



Selecting the cooling water mass flow rate for a power plant under variable load with entropy generation rate minimization



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ABSTRACT

The paper deals with selecting the mass flow rate of cooling water under variable load of a power unit such that optimum operating parameters of the unit can be achieved. The change in the cooling water mass flow rate influences the resistance to flow (on the cooling water side) and the pressure of the condensing steam. A higher cooling water mass flow rate increases the resistance to flow and power supplied to the cooling water pump, but it also results in a drop in the condensing steam pressure and an increase in the power generated in the LP (low-pressure) part of the turbine. Since the change in the mass flow rate affects the performance of the condenser, the LP part of the turbine, and the cooling water pump, a system comprising these components was analyzed. The cooling water mass flow rate was chosen via minimization of the total entropy generation rate in these components and a change in the unit's power output defined as a difference between the power outputs of the LP part of the turbine and the cooling water pump. The aim of this paper is to find the optimum value of the mass flow rate of cooling water under variable load of the power plant.

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1. Introduction

A steam condenser is the largest heat exchanger in a power plant; it is where steam fed from the LP (low-pressure) part of the turbine condenses. To cool down the steam, water, taken from rivers, lakes or cooled in cooling towers, is most often used. Steam condensers are normally shell and tube heat exchangers. The cooling water flows inside the tubes, and the steam condenses on their outer surface. The condenser makes it possible to close the thermal cycle and transfer the heat of condensation to the environment.

For designing condensers and assessing their performance two main methods are applied: one based on heat transfer effectiveness ε – NTU [1,2], and a classic one (correction) [1,2]. Both these methods are based on the first law of thermodynamics – the energy balance, Peclet's law, criteria relations, and similarity numbers, such as the Nusselt, Reynolds, and Prandtl numbers, which are used for determining the heat transfer coefficient and the overall heat transfer coefficient [1,2]. Depending on the task, these two methods can be used to determine the heat transfer surface

area or outlet parameters (temperatures). A steam condenser design based only on the first law of thermodynamics fails to consider all the processes occurring in the heat exchanger. Heat transfer is accompanied by irreversible processes which result from the heat flow from the hot fluid to the cold one and from the resistance of heat-transferring fluids to flow (pressure losses). Therefore, for a more comprehensive evaluation of the heat exchanger performance, the second law of thermodynamics is employed; according to this law, the measure of the irreversible processes is an increase in entropy generation. When designing a steam condenser that is cooled with river or lake water, one has to consider variations in temperature at the condenser inlet in summer and winter months, and that the cooling water mass flow rate can be adjusted by setting the blade angle in a pump [3,4]. Changes in cooling conditions (inlet temperature and the cooling water mass flow rate) affect the power output of the cooling water pump, the steam condenser performance [5–7], and the condensing steam pressure [8–10], which in turn affects the operating conditions of the low-pressure (LP) part of the turbine and the internal power it achieves [11]. In the literature, papers can be found which examine the effect of particular parameters, such as cooling water temperature at the condenser inlet [5,12] and cooling water mass flow rate [3,6,13], on the performance of condensers and the efficiency and power of entire systems. Ref. [6] sought the optimum

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cooling water mass flow rate by considering total costs and assuming the system efficiency as the objective function [5] focused on assessing the optimum temperature of cooling water for the condenser by applying exergy loss minimization.

One of key tasks of the steam condenser is to provide the lowest possible vacuum for increasing the isentropic drop (power) achieved in the turbine. Due to the subatmospheric pressure in the condenser, inert gases (air) are sucked inside it through leaks in the connection between the turbine and the condenser and cause a pressure rise in the steam condenser and a deterioration of its performance. The deterioration of heat transfer conditions also results from sediment collecting on the inner surface of tubes. Numerous models were proposed [14–17] for assessing how inert gases and sediment affect the steam condenser performance. The effect of sediment and inert gases on the condenser performance has to be taken into account when the condenser is designed. Heat exchanger designers should also consider building and operating costs. Thus, choosing a steam condenser and its operating parameters for a power unit is an issue involving multiple criteria. Since there are different criteria for selecting heat exchangers, their designers use optimization models in which it is, for instance, the increase in entropy generation rate [18], exergy loss [19–21], the loss of available work [22], or the costs of building and operating a heat exchanger [23–25] that are subject to minimization.

In the paper, the entropy EGM (generation minimization) is used for selecting the cooling water mass flow rate; this method takes into account entropy generation resulting from the heat flow and the resistance to flow (pressure losses).

