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An Approximate Relation for Describing the Performance of a Condenser in Off-design Conditions

Rafał Laskowski[1*], Adam Smyk[1] and Artur Rusowicz[1]

[1]Institute of Heat Engineering, Warsaw University of Technology, 21/25 Nowowiejska Str., 00-665, Warsaw, Poland.

Authors' contributions

This work was carried out in collaboration between all authors. All authors read and approved the final manuscript.

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ABSTRACT

Operating parameters of a condenser have significant effect on the performance of a power generation unit. Heat transfer effectiveness is used to assess the steam condenser performance. Heat transfer effectiveness of a steam condenser is a function of an overall heat transfer coefficient, heat transfer surface area, and the cooling water mass flow rate. In this paper, an attempt was made to produce a simpler relation for heat transfer effectiveness of a steam condenser under off-design conditions as a function of inlet water temperature, the cooling water mass flow rate and steam temperature. A simulator of a condenser in a 200-MW power generation unit was used to investigate how inlet cooling water temperature, the cooling water mass flow rate, and the steam temperature affect the outlet cooling water temperature. Based on simulator data, a new approximate relation for heat transfer effectiveness of the condenser (outlet cooling water temperature) in off-design conditions with four constant coefficients was given. A simplified form of

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[*]Corresponding author: E-mail: rlask@itc.pw.edu.pl;

the proposed relation can be given with three constant coefficients. A good agreement was achieved between the heat transfer effectiveness obtained from the definition and from the proposed relation. The relation can be used to determine the condenser performance in off-design conditions in a simple way, or to determine a reference performance of a new or overhauled condenser.

Keywords: Steam condenser; condenser performance; off-design conditions.

NOMENCLATURES

A - *heat transfer area, m*^{2}
d_{2i} - *tube inner diameter, m*
d_{2o} - *tube outer diameter, m*
h - *specific enthalpy, kJ/kg*
U - *overall heat transfer coefficient, kW/(m*^{2}*K)*
$\dot{m}_2$ - *cooling water mass flow rate, kg/s*
$\dot{m}_1$ - *steam mass flow rate, kg/s*
t_{2i} - *inlet water temperature, ℃*
t_{2o} - *outlet water temperature, ℃*
t_s - *steam saturation temperature, ℃*
$\dot{Q}$ - *heat flow rate, W*
α_1 - *coefficient of heat transfer from steam to the external wall, kW/(m*^{2}*K)*
α_2 - *coefficient of heat transfer from cooling water to the wall, kW/(m*^{2}*K)*
ε - *heat exchanger effectiveness, -*
λ_m - *thermal conductivity of tube material, kW/(mK)*

SUBSCRIPTS

1 - hot fluid
2 - cold fluid
i - inlet
o - outlet, reference value
s - saturated conditions
max - maximum value

1. INTRODUCTION

In a power plant, a steam condenser serves as a lower heat sink where heat flux is rejected from the system to the environment. For open cooling systems, river water flowing inside tubes is used to cool the steam condenser. Following the change of river water temperature, the water temperature at the inlet to the steam condenser changes. Also, the cooling water mass flow rate and steam pressure may change. Due to changing parameters at the condenser inlet, its operating conditions change, which results in the change in the cooling water outlet temperature.

Heat transfer effectiveness, defined as the ratio of the actual to the maximum rate of heat flow, is most often used to describe the condenser performance under off-design conditions [1-3]:

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} \tag{1}$$

Other quantities are also used to assess the exchanger performance, e.g. the heat exchanger efficiency defined as the ratio of the actual to the optimum rate of heat transfer [4–6]. To determine the performance of heat exchangers, the required, or obtained, heat transfer units [7] were also proposed.

