BOILER TURNDOWN

How much is enough?

An Internet search for "boiler turndown" or "burner turndown" using one of the search engines with advanced search capabilities will return a substantial number of documents. Most of these documents are commercial, not academic or scientific, in nature, and all of them advance the thesis that turndown is always good, and the more turndown one has the better, regardless of the specific application or the type of boiler—even (or especially) the Scotch marine firetube boiler. So the conventional wisdom, clearly, promotes high turndown ratios as a very desirable characteristic in all boiler systems.

But is that really the case? Or is it a marketing myth, advanced by boiler and burner manufacturers?

If we are to test this theory then, logically, we must first address the question of what exactly is meant by burner and/or boiler turndown. If one accepts our simple definition of boiler turndown (ratio) as "the ratio of repeatable maximum to minimum boiler output," then it would appear that high turndown should be more fuel-efficient than a lower turndown ratio, be-

TABLE 2. ***Combustion efficiencies for burners firing natural gas.***

Power burners			Recommended ranges										
			Net stack temperature – F										
Excess air	Percent O_2	Percent CO_2	300	320	340	360	380	400	420	440	460	480	500
9.5	2.0	10.7	83.1	82.6	82.2	81.7	81.2	80.8	80.3	79.8	79.4	78.9	78.4
12.1	2.5	10.4	83.0	82.5	82.0	81.5	81.1	80.6	80.1	79.6	79.1	78.7	78.2
15.0	3.0	10.1	82.8	82.3	81.8	81.4	80.9	80.4	79.9	79.4	78.9	78.4	77.9
21.1	4.0	9.6	82.5	82.0	81.5	81.0	80.5	79.9	79.4	78.9	78.4	77.9	77.4
24.5	4.5	9.3	82.3	81.1	81.3	80.8	80.2	79.7	79.2	78.7	78.1	77.6	77.1
28.1	5.0	9.0	82.1	81.6	81.1	80.5	80.0	79.5	78.9	78.4	77.8	77.3	76.7
31.9	5.5	8.7	81.9	81.4	80.8	80.3	79.7	79.2	78.6	78.1	77.5	77.0	76.4
35.9	6.0	8.4	81.7	81.1	80.6	80.0	79.5	78.9	78.3	77.8	77.2	76.6	76.0
40.3	6.5	8.2	81.5	80.9	80.3	79.7	79.2	78.6	78.0	77.4	76.8	76.2	75.6
44.9	7.0	7.9	81.2	80.6	80.0	79.4	78.8	78.2	77.6	77.0	76.4	75.8	75.2

cause performance is being optimized to the actual load profile. Burner turndown has also been defined as "the reciprocal of the heat release of the burner normalized by the full firing rate."[1] That definition would, too, imply the desirability of high turndown. However, without an analysis of the boiler loads, operating cycles, and overall boiler efficiencies, those assumptions should not be made.

This article will examine the energy loss and resulting impact on boiler efficiency when comparing a boiler operating with a modulating burner having a 10:1 turndown to the same boiler operating at a 4:1 turndown. The energy balance approach taken is both simple and straightforward and presents a reasonable evaluation that should be understood by anyone familiar with boiler and burner theory.

