB which is typically fluidized at roughly 5 m/s. Due to the entrainment in the CFB furnace, solids are naturally lifted and carried into the BFB as shown in Figure 7. A surplus of solids

![Figure 6. B&W PGG Supercritical Once-Through CFB with IBHX](image)

![Figure 7. IBHX Functionality](image)
is carried into the BFB, and for a mass balance, the equivalent amount of solids flows through the underflow ports and overflow ports. Solids flow through the underflow port is varied through localized slumping, and is thus controllable. Excess solids that do not flow through the tube bundle through the underflow port simply flow out the overflow ports, maintaining a constant BFB level, and therefore constant pressure differential across the bed. Ultimately, the ability to control solids flow through the underflow port can be directly related to the ability to control absorption in the tube bundle and has been verified through hot pilot testing facilities located at Southeast University in Nanjing, China.

Three levels of modeling have been performed to validate and verify IBHX performance and functionality as shown in Figure 8: simulation, cold pilot testing and hot pilot testing. Using a three-dimensional particle fluid dynamics software package, designs for both subcritical and supercritical applications have been modeled. Simulation models were used to characterize port sizing and achieve desired hydrodynamics between the CFB and BFB. Results obtained from simulations have been implemented on the cold pilot for hydrodynamic verification. The cold pilot is ¼ scale of the hot pilot facility; where scaling has been performed according to Glicksman, et al., and is constructed of

![Figure 8. IBHX Verification and Validation](image-url)
plexiglass to visually observe furnace hydrodynamics. Using the cold model, results obtained from simulation are tuned and furnace hydrodynamics are verified for various furnace operating conditions. Upon hydrodynamic verification, results are implemented into the hot pilot for performance verification. The 2.5 MWth hot pilot features adjustable underflow ports, overflow ports, partition wall height, tube bundle arrangement, and bubble cap arrangement. It is large enough to simulate full-scale hydrodynamics and includes water cooled tubes and heat transfer probes to measure heat transfer within the IBHX to confirm both local and overall heat transfer characteristics. For various arrangements, performance related to the IBHX and the ability to control performance of the IBHX is characterized.

Supercritical once-through CFB is ideal for washery rejects because it combines the benefits of a CFB (fuel flexibility, ash contents up to 60%, heating values as low as 1800 kcal/kg, low emissions), and the benefits of a BFB having in-bed surface (exceptional heat transfer characteristics), with the benefits of supercritical circulation (superior plant efficiency with steam conditions capable of greater than 270 kg/cm² with 600C superheat, 600C reheat). In addition, a two-stage separation system (proven technology in India through 18 CFBs firing washery rejects) offers significant advantages over cyclone technology.

Economically, using a two-stage separation system allows a more compact design resulting in a lower footprint, reduced height, and lower cost. Typical supercritical once-through boiler designs requires about 2600 kJ/kg enthalpy at the separator at maximum continuous rating (MCR). This allows adequate superheating to keep the separator dry and prevent moisture carryover to the superheater as load and pressure are reduced. Typical cyclone designs have a high acceleration of solids entering the cyclone, and prevents including surface area in front of the cyclones due to erosion. As a result, for a given plan area, furnace height is set by required surface area to achieve proper absorption before the separator. As shown in Figure 9, using a two-stage separation system, there is no acceleration of solids across the U-beams, and therefore, surface area can be placed in front of the U-beams using water-cooled wingwalls. As a result, furnace height is set by gas residence time and surface area is supplemented by water-cooled wingwalls to achieve a separator enthalpy of approximately 2600 kJ/kg at MCR. A typical circuitry and enthalpy diagram for a supercritical once-through CFB is shown in
Figure 10. Ultimately, water-cooled wingwalls allow a significantly shorter and more compact design that reduces building steel resulting in lower cost.

Functionally, using a two-stage separation system allows the boiler to have an excellent turndown ratio, as wide as 5:1 because of controllable MDC recycle. With the IBHX being internal to the furnace, a high solids influx with relatively constant temperature is maintained throughout turndown. To control final superheat and final reheat absorption within the IBHX throughout such a wide control
range, two control methodologies are used. The first method of IBHX control is solids flow through the underflow port. As shown in Figure 11, hot pilot testing has confirmed with the current configuration that absorption can be varied by approximately 20% using solids flow alone, and testing continues to expand upon this range. The second control method is through a compartmentalized windbox which will allow slumping of portions of the in-bed tube bundle, effectively removing surface from being able to transfer heat. By using bed slumping and solids flow through the underflow port, IBHX absorption can be controlled throughout turndown. Furthermore, since final reheat and final superheat are placed in the IBHX, the required quantity of high alloy metal is drastically reduced.

![Hot Pilot Absorption](image)

**Figure 11. IBHX Absorption Control**

Typical heat transfer coefficients can be 5 times greater than that of the convection pass, meaning that when surface is moved from the convection pass to the IBHX, it will do so with 1/5\(^{th}\) the surface area. Since the IBHX is fluidized with air, final reheat and final superheat remain in an oxidizing atmosphere. This allows the use of high chlorine and sulfur fuels without concerns for corroding high alloy metals.

For high ash fuels, as is the case with washery rejects, a reliable bottom ash handling system is required to handle the quantity and constant removal of ash from the CFB. Water-cooled screws have been successfully operating for over 20 years in an IR-CFB boiler in Ebensburg, Pennsylvania, USA (waste fuel with 40 to 50% ash). As a result, the plant has experienced no forced outage time due to the ash handling system. Similarly, successful operation of water-cooled rotary ash coolers for waste
fuel with a high ash removal rate at a 250 t/h washery rejects boiler located at a ferro alloy unit in eastern India has been demonstrated. Again, no forced outages have been experienced due to the ash handling system. The cooling water in the ash handling system can utilize an open or closed loop system — the open loop system being the most simple and the closed loop system providing the advantage of improved plant efficiency and reduced water consumption in regions where water availability is scarce. Heat is recovered to the system with low pressure condensate heating.

**Conclusions**

The use of circulating fluidized-bed technology provides a method for utilizing high ash, low GCV waste coal produced through washing. By advancing CFB technology to supercritical steam cycles, this can now be done more efficiently and with a smaller carbon footprint than before. This provides an economical and environmentally responsible way of disposing of waste coal.

**References**


**Bibliography**


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