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Energy efficiency analysis of steam ejector and electric vacuum pump for a turbine condenser air extraction system based on supervised machine learning modelling

Dušan Strušnik [a,*], Milan Marčič [b], Marjan Golob [c], Aleš Hribernik [b], Marija Živić [d], Jurij Avsec [a]

[a] University of Maribor, Faculty of Energa Technology, Hočevarjev trg 1, SI-8270 Krško, Slovenia
[b] University of Maribor, Faculty of Mechanical Engineering, Smetanova ulica 17, SI-2000 Maribor, Slovenia
[c] University of Maribor, Faculty of Electrical Engineering and Computer Science, Smetanova ulica 17, SI-2000 Maribor, Slovenia
[d] J.J. Strossmayer University of Osijek, Mechanical Engineering Faculty in Slavonski Brod, Trg Ivane Brlić-Mažuranić 2, HR-35000 Slavonski Brod, Croatia

HIGHLIGHTS

- Steam ejector pump and electric liquid ring vacuum pump are analysed and modelled.
- A supervised machine learning models by using real process data are applied.
- The equation of ejector pumped mass flow from steam turbine condenser was solved.
- The loss of specific energy capable of work in a SEPS or LRVP component was analysed.
- The economic efficiency analysis per different coal heating values was made.

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ABSTRACT

This paper compares the vapour ejector and electric vacuum pump power consumptions with machine learning algorithms by using real process data and presents some novelty guideline for the selection of an appropriate condenser vacuum pump system of a steam turbine power plant. The machine learning algorithms are made by using the supervised machine learning methods such as artificial neural network model and local linear neuro-fuzzy models. The proposed non-linear models are designed by using a wide range of real process operation data sets from the CHP system in the thermal power plant. The novelty guideline for the selection of an appropriate condenser vacuum pumps system is expressed in the comparative analysis of the energy consumption and use of specific energy capable of work. Furthermore, the novelty is expressed in the economic efficiency analysis of the investment taking into consideration the operating costs of the vacuum pump systems and may serve as basic guidelines for the selection of an appropriate condenser vacuum pump system of a steam turbine.

1. Introduction

A steam condenser 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 [1]. Exhaust gases are multiphase gases, comprising a condensable and a non-condensable gas phase. The condensable gas phase includes dry and wet vapour. Water vapour is removed from the turbine condenser through its condensation and by pumping the condensate into the boiler feeding system [1]. Non-condensable gases are evacuated by means of a vacuum pump system. Two steam vacuum pump systems are most frequently used in practice, namely the steam ejector pump system (SEPS) and the liquid ring vacuum pump system (LRVP) [1]. Some other authors have analysed in their research the operation of vacuum pump systems. Dennis et al. [2] have analysed the SEPS by mathematical methods. The LRVP for Tokamak have analysed and designed by Khan et al. [3]. Zhu et al. [4] and Chong et al. [5] proposed a 2D exponential model to predict the velocity distribution in ejector, however the pressure is still assumed to be uniform in the radial direction. Sözen et al. [6] explored the exergy analysis of an ejector-absorption heat transformer using artificial neural network approach. We didn't find the article that compare the SEPS

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

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Nomenclature

Abbreviations

ANN	artificial neural networking
ANFIS	adaptive network-based fuzzy inference system algorithm
CHP	combine heat and power
LRVP	liquid ring vacuum pump
MAE	mean absolute error
MF	membership functions
MSE	mean square error
PID	proportional-integral-derivative
R^2	correlation coefficient
RMSE	root mean square
SCADA	supervisory control and data acquisition
SEPS	steam ejector pump system

