International Journal of Thermal Sciences 91 (2015) 105–112

Contents lists available at ScienceDirect

International Journal of Thermal Sciences

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

Optimization of a seawater once-through cooling system with variable speed pumps in fossil fuel power plants

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ARTICLE INFO

Article history:
Received 26 October 2013
Received in revised form
2 January 2015
Accepted 5 January 2015
Available online

Keywords:
Power plant
Once-through cooling system
Cooling water pump
Variable speed
Optimum operation

ABSTRACT

Optimization of a seawater once-through cooling system using variable speed pumps (VSPs) is presented to improve the efficiency of power plants. This study is focused on the VSP running number optimization and VSP speed optimization. A novel method is proposed to optimize the VSP running number with the varying condenser inlet water temperature and unit load. A novel method is also proposed to determine the optimum VSP speed by dividing the system operating conditions into two parts with different optimization algorithms. The method helps to choose the proper optimization algorithm at different operating conditions, which will reduce workload and improve working efficiency. A case study shows that the VSP running number optimization could help to reduce annual costs for VSPs by 14%.

1. Introduction

The production of sufficient power to satisfy the world's energy requirements relies heavily on fossil fuels for electricity generation [1]. Despite the depletion of fossil fuel reserves and environmental concerns such as climate change, demand for oil is expected to rise to 47.5% between 2003 and 2030, demand for natural gas will rise to 91.6% and demand for coal will rise to 94.7% [2]. Therefore, our continued reliance on fossil fuels for the foreseeable future makes it all the more important to enhance the operation efficiency of fossil fuel power plants, which could not only save energy, but also reduce environmental impacts.

One approach to improve the cycle efficiency of fossil fuel power plants is the optimization of the cooling water system to reject heat at approximately twice the rate at which electric power is generated [3]. It is worth underlining that small improvements to the cooling water system can lead to large fuel savings and consequently efficiency enhancement [4]. The effectiveness of the cooling water system can be quantified through the condenser pressure – the effects become more obvious as the condenser pressure decreases [5]. The condenser pressure depends only on the condenser shell-side steam temperature, which is determined by the cooling water flow under the given boundary conditions (namely, the same unit load and condenser inlet water temperature) according to the heat and power loss algorithm in Ref. [6]. Thus, the optimization of the cooling water system could be realized by operating at optimum cooling water flow.

This study was inspired by the operation of a seawater once-through cooling system in which the seawater is pumped to the condenser using cooling water pumps (CWPs) and the return hot water is passed through the condenser and let back to the sea via a seal well structure. For fossil fuel power plants employing constant speed pumps (CSPs) as CWPs, the seawater level in the sump of the CWP station changes with variations in the sea's tidal level, leading to variations in cooling water flow, CWP power consumption and turbine cycle heat rate. However, it is almost impossible to attain optimal cooling water flow because only a few discrete set points for the flow are supplied by CSPs. Compared with the CSP, the variable speed pump (VSP) can provide variable cooling water flow and achieve significant energy savings by running at variable speeds [7–9]. In this study, the optimization of a seawater once-through cooling system employing VSPs as CWPs is investigated to reduce operating costs and improve plant efficiency.

Many researchers have investigated individual components in the seawater once-through cooling system, such as the performance characteristics of condensers [10–12]. However, few studies have been devoted to a systematic analysis and overview of the optimization process. Harish et al. [13] developed a theoretical

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http://dx.doi.org/10.1016/j.ijthermalsci.2015.01.005

model to establish the viability of employing VSPs as CWPs in power plants with the seawater once-through cooling system, which will help cooling water system designers to decide whether or not they want to opt for the VSP. However, the mathematical model using VSPs to keep the cooling water temperature at its upper limit could not guide the optimum operation of the system, especially in part load conditions. This paper proposes novel methods to optimize VSPs to achieve optimal cooling water flow in all operating conditions.

This paper is organized as follows: Section 2 proposes the mathematical model for the optimization of seawater once-through cooling system, i.e., VSP optimization. Novel methods to determine the optimum VSP running number and the optimum VSP speed are presented in Section 3. A case study is presented in Section 4. Finally, conclusions are given in Section 5.

2. Mathematical model

2.1. Condenser pressure

For fossil fuel power plants whose feed water pumps are supported by steam turbines, the energy balance can be expressed as [6]:

$$Q_b + P_{cp} = Q_c + P_t \tag{1}$$

When operating in turbine follow mode, power plants will be operated with a constant P_t. In addition, P_{cp} is considered to be fixed, as the variation in condensate pump demand is minor compared to the other elements of the energy balance [6]. Thus, the magnitude of the change in Q parameters is equal as the following relation:

$$\Delta Q_b = \Delta Q_c \tag{2}$$

The variation of ΔQ_b due to the heat rate variation can be expressed as

$$\Delta Q_b = \frac{HR_c \cdot HR_b \cdot P_t \cdot 4.18}{3600} \tag{3}$$

where HR_b is the baseline heat rate and is provided by the steam turbine manufacture.

