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Original Article

Failure of Frontline Tubes of a Superheater Bundle in a Waste Heat Recovery Boiler Due to Thermal Fatigue Stresses and Solution to Eliminate Them

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Abstract *- The Waste Heat Recovery Boiler is designed to recover the escaping heat of a combustion process through heat transfer between hot flue gases and banks of tube bundles (Figure 1). The frontline tubes of the superheater bundle of a Waste Heat Recovery Boiler (WHRB) face high-temperature flue gases entering the boiler, raising the steam temperature to the designed superheated level before the steam escapes through the outlet header. It is reported that the frontline tubes of the superheater bundle frequently fail during operations. The metallurgical failure analysis of the frontline tube reported that the tubes developed fatigue cracks at the joint where they weld to the couplings connecting the outlet header of the superheater bundle. On reviewing the reports of metallurgical failure analysis, the author observes that the cracks develop only on the front side of the tube periphery and that incoming hot gases do not heat the tubes at the same uniform temperature around its periphery resulting in a differential thermal expansion between the front and rear side of same tubes causing the tubes to bow (a bi-metallic strip effect). The author observes that the design and construction of the superheater bundle tube do not allow free movement in the front line of tubes to accommodate changes in tube length due to differential thermal expansion, causing the bowing effect on the tube resulting in severe fissures at the weld joint with outlet header coupling. The paper recommends engineering solution to the design by introducing a tube-coil (loop) between the superheater tube and header coupling to absorb the thermal expansion such that the thermal fatigue stresses are minimised/eliminated, preventing premature tube failure at the weld joint with the steam header above. The bowed tube generates moments at the coil joint, transferring the same moment to the header coupling joint. The stresses due to differential thermal expansion are widespread and very high in magnitude. They are normally present in every boiler design. The above-described solution can be applied to varieties of waste heat recovery boilers.*

Keywords – *WHRB, Superheater- Bundle of tubes in a boiler which comes in contact of hot gases at highest temperature (upstream) to heat up the steam converting it into superheated state, Bowing- Bending of the tube due to differential temperature between front and rear of the same tube causing uneven length expansion, Fissures-concentration of cracks due to excessive stresses either compressive or tensile.*

1. Introduction

The paper describes the author's review and analysis of reports of frequent failures of Superheater tubes, review of the design of the superheater bundle and finding the constraints the tube arrangements had. The author observed that the superheater bundle tube arrangement had inherent design constraints and did not allow flexibility to absorb tube distortion due to differential thermal expansions resulting in compressive stresses at the weld joint between the front row of tubes and the outlet header couplings.

Figure 1 below shows the Waste Heat Recovery Boiler tubes' arrangement, identifying the location of the Superheater tube bundle.

Waste Heat Recovery Boiler Arrangement

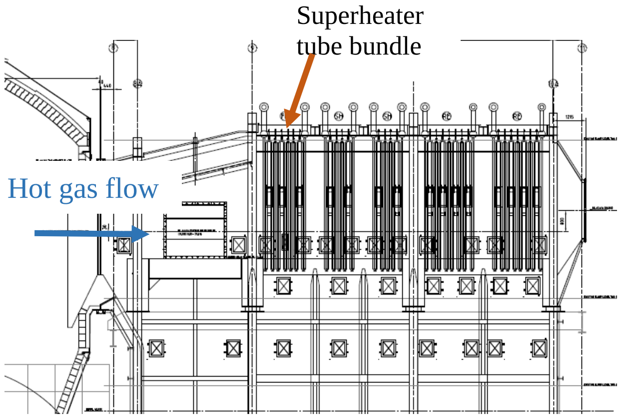


Fig. 1 WHRB tube arrangement

The tube bundle with an arrow on the top is the Superheater Tube bundle. The superheater tubes carry saturated steam and, when they flow through the coils, become superheated when the hot flue gases flow past the bundle. The superheated steam leaves the bundle from the outlet header, as shown in Figure 2 below. The Superheater tube bundle, illustrated in the present case, has 32 coils of tubes connecting the inlet and outlet headers to provide adequate surface areas to transfer heat and convert saturated steam into superheated steam. The inlet header is at the rear of the bundle, and the outlet header is at the front of the bundle to face hot gases at the highest temperature.

