Annals of Nuclear Energy 113 (2018) 37–47

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Investigation of the thermal characteristics of condensers in nuclear power plant by simulation with zoning model

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ARTICLE INFO

Article history:
Received 12 April 2017
Received in revised form 27 September 2017
Accepted 7 November 2017

Keywords:
Simulation
Condenser
Vapor-condensation
Distribution of thermal parameters

ABSTRACT

For the simulation of condensers in a nuclear power plant, in general two approaches can be used, the lumped parameter model and the numerical method. The lumped parameter method is simple and rapid thus widely used in real-time simulations. The numerical method can provide more detailed information and achieve higher accuracy in comparison with the lumped model, but increases implementation complexity and computational cost. In real-time simulations of nuclear power plants, to solve the problem of uneven distribution of thermal parameters in condensers, which is not feasible for the lumped parameter method, a new method for the simulation of condensers was proposed in this research. The method divides the shell side and tube side of the condenser to different zones, and apply the lumped parameter method in each zone. The mass flow between zones in the model are calculated as flow nets. A posteriori testing has been conducted for the proposed model, thermal parameters in each zone are simulated and the results are verified with experimental benchmark data from an actual condenser. The comparison confirms that the proposed method is highly accurate not only in different steady state operations, the responses of each zone in dynamic-state operations are consistent with theoretical analyses as well. Unlike previous works, the model made it possible to get the distributions of thermal parameters in a condenser through real-time simulations on the actual working processes.

1. Introduction

Condenser is one of the major devices in the secondary loop of nuclear power plants. As the cold source of Ranking-Circle, condenser is a tube-shell heat exchanger, condensing the vapor and keeping the vacuum of turbine outlet by the large flow rate of cooling water. So the quality differences of condensers directly affect the vacuum of turbine outlet, thus essential for the efficiency of the nuclear power plant.

The approaches for simulating the condensers in a nuclear power plant can be classified into two categories, numerical method and the lumped parameter model. By implementing numerical methods through computer codes (Colorado et al., 2011) or CFD software (Shojaeefard et al., 2017), one can get the inner fields of thermal parameters and accurate simulation results. However, the large computation load and complex solving procedures made numerical methods difficult for real-time simulation. On the other hand, the lumped parameter model regard the condenser as a simple control node by energy balanced model (Botsch et al, 1997), which makes the calculation fast enough to fulfil the requirement of real-time simulation. By further taking actual heat transfer models into account (He et al., 1997), the condenser can be simulated as two nodes with the transferred heat calculated by condensation, conduction and convection. When the number of sensors installed in condensers increases, Cui et al (2007) divided the condenser to different zones to solve the distribution of thermal parameters in condensers by real-time calculation. Recently in Zhu et al. (2015) presented a way to divide zones and calculate the flow and heat transfer between zones.

However, there still exists some open questions that none of the previous methods were able to solve. In particular, how to theoretically calculate the mass and energy flow between zones, and if they are suitable in flow networks. In this paper, we extended the model by dividing condensers to different zones and connected them as flow networks, each zones transfer heat independently so that we can solve all thermal parameters in a matrix, which is referred to as "Zoning model". In the present work, the model is build based on the flow networks so it is automatically suitable in the flow network model without any additional complexity combining the models. In each zone, we apply heat transfer models based on the film-condensation, heat conduction and forced convection to get the parameters distributions in the condensers,

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https://doi.org/10.1016/j.anucene.2017.11.015
0306-4549/

Nomenclature

Variable

M	mass in the zone, kg
τ	time, s
f	mass flow rate, kg/s
ρ	density, kg/m^3
V	volume, m^3
P	pressure, MPa
h	enthalpy, kJ/kg
b_0	saturation flag
A	area, m^3
C	coefficient
Q	transferred heat, kW
F	dynamics and resistance, N
t	temperature, °C
S	concentration, kg/kg
a	acceleration, m/s^2
λ	heat conductivity coefficient, W/(m·K)
η	kinetic viscosity, Pa·s
N_p	the number of tubes
l	length, m
c_p	specific heat at constant press, kJ/(kg·K)
g	acceleration of gravity
Nu	Nusselt number
Re	Reynolds number
Pr	Prandtl number
R	latent heat of vaporization, kJ/kg
Rg	gas constant

