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THE POWER OF COOLERS OPERATING INDIRECTLY IN UNSTEADY STATES

MOC CHŁODNIC POWIETRZA O DZIAŁANIU POŚREDNIM W STANACH NIEUSTALONYCH

This article examines and discusses unsteady states of mining surface air coolers operating indirectly. Coolers working both with and against the flow-direction are evaluated with a special emphasis on their thermal power. Two components were distinguished in the total power of the cooler (N_c): cooling power (N_{cs}) related to the temperature reduction of the air which is being cooled and its drying power (N_{cw}) resulting from the condensation of water from the air being cooled.

This work is based on the equations of a mathematical model of air-cooling using the coolers mentioned above, which are presented alongside mathematical derivations from previous articles. To illustrate the work of the coolers under discussion the results of typical calculations are appended in the form of time-based graphs $N_c(\tau)$, $N_{cs}(\tau)$ and $N_{cw}(\tau)$, where τ — time.

Two situations were taken into consideration: a slow exponential fall in the temperature of the cooling water at the entry to a cooler and a sudden change in this temperature. The results obtained verify both the time-variable of the power of a cooler in conditions similar to its normal work and the influence of the dynamics of a cooler itself on the change of its power on a time-scale, which can be linked e.g. to the notion of the dynamic identification of a cooler as a component of an automatic control system.

Key words: mining aerology, air-conditioning of mines, surface coolers, power of air coolers

W artykule zajęto się zagadnieniem nieustalonych zmian mocy przeponowych chłodnic powietrza o działaniu pośrednim. Rozważono współprądową oraz przeciwprądową ich pracę. W całkowitej mocy cieplnej takich chłodnic wyodrębniono moc ochładzania, związaną ze zmianą na sposób jawny entalpii powietrza suchego i pary wodnej, oraz moc osuszania powietrza, związaną z procesem kondensacji pary wodnej zawartej w chłodzonym powietrzu. Sposób wyznaczania każdej z tych mocy na podstawie parametrów termodynamicznych powietrza przed i po schłodzeniu przedstawiono w postaci wzorów (13)—(15). W oparciu o podane we wcześniejszych pracach równania, stanowiące modele matematyczne opisujące proces chłodzenia powietrza chłodnicami rozważanego typu, wykonano numeryczne obliczenia ich całkowitej mocy chłodniczej, mocy ochładzania i mocy osuszania. Wyniki obliczeń podano w formie graficznej na ośmiu wykresach pogrupowanych w dwa rysunki. W obliczeniach

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rozróżniono nie tylko współprądową i przeciwprądową pracę chłodnic wspomnianego typu, lecz również dla określonego charakteru pracy chłodnicy rozróżniono rodzaj wymuszenia, którym było powolne — z określoną stałą czasową, lub natychmiastowe — w postaci funkcji Heaviside'a obniżenie temperatury wody chłodzącej na wlocie chłodnicy. Dodatkowo rozważono przypadki mniej i bardziej intensywnego ochładzania powietrza, w postaci dwóch różnych wartości natężenia przepływu zimnej wody. Na podstawie otrzymanych rezultatów obliczeń sformułowano wynikające z nich wnioski.

Słowa kluczowe: aerologia górnicza, klimatyzacja kopalń, chłodnice przeponowe, moc chłodnic powietrza

