Firetube Boiler Forever Changed by Advancements in Analytical Design Techniques

By Florian Wisinski
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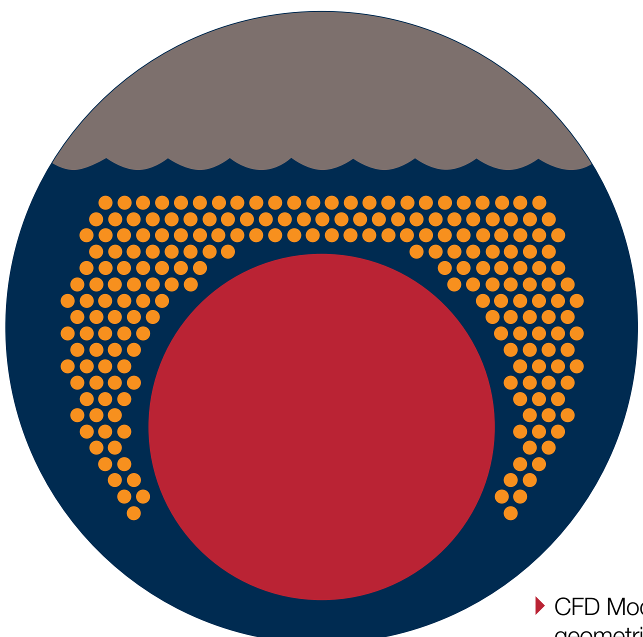
For decades, engineers have been trying to build a better boiler system. Their efforts have resulted in numerous innovations in boiler technology, burner technology, and controls, but none has really revolutionized the industry. In fact, today's core firetube design is fundamentally the same as it was when it was introduced 70 years ago, during World War II.

Credited with developing the first packaged firetube boiler and leading industry innovations over the years, Cleaver-Brooks engineers possess the fundamental knowledge required to transform scientific discovery into innovative new products, processes, and solutions. Recent advancements in computational fluid dynamics (CFD) and other analytical design techniques have given these engineers the ability to perform the sophisticated calculations necessary to design the next-generation firetube boiler.



Optimizing the geometry of the furnace for near-perfect combustion.

Recognizing that most efforts to develop new visions for the industry have remained relatively close to the status quo, engineers at Cleaver-Brooks challenged themselves to develop an entirely optimized system from the ground up. They asked, “If we were to optimize a firetube boiler for combustion and thermal performance, starting with a blank sheet of paper, what could be achieved?”

Their recent efforts have resulted in a revolutionary boiler system, termed CBEX Elite, that features the lowest emissions, most robust combustion, and best thermal efficiency across all operating ranges. Compared to existing models, the CBEX attains the highest fuel efficiency in lower firing ranges. It also emits fewer air pollutants than any other firetube system on the market today.

Specifically, the CBEX Elite achieves several industry firsts, including: the use of ultra low NOx burner technology that results in meeting sub-5 ppm NOx on select models without selective catalytic reduction (SCR). In addition, its standard low NOx burners produce 30 ppm NOx and maintain 3% O_2 across the full operating range with 10:1 turndown.

The CBEX is available in sizes ranging from 100 to 2,200 HP. Design pressures are 150, 200, and 250 psig for steam, and hot water design pressures are 30 and 125 psig.

