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Research Article

Boiler feed water pumps: techniques for improvement in design and balance of the drum

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Abstract

Boiler Feed Water Pumps (BFWP) are considered a critical part of boilers in power plant operations. The performance of the pump in a system is estimated by one of these quantifiers in pump performance (power, efficiency, head, and flow). The design and balance of the drum in the boiler feed pump are critical for the smooth flow and optimum efficiency of the pump. The wearing tolerance limits of the drum are correlated with the type of pump and the characteristics of the system in which it is installed. A study was conducted to evaluate the drum design at Saudi Aramco Jazan Integrated Gasification Combined Cycle (IGCC) Power Block Project. The study provided a mechanism for improvement in the design issues associated with the internal clearance of balance drums related to the BFWPs. Furthermore, gradual design improvements were also implemented. Successful performance testing of Boiler Feed Water Pumps (BFWPs) fitted with upgraded balance drums was also performed. This study provides a better understanding of drum design and techniques to improve the balance of the drum.

Keywords: centrifugal pumps, high pressure pumps, balance drum, internal clearance, performance testing.

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1. Introduction

Boiler feed pump are among the devices with critical effects on electricity production in power plants (Moleda *et al.*, 2020). Malfunctioning in such parts could be disastrous as the whole production unit could cease and had a long-term impact (Fortino *et al.*, 2017). It is always important to keep a check on the wearing of the internal ring of the pump. It is observed that wearing at the sealing ring interface may let the liquid re-enter from impeller outlet to suction. This leakage flow is approximately proportional to the clearance and is approximately constant over the pump flow range (Beebe, 2004). Recently, the operational basis of power plants has been changing rapidly. It is mostly due to the availability of renewable energy resources as an alternative to conventional and less efficient thermal power plants (Sunil *et al.*, 2020).

The current evolution in the energy sector has revolutionized the energy sector in term of operations and controls. A number of studies (Bird *et al.*, 2013; Shafiullah *et al.*, 2013) have predicted a significant effect of renewable energy integration on the power sector and has outlined related challenges. Many of these studies have pointed out the operational flexibility of thermal power plants in order to improve the efficiency of electrical grid in terms of its availability and stability. As a result, research and exploration of operational flexibility of thermal power plants has become an emerging interest to industrial as well as academic researchers (Eser *et al.*, 2016; Tan *et al.*, 2005) which is important to deal with the uncertainty of future generation as well as loads in the ecosystem in the long run. One of such key component of a thermal power plant is the boiler unit and associated subsystems. In the context of these recent advancements, the boiler system is expected to be more flexible to varying loads instead of the traditional fixed base-load or part-load operations (Moleda *et al.*, 2020). Hence, the optimum performance of boilers across a wide range of operations is a crucial control design requirement for thermal power plants.

The steam drum of a power unit is a place where the liquid water is separated from the steam in the thermal power plant. It is an important and crucial component of the system as it provides a steady supply of steam to the turbine unit and also prevents it from absorbing liquid water. If the liquid water gets into the turbine, it may cause adverse effects events like high salt concentrations, which can be dropped onto the pipeline fittings and inside the turbine. Similarly, too little water can trigger burning of the screens above the burner. As a result, an emergency shutdown of the whole power unit may trigger (Alouani *et al.*, 1991; Chakraborty *et al.*, 2014). Furthermore, irregularities can also happen if one component of the control system becomes faulty, in particular if it applies to the measurement circuit or output devices (Pawlak, 2018).

A number of studies have addressed the issue of accurate readings of the measured values from different sensors (Blesa *et al.*, 2014; Li *et al.*, 2018; Rotondo *et al.*, 2014; Sami & Patton, 2013; Shaker & Patton, 2014). Suitable diagnostic systems are used to avoid faults in the system (Youssef *et al.*, 2017). The basic task of a diagnostic system is improving the reliability of the automation system equipment in a power plant. Thus, the system must strive for the best possible ability to detect and differentiate faults, while maintaining the lowest operational expenses (Paoli *et al.*, 2011). The level of balance drum in the boiler is one of the most critical parameters in the operation of the power plant. Thus, it must be regulated for an optimum level between heat and material of the system. The level of the boiler balance drum is one of the most critical and challenging tasks in designing and tuning of the system, even in a fixed-load operational situation. The non-linear and inverse-response behaviours of the balance drum are the most plausible explanation for this difficulty in the levelling of the drum (Rotondo *et al.*, 2014). To overcome this challenge, feedback + feedforward control system is widely practiced according to the current industry standards. These structures are commonly known as two-element and three-element controls for drum-type boilers.