1. Introduction

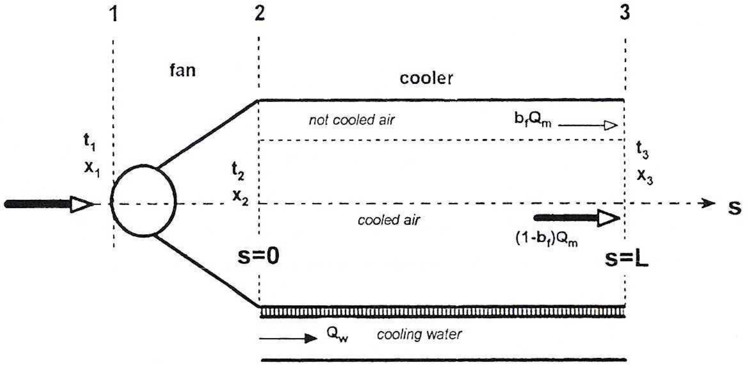
Surface air coolers operating indirectly are used in underground mining to reduce thermal hazard. They are characterised by the existence of a medium between a heat exchanger in a cooler itself and a heat exchanger in a refrigerating unit. In the coolers considered the medium is pre-cooled water, which, whilst flowing through the pipes of a heat exchanger cools the air flowing round this exchanger externally. There are two physical arrangements: co-current and counter-current, depending on the direction of the flow of cooling water in relation to the direction of air flow.

The temperature of the cooling water flowing into a cooler under normal conditions falls gradually, in an approximately exponential manner, with time constant (T) depending on the work of a refrigerating unit and pipes connecting it with the cooler. On the basis of some previous measurements (Dziurzyński et al. 1999; Filek et al. 1999a; Holesz 1997) T is a few minutes in duration.

The steady value of the total power of a cooler depends on flow rate intensity and intake temperatures of the media exchanging heat, that is air and water. However the way of obtaining this established value, that is the shape of a change of power in time, is determined, for a steady state of air at the entry to a cooler, by a time-constant of the fall in the temperature of cooling water. At time-constant T, equal to a few minutes as mentioned above, the inertial character of a cooler is too small for the changes, introduced by it to initial values such as the temperature of cooled air or the power of a cooler, to be observed. Conversely, the change in power as a reaction of a piece of equipment to the change in the temperature of cooled water flowing into it, is not instantaneous. The reaction of a cooler to a sudden change in the temperature of water can be of great interest when considering some problems e.g. its use in an automatic control system. Therefore this article also considers this problem.

A fan installed at the entry to a cooler forces air flow through a cooler of length L. The schematic connection of these two pieces of equipment is presented in Figs. 1a and 1b (a — a co-current cooler, b — a counter-current cooler). The directions of flow of air and water, axis of co-ordinate "s" running along a cooler in accordance with the direction of air flow and also three characteristic cross-sections of a fan/cooler set: cross-section "1" at the entry to a fan, cross-section "2" at the entry to a cooler and cross-section "3" at its outlet are shown diagramatically; b_f signifies the cooler by-pass factor. The meaning of all the other symbols is explained below.

a.



b.

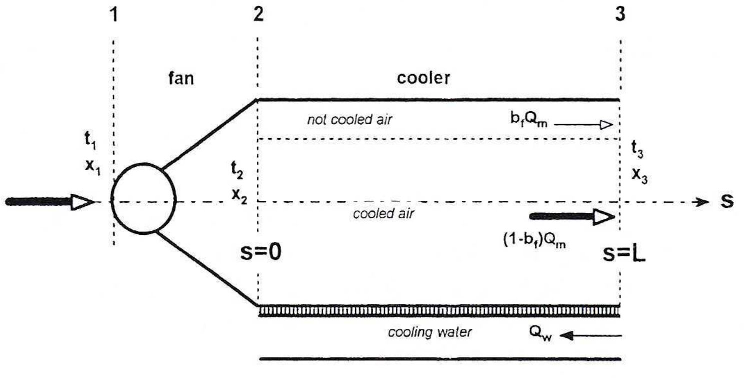


Fig. 1. Scheme of the flow of cooled air and cooling water through
a — a co-current; b — a counter-current cooler

Rys. 1. Schemat przepływu chłodzonego powietrza i wody chłodzącej przez chłodnicę
a — współprądową; b — przeciwprądową

2. Thermal power of an air cooler

Thermal power (cooling power) is one of the most important parameters characterising a cooler. The producers of coolers provide technical information about their performance complying with a standard of steady state operation; however, it must be remembered that these are nominal values, true only for specific values of parameters of cooled air and cooling water. Actual power, related to the energy exchanged between air and water, can be much smaller or greater than nominal power.

