Efficiency in Boiler Feed Pumps for Industrial Steam Generation

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Abstract: This paper presents some opportunities to improve feedwater system efficiency for industrial boilers, usually consisting of multistage centrifugal pumps driven by three-phase induction motors. There is abundant literature on the efficiency in steam boilers. However, few deal exclusively with feedwater systems. The total horsepower in boiler feed pumps and the corresponding energy consumption estimated for Brazilian industries are as follows: 110.5 MW_E of motor driven power and a yearly electricity consumption of 442 GWh for a population of 7,800 steam boilers, approximately. It is estimated that there can be an efficiency improvement in feedwater systems for industrial boilers of 30% on average. To a large extent, these opportunities reside in older boilers that are very common in the Brazilian industrial sector. The most common causes for the low efficiency of feedwater systems are: the control loop of the feedwater, oversized boilers and excessive operational pressure set. Sometimes, the boiler feedwater system can present more than one problem simultaneously. Any kind of solution involves some form of intervention in boiler feed pumps, such as: impeller trim, speed regulation, new pump and number of pumps. Each problem may have more than one solution. Three distinct industrial steam generation facilities were selected in which common inefficiencies are present. The suggested solutions were analyzed. In these three cases, the improvement in efficiency can get to 37%.

Key words: Industrial boiler, boiler feed pump, industrial energy efficiency.

1. Introduction

Steam can be used for power generation, process and space heating. Boilers for power plants are very large and their characteristics are very specific. On the other hand, boilers for space heating are usually small and not used in Brazil. Intermediate boilers are predominant in the industrial sector. The steam produced is used for a wide range of heating processes. In large industries, steam can be used for the cogeneration of electricity.

Steam boilers can be classified by their thermal capacity (MW_T) or by steam production (t/h). Fig. 1 illustrates the range of boiler applications [1].

This paper deals exclusively with industrial boilers. In general, the thermal capacity of industrial boilers

ranges between 3 MW_T and 300 MW_T, at some point between 4 t/h and 400 t/h of steam output. Usually, boilers with less than 30 t/h of output are of the firetube type, and while the ones with over 30 t/h are of the watertube type. Feedwater pumps and draft fans are the main apparatuses driven by electric motors in boilers to generate steam for industrial purposes. Both sets of equipments have numerous opportunities for improvement in their energy performance. However, in industrial facilities, the thermal efficiency of boiler receives greater attention due to fuel consumption. The efficiency of these systems is considered only in large boilers of power plants. This paper is going to present some opportunities to improve the feedwater system efficiency for industrial boilers, usually consisting of multistage centrifugal pumps driven by three-phase induction motors.

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Fig. 1 Range of boiler applications.

The total installed horsepower in boiler feed pumps and the corresponding energy consumption were estimated for Brazilian industries. There is no such data survey in Brazil. This estimate was performed through relations based on available data from the USA. Basic pieces of information were presented to support the energy efficiency assessment of pumps, including flow control systems. The most common causes of inefficiency were identified. The three main reasons were analyzed based on real situations of different industrial plants. It is estimated that the efficiency improvement in feedwater systems for industrial boilers can reach 30% on average.

2. Inventory of Industrial Boilers

An inventory was conducted in the USA. It indicates that there are about 43,000 boilers in the industrial sector with a total capacity of 470 GW_T [1]. The average capacity of boilers is 11 MW_T. Their energy consumption is estimated at 6,500 TBtu (154×10^6 toe((*) toe: tons of oil equivalent = 42.000 MJ)). This represents between 35% and 37% of total fuel consumption in the industrial sector [1, 2].

Approximately 21,000 industrial installations have boilers, i.e., 10% of all installations. About 76% of boilers are over 30 years old. For large boilers, this percentage decreases to 66%. Only 7% of the total capacity of boilers is less than 10 years old [1].

The boiler market grows quickly during the industrial development of a country and tends to decline to a stable substitution market after the industrialization process. Their growth in sales is currently concentrated in developing countries, especially China and India [3].