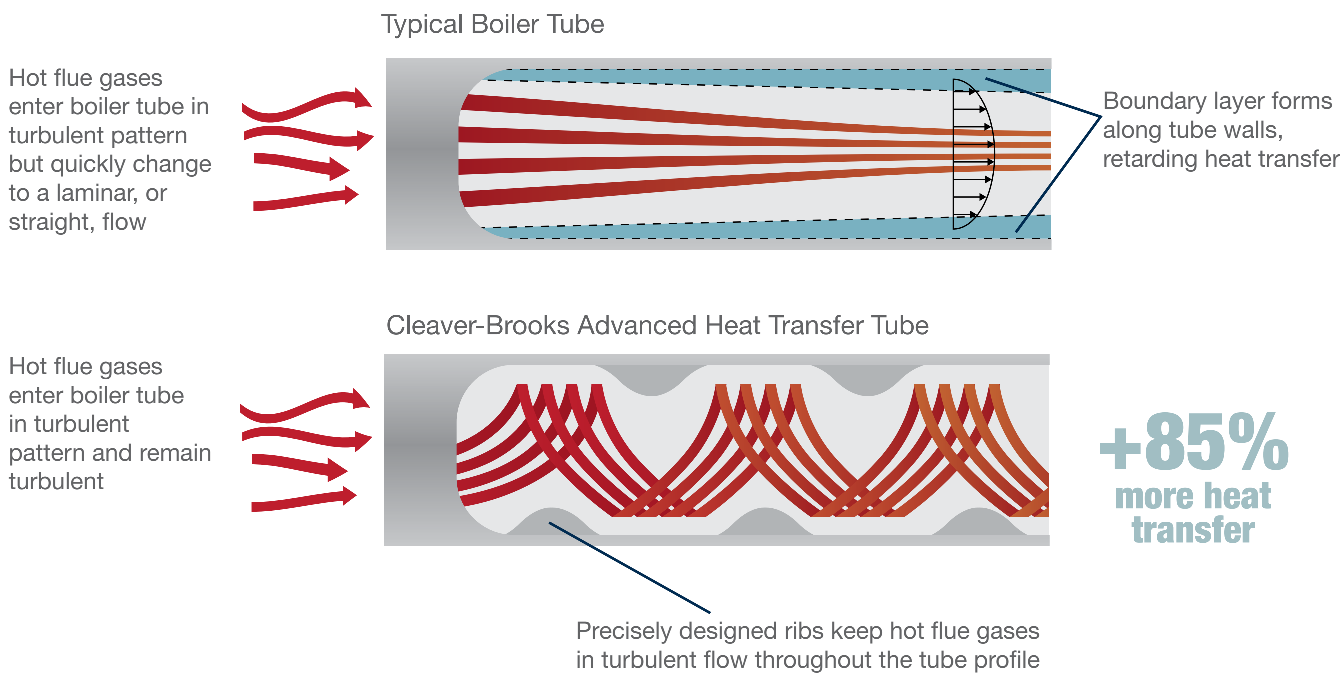
Pictured is the CBEX Elite 1,300 to 2,200 HP. The boiler also is available in sizes from 100 to 1,200 HP.

Achieving an Engineered, Balanced Design

Twenty years ago, a significant advancement was made in boiler tube technology—the spiral tube was introduced. This internally enhanced tube features helical ribs that significantly increase the heat transfer of gas flow compared to a traditional bare tube. Better heat transfer within a spiral tube is a result of an increased surface area as well as a complex boundary layer separation-reattachment phenomenon.

In a traditional bare tube, which is used in the majority of boiler designs, hot combustion gases enter the tubes in a turbulent flow pattern. This turbulent pattern produces good heat transfer initially, but the hot flue gas pattern quickly changes to a laminar flow, or straight parallel flow of gases. With the gases traveling in this straight pattern, a boundary layer forms along the tube walls, increasing with the distance of the tube. This layer serves as a barrier, retarding the heat transfer. As a result, a bare tube only utilizes a fraction of its diameter for heat transfer, which equates to a lot of wasted space.

Because 30% to 40% of a boiler's heat transfer takes place in the tubes, it is important to move as much heat as possible through them. Knowing that the laminar flow of flue gases causes poor heat transfer, for more than a decade engineers have been exploring ways to create turbulence of the flue gases throughout the length of the tube to increase heat transfer and decrease the formation of boundary layers. By adding helical ribs, or embossed spiral patterns, to the inside of a tube, engineers were able to create more turbulence of the hot flue gases and thereby create more heat transfer.



Typical boiler tube vs. C-B advanced heat transfer tube.

Rooted in sound engineering principles, the spiral tube fell short of its promised results of increased boiler efficiency because many of the tests of how the tube would affect the boiler were conducted via trial and error in the field. Within the past three years, a number of advanced software programs have become available, allowing engineers to perform extremely complex calculations on various elements of a boiler system, applying known engineering principles. One such program is CFD that uses numerical methods and algorithms to solve and analyze problems that involve fluid flows. Computers perform the complex calculations required to simulate the interaction of liquids and gases with surfaces defined by boundary conditions.

Using CFD, finite element analysis, and mathematical modeling, Cleaver-Brooks engineers began to improve the tube profile. Coupling the new modeling technology with their extensive knowledge of boiler systems, Cleaver-Brooks engineers dedicated countless hours to spiral tube engineering to perfect heat transfer within the proprietary spiral tube. They defined different boundary conditions and loads and fed the information into the computer to crunch the numbers. The computer gave them the ability to simulate various conditions and immediately test them in Cleaver-Brooks dedicated R&D center. The engineers would then analyze the calculations, continuing to refine the geometry to achieve the optimal result.