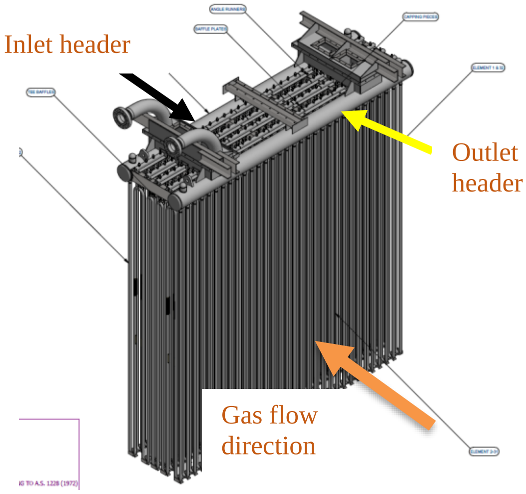


Fig. 2 Superheater tube bundle showing tube coils between the inlet header (at the rear) and outlet header (in the foreground)

There are 32 rows of coils connecting the inlet and outlet headers. A single coil is shown in Figure 3 below.

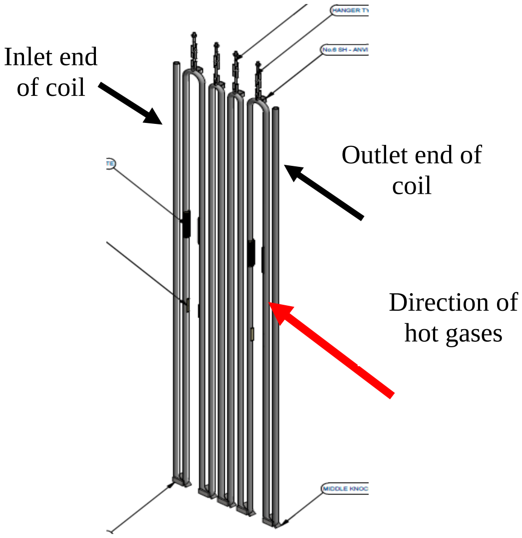


Fig. 3 A tube coil connecting inlet and outlet headers

2. Review of Past Failure-Analysis Reports

Recurring failures of the superheater tubes of WHRB in a process plant were observed, especially after increasing the frequency of shutdowns of the WHRB. Failure investigations were conducted at every failure incident, and findings were reported.

The outcomes were consistent across all metallurgical failure analysis reports, which show that the tubes were experiencing premature thermal fatigue cracking at the front line of tubes at the top where they are connected to the header couplings (see Figure 2).

Identical failures were reported from the metallurgical failure analysis reports from 2020, 2019, 2008 and 2007 incidences.

An additional visual examination of the latest failed tubes was performed to confirm the hypothesis of the failure mechanism. It was observed that the tubes developed a crack on the partial periphery of the circumferential joint, the side which faced the hot gases.

It is assumed that the tube surface facing hot gases achieves a higher temperature and has differential thermal expansion from the rear side of the same tube. A temperature measurement activity by installing thermocouples was recommended to confirm evidence of the assumed failure mechanism.

The number of tubes was inspected to study the fatigue crack propagation around the periphery of the tubes. The circumferential included angle of crack propagation around the tube periphery was found to be between 62 degrees and 141 degrees. (Less than half of the periphery). It was assumed to be due to the tubes bending on one side rather than stretching axially over the whole periphery, causing fatigue stresses.

The through wall cracks were observed to be propagating from outside to inside, reinforcing the hypothesis that fatigue stresses are induced due to the tube bending outward, on the side facing gas in-flow, trying to expand approximately 1/3rd cross-section of the tube and developing fissures (due to folding) at the weld joint with header coupling.

No generalized thinning of the tubes, Due to wear or corrosion, no generalized thinning of the tubes was detected. Under high temperatures getting weaker, the hot side fails earlier, under compressive stresses, than the cold side, which experiences tensile stresses.

Fig. 4 The front side edge of tubes with cracks

Fig. 5 Rear side of the tubes with no cracks

3. Analysis and Discussion

Victor Rogers[1] highlighted in his article “Heat Recovery Steam Generators: Vulnerable to Failure” in July 2016 “Engineering 360” where he identified "Thermal Fatigue "and “Bowing "of the tubes as important damage mechanisms that can cause the failure of the tube at the weld joint to the header coupling. The bowing is explained by Victor Rogers as follows:

“Bowing is a common failure mechanism caused by differential expansion, quenching and tube fabrication disparities. Reheater tubes near attemperators or duct burners are especially susceptible to bowing. Some units experience tube bowing to the degree that crimping and local yielding results in premature tube failures.” The bowing of the tube is shown in a schematic sketch drawn in Figure 10 below.