According to the energy balance and Peclet's law for the condenser the following equations can be written:

$$\dot{Q} = \dot{m}_2 c_2 \left(t_{2o} - t_{2i}\right) = \dot{m}_1 \left(h_{1i} - h_{1o}\right) \tag{2}$$

$$\dot{Q} = UA \frac{\left(t_{2o} - t_{2i}\right)}{\ln \dfrac{t_s - t_{2i}}{t_s - t_{2o}}} \tag{3}$$

On rearranging Eqs. (2) and (3) the heat transfer effectiveness of the condenser can be written as a function of the overall heat transfer coefficient, heat transfer surface area and the cooling water mass flow rate

$$\varepsilon = \frac{t_{2o} - t_{2i}}{t_s - t_{2i}} = 1 - \exp(-\frac{UA}{c_2 \dot{m}_2}) \tag{4}$$

The operating conditions of the condenser mainly depend on the values of the following variables: cooling water mass flow rate, cooling water temperature, and steam pressure and mass flow rate. Only three of these four variables are independent, while the fourth one can be determined from the energy balance (Eq. (2)).

For the analysed condenser, the cooling water mass flow rate, cooling water temperature, and steam pressure (temperature) were chosen as independent variables, as these quantities are measured. Further in the paper, the steam temperature instead of pressure was considered as an input variable, although it is pressure that is measured; the reason for this is that the heat transfer relates to the difference in temperatures of heat transfer fluids. For the assumed input variables, the outlet cooling water temperature and the steam mass flow rate are calculated as output variables.

Determining the heat transfer effectiveness of the condenser according to Eq. (4) requires additional equations, e.g. for heat transfer coefficients from the water and steam sides [8,9] and thermodynamic properties of water and steam. The complete model for determining the condenser's heat transfer effectiveness according to Eq. (4) is a set of about 25 linear and non-linear equations [8,10]. Due to non-linearity of the equations, calculations have to be performed iteratively.

For more efficient calculations regarding power generation units in off-design conditions, approximate relations concerning the equipment have been developed. In the literature, some approximate relations can be found that make it possible to determine the effectiveness of a counter-flow heat exchanger quickly and with good accuracy as a function of the number of transfer units and the thermal capacity ratio [11, 12]. One example of the approximate relation which can be applied to calculate the heat transfer effectiveness of a steam condenser in off-design conditions was proposed by Beckman [13]:

$$\frac{\varepsilon}{\varepsilon_o}=\left(\frac{t_s}{t_{so}}\right)^{\alpha_1}\left(\frac{t_{2i}}{t_{2io}}\right)^{\alpha_2}\left(\frac{\dot{m}_2}{\dot{m}_{2o}}\right)^{\alpha_3} \tag{5}$$

Eq. (5) has the form of a power function with three constant exponents. The model input variables are the steam saturation temperature, the inlet cooling water temperature, and the cooling water mass flow rate. Reference parameters are included in the equation so that all the variables are dimensionless. The reference parameters are usually those that are relevant under nominal operating conditions.

From Eq. (5) it follows that the cooling water temperature at the condenser outlet can be expressed as

$$t_{2o}=t_{2i}+\left(t_s-t_{2i}\right)\varepsilon_o\left(\frac{t_s}{t_{so}}\right)^{\alpha_1}\left(\frac{t_{2i}}{t_{2io}}\right)^{\alpha_2}\left(\frac{\dot{m}_2}{\dot{m}_{2o}}\right)^{\alpha_3} \tag{6}$$

The power exponents in Eqs. (5) or (6) should be determined; this can be achieved, for instance, by means of the least squares method, based on data provided in technical documentation or based on actual measurement data concerning the condenser under study.

The equation proposed by Beckman allows us to determine the condenser's heat transfer effectiveness (outlet cooling water temperature) in off-design conditions in an easier way.

The present paper adopted another approach to describing the condenser's heat transfer effectiveness. The condenser was considered as a 'black box', and the effect of input variables on the output ones was investigated so that an approximate relation for describing the condenser performance in variable conditions can be proposed. A schematic diagram of the condenser as the 'black box' with marked inputs and outputs is shown in Fig. 1.

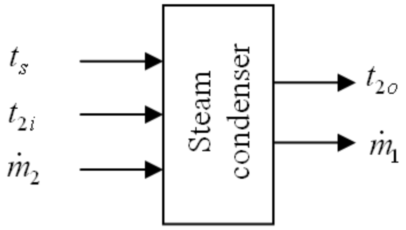

Fig. 1. Input and output variables in the schematic diagram of the condenser as a 'black box'

The issue of determining performance in off-design conditions is encountered not only with heat exchangers, but also with other pieces of equipment [14-19].

