Applied Energy 127 (2014) 34–43

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Heat load capability matching principle and its applications to anti-freezing of air-cooled condenser

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HIGHLIGHTS

- It is of use to propose anti-freezing measures for air-cooled condenser.
- Heat load capacity matching principle for the anti-freezing is suggested.
- Anti-freezing steam flow rate increases with decreasing ambient temperature.
- Anti-freezing fan flow rate increases with increasing exhaust steam flow rate.
- Back pressure can be much more reduced at secure steam flow rates.

ARTICLE INFO

Article history:
Received 21 January 2014
Received in revised form 1 April 2014
Accepted 9 April 2014
Available online 3 May 2014

Keywords:
Air-cooled condenser
Heat load capability
Anti-freezing
Back pressure
Ambient temperature
Axial flow fan

ABSTRACT

Air-cooled condenser in power plants takes a risk of freezing in extremely cold days, so it is of benefit to the safe and economical operation of direct dry cooling system to propose the anti-freezing principles and take measures. On the basis of the heat load balance between the exhaust steam and cooling air, the heat load capacity matching principle for the anti-freezing of air-cooled condenser is proposed with reference to the freezing point of water. By applying heat exchanger model to the finned tube bundles of air-cooled condenser, the thermo-aerodynamic behavior of cooling air, the condensation of exhaust steam and the sensible heat rejection of condensate in a representative air-cooled condenser cell are synchronously modeled and resolved. The correlations among the ambient temperature, flow rate of cooling air, exhaust steam flow rate and quality, and back pressure of turbine that prevent the air-cooled condenser from freezing are discussed, and the anti-freezing flow rate of exhaust steam, back pressure of turbine and flow rate of axial flow fan are obtained. The results show that the anti-freezing flow rate of exhaust steam and back pressure both increase with decreasing the ambient temperature and increasing the flow rate of axial flow fan, from which derive the secure steam flow rate that can reduce the back pressure as much as possible to improve thermal efficiency. The anti-freezing fan flow rate increases with increasing the exhaust steam flow rate and ambient temperature, but varies little with back pressure. The increased steam quality will result in a higher heat load at the steam side, which allows a higher rotational speed of fan to be free of freezing for air-cooled condenser. The application of heat load capacity matching principle to the anti-freezing of air-cooled condenser contributes to the secure and optimal operation of dry cooling system in power plants.

1. Introduction

Dry cooling system has been increasingly developed in the condenser heat rejection of power plants in the past years due to urgent water resource issues all over the world. As one of the dry cooling technologies, direct dry cooling system makes use of air-cooled condenser to reject the exhaust steam heat to the ambient atmosphere, so the ambient temperature, ambient wind speed and direction, and the like play important roles in the operation of air-cooled condensers. In extremely cold days, air-cooled condenser is even faced with the freezing risk that the finned tube bundles may encounter damage. It is helpful for the safe and economical operation of air-cooled condenser in power plants to propose anti-freezing approaches.

With regard to the freezing mechanism for water and other working media, many investigations have been thoroughly carried out. Smith and Meeks [1] considered the effects of a thick wall on

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http://dx.doi.org/10.1016/j.apenergy.2014.04.025
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Nomenclature

a	core friction coefficient
A	heat transfer surface area (m^2)
b	core friction exponent
c_p	specific heat ($J\,kg^{-1}\,K^{-1}$)
f	flow friction factor
f_n	polynomial coefficient for the pressure rise of axial flow fan
g_n	polynomial coefficient for the tangential velocity of axial flow fan
h	specific enthalpy ($J\,kg^{-1}$)
k	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
k_n	turbulence kinetic energy ($m^2\,s^{-2}$)
K	loss coefficient
m	mass flow rate ($kg\,s^{-1}$)
n	rotational speed ($r\,min^{-1}$)
p	pressure (Pa)
q_v	volumetric flow rate ($m^3\,s^{-1}$)
Q	heat rejection (W)
r	latent heat of condensation ($kJ\,kg^{-1}$)
R	radius of fan (m)
Re	Reynolds number
S	source term in generic equation
t	temperature (K)
u	velocity ($m\,s^{-1}$)
v	specific volume ($m^3\,kg^{-1}$)
x	steam quality
x_j	x-coordinate (m)