MacClintock [26] and Prigogine [27] were the first to assess the heat exchanger performance by introducing the EGM method. Bejan [28] proposed an entropy generation number N_s , defined as the entropy generation rate (S) divided by the lower heat capacity rate of the fluid, as the parameter subject to minimization. Based on the total entropy generation rate of both fluids, other researchers proposed parameters which were defined in a different way. For example, Hesselgreaves [29] proposed the revised entropy generation number [30], i.e. a parameter that is equal to the sum of entropy generation rates for the heat exchanger divided by the heat flow rate, so that the proposed parameter is dimensionless, multiplied by the inlet temperature of the cold fluid.

The EGM method was mainly employed in selecting optimum geometric parameters of the heat exchanger, such as the tube inner diameter [18,20,31], the pitch of tubes in a bank [32–34], or the height or width of a channel. For EGM-based selection of optimum geometry, various types of heat exchangers were analyzed: cross-flow heat exchangers [35–37], counter-flow heat exchangers [38], steam condensers [31], shell-and-tube heat exchangers [39], ground heat exchangers with a single U-tube [40], plate-fin heat exchangers [41], and double-pipe pin fin heat exchangers [34].

The entropy generation minimization (EGM) has been used mainly for the selection of the optimal geometry of the heat exchangers. In this article, the authors decided to apply the entropy generation minimization for the existing steam condenser (the geometry of the steam condenser is known and it is not of the subject of optimization) in order to select the optimum mass flow rate of cooling water. According to the authors' knowledge such analysis has not been done so far.

The change in the cooling water mass flow rate at the condenser inlet causes a change in the pump power output, water velocity in tubes (which affects heat transfer conditions), the resistance to flow, and the pressure of the condensing steam (which influences the performance of the low-pressure part of the turbine). Thus, the steam condenser is a component of a larger subsystem with which it interacts and thus changes the performance of the whole power generation unit.

Then, if the influence of the cooling water mass flow rate on the steam condenser operation is to be analyzed, it is the thermal system of the whole power generation unit within which the condenser operates that should be analyzed. However, a change in the cooling water mass flow rate influences mainly the performance of the cooling water pump, the steam condenser, and the low-pressure part of the turbine. Hence, it is reasonable to analyze the subsystem comprising these components. The proposed model takes into account five entropy generation components: due to heat flow from condensing steam, heat flow to cooling water, and the resistance of cooling water flow through the condenser tubes, in the cooling water pump, and in the low-pressure (LP) part of the turbine between the last bleed and the outlet.

In order to verify the minimum entropy generation method, an increase in the unit power output—due to the increase in the power output of the LP part of the turbine less the increase in the power used for driving the cooling water pump—was considered.

A diagram of the steam condenser under consideration and the notation used are shown in Fig. 1.

The search for the optimum mass flow rate of cooling water must take into account constraints of the system parameters. For instance, steam pressure must not exceed the minimum and maximum values, which are due to technical limitations of the power plant; the temperature of cooling water at the inlet of the steam condenser should be higher than 10 °C, which is a prerequisite for the proper operation of the cooling water pump; and the mass flow rate of cooling water should be greater than the minimum mass flow rate (approx. 50% of the nominal value) and should not exceed the maximum one (approx. 125% of the nominal value).

2. Entropy generation model

2.1. Entropy generation rate on the cooling water side

In order to determine entropy generation due to heat flow to cooling water and the resistance of water flow through the condenser tubes, the first and second laws of thermodynamics and a pressure loss equation were employed.

For an open cycle, the increase in water enthalpy can be expressed in the differential form as

$$dh_2 = dq_2 + dp_2/\rho_2 \quad (1)$$

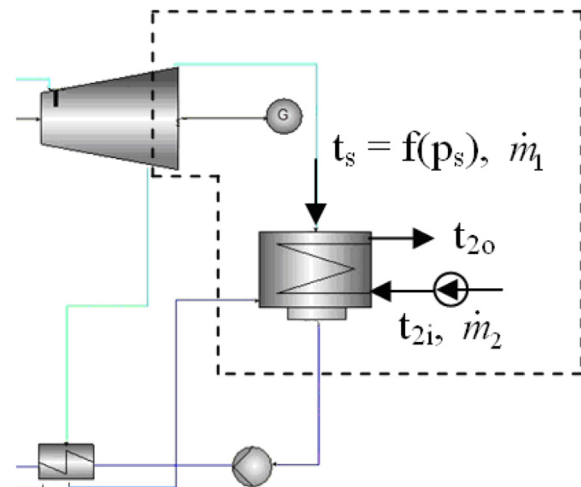


Fig. 1. A diagram of a condensing power plant with the nomenclature used.

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