Annals of Nuclear Energy 68 (2014) 61–69

Contents lists available at ScienceDirect

Annals of Nuclear Energy

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

Weight optimal design of the primary coolant system for a pressurized water reactor

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ARTICLE INFO

Article history:
Received 13 June 2013
Received in revised form 16 December 2013
Accepted 3 January 2014
Available online 1 February 2014

Keywords:
Reactor coolant system
Optimal design
Sensitivity analyses
Genetic algorithm

ABSTRACT

In order to reduce the component sizes for high power reactors, optimization methodology is employed in the preliminary design of a nuclear power plant, by which one can find the best combination of the operation and the structural parameters. This not only meets design requirements, but also satisfies safety regulations. In this work, a thermal hydraulic model for the reactor core was developed to improve the optimization process, and to provide parameters for the weight estimation of the reactor vessel. Meanwhile, functional relationships involving component weights and the operation as well as the structural parameters of the reactor coolant system were established and verified. Parameters, having a great impact on the net weight of reactor coolant system, were picked out as the design variables by the sensitivity analyses, and were optimized by means of genetic algorithm. An optimal scheme was obtained, by which 13.15% of the net weight of the reactor coolant system is reduced.

1. Introduction

For efficient and economic operation of nuclear power plants, optimization methodology has been widely and successfully employed in the area of reactor core design (Pereira, 2004; Sacco, 2009), refueling (Marcio and Roberto, 2011), maintenance scheduling (Pereira and Lapa, 2010), etc. In recent years, component size has been one of the most interested optimization objectives because of the difficulties encountered in manufacture, transport and layout of the large components of those nuclear power plants with high powers. Besides, compact nuclear power plants are required in some special situations, such as marine transportation and space station. The reduction of component size could be achieved by optimal selection and reasonable combination of the operation and structural parameters.

In the weight optimization design of a steam generator, Liu et al. (2012) built the steam generator mathematical model, upon which the functional relationship between its weight and design parameters was defined, a new hybrid particle swarm optimization algorithm was also proposed, which was employed to optimize the weight by seeking out the best combination of the secondary circuit pressure, the U-tube outer diameter, the tube pitch, the coolant velocity in the U-tube. The results indicated that the weight could be optimized by 15.1%. He et al. (2010) proposed the mathematical model for an electrically heated pressurizer and optimized the primary system pressure, the reactor inlet temperature, the reactor outlet temperature and the diameter in its design phase, the results proved that the volume could be reduced by 40.9%. In the research of coupled-component size reduction, Zheng et al. (2011) established the functional relationship between the weight of a turbine unit and its design parameters, and optimized the weight by adjusting those parameters; finally, 19.66% weight reduction was achieved. Chen et al. (2013) coupled the design of the steam generator and the pressurizer of a nuclear power plant, and optimized the weight by 18.61%. In the multi-objective optimization, Li et al. (2011) assigned a weighting coefficient to the weight and the volume of a main pump, respectively, and then transformed the multi-objective problem to a single one; finally, a complex-generic algorithm was used to optimize the design.

In the previous work, great achievement has been made in the size reductions of the single and coupled components. However, little attention is devoted to the size reduction of a system. From the view of practical engineering application, size reduction should be conducted in a system perspective. The objective of this study is to provide a method to optimize the reactor coolant system (RCS) of the Qinshan I nuclear power plant. The power plant is a pressurized water reactor with thermal rating of 966 MW and electrical output of 300 MW. It has two circulation loops and vertical natural circulation steam generators through which the heat generated in the core is transferred to the secondary side (Ouyang, 2000).