Greek symbols

Γ	diffusion coefficient ($m^2\,s^{-1}$)
ε	heat exchanger effectiveness
ε_p	turbulence dissipation rate ($m^2\,s^{-3}$)
μ	dynamic viscosity ($kg\,m^{-1}\,s^{-1}$)
ρ	density ($kg\,m^{-3}$)
σ	minimum flow to face area ratio
σ_p	turbulent Prandtl number
φ	scalar variable
ψ	correction factor for the log mean temperature difference

Subscripts

0	rated
1	inlet
2	outlet
a	air
ab	ambient
c	core
e	exit
f	face
i	inlet
m	mean
min	minimum
o	outlet
s	steam
T	turbulence
w	water
wa	water-air
z	axial direction
θ	tangential direction
φ	scalar variable

the freezing process occurring inside a cylindrical container, finding that the wall temperature and thermal diffusivity play roles in the freezing rate and the shape of interface between the solid and liquid. Seeniraj and Hari [2] studied the solidification characteristics of a liquid flowing through a convectively cooled pipe under different flow situations, and obtained the limiting conditions for the commencement of the solidification. Tay et al. [3] investigated the phase change thermal energy storage performances for the pinned and finned tubes in freezing process, finding that the finned tube design performed 20–40% better in effectiveness and took 25% lesser time for the phase change process. Amin et al. [4] carried out freezing and melting tests in a tank filled with PCM encapsulated spheres, proving that the effectiveness–NTU method is applicable for PCM freezing and melting. Tan et al. [5] numerically studied the two-dimensional transient freezing problem for recovery and storage of the cryogenic gas cold energy by using Solidification and Melting model, pointing out that dimensionless numbers, such as Biot number and Stefan number of PCM, and the Stanton number of the coolant flowing in the tube, have remarkable effects on the characteristics of the freezing. Habeebullah [6] studied the growth rate of ice on the outside of cooled copper tubes by experimental measurement, discovering conspicuous axial growth rate of ice at low coolant Reynolds numbers and short freezing times. The slope of the ice thickness with axial distance showed moderate dependency on time, but varied with coolant flow rate, Stanton and Biot numbers. Lamberg and Siren [7] proposed a simplified analytical model to predict the solid–liquid interface location and temperature distribution of the fin in the solidification process with a constant end-wall temperature in the two dimensional PCM storage. A factor called the fraction of solidified PCM is also introduced, by which the solidification picture at a given time can be predicted. Conde et al. [8] developed a two-dimensional model of heat transfer and solidification of a laminar flow inside a tube, and obtained a correlation to predict the blocking lengths of different fluids and operating conditions such as pipe diameter, mean velocity, wall and liquid temperatures.

Emphases are placed on the liquid/solid phase change process in the aforementioned literatures. Moreover, Barigozzi et al. [9] investigated the variations of the net power output, fan load and exhaust steam pressure with ambient temperature and flow rate of district heating water for combined wet and dry cooling system in coldest months, and obtained the optimized running parameters free of freezing, but unfortunately, the freezing mechanism and anti-freezing measures for air-cooled condenser are hardly mentioned. Air-cooled condenser generally consists of tens of A-frame condenser cells with the finned tube bundles and the axial flow fan below [10]. The particular A-frame finned tube bundle configuration and turbulent aerodynamic behavior at the exit of axial flow fan result in the bad-proportioned flow and temperature fields across the finned tube bundles, so the freezing inside the tube of the finned tube bundles becomes more complicated. And moreover, the freezing process for the air-cooled condenser is composed of two unlike courses, first of which is the condensation of the exhaust steam from turbine, and second is the sensible heat rejection from the condensate to the liquid water at the freezing point. But unfortunately, no research work can be found concerning the freezing process of air-cooled condenser and the anti-freezing measures taken by the direct dry cooling system in power plants.