The inventory shows that five industries account for

71% of the total population of boilers and 82% of installed capacity. They are: pulp and paper, chemical, oil refining, food and beverage, and primary metals. Another study [2] reports that only four segments account for 88% of total fuel consumption for steam generation. They are: (1) pulp and paper; (2) chemical; (3) oil refining; (4) food and beverage. In these industries, the shares of energy with steam generation in relation to the total fuel consumption are 75%, 44%, 31% and 52%, respectively [2, 4]. The graphs in Fig. 2 show the participation of boilers in each segment with respect to the total population, capacity and consumption of these four industries.

In Brazil, there are no reliable statistic terms on steam generation. A rough estimate could be made by applying the data from the U.S. to the actual Brazilian consumption. Table 1 shows the total fuel consumption of four industries in Brazil [5], and the estimated consumption for steam generation considering the indices of the U.S..

Assuming that these industry segments represent 88% of the total consumption for steam generation, as it occurs in the U.S., it is concluded that the final consumption is 29.3×10^6 toe, or about 19% of the U.S. consumption.

Based on American studies [1], with a total capacity of 470 GW_T and an annual consumption of 154×10^6 toe, it follows that the average operational time per year was estimated at 4,000 hours. Likewise, the Brazilian capacity would be 85.5 GW_T. The average capacity of industrial boilers in the U.S. is 11 MW_T. Considering the same average for Brazil, it is inferred that the population of Brazilian boilers would be on the order of 7,800 units.

A thumb rule widely used in Brazil believes that 1

Fig. 2 Participation of boilers in the US industrial sector.

Table 1 Estimation of energy consumption for industrial steam generation in Brazil.

Industry	Total consumption (10 ³ toe)	% Steam gen	Cons. Steam gen (10 ³ toe)
Paper and pulp	8,540	75%	6,405
Chemical	5,450	44%	2,398
Refining ^a	20,376	31%	6,316
Food and beverage	20,630	52%	10,727
Subtotal	54,996		25,846

^(a)includes refinery, ethanol plants, natural gas processing, etc. [5].

toe generates 15 tons of steam, i.e., the average boilers efficiency is 70%. This represents an average steam production of 110×10^3 t/h (29.3×10^6 toe $\times$ 15 t/toe/4,000 h). Assuming, as in the case of the U.S., that the medium pressure of steam produced is 2.2 MPa ($\approx$ 22 bar) and the average efficiency of the motor and pump assembly is 65%, the drive power involved would be of about 110.5 MW_E (Eq. (1)), and an electricity consumption of 442 GWh per year.

3. Boiler Feed Pump

The motor power (W) to drive the pump is given by Eq. (1):

$$P_{ele} = \frac{\gamma \cdot Q \cdot H_p}{\eta_p \cdot \eta_m} \quad (1)$$

where, γ is the specific weight at feedwater temperature (N/m³), Q is the flow rate (m³/s), H_p is the total pump discharge head (m), η_p is the pump efficiency and η_m is the motor efficiency.

The total head required is obtained by adding the following parcels: steam pressure in the boiler ($p/\gamma =$ cte), head loss in piping ($h_f \approx k \cdot Q^2$), and geometric height difference between the boiler and the deaerator

($h_g =$ cte). The head loss in piping involves losses in flow control valves, check valves, stop valves, fittings, pipes (including passes for economizers and super heaters, if there is any), and other devices. Typically, the steam pressure accounts for approximately 80% of the total head at a nominal pump flow rate.

$$H_b = \frac{P_{vap}}{\gamma} + h_f + h_g \quad (2)$$

The centrifugal pump characteristic curve (H_xQ) can be approximated, as Eq. (3):

$$H_p \cong H_0 - a \cdot Q - b \cdot Q^2 \quad (3)$$

where, a and b are constants for each pump, H_0 is the shut-off head (m) and Q is the flow rate (m³/s). The system operating point is given by $H_p = H_b$.

