Entropy generation in a condenser and related correlations

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Abstract The paper presents an analysis of relations describing entropy generation in a condenser of a steam unit. Connections between entropy generation, condenser ratio, and heat exchanger effectiveness, as well as relations implied by them are shown. Theoretical considerations allowed to determine limits of individual parameters which describe the condenser operation. Various relations for average temperature of the cold fluid were compared. All the proposed relations were verified against data obtained using a simulator and actual measurement data from a 200 MW unit condenser. Based on data from a simulator it was examined how the sum of entropy rates, steam condenser effectiveness, terminal temperature difference and condenser ratio vary with the change in the inlet cooling water temperature, mass flow rate of steam and the cooling water mass flow rate.

Keywords: Steam condenser; Entropy generation

Nomenclature

A	–	heat transfer area, m^2
c_p	–	specific heat at constant pressure, J/(kg K)
c_w	–	specific heat of water, J/(kg K)
d	–	diameter, m
k	–	overall heat transfer coefficient, W/(m^2 K)

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L	–	length of the steam condenser, m
$\dot{m}$	–	mass flow rate, kg/s
M	–	condenser ratio $\dot{m}_2/\dot{m}_1$
p	–	pressure, Pa
r	–	heat of phase change, J/kg
s	–	specific entropy, J/(kg K)
t	–	temperature, °C
$\bar{t}$	–	mean temperature, °C
$\overline{T}$	–	mean temperature, K
$\dot{Q}$	–	heat flow rate, W

Greek symbols

$\delta t_{\min}$	–	terminal temperature difference, K
ε	–	heat exchanger effectiveness

Subscripts

1	–	hot fluid
2	–	cold fluid
i	–	inlet
o	–	outlet
s	–	saturated conditions
max	–	maximum value

1   Introduction

At steam power plants, condensers are used to liquefy the fluid; slightly subcooled water is obtained from nearly saturated steam. Shell-and-tube condensers are most often used at steam power plants. The cooling water, drawn from a river, a lake or a cooling tower basin, flows through tubes [1–5]. The steam flowing from a turbine condenses on the outer surface of the tubes. Figure 1 shows a condenser diagram with the nomenclature used.
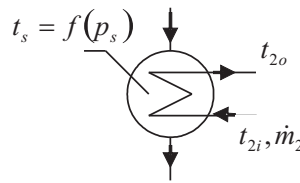

Figure 1: A condenser diagram with the nomenclature used.

Various parameters are used to assess condenser performance, one of commonly employed being heat exchanger effectiveness, defined as the ratio of

the actual to the maximum (theoretical) rate of heat flow which could be transferred [6–9]

$$\varepsilon = \frac{\dot{Q}}{\dot{Q}_{\max}} \ .$$ (1)

Actual heat flow is equal to

$$\dot{Q} = \dot{m}_2 c_{p2}(t_{2o} - t_{2i}) \ .$$ (2)

Maximum heat flow is equal to the heat flow which would be transferred in the steam condenser of an infinitely large heat transfer area ($A = \infty$), which means that the outlet temperature of the cooling water has reached the saturation temperature ($t_{2o} = t_s$). The maximum heat flow is therefore equal to

$$\dot{Q} = \dot{m}_2 c_{p2}(t_s - t_{2i}) \ .$$ (3)

The heat exchanger effectiveness is sometimes called the thermodynamic efficiency of the heat exchanger [10].

For evaluation of the steam condenser performance the terminal temperature difference, which is equal to the difference between the steam saturation temperature and the outlet cooling water temperature, is very often used

$$\delta t_{\min} = t_s - t_{2o} \ .$$ (4)

The terminal temperature difference is also used to determine the degradation of the performance of the steam condenser as a result of fouling on the internal surface of the tubes [3–5,11–17], as well as the inert gases (air) flowing into the condenser through leaks [3-5,14–17].

To assess the performance and optimal working conditions of condensers, the second law of thermodynamics and entropy generation, which follows from it, are utilized. The rate of heat flow transferred in the condenser is significant due to a large phase transition heat of water. The higher the heat flow rate, the higher the increase in entropy in the system. The entropy increase in the condenser is one of the largest across the steam power plant [18].

The authors decided to examine the relations between temperatures of water at the condenser inlet and outlet, and the steam temperature; what are the limits of these temperatures; and what relations are implied by them. For this purpose, the ratio of mean cooling water temperature to the steam temperature was investigated. The connections between entropy generation rate and other parameters of the condenser performance, including its ratio

(the ratio of the cooling water mass flow rate to the steam mass flow rate) and heat exchanger effectiveness, were examined.

Theoretical considerations allowed to determine limits of individual parameters which describe the condenser operation. The results of these analyses can be useful, for example, when it comes to assess the correctness of measurements in power units. If the results of measurements exceed the limits defined in the research, presented in this paper, this may indicate that the measurement system works incorrectly.

In order to obtain the relations and connections between the essential parameters of the condenser, various relations for average cold fluid temperature, calculated from logarithmic mean temperature difference, arithmetic mean and the definition of entropy, were used interchangeably. The various relations for the average cold fluid temperature were compared with each other to justify their interchangeability.

