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A practical approach to calculate the detailed spatial distribution of the heat transfer fluid temperature in thermosolar supporting boilers

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A B S T R A C T

Temperature of the oil used as the Heat Transfer Fluid (HTF) in power supporting natural gas boilers is the most critical factor due to the proximity of its degradation point to the working regime. Detailed predictions through Computational Fluid Dynamics (CFD) calculations are too expensive in both time and resources. This paper deals with an alternate, substantially more economical procedure to obtain the detailed temperature distribution inside the circulating oil in such kind of furnaces. The proposed approach consists in limiting the detailed CFD calculations for the critical part of the coils situated closer to the flame in the lower part of the furnace, where oil temperature is higher, with appropriate boundary conditions obtained from an ad hoc zonal calculation of the furnace.

1. Introduction

In order to achieve economical profitable performances, modern, state-of-the-art HTF oils (Therminol-1 and Technical, 2008) used in power plants usually reach an operating temperature close to 400 °C point. When the solar radiation is weak, the oil coming out from the solar heating system enters the boiler with some temperature increase, but still needing more heat to reach the correct process temperature. At those times, thermal support boilers provide the extra energy needed to heat the HTF up to the right temperature, see e.g. (Baharoon et al., 2015) and (Muñoz et al., 2009).

These boilers are of the family of water-tube (also known as water-wall) boilers, with thermal oil which circulates in the arranged tubes covering the inside part of the furnace wall instead of water. In contrast to the water-wall boilers, HTF oil does not change phase as it circulates. Having also more heat capacity, it effectively captures the heat from the flame and burnt gases inside the combustion chamber until reaching the above mentioned working temperature close to 400 °C. Also, for a cleaner process, those furnaces are feeded with natural gas, as fuel. Out of the available types of water-tube boiler, the helically-coiled ones are a popular choice due to their particular thermo-hydraulic aspects, and efforts are made in developing calculation codes that can assist in the design phase, see (Sogni and Chiesa, 2014).

Unfortunately HTF oils are not stable when their temperature exceeds a certain limit, for the particular case studied, 400 °C in the core of the flow and 425 °C in the boundary layer (film temperature). These are values close to the working temperature, which makes the right thermal balance of the system a critical issue. Once the critical temperature is overpassed, the oil degradates and may decompose in other volatile lighter oils and form solid particles, by cracking. This causes a loss of the system performance, as those volatile oils are not suitable for heat transfer, effectively reducing the thermal carrier capacity, and eventually leading to accidents by coil rupture: the deposition of the solid material on the interior part of the oil tubes prevents a proper heat transfer, and finally damages the outer part of the tube exposed to the high radiation zone in the flame chamber.

To achieve a detailed assessment of the thermal behaviour of the HTF oil, in the present paper a combined approach is proposed. It is acknowledged that the area where detailed CFD is needed is restricted to the coils facing the combustion chamber in the lower part of the furnace, where its temperature is higher and the radiation is more intense. As the oil has a high thermal capacity and its flow is turbulent, it is therefore able to smooth local variation of thermal magnitudes, so there is not need of a detailed description of boundary conditions. A coarse although properly provided description would suffice. Taking this fact into account, a general zonal method is used to predict the behaviour of the furnace in a