2. MATHEMATICAL MODEL OF A STEAM CONDENSER

To accomplish this task, a condenser simulation was developed based on a steady-state zero-dimensional model, in which criteria relations, known in the literature [8,20-22], for water and steam overall heat transfer coefficients were used.

In the condenser simulator, the equation for heat flow rate was used according to Peclet's law

$$\dot{Q} = U \cdot A \cdot \Delta t_{\ln} \tag{7}$$

The mean logarithmic temperature difference is

$$\Delta t_{\ln} = \frac{(t_s - t_{2o}) - (t_s - t_{2i})}{\ln\left(\frac{t_s - t_{2o}}{t_s - t_{2i}}\right)} \tag{8}$$

The overall heat transfer coefficient (*U*) was determined from the equation

$$U = \frac{1}{\frac{d_{2o}}{\alpha_2 \cdot d_{2i}} + \frac{d_{2i}}{2 \cdot \lambda_m} \cdot \ln\left(\frac{d_{2o}}{d_{2i}}\right) + \frac{1}{\alpha_1}} \tag{9}$$

The coefficient of heat transfer (α_2) from cooling water to tube walls was determined from the Dittus-Boelter equation [1,2] and the coefficient of heat transfer (α_1) on the side of condensing steam was assumed according to [8,10,20-22].

The simulator's input variables are: temperature of cooling water at the steam condenser inlet, cooling water mass flow rate, and steam temperature. The calculated (output) variables are: cooling water temperature at the condenser outlet and steam mass flow rate to the steam condenser.

The simulator input parameters varied within the following ranges: water temperature at the condenser inlet from 10 to 25°C, cooling water mass flow rate from 6,000 to 10,500 kg/s, and steam pressure (temperature) from 0.0282 (23°C) to 0.0632 bar (37°C).

The condenser reference conditions were adopted as for a 200-MW power generation unit: cooling water mass flow rate 7,995 kg/s, inlet cooling water temperature 17°C, steam pressure 0.0414 bar and the corresponding steam temperature 29.56°C, steam mass flow rate 123 kg/s, and outlet cooling water temperature 25°C.

3. METHODOLOGY AND RESULTS

Using data obtained from the condenser simulator it was investigated how each inlet variable, i.e. the cooling water temperature and mass flow rate at the condenser inlet, and steam temperature affect the outlet cooling water temperature.

For a constant cooling water mass flow rate and steam temperature, the effect of the cooling water temperature at the condenser inlet on the cooling water temperature at the condenser outlet is displayed in Fig. 2.

The data shown in Fig. 2 indicates that the relation between the inlet and outlet feed water temperatures can be given as the linear function

$$t_{2o} = a_1 t_{2i} + a_2 \tag{10}$$

Cooling water temperature at the condenser outlet as a function of the steam saturation temperature for a constant cooling water mass flow rate and constant cooling water temperature at the condenser inlet is shown in Fig. 3.

Similarly, the effect of the steam saturation temperature on the feed water temperature at the condenser outlet can be approximated by a linear function of the form

$$t_{2o} = a_3 t_s + a_4 \tag{11}$$

The simultaneous effect of the feed water temperature and steam saturation temperature on the cooling water temperature at the condenser outlet can be written as

$$t_{2o} = (b_1 t_s + b_2) t_{2i} + (b_3 t_s + b_4) \tag{12}$$

$$t_{2o} = b_1 t_s t_{2i} + b_2 t_{2i} + b_3 t_s + b_4 \tag{13}$$

Based on the simulator data for these two trends, coefficients in Eq. (13) were determined, and b_2 turned out to be close to zero. Further in the paper it was assumed that $b_2 = 0$.