Fig. 3 shows the characteristic curves of the pump ($H_p \times Q$ and $\eta_p \times Q$), and the feedwater system of an industrial boiler ($H_b \times Q$). The figure on the left shows two distinct points of operation, increasing the valve control opening along the path from 1 to 2. The figure on the right shows the same change in flow produced by a pump speed increase where the valve opening is kept constant. By applying Eq. (1), it is obvious that the

Fig. 3 Flow control by throttling and variable speed.

energy efficiency for the flow variation is greater in the second case.

For pump sizing, seven steps should be considered [6]: number of pumps, feedwater control type, total head of the system (H_b), discharge (Q), NPSH (net positive suction head) required, protection for minimum flow, and the verification of the conditions established by ASME (American Society of Mechanical Engineers).

If the steam plant is “base loaded” with very little load swing, one pump may be used to serve multiple boilers. Otherwise, there must be at least one pump for each boiler. The modulating feedwater control should be used. The calculation of H_b has already been explained above. Special attention must be given to the NPSH, since the feedwater is generally at an elevated temperature. A “gap” between the available NPSH and the one required by the pump must be sufficient to avoid cavitation problems. If it is necessary to protect the pump for a minimum flow by recirculation, it should be 20% of the flow at the best efficiency point of the pump (Q_{BEP}), or what is stated by the manufacturer.

The calculation of the net pump flow rate (Q_{nom}) must take into account the boiler evaporation rate (Q_{EV}) and its catch-up capacity (Q_{CT}). The evaporation rate includes the steam flow to the system, purge, and possible diversion to deaerator. The catch-up capacity should be 25% of Q_{EV} for modulating control and 100% of Q_{EV} for on/off control. The ASME Code requires that the pump is able to maintain a flow rate

that is equal to evaporation rate at pressure 3% greater than set pressure to the safety valves of the boiler.

4. Feed Water Control

Steam load in industrial facilities is not constant. It varies throughout the day (time variation) and along the year (seasonal variation). So, feedwater flow should also vary. This variation is obtained by throttling the flow control valve or the variable speed pump, as illustrated in Fig. 3. The control system of the boiler controls these devices. Signals obtained by level sensors are processed by means of an inverse relation, that is, the higher the water level in the boiler is, the lower the flow rate gets, and vice versa. Differential pressure signals may also be used. The water level in the boiler must remain within maximum and minimum limits. Excess water causes flooding of separation moisture devices, causing drag of the liquid phase along with steam into the system. Lack of water can cause overheating of the heat exchange surfaces.

When the steam demand increases, the formation of bubbles in water increases, the average density of the mixture reduces, and it increases the water level in the boiler, even in absence of water intake. This phenomenon is known as “swell”. In contrast, if the steam demand decreases, the average density of the mixture increases and lowers the water level in the boiler, which is a phenomenon called as “shrink”. These phenomena cause unwanted fluctuations in the boilers feedwater.

Fig. 4 Modes of boiler level control.

There are four modes for boiler level control: (a) turning the pump on/off; (b) through feed control; (c) variable speed pumps; (d) the combination of the last two, as Fig. 4 shows a schematic of these modes [7].

For the aforementioned reasons, the on/off control is applied only for small boilers. When the water level falls, the pump starts pumping a large quantity of relatively cold water into the boiler. This will reduce the quantity of steam in the boiler and result in a pressure drop. Water may possibly be dragged along with the steam into the system. The other modes are applied in larger boilers, known as modulating controls. The control loop can have one (level), two (level and steam flow rate), or three elements (level, steam and water flow) [8, 9]. The signal processing of steam and water flow elements allows a smooth oscillation of the boiler feed. In the case of control by means of throttling valves, whether being with or without variable speed pump, the existence of recirculation systems is strongly recommended, i.e., a link between the pump discharge and the deaerator. This ensures a minimum pump flow in order to prevent damage by overheating and other detrimental effects of reduced flow in pumps.

