Structural Analysis and Design of Replacement Water Columns for Boilers


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1 Introduction

A water column on a boiler is used to create a non-turbulent water zone to accurately show the water level in the steam drum. Level sight glasses, level transmitters, and level shutdown switches are connected to the water column in order to determine the correct steam drum water level and to alarm or shutdown the boiler in the event of low water. The water column is critical for proper boiler operation.

Package boilers, i.e., boilers that are fabricated in a shop and shipped to the job site, come with water columns already designed and installed as shown in Figure 1.

Figure 1: Side View of Package Boiler with Water Column

Based upon a required review of the Safety Instrumented Systems (SIS) of a boiler, additional water level transmitters were required to improve the boiler safety. The existing water columns were too small to support additional water level transmitters. The water column on the burner end of the boiler was chosen to be replaced with a larger water column. The new, larger water column was also to be offset from the drum in order for periodic maintenance to be performed on the level transmitters.

The engineering structural analysis entailed designing new water column, offset piping to the new water column, and a support for the new water column. The existing water column was directly cantilevered and supported from the drum connections by the connecting piping. The stresses in the existing piping and connections to the existing water column were within ASME B31.1, Power Piping, code requirements.
ASME Section I, Rules for Construction of Power Boilers, ASME B31.1, Power Piping, and ASME Section II, Part D, Properties (Customary) Materials, were used in designing the new water column, interconnecting piping, and supports.

2 Water Column Design

ASME Section I was used for the water column design. The water column with connections is shown in Figure 2.

The minimum thickness of the cylindrical water column due to circumferential stresses from internal pressure was determined by using the following Eq. (1) from ASME Section I, paragraph PG – 27.2.2.

\[
t = \frac{PD}{2SE + 2yP} + C \quad (1)
\]

Where \( t \) is the minimum required thickness (inches), \( P \) is the maximum allowable working pressure (psig), \( S \) is the maximum allowable elastic stress (psi) per ASME Section II at the design temperature of the water column, \( D \) is the outside diameter (inches) of the cylindrical water column, \( C \) is the minimum allowance for threading and structural stability (inches), \( E \) is the joint efficiency, and \( y \) is the temperature coefficient as specified in ASME Section I.

Since the cylindrical water column was seamless, \( E \) was 1.0. Also, since the maximum design temperature of the ferritic steel water column was below 900°F, \( y \) was 0.4 per ASME Section I. For this case, there were no threads and structural instability was not an issue. However, a corrosion allowance of 0.0625 inches was imposed and, therefore, \( C \) was taken as 0.0625 inches. Since the water column material was SA – 106 – Gr – B and its maximum design temperature was 550°F, the corresponding maximum allowable elastic stress was 17,100 psi per ASME Section II. The outside diameter of the water column was 8.625 inches. Its maximum allowable working pressure (MAWP) was 600 psig: the same as the MAWP of the boiler.

Once these values were entered in the equation, the resulting minimum thickness was 0.212 inches. The cylindrical portion of the water column was constructed from an 8 inches nominal, schedule 80 pipe with an average thickness of 0.594 inches and a corresponding minimum thickness of 0.520 inches. Since the required minimum thickness was only 0.212 inches, this pipe selection for the water column was more than adequate to meet the ASME Section I code requirements.

Along with analyzing the cylindrical portion of the water column, the cap was also analyzed for internal pressure per ASME Section I. The following Eq. (2) was used from ASME Section I, paragraph PG – 29.1.

\[
t = \frac{5PL}{4.8Sw} + C \quad (2)
\]
Where \( t \) is the minimum required thickness (inches), \( P \) is the maximum allowable working pressure (psig), \( L \) is the radius to which the head is dished (inches), \( S \) is the maximum allowable working elastic stress, and \( w \) is the weld joint strength reduction factor per PG – 26 in ASME Section I. In this case, \( C \), a corrosion allowance (inches), was added to the minimum required thickness to the ASME Section I.

