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Numerical model for on-condition monitoring of condenser in coal-fired power plants

Vedran Medica-Viola *, Branimir Pavković, Vedran Mrzljak

Department of Thermodynamics and Energy Engineering, Faculty of Engineering, University of Rijeka, Croatia

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ABSTRACT

Steam saturation pressure in the condenser has the significant impact on the power plant efficiency. The aim of this paper is to provide a reliable tool for quick operating state assessment, which could be used by the power plant staff. Steam condenser numerical model was developed using the steady state conservation laws for mass and energy. Numerical model includes four easily-switchable heat transfer coefficient (HTC) algorithms. Algorithms are described and explained. Numerical model with each of the algorithms, was validated using measurements from the existing coal-fired power plant condenser. Physical algorithm for dropwise condensation showed best correlation with the provided measurements, while Physical algorithm for film condensation showed worst correlation. In order to be able to quickly calculate the steam saturation pressure, a numerical model was not based on CFD simulations. Thus the model can be used for on-condition monitoring. Developed model can also be used for the multi-objective optimization of condenser operating parameters.

1. Introduction

Steam condenser is one of the essential components of coal-fired power plant. Its performance has major impact on the entire steam plant thermal performance [1,2].

Influence of cooling water temperature [3–6] and flow rate [7–9], steam pressure [10] and fouling [11–13] on condenser performance were investigated. The condensing steam pressure varies according to the turbine load, cooling water flow and temperature. The cooling water flow rate is adjusted by the control system, according to the turbine load. Cooling water inlet temperature varies according to the water source (sea, river, etc.). Heat transfer performance degrades during condenser operation due to formation of fouling caused by impurities, mud and biomass or mineral ions in the cooling water. Over time, fouling layer grows on the condenser tube walls. Usually, multiple fouling mechanisms occur at the same time and they have an interferential effect on the overall fouling rate. Variable steam flow rate, cooling water and fouling parameters must be considered during the condenser design and operation.

Steam pressure and turbine power are negative correlated. At a lower condenser steam pressure the enthalpy drop available for the expansion in the turbine is higher, Fig. 1, thus enabling higher cycle efficiency and turbine power. Lower condensing temperatures and corresponding pressures are therefore desirable [1,2].

Steam condensation can be dropwise or filmwise. Heat transfer coefficient (HTC) is 15–20 times higher at dropwise condensation [14], but filmwise condensation is the most common in industrial condensers. Heat exchanging surface hydrophobicity has the major influence on condensation type. Del Col et al. [15] investigated the wetting properties during steam condensation on vertical surface and proposed obtaining of the hydrophobic surface by modifying an aluminum substrate. Charef et al. [16] studied the liquid film condensation from the vapor–gas mixtures inside a vertical tube. The numerical model uses an implicit finite difference method to solve the governing equations for liquid film and gas flow together including the boundary and interfacial matching conditions. Zhai et al. [17] analyzed the enhancement of laminar film condensation with diversion panels for large space.

Starting with Schmidt et al. [18] in 1930 many researchers have investigated dropwise condensation. Liu and Cheng [19] modified and improved numerical model for HTC of dropwise condensation. Effects of subcooling, thickness and thermal conductivity of the coating layer and contact angle on the droplet nucleation density, condensation heat flux and critical condensation HTC are included in the improved numerical model. Cheng et al. [20] proposed the use of dropwise condensation promoter that can improve internal condensation HTC for tubes of different geometries. The observed

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* Corresponding author.
E-mail addresses: vedran.medica@uniri.hr (V. Medica-Viola), branimir.pavkovic@riteh.hr (B. Pavković), vmrzljak@riteh.hr (V. Mrzljak).