Subscript

sh	shell side
tu	tube side
tube	heat transfer tube
g	steam
l	water
in	inside
out	outside
cond	condensate
vap	vaporization
fm	water film outside of the tube
s	saturation
f	fraction
d	diffusion
nc	non-condensable gases
fc	forced convection
wp	whole pressure
ori	original value
cdt	heat conductivity

Superscript

(i)	current zone or flow number
(j)	upper zone number
(k)	downstream zone number

which is equivalent to corresponding sensors installed in real equipment. These approaches reduced the time complexity of the model, in general the calculation can be finished instantaneously in real time speed (the calculation frequency is no less than 16 Hz).

The symmetric, double tube-passes condensers are widely used in nuclear power plants. The operational principle of this kind of condensers is given in Fig. 1. The steam from turbine was condensed as film on the outer surface of heat transfer tube. The tube transfers the heat to the cooling water by forced convection heat transfer, then the condensation heat was carried out of the condenser by cooling water thus complete the condensation process. The asymmetric operating parameters in two sides of condensers are common and important, however, traditional models with lumped parameter method take the condenser as a simple node, making it difficult to simulate this condition.

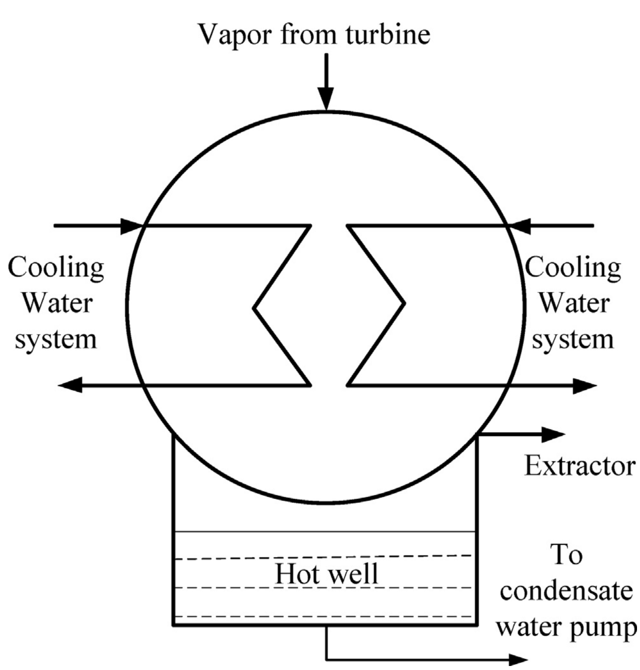

Fig. 1. The operational principle of symmetric, double tube-passes condensers.

The objective of this research is to establish a zoning model by dividing the condensers into three-dimensional zones. By taking the structure and the interface of other equipment into account, the symmetric, double tube-passes condensers will be divided into 10 zones in shell side and 14 zones in tube side. Heat transfer will be calculated by film-condensation, heat conduction of metal tube, and forced convection heat transfer in tubes with some coefficients of influencing factors. The thermal parameters will be computed by lumped parameter method in each zone, and the mass flow among zones will be solved by the ways in flow nets. The present model is verified through the simulation of a real condenser N-5100.

2. Mathematical model

2.1. Zone division

The symmetric and double tube-passes condensers are symmetrically distributed on the of shell side. The cooling water in tube flows though the heat transfer area twice and the air extractor is arranged only on one side. As shown in Fig. 2, the shell side is divided into 10 zones. The zones 1–8 are condensation area, which can represent the symmetry, double tube-passing and the air extractor well.

The heat transfer area in tube side is divided into 8 zones and every zone number corresponds to the shell side. On each side,