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Monitoring of thermal stresses in pressure components based on the wall temperature measurement

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ABSTRACT

Thick-wall boiler components limit maximum heating and cooling rates during start-up or shut-down of the boiler. First, the allowable heating rates of the critical pressure components of the boiler were determined, and the temperature of the fluid was determined. The rate of change of the wall temperature of the pressure element and the thermal stress on the inner surface are controlled online and compared with the permissible values. Boiler manufacturers designate thermal stresses on the inner surface of the pressure component on the edge of the hole based on the measurement of the wall temperature at two points located inside it. Due to the low accuracy of the method used by boiler manufacturers, a new stress-determination method has been proposed in this paper in which only the internal temperature measurement point is used to determine the stresses on the inner surface of the component. In the method proposed in the paper, first, the internal surface temperature is determined from the inverse heat conduction solution, and then the stresses are calculated. Numerous computational tests were performed for cylindrical and spherical elements. Thermal stresses on the inner surface were also determined based on actual measurement data. Thermal stresses can be monitored at small time intervals. The advantage of the method is its high accuracy even at rapid changes in the fluid temperature.

1. Introduction

A mixed structure characterizes the contemporary energy system. In addition to thermal, classical or nuclear power plants, wind farms, photovoltaic cells, and other renewable energy sources are also important [1]. Buttler et al. [1] measured time series of wind power, solar power and load of the year 2014 to identify the current challenges of the integration of wind and solar power in the electricity system of the EU (European Union). Big changes in power output are typical for wind and solar power. More flexibility is therefore demanded from classic thermal blocks [2–5]. Four different types of conventional power plants were investigated in Ref. [2] for different options with increasing CO_2 and fuel prices to determine the impact of different flexibility solutions. In Ref. [3], a computer simulation of a steam-gas power unit with a Benson once-through boiler was performed to study the fast gas turbine start-up (within 20 min) on the dynamic behavior of a Benson heat recovery steam generator. A dynamic sub-critical Benson HRSG (Heat Recovery Steam Generator) model was developed using the commercial software “Advanced Process Simulation Software” (APROS) [3]. Hentschel et al. [4] carried out the detailed modeling of a hard coal-fired power plant using the thermos-hydraulic simulation code APROS to improve the boiler flexibility. A review of programmes for dynamic simulation of thermal power plants for such as ASPEN PLUS DYNAMICS, DYMOLA and APROS were conducted in Ref. [5]. Combined steam and gas, pulverized coal, and nuclear power units were simulated using various codes.

The subject of the present work is closely related to the improvement of the flexibility of thermal power plants. In connection with the development of wind farms, characterized by high variability of generated power over time, thermal steam blocks must be quickly started and switched off, so that the power supply in the system and its demand by the recipients are equal. For this reason, the time of start-ups and shut-downs of the boiler should be as short as possible, while maintaining safe and long-term boiler operation. Determining the allowable heating and

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Nomenclature

Symbols

c_w	specific heat capacity, J/(kg·K)
d_{in}	inner diameter, m
d_m	mean diameter, m
d_{out}	outer diameter, m
E	Young's modulus, Pa
f	wall temperature measured at the node **2** located at the distance δ from the inner surface of the component, °C
G	wall temperature measured at the outer surface of the component, °C
FEM	Finite Element Method
FVM	Finite Volume Method
Fo	Fourier number, $Fo = \kappa_w t/s^2$
Fo^*	Fourier number after which the quasi-steady state is formed, $Fo^* = \kappa_w t^*/s^2$
h	heat transfer coefficient, W/(m^2·K)
k_w	thermal conductivity, W/(m·K)
N	number of control volumes in the radial direction
m	the parameter in heat conduction equation ($m = 1$ for the cylindrical wall, $m = 2$ for the spherical wall)
p	pressure, Pa
$\mathrm{P}_1, \mathrm{P}_2, \mathrm{P}_3$	points on the inner surface of the pressure element on the edge of the opening
r_c	mean radius, $r_c = (r_{in} + r_{out})/2$, m
r_{in}	inner radius of the component, m
r_m	radius of the point at which the wall temperature equals the average temperature, m
RMSE	root-mean-square error (RMSE)
r_{out}	outer radius of the component, m
r_s	radius at with the temperature sensor is located, m
s	wall thickness, m
t	time, s
t^*	time after which the quasi-steady state is formed, s
T	temperature, °C or K
T_c	temperature measured in the center of the wall, °C or K
$T_{f\,0}$	initial fluid temperature, °C or K
T_f	fluid temperature, °C or K
$T_{w1}, T_{w2}, T_{w3},$	wall temperature at nodes 1,2, and 3, °C or K
T_w	wall temperature, °C or K
T_w^m	measured wall temperature, °C or K
$T_{w,m}$	mean temperature on the wall thickness, °C or K
u	the ratio of the outer to the inner radius, $u = r_{out}/r_{in}$
v_T	rate of temperature variation, K/s

Greek symbols

α_T	stress concentration factor for circumferential thermal stress
α_p	stress concentration factor for circumferential stress due to pressure
β	linear thermal expansion coefficient, 1/K
δ	distance of the temperature sensor from the inner surface of the component, m
δ_1	distance of the temperature sensor from the outer surface of the component, m
Δr	radial step in the solution of direct heat conduction problem, m
Δr_1	radial step in the solution of direct heat conduction problem, m
Δt	time step, s
ΔT	initial jump in fluid temperature, °C or K
Δt_s	sampling time of the wall temperature measurement, s
$\varepsilon_T, \varepsilon_\sigma$	relative error of temperature and stress determination at inner surface, %
$\varepsilon_1, \varepsilon_2$	relative errors, %
ν	Poisson's ratio
ρ_w	density, kg/m^3
σ_T	circumferential thermal stress, MPa
σ'_T	circumferential thermal stress given by Eq. (20), MPa
σ''_T	circumferential thermal stress given by Eq. (21), MPa
σ_T^2	variance of pseudo-random errors
σ_{al}	allowable stress, MPa
σ_p	circumferential stresses caused by pressure, MPa
σ_{φ,P_i}	circumferential stress at point $\mathrm{P_i}$, MPa
ϕ	shape factor
κ_w	thermal diffusivity, m^2/s
∇	gradient operation (nabla)

Subscripts

al	allowable
c	center
dir	direct solution
in	inner
inv	inverse solution
m	mean
nom	nominal
out	outer
p	pressure
P_i	at point $\mathrm{P_i}$
T	thermal
w	wall
0	initial
φ	circumferential

Superscripts

m	measured
n	number of time step
*	beginning of a quasi-steady state

cooling rates of critical boiler pressure elements is, therefore, crucial to shortening the boiler start-up and shut-down operations. It is also necessary to develop a method for monitoring the rate of temperature changes of the critical element walls of the boiler and monitoring thermal stresses on their internal surface so that during the boiler operation, instantaneous heating and cooling rates and thermal stresses do not exceed the allowable values. Combined -cycle power plants are increasingly used in power systems with a high share of renewable energy because of their better flexibility [6–10]. Different aspects of cycling operation of combined cycle power plants were investigated.

During the starts, shutdowns and load changes of steam boilers, thick-walled pressure components of complex shape are subjected to rapid temperatures variations and high thermal stresses. The critical pressure components such as the drum, steam-water separator, inlet and outlet headers of the superheaters stages,