The author observes that when frontline superheater tubes face the flue gases, the heat is not conducted uniformly around the tube periphery. The area facing the hot gases gets heated more than the area at the back of the same tube. It may have caused the tube to bend outward due to differential thermal expansion (bowing). The superheater tube coils (Figure 3) are rigidly held at the bottom end. Figure 6 below shows the welded knocker plates at the bottom of the coil. It prevents the tube from absorbing the differential thermal expansion developed in the front side, causing it to push towards the top weld joint with Header coupling. The header coupling is a heavy wall fitting fixed to the header pipe. The expanding superheater tube does not have room to move, causing heavy fissures at the weld joint. It is assumed that the tube bows out towards the tube's half-circular face exposed to hot gases. Hence fissures occur on the hot side.

Research has been carried out and published by M. Pronobis, W. Wojnar, and J. Czepelak[2] describing the “Influence of non-uniform heating on the stresses in tubes of superheaters in boilers”.

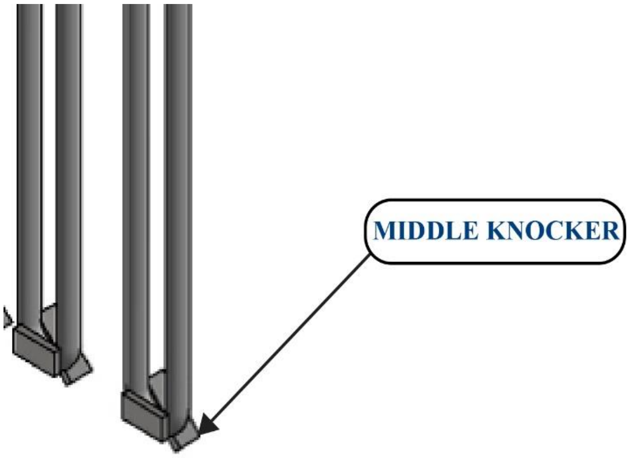


Fig. 6 The fixed bottom end of a coil

The paper explains the non-uniform heat flux distribution resulting from radiation (from flue gases entering the superheater as well as from the furnace) and from convection. The heat flux distribution around the perimeter of the first row of superheater tubes varies considerably from 100% to as low as 14% as the hot gases flow around the tube perimeter. The temperature differential between the front and rear sides of the tube (between 0 to 180 degrees) of the frontline tubes varies by approximately 16%. Figure 7 below shows the temperature distribution of the tube around the perimeter with the position of 0 degrees facing the hot gases and 180 degrees at the rear side of the same tube (a blind spot for heat transfer from the gases).

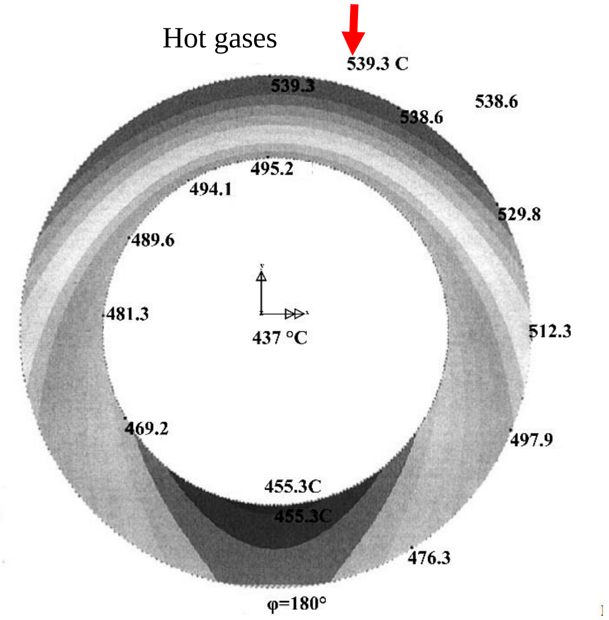


Fig. 7 Temperature distribution around tube perimeter

Fig. 8 Half-circle crack/fissures due to bowing and compressive stresses [3]

From the above publication, it was confirmed that the vertical tube section of the tube coil element (shown in Figure 3) facing hot gases had an un-even temperature around its perimeter, developing higher temperature at the front surface (0 degrees too hot gas impingement shown in above Figure 7). Lower temperature (at a 180-degree impingement angle) at the back of the same tube causes the front of the tube to expand more than the rear and causes the tube to bow (like a bimetallic strip in a thermostat). Since the front coil is fixed between the top (header) and bottom (middle knocker shown in Figure 6), the front surface of gas facing tube is restricted from expanding. Hence, it experiences very high compressive stresses causing fissures. Figure 8[3] below shows a typical superheater front line tube; the crack is developed only in the front half of the periphery of the tube.

