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Effect of non-condensable gas on heat transfer in steam turbine condenser and modelling of ejector pump system by controlling the gas extraction rate through extraction tubes

Dušan Strušnik [a,*], Marjan Golob [b], Jurij Avsec [a]

[a] University of Maribor, Faculty of Energy Technology, Hočevarjev trg 1, SI-8270 Krško, Slovenia
[b] University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, SI-2000 Maribor, Slovenia

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ABSTRACT

The paper describes the impact of non-condensable gas (NCG) on heat transfer in a steam turbine condenser (STC) and modelling of the steam ejector pump system (SEPS) by controlling the gas extraction rate through extraction tubes. The ideal connection points for the NCG extraction from the STC are identified by analysing the impact of the NCG on the heat transfer and measuring the existing system at a thermal power plant in Slovenia. A simulation model is designed using the Matlab software and Simulink, Neural Net Work, Fuzzy Logic and Curve Fitting Toolboxes, to control gas extraction rate through extraction tubes of the gas pumped from the STC, thus optimising the operation of the steam ejector pump system (SEPS). The gas extraction rate from the STC is controlled in the extraction tubes by pumping only the NCG to the maximum extent. The SEPS is optimised by selecting a Laval nozzle of appropriate size to reduce the steam for the operation of the SEPS, whereby the amount of the extracted NCG is maintained. As the SEPS motive steam is produced in a boiler, the consumption of coal for the production of the SEPS motive steam is reduced as well as the greenhouse gas environmental pollution.

1. Introduction

A STC is an important subset of a condensing steam turbine. Its main purpose is to maintain the prescribed vacuum condition of around 0.01 MPa by evacuating exhaust gases from the steam turbine. Exhaust gases are multiphase gases, comprising a condensable gas (CG) and a NCG. The CG includes dry and wet vapour. Water vapour is removed from the STC through its condensation and by pumping the condensate into the boiler feeding system. NCG is evacuated by means of a SEPS. If no NCG evacuation takes place from the STC, the condensation area in the STC would be filled with the NCG and the condensation process would stop. Fig. 1 shows the principle of exhaust gas evacuation from the STC by means of the SEPS [1,2].

It is evident from Fig. 1 that cooling water from a nearby river is used for the CG condensation. The condensate is collected at the bottom of the STC and pumped into the boiler feeding system using the condensate pump, while the NCG phase is pumped into the atmosphere through the connection tube and using the SEPS. The connection element is installed in the upper part of the STC.

SEPS are devices designed to use the pressure energy of a working fluid for the transport of another working fluid, whereby no mechanical work is supplied or recovered. SEPS can be operated with incompressible fluids (liquids), and in this application they are normally referred to as jet pumps or educators. They are used as vacuum compressors or vacuum pumps in order to produce vacuum in steam turbine systems, in refrigeration systems, for bulk material transport etc. The actual efficiency is low, ranging from 0.1 to 0.35 [1,2]. The process is non-reversible due to mixing of two flows. Some other authors also analysed the SEPS in the following papers [3–7]. Water vapour from the turbine steam extraction 1, previously expanded in the steam turbine, thus emitting part of its energy, is used for the operation of the SEPS. The quality of water vapour, travelling to steam extraction 1 of the steam turbine is regulated with pressure amounting to approx. 0.9 MPa and temperature to approx. 570 K. In our case, a SEPS is a two-stage flow-type compressor of a primary and secondary stage [1,2]. In the primary stage, i.e. the condensation stage, the pumped gas from the STC is compressed at a pressure of approximately 0.01 MPa. A mixture of the pumped gas from the STC and motive steam from the primary

* Corresponding author.
E-mail address: dusan.strusnik@gmail.com (D. Strušnik).

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Nomenclature

Abbreviations

ANN	artificial neural network
ANFIS	adaptive neural fuzzy inference system
B, C	article
Cl	close
CG	condensable gas
FLC	fuzzy logic controller
F-Cl	fast close
F-Op	fast open
HP	high pressure
LP	low pressure
MAE	mean absolute error
MP	middle pressure
MSE	mean square error
NCG	non-condensable gas
Op	open
R^2	correlation coefficient
RMSE	root mean square error
SCADA	supervisory control and data acquisition
SEPS	steam ejector pump system
STC	steam turbine condenser