In the end, the advanced heat transfer spiral tube designed for the CBEX utilizes 100% of the tube diameter and increases heat transfer by 85% compared to a traditional bare tube. This proprietary tube is the only one to achieve these results.

Focusing on the Furnace

After redesigning the spiral tube, Cleaver-Brooks engineers began to analyze the furnace and pressure vessel to maximize the overall performance of the entire system. By perfecting the heating surface of the spiral tube, which transfers more heat in less space compared to a bare tube, the engineers were afforded the space to geometrically optimize the size and shape of the furnace, where 60% to 70% of heat transfer takes place. Utilizing advanced CFD modeling techniques, Cleaver-Brooks engineers maximized the heat transfer in the furnace radiant zone in order to achieve the optimum balance of high heat transfer with the lowest pressure drop.

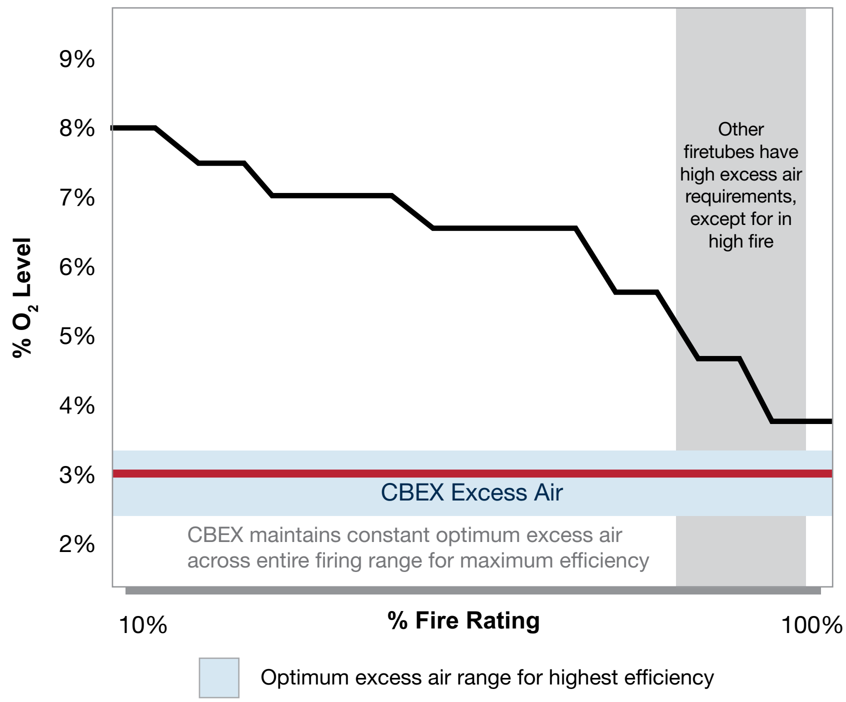
Balancing the heat transfer with the pressure drop was important because previous generation boilers with less heating surface per square foot often overheated in the field, specifically the rear tube sheet attachment. The optimized furnace Cleaver-Brooks designed for the CBEX has an average heat release rate of 125,000 BTU/hour/cubic foot compared to a boiler industry average of 150,000 BTU/hour/cubic foot. A low heat release rate keeps the flue gas temperature lower and reduces thermal expansion. A lower flue gas turnaround temperature at the end of the furnace reduces the temperature gradient of the tube sheet.

Engineers have learned that designing a larger, geometrically optimized furnace with lower heat release translates into lower NOx and better combustion. Better combustion results in high turndown and minimum excess air, which leads to greater energy efficiency. Competitive boilers require more excess air than the CBEX, which lowers operating efficiencies and spikes expenses.

In theory, to achieve perfect combustion, the quality of fuel and air would be a 1:1 ratio, with no unused fuel or air. This type of theoretical perfect combustion is called stoichiometric combustion. In practice, however, for safety and maintenance needs, additional air beyond the theoretical “perfect ratio” needs to be added to the combustion process. This additional air is referred to as “excess air.” With boiler combustion, if some excess air is not added to the combustion process, unburned fuel, soot, smoke, and carbon monoxide exhaust will create additional emissions and surface fouling. Even though excess air is needed from a practical standpoint, too much excess air can lower boiler efficiency, so a balance must be found between providing the optimal amount of excess air to achieve ideal combustion and prevent combustion problems associated with too little excess air, while not providing too much excess air to reduce boiler efficiency.

