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Thermal simulation of superheaters taking into account the processes occurring on the side of the steam and flue gas

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HIGHLIGHTS

- Nonlinear model of the steam superheater with mixed flow arrangement.
- Scale deposits on the tube inner surfaces and ash fouling on the outer tube surfaces.
- Steam temperature maldistribution caused by uneven flue gas temperature across the width of the superheater.
- Steam pressure distribution along the steam flow path.
- Influence of internal and external deposits on steam, tube wall, and flue gas temperature.

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ABSTRACT

Superheater model was used to analyzing the impact of ash deposits on the outer tube surfaces and scales formed on the inner tube surfaces on the heat flow rate transferred from the flue gas to the steam. The influence of uneven heating of parallel superheater tubes on the flow and temperature maldistribution was also examined. Excessive heating of some tubes reduces the mass flow rate of the steam flowing through these tubes. It may result in overheating of the tube material. Excessive local tube heating by a higher temperature flue gas, in combination with lower steam mass flow rate through each tube, can contribute to the overheating of the tube material. Ash fouling causes a significant decrease in heat flux absorbed by the steam and lowering the temperature of the tube metal. Scale depositions on the inner surface of the tube cause a big increase in wall temperature of superheater tubes despite a decrease in the heat flux transferred from the flue gas to the steam.

1. Introduction

Superheaters are tubular cross-flow heat exchangers. However, they differ very significantly from the other heat exchangers operating at moderate temperatures. The characteristic feature of the superheaters is complicated flow arrangement and high water steam and flue gas temperature (Fig. 1). Because of the high dependence of the water steam specific heat on pressure and temperature, the superheater cannot be calculated as a typical heat exchanger using conventional methods such as the ε-NTU method (effectiveness – number of transfer units) or the method based on the logarithmic mean temperature difference between the fluids (the LMTD method) [1–3]. Good design of the superheater is very difficult. The reason for this is the complexity of heat transfer by radiation of flue gas with a high content of ash particles and the fouling of heating surfaces by slag and ash [4–7]. The degree of the slag and ash deposition is hard to assess, both at the design stage and during the boiler operation. In consequence, the proper size of superheaters is being assumed only after boiler starting. In cases when the temperature of superheated steam at the exit from the superheater stage under examination is higher than design value, then the area of the surface of this stage has to be decreased. However, if the exit temperature of the steam is below the desired value, then the surface area is increased.

Due to the high cost of alloy steels each superheater stage is usually made of different steel. Detailed calculation of superheater tube wall temperature is critical. The steel grade can be correctly selected to avoid overheating of the superheater material if the tube wall temperature is known over the entire length of the superheater.

Superheaters and reheaters are the heat exchangers in which tube walls attain the highest temperatures in a boiler, and for this reason, require the greatest attention in design and operation [8].

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Nomenclature

d_h hydraulic diameter of the superheater tube (for a circular tube, this equals the inner diameter of the tube), m
f_1 steam inlet temperature, °C
f_2 flue gas inlet temperature, °C
h_e equivalent heat transfer coefficient, W/(m^2 K)
h_g heat transfer coefficient on the flue gas side, W/(m^2 K)
h_s heat transfer coefficient at the inner tube surface, W/(m^2 K)
k_a ash deposit thermal conductivity, W/(m K)
k_s iron oxides or scales thermal conductivity, W/(m K)
L_r tube length, m
N number of finite volumes on the tube length
$\dot{m}_s$ steam mass flow rate per tube, kg/s
$\dot{m}_g$ flue gas mass flow rate per tube, kg/s
p static pressure, Pa
$\dot{Q}$ heat flow rate, W
r radius, m
r_a outer radius of deposit layer, m
r_{in} inner radius, m
r_o outer radius, m
R thermal resistance, m^2 K/W
R_a tube roughness, mm
s coordinate along the flow path in direction of flow, m
s_1 longitudinal pitch perpendicular to the flue gas flow direction, m
s_2 longitudinal pitch parallel to the flue gas flow direction, m
T_{fe} flue gas temperature at the furnace exit, °C
T_g gas temperature, °C
$\overline{T}_g$ mean gas temperature over the row thickness, °C
T_{ge} flue gas temperature after the superheater, °C
$T'_{g,i}$, $T''_{g,i}$ gas temperature before and after the tube, °C
T_{gs} flue gas temperature, °C
T_s steam temperature, °C
T_w tube wall temperature, °C

