

# Calculation of Steam Pressure on the Inner Wall of Boiler Tube Based on Outer Wall Temperature and Strain

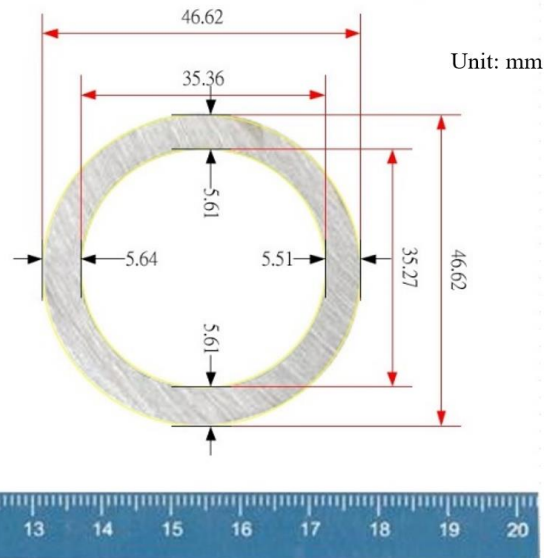
Energy Research Lab: Tzeng, Chian-Wei; Kao, Chuan-Sheng; Su, Kwei-Yuan; Yang, Xue-Wen

## 1. Research background

During operation, the furnace temperature of a power boiler can reach over 1100 degrees Celsius. Conventional instruments cannot withstand such high temperatures and can only be installed on the external manifold sections, making it difficult for maintenance personnel to monitor the unit's health status or perform appropriate diagnostics. The purpose of this study is to develop diagnostic charts based on furnace tube surface temperature and strain data. By referencing these charts, maintenance personnel can determine the internal steam pressure in the heat exchange tubes, enabling assessment of abnormal swelling or ruptures that may lead to steam leakage.

## 2. Research content

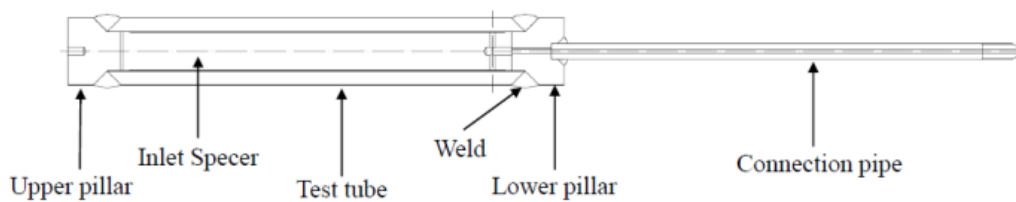
This study used heat exchange tubes made of low-alloy steel as specimens, with an inner diameter of 35.3 mm, an outer diameter of 46.6 mm, and an axial length of 330 mm. The cross-sectional dimensions of the furnace tubes are shown in Figure 1.



Source: This study's illustrations.

Figure 1. Cross-sectional Dimensions of the Boiler Tube

The specimen assembly consists of the connection pipe, lower and upper pillars, an inlet spacer, the test tube, and the associated weld (Figure. 2). The upper and lower pillars are convex stainless-steel structures. The total length of the specimens exceeds  $150 \text{ mm} + 2D_0$  (where  $D_0$  represents the outer diameter of the tube). Following mechanical cutting, the tube surfaces underwent non-destructive testing; only samples that satisfied the non-destructive testing requirements were selected for subsequent processes.



Source: This study's illustrations.

Figure 2. Schematic Diagram of Boiler Tube Sample

The inlet spacer of the boiler tube sample was made of stainless steel and maintained at a clearance of 0.5 mm from the inner wall. The connection pipe was composed of high-pressure grade stainless steel. The processing on the welded end of the boiler tube followed the AWS D1.1/D1.1M guideline [1], where the upper pillar, lower pillar, and the connection pipe were welded by tungsten argon arc welding. After the welding was completed, the welding bead satisfied the requirements for radiographic testing.

The boiler tube specimen was sealed at both ends and filled with deionized water as a pressurization medium until the target pressure was reached and stabilized. The pressurizing circuit integrated a pressure relief valve and a pressurization valve. Moreover, the required pressure was continuously applied to adjust the internal pressure of the specimen through the connection pipe. The experimental pressures ranged from 5% to 100% of the operational pressure, with a relative error maintained within 1.0%. During the experiment, if the steam pressure dropped by 1.0% from the set point, pressurization was immediately applied to restore and maintain a constant pressure. The duration of this pressure deviation was restricted to less than one minute.

The high-temperature boiler comprised three

regions whose temperatures were controlled independently, with a temperature deviation within  $\pm 3$  °C. The outer wall of the heating tube was heated at a rate of 4 °C per minute while simulating the actual operating conditions. The isothermal zone was more than 1.2 times the length of the sample boiler tube. An R-type thermocouple was used to control the heater temperature, while a K-Type thermocouple was used to measure the temperature of the boiler tube. The temperature controller had a resolution of 0.1 °C and a precision within  $\pm 1$  °C for temperature compensation.