2 Entropy generation in a condenser

The heat flow is driven by weighted average temperature difference between the hot and cold fluids, which can be expressed as a difference between weighted mean temperatures of these fluids

$$\overline{\Delta t} = \overline{t_1} - \overline{t_2} \, . \tag{5}$$

Figure 2 shows an exemplary temperature distribution of both fluids along the heat transfer surface.
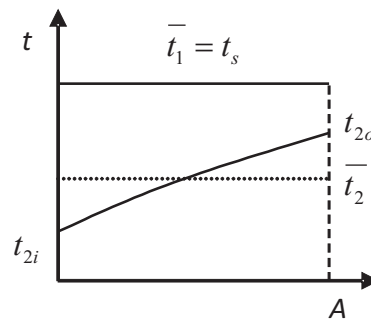

Figure 2: Temperature distribution of both fluids along the heat transfer surface.

For the condenser, the weighted mean temperature difference is equal to

a logarithmic mean temperature difference [7–9,11,12]

$$\overline{\Delta t} = \frac{(t_s - t_{2i}) - (t_s - t_{2o})}{\ln \left(\frac{t_s - t_{2i}}{t_s - t_{2o}} \right)} = \frac{t_{2o} - t_{2i}}{\ln \left(\frac{t_s - t_{2i}}{t_s - t_{2o}} \right)} = \overline{t_1} - \overline{t_2} \ . \tag{6}$$

For temperatures of the fluids inside the condenser, the following relation can be written

$$0 < t_{2i} < t_{2o} < t_s \ . \tag{7}$$

Due to phase transition, the average temperature of hot fluid (steam) is constant and equal to saturation temperature

$$\overline{t_1} = t_s \ . \tag{8}$$

The average cold fluid temperature can be determined by transforming relation (5) as a function of saturation temperature, water inlet temperature, and water outlet temperature

$$\overline{t_2} = t_s - \frac{t_{2o} - t_{2i}}{\ln \left(\frac{t_s - t_{2i}}{t_s - t_{2o}} \right)} \ . \tag{9}$$

The average cold fluid temperature can be replaced, with good approximation, with an arithmetic mean [19,20] of inlet and outlet temperatures

$$\overline{t_2} \approx \frac{t_{2o} + t_{2i}}{2} \ . \tag{10}$$

From relation (6) the following formula can be written using temperatures expressed in Kelvins

$$T_{2o} + T_{2i} < 2T_s \ . \tag{11}$$

Introducing heat flow exchanged in the condenser the above formula can be rearranged to the form

$$-\frac{\dot{Q}}{T_s} + \frac{\dot{Q}}{\frac{T_{2o} + T_{2i}}{2}} > 0 \ . \tag{12}$$

If one takes into account the relations for the rate of heat given off by the steam and the relation for the rate of heat absorbed by the cooling water, relation (12) may be written as

$$-\frac{\dot{m}_1 r}{T_s} + \frac{\dot{m}_2 c_w (T_{2o} - T_{2i})}{\frac{T_{2o} + T_{2i}}{2}} > 0 \ . \tag{13}$$

According to the convention in thermodynamics concerning the sign of the heat flow rate, a negative sign means that the fluid has given off the heat and its energy has decreased; therefore, the steam heat flow in relation (13) has a negative sign. If the rate of heat flow has a positive sign, it means that the fluid has absorbed the heat and its energy has increased; therefore, the water heat flow rate in relation (13) has a positive sign. Relation (13) can be presented taking into account the entropy changes of steam and cooling water.

The entropy change at the phase transition is [19,21–23]

$$\Delta s_1 = -\frac{r}{T_s} \ . \tag{14}$$

The entropy change for water is [19,21–23]

$$\Delta s_2 = c_w \ln\left(\frac{T_{2o}}{T_{2i}}\right) \ . \tag{15}$$

From the second law of thermodynamics, we know that for real processes the sum of increases in entropy in the system should be greater than zero [19,24–28].

$$\dot{m}_1 \, \Delta s_1 + \dot{m}_2 \, \Delta s_2 > 0 \ . \tag{16}$$

By comparing relations (13), (15), and (16) we can conclude that

$$\frac{(T_{2o} - T_{2i})}{\frac{T_{2o}+T_{2i}}{2}} \approx \ln\left(\frac{T_{2o}}{T_{2i}}\right) \ . \tag{17}$$

From the above relation we can get a correlation that allows to estimate the average cold fluid temperature

$$\frac{(T_{2o} - T_{2i})}{\ln\left(\frac{T_{2o}}{T_{2i}}\right)} \approx \overline{T_2} \ . \tag{18}$$

3   Entropy generation in a condenser and its connection with the condenser ratio

From the definition of the change in entropy [19,21–23]

$$ds = \frac{\delta q}{T} \tag{19}$$

an instantaneous temperature of the fluid can be determined:

$$T' = \frac{\delta q}{ds} \, , \tag{20}$$

where δq denotes the infinitesimal heat flow. By formulating relation (20) for the whole process, an average temperature of the fluid can be defined as

$$T = \frac{q}{\Delta s} \, , \tag{21}$$

where Δs deonotes the change of entropy. Generally, the mean fluid temperature as determined from relation (21) differs from the one determined from the arithmetic or logarithmic mean. For fluid phase transition, as is the case with the condensing steam, average temperatures calculated from relation (21) and as the arithmetic mean are equal, since the inlet and outlet temperatures are equal; therefore, they need not be distinguished. Thus, the average temperature of the hot fluid can be expressed as

$$T_s = \overline{T_1} = \frac{r}{|\Delta s_1|} \, . \tag{22}$$

Considering the rate of heat flow, relation (22) can be written as

$$T_s = \overline{T_1} = \frac{\dot{m}_1 \, r}{\dot{m}_1 \, |\Delta s_1|} = \frac{\dot{Q}}{\dot{m}_1 \, |\Delta s_1|} = \frac{kA \left(\overline{T_1} - \overline{T_2} \right)}{\dot{m}_1 \, |\Delta s_1|} \, . \tag{23}$$