Usually, the control system of the boiler unit is designed and adjusted to meet the requirements of the full-load operational system. This type of control was more appropriate in the past years as boilers were rarely operated at part-load. Similarly, load-swings were also rare except during start-up and shut-down procedures of the power plant. As a result, the conventional three-element control system was adequate and further advancement were not required by the industry. Recently however, the performance of the traditional boiler-control system has been found to reduce in other operation modes (start-up, load transitions, and part-load). A recent study by ASME showed that on a combined-cycle power plant, during the start-up procedure 30% of boiler trips occurred during start-up due to the balance of the drum (Pawlak, 2018). They also observed fast load manoeuvring as a purpose for design modifications in the balance drum of the water feed pump.

Owing to equipment monitoring and fault detection, it is possible to make a transition from preventive to predictive maintenance methods. Predictive maintenance requires comprehensive information on the current state of health of the devices. Additional metering, physical process modelling, or data-driven models can be used to obtain the information. A contract was awarded to a well-reputed vendor to supply twenty Boiler Feed Water Pumps (BFWP) for the Jazan IGCC Power Block Project. These pumps are considered an essential part of the Power Block project overall Boiler Feed Water Systems are used primarily to supply feed water to the Heat Recovery Steam Generators (HRSG), Very High Pressure (VHP) and Intermediate Pressure (IP) economizers, and the Inside Boundary Limits (ISBL) process unit including Gasification Unit (GFU) and Sulfur Recovery Unit (SRU), as well as providing spray water to various attemperator stations.

The current study evaluated the design of the available balance drum at study site (Saudi Aramco Jazan Integrated Gasification Combined Cycle (IGCC) Power Block Project). A series of experiments were conducted to improve the design and performance of drum balance.

2. Materials and methods

This study was disgn to evaluate and provide improvements on the original design philosophy of the BFWPs balance drum and provide empirical data on the performance of improved balance drum. The test pumps were originally designed with API 610 clearances on all wear fits, but with standard manufacturer's clearance of 0.014″ between the balance drum and sleeve. The current study aimed to alter the designs of the balance drum and improve them to perform better with improved balance clearance (table-1) on the balance drum.

2.1. Original design

As part of the original design standard diametric clearance of 0.014″ was applied between the pumps balance drum and sleeve in order to optimize BFWPs efficiency. This was 66% of the minimum diametral clearance valve of 0.021″ (table-1). The following criteria was used for their design selection.

- Material combination of drum and sleeve providing sufficient hardness difference.
  - Drum is A582TP416 cond. T with of 262-302 HBN (Hardness Brinell Number).
  - Sleeve is A582TP416 cond. T with hardness of 352-415 HBN.
- The shaft deflection analysis of the rotor demonstrated that at middle location of balance drum the sag was 0.0035″. The radial clearance at that same location was 0.007″, meaning that sag was only 50% of the radial clearance and that there should be no static contact.
- Vendor experience on pumps with reduced clearance on balance drums.

All of the pumps were tested and were found to meet the hydraulic performance requirements. An overview of the measured efficiency and gain in power realized by applying the standard clearance on the balance drum/sleeve (table-1). The performance of balance drum clearance values was tested by physical inspection on randomly selected pump followed by pump performance testing. This was to verify that there were no rubbing marks and material loss for balance drum. Accordingly, one of the pumps was opened after completion of witness testing to inspect the balance drum for rubbing marks. Some minor rubbing marks in the sleeve have been observed with a maximum depth of 0.08 mm. The rubbing marks were deemed fully acceptable to vendor in line with their internal procedure.

Table-1: Pumps as tested with standard clearance on balance drum

S.#.	Efficiency (%)				Power (KW)	
	Cold Witness	Hot Witness	Hot Guaranteed	Delta Hot	Rated Power	Delta Power*
1	80.9	83.2	82.4	0.80	3738	-29.9
2	81.7	83.9	82.4	1.50	3738	-56.1
3	81.34	83.6	82.4	1.20	3738	-44.9
4	81.6	83.8	82.4	1.40	3738	-52.3
5	81.4	83.6	82.4	1.20	3738	-44.9
6	80.9	83.2	82.4	0.80	3738	-29.9
7	81.6	83.8	82.4	1.40	3738	-52.3
8	81.8	84.0	82.4	1.60	3738	-59.8
9	81.7	84.0	82.4	1.60	3738	-59.8
10	81.5	83.8	82.4	1.40	3738	-52.3
11	81.8	84.0	82.4	1.60	3738	-59.8
12	81.7	83.9	82.4	1.50	3738	-56.1
13	81.7	83.9	82.4	1.50	3738	-56.1
14	81.6	83.8	82.4	1.40	3738	-52.3
15	81.8	84.0	82.4	1.60	3738	-59.8
16	82.0	84.2	82.4	1.80	3738	-67.3
17	81.6	83.8	82.4	1.40	3738	-52.3
18	81.9	84.1	82.4	1.70	3738	-63.5
19	81.8	84.0	82.4	1.60	3738	-59.8
20	81.9	84.1	82.4	1.70	3738	-63.5

Note: Minus represents a power benefit

According to this procedure, minor rubbing is allowed if the following criteria are met:

- No material transfer between wear surfaces.
- In case of rubbing, the depth of indications or scratches shall not exceed 0.1 mm.