For this cap, \( P \) was as 600 psig, \( S \) was 17,100 psi for SA – 106 – Gr B material at 550°F maximum allowable temperature, \( C \) was 0.0625 inches, \( L \) was 4.000 inches, and \( w \) was 1.0 per ASME Section I. Once these values were entered in the above equation, the minimum cap thickness was determined to be 0.209 inches. Since the cap was an 8 inches nominal, schedule 100 cap, the average thickness was 0.594 inch with a corresponding minimum thickness of 0.520 inches. Since the required minimum thickness was only 0.209 inches, this cap selection for the water column was more than adequate to meet the ASME Section I code requirements.

Since the blind flange was rated for 600 psig, it did not need to be analyzed. However, the water column was checked for a full vacuum with an external atmospheric pressure of 14.4 psia. The procedure outlined in ASME Section VIII, Div. 1, Rules for Construction of Pressure Vessels, and ASME Section II, Part D, were used to determine the MAWP due to external pressure. The results of this procedure yielded a MAWP working pressure due to a full vacuum on the water column was 984 psig: well within the design pressure of 600 psig as stated before.

3 Interconnecting Piping from the Steam Drum to the Water Column

The interconnecting piping from the steam drum to the water column as shown in Figure 3 was analyzed in accordance with ASME B31.1:

\[
\frac{PD_0}{2(SE + Py)} + A
\]

Where \( t_m \) is the minimum required wall thickness (inches), \( P \) is internal design pressure, MAWP, (psig), \( D_0 \) is the pipe outside diameter (inches), \( SE \) is the maximum allowable stress (psi) and joint efficiency for the pipe material and design temperature, \( y \) is a coefficient specific by ASME B31.1 from table 104.1.2(A), and \( A \) is an additional thickness (inches) due, in this case, to corrosion.
The top and bottom interconnecting piping as shown in figure 3 is SA – 106 – Gr B material, 1.5 nominal, schedule 80 pipe with an average thickness of 0.200 inches and a minimum thickness of 0.175 inches. The outside diameter for this pipe schedule is 1.900 inches. From ASME B31.1, the SE factor the material given was 17,100 psi. Also from ASME B31.1, table 104.1.2(A), the y factor was 0.400 for a design temperature of 550°F. The corrosion allowance, A, was 0.0625 inches. The maximum allowable working pressure was the same as for the water column and boiler – 600 psig.

When all these values are put in the above equation, the required minimum thickness of the piping due to internal pressure is only 0.095 inches – well below the minimum thickness of the selected pipe.

Like the water column, the piping was also analyzed for a full vacuum operation based upon the procedure in ASME Section VIII, Div. 1. This calculation produced a MAWP of 1,707 psig for the 1.5 inch nominal diameter piping – well within the design MAWP of 600 psig.

The socket weld elbows, valves, and flanges did not need to be analyzed, since they conformed to the standards listed in table 126.1 in ASME B31.1.

The interconnecting piping bending, torsional, and lateral stresses were determined due to the piping acting as support for the water column.

4 Water Column Support

In order to support the new water column, three different types of water column supports were analyzed: cantilevered, bottom support, and top support with a constant force spring:

4.1 Cantilever Support

With the cantilevered system, the top and bottom interconnecting piping had to support the total weight of the water column. The combined weight of the water column, cap, blind flange, fittings, and water in the water column, interconnecting piping, valves, and transmitters on the water column was calculated to be 1,086 lbs.

Since the water column was cantilevered from the steam drum, the maximum bending and torsional stresses occurred at the steam drum connections. These connections were analyzed first. If they did not meet the maximum allowable stress, then none of the piping system would be adequate.

The top pipe segment from the steam drum connection to the water column is slightly shorter than the bottom segment. Therefore, the piping system is not totally symmetrical, but very close to being symmetrical. For this analysis, about half of the water column’s weight would be supported by the top and bottom interconnecting piping, respectively. The bending moments at the steam drum were calculated along the top and bottom pipe segments taking into account the isolation gate valves, the piping distributed weight, and the water weight in the pipe. As to be expected, the water column weight and bending over shadowed the other weights and bending moments.