Parameters

A_L	narrowest Laval nozzle cross section area, m^2
A_2	inlet diffuser cross sectional area, m^2
c_1	steam speed at the exit from the Laval nozzle, m/s
c_2	inlet diffuser mixed gas speed, m/s
$e_{in,LRVP}$	amount of specific energy capable of work in the LRVP, kJ/kg
$e_{loss,p}$	loss of specific energy capable of work in a specific part, kJ/kg
h	gas enthalpy, J/kg or kJ/kg
h_b	boiler steam specific enthalpy, kJ/kg
$h_{in,p}$	specific enthalpy of a gas mixture to a specific part, kJ/kg
$h_{out,p}$	specific enthalpy of a gas mixture from a specific part, kJ/kg
h''_{out}	turbine exhaust steam specific enthalpy, kJ/kg
h_0	specific enthalpy of motive steam, J/kg
h_1	specific enthalpy of steam Laval nozzle expansion, J/kg
h_{1s}	specific enthalpy of steam isentropic Laval nozzle expansion, J/kg
h_3	diffuser outlet mixed gas specific enthalpy, J/kg
$h_{3'}$	isentropic specific enthalpy of diffuser outlet mixed gas, J/kg
h_4	specific enthalpy of pumped gas, J/kg
I_c	investment cost, EUR
$m_{non\text{-}in}$	mass of the non-condensable gas entering the turbine condenser, kg
$m_{non\text{-}out}$	mass of non-condensable gas pumped form the turbine condenser, kg
$m_{tot\text{-}c}$	total mass of the non-condensable gas of the turbine condenser, kg
n	LRVP impeller speed, rpm
p_c	pressure in the turbine condenser, Pa or MPa
p_{in}	pressure on the suction side of the LRVP, Pa
p_{out}	pressure of the pumped gas on the pressure side of the LRVP, Pa
p_1, p_4, p_x	pressure in the mixing section, Pa
p_0	inlet motive steam pressure, Pa
p_2	diffuser inlet mixed gas pressure, Pa
p_3	exhaust ejector mixed gas pressure, Pa
P_{gen}	generated power in the case of SEPS motive steam expansion in the turbine, kW
P_{LRVP}	LRVP power consumption, kW
$qm_{non\text{-}in}$	mass flow of non-condensable gas penetrating into the turbine condenser, kg/s
$qm_{non\text{-}out}$	mass flow of the pumped non-condensable gas from the turbine condenser, kg/s
qm_{H_2O}	mass flow of the pumped condensable gas, kg/s
qm_O	motive steam mass flow through the Laval nozzle, kg/s
qm_{LRVP}	masni pretok črpane plinaste zmesi LRVP, kg/s
qm_4	pumped gas mass flow, kg/s
qV	volumetric flow rate of the pumped out gas, m3/h
$qV_{non\text{-}gas}$	volumetric flow rate of the pumped non-condensable gas, m^3/h
qV_{H_2O}	volumetric flow rate of the pumped condensable gas, m^3/h
R_0	motive steam gas constant, J/(kg K)
R_{mix2}	gas constant of the gas mixture in the mixing section, J/(kg K)
R_n	gas constant of the non-condensable gas, J/(kg K)
$s_{in,p}$	specific entropy of a gas mixture to a specific part, J/(kg K)
$s_{out,p}$	specific entropy of a gas mixture from a specific part, J/(kg K)
t	time, minute, second
T	temperature, K
T_a	ambient temperature, K
T_c	temperature in the turbine condenser, K
T_0	inlet motive steam temperature, K
T_2	diffuser inlet mixed gas temperature, K
v_2	inlet diffuser specific volume of the mixed gas, m^3/kg
V_c	turbine condenser volume, m^3
V_{cell}	LRVP impeller blade cell volume, m^3
ρ_c	density of non-condensable gas in the turbine condenser, kg/m^3
$\rho_{non\text{-}out}$	density of the pumped non-condensable gas, kg/m^3
ρ_{H_2O}	density of the pumped condensable gas, kg/m^3

Subscripts and superscripts

B, C	article
d	differential
HP	high pressure
j, k	iterations
LP	low pressure
M	Mach number
MP	middle pressure
M_2	Mach number in the mixing section
o_j	output value
p, s	pattern
t_j	target value
$\eta_{dif\text{-}is}$	diffuser isentropic efficiency
η_{em}	LRVP electromechanical efficiency
$\eta_{Laval\text{-}is}$	Laval nozzle isentropic efficiency
$\varkappa_0$	motive steam specific heat ratio
$\varkappa_{mix2}$	specific heat ratio of the gas mixture in the mixing section
$\sum E_{electric}$	consumed or additionally generated energy at an annual level in case of 6000-h yearly operation

and LRVP power consumptions in the CHP system in thermal power plant with machine learning algorithms by using real process data.

Simulations models copying the functioning and behaviour of a real vacuum pumping system was designed using the supervised machine learning algorithms and real process data. The real process data was obtained from the supervisory control and data acquisition system (SCADA) [7], comprising the information on the operation of a CHP system in thermal power plant in Slovenia. SCADA [7] contains more than 850 data groups on the operation of a CHP system in thermal power plant and are constantly recorded on an hourly basis 365 days a year. The data on the 2013/2014