5. Opportunities for Efficiency Improvement

There is abundant literature on the efficiency in steam boilers [10-12]. However, few deal exclusively with feedwater system. As it can be seen from Eq. (1), the input power of the pumps depends on pressure (discharge head), flow rate, and pump efficiency. All these variables are linked to characterize the performance of the pump. Based on studies of various steam generation plants for industrial purposes, it was observed that some inadequacies are present routinely. Usually, there is more than one mismatch in the same plant. A significant part of this situation is due to the age of the facilities with their old projects and equipment. Highlighted, are three very common situations:

- Control loop of the feedwater system. Typically, there are boilers with a modulating control of a single element, namely the control of the throttling valve is done solely with the water level signal of the boiler. The pump flow becomes very swinging, i.e., it fluctuates from very low flows to one beyond the rated condition. Sometimes, the pump reaches a shut-off state briefly. This causes severe vibration due to hydraulic imbalance and a severe degradation of

mechanical conditions, especially the sealing system. Efficiency is greatly reduced by low flow.

- Oversized boiler. Sometimes the boiler is selected for attending a particular load which was not observed. There are several reasons for this fact. In this case, the pump operates at a very low flow which is far from its BEP (best efficiency point). Thus, the pump efficiency can be dramatically reduced. It is well known that pumps continuously operating with very low flows are subject to a higher failure rate.

- Steam pressure reduction. It is not uncommon to find facilities in which the set pressure of the boiler is higher than the processes needs. As an example, a certain industrial plant had a small boiler (5 t/h) with pressure set to 10 bar_g. The saturated steam in this condition has a temperature of 183 °C. None of the heating processes required temperature that is higher than 164 °C, or pressure of 6 bar_g. Without any major difficulties [12], the boiler could be set to produce saturated steam at 7 bar_g, which is sufficient to increase the feedwater system efficiency in 30%. Another situation found routinely is the steam consumption in two levels of pressure. Parts of the processes demand 6 bar_g and others 18 bar_g, for instance. In this case, the boiler generates steam in 18 bar_g and the level of 6 bar_g is obtained by pressure reducing valve. Therefore, the energy dissipated in the valve is supplied by the pump.

Three cases of each of the aforementioned situations are presented below.

6. Cases

6.1 Case 1: Inadequate Control Loop

Watertube boiler, natural gas, 30 t/h, 2 feedwater pumps (1 stand-by), LIC (loop control with 1 element), 25 years, feedwater at 60 °C.

Note: draft fan motor, 100 cv.

Centrifugal pump, barrel type, 7 stages, gland packing, 3,500 rpm, 60 cv.

Design: $Q_{proj} = 39 \text{ m}^3/\text{h}$, $H_{proj} = 268 \text{ m}$, $\eta_{proj} = 66\%$.

Nominal: $Q_{nom} = 30 \text{ m}^3/\text{h}$, $H_{nom} = 341 \text{ m}$; $\eta_{nom} = 64\%$.

Characteristic curves (adjusted):

$$H_p = 329.5 + 1.005Q - 0.0725Q^2 \quad (4)$$

$$\eta_p = 0.0002Q^3 - 0.0658Q^2 + 3.9026Q - 0.1548 \quad (5)$$

Operating time: 24 hour/day.

Monthly steam production (t): see Fig. 5.

Load of a typical day: see Fig. 6 and Table 2.

The considered average production of steam during the day was 20.6 t/h. The total energy consumption was 798 kWh. If a control system with 3 elements could ensure a uniform discharge of 20.6 t/h, the total head of the pump would be 319.4 m and its efficiency of 54%. With this, the consumption in over 24 hours would be of 796 kWh. Therefore, there is no energy efficiency improvement to be taken into account.

Fig. 7 shows the feedwater flow during 1 hour of a typical day (measurements every 2 seconds).

The swing of the discharge causes loud noise and vibration in the pump. The gland packing failure rate is quite high. If the production were uniform, the problem of damage to the gland packing would be greatly improved.

Fig. 5 Monthly production (t).

Fig. 6 Histogram and cumulative output percentage on a typical day (24 hours).

Table 2 Steam production characteristics on a typical day—Average production for bands.