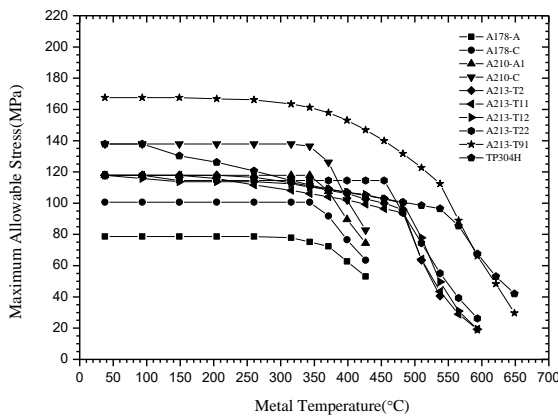
Before the experiment, a water pressure test was performed at a pressure 1.2 times the test pressure, where the pressure was held constant for 10 min. Subsequently, the pressure was set to the test pressure and maintained constant for 10 min before heating was applied while maintaining the working environment temperature between 10 °C and 30 °C. Thermocouples were installed in the upper, middle, and lower sections of the boiler tube, while a circumferential strain gage was installed in the middle section (Figure. 3). The actual operating condition of the boiler tube in a power plant was simulated, and the strain response to the temperature changes in the boiler tube material under different steam pressures was recorded.



Source: This study's illustrations.

Figure 3. Thermocouples and Strain Gage Installation on the Sample Boiler Tube

The maximum allowable stresses for different boiler tube materials, such as carbon steel, low-alloy steel, and stainless steel, vary at high temperatures [2]. A high content of alloying elements enhances the creep resistance of the boiler tube and thus reduces the probability of failure in the heat exchange tubes [3]. The content of alloying elements affects the temperature at which a sharp reduction in the maximum allowable stress occurs (Figure. 4). In addition to factors such as the outer diameter and wall thickness of the tube, the behavior of the maximum allowable stress at high temperatures determines the deformation of the boiler tube under high-temperature, high-pressure conditions.

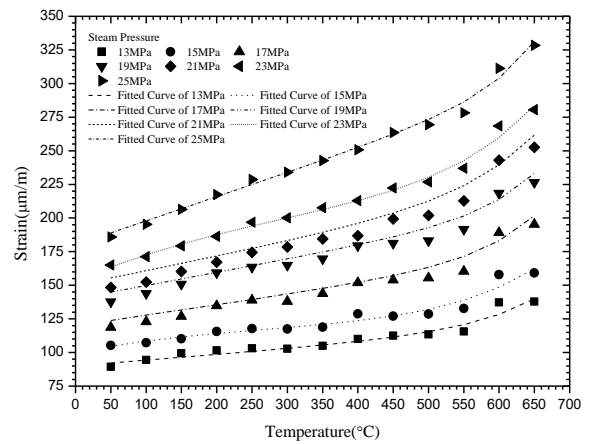


Source: This study’s illustrations.

Figure 4. Maximum Allowable Stress in Tension

At a fixed temperature, the amount of strain increases steadily with increasing steam pressure. For every increase of 1 MPa in steam pressure, the strain value of the outer wall of the boiler tube increases by 5  $\mu\text{m}/\text{m}$  to 10  $\mu\text{m}/\text{m}$ . With increasing temperature, the strain trends in the strain of the boiler tube materials under different steam pressures remain consistent. As shown in Fig. 8, the significant increase in the strain at temperatures higher than 550  $^{\circ}\text{C}$  is attributed to the precipitation of secondary

phases at the grain boundaries. Under normal operating conditions, the change in strain can be reasonably explained; however, if the boiler tube is operated under abnormal steam pressures or experiences long-term or short-term overheating, a sharp change in strain will occur immediately. Hence, it is possible to predict when the tube rupture will occur based on the increase in the creep rate.



Source: This study’s illustrations

Figure 5. Boiler tube inner wall steam pressure chart

The curves drawn from the experimental data were fitted to obtain the steam pressure chart represented by the empirical formula:

$$\varepsilon = A \times e^{-T/B} + C \times e^{-T/D} + E \quad (1)$$

For example, at a steam pressure of 17 MPa, the parameters are  $A=0.0085$ ,  $B= -79.46$ ,  $C= -4.74 \times 10^6$ ,  $D= 6.16 \times 10^7$ , and  $E=4.74 \times 10^6$ . Here,  $\varepsilon$  is the strain of the outer wall material of the boiler tube, and  $T$  is the temperature of the outer wall of the boiler tube in degrees Celsius. The deformation of the metal under different steam pressures as a function of the operating temperature is expressed by an exponential equation.

### 3. Conclusions

This study demonstrates that it's feasible to create a steam pressure chart by using the boiler tube surface temperature and the material strain, from which the steam pressure inside the boiler tube can be obtained. Alternatively, the steam pressure can be calculated using the empirical equation (1). If the boiler tube operates under abnormal conditions, a sharp change in strain will occur immediately. Furthermore, the increase in the creep rate can be employed to predict when tube rupture will occur.

### 4. References

- [1] *Structural Welding Code—Steel*, AWS D1.1/D1.1M, 2008.
- [2] *Power Piping*, ASME B31.1, 2007, pp. 102–159.
- [3] B. Haghghat-Shishavan, H. Firouzi-Nerbin, M. Nazarian-Samani, P. Ashtari, and F. Nasirpouri, “Failure analysis of a superheater tube ruptured in a power plant boiler: Main causes and preventive strategies,” *Eng. Fail. Anal.*, pp. 131–140, Oct. 2019.