- In case of rubbing, this should not result in a clearance increase of 0.025 mm max from initial clearance before the test.

Although the standard design of the balance drum met the minimum requirement for the selection criteria. However, pumps with rubbing marks were a high potential risk for pump seizure during operation (table-2 and 3). Similar findings were also observed on a second pump with the same standard design. Furthermore, here some minor rubbing marks were found at the bottom of the sleeve (6 o'clock position) over an angle of ~120°, and this on the inside of the sleeve (figure 1).

Figure 1: Measured on balance sleeve after dismantling

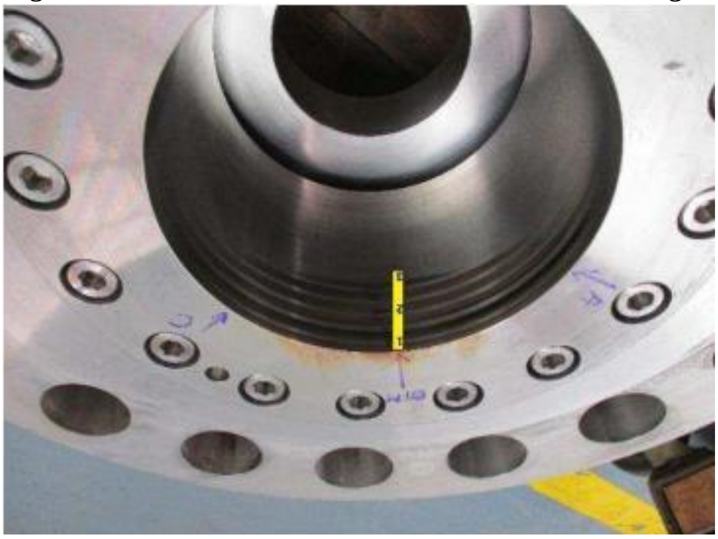


Table-2: Depth rubbing marks (affected area is 2.75″ total height is 7.50″)

Position	Reading	Depth		Position	Reading	Depth		Position	Reading	Depth	
		Inch	Mm			Inch	mm			Inch	mm
1A	0.004	0.002	0.051	1B	0.00505	0.0031	0.077	1C	0.0395	0.0002	0.049
2A	0.0032	0.0012	0.03	2B	0.00425	0.0023	0.057	2C	0.0044	0.0024	0.061
2A	0.00275	0.0007	0.017	2C	0.0036	0.0016	0.041	3C	0.0036	0.0016	0.041

Table-3: Inner diameter

Position	Inner diameter		Position	Inner diameter		Position	Inner diameter	
	Inch	mm		Inch	mm		Inch	mm
1A	9.347	237.41	1B	9.347	237.41	1C	9.345	237.36
2A	9.3455	237.38	2B	9.346	237.39	2C	9.345	237.36
2A	9.3455	237.38	2C	9.3455	237.38	3C	9.345	237.36

2.2. Alternative design

The following objectives were identified for the alternative design.

- Pumps to be meeting hydraulic performance and efficiency.
- No surface-to-surface contact on the balance drum excluding risk of seizure.

- Pumps mechanical operation in accordance with specifications.

In order to meet above specified criteria, series of tests were performed on a randomly selected pump. This was to make sure the results could be compared with the originally designed and tested pumps. Following alternative designs were tested:

- Tight fit balance drum to shaft/vendor clearance.
- Tight fit balance drum to shaft/75% API clearance.

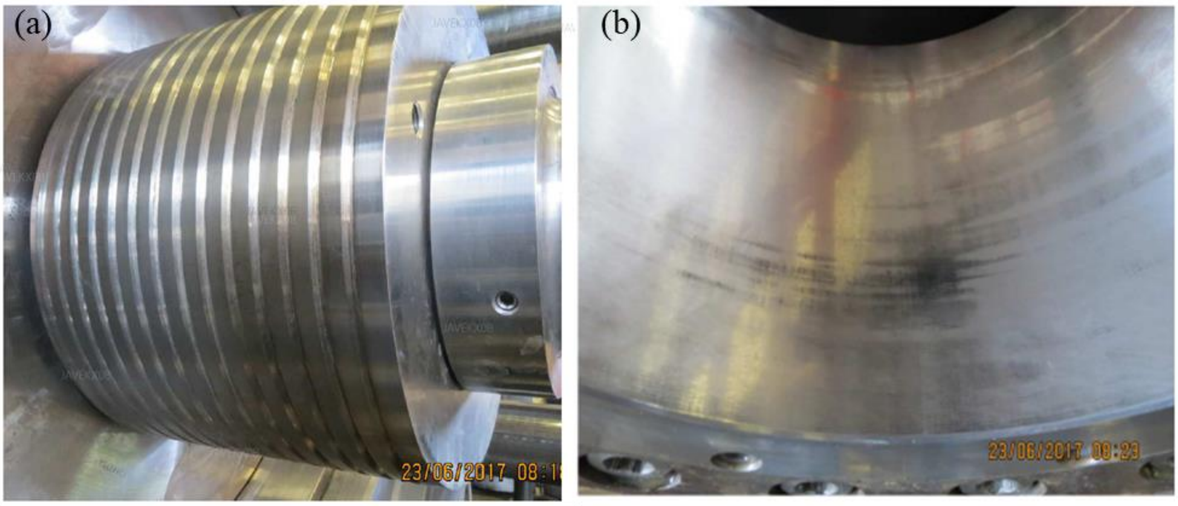
2.2.1. Tight fit balance drum to shaft/vendor clearance