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Nomenclature

A	area (m^2)
b	purity factor (–)
C	coefficient (–)
c	specific heat capacity (J/kg K)
d	diameter (m)
e	calculated error (–)
f	terminating condition for iterations (–)
g	gravity acceleration (m/s^2)
h	specific enthalpy (kJ/kg)
k	overall heat transfer coefficient (W/m^2 K)
L	length (m)
$\mathcal{L}$	characteristic length of the flow (m)
$\dot{m}$	mass flow rate (kg/s)
n	number of tubes (–)
Nu	nusselt number (–)
P	perimeter of the tube bundle layer (m)
p	pressure (Pa)
$\dot{Q}$	heat transfer rate (kW)
R	thermal resistance (K/W)
Re	Reynolds number (–)
T	temperature (K)
v	Velocity (m/s)
x	steam quality (–)
z	number of cooling water passages (–)

Greek symbols

α	heat transfer coefficient (W/m^2 K)
β	condensation wall angle (°)
Δ	difference (–)
δ	thickness (m)
ε	void fraction (–)
λ	thermal conductivity (W/m K)
μ	dynamic viscosity ($N\,s/m^2$)
ν	Kinematic viscosity (m^2/s)
ρ	density (kg/m^3)

Indices

asm	assumed
avg	average
C	condensate
calc	calculated
col	columns in tube bundle
CW	cooling water
DW	drop-wise
emp	empirical
F	fouling layer
FW	film-wise
g	due to gravity
i	inner
ig	inert gases
in	inlet
m	logarithmic mean value
mt	material
o	outer
OL	observed tube bundle layer
out	outlet
row	rows in tube bundle
S	saturated steam
sum	for all tubes
T	tube
therm	due to thermal effects
TL	tube bundle layer
W	tube wall
wi	wall inclination

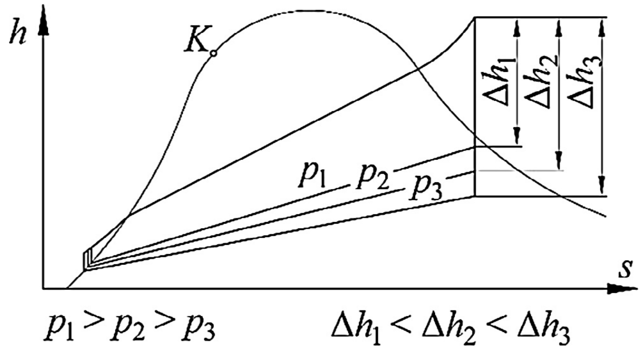

Fig. 1. Condenser pressure effect on turbine power.

hydrophobic promoter can increase HTC by 50%. Khatir et al. [21] performed multi-disciplinary investigation of heat transfer at dropwise condensation. The process of droplets jumping, against adhesive forces, from a solid surface upon coalescence, has been studied using both experimental and computational fluid dynamics analysis. A superhydrophobic surface design optimization framework is also presented.

Mirzabeygi and Zhang [22] developed a complex three-dimensional numerical model for the fluid flow and heat transfer simulation in industrial steam surface condensers. The numerical model is based on the Eulerian-Eulerian two-phase model which solves the conservation equations of mass and momentum for both gas-phase and liquid-phase, and the mass fraction conservation equation for the non-condensable gases. Same authors [23] analyzed and compared various turbulence models to determine the most accurate model in simulating two-phase fluid flow and heat transfer in steam surface condensers. Saari et al. [24] analyzed heat transfer models for the large power plant condenser and developed a numerical model capable of predicting the condenser pressure and overall HTC. This kind of numerical model can be used for condenser condition monitoring. Xiao and Hrnjak [25] and Yuan et al. [26] investigated the steam condenser pressure drop and heat transfer.

Research of Aljundi [27] and Kopac and Hilalci [28] proved that condenser is the only component of analyzed steam plants whose exergy efficiency sensibly increases due to the ambient temperature increase, while exergy efficiency of other components slightly decreases. These studies suggest that the influence of the ambient temperature should be considered during a steam condenser analysis.

This paper presents a numerical model of a water cooled shell-and-tube steam condenser with one cooling water passage. The model is aimed to serve as a tool for predicting operating states in variable operating conditions. The most important steam parameter is condensing pressure, which strongly affects system efficiency.

It is presented how the developed numerical model quickly determines condensing pressure. Numerical model contains various HTC algorithms. The model can be used for the condenser