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Research Paper

Prediction of wall temperature and oxide scale thickness of ferritic–martensitic steel superheater tubes

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HIGHLIGHTS

- The thermal deviation theory and thermal constraint conditions are used.
- The wall temperature distribution is estimated along the steam flow at one moment.
- The thicknesses of oxide scale on the inner tubes are predicted along the steam flow.
- The heat fluxes at one position of the tubes are predicted as a function of time.

ARTICLE INFO

Keywords:
Wall temperature
Oxide scale thickness
Superheater tube
Ash deposit

ABSTRACT

Based on the thermal deviation theory and local energy and mass balance of the superheater tube, a new method of calculating tube wall temperature is proposed. The wall temperature distribution and the thickness of oxide scale of the superheater tubes of a supercritical boiler are estimated over the length of the steam flow path for different periods of service. This calculation of oxide scales on the steam side takes into account ash deposits on the flue gas side. The results of oxide scale thickness of boiler superheater tubes for different exposure time are compared with field measurement data. There is a sudden increase in the wall temperature at the tube elbow (position N) because of high gas temperature and high heat transfer coefficient. The distribution of the gas temperature field along the height of the heating surface has a great influence on the final wall temperature calculation results.

1. Introduction

Superheater tubes are generally exposed to high temperature gas at the outer surface and high pressure at the inner surface. The main cause of boiler tube failures is due to tube temperature higher than expected in the original design [1]. The oxide scales on superheaters have been detailedly reported in the literature [2,3] mainly due to its strong influence on the safety and efficiency of a utility boiler. The oxide scales formed on high-temperature heating surfaces of superheater tubes reduce the heat transfer from the gas side to steam side and its exfoliation may cause tubes burst failures due to overheating. The oxide scales inside superheaters have been found to be one of the major contributors to the tube rupture. The growth and exfoliation of thermally grown oxide scales in steam is a complex phenomenon that depends on alloy composition, microstructure (including surface condition), temperature, pressure, and plant operation [4]. An EPRI survey of U.S. utilities showed that over 50% of respondents experienced exfoliation-related damage in their power plants [4].

The oxide scale growth is extremely dependant on temperature for one alloy steel. It is critical to monitor or calculate the tube wall temperature of superheater. The suitable steel grade can be selected to avoid overheating of the tube material if the tube wall temperature is known along the steam flow path of superheater tubes. It is difficult to measure the wall temperature for a long period of operation due to high temperature damage of the measuring instrument on the superheater of utility boiler.

Significant effort has been expended to predict the tube wall temperature of superheater. N.W. Kuznetsov et al. present a standard method for hydraulic and thermal design calculations of steam superheaters [5]. Rayaprolu discussed the basic superheater and reheater design principles and described simple design and performance procedures of superheater calculating in detail [6]. Factors causing temperature difference in each platen superheater panel have been analysed [7]. A method for calculating the temperature difference was introduced and the results of the calculations performance on six utility boilers were compared with measured values. The reasons of thermal

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Nomenclature

a_{as}	ash wall surface emissivity, 0.85
a_g	gases emissivity
a_{fg}	front gases emissivity
a_{rg}	rear gases emissivity
C_P	specific heat, J/(kg·K)
C_{syn}	Integrated coefficient of radiant heat exchange
d	inner diameter of the tube, m
D	outer diameter of the tube, m
E_0	a correction factor for the middle tube area
h_s	convection heat transfer coefficient of steam side, W/(m^2·K)
h_g	heat transfer coefficient of gas side, W/(m^2·K)
h_c	convection heat transfer coefficient of gas side, W/(m^2·K)
h_r	radiation heat transfer coefficient of gas side, W/(m^2·K)
H_0	bundle radiation heat transfer area of middle tube, m^2
H_r	heat transfer area of middle tubes bundle radiation, m^2
H_c	heat transfer area of middle tubes bundle convection, m^2
H_{fr}	heat transfer area of front gas room radiation, m^2
H_{rr}	heat transfer area of rear gas room radiation, m^2
l	length of tube, m
m	total steam mass flow rate, kg/s
m_a	steam mass flow rate of tube segment A, kg/s
m_c	steam mass flow rate of the calculated tube, kg/s
Nu	Nusselt number
n	number of tubes of one serpentine
p_{fr}	Radiation factor of front gas room
p_{rr}	Radiation factor of rear gas room
Pr	Prandtl number
Q_{wh}	total absorbed energy of the whole calibrated tube, W
Q_{tot}	total absorbed energy for each of the tube, W
Q_a	heat absorption of segment A, W
q_r	thermal load of middle tubes bundle convection, W/m^2
q_c	thermal load of middle tubes bundle radiation, W/m^2
q_{fr}	thermal load of front gas room radiation, W/m^2
q_{rr}	thermal load of rear gas room radiation, W/m^2
Re	Reynolds number
s_L	longitudinal pitch, m
s_T	transversal pitch, m
T_{as}	ash deposits temperature of, K
T_g	flue gas temperature, K
T_s	steam temperature, K
T_{fg}	front gas temperature, K
T_{rg}	rear gas temperature, K
T_{w1}	temperature of the oxide scale surface, K
T_{w2}	temperature of the oxide scale/steel interface, K
T_{w3}	temperature of the steel/ash deposits interface, K
T_{w4}	temperature of the ash deposits surface, K
w_g	gas velocity, m/s
x	radiation angle factor of the middle tube
x_f	radiation angle factor of the tube in different positions
Z	number of tube wide