Pronobis, Wojnar, and Czepelak show the temperature differential to be around 70 deg C, ($539^0 – 469^0$) between the front and rear surface of the tube.

No wall loss was due to corrosion or erosion detected in the failed area, ruling out any thinning of the tube wall thickness. It was observed that the thermal fatigue occurred only on the partial perimeter of the tube, developing differential thermal expansion and bowing. The crack spread around the tube perimeter only with an envelope angle between 60 and 140 degrees (in the half tube circumference facing hot gases). The cracks in the failed tubes were found only on the side facing the hot gases confirming the hypothesis that the bowing of the tube causes very high compressive stresses on the fixed ends.

The envelope angle of the tube suggests 1/3 periphery of the tube expiring thermal expansion and resultant compressive stresses compared to the 2/3 periphery of the tube developing reactive tensile stresses. The tensile stresses are distributed on a larger periphery causing the front 1/3 tube perimeter to fail.

Figure 9, below, shows how the tube is assumed to bend/bow with differential thermal expansion restricted at the right end and guided at the left end ends.
Reference to Roark's Formulas for Stress and Strains[4], Table 8.1 End restraints reference no. 6b.

6b. Left end guided
Right end fixed

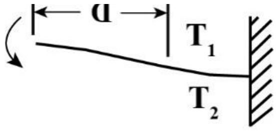


Fig. 9 The temperature differential T2>T1, bends the with convex bow on the T2 side

The boundary values are as per the equations shown in Table 8.1, which are reproduced below:

$$R_A = 0 \qquad \Theta_A = 0$$

$$M_A = \frac{-EI\Upsilon}{lt}(T_2 - T_1)(l - a)$$

$$y_A = \frac{a\Upsilon}{2t}(T_2 - T_1)(l - a)$$

$$R_B = 0 \qquad M_B = M_A$$

$$\Theta_B = 0 \qquad y_B = 0$$

M_A is maximum when a = 0
Hence moment generated at the end of the vertical front tube of the front coil is found to be:

$M = M_A$ where; max possible value is $= \frac{-EI\Upsilon}{lt}(T_2 - T_1)$ $when\ a = 0$

The Superheater tube attributes are as follows;

Do = Outside diameter = 42.4 mm
Di = Inside diameter = 34.4 mm
Wall thickness t = 4.0 mm
I = Area moment of Inertia = 89908.59 mm^4
E = Modulus of Elasticity = 200000 MPa
Section Modulus Z = 3486.914 mm^3
γ = Coefficient of linear thermal expansion = 1.11E-05 mm/mm/deg C

It is assumed that the difference between the temperature at the front of the tube and the rear surface of the tube is

$$T2 - T1 = 70\ ^0 C$$

In the above case, the differential thermal expansion will cause the tube to bend (similar to a bi-metallic strip). The moment generated at the left-hand side end of the tube will bend the tube-to-header coupling weld joint (Figure 10). The tube is held between the header and bottom "middle knockers", as shown in Figure 6.

4. Recommendations

The design and construction of the tube bundle are such that the hot gases will heat up the frontline tubes un-evenly around its perimeter, causing differential thermal expansion and hence a bowing effect on the tube due to fixed ends (Figure 10). The differential thermal expansion is required to be absorbed in the coil, and one of the fixed ends is required to allow free movement of the tube in the vertical plane of the coil.

For the temperature differential along the whole length of the tube, the value of 'a' becomes =0.
Hence equation

Hence $M = 3295230$ N.mm

Induced stresses due to the above bending stresses are found to be $\sigma b = M/Z = 94.5.$ MPa

So, it is observed that from Roark's load case "6b", the bending stresses induced due to the temperature difference between the front and rear side of the tube is found to be 94.5 MPa when the whole length of the tube is exposed to the temperature differential.

It should be noted that Load case 6b considers one end condition as "fixed", but the tube is allowed to expand along its axis.

In the actual case, the front and rear of the tube form one circular section with different temperatures. (As shown in Figure 10) the tube is fixed at the top and the bottom end. It can cause the tube to bend bowing frontward (front face thermally-differentially expanding more) and induce extremely high compressive stresses at the top weld joint.