Bands (t/h)	< 15 t/h	15-20 t/h	20-25 t/h	> 25 t/h
% time	12.2	21.3	55.2	11.3
Avg. Output (t/h)	10.76	18.00	22.73	26.17
H_P (m)	331.9	324.1	314.9	306.2
η_P (%)	34.4	49.9	56.9	60.5
P_P (kW)	28.3	31.8	34.3	36.1
EE (kWh/day)	82.86	162.56	454.4	97.9

P_P : pump input power, EE : input energy.

Fig. 7 Boiler feedwater flow rate for 1 hour.

It is possible to introduce a frequency inverter under the control loop of 3 elements. In this case, the flow control valve would be kept fully open for operating the pump at design conditions, i.e., $Q = 39 \text{ m}^3/\text{h}$, $H_P = 268 \text{ m}$, and $\eta_P = 66\%$. The static head of the system is 197 m. The adjusted curve is given by Eq. (6):

$$H_b \approx 197 + 0.0467Q^2 \quad (6)$$

With the valve open, head H_b is equal to 217 m. Applying $Q = 20.6 \text{ m}^3/\text{h}$ and $H = 217 \text{ m}$, the pump shut-off head equals $H_0 = 227 \text{ m}$ (Eq. (4)). Through similarity ratio (Eq. (7)), one obtains a rotation of 2,900 rpm.

$$\frac{H_{01}}{H_{02}} = \left(\frac{N_1}{N_2} \right)^2 \quad (7)$$

To determine the input power in this case, it is necessary to estimate the efficiency of the pump. For this, the flow of $20.6 \text{ m}^3/\text{h}$ at 2,900 rpm needs to be reflected in the 3,500 rpm curve, applying the similarity relations of Eq. (8).

$$\frac{Q_{1'}}{Q_2} = \frac{N_1}{N_2} \quad (8)$$

This results in a reflected flow of $24.8 \text{ m}^3/\text{h}$. With the application of the efficiency equation, its estimated value is 59.2% (Eq. (5)). In this new condition, the input power is 20.6 kW. Thus, the daily energy consumption would be of 495 kWh/day for a uniform steam production. The gain is 38% compared to the previous situation of 798 kWh/day. Fig. 8 illustrates this new condition.

6.2 Case 2: Oversized Boiler

Two watertube boilers, sugar cane bagasse, 150 t/h each, 43 bar_g, 410 °C, loop control with 3 elements (LIC , FIC_{water} , FIC_{steam}), feedwater at 110 °C.

Note: the power of the primary and secondary fans sum is by 450 cv per boiler.

Two centrifugal pumps, 8 stages, 350 cv each, 3,500 rpm, parallel operation.

Design: $Q_{proj} = 98 \text{ m}^3/\text{h}$, $H_{proj} = 608 \text{ m}$, $\eta_{proj} = 72\%$.

Nominal: $Q_{nom} = 79 \text{ m}^3/\text{h}$, $H_{nom} = 656 \text{ m}$, $\eta_{nom} = 68\%$.

There is a further pump driven by the steam turbine in parallel with the electrical assembly, input power 700 cv, $Q_{proj} = 196 \text{ m}^3/\text{h}$, $H_{proj} = 608 \text{ m}$.

Fig. 8 Pump operating conditions for a steam output of 20.6 t/h.

Operating time: 220 days/year, 24 hours/day.

The average output and the included blowdown: see Table 3.

The two boilers operate simultaneously. For the average feeding of 118 m³/h of the assembly, each pump has a discharge medium under the following conditions:

$$Q_{op} = 29.5 \text{ m}^3/\text{h}, H_{op} = 720 \text{ m}, \eta_{op} = 40\%$$

The input power to drive each pump will be $P_{op} = 137.6 \text{ kW}$. In this case, there are four pumps operating simultaneously. The oversizing is evident. It only takes one boiler to meet the demand.

When shutting down one boiler, the operating condition of each pump becomes:

$$Q_{op} = 59 \text{ m}^3/\text{h}, H_{op} = 680 \text{ m}, \eta_{op} = 60\%$$

The input power for each pump will be $P_{op} = 173.3 \text{ kW}$.