Standard pump design had balance drum fitted to the shaft with one fit on the outboard side. For maintenance purposes this fit was loose between 0.001″ to 0.003″. As the balance drum is a very highly loaded part, this design could lead to a reduction in radial clearance between drum and sleeve as a result of pushing the drum radially in one direction or this could even lead to an angular deflection of the drum. To overcome this problem, modification of the drum design to have a tight fit between the drum and the shaft on the out- and inboard was performed.

The tested parts were modified and fitted to the pumps, followed by tests conducted with the original minimum clearance of 0.014″ between sleeve and drum. The hydraulic and mechanical performance during this test run was fully in line with the results of the witness test.

An inspection was performed to confirm any material rubbing marks between the balance drum and sleeve. This inspection revealed that there were no visual contact marks, other than light colouring of the drum due to the heating of the drum for assembly. For sleeve, light superficial polishing marks were visible on a couple of locations however, no measurable marks (figure 2).

Figure 2: (a) Balance drum, and (b) Balance sleeve



2.2.2. Tight fit balance drum to shaft/75% API clearance

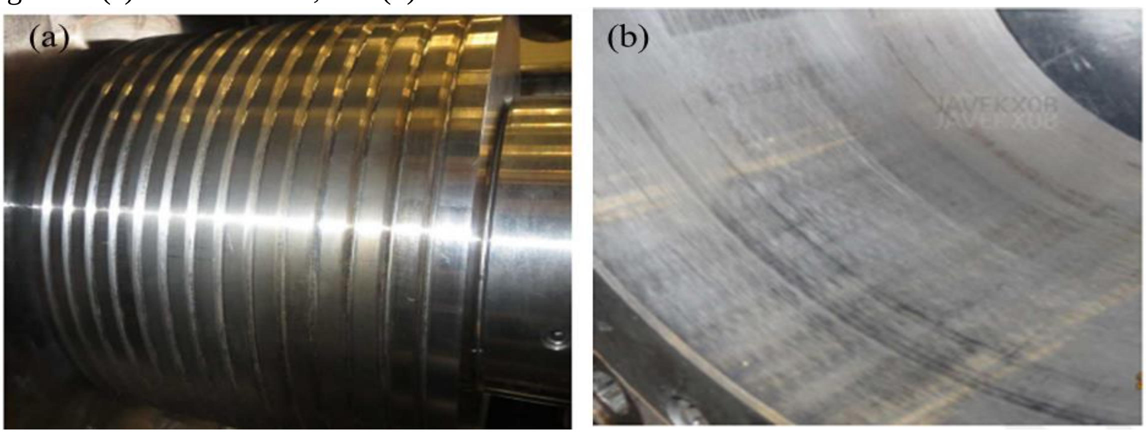
After the test conducted with pumps original design clearance, a second test with the same configuration but with an increased clearance between sleeve and drum was also conducted.

The new clearance was 0.016” corresponding to 75% of (API-610) clearance in line with the latest requirement (31-SAMMS-004, 2012). This resulted in:

- Hydraulic performance for an inlet flow of 802.4 m^3/h.
  - HP TDH (total dynamic head): 1663.6 m-5.4 m compared to the witness test.
  - ITO TDH: 708.0 m, - 2.0 m compared to the witness test.
  - Test efficiency cold: 81.3%-0.6% point compared to the witness test.
- Mechanical behaviour (vibrations and bearing temperatures) was comparable as the ones during the witness test.

An inspection of the balance drum and sleeve was performed and it showed no visual contact marks on balance drum, only light colouring of the drum due to the heating of the drum for assembly. For balance sleeve light superficial polishing marks were visible in several locations, however no measurable marks.

Figure 3: (a) Balance drum, and (b) Balance sleeve



After these tests, it was concluded that that the pumps’ original design with 0.014″ clearance for the balance drum, was considered a reliable operation. However, the balance drums clearance was increased up to 75% of API-610 (0.016″) to improve the pumps performance criteria as well as minimizing the material rubbing during normal operation (figure 3).