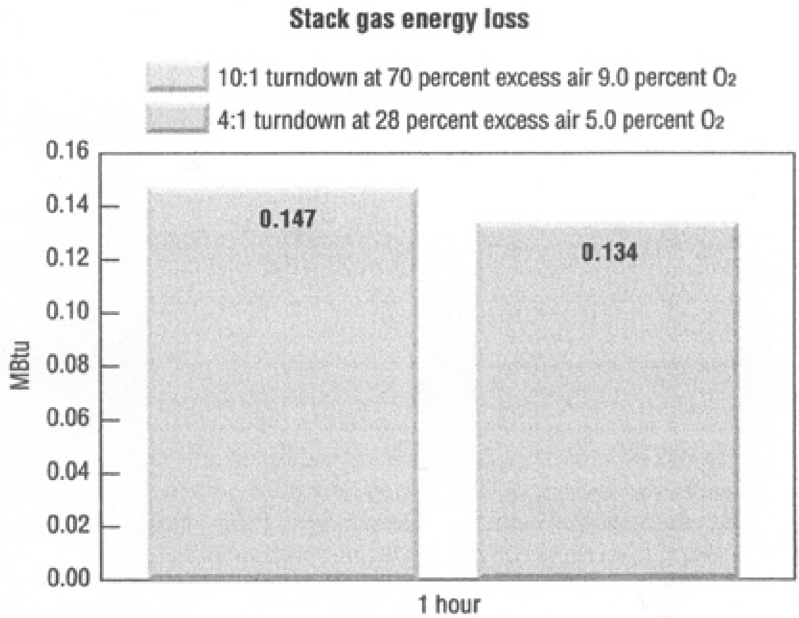

FIGURE 1. *One-hour stack-gas energy loss.*

Boiler Selection

The boiler selected for this study was a 750 Bhp Scotch marine hot-water boiler firing only natural gas. This type of boiler was chosen because of its relatively low stack temperatures compared to, for instance, a high-pressure steam boiler. If our argument is correct—that higher turndown may not always yield higher overall efficiencies—then the hot-water boiler represents a "best-case" scenario for the heat loss analysis because at higher stack temperatures, the differences between high- and low-turndown operations should be even greater.

Purge times	
Pre-Purge:	1 min
Post-Purge:	15 sec
Exit gas temperatures	
Exit gas temperature during purge	220 F
Exit gas temperature at 4:1 turndown	230 F
Exit gas temperature at 10:1 turndown	224 F
Percent of excess air	
At high fire	15%
At 4:1 turndown	28%
At 10:1 turndown	70%

TABLE 1. *Key parameters and calculated results for the case study.*

The boiler-water outlet temperature was set at 220 F, resulting in a corresponding stack-gas outlet temperature of approximately 251 F at high fire. Proprietary heat-transfer programs were used to calculate exit-gas temperatures for the 10:1 turndown, 4:1 turndown, pre-purge, and post-purge cases.

Key parameters and calculated results for the case study are shown in Table 1.

Note that the amount of excess air required at the higher turndown ratio is significantly greater than that required for the lower turndown condition. This is due to the need to maintain good mixing at the burner front and cool the firing head. The flue-gas O_2 concentrations used in this analysis were 9 percent and 5 percent, respectively, for the 10:1 and 4:1 turndown cases. As a practical matter, burners operating at lower turndown ratios can typically be set up with lower O_2, which would result in additional energy savings.

Energy Production

Our energy analysis focused on the boiler's energy input and losses. A control volume was used that included the burner and boiler losses through the stack. The analysis did not include the electrical and other non-thermodynamic system losses, concentrating instead only on the boiler heat transfer and stack gas losses.

The time frame used for the study was one to eight hours for the case of the boiler load conforming to a 10:1 turndown. In other words, the energy output required by the system is $\frac{1}{10}$ of the normal full-load energy demand. Therefore:

$$\text{Boiler load} = \frac{\text{Boiler full rate}}{10}$$

This required energy output formed the basis of our analysis. For example, if the boiler for our analysis had been a 1,000-Bhp boiler, then we could at a 10:1 turndown assume a minimum energy-output requirement equivalent to a 100-Bhp boiler (as one might see during nighttime operation). In that scenario, with the burner operating at a 10:1 turndown, it could run all night without being shut down. It then follows that a boiler operating at a 4:1 turndown would run for a significantly shorter amount of time to produce the same amount of energy in either steam or hot water to the system. The actual operating time, at the 4:1 condition, is easily calculated as:

$$1\ \text{hr} \times \frac{\text{Full load Btuh}}{10} = t_{4:1} \times \frac{\text{Full load Btuh}}{4}$$

Therefore:

$$t_{4:1} = \frac{4 \times 1\ \text{hr}}{10} = 0.4\ \text{hr or } 24\ \text{min}$$

This tells us that, in order to have the same energy output as the boiler operating at a 10:1 turndown for one hour, the 4:1 turndown boiler must operate for 24 minutes out of that hour.

