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Optimization of a moisture separator reheater

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ABSTRACT

The optimization of component size aimed to minimize the weight and volume is an important issue to a nuclear power plant design. The optimization algorithm is applied to determine the optimum structural and operation parameters of components in order to reduce the difficulty of manufacture and transport of large components in those nuclear power plants with high powers. A preliminary optimal design is performed on the moisture separator reheater of Qinshan I nuclear power plant in this paper. A self-adapting multi-complex-shape algorithm has been developed and coupled with the thermal mathematical model of the moisture separator reheater, written in C#. The steady-state thermal mathematical model of moisture separator reheater is used to estimate the weight of moisture separator reheater according to the variation of a given number of structural and operation parameters. Then, the thermal mathematical model coupled with the self-adapting multi-complex-shape algorithm permits a set of best structural and operation parameters of the moisture separator reheater to be determined. The results clearly show that there is plenty of potential to improve the design of moisture separator reheater, while satisfying the structural and performance constraints. The results can also help both designers and operators to make a more convenient selection of the structural and operation parameters of moisture separator reheater.

1. Introduction

With the development of optimization methodology, it has been successfully applied to the fields of the nuclear reactor core fuel reloading (Silva and Schirru, 2011; Meneses et al., 2009; Waintraub et al., 2009), the optimization of thermodynamic efficiency and output power (Teyssedou et al., 2010), reactor core design (Waintraub et al., 2009), etc. The investigation of minimization component size has also attracted intense attention during recent years. The aim is to find the optimum structural and operation parameters of components in order to reduce the difficulty of manufacture and transport of large components in those nuclear power plants with high powers. In addition, to fulfill some special conditions, e.g., in the space station and in the marine transportation, a more compact nuclear power plant is required.

For the size optimization of single component, the optimized results clearly show that there is a great deal of potential to reduce the size of the main components in a nuclear power plant. The investigations are performed on optimal design of the steam generator (Liu et al., 2012; Qin et al., 2011), the pressurizer (He et al., 2010), the reactor coolant pump (Li et al., 2011; Lv et al., 2012), and the turbine unit (Zheng et al., 2011). Liu et al. (2014) optimized the main component size and nuclear power system thermodynamic efficiency, without taking into account the size optimization of moisture separator reheater (MSR).

In a pressurized water nuclear reactor, the high pressure (HP) turbine outputs power with close to saturation steam entering. At the HP turbine exhaust, the steam may have as much as 15% moisture. This can corrode and also erode the low pressure (LP) turbine. In addition, operation with wet steam causes inefficiency. That is why the moisture has to be removed through the moisture separators and the vapor has to be reheated through the reheaters. Thus, the MSR is the important component in a nuclear power plant for increasing the efficiency and diminishing the risk of erosion or corrosion damage to the components connected downstream of the MSR. However, the investigation on the size optimization of reheat component is less advanced. In this paper, the objective is to propose a method to optimize the net weight of MSR.

In the present work, the operation and structural parameters of MSR of Qinshan I nuclear power plant are optimized with the optimal object of net weight, while satisfying the corresponding design and performance constraints. The rest of this paper is organized as follows. Section 2 is devoted to the description of the mathematical model of MSR. The self-adapting multi-complex-shape algorithm is discussed in Section 3. Application of the self-adapting multi-complex-shape algorithm for optimal design of MSR net weight is

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Nomenclature

Abbreviation

MSR	moisture separator reheater
HP	high pressure
LP	low pressure
s_f	fin pitch (m)
G_{o1}	mass flow density of the heated steam (kg/(m^2 °C))

Superscript

1	the first stage reheater bundle
2	the second stage reheater bundle

Function

$I_{(0)}(\,)$	the first zero-order Bessel function
$I_{(1)}(\,)$	the first 1st-order Bessel function
$K_{(0)}(\,)$	the second zero-order Bessel function
$K_{(1)}(\,)$	the second 1st-order Bessel function