For the cold fluid, the mean temperature difference calculated from the definition of entropy (20) slightly differs from the one calculated from the logarithmic relation, because these means are defined in different ways. From the definition of entropy, one can write that the mean cold fluid temperature is equal to

$$\overline{T_2} = \frac{c_w \left(T_{2o} - T_{2i} \right)}{\Delta s_2} = \frac{\left(T_{2o} - T_{2i} \right)}{\ln \left(\frac{T_{2o}}{T_{2i}} \right)} \, . \tag{24}$$

The average cold fluid temperature, as determined from the definition of entropy, is given by relation (17). Taking into account the heat flow rate from relation (24), we obtain [17,18,33–35]

$$\overline{T_2} = \frac{\dot{m}_2 \, c_w \left(T_{2o} - T_{2i} \right)}{\dot{m}_2 \, \Delta s_2} = \frac{\dot{Q}}{\dot{m}_2 \, \Delta s_2} = \frac{kA \left(\overline{T_1} - \overline{T_2} \right)}{\dot{m}_2 \, \Delta s_2} \, . \tag{25}$$

By dividing relations (25) by (23), we obtain

$$\frac{\overline{T_2}}{T_s} = \frac{\dot{m}_1 \, |\Delta s_1|}{\dot{m}_2 \, \Delta s_2} \, . \tag{26}$$

As the ratio of the mean temperatures $\overline{T_2}/T_s$ is smaller than one, it follows that the increase in the entropy rate on the water side is greater than the absolute value of the increase in the entropy rate on the steam side

$$\dot{m}_2 \, \Delta s_2 > \dot{m}_1 \, |\Delta s_1| \; . \tag{27}$$

The same relation can be obtained directly from inequality (16). The above inequality can be rearranged to the form showing the relation between the condenser ratio (defined as the ratio of mass flow rates between the cooling water and steam; in other words, this parameter tells how many kilograms of water account for the condensation of one kilogram of steam during condensation) and the ratio of entropy changes for both fluids

$$M = \frac{\dot{m}_2}{\dot{m}_1} > \frac{|\Delta s_1|}{\Delta s_2} \; . \tag{28}$$

4   Entropy generation in a condenser and its connection with its effectiveness

By definition (1), condenser effectiveness is equal to [6–9]

$$\varepsilon = \frac{T_{2o} - T_{2i}}{T_s - T_{2i}} \; . \tag{29}$$

Considering relation (17), the heat exchanger effectiveness can be given as

$$\varepsilon = \frac{T_{2o} - T_{2i}}{T_s - T_{2i}} \approx \frac{\frac{(T_{2o}+T_{2i})}{2} \ln\left(\frac{T_{2o}}{T_{2i}}\right)}{\frac{(T_s+T_{2i})}{2} \ln\left(\frac{T_s}{T_{2i}}\right)} = \frac{(T_{2o} + T_{2i})}{(T_s + T_{2i})} \frac{\Delta s_2}{\Delta s_{2\,\max}} \; . \tag{30}$$

In the above transformations the relation (17) was introduced into a denominator. In addition, outlet water temperature in Eq. (17) was replaced with saturation temperature of steam. This substitution is justified because the values of these temperatures are very close to each other.

    The temperature ratio is close to one, because the temperatures are expressed in kelvins; therefore, the condenser effectiveness can be, approximately, given as the ratio of the change in the cooling water entropy to the maximum increase in the cooling water entropy

$$\varepsilon \approx \frac{\Delta s_2}{\Delta s_{2\,\max}} \; . \tag{31}$$

The following relation is implied by the condition that the temperature ratio from relation (30) is smaller than one:

$$\varepsilon < \frac{\Delta s_2}{\Delta s_{2\max}} \ . \tag{32}$$

Taking into account the heat exchanger effectiveness expressed by relation (29), the relation (16) can be given as

$$\dot{m}_2 \, c_w \left(1 - \frac{T_{2i}}{T_s}\right) \varepsilon + \dot{m}_2 \, c_w \ln\left[1 + \left(\frac{T_s}{T_{2i}} - 1\right) \varepsilon\right] > 0 \ , \tag{33}$$

where:

$$\dot{m}_1 \, \Delta s_1 = \dot{m}_2 \, c_w \left(1 - \frac{T_{2i}}{T_s}\right) \varepsilon \ , \tag{34}$$

$$\dot{m}_2 \Delta s_2 = \dot{m}_2 \, c_w \ln\left[1 + \left(\frac{T_s}{T_{2i}} - 1\right) \varepsilon\right] \ . \tag{35}$$

Maximum entropy flux increase for water and steam is for the condenser effectiveness equal to 1:

$$\dot{m}_1 \, \Delta s_{1\max} = \dot{m}_2 \, c_w \left(1 - \frac{T_{2i}}{T_s}\right) \ , \tag{36}$$

$$\dot{m}_2 \Delta s_{2\max} = \dot{m}_2 \, c_w \ln\left(\frac{T_s}{T_{2i}}\right) \ . \tag{37}$$