Eq. (13) can be transformed into a form which contains the heat transfer effectiveness

$$\varepsilon = \frac{t_{2o} - t_{2i}}{t_s - t_{2i}} = 1 - \frac{(c_1 t_{2i} + c_2 t_s + c_3)}{t_s - t_{2i}} \tag{14}$$

For constant inlet water temperature and constant steam pressure, the effect of the cooling water mass flow rate on cooling water temperature at the condenser outlet was investigated (Fig. 4).

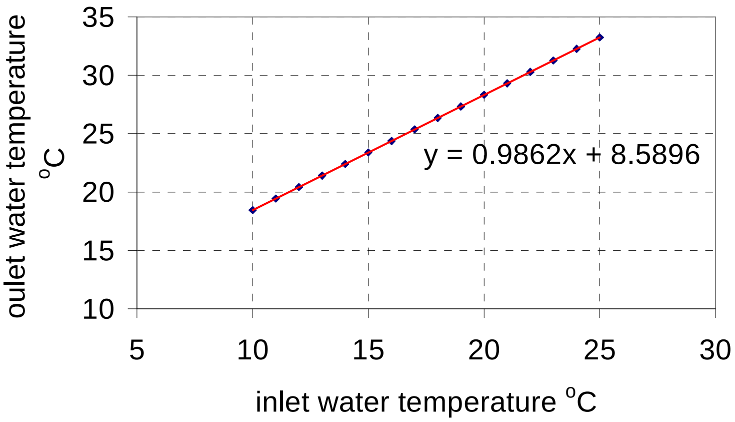

Fig. 2. Cooling water temperature at the condenser outlet vs. water temperature at the condenser inlet

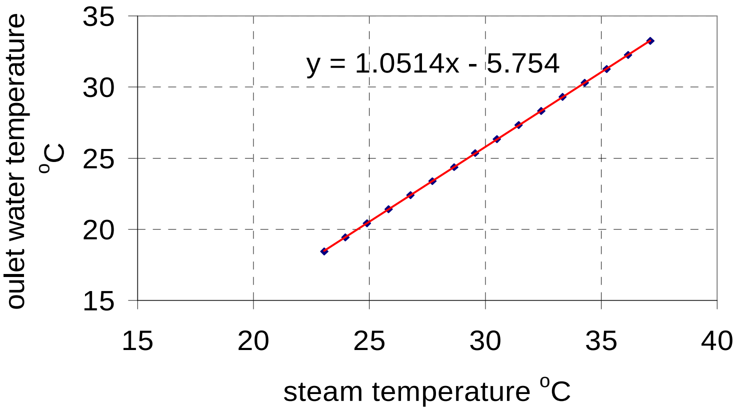

Fig. 3. Cooling water temperature at the condenser outlet vs. steam temperature

Using data in Fig. 4 it is difficult to name the exact type of function which describes the relation between the cooling water mass flow rate and the outlet cooling water temperature. It was decided to approximate the trend by an exponential function of the form

$$t_{2o} = t_s - a_5\left[1-\exp\left(-a_6\frac{\dot{m}_2}{\dot{m}_{2o}}\right)\right] \tag{15}$$

Water temperatures at the condenser outlet as obtained from the simulator and from the proposed approximate relation (15) are compared in Fig. 4. According to the data, the proposed Eq. (15) provides a very good approximation of changes in the cooling water temperature at the condenser outlet following changes in the cooling water mass flow rate (in the diagram the points of data determined from the simulator and the proposed equation match each other). Table 1 lists cooling water outlet temperatures as obtained from the simulator and from the proposed Eq. (15) and differences between them.

The reason for choosing the form of the function was that as the cooling water mass flow rate approaches zero, the outlet cooling water temperature approaches the value of the steam saturation temperature. The cooling water mass flow rate in reference (nominal) conditions was also taken into account in the equation so that the argument of the exponential function is dimensionless.