In order to fully eliminate the risk of pump seizure during start-up and/or controlled shutdown scenarios, the study proposed to apply a superficial hardening of the balance sleeve with the TUFFTRIDE process. This is a nitrogen salt bath diffusion process which improves the sliding properties and wear resistance. Furthermore, the increased clearance from original 0.014″ to 0.016″ resulted in pump efficiency reduced by 0.54%. Saudi Aramco approval for vendor proposed balance drum design and clearance was obtained against the following conditions.

- Inspection of one pump balance drum at random and confirm no material.
- Confirm that all pumps will have the new balance drum clearance and full performance, tested with these new balance drum design.

3. Post-balance drums design modification performance testing

Performance testing was carried out following completion of the pumps design modification including increased balance drum and sleeve clearance of 0.016″ (75% of API610) (table-4), application of TUFFTRIDE film and rather tight fit between the balance drum and shaft. Post-performance testing inspections although satisfied hydraulic performance requirement however, still the material rubbing was observed due to which pumps could not be officially accepted by Saudi Aramco. Table-4 describes pumps efficiencies and power consumption when tested with the increased clearance and fitted with the new balance drum design.

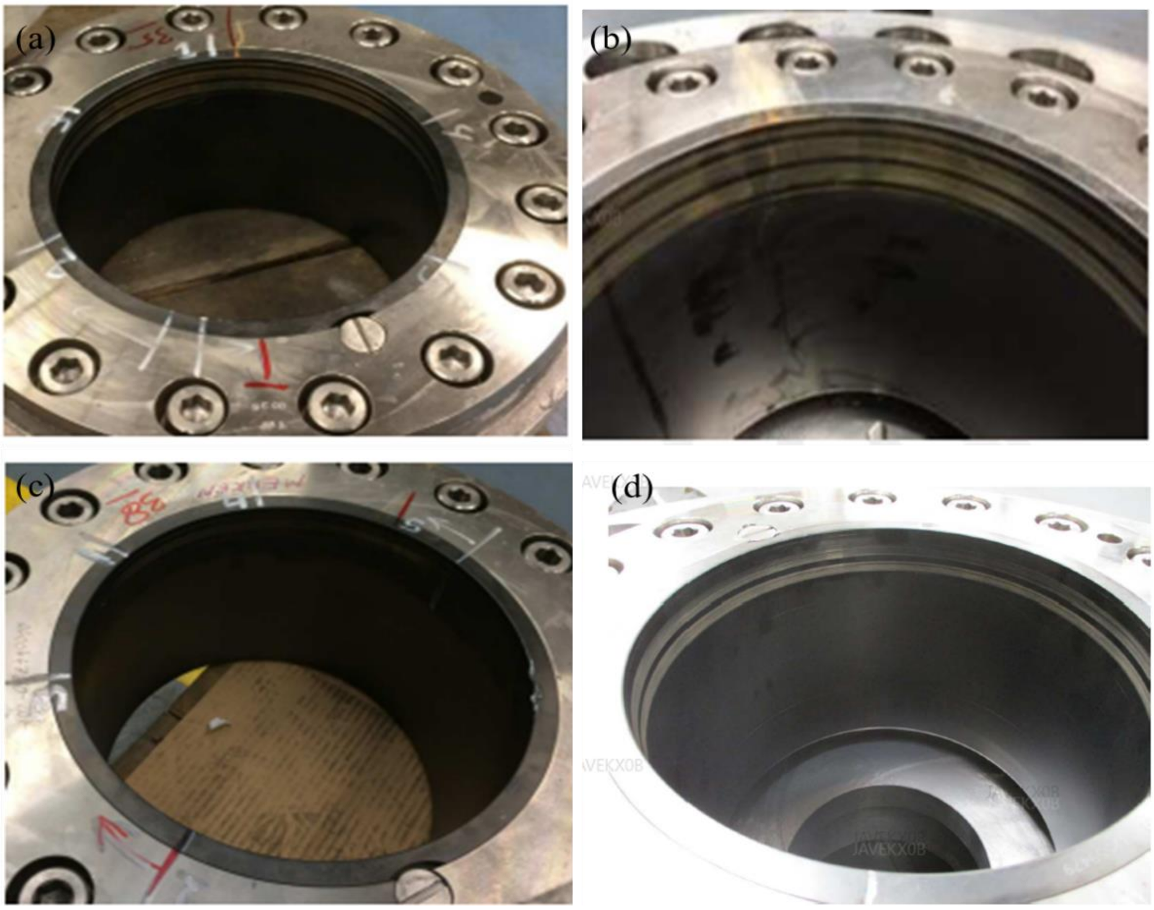
Table-4: Pumps as tested with 75% of API clearance and new balance drum design

	Efficiency (%)				Power (kW)	
Pumps	Cold Witness	Hot Witness	Hot Guaranteed	Delta Hot	Rated	Delta Hot*
Pump A	81.5	83.7	82.4	1.3	3738	-48.6
Pump B	81.1	83.4	82.4	1.0	3738	-37.4
Pump C	81.2	83.4	82.4	1.0	3738	-37.4
Pump D	81.2	83.4	82.4	1.0	3738	-37.4

*Minus represents a power benefit

Dismantling inspection was performed on all four pumps and it showed varying level of material rubbing however, it was localized at the inboard side of the balance drum (figures 4).

