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A VIEW FROM THE PENTHOUSE: USEFUL INFORMATION FOR THE WORLD OF BOILERS

BENT TUBES

Large utility boilers contain thousands of feet of boiler tubing. Each portion of the superheater, reheater, or economiser (SRE) contains several hundred individual tubes and each tube may contain a dozen bends. Thus it seems appropriate to discuss some design and fabrication aspects of boiler tubing.

The ASME Boiler and Pressure Vessel Code gives rules for the calculation of the minimum wall thickness (MWT) of a cylinder from the design pressure, tube diameter, and allowable stress. The allowable stress is given in Tables PG 23.1 - 23.3 for all alloys and all temperatures. Notice the Code refers to cylinders, see paragraph PG 27. A cylinder is a specific geometry and a bend is a torus, NOT A CYLINDER. Thus the Code does not directly discuss calculations for wall thickness of a bent tube. The Code does discuss bends in an indirect way: Paragraph A22, Proof Tests to Establish Maximum Allowable Working Pressure, (MAWP). "The MAWP for pressure parts of a boiler for which the strength cannot be computed with satisfactory assurance of accuracy shall be established in accordance with the requirements of this paragraph..." Paragraph A22.2.1.2 "Tests based on bursting the part", and Paragraph A22.6.3 given an equation for determining MAWP from burst tests. Thus bends fall into this category because no calculations are given for a torus.

$$P = \frac{B}{5} \times \frac{S}{Sa \text{ or } Sm} \qquad \text{PGA22.6.3.2.1}$$

B = bursting test pressure
S = specified minimum tensile strength, psi
Sa = average actual tensile strength of test specimens
Sm = maximum tensile strength of range of specification

For use at elevated temperatures, room temperature bursting tests are "corrected" by PGA22.8.

$$P = P_T \frac{So}{S_T}$$

P = MAWP at operating temperature
P_T = MAWP at room temperature
So = Max. allowable stress at operating temp.
S_T = Max. allowable stress at room temp.

Paragraph PG27.2 of the Code gives the equation for calculating MWT, W, of a cylinder:

$$W = \frac{PD}{2S+P} + 0.005D + e \qquad \text{EQ PG27.2.1}$$

where: W is MWT, inches
P is design pressure, psi
D is tube outside diameter, inch
S is Code allowable stress from PG23.1-23.3, psi
e is rolling allowance, 0 for welded construction.

The equation above is close to the equation for hoop stress in a thin walled cylinder given in any text on stress calculations:

$$S = \frac{PD_m}{2W} \qquad \text{EQ 1}$$

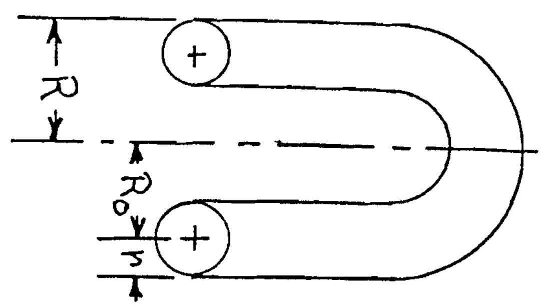
Where S is hoop stress, psi
P is internal pressure, psi
W is tube wall thickness, inch
D_m is mean diameter, equals D-W, inch.

A rearrangement of EQ 1 gives:

$$W = \frac{PD}{2S+P} \qquad \text{EQ 2}$$

Compare with EQ 27.2.1

There are equations for calculation of the hoop stress in a torus. Sketch A shows a 180°



Sketch A

bend, the tube diameter is 2r, the bend radius is R_o from the center of the bend to the center of the tube. Thus $R = R_o + r$. The inside of the bend, a, is called the intrados and the outside of the bend, b, is called the extrados. For thin wall tubes, EQ 1 becomes

$$S = \frac{PD}{2W} = \frac{Pr}{W} \qquad \text{EQ 3}$$

which assumes D and D_m are the same. For a torus the hoop stress on the extrados is:

$$S = \frac{Pr}{2W}\left(\frac{2R_o + r}{R_o + r}\right) \qquad \text{EQ 4}$$

where S, P, and W are defined under EQ 1 and R_o and r are shown in Sketch A. Note that when R_o is very large, $R_o + r$ is approximately R_o and EQ 4 becomes EQ 3. The hoop stress at the intrados is:

$$S = \frac{Pr}{2W}\left(\frac{2R_o - r}{R_o - r}\right) \qquad \text{EQ 5}$$

The hoop stress at the intrados is larger than the hoop stress at the extrados.

Tubes are bent in several ways depending on the diameter, wall thickness, and radius of the bend. The most common technique is to bend the tube over a wheel grooved on the rim to fit the tube. A similarly grooved arm moves around the wheel to make the bend with minimum distortion to the tube. The bend radius is fixed by the wheel diameter. To prevent the extrados from collapsing, a mandrill of a diameter equal or close to the inside diameter of the tube may be inserted. The position of the ball-shaped end is at the tangent point of the wheel where the moving arm makes the bend.

It is obvious that the extrados of the bend travels further than the intrados in their journeys around the wheel. Thus there is considerable thinning on the outside of the bend. To reduce this thinning there are computer controlled hydraulic devices that help to push the tube around the wheel. The part of the tube that becomes the intrados may be heated to allow greater metal flow on the inside and thus reduce the wall thinning on the outside.

The net result is that the intrados has a thicker wall than the extrados; thus the actual stress is less on the inside than on the outside. In general, bent tubes fail in service on the extrados.

It is instructive to calculate the wall thickness at the extrados that gives equal hoop stress in a cylinder. EQ 3 is set equal to EQ 4 and the wall thickness in the cylinder is W_c and in the torus or bend, W_t thus:

$$\frac{Pr}{W_c} = \frac{Pr}{2W_t}\left(\frac{2R_o + r}{R_o + r}\right) \qquad \text{EQ 6}$$

When EQ 6 is solved for W_t in terms of $R_o = kr$, where the bend radius is a multiple of the tube radius, we get the following table. In every case the torus wall thickness is less than the cylinder wall thickness to give equal hoop stress.

$R_o = r \quad W_t = .75W_c$
$R_o = 1\frac{1}{2}r \quad W_t = .80W_c$
$R_o = 2r \quad W_t = .83W_c$
$R_o = 3r \quad W_t = .88W_c$
$R_o = 4r \quad W_t = .90W_c$
$R_o = 5r \quad W_t = .92W_c$

Wall thinning does occur in practice, but common industry standards limit the actual wall thickness on the extrados to 90% MWT. Thus if the MWT is 0.240", the measured wall thickness (usually made by ultrasonic thickness measurements) should be 0.216" or thicker for all bends.

Burst test data show that rupture occurs in the cylinder portion not the torus section even though the wall thickness was reduced at the extrados by up to 25%. It is safe to have SRE elements with wall thinning of up to 10% in the tube bends, therefore.

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