Eq. (15) can be transformed into a form which contains the heat transfer effectiveness

$$\varepsilon = 1-\frac{a_5}{t_s - t_{2i}}\left[1-\exp\left(-a_6\frac{\dot{m}_2}{\dot{m}_{2o}}\right)\right] \tag{16}$$

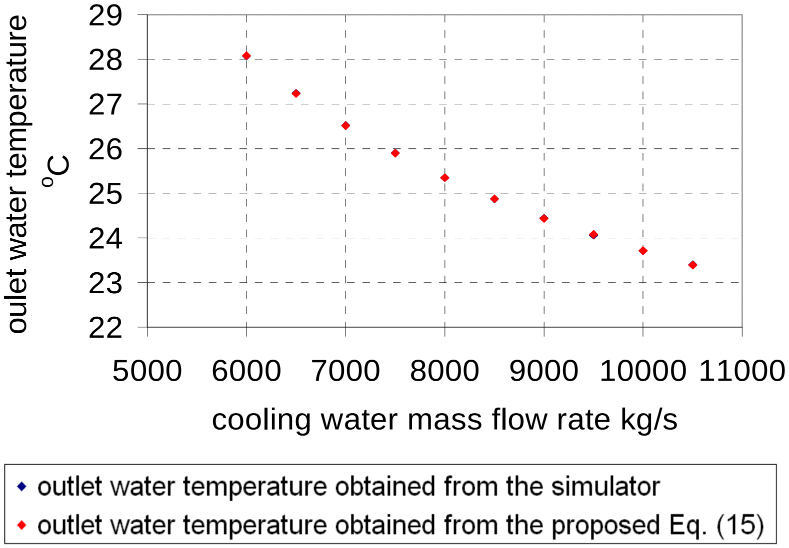

Fig. 4. Cooling water temperature at the condenser outlet vs. the cooling water mass flow rate based on data obtained from the simulator and from the proposed Eq. (15)

Table 1. Cooling water outlet temperatures as obtained from the simulator and from the proposed Eq. (15)

Mass flow rate of cooling water, kg/s	Outlet water temperature from the simulator, °C	Outlet water temperature from the proposed Eq. (15), °C	Difference, °C
6000	28.07	28.08	-0.01
6500	27.24	27.23	0.01
7000	26.52	26.51	0.01
7500	25.9	25.90	0.00
8000	25.35	25.35	0.00
8500	24.87	24.87	0.00
9000	24.44	24.44	0.00
9500	24.06	24.08	-0.02
10000	23.71	23.71	0.00
10500	23.4	23.39	0.01

Finally, by comparing Eqs. (14) and (16), the approximate relation for the heat transfer effectiveness of the condenser is obtained in the form

$$\varepsilon = \frac{t_{2o} - t_{2i}}{t_s - t_{2i}} = 1 - \frac{\left(A_1 t_{2i} + A_2 t_s + A_3\right)}{t_s - t_{2i}} \left[1 - \exp\left(-A_4 \frac{\dot{m}_2}{\dot{m}_{2o}}\right)\right] \tag{17}$$

From Eq. (17) it follows that the cooling water temperature at the condenser outlet can be written as

$$t_{2o} = t_s - \left(A_1 t_{2i} + A_2 t_s + A_3\right)\left[1 - \exp\left(-A_4 \frac{\dot{m}_2}{\dot{m}_{2o}}\right)\right] \tag{18}$$

Eq. (17) can be simplified for a case when the cooling water mass flow rate is approximately equal to the cooling water mass flow rate in reference conditions. By expanding the exponential function into the series

$$e^{-x} = 1 - x + \frac{x^2}{2!} - \ldots \qquad (19)$$

and by including the first two terms in the expansion, Eq. (17) takes the form

$$\varepsilon = \frac{t_{2o} - t_{2i}}{t_s - t_{2i}} = 1 - \frac{\left(B_1 t_{2i} + B_2 t_s + B_3\right)}{t_s - t_{2i}} \frac{\dot{m}_2}{\dot{m}_{2o}} \qquad (20)$$

As confirmed in [23-27], a linear relation between the heat transfer effectiveness and the cooling water mass flow rate is observed for slight changes in the cooling water mass flow rate.

From Eq. (20) it follows that the cooling water temperature at the condenser outlet can be written as

$$t_{2o} = t_s - \left(B_1 t_{2i} + B_2 t_s + B_3\right) \frac{\dot{m}_2}{\dot{m}_{2o}} \qquad (21)$$

Using data obtained from the condenser simulator, constant coefficients were determined in equations for the outlet cooling water temperature (6), (18), and (21) by means of the least squares method.