The input power in the former situation is 550 kW (4 × 137.6 kW) and in the proposed situation is 347 kW (2 × 173.3 kW). An improved efficiency of 37% is obtained.

6.3 Case 3: High Pressure (Old Installations)

Firetube boiler, natural gas, 20 t/h, 18 bar_g, feedwater temperature 50 °C, loop control (LIC, FIC_{steam}), two feed pumps (1 stand-by).

Centrifugal pump, barrel type, five stages, mechanical seals, 3500 rpm, 50 cv.

Design: $Q_{proj} = 24 \text{ m}^3/\text{h}$, $H_{proj} = 235 \text{ m}$, $\eta_{proj} = 58\%$.

Nominal: $Q_{nom} = 20 \text{ m}^3/\text{h}$, $H_{nom} = 240 \text{ m}$, $\eta_{nom} = 53\%$.

Operating time: 16 hours/day, 6 days/week.

Average output: 16 t/h.

$Q_{op} = 16 \text{ m}^3/\text{h}$, $H_{op} = 243 \text{ m}$, $\eta_{op} = 46\%$, $P_{op} = 23 \text{ kW}$.

The plant consumes 90% of the steam at a pressure of 10 bar_g/183 °C and only 10% at a pressure of 18 bar_g/208 °C. All the steam is generated at 18 bar_g, and then reduced to 10 bar_g through pressure reducing valve, as illustrated in Fig. 9. Only one point of the plant consumes steam at 18 bar_g. Strictly speaking, this point should have its own heating system, or else the process should be investigated for the possibility of

Table 3 Average output of each boiler (B1 and B2) and the set*.

Boiler	B1 (t/h)	B2 (t/h)	B1 + B2 (t/h)	B1 + B2 (m ³ /h)
Average	60.6	53.4	112.1	118
Max	71.3	71.3	129.2	136
Min	49.9	41.3	98.8	104

* average, maximum and minimum values for each boiler are not concurrent.

Fig. 9 Plant layout.

reducing its temperature from 200 °C down to 180 °C. The elimination of this point, by means of another form of heating, could result in reduced operating pressure of the boiler, and thus increasing the efficiency of feedwater. This new situation can be obtained by installing a new pump assembly or by reducing pump speed, similar to that described in Case 1. In the case of a new pump, it has:

Design: $Q_{proj} = 1.2 \times 20 = 24 \text{ m}^3/\text{h}$, $H_{proj} = 130 \text{ m}$, $\eta_{proj} = 52\%$, pump KSB WL 40/5 stages, 3,500 rpm, $P_{motor} = 30 \text{ cv}$.

Nominal: $Q_{op} = 0.9 \times 16 = 14.4 \text{ m}^3/\text{h}$, $H_{op} = 170 \text{ m}$, $\eta_{op} = 46\% \geq P_{op} = 14.5 \text{ kW}$.

Increased efficiency is 37%.

7. Conclusions

Feedwater systems for industrial boilers in Brazil have an estimated installed power of 110 MW_E and an energy consumption of 442 GWh per year. There are opportunities to improve the performance of these systems. Three analyzed cases showed a potential efficiency improvement of 37%. To a large extent, these opportunities reside in older boilers which are very commonly found in Brazilian industries. There is no single solution for all cases. Predominant problems focus on control systems level, in oversizing, and excessive pressure. It is not unusual for a boiler to present more than one problem simultaneously.

The efficiency of the boiler feedwater in power plants is widely studied. The same does not occur with the intermediate size boilers to generate steam for industrial purposes. The present Article has not presented any technological innovation. It only sought to demonstrate that there is a significant potential for improving energy efficiency in an application where this issue is commonly ignored. It is expected that it will be able to raise awareness among energy managers of industries with high steam consumption, such as the chemical sector, food and beverage, pulp and paper, sugar and ethanol, in addition of refineries and petrochemical plants. The results obtained in the three cases evaluated are above expectations outlined in international literature. In part, this is due to inattention to the problem.

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