The total power of a cooler is equal to the difference, per time unit, in the enthalpy of air at the entry to a cooler and the total of enthalpy of air at its outlet and the enthalpy of water condensed from the air.

$$N_c = H_2 - (H_3 + H_w) \tag{1}$$

where:

- N_c — total thermal power of a cooler [W],
- H_2 — enthalpy of air flowing into a cooler per time unit [W],
- H_3 — enthalpy of air flowing out of a cooler per time unit [W],
- H_w — enthalpy of water condensed from the air per unit time [W].

However (Frycz 1981; Roszczynialski et al. 1992)

$$H_2 = Q_m h_2 = Q_m (c_p t_2 + c_w t_2 x_2 + r_p x_2) \tag{2}$$

$$H_3 = Q_m h_3 = Q_m (c_p t_3 + c_w t_3 x_3 + r_p x_3) \tag{3}$$

and assuming that the temperature of the condensed water is equal to the temperature of the cooled air:

$$H_w = Q_m h_w = Q_m c_c t_3 (x_2 - x_3) \tag{4}$$

where:

- Q_m — mass rate of air flow through a cooler (related to dry air) [kg/s],
- h_2 — specific enthalpy of air at the entry to a cooler [J/kg],
- h_3 — specific enthalpy of air at the outlet from a cooler [J/kg],
- h_w — enthalpy of water condensed from air per unit of air mass [J/kg],
- t_2 — temperature of air at the entry to a cooler [°C],
- t_3 — temperature of air at the outlet from a cooler [°C],
- x_2 — specific humidity of air at the entry to a cooler [kg of water vapour/ kg of dry air],
- x_3 — specific humidity of air at the outlet from a cooler [kg of water vapour/ kg of dry air],
- c_c — specific heat of water [J/(kgK)],
- c_p — specific heat of air at constant pressure [J/(kgK)],
- c_w — specific heat of water vapour at constant pressure [J/(kgK)].

By means of replacements, formula (1) can be transformed into the following form:

$$N_c = Q_m [c_p (t_2 - t_3) + c_w (t_2 x_2 - t_3 x_3)] + Q_m (r_p - c_c t_3)(x_2 - x_3) \tag{5}$$

The first component on the right side is a unit enthalpy of air exchanged openly; the change in enthalpy of dry air and in enthalpy of water vapour can be distinguished. This component is called here *the power of cooling of air* and is denoted as as N_{cs}. However, the second component is related to the process of condensation of water vapour contained in cooled air. It consists of a latent change in the enthalpy of vapour changing itself into a liquid state and of open enthalpy of water resulting from this process. This component is called *the power of drying of air* and signified as N_{cw}. Therefore:

$$N_c = N_{cs} + N_{cw} \tag{6}$$

$$N_c = Q_m [c_p(t_2 - t_3) + c_w(t_2 x_2 - t_3 x_3)] \tag{7}$$

$$N_{cw} = Q_m (r_p - c_c t_3)(x_2 - x_3) \tag{8}$$

For unsteady states equation (5) can be expressed in the following way:

$$\begin{aligned} N_c(\tau) = Q_m(\tau)\big[c_p[t_2(\tau) - t_3(\tau)] + c_w[t_2(\tau)x_2(\tau) - t_3(\tau)x_3(\tau)]\big] + \\ + Q_m(\tau)[r_p - c_c t_3(\tau)][x_2(\tau) - x_3(\tau)] \end{aligned} \tag{9}$$

where:

τ — time [s].