From the comparison of relations (34) and (36), we obtain

$$\varepsilon = \frac{\Delta s_1}{\Delta s_{1\max}} \ . \tag{38}$$

5 Average cold fluid temperature

The average cold fluid temperature can be calculated from relation (8), where the variables are the cooling water temperatures at the inlet and outlet of the heat exchanger, and the steam temperature. As was shown in [19,23], the average cold fluid temperature can be, approximately, replaced with the arithmetic mean of water temperatures at the inlet and outlet of the condenser according to relation (10). Assuming that the average cold fluid temperatures, as calculated from relation (24), which stems from the definition of entropy, and using the logarithmic mean temperature

difference (8), are approximately equal, the average cold fluid temperature can be calculated from relation (18), which contains only the cooling water temperatures at the inlet and outlet of the condenser. Other relations for mean temperature difference, which allow to determine the mean fluid temperature, can be found in [20,29,30].

6   Results of computational analyses – data from a simulator

The proposed relations (18), (27), (28), and (32) terminal temperature difference and steam condenser effectiveness were verified against data obtained from a condenser simulator (developed using a zero-dimensional steady-state model [4,6–9,22]). The simulator was developed on the basis of commonly used correlations for the estimation of overall heat transfer coefficients for water and steam [3,4,7-9,31,32].

The input parameters of the simulator were: water temperature at the inlet of the condenser, cooling water mass flow rate, and steam mass flow rate. The output parameters were: water temperature at the outlet of the condenser, and steam pressure (temperature). The following condenser ratings were assumed: cooling water mass flow rate 7995 kg/s, cooling water temperature 17 °C, steam pressure 4140 Pa, steam temperature 29.56 °C, steam mass flow rate 123 kg/s. By changing the three input parameters, a set of data was obtained for variable operating conditions of the condenser.

Figure 3 shows the variations the rates of entropy increase for water and steam (for steam it is an absolute value of a change in entropy) as calculated using relation (27) and the simulation results. For points 1 to 16 it was the cooling water temperature at the inlet of the condenser that changed: from 10 °C to 25 °C in one-degree increments. For points 17 to 26 it was the steam mass flow rate that changed: from 70 kg/s to 150 kg/s in 10 kg/s increments. For points 27 to 37 it was the cooling water mass flow rate that changed from 6000 kg/s to 10 500 kg/s in 500 kg/s increments.
The data shown in Fig. 3 indicate that the change in the water entropy rate is greater than the change in the steam entropy rate according to relation (27).

Figure 4 shows a comparison between the condenser ratio and the ratio between the increases in steam and water specific entropies, using simulation results.
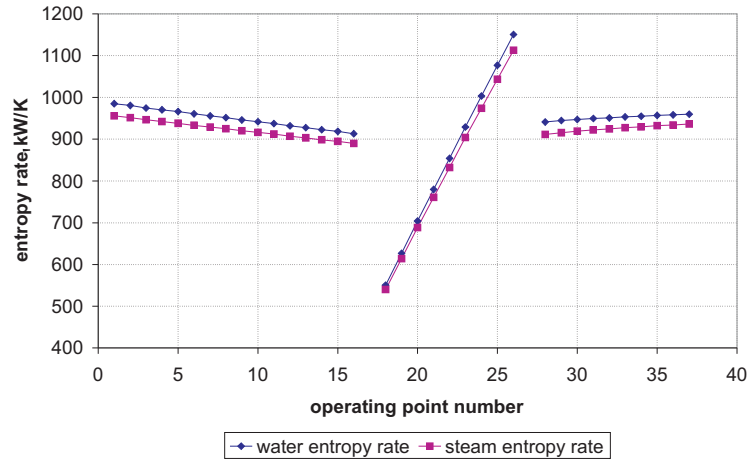
Figure 3: Change in entropy rates of water and steam according to simulation results.
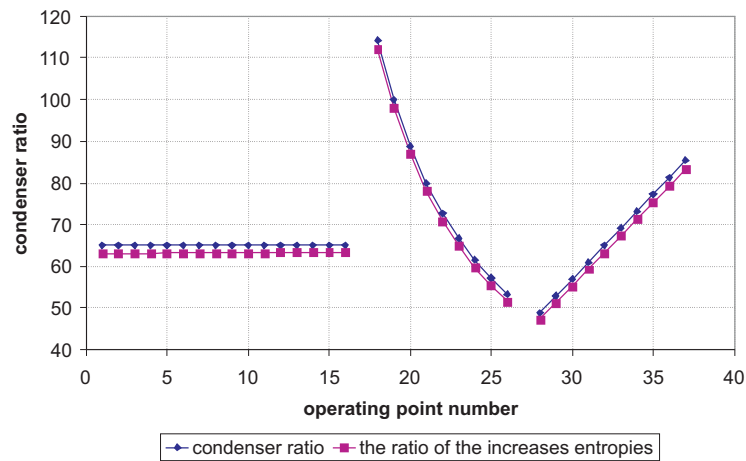

Figure 4: A comparison between the condenser ratio and the ratio between the increases in steam and water entropies, using simulation results.

As can be seen the condenser ratio is approximately equal to the ratio of changes in the steam and water entropies and the relation between them is according to formula (28).