The heat rate variation caused by the change of condenser pressure can be obtained with turbine cycle heat rate curves provided by the steam turbine manufacture [13], as shown in Fig. 1. The curves depict the heat rate variation as a function of the condenser pressure in different unit loads.

$$HR_c = f_h(p_k, UL) \tag{4}$$

The relationships that define the energy balance in the condenser are given in Eqs. 5–7 [6].

$$Q_{c1} = Q_{c,d} + \Delta Q_c \tag{5}$$

$$Q_{c2} = \frac{UA(T_{w2} - T_{w1})}{\ln \frac{T_s - T_{w1}}{T_s - T_{w2}}} \tag{6}$$

$$Q_{c3} = m_w c_P (T_{w2} - T_{w1}) \tag{7}$$

The heat transfer coefficient U can be estimated as [14]

$$U = U_1 \cdot U_W \cdot U_M \cdot U_C \tag{8}$$

The cooling water flow depends on the VSP operation point determined by the pump characteristic curve and the piping head loss curve [15], as shown in Fig. 2. When it runs at different running numbers or speeds, VSP has different characteristic curves that can be fitted to an expression as shown in Equation (9). For a seawater once-through cooling system with fixed components, its piping head loss curve depends on its static head, since its flow resistance coefficient is considered to be constant. The static head changes with the variations in the tide level variation of the sea. Thus, the piping head loss curve can be given in Equation (10). The cooling water flow is determined by solving the following two equations.

$$m_w = f_{w1}(N_P, n, H_P) \tag{9}$$

$$m_w = f_{w2}(H_t, H_P) \tag{10}$$

The condenser pressure can be obtained according to an empirical formula [16], i.e.,

$$p_k = 9.81\left(\frac{T_s + 373.15}{57.66}\right)^{7.46} \tag{11}$$

Under certain optimal variables and boundary conditions, the condenser pressure can be calculated by Eqs. (2)–(11) with iteration and the algorithm shown in Fig. 3.

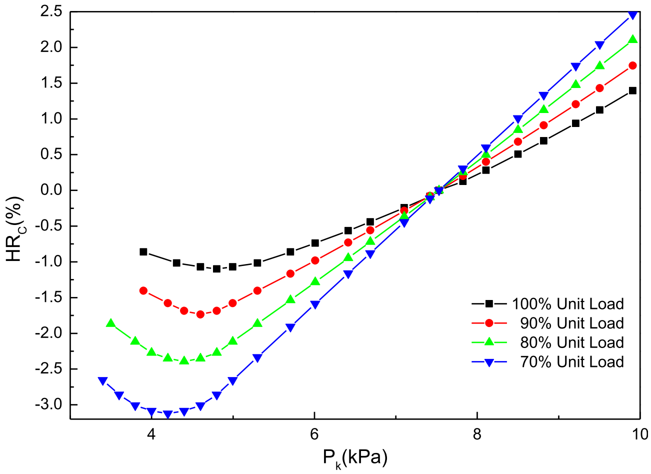

Fig. 1. Turbine cycle heat rate curves in different unit loads.

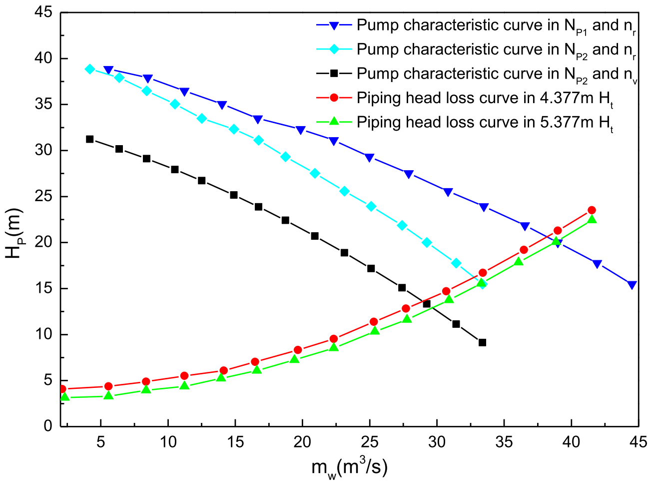

Fig. 2. VSP operation point.