For this analysis, the effects of convection and radiation have been neglected because they are constant for a given boiler at a specified outlet temperature, regardless of turndown. Because the shell temperature of a boiler is unrelated to the burner turndown, the so-called "shell losses" can be ignored.

Stack Gas Analysis

For both the 10:1 and 4:1 turndown conditions, the energy lost during boiler operation was evaluated using a stack-gas analysis. The methodology for obtaining the fuel higher heating value (HHV), products of combustion (POC) at various O_2 levels, and the enthalpy (h_f) of the mixtures is found in ASME PTC-4.[2] Enthalpies were calculated using the JANAF tables.[3] Combustion efficiencies associated with various stack temperatures for boilers firing natural gas are shown in Table 2. By evaluating the enthalpy remaining in the flue gas when it exits the boiler, the energy lost to the stack can be calculated using:

Stack losses = $m(h_{out} - h_{in})$

Prior to lighting the burner, the prepurge cycle ensures that a minimum of four air changes through the boiler furnace are made through the combustion-air blower. During this time, there is no heat being added to the system. However, as the cooler air travels through the pressure vessel, it removes heat—and, therefore, energy—from the boiler control volume. With the use of the JANAF tables and the above equation, that energy loss can also be calculated.

Similarly, the post-purge cycle also requires relatively cooler combustion air to be forced through the pressure vessel, resulting in another energy loss that is calculated in the same manner.

It should be noted that in order to eliminate energy losses unrelated to actual operational considerations and provide for a heat loss out of the stack that was consistent for one hour, the 4:1 boiler was equipped with a stack damper that remained closed when the boiler was off (36 min. out of the hour). Note that this can also be accomplished by closing the burner fresh-air dampers when the burner is off.

Results

The results of operating the boiler at the two turndown ratios for one hour are shown in Figure 1.

In the instant case, then, the 10:1 turndown offers no improvement in efficiency over the lower-turndown-ratio burner; in fact, it is slightly less efficient. This is due to the longer operating time (60 min vs. 24 min) at high excess-air levels with hot gases continually exiting the boiler. Even with the energy wasted during startup and shutdown (pre- and post-purge cycle losses), the 36-min. idle time of the 4:1 boiler conserves more energy than does the 10:1 case.

Figure 2 presents a graphical representation of the cumulative energy loss over an eight-hour operating period. Although the lower turndown boiler initially loses more energy, by the end of the first hour, it has recovered its advantage over the higher turndown boiler. As the operating