When the boiler tube is considered as thermally expanding independently between the hot and cold sides, the tube experiences restraint in the axial direction due to non-uniform temperature around the tube circumference. Bednar [4] explains the stresses induced in a linear direction in Section 9, para 9.2, as shown below:

9.2 Basic thermal stress equations
A body can be visualized as composed of unit cubes of uniform average temperature. If the temperature of a unit is changed from T to T_1, the growth of the cube is restrained; there are three cases to consider:

1. Restrain in the x-direction. A stress σ_x is induced:
$$\sigma_x = -\alpha E(T_1 - T)$$

Where α is the Coefficient of Differential Thermal Expansion.
E is the Modulus of Elasticity. The term (T1-T) is temperature differential.
Hence in the superheater tube case,

$$\sigma_x = -\gamma E(T_1 - T)$$

Where "α" *is termed as* "γ".

$$\sigma_X = -155.4 \text{ MPa}$$

The above compressive stresses generate fissures at the anchored end (header weld joint) at high temperatures on the top of the tube (see Figure 8). The fissures are induced only on the front half of the circumferential weld joint at the tube's header end, which is exposed to hot gases and undergoing thermal expansion. Figure 10, below, shows how the tube will expand and bend with a convex curve on the hot side (due to the larger peripheral length). As shown in the above equation, the compressive stresses resulting in fissures are very large. Frequent start-stop cycles can cause thermal fatigue due to fluctuating stresses and tube failures.

It is recommended to minimize the large compressive stresses and isolate the fixed joint between the tube and header by adding a coil which absorbs the direct compressive stresses and transmits only a bending moment to the anchored end at the top.

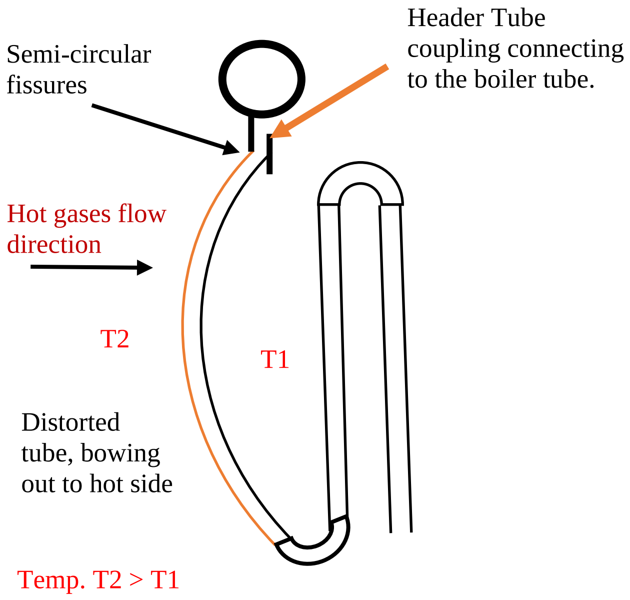
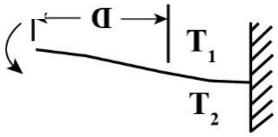


Fig. 10 The exaggerated view of distortion in the expanding tube with ends fixed

The tube configuration is broken into two parts:

1) Roark's Formulas for stress and strain[5] Section 8, Table 8.1 End restraint reference no. 6b as shown below;

Left end guided,
right end fixed

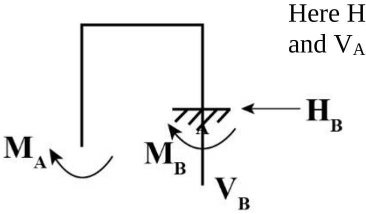


2) Moment transferred to an In-plane loading frame anchored at the other end to transfer only bending moment. As shown in

Roark's[4] Table 8.2. End restraint reference number and loading case 11 are shown below:

Left end guided by moment
only (zero slope at the left
end), right end fixed

Here $H_A = 0$
and $V_A = 0$



The new configuration of the front superheater tube can be described as follows:

The tube is fixed at the bottom end and guided at the top end to transmit pure bending moment. This guided end is then connected to an in-plain frame, allowing flexibility in the tube. Figure 11 below shows a combination of 1) a cantilever tube (beam) under bending due to temperature difference and 2) adding the in-plain frame.