The accuracy and usability of the proposed equations were assessed based on the differences between the outlet cooling water temperatures as obtained from the simulator and from the approximate relations (6), (18), and (21).

Fig. 5 depicts the differences between outlet cooling water temperatures as obtained from the simulator and from the approximate relations (6), (18), and (21).

Table 2 lists cooling water outlet temperatures as obtained from the simulator and from Eqs. (6), (18), and (21), respectively, and differences between them.

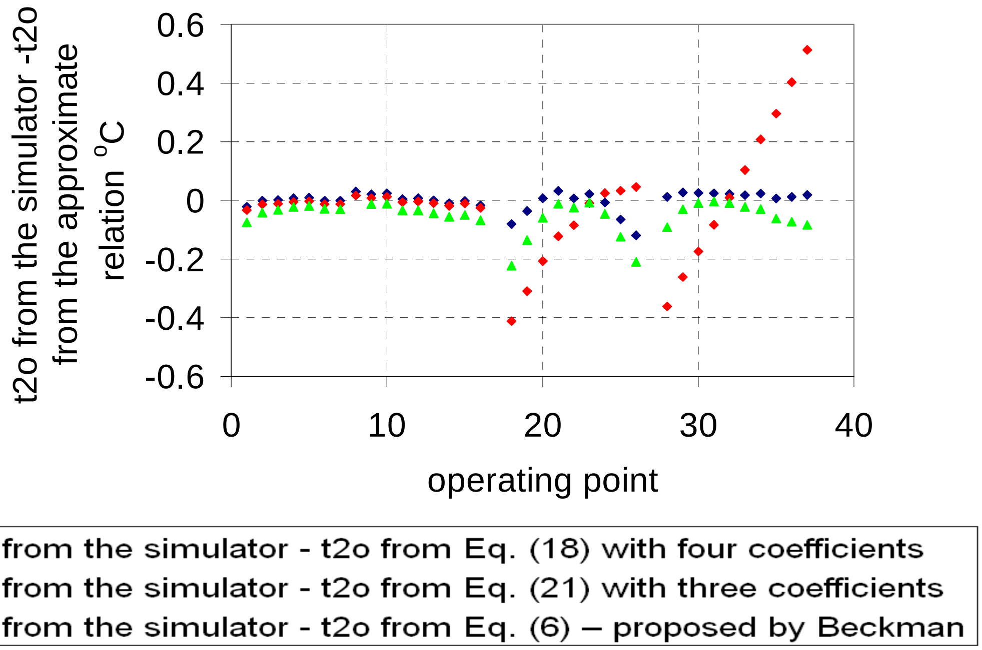

Fig. 5. Comparison of the differences between the outlet cooling water temperatures as obtained from the simulator and from the approximate relations (Eq. 6 – proposed by Beckman), (Eq. 18 with four coefficients), and (Eq. 21 with three coefficients)

Table 2. Cooling water outlet temperatures as obtained from the simulator and from Eqs. (6), (18), and (21)