The correctness of relation (32) was verified against the simulation data and presented in Fig. 5. Based on these data it should be noted that the relation (31) gives slightly greater efficiency values, which stems from a simplification employed in relation (30), concerning the temperature ratio,
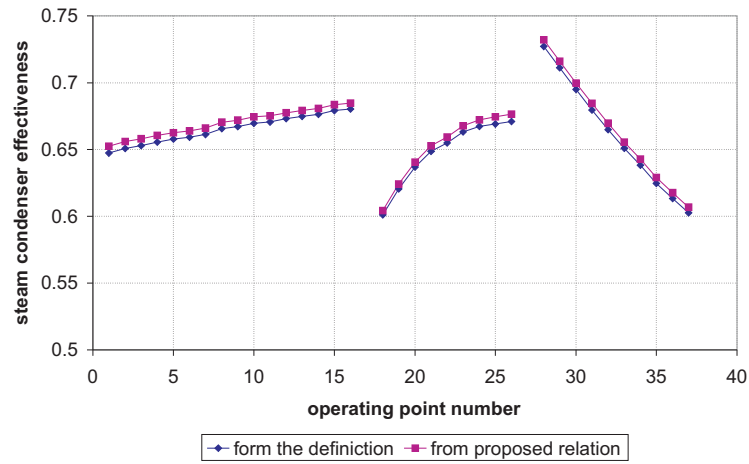
Figure 5: A comparison between the heat exchanger effectiveness as calculated from the definition (1) and from the relation (32), using simulation results.

and is also reflected in relation (32).

Figure 6 shows a comparison of the values of the average cold fluid temperature obtained by three different approaches, i.e., using relations (9), (10), and (18). The analysis was based on data taken form the simulator.
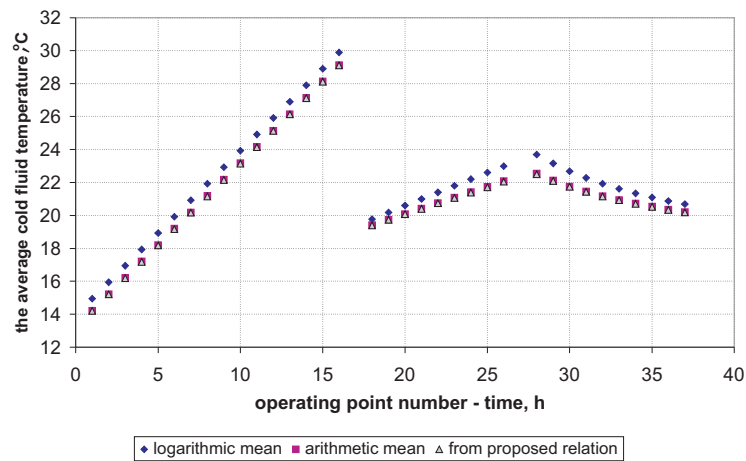

Figure 6: Average cold fluid temperature as calculated from relations (8), (10) and (18), using simulation results.

The data shown indicate that the difference between the logarithmic and arithmetic mean temperature differences is about 2 K. The values of the average cold fluid temperatures as calculated using arithmetic mean (10) and relation (18) practically coincide.

Figures 7–12 show how a change in inlet cooling water temperature, mass flow of steam and cooling water mass flow rate affect the condenser effectiveness, the sum of entropy rates, terminal temperature difference and condenser ratio. The influence of each of the above mentioned parameters is analyzed independently, i.e, two others are set constant.

The influence of the change in inlet cooling water temperature from $10\,°C$ to $25\,°C$ on the condenser effectiveness and the sum of entropy rates is shown in Fig. 7 and on the terminal temperature difference and the condenser ratio in Fig. 8. The mass flow rate of the cooling water and the mass flow rate of steam were constant, equal to the nominal values. The increase
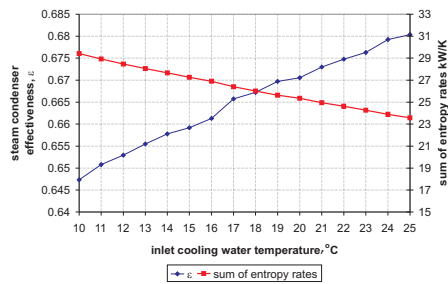

Figure 7: Change in the steam condenser effectiveness and sum of entropy rates as a function of inlet cooling water temperature.
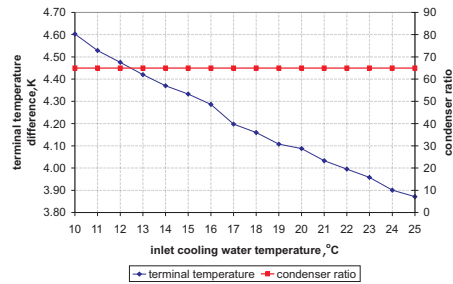
Figure 8: Terminal temperature difference and condenser ratio of the steam condenser as a function of inlet cooling water temperature.

in water temperature at the inlet to the steam condenser causes an increase in the effectiveness, a decrease in the sum of entropy rates and terminal temperature difference.