This work is organized as follows: in this section, the background and the motivation are presented. Section 2 is devoted to the mathematical models of the main components in the RCS. In Section 3, the mathematical models are verified by the parameters

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http://dx.doi.org/10.1016/j.anucene.2014.01.001

Nomenclature

P	pressure (MPa)
T	temperature (°C)
d	diameter (m)
V	volume (m^3)
W	weight (t)
$Capa$	capacity (m^3)
h	height (m)
t	thickness (m)
S	allowable stress (MPa)
E	welded joint coefficient
x_e	thermodynamic quality
x_T	'true' quality
x_h	dryness in the outlet of the hot channel
A_r	overall area of the fuel rods (m^2)
N_r	number of the fuel rods
n_r	number of the fuel rods in one assembly
N_{as}	number of the assembly
T_{as}	The length of the side of fuel assembly lower end fitting (water gap considered) (m)
R_E	heat resistance (sum of fuel, gap, cladding and coolant)(m^2 K/W)
L_{ef}	the equivalent length of the core (m)
G	mass flux (kg/(m^2 s))
D_e	channel equivalent diameter (m)
C_P	specific heat at constant pressure (kJ/(kg K))
k_f	liquid heat conductivity coefficient (W/(m K))
$\bar{u}_{gj}$	drift velocity (m/s)
u_{lo}	inlet liquid velocity (m/s)
g	gravity (N/kg)
L_{min}	the lower limit of the U-tube length (m)
L_{max}	the upper limit of the U-tube length (m)

Greek letters

α	void fraction
σ	surface tension (N/m)
γ	latent heat (kJ/kg)
ρ_l	liquid density (kg/m^3)
ρ_g	vapor density (kg/m^3)

Superscript

pr	pressurizer
rv	reactor vessel
$pipe$	main pipe
sg	steam generator
$total$	a pressurizer, a reactor vessel, two steam generators and main pipe
D_{ef}	the equivalent diameter of the core (m)
M	mass flow rate (kg/s)
A	flange outer diameter (m)
B	flange inner diameter (m)
C	bolt diameter (m)
v	velocity (m/s)
q_c	heat flux at the center of the channel (W/m^2)
$q_{V,c}$	volumetric heat release rate at the center of the channel (W/m^3)

Subscripts

cs	cladding outside surface
i	inner
in	inlet
out	outlet
D	design value

Abbreviation

$MDNBR$	Minimum Departure Nucleate Boiling Ratio

of the RCS. In Section 4, the optimization variables are picked out by sensitivity analyses and the net weight of the RCS is optimized by means of genetic algorithm. The conclusions of this work and suggestions for the future work are presented in Section 5.

2. The mathematical models

In this section, mathematical model describes the functional relationship between design targets and design parameters, such as primary pressure and reactor inlet temperature. In the thermal hydraulic model for the reactor core, the targets are the reactor core design criterions; for component, the target is its weight.

2.1. The thermal hydraulic model for the reactor core for the RCS

The thermal hydraulic model for the reactor core is based on the single-channel model (Yan, 2004). It consists of structure design, hydraulic calculation and thermal calculation. In the process of the hydraulic calculation, parameters such as coolant mass flux and pressure drop in the core, are calculated. The distributions of temperature field, enthalpy field and void fraction along the axial of fuel rod are determined in the process of the thermal calculation. Finally, parameters, related to the design criterions, are obtained, such as the *MDNBR*, the highest fuel central temperature, and the highest cladding outside surface temperature.

2.1.1. Structure design

The reactor core consists of an array of mechanically identical fuel assemblies in an arrangement that approximates a right circular cylinder. The structure design of the core is based on the heat transfer area of all the fuel rods.

The number of fuel rods is estimated by Eq. (1). The fuel rods are arranged in a 15 × 15 square array (Ouyang, 2000) to form a fuel assembly, the number of the assembly is estimated by Eq. (2), by which the equivalent diameter of the core is also obtained.

$$N_r = \frac{A_r}{\pi d_{cs} L_{ef}} \tag{1}$$

$$N_{as} T_{as}^2 = \frac{N_r}{n_r} T_{as}^2 = \frac{\pi}{4} D_{ef}^2 \tag{2}$$

The ratio between L_{ef} and D_{ef} is 1.2, which is referred from the power plant (Ouyang, 2000).

2.1.2. Hydraulic design

The core provides a flow path for the forced circulation coolant to remove heat generated by it. The main work of the hydraulic calculation is to calculate out the pressure drop and coolant mass flux in the path. To evaluate the pressure drop in subcooled boiling, it is necessary to know the bubble departure point (Yan, 2004) and local void fraction (Kroeger and Zuber, 1968), which are estimated by Eqs. (3) and (4), respectively.