Parameters

A	surface, m^2
A_i	inner tube cross-section, m^2
A_L	narrowest Laval nozzle cross section area, m^2
A_t	tube surface area, m^2
A_2	inlet diffuser cross sectional area, m^2
c	mixture molar density, kmol/m^3
cp_c	cooling water specific conductivity, J/(kg K)
c_1	steam speed at the exit from the Laval nozzle, m/s
c_2	inlet diffuser mixed gas speed, m/s
D	molecular diffusivity, (MPa m^2)/s
$D_{CG\text{-}NCG}$	diffusion of condense gas in binary mixture, condense gas in non-condensable gas, (MPa m^2)/s
$D_{CG\text{-}NCG,Tex}$	diffusion of condensable gas in non-condensable gas at T_{ex}, (MPa m^2)/s
$D_{CG\text{-}NCG,T2}$	diffusion of condensable gas in non-condensable gas at T_2, (MPa m^2)/s
$D_{NCG\text{-}CG}$	diffusion of non-condensable gas in a binary mixture of condensable gas in non-condensable gas (MPa m^2)/s
$D_{(pex,Tex)}$	experimental value of diffusivity of component at p_{ex} and T_{ex}, (MPa m^2)/s
$D_{(p2,T2)}$	diffusivity of a component at p_2 and T_2, (MPa m^2)/s
D_i	tube inner diameter, m
D_o	tube outer diameter, m
dT_{NCG}	temperature difference of condensate boundary layer due to non-condensable gas layer, K
$dqQ_{NCG\text{-}loss}$	heat loss difference due to the non-condensable gas layer around the tube, W
dn_{NCG}	differential of non-condensable gas quantity, kmol
g	gravitational acceleration, m/s^2
h	gas enthalpy, kJ/kg
h_0	specific enthalpy of motive steam, kJ/kg
h_1	specific enthalpy of steam Laval nozzle expansion, kJ/kg
h_{1s}	specific enthalpy of steam isentropic Laval nozzle expansion, kJ/kg
h_3	diffuser outlet mixed gas specific enthalpy, kJ/kg
$h_{3'}$	isentropic specific enthalpy of diffuser outlet mixed gas, kJ/kg
h_4	specific enthalpy of the pumped gas, kJ/kg
k	heat transfer through a tube, W/(m^2 K)
m_{NCG}	share of non-condensable gas in pumped-out mixture, %
$\overrightarrow{N_{CG,z}}$	condensable gas molar flux density at a distance of z, kmol/(m^2 s)
n_{NCG}/A	amount of non-condensable gas per surface area unit, kmol/m^2
p	pressure, MPa
$p_{NCG\text{-}z}$	partial pressure of non-condensable gas at a distance along the z axis, MPa
$p_{NCG\text{-}1}$	partial pressure of non-condensable gas on the condensate layer surface, MPa
p_{ac}	actual pressure, MPa
p_{ex}	experimental pressure, MPa
p_{Air}	partial air pressure, MPa
p_{H2O}	partial steam pressure, MPa
p_s	saturation water vapour pressure, MPa
p_x, p_1	pressure in the mixing section, MPa
p_0	inlet motive steam pressure, MPa
p_2	diffuser inlet mixed gas pressure, MPa
p_3	exhaust ejector mixed gas pressure, MPa
p_4	pumped gas pressure, MPa
$p_{CG(298\,K)}$	saturation water vapour pressure at a temperature of 298 K, MPa
$p_{CG(313\,K)}$	saturation water vapour pressure at a temperature of 313 K, MPa
qQ_t	heat transfer difference of STC tube
qP_{gen}	generated power in the case of SEPS motive steam expansion in the turbine, kW
qm_i	mass flow of working fluid cross individual turbine component, kg/s
qm_t	amount of cooling water through a tube of the STC, kg/s
$qm_{non\text{-}out}$	mass flow of the pumped non-condensable gas from the STC, kg/s
qm_0	motive steam mass flow through the Laval nozzle, kg/s
qm_4	pumped gas mass flow, kg/s
R	gas constant, kJ/(kg K)
R_0	motive steam gas constant, kJ/(kg K)
R_m	universal gas constant, kJ/(kmol K)
R_{mix2}	gas constant of the gas mixture in the mixing section, kJ/(kg K)
$r_{NCG\text{-}o}$	outer radius of non-condensable gas layer around tube, m
r_i	tube inner radius, m
r_o	tube outer radius, m
T_{ac}	actual temperature, K
T_{ex}	experimental temperature, K
T_m	temperature of the mixture, K
T_{mean}	average temperature of extracted gases, K
T_{mix2}	diffuser inlet mixed gas temperature, K
T_{ov}	temperature of tube outer wall, where the steam condenses, K
T_s	water vapour saturation temperature, K
$T_{p\text{-}1}$	temperature of extracted gas of tube-i, K
T_0	inlet motive steam temperature, K
T_2	corrected temperature of the binary mixture, K
V_i	valve position of tube -i, %
v_2	inlet diffuser specific volume of the mixed gas, m^3/kg
α_i	heat transfer coefficient on tube inner side, W/(m^2 K)
α_o	heat transfer coefficient on tube outer side, W/(m^2 K)
Δh_{co}	water vapour steam condensation enthalpy, kJ/kg
ΔT_{Air}	driving air temperature difference, K
ΔT_c	inlet-outlet cooling water temperature difference of the STC, K