General symbols

W_{sm}	moisture separators model weight (t)
m_o	mass flow of moisture separators (kg/s)
m_{mo}	mass flow of moisture separators model (kg/s)
d_{i1}	finned tube inner diameter (m)
d_{o1}	finned tube outer diameter (m)
h_f	fin height (m)
s_1	finned tube pitch (m)
y_1	inner humidity of the tubes
g	gravity acceleration (m/s^2)
ρ_{fi1}	density of the saturation water (kg/m^3)
ρ_{gi1}	density of the saturation steam (kg/m^3)
α_{i1}	inner heat transfer coefficient of tubes (W/(m^2 °C))
λ_{f1}	conductivity of the saturation water (W/(m °C))
γ_1	latent heat (J/kg)
υ_{f1}	kinematic viscosity coefficient of the saturation water (m^2/s)
t_{s1}	saturation temperature of the heating flow (°C)
t_{wi1}	inner temperature of the tube wall (°C)
k_1	heat transfer coefficient (W/(m^2 °C))
R_{fo1}	outer fouling resistance of the tubes (m^2 °C/W)
R_{fi1}	inner fouling resistance of the tubes (m^2 °C/W)
δ_{t1}	thickness of the tube wall (m)
λ	conductivity of the tube wall (W/(m °C))
l_{e1}	average effective length of the finned tube bundle (m)
Q_{t1}	heat transfer rate (W)
Q_{l1}	heat transfer rate per unit length (W/m)
C_{po1}	specific heat at the heated flow pressure (J/(kg °C))
m_{ro}	outer mass flow of the tubes (kg/s)
t_{o1}	outlet temperature of the heated flow (°C)
t_{i1}	inlet temperature of the heated flow (°C)
h_{i1}	depth on the concave side of head (m)
h	length of the straight edge of head (m)
l_{t1}	average length of the finned tube (m)
N_1	number of the tubes
γ	ratio
D_{b1}	bundle diameter (m)
A_{o1}	outer surface area of finned tube per unit length (m^2/m)
A_{f1}	surface area of fins per unit length (m^2/m)
A_{t1}	outer surface area of tube between fins per unit length (m^2/m)
N_f	fins number per unit length
δ_{fa}	fin average thickness (m)
C_f	fin shape modifiable factor
A_{i1}	inner surface area of finned tube per unit length (m^2/m)
r_{ob1}	finned tube radius at the fin base (m)
r_{o1}	finned tube outer radius (m)
Re_1	Reynolds number of the heated flow
Pr_1	Prandtl number of the heated flow
l_{o1}	flow length of the heated steam (m)
d_{e1}	equivalent diameter (m)
α_{o1}	outer heat transfer coefficient of the tubes (W/(m^2 °C))
μ_{o1}	dynamic viscosity coefficient of the heated steam (Pa s)
μ_{wo1}	outer dynamic viscosity coefficient of the tube wall (Pa s)
λ_{o1}	conductivity of the heated flow (W/(m °C))
G_1	inner mass flow density of the tubes (kg/(m^2 s))
A_{l1}	inner heat transfer area of the tubes per unit length (m^2/m)
C_{q1}	cross-flow scrubbing modifiable factor
δ_s	thickness of the shell (m)
δ_h	thickness of the ellipsoidal head (m)
δ_{ts}	thickness of the tube sheet of reheater (m)
P_{ds}	design pressure on concave side of head (MPa)
P_{d1}	design pressure on the tube-side (MPa)
D_{si}	inner diameter of the shell (m)
D_t	diameter of tube sheet (m)
S	allowable stress value of the material (MPa)
c	additional thickness (m)
F_a	modifiable factor
d	diameter of tube hole (m)
r	tube hole pitch (m)
L_s	length of the shell (m)
ρ_s	density of the shell (kg/m^3)
ρ_h	density of the ellipsoidal head (kg/m^3)
ρ_t	density of the tube (kg/m^3)
ρ_{ts}	density of the tube sheet of reheater (kg/m^3)
V_{ho}	volume on the convex side of head (m^3)
V_{hi}	volume on the concave side of head (m^3)
h_{o1}	depth on the convex side of head (m)
t_o	heated steam outlet temperature of the moisture separator reheater (°C)
m_1	mass flow of the heating steam (kg/s)
P_{i1}	inlet pressure of the heating steam (MPa)
E	lowest efficiency of any joint in the head

discussed in Section 4. Section 5 discusses the obtained results. Section 6 concludes the paper.

2. Moisture separator reheater mathematical model

In a pressurized water nuclear reactor, close to saturation steam is used at the entrance of the HP turbine. The steam leaves the HP turbine as slightly-wet saturated steam. The increase of steam humidity content (i.e., formation of liquid droplets) tends to increase the erosion of the blades and deteriorate the efficiency of power plant. A vapor superheating is absolutely necessary before it enters into the LP unit. In Qinshan I nuclear power plant, wetted steam at the exhaust of the HP turbine flows through moisture separators of the MSR which collect the moisture, mechanically dry the vapor and drain out the liquid. Then, the vapor is reheated through the reheaters of the MSR. The required superheating is obtained by a derivation of a fraction of the steam