Figure 4: (a) Pump A balance sleeve, (b) Pump B balance sleeve, (c) Pump C balance sleeve, and (d) Pump D balance sleeve

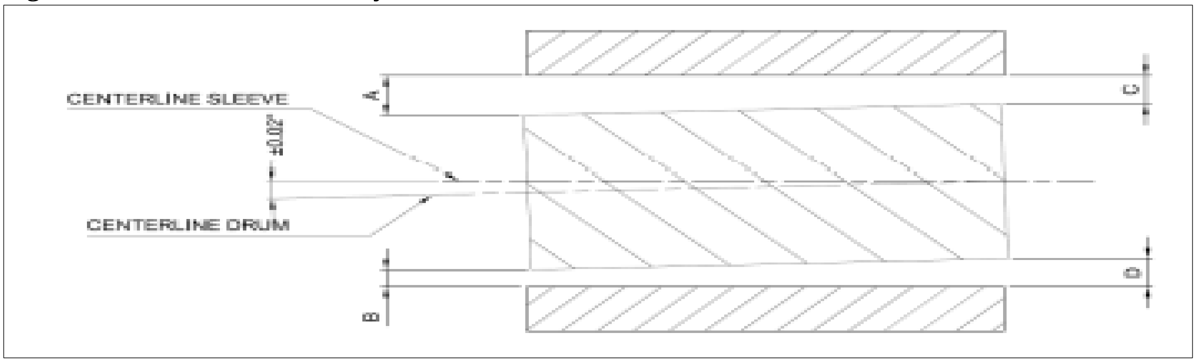


Although these localized material rubbing marks can be classified as acceptable in accordance with the internal workshop practices. However, these cannot be qualified as “no contact” and therefore the balance drum was remodelled to improve the performance of the pump and reduce the risk of pump seizure during high temperature working.

4. Technical analysis

A detailed shaft deflection analysis was performed in order to fully understand the issue and address localized material rubbing. This analysis demonstrated that at the middle location of the balance drum, sufficient clearances were present confirming a no contact design. Static deflection at the balance drum was 0.0035″ while radial clearance at that location was 0.008″ minimum (half of 75% API clearance). Although the contact was localized at the inboard side of the balance drum, however, operational dynamic loads were being applied to the balance drum increasing deflection at this location. Combined with the hydrostatic forces produced by the pressure drop across the balance drum and sleeve clearance, unbalanced hydraulic forces can result from the relative position (tilt) of the balance drum in the sleeve produced by a very small angle resulting from rotor sag. The tapered gap between drum and sleeve was created in the vertical plane at the upper and lower side of the drum. Gaps A, B, C, and D are different from each other (figure 5).

Figure 5: Shaft deflection analysis



The larger gap at the top of the drum/sleeve clearance would have a lower entrance loss increasing the pressure in the top portion of the clearance, while the opposite is true for the lower portion of the clearance. This pressure difference results in an unbalanced force on the drum. The extent of these forces can be elaborated further with the following equation (Blackburn, 2022; Manring & Fales, 2019)

$$F = \frac{\pi l r T P}{2B}\left[1 - \left(\frac{2c + T}{\sqrt{(2c+T)^2 - 4B^2}}\right)\right]$$

Where,

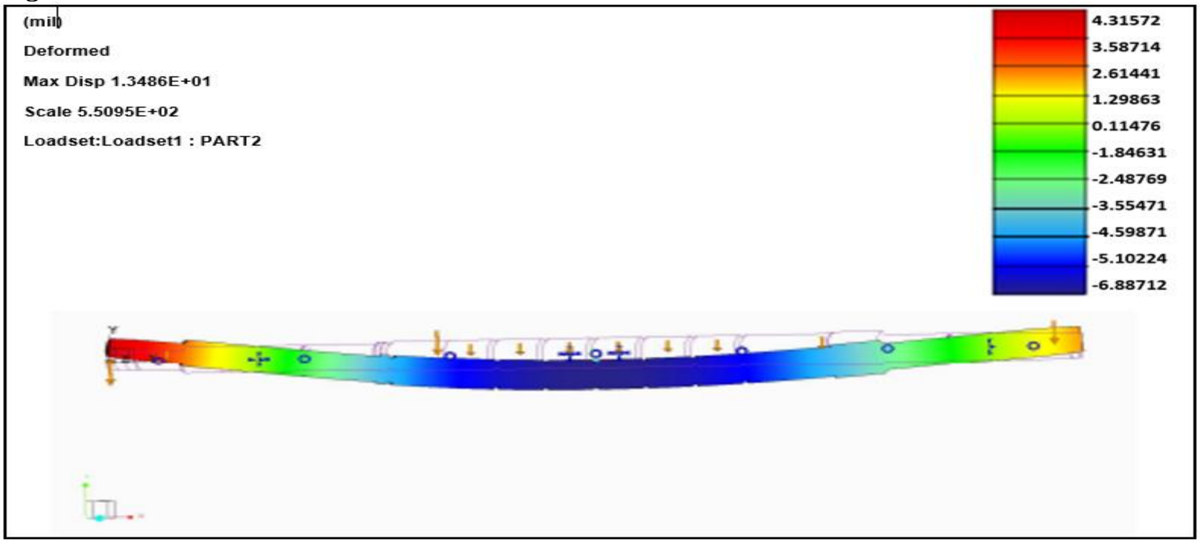
F = Radial force (lbs)
l = Length of the sleeve (in)
T = Total taper along the length of the sleeve due to misalignment or tapered machining (in)
r = Drum radius (in)
P = Pressure drop across the sleeve (psi)
B = Difference between the sleeve centreline and bushing centreline
c = Radial clearance of the centred sleeve at the large end (in)