Outlet cooling water temperature from the simulator, ℃	**Outlet cooling water temperature from the approximate relation (18), ℃**	**Outlet cooling water temperature from the approximate relation (21), ℃**	**Outlet cooling water temperature from the approximate relation (6), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (18), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (21), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (6), ℃**
18.45	18.47	18.48	18.52	-0.02	-0.03	-0.07
19.44	19.44	19.45	19.48	0.00	-0.01	-0.04
20.42	20.42	20.43	20.45	0.00	-0.01	-0.03
21.41	21.40	21.42	21.43	0.01	-0.01	-0.02
22.4	22.39	22.40	22.42	0.01	0.00	-0.02
23.38	23.38	23.39	23.41	0.00	-0.01	-0.03
24.37	24.37	24.38	24.40	0.00	-0.01	-0.03
25.36	25.33	25.34	25.36	0.03	0.02	0.00
26.34	26.32	26.33	26.35	0.02	0.01	-0.01
27.33	27.31	27.32	27.34	0.02	0.01	-0.01
28.32	28.32	28.33	28.35	0.00	-0.01	-0.03
29.3	29.29	29.30	29.33	0.01	0.00	-0.03
30.29	30.29	30.30	30.33	0.00	-0.01	-0.04
31.27	31.28	31.29	31.33	-0.01	-0.02	-0.06
32.26	32.26	32.27	32.31	0.00	-0.01	-0.05
33.24	33.26	33.27	33.31	-0.02	-0.03	-0.07
21.81	21.89	22.22	22.03	-0.08	-0.41	-0.22
22.48	22.52	22.79	22.62	-0.04	-0.31	-0.14
23.16	23.15	23.37	23.22	0.01	-0.21	-0.06
23.83	23.80	23.95	23.84	0.03	-0.12	-0.01
24.49	24.48	24.57	24.51	0.01	-0.08	-0.02
25.16	25.14	25.17	25.17	0.02	-0.01	-0.01
25.82	25.83	25.80	25.87	-0.01	0.02	-0.05
26.48	26.55	26.45	26.60	-0.07	0.03	-0.12
27.14	27.26	27.09	27.35	-0.12	0.05	-0.21
28.07	28.06	28.43	28.16	0.01	-0.36	-0.09

Outlet cooling water temperature from the simulator, ℃	**Outlet cooling water temperature from the approximate relation (18), ℃**	**Outlet cooling water temperature from the approximate relation (21), ℃**	**Outlet cooling water temperature from the approximate relation (6), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (18), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (21), ℃**	**t_{2o} from the simulator – t_{2o} from the approximate relation (6), ℃**
27.24	27.21	27.50	27.27	0.03	-0.26	-0.03
26.52	26.49	26.69	26.53	0.03	-0.17	-0.01
25.9	25.88	25.98	25.90	0.02	-0.08	0.00
25.35	25.33	25.34	25.36	0.02	0.01	-0.01
24.87	24.85	24.77	24.89	0.02	0.10	-0.02
24.44	24.42	24.23	24.47	0.02	0.21	-0.03
24.06	24.05	23.76	24.12	0.01	0.30	-0.06
23.71	23.70	23.31	23.78	0.01	0.40	-0.07
23.4	23.38	22.89	23.48	0.02	0.51	-0.08
$\sum\left\|\text{t2o from the simulator - t2o from approximate relation}\right\|$				0.73	3.86	1.81

4. CONCLUSIONS

During the steam condenser operation, inlet parameters (water temperature, cooling water mass flow rate, steam pressure) tend to vary. Heat transfer effectiveness is most often used to assess the condenser performance under off-design conditions. In the classical approach, the heat transfer effectiveness of a condenser is a function of the overall heat transfer coefficient, heat transfer surface area, and the cooling water mass flow rate. Beckman proposed a relation describing the heat transfer effectiveness of a condenser as a power function of the parameters at the inlet to the condenser, i.e. water temperature and the mass flow rate at the inlet, and steam temperature.

In the paper an attempt was made to provide a simpler relation for the heat transfer effectiveness (outlet cooling water temperature) of a condenser as a function of the inlet cooling water temperature and mass flow rate, and the steam temperature. To this end, the condenser was considered as a 'black box', and using data obtained from a condenser simulator (in this instance, for a 200-MW power generation unit) it was investigated how the inlet parameters (the cooling water temperature and mass flow rate, and the steam temperature) affect the outlet cooling water temperature. Based on the responses to the inputs, the relation for the effectiveness with four constant coefficients was provided. If only slight changes in the mass flow rate occur, the proposed Eq. (18) can be simplified to Eq. (21) with three constant coefficients.

Following an analysis, the proposed Eq. (18) was found to provide a better description of the condenser performance than the equation proposed by Beckman (6). Simplifying Eq. (18) to the form of Eq. (21) results in little lower accuracy.

The proposed Eqs. (18) and (21) can be used to determine the heat transfer effectiveness of a steam condenser under off-design conditions.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

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