Research has shown that 15% excess air is the optimal amount to introduce into the boiler combustion process. While some boilers have been able to achieve 15% excess air at the top end of the firing range, the challenge presents itself at the lower end of the firing range, or below 60% of the boiler’s maximum capacity. In general, most boilers tend to increase excess air requirements as the firing rate of the boiler decreases, leading to a reduction in efficiency at the lower end of the firing range. Most boilers operate on the lower end of the firing range, so selecting a boiler that has low excess air throughout the firing range is important.

The terms excess air and excess oxygen can be used synonymously to define combustion, but they have different units of measurement. The percentage of excess air is the amount of air above the stoichiometric requirement for complete combustion. The excess oxygen is the amount of oxygen in the incoming air not used during combustion and is related to percentage of excess air. For example, 15% excess air equals 3% oxygen while firing natural gas.



Highest operating efficiency of any firetube: 10:1 turndown while maintaining 3% O_2 across the firing range.

Boiler turndown is critical and was also a key area of focus for Cleaver-Brooks engineers. The typical boiler plant has boiler capacity larger than what would normally be required to run their given process. This is due to redundancy requirements, changes in long-term plant demand, new efficiencies in the process, or any number of other factors. Often, over-sizing of the boiler is incorporated into the original design. The over-capacity, paired with the changing requirements for steam or hot water at a given time in the process, means boilers have to move through their firing ranges to meet demand, most of the time operating at 60% or less of their full firing range (capacity).

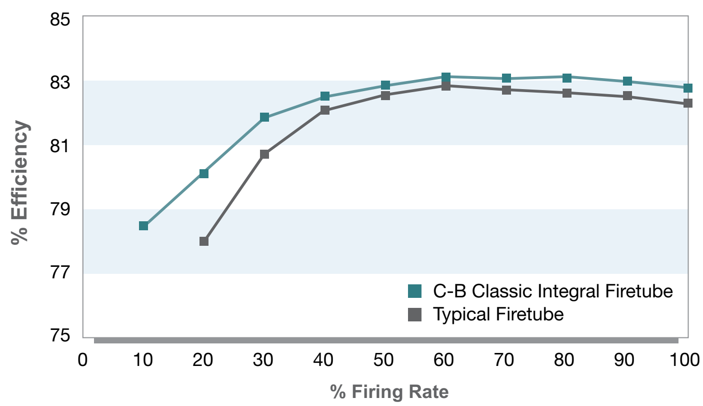
This leaves two important factors to consider: boiler turndown and boiler efficiency throughout the firing range. All burners have a specific turndown, ranging from 4:1 to 10:1 or higher, depending upon the burner design. As the demand for steam or hot water decreases, the boiler's burner "turns down" to try to only meet the required demand. If a burner only has 4:1 turndown, that means it can only operate at 25% of firing capacity (100%/4 = 25%). As demand continues to decrease, the firing rate must decrease. However, if the demand falls below the minimum turndown, the boiler will quickly meet the minimum process demands and then "cycle off" until more demand is needed. A boiler cycle consists of a firing interval, a post-purge, an idle period, a pre-purge, and a return to firing – causing valuable energy to be wasted.

Recognizing this, in 1990, Cleaver-Brooks engineers made 10:1 turndown standard in its classic line of firetube boilers, featuring the industry's benchmark integral burner. With 10:1 turndown, a boiler can "turn down" to 10% of capacity without cycling, preventing needless energy losses.

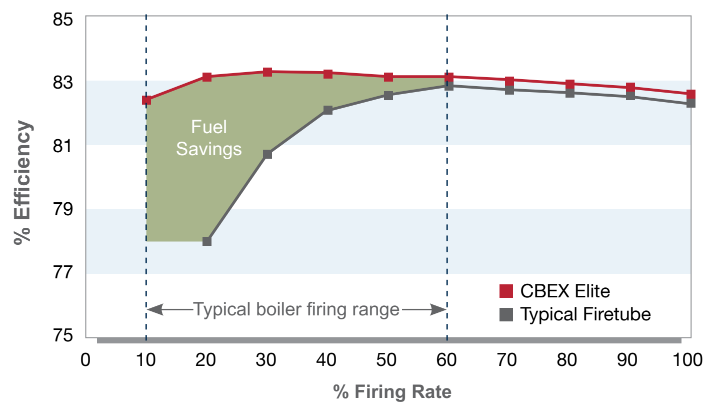
Boiler efficiency changes throughout the firing range – often falling dramatically as the boiler enters the lower end of the firing range. If boilers are operating at 60% of capacity, this decrease in efficiency leads to lower operating efficiencies and increased fuel expense.