Assuming constant values for geometry and pressure differential, there is a range of possible radial forces based on misalignment and the difference between the sleeve and bushing centreline. For further analysis, a finite element analysis (FEA) was conducted including the following.

4.1. Static shaft deflection considering all rotor components

- All rotor components: impellers, balance drum, coupling and thrust collar weights included.
- Point load supports located at bearing locations.
- Visual representation of shaft distortion.
- Maximum deflection observed near rotor midpoint is 6 mils confirming no contact under static load conditions (figure 6).

Figure 6: Shaft deflection simulation

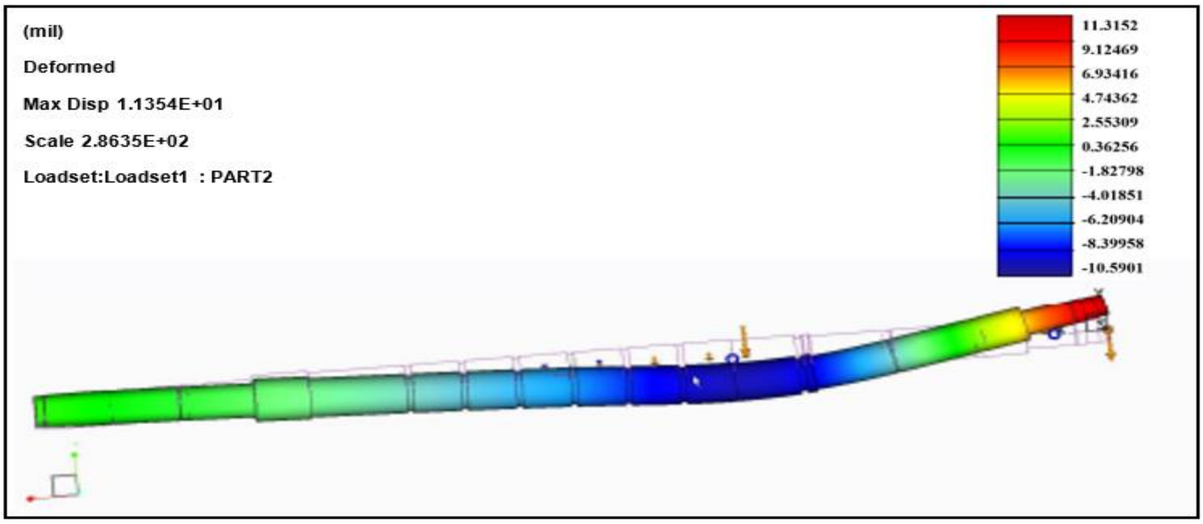


4.2. Dynamic shaft deflection considering all rotor components and additional constraints at impellers

- Added fixed displacement constraint to impeller locations (4^{th} and 5^{th} stages) of .006″. This creates an idealized infinite stiffness to simulate either high Lomakin stiffness or wear ring contact in that area.
- A 1000 lb load applied at the balance drum simulating the “tilt” effect showing a deflection of ~11 mils at the drum location.

Deflections shown in the illustrations (figure 7) were higher than expected, however technical calculations demonstrated that forces of the expected direction and magnitude, when applied to the rotor could produce deflections and contact in a manner observed during the dismantle inspection. To account for these types of deflection, materials were incorporated in close running clearance areas where minor internal contact might occur, ensuring reliable operation. Therefore, to eliminate or minimize potential for rotor contact caused by the hydro-dynamic operational loads, pressure differences around the balance drum will have to be further equalized. The study concluded that by adding groves around the pump design will adequately normalize the pressure unbalance and in turn result in reducing the risk of potential material rubbing.