Greek symbols

Δi	enthalpy rise between the inlet and outlet of the tube, J/kg
δ	thickness, m
ζ	correction factor in Eq. (34)
η_{fl}	flow rate deviation coefficient
η_h	thermal load deviation coefficient in the height direction
η_w	thermal load deviation coefficient in the width direction
λ	thermal conductivity, W/(m·K)
μ	dynamic viscosity, Pa·s
ξ	mean resistance factor of tubes of the same serpentine
ξ_a	resistance factor of the calculated tube
ξ_r	radiation correction factor in Eq. (15)
ξ_c	convection correction factor in Eq. (16)
σ_0	stefan Boltzmann constant, 5.67×10^{-8} W/(m^2·K^4)
ν	mean specific volume of tubes of the same serpentine, m^3/kg
ν_a	specific volume of the calculated tube, m^3/kg
ν_g	kinematic viscosity of flue gas, 10^{-6} m^2/s
Φ	heat rate, W

Superscripts

a	tube segment A
as	ash deposits
g	gas
m	metal
ox	oxide scale
s	steam

deviation of superheaters and reheaters of large capacity utility boiler were analysed in detail [8]. A general computing model of thermal deviation of superheaters and reheaters was presented firstly. A novel model for estimating the highest tube wall temperature of the convective heat transfer surface is proposed [9]. This model takes into account the thermal restrictive condition based on the energy and mass balance for the tube concerned. The advantage of the proposed method over the previous method was that calibrated calculation was carried out according to the actual conditions. A thermal load model that is based on the power plant thermodynamic parameters, thermal deviation theory, and flow rate deviation theory was proposed [10]. This model has actually been used to predict and prevent the boiler tube failures in the power station. A model that focuses on obtaining the thermal behaviour of the tubes of the serpentines forming the reheater of a utility boiler was described [11,12]. The model describes the domain in 3-D and the continuity, momentum and energy equations are solved in a coupled way. The results predicted by the model of the temperature of the tubes at the reheater outlet and the outlet steam temperature are satisfactorily compared with the experimental measurements. Based on the finite volume method, a numerical modeling of steam superheaters was used for detailed analysis of flow and thermal phenomena in superheaters [13,14,15]. Mathematical simulation of superheater operation considering fouling processes on the flue gas and steam side allows assessing the impact of the flue gas temperature unevenness in the channel cross-section on the flow and the wall temperature of the steam superheater tubes.

According to the parabolic law of high-temperature oxidation, Arrhenius equation, and related basic theories of heat transfer, an oxide scale growth model of boiler superheater tubes was proposed through iterative technique [16,17]. The model involve forced convections on the inner surface due to the turbulent flow of steam and on the outer surface due to cross flow of the hot flue gas over ash tubes. A procedure to estimate the oxide scale growth in superheater and reheater tube utilizing the empirical formula correlating the scale thickness with Larson-Miller Parameter (LMP) and the finite element modeling was proposed [18,19]. An iterative procedure consisting of empirical formulae and numerical simulation is used to determine scale thickness as both temperature and time increase.

In this paper, a new method of calculating tube wall temperature based on local energy and mass balance of the calibrated tube is proposed. According to the measured values or design values of the inlet and outlet steam temperature, the actual heat absorption of a tube