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Nomenclature

q_v	Volumetric power in furnace
V_F	Furnace volume
$\dot{Q}_{g1i}$	Heat given off by gas in the first stage to inside coil
$\overline{\Delta T}_{\mathrm{log1i}}$	Ave. Log. Temp. in the first stage for inside coil
α_{g1}	Local heat transfer coefficient in the first stage
α_{g2}	Local heat transfer coefficient in the second stage
$\dot{Q}_i$	Release heat in surface i
$\dot{Q}_T$	Total power delivery by the fuel
$\dot{Q}_{\mathrm{aAH}}$	Heat absorbed by air in air heater
$\dot{Q}_{\mathrm{loss2}}$	Conduction loss heat in outside coil
$\dot{Q}_{\mathrm{lossAH}}$	Conduction loss heat in air heater
$\dot{Q}_{\mathrm{oilIn}_d}$	Heat absorbed by oil in inside coil
$\dot{Q}_{\mathrm{oilOut}_d}$	Heat absorbed by oil in outside coil
$\dot{Q}_{\mathrm{u}}$	Useful power in the boiler
$\dot{Q}_{g1}$	Heat released by gas in the first stage
$\dot{Q}_{g2}$	Heat released by gas in the second stage
$\dot{Q}_{gF}$	Heat given off by gas in furnace
η	Thermal efficiency
λ_{g1}	Gas conductivity in the first stage
λ_{g2}	Gas conductivity in the second stage
ν_{g1}	Gas viscosity in the first stage
ν_{g2}	Gas viscosity in the second stage
$\overline{\Delta T}_{\mathrm{log2}}$	Ave. Log. Temp. in the second stage
$\overline{\Delta T}_{\mathrm{log1o}}$	Ave. Log. Temp. in the first stage for outside coil
$\overline{\Delta T}_{\mathrm{logAH}}$	Ave. Log. Temp. in air heater
$\overline{\mathrm{C}}_{\mathrm{F}}$	Average specific heat of gases in the furnace
$\overline{C_F}$	Average specific heat of gases in the furnace
Ψ_{F}	Wall thermal effectiveness
LHV	Low heating value
φ_{coil2}	Thermal effectiveness coefficient for second stage
φ_{coil1}	Thermal effectiveness coefficient for first stage
a_F	Thermal emission of the furnace
a_F	Thermal emission of the furnace
a_{flam_l}	Thermal emission of the luminous flame
A_{g1}	Gas flow area in the first stage
A_{g2}	Gas flow area in the second stage
$ALFA$	Air excess coefficient in exhaust gas
$ALFA_2$	Air excess coefficient in outside coil
B	Volumetric flow rate
D	Mass flow rate
D_{nom}	Nominal mass flow rate
d_{air}	Cold air moisture
d_{fuel}	Fuel gas moisture
D_{nom}	Oil mass flow rate (nominal)
d_{se}	Outside coil diameter
d_{si}	Inside coil diameter
F_{AH}	Air heater area
F_{F}	Furnace heat transfer surface a
F_{g1i}	Inside coil heat transfer area
F_{g2}	Outside coil heat transfer area
F_F	Furnace heat transfer surface
F_{g1i}	Inside coil heat transfer area
F_{g2i}	Outside coil heat transfer area
F_{AH}	Air heater area
H_{CA}	Cold air antalphy
H_{eg}	Exhaust gas antalphy
k_c	Attenuating coefficients of free carbon
k_g	Attenuating coefficients of a triatomic gas
k_i	Global heat transfer coefficient for surface i
k_{Ca}	Global heat transfer coefficient in air heater
k_{g1}	Global heat transfer coefficient in the first stage
L_{s2}	Outside coil length
L_{si}	Inside coil length
M	Relative height of maximum temperature zone
m_l	Furnace volume fraction occupied by the luminous flame
N_{si}	Inside coil number
N_{s2}	Outside coil number
p	Total pressure in furnace
p_g	Triatomic gas partial pressure in furnace
Pr_{g1}	Prandtl number in the first stage
Pr_{g2}	Prandtl number in the second stage
q_5	Heat loss due to conduction
Q_{air}	Sensible heat of air
Q_{d}	Available heat
Q_{fuel}	Sensible heat of fuel
Q_{Furn}	Total heat entering the furnace
Q_F	Total heat entering the furnace
q_2	Heat loss due to exhaust gas
Q_{g1o}	Heat released by gas in the first stage to outside coil
$Q_{g\mathrm{AH}}$	Heat released by gas in air heater
r_G	Triatomic gas fraction at the furnace
S_{H}	Effective thickness of the furnace volume
t_{airOut}	Hot air temperature
T_{a}	Adiabatic flame temperature
t_{gEsc}	Exhaust gas temperature
t_a	Adiabatic temperature
t_{airOut}	Hot air temperature
t_{exit}	Assumed gas temperature at the exit of boiler
$t_{\mathrm{F,exit}}$	Gas temperature at furnace exit
t_{gexit}	Gas temperature at the exit of boiler
t_{oilInt}	Oil temperature at the exit of inside coil (intermediate oil temperature)
t^{*}_{oilInt}	Design temperature at the exit of indoor coil (intermediate oil temperature)
t_{oilOut}	Outlet oil temperature
t^{*}_{oilOut}	Design outlet oil temperature
$t_{\mathrm{oil}_{\mathrm{in}}}$	Inlet oil temperature
t_{ref}	Reference temperature
t_{gs1}	Gas temperature at the exit of inside coil
t_{gs2}	Gas temperature at the exit of outside coil
t_{gs2}	Gas temperature at the exit of outside coil
t_{gsF}	Gas temperature at furnace exit
t_{air}	Cold air temperature
t_{fuel}	Fuel gas temperature
V_{g1}	Gas velocity in the first stage
V_{g2}	Gas velocity in the second stage
$\dot{Q}_u$	Useful power produced by the boiler
η	Efficiency
Ψ_F	Wall thermal effectiveness in furnace
$\mathrm{AirL}_{\mathrm{AHn}}$	Air leakage in the air heater
B	Fuel gas volumetric flow rate (STP)
D_F	Furnace diameter
D	Oil mass flow rate
h_F	Furnace height
k_{g_2}	Global heat transfer coefficient in the second stage
m_l	Furnace volume fraction occupied by luminous flame
M	Relative height of the maximum temperature zone
q_2	Exhaust gas loss
q_5	Conduction loss heat
Q_d	Total heat introduced by fuel to the furnace
LHV	Fuel low heating value
$AirL_{2n}$	Air leakage in the second stage of economizer
$ALFA_F$	Air excess coefficient in furnace