The influence of the change in the steam mass flow rate from 70 kg/s to 150 kg/s on the steam condenser effectiveness and the sum of entropy rates is shown in Fig. 9, and on the terminal temperature difference and condenser ratio in Fig. 10. The inlet cooling water temperature and the mass flow rate of the cooling water were constant, equal to the nominal values. The increase in the steam mass flow rate causes an increase in steam condenser effectiveness, the sum of entropy rates and the terminal temperature difference. For a constant mass flow rate of cooling water the increase of
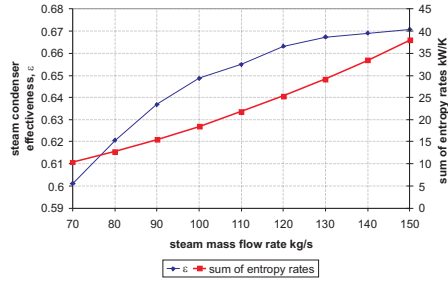
Figure 9: Steam condenser effectiveness and sum of entropy rates as a function of the steam mass flow rate.
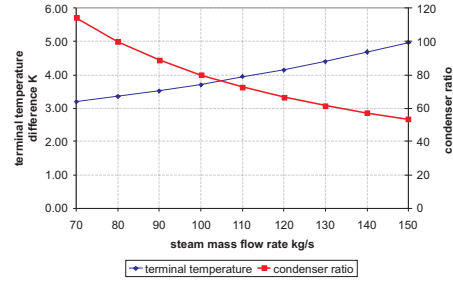

Figure 10: Terminal temperature difference and condenser ratio of the steam condenser as a function of the steam mass flow rate.

steam mass flow rate causes a decrease in the condenser ratio.

The influence of the change in the cooling water mass flow rate from 6000 kg/s to 10 500 kg/s on the steam condenser effectiveness and the sum of entropy rates is shown in Fig. 11, and on the terminal temperature difference and the condenser ratio in Fig. 12. The cooling water temperature and the steam mass flow rate were constant and equal to the nominal values.
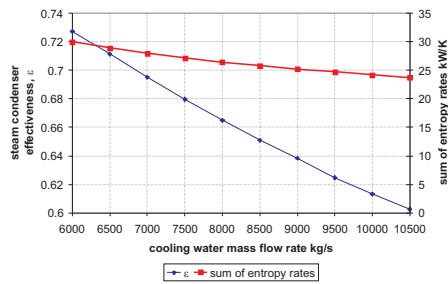

Figure 11: Steam condenser effectiveness and sum of entropy rates as a function of the cooling water mass flow rate.
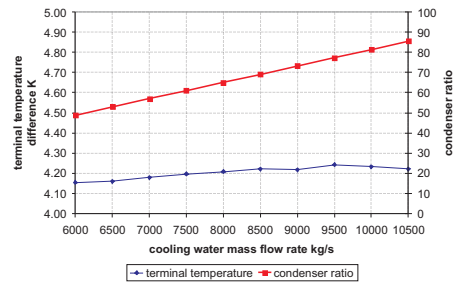

Figure 12: Terminal temperature difference and condenser ratio of the steam condenser as a function of the cooling water mass flow rate.

The increase in the cooling water mass flow rate causes a decrease in the steam condenser effectiveness and the sum of entropy rates and an increase in the terminal temperature difference and a drop in the steam pressure in the condenser. For a constant mass flow rate of steam the increase of mass flow rate of cooling water causes an increase in the condenser ratio.

7 Results of computational analyses – measured data

Proposed relations (18), (27), (28), and (32) and also relations between terminal temperature difference and steam condenser effectiveness were verified against measurement data obtained from one condenser operating in a 200 MW power unit. The condenser was cooled with river water and basic data for the analyzed condenser are shown in Tab. 1.

Table 1: Basic data of the analyzed condenser, type SF 11420 [5].

Description	Symbol	Unit	Value
heat transfer area	A	m^2	2x5710=11420
number of tubes	–	–	2x6878=13756
cooling water mass flow rate	$\dot{m}_2$	Mg/h	2x14500=29000
inlet cooling water temperature	t_{2i}	°C	17
outlet cooling water temperature	t_{2o}	°C	25.7
steam mass flow rate	$\dot{m}_1$	kg/s	122.2
outer diameter of tube	d_o	mm	30
internal diameter of tube	d_i	mm	28
length of the steam condenser	L	mm	9000
average water pressure	P_2	Pa	3
terminal temperature difference	$\delta t_{\min}$	K	5

For the analyzed condenser the following parameters are measured: the inlet and outlet cooling water temperature, the mass flow rate of cooling water and steam pressure. Steam mass flow rate is commonly calculated from the energy balance for the steam condenser.

Figure 13 shows a comparison between changes in water and steam entropy rates based on hourly averaged measurement data. During 39 h of the condenser operation, the input parameters varied within the following ranges: cooling water temperature at the inlet of the condenser from 9.7 °C to 13.5 °C, cooling water mass flow rate from 6594 kg/s to 6827 kg/s, and steam mass flow rate from 76 kg/s to 117 kg/s. The data shown indicate that the change in the water entropy rate is greater than the change in the steam entropy rate according to relation (27).