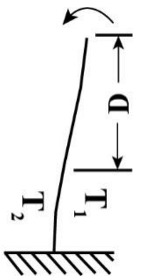


Fig. 11 The In-plane frame added to the boiler tube length to absorb the compressive stresses

The loading terms in the above In-plane frame are governed by equations given in Loading Ref. No. 5h of Table 8.2 of Roark's Formulas for Stress and Strain[4]. Figure 12 below shows loading conditions and governing equations for resultant reactions at both ends of the frame.

Concentrated moment on the
left vertical member

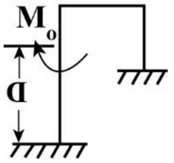


Fig. 12 In-plane loading with moment on the left end and reaction moment on the right side, fixed end.

Loading Terms are

$$LF_H = M_o\left(-C_{HM} + \frac{a^2}{2E_1 I_1}\right)$$

$$LF_V = M_o(-C_{VM})$$

$$LF_M = M_o\left(-C_{MM} + \frac{a}{E_1 I_1}\right)$$

For a = 0, the above Loading Terms are simplified as below:

$$LF_H = -M_O * C_{HM}$$
$$LF_V = -M_O * C_{VM}$$
$$LF_M = -M_O * C_{MM}$$

From the above calculations, it observed that only the moment M_A is acting on the left end of the frame where:
$M_A = M_O$.
Under the law of equilibrium, $M_A = M_B$

From the above analysis, it is noted that the moment acting on the straight vertical tube due to thermal stresses will be acting on the in-plane frame and in a loop form, it transfers the same moment to the fixed end. The compressive stresses due to the thermal expansion of the tube causing fissures are eliminated by the addition of the in-plane frame (a rectangle or an elliptical loop).

The above model can be further modified to attach a closed loop (or two loops) of the tube before the tube gets anchored to the header. A view of the spiral coupling is shown in Figure 13 below. This coil can be modified to suit the space available in front of the superheater tubes so the withdrawal of the tube bundle from the top is not obstructed.
The coil is analyzed as two in-plain frames welded to make a closed-loop spiral connection straight tube to header coupling.

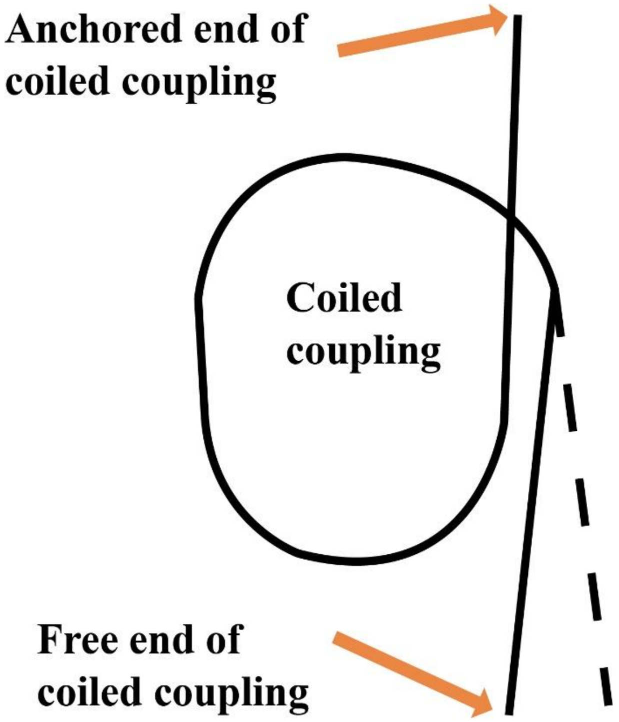


Fig. 13 Isometric view of the coil-coupling connecting the tube to the header coupling

5. Conclusion

From the above analysis and recommendations, it can be concluded that in the absence of evidence of damages of wear and corrosion in the superheater tubes' failures, the reason for cracks at the weld joint between the tube and outlet header coupling can be attributed to differential thermal expansion experienced by front line tubes and can be absorbed by introducing a looped tube (coiled) before the weld joint. This eliminates severe fissures introduced by the bowing tube due to temperature differential. The shape of the loop can be made to allow the removal of the tube bundle from above in a restricted area.

Plagiarism Check

The author does not feel to check for any plagiarism as the research and analysis presented in this paper are his own. The theory applied is his own hypothesis because of his own knowledge and practice.

Acknowledgement

The author acknowledges his employer ALS Industrial for getting the tube front and rear face temperatures measured experimentally by installing thermocouples and making inspection reports available as a part of the investigation and research.

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