Greek symbols
δ_a thickness of ash deposits, m
δ_s thickness of iron oxide or scale deposits, m
$\Delta\dot{m}_g$ mass flow rate of the flue gas through a control volume, kg/s
φ angle between tube axis and horizontal plane
ρ steam density, kg/m^3
ξ friction factor

Subscripts
a ash
c clean
calc calculated
cg convection
e effective or equivalent
g gas
h hydraulic
in inner
meas measured
o outlet
out outlet
rg radiation
s scale
w wall

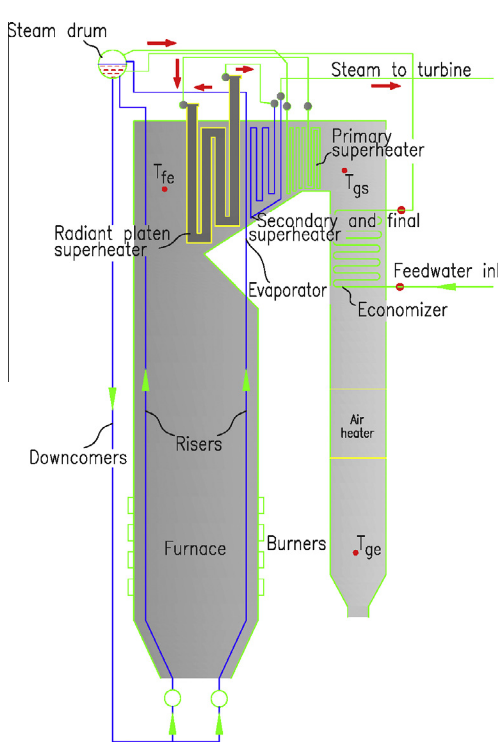

Fig. 1. Coal-fired utility boiler with natural circulation: T_{fe} T_{gs}, and T_{ge} denote flue gas temperature at the combustion chamber exit, after the superheaters and after the air heater, respectively.

A standard method for hydraulic and thermal design calculations of steam superheaters is presented in [4–6]. Although manufacturers of boilers widely use the boiler standards, they adopt for the calculation of the superheaters procedures that are used in design or performance calculations of typical heat exchangers assuming constant physical fluid properties. The basic superheater and reheater design principles are discussed in detail by Rayaprolu [9]. Simple design and performance procedures, for superheater calculating, were described. Much attention has been paid to analyzing start-ups of steam boilers. Damage of steam superheaters causes approximately 40% of all boiler failures due to the overheating of the material [10]. Therefore, steam superheaters are modeled mathematically or monitored to avoid overheating of the tube material.

Mathematical modeling of superheaters is the subject of few publications despite great practical significance of the problem. The main reason for this situation is the difficulty of the description of complex flow and thermal phenomena in the steam superheaters both in pulverized coal and fluidized boilers.

In the last decade, CFD (Computational Fluid Dynamics) modeling was used to analyze the flow and thermal processes occurring in the combustion chambers and convection passages on the flue-gas side of coal-fired boilers [11–18]. Despite the development of computers with high computational power, it is not possible simultaneous CFD simulation of phenomena on the flue gas side and the water–steam side. The combustion chamber and the convective section of the boiler can be calculated by combining three-dimensional CFD fire side models with one-dimensional tube side model for simulation water, water–steam or steam flow in the tubes. However, the modeling of thermal and hydraulic processes in steam superheaters and economizers on the tube side is very