The bending moment was calculated by using engineering statics. For the top pipe segment bending moment was calculated to be 14,600 in – lb\(_e\) while the bending moment for the bottom pipe segment was calculated to be 16,750 in – lb\(_e\). Once the bending moments were determined the bending stress was calculated by the following Eq. (4).

\[
S_B = \frac{M_B(y_R)}{I}
\]  

Where \(S_B\) = bending stress (psi), \(M_B\) is the bending moment (in – lb\(_e\)), \(I\) is the moment of inertia (in\(^4\)), and \(y_R\) is the radius from the
neutral axis to the center of the pipe metal thickness.

For the 1.5 inches nominal, schedule 80 carbon steel, SA – 106 Gr B, piping, the outside diameter is 1.900 inches and the average inside diameter is 1.500 inches. The moment of inertia is 0.391 in$^4$ and the radius, $y_R$, is 0.850 inches. When these values are substituted in the above equation along with the respective bending moments, the resulting bending stress for the top segment is 31,765 psi and for the bottom segment is 36,402 psi. The maximum allowable elastic stress for this material at a design temperature of 550°F is only 17,100 psi. Because of the water column’s weight, the bending stress, alone, greatly exceeds the maximum allowable elastic stress and, therefore, the water column should not be cantilevered from the steam drum connections. Other stresses such as the stress due to torsion and longitudinal stress were calculated and coupled with the bending. The overall result stress was 44,500 psig for the top segment and 48,000 psig for the bottom segment. Again, clearly this water column design should not be cantilevered from the steam drum connections.

### 4.2 Bottom Support

The next option analyzed was a bottom support option. On the surface this option looked viable, since the water column weight would be directly supported by a platform located at the steam drum (see Figure 4). The water column had to be installed while the boiler’s temperature was ambient. The boiler will thermally grow upwards while in operation creating a significant interconnecting piping deflection at the water column connections. Because the top connection is higher than the bottom connection, the top connection will grow slightly more than the bottom connection.

The heated components in the boiler are carbon steel. The thermal expansion of this material per ASME Section II, Part D is $7.33 \times 10^{-6}$ in/(in–°F) at the boiler’s design temperature of 550°F. The boiler height from the centerline of the boiler’s bottom drum to the bottom steam drum piping segment connecting the steam drum to the water column was 137.750 inches with a corresponding upward growth of 0.495 inches at a design temperature of 550°F. Due to this growth and applying the formulas that relate deflection to load for both bending and torsional conditions, the resultant of the bending and torsional moments at the water column was determined to be 14,700 in–lbf with a corresponding stress of 31,500 psi: greatly exceeding the carbon steel piping’s maximum allowable elastic stress of 17,100 psi.

Likewise, the boiler height from the centerline of the boiler’s bottom drum to the top steam drum piping segment connecting the steam drum to the water column was 158.750 inches with a corresponding upward growth of 0.570 inches at a design temperature of 550°F. Due to this growth and applying the formulas that relate deflection to load for both the bending and torsional moments at the water column was determined to be 16,250 in–lbf with a corresponding stress of 35,300 psi – greatly exceeding the carbon steel piping’s maximum allowable elastic stress of 17,100 psi.

A stress difference due to the thermal growth between the top and bottom piping segments will exist. However, this stress should not
exceed 5,000 psi: well within the acceptable elastic stress range.

4.2 Top Support with a Constant Force Spring

Clearly, the bottom support like the cantilever support was not a viable option, since the stresses in the piping connections would exceed the maximum allowable elastic stresses as established by ASME documents. The other support option was a top support.

A top support for the water column with a constant force spring was decided upon as shown in Figure 5. This type of support will support the water column independently of the stream drum and allow the water column to grow upward with the stream drum. This type of support is also sanctioned by ASME B31.1, paragraph 121.7.4, Constant Supports.

5 Conclusion

The new water column design in accordance with ASME standards and classical structural engineering formulas is adequate provided it is top supported by a constant force spring.

References