Figure 14 shows a comparison between the condenser ratio and the ratio between the increases in steam and water entropies, using actual data.
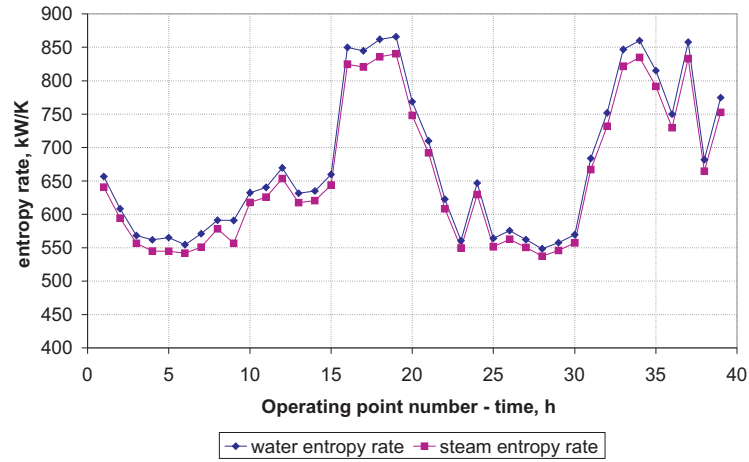
Figure 13: Change in entropy rates of water and steam according to actual data.
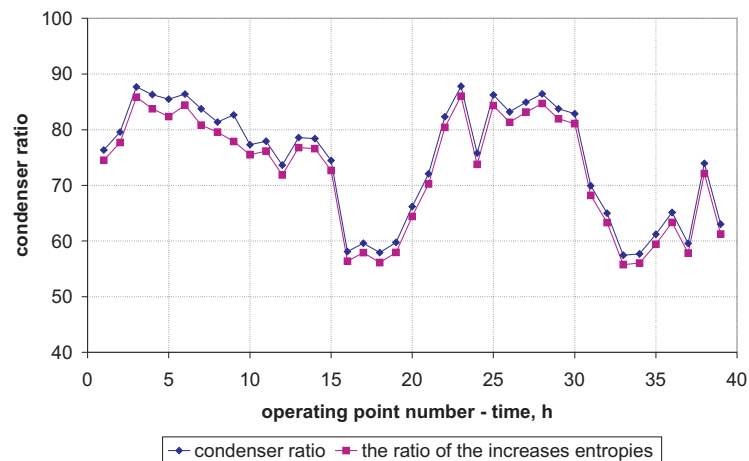

Figure 14: A comparison between the condenser ratio and the ratio between the increases
in steam and water entropies, using actual data.

As can be seen the condenser ratio is approximately equal to the ratio of changes in the steam and water entropies and the relation between them is consistent with the condition laid down by formula (28).

The correctness of relation (32) was verified against the measurement data and the results of analysis are presented in Fig. 15. It should be noted that relation (31) gives slightly greater effectiveness values, which stems from a simplification employed in relation (30), concerning the temperature
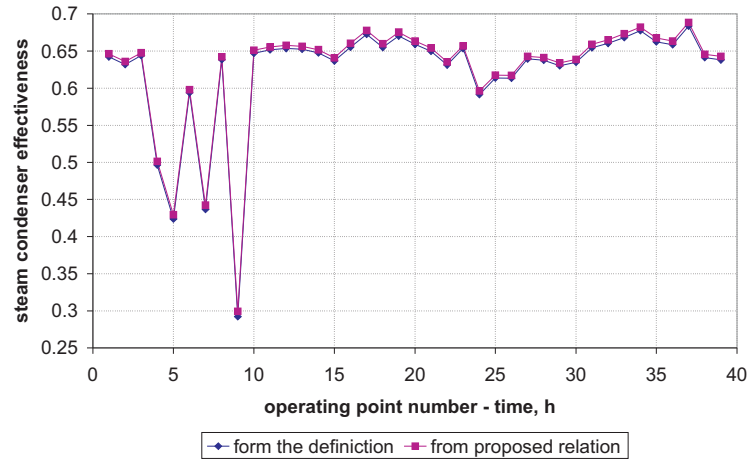
Figure 15: A comparison between the heat exchanger effectiveness as calculated from definition (1) and from relation (32), using actual data.

ratio, and is also reflected in relation (32).

Figure 16 shows a comparison between the three relations (8), (10), and (18) for the average cold fluid temperature, using actual data.
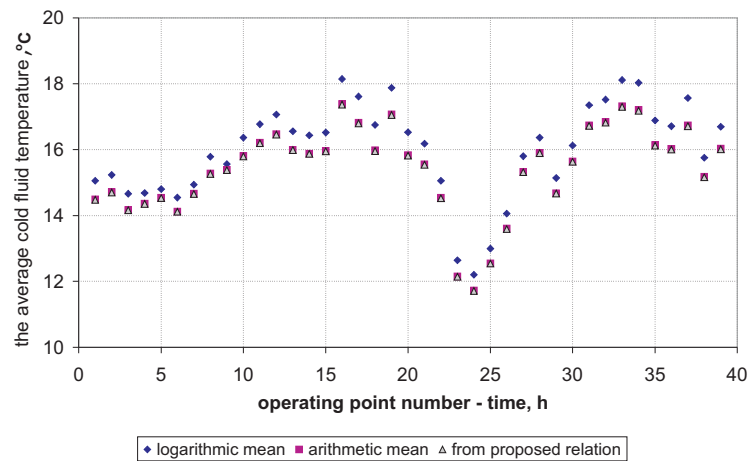

Figure 16: Average cold fluid temperature as calculated from relations (8) – logarithmic mean, (10) – arithmetic mean, and proposed relation (18), using actual data.

The actual data shown in Fig. 16 indicate that for most of the operating points analyzed, the difference between results obtained for the case when the logarithmic and arithmetic means were applied, is smaller than 1 K. The

values of the average cold fluid temperatures as calculated using arithmetic mean (10) and relation (18) practically coincide.