Most of the CBEX Elite line features 10:1 turndown while maintaining the highest efficiencies ever achieved across the lower turndown range. Specifically, as the boiler turns down to 60% or below, the efficiencies remain high all the way down to the 10% firing range, not decreasing like other firetube boilers. With the advanced CBEX firetube boiler's 10:1 turndown combined with unprecedented high efficiencies across the turndown range, operators will recognize tremendous fuel savings while operating below the 60% firing rate and throughout the boiler's entire firing range.

EFFICIENCY % FOR A C-B CLASSIC INTEGRAL FIRETUBE VS. TYPICAL FIRETUBE THROUGH THE FIRING RANGE



EFFICIENCY % OF A CBEX ELITE VS. TYPICAL FIRETUBE THROUGH THE FIRING RANGE



Efficiency curves based on natural gas firing at 125 psig steam at 30 ppm NOx. Efficiencies do not reflect secondary heat recovery options.

The Power of Integration

Ultimately, the performance of a boiler is based on the ability of the burner, boiler, and controls to work together. Controlling the CBEX is the Cleaver-Brooks Hawk, an integrated control system, embodying precise boiler/burner management and safety with logic-based ancillary devices and functions.

The Hawk provides the ability to actively monitor efficiency trends and alerts operators when performance problems occur, before heat and energy loss becomes an issue. As a result, the boiler automatically tunes as a reaction to changes in environmental conditions.

Because the boiler remains tuned all the time, the operating efficiency of the boiler remains high, compared to a boiler that relies on manual tune-ups. Available options on the system include a variable speed drive (VSD) control and NOx trim for controlling the ultra-low NOx burners.

Advanced Hawk linkageless controls ensure precise repeatability.

The engineering optimization and commitment to integration available on the CBEX translate into a number of significant benefits compared to traditional firetube models. Among these are:

Highest Operating Efficiency of Any Firetube: 10:1 turndown while maintaining 3% O_2 – Perfecting the design of the tubes and furnace achieves the optimum balance of high heat transfer with the lowest pressure drop. This enables the CBEX to achieve 10:1 turndown while maintaining 3% 0_2 on most models. Due to the high turndown rate, the boiler cycles less, thereby minimizing purge losses and associated fuel costs. Better combustion results in minimum excess air and thus high efficiency across even the low operating range—where most boilers operate. The high efficiency and turndown across the operating range save a significant amount of fuel and reduce operating expenses.

Lowest Possible NOx (sub-5 ppm without SCR): The optimized furnace in the CBEX warrants lower heat release and optimizes combustion. This, combined with the Hawk integrated control system, reduces emissions to unprecedented levels. The CBEX can achieve 5 ppm NOx on select models. CBEX 30 ppm NOx burner models can achieve less than 10 ppm CO on select sizes.

Quick Steam Up: Due to smaller footprint and lower water volume, the system heats up 20% quicker than traditional firetube models.

Smaller Footprint and Weight: By optimizing the heat transfer of both the tubes and furnace, the CBEX requires less square footage of heating surface to achieve the same BTU output as traditional firetubes, all while maintaining the highest possible efficiencies. This facilitates a more compact boiler system design. As a result, the CBEX on average has a 15% smaller footprint and weighs 20% less than traditional boilers.

Extended Life: The low heat release rate keeps flue gas temperature lower and reduces thermal expansion. A lower flue gas turnaround temperature at the end of the furnace reduces the temperature gradient of the tube sheet. This, combined with the reduced thermal expansion of the furnace, increases the tube sheet and tube attachment's life, leading to longer pressure vessel life. As a result, Cleaver-Brooks offers an industry-leading, 15-year pressure vessel limited warranty on its CBEX Elite model.

At the end of the day, the engineers at Cleaver-Brooks did what they set out to do. They built a radically improved firetube in the CBEX, enabling a facility to operate more efficiently while significantly reducing floor space, fuel costs, and emissions.

Cleaver-Brooks is the only manufacturer in the world that offers a completely integrated boiler, burner, and heat recovery system. Because its engineers have the ability to test and refine integrated components, they can align cutting-edge boiler and burner technology in the industry with the latest in advanced controls. Using state-of-the-art computer programs such as advanced CFD modeling enables the engineers to perform extremely complex calculations that advance design performance, optimizing the integration of core competencies.

Cleaver-Brooks is a leading provider of boiler room products and systems that is committed to providing efficient solutions to help its customers and the industry reduce energy usage, cost, and environmental impact. It has a dedicated alliance of representatives available for consultation, sales, maintenance, and aftermarket support.

To locate a representative, visit cleaverbrooks.com or call (800) 250-5883.