In the further part of this work it is assumed that both the state of air at the entry to a cooler (in cross-section 2) and its flow rate are known and do not change in time, which can be expressed in the following way where:

$$Q_m = \text{const.} \tag{10}$$

$$t_2 = \text{const.} \tag{11}$$

$$x_2 = \text{const.} \tag{12}$$

Then dependencies (5), (7) and (8) can be expressed in the following form:

$$\begin{aligned} N_c(\tau) = Q_m\big[c_p[t_2 - t_3(\tau)] + c_w[t_2 x_2 - t_3(\tau)x_3(\tau)]\big] + \\ + Q_m[r_p - c_c t_3(\tau)][x_2 - x_3(\tau)] \end{aligned} \tag{13}$$

$$N_{cs}(\tau) = Q_m\big[c_p[t_2 - t_3(\tau)] + c_w[t_2 x_2 - t_3(\tau)x_3(\tau)]\big] \tag{14}$$

$$N_{cw}(\tau) = Q_m[r_p - c_c t_3(\tau)][x_2 - x_3(\tau)] \tag{15}$$

Time-variable parameters of cooled air i.e. its temperature $t_3(\tau)$ and proper humidity $x_3(\tau)$, present in the dependencies above, can be obtained from equations of the mathematical model presented in many previous works (Filek et al. 1999a, b; Filek, Nowak 2000). Therefore this work does not present this model.

3. Time patterns of the power of a cooler during an exponential slow fall in the inflow temperature of cooling water

On the basis of measurements conducted in mining conditions (Holesz 1997) it can be concluded that from the moment an air-conditioning unit is switched on, the temperature of cooling water flowing into a cooler falls according to an exponential dependence (Fig. 2).

$$t_w(\tau) = (t_{w0} - t_{wu})e^{-\frac{\tau}{T}} + t_{wu} \tag{16}$$

where:

- t_{w0} — temperature of cooling water at the entry to a cooler at initial instant ($\tau = 0$) [°C],
- t_{wu} — temperature of cooling water at the entry to a cooler for a steady state ($\tau \to \infty$) [°C],
- T — time constant of exponential reaching of the temperature of water at the entry to a cooler [s],
- τ — time [s].

Equation (16) refers to cross-section 2 (Fig. 1) in the case of a co-current cooler and to cross-section 3 in the case of a counter-current cooler.

Four examples (1–4) were solved using computer programmes based on mathematical models in order to illustrate time changes in the power of a cooler for the case of

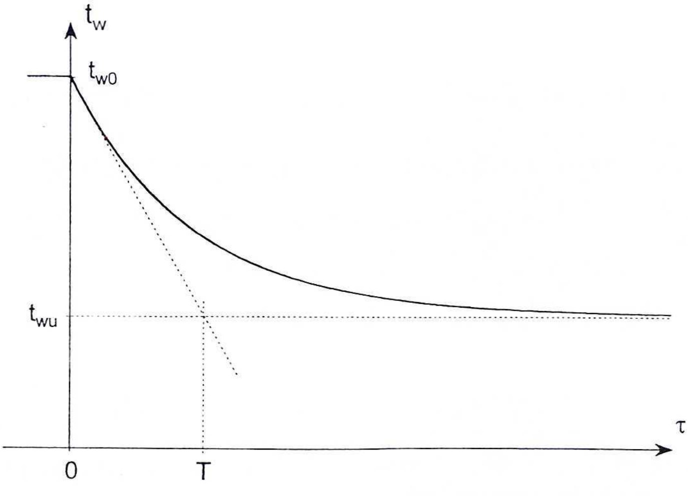


Fig. 2. Time pattern of the temperature of cooling water at the entry to a cooler during its exponential fall from value t_{w0} to t_{wu}

Rys. 2. Czasowy przebieg temperatury wody chłodzącej na wlocie chłodnicy przy jej wykładniczym opadaniu od wartości t_{w0} do t_{wu}