In Fig. 17 the condenser effectiveness and the sum of entropy rates are shown and in Fig. 18 the terminal temperature difference and the condenser ratio are presented for actual data.
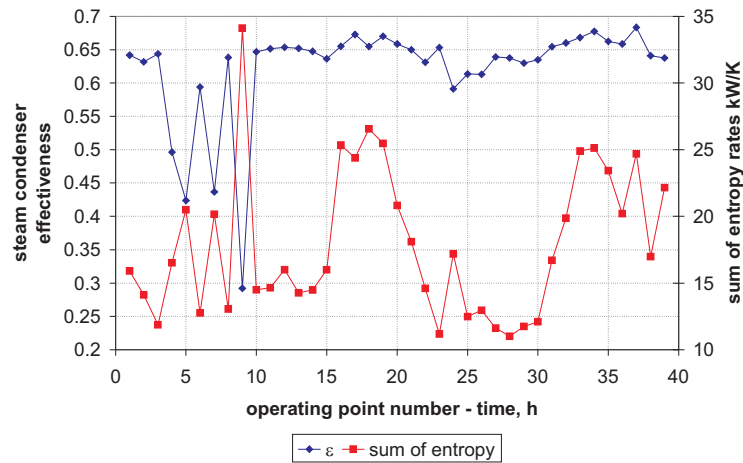

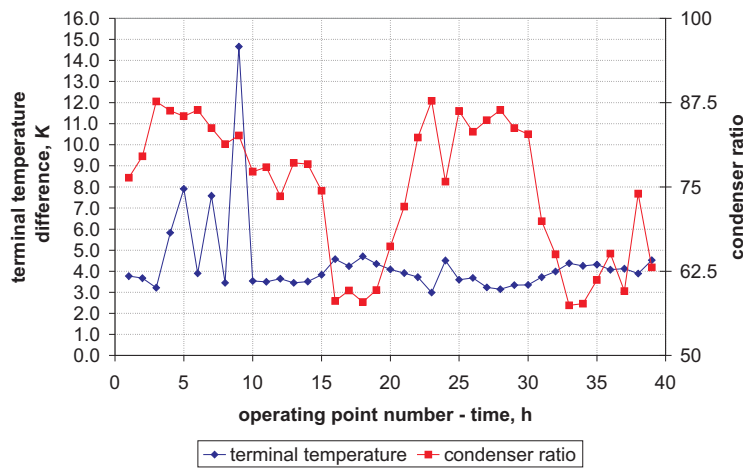Figure 17: The steam condenser effectiveness ε and sum of entropy rates for actual data.

Figure 18: Terminal temperature difference and condenser ratio of the steam condenser for actual data.

   The terminal temperature difference for the analyzed steam condenser should be in the range (3–6) K [3–5]. On the basis of the data presented in Fig. 18 we can see that for the three operating points the terminal temperature difference exceeded the accepted range of change. A significant increase in the terminal temperature difference causes a decrease in the steam condenser effectiveness (Fig. 17). After analyzing the measurement data, it turned out that the increase in the terminal temperature difference is due to incorrect values of steam pressure. Measurement of steam pressure inside the condenser is affected with relatively big error, which is caused by a large space occupied by the steam, local changes in the steam pressure along the heat transfer area, high speed of steam, and the presence of the liquid phase, inert gases, turbulences and stagnation areas of steam [36].

8   Conclusions

The paper presents an analysis of entropy generation for a steam condenser. Relations between the entropy generation and the condenser ratio (33), and between entropy generation and the heat exchanger effectiveness of a condenser (38) are given. From Eq. (6) a known relation for entropy generation for a heat exchanger (16) was derived. On the basis of the derivation the relation (18) for average cold fluid temperature was obtained. An analysis was performed to find out how differently calculated average cold fluid temperatures affect the results obtained from calculations of changes in entropies of fluids in the condenser, and its effectiveness. The logarithmic mean temperature difference Eq. (9), arithmetic mean Eq. (10), and average temperature determined from relations stemming from the definition of entropy Eq. (18) are compared. It was shown that, with good enough accuracy, the differently defined average cold fluid temperatures, Eqs. (9), (10), and (18) for the condenser can be used interchangeably.

   All the proposed correlations and relations between them were verified against data obtained from a condenser simulator and measurement data of a condenser operating in a 200 MW power unit, cooled with a river water in an open-cycle system. The verification confirmed the validity of all proposed relations.

   Based on data from a condenser simulator it was analyzed how a change in the inlet cooling water temperature, cooling mass flow rate and the steam mass flow rate affects the sum of entropy rates, steam condenser effectiveness, terminal temperature difference, and the condenser ratio.

The steam condenser effectiveness, sum of the entropy rates, terminal temperature difference and the condenser ratio were analyzed based on actual data. The terminal temperature difference turned out to be a very good parameter to assess the reliability of measurements. For three operating points the terminal temperature difference exceeded the allowed temperature range due to incorrect values of steam pressure. Incorrect values of the steam pressure caused a decrease in the steam condenser effectiveness below the level of 0.5. Both the terminal temperature difference and the steam condenser effectiveness are good parameters that can be used to assess the reliability of the actual data. If the terminal temperature difference exceeds the established range, e.g., 3–6 K, or if the steam condenser effectiveness falls below 0.5, it may indicate that the measuring system of the steam condenser is not working properly.

Incorrect values of steam pressure were detected because the terminal temperature difference and the steam condenser effectiveness exceeded their ranges of change. Nevertheless, the proposed relations are met, and based on them it is very difficult to eliminate incorrect measurement data. This is due to the fact that the mass flow rate of steam was not measured but calculated from the energy balance of the steam condenser.

The sums of the entropy rates for the data from the simulator and the actual data have similar values to those presented in [37].

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