Figure 7: Shaft deflection simulation

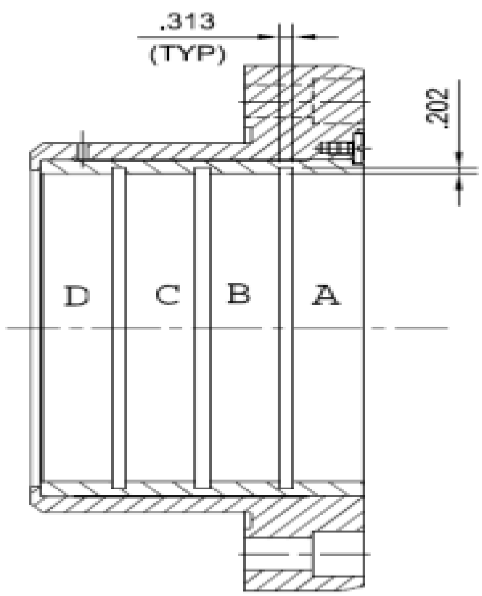


4.3. Further design optimization

In order to equalized the pressure around balance drum, adding three cylindrical grooves to the pump sleeve are suggested in future (figure 8). To find a good compromise between the hydraulic performance of the pump as well "no contact" condition, clearances between different sections of the pump sleeve were optimized accordingly as per the following:

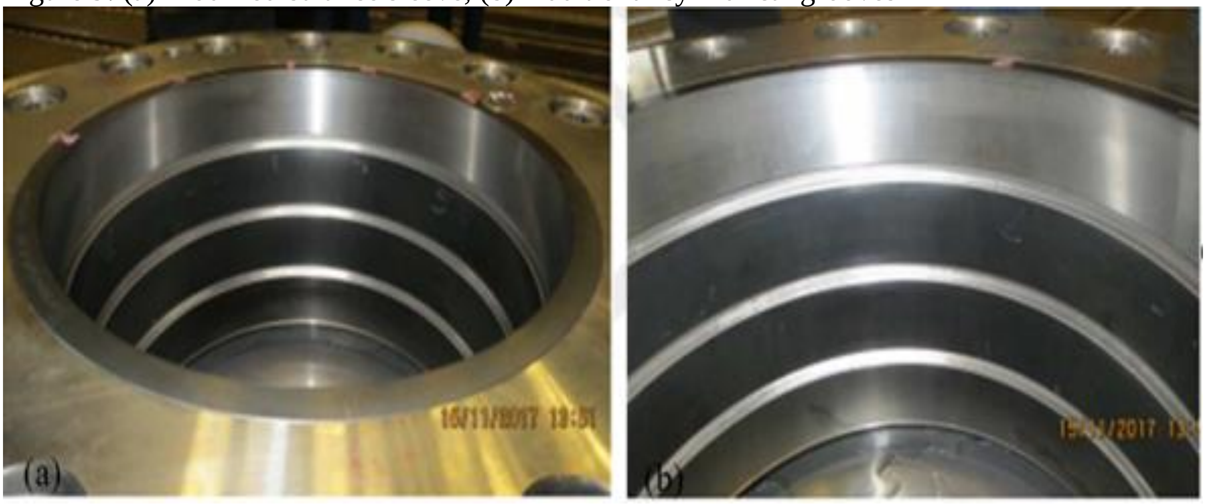
- Section A: 0.021″ (100% API)
- Section B & C: 0.018″- 0.019″
- Section D: 0.016″ minimum (75% API)

Figure 8: Additional cylindrical grooves



A random pump was selected to incorporate new three groove balance drum and performed a series of in-house tests. Test results followed by pump dismantling inspection revealed significant improvements (figure 9).

Figure 9: (a) Modified balance sleeve, (b) Additional cylindrical grooves



Localized material rubbing marks from last design improvement, were not visible anymore. Also, the pumps hydraulic performance remained within acceptable tolerances (table-5).

Table-5: Pump ‘A’ in-house testing (fitted with 3x cylindrical grooves to balance drum)

	Efficiency (%)				Power (kW)	
Pumps	Cold Witness	Hot Witness	Hot Guaranteed	Delta Hot	Rated	Delta Hot*
Pump A	80.9	83.2	82.4	0.80	3738	-29.9

*Minus represents a power benefit

After detailed testing and analysis of the improved parts, three cylindrical grooves design were finalized as the best optimal solution. This design offered a minimal compromise on pump hydraulic performance for all operating conditions as well as demonstrated no material rubbing and hence met “no contact” requirement between the balance drum and sleeve.

5. Conclusion

This study provided an upgraded design of BFWPs for better performance and reduced risk of seizure during operations at extreme temperatures. The improved design of the balance drum will be more durable with reduced wearing and tearing. It will be helpful for the better performance of boiler feed water pumps, improved shelf life of the balance drum, as well as reduced risk of failure and shut down of the whole plant.

Declaration of conflict of interest

The author(s) declared no potential conflicts of interest(s) with respect to the research, authorship, and/or publication of this article.

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