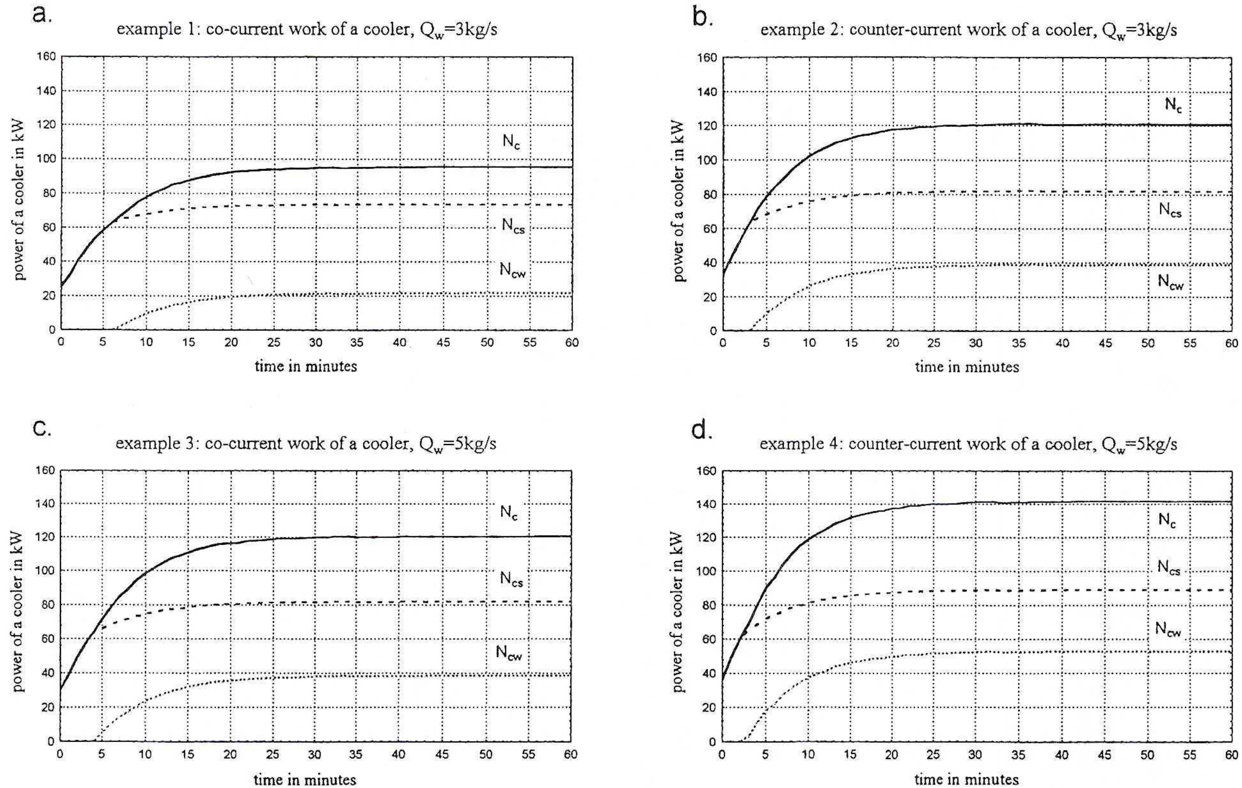


Fig. 3. Power of a cooler in the case of an exponential fall in the inflow temperature of cooling water at time constant $T = 360$ s from value $t_{w0} = 24°C$ to $t_{wu} = 12°C$

a — co-current work of a cooler, quantity of cooling water $Q_w = 3$ kg/s; b — counter-current work of a cooler, quantity of cooling water $Q_w = 3$ kg/s; c — co-current work of a cooler, quantity of cooling water $Q_w = 5$ kg/s; d — counter-current work of a cooler, quantity of cooling water $Q_w = 5$ kg/s

Rys. 3. Moc chłodnicy w przypadku wykładniczego opadania wlotowej temperatury wody chłodzącej ze stałą czasową $T = 360$ s od wartości $t_{w0} = 24°C$ do $t_{wu} = 12°C$

a — współprądowa praca chłodnicy, wydatek wody chłodzącej $Q_w = 3$ kg/s; b — przeciwprądowa praca chłodnicy, wydatek wody chłodzącej $Q_w = 3$ kg/s; c — współprądowa praca chłodnicy, wydatek wody chłodzącej $Q_w = 5$ kg/s; d — przeciwprądowa praca chłodnicy, wydatek wody chłodzącej $Q_w = 5$ kg/s such an exponential fall in the temperature of the cooling water. Each example refers to a cooler of type GCCP-115 and the following numerical data:

- absolute pressure of air at the entry to a fan b = 105 kPa,
- mass flow rate of cooled air (with reference to dry air) Q_m = 10 kg/s,
- temperature of air at the entry to a fan t_1 = 27°C,
- increase in temperature of air in a fan Δt_{went} = 2°C,
- specific humidity of air at the entry to a fan x_1 = 16 g of water vapour/kg of dry air,
- temperature of cooling water at the entry cross-section of a cooler in an initial instant t_{w0} = 24°C,
- temperature of cooling water at the entry cross-section of a cooler in a steady state t_{wu} = 12°C,
- time constant of entry temperature of water T = 360 s.

The differences in the remaining data from particular examples are presented below:

- example 1 — co-current work of a cooler, quantity of cooling water Q_w = 3 kg/s,
- example 2 — counter-current work of a cooler, quantity of cooling water Q_w = 3 kg/s,
- example 3 — co-current work of a cooler, quantity of cooling water Q_w = 5 kg/s,
- example 4 — counter-current work of a cooler, quantity of cooling water Q_w = 5 kg/s.

The results are presented in the form of time patterns of the power of a cooler (total power N_c, cooling power N_{cs} and drying power N_{cw}) in Fig. 3.

4. Time patterns of the power of a cooler during a sudden fall in the inflow temperature of cooling water

Delivery of water, whose temperature changes abruptly according to formula (17), to the entry gives information on the dynamics of a cooler, without the interference of other factors e.g. time course $t_w(\tau)$. Such a change in the temperature of the water can be expressed in the following form:

$$t_w(\tau) = t_{w0} - (t_{w0} - t_{wu}) \cdot 1(\tau) \tag{17}$$

where $1(\tau)$ signifies Heaviside's unit function and t_{w0} and t_{wu} — the initial and final temperature of the water. Pattern (17) is presented in Fig. 4. Equation (17), like equation (16), refers to the cross-section of a cooler where the cooling water enters: cross-section 2 for a co-current cooler and cross-section 3 for a counter-current one.

Analogically to the previous examples, 4 examples (5–8) referring to a sudden change in the temperature of the water flowing into a cooler were solved. The same order as in the case of examples 1–4 was retained. Therefore:

- example 5 — co-current work of a cooler, quantity of cooling water Q_w = 3 kg/s,
- example 6 — counter-current work of a cooler, quantity of cooling water Q_w = 3 kg/s,
- example 7 — co-current work of a cooler, quantity of cooling water Q_w = 5 kg/s,

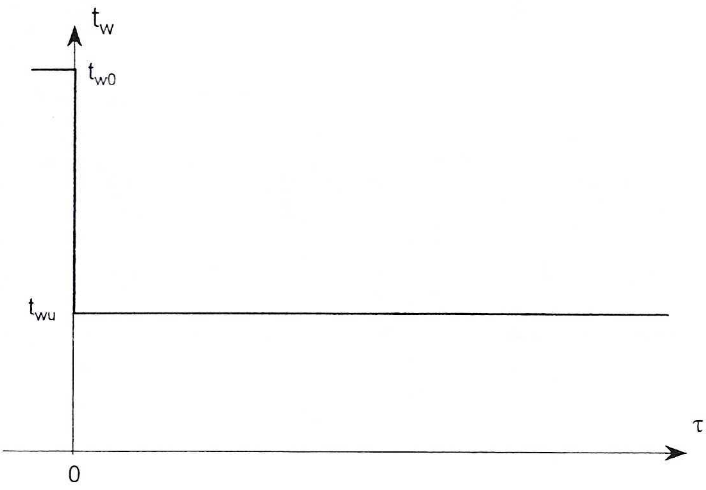


Fig. 4. Time pattern of the temperature of cooling water at the entry to a cooler during its jump fall from value t_{w0} to t_{wu}

Rys. 4. Czasowy przebieg temperatury wody chłodzącej na wlocie chłodnicy przy jej skokowym spadku od wartości t_{w0} do t_{wu}

- example 8 — counter-current work of a cooler, quantity of cooling water $Q_w = 5$ kg/s.

The results are also presented in the form of time patterns of power N_c, N_{cs} and N_{cw} (Fig. 5), in the order analogical to the previous one. In comparison with Fig. 3 only the time scale was changed because of much quicker processes during sudden changes in the temperature of the water.

5. Conclusions

The following conclusions can be drawn on the basis of the observation of curves presented in Figs. 3a–d and 5a–d.

The increase in power, of both a co- and counter-current cooler in time principally determines the character of changes in the temperature of the cooling water flowing into a cooler. The time-patterns of power N_c, N_{cs} and N_{cw} are similar to exponential ones (inertia of order I) with time constant only slightly greater than the time constant of changes in the temperature of the cooling water. In curve $N_c(\tau)$ in Fig. 3a an inflexion in the initial part, suggesting inertia higher than of the first order, can be observed, but this effect is very weak. Therefore it can be assumed that during slow exponential fall in the temperature of cooling water flowing into a cooler the power of the cooler also increases exponentially with an approximate time constant. Steady values for the power of drying of air N_{cw} are closely related to the steady value for total power N_c and they constitute the

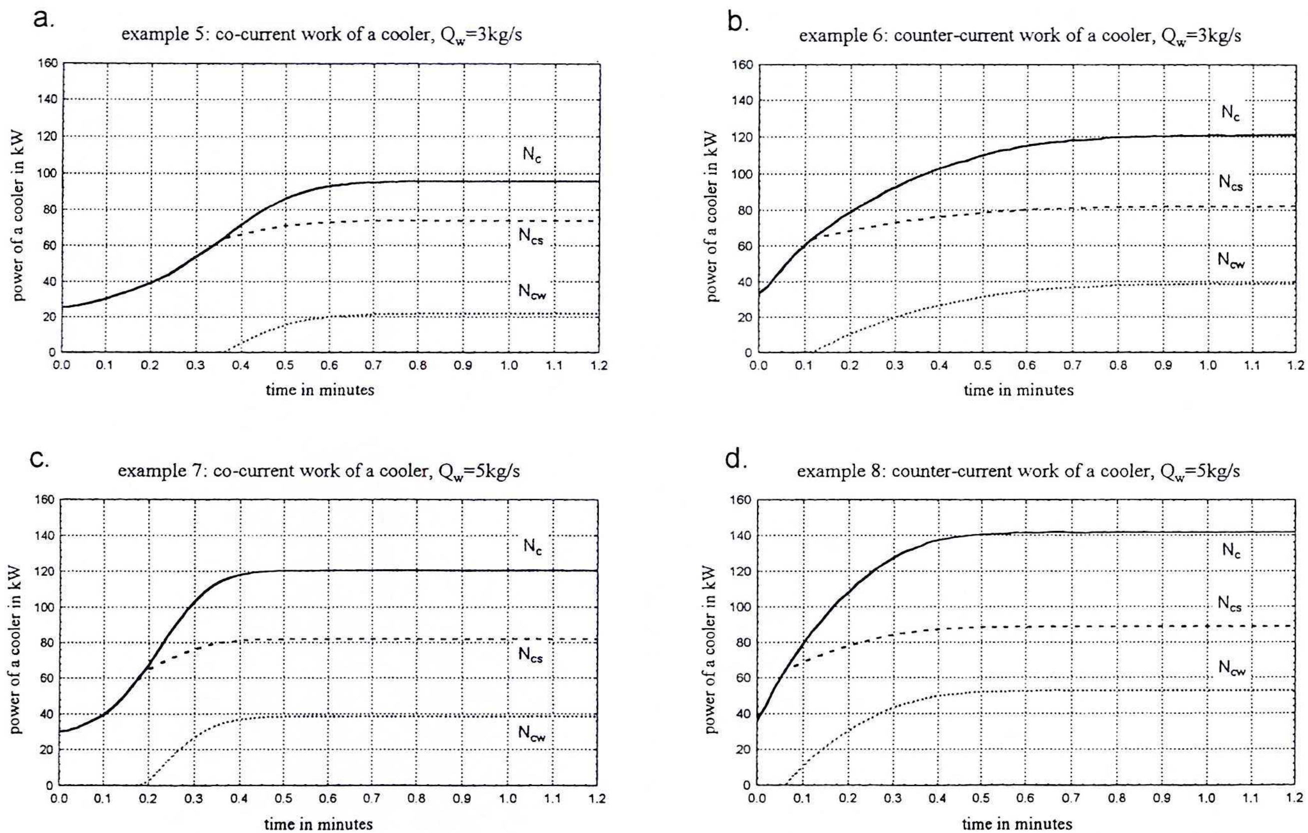


Fig. 5. Power of a cooler in the case of a sudden fall in the inflow temperature of cooling water from value t_{w0} = 24°C to t_{wu} = 12°C
a — co-current work of a cooler, quantity of cooling water Q_w = 3 kg/s; b — counter-current work of a cooler, quantity of cooling water Q_w = 3 kg/s; c — co-current work of a cooler, quantity of cooling water Q_w = 5 kg/s; d — counter-current work of a cooler, quantity of cooling water Q_w = 5 kg/s

Rys. 5. Moc chłodnicy w przypadku skokowego spadku wlotowej temperatury wody chłodzącej od wartości, t_{w0} = 24°C do t_{wu} = 12°C
a — współprądowa praca chłodnicy, wydatek wody chłodzącej Q_w = 3 kg/s; b — przeciwprądowa praca chłodnicy, wydatek wody chłodzącej Q_w = 3 kg/s; c — współprądowa praca chłodnicy, wydatek wody chłodzącej Q_w = 5 kg/s; d — przeciwprądowa praca chłodnicy, wydatek wody chłodzącej Q_w = 5 kg/s

greater part of power the greater the power is. Quantitative dependencies for the cases examined can be expressed in the following form:

- example 1 (Fig. 3a):

$$N_c(\tau \to \infty) = 95.81\ \text{kW} \qquad N_{cw}(\tau \to \infty) = 21.90\ \text{kW}$$

$$\frac{N_{cw}(\tau \to \infty)}{N_c(\tau \to \infty)} = 22.9\%$$

- example 2 (Fig. 3b):

$$N_c(\tau \to \infty) = 120.92\ \text{kW} \qquad N_{cw}(\tau \to \infty) = 38.84\ \text{kW}$$

$$\frac{N_{cw}(\tau \to \infty)}{N_c(\tau \to \infty)} = 32.1\%$$

- example 3 (Fig. 3c):

$$N_c(\tau \to \infty) = 120.52\ \text{kW} \qquad N_{cw}(\tau \to \infty) = 38.57\ \text{kW}$$

$$\frac{N_{cw}(\tau \to \infty)}{N_c(\tau \to \infty)} = 32.0\%$$

- example 4 (Fig. 3d):

$$N_c(\tau \to \infty) = 141.89\ \text{kW} \qquad N_{cw}(\tau \to \infty) = 52.81\ \text{kW}$$

$$\frac{N_{cw}(\tau \to \infty)}{N_c(\tau \to \infty)} = 37.2\%$$

Great consistency between the values of power obtained in examples 2 and 3 is well-worth mentioning. It means that for a steady state the participation of the drying power in the total power (for the same remaining data given earlier) does not depend on the method of obtaining these values — either if counter-current directions of water and air flow were preserved during a lower flow of water (example 2) or if the flow of cooling water was increased for co-current work of a cooler (example 3).

In the case of a sudden fall in the inflow temperature of the cooling water (examples 5–8) the steady values both for the total power of a cooler N_c, N_{cs} and N_{cw} are the same as for an exponential fall in temperature (examples 1–4). The total power of a counter-current cooler reaches a steady state in the way comparable to inertia of order I while a time constant of this pattern