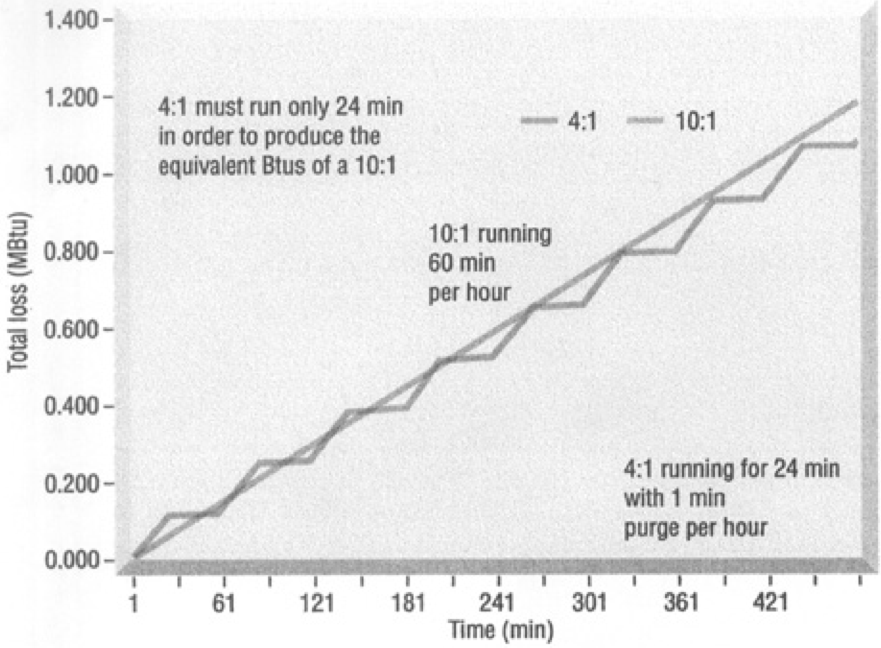

FIGURE 2. ***Cumulative stack losses over eight hours of operation.***

time continues, the advantage becomes more significant.

So, strictly from a thermodynamic perspective, the conclusion can be drawn that—contrary to conventional wisdom—there is not necessarily an efficiency advantage to operating with high turndown.

And there are other factors to be considered when specifying turndown. Proponents of high-turndown burners will argue that it reduces thermal stresses on the boiler. And there may be some validity to that argument. However, once a Scotch marine boiler of quality construction reaches temperatures greater than 180 F, it is capable of high-cycle operation without damage.

And, conversely, it is widely accepted that high turndown burners—which by their nature require closer control of both fuel and air delivery—are more difficult to tune to and maintain at optimum performance.

Also, higher efficiency in a non-condensing boiler is not always desirable because stack temperature is inversely proportional to combustion efficiency. Obviously, as stack temperatures decrease, approaching the dew point of the flue gases, condensation in the stack can occur. This condition is highly undesirable because it can be damaging to the boiler and steam-system components. In a four-pass, wetback boiler, such as the one selected for the instant case largely because of its higher efficiency and resultant lower stack temperature, measured stack temperatures are typically in the range of 30 to 50 F above the boiler saturation temperature at high fire. Condensation in this boiler will then be a function of the temperature and water content of the combustion air (and, obviously, the resultant POCs), and we have found that the dew point under these operating conditions will be in the range of 140 to 180 F. The use of a double-wall-insulated stack can help lessen these condensation problems.

Burner turndown is not a panacea for correcting low efficiency or compensating for poor equipment selection. There are certainly applications where higher turndown is desirable. In those processes that demand very tight maintenance of temperature or pressure setpoints, for example, there is an obvious benefit from high turndown. However, if a system has extremely significant load swings in very short cycle times, as some of those processes can, then a three- or four-pass Scotch marine boiler—regardless of burner turndown—may not be the proper solution. There are boilers specifically designed for these types of applications, such as specially designed two-pass firetube boilers that have larger steam release and steam storage volumes. Where thermal shock is a critical consideration, there are coil-type forced circulation watertube steam generators that can be continuously cycled and provide output (not just burner) turndown ratios as high as 13:1.[4] Those steam generators, however, are limited in size (generally less than 600 Bhp) and are significantly more expensive than firetube boilers in the same application.

Boiler and burner selection and turndown requirements are just some of the determinations that should be made on a case-by-case basis by technically qualified individuals for any contemplated boiler application.

References

1) Colannino, J. (1997, April). NOx and CO: Semi-empirical models for boilers. Presented at American Power Conference, 59th Annual Meeting.

2) American Society of Mechanical Engineers. 1964 (Rev. 1991) *Performance Test Code - Steam Generating Units.* ANSI/ASME PTC 4.1.

3) Chase, M.W. (1998). "NIST-JANAF Thermochemical Tables." Fourth edition. J. Phys. Chem. Ref. Data, Monograph 9.

4) Clark, L.(1999, September). Coil-Type Steam Generators for Heating Plant Applications. *HPAC Engineering.*

About the author:

David Thornock is director of engineering at Johnston Burner Co. He can be reached at davidthornock @johnsonboiler.com.

Larry Clark is regional sales manager for MEPCO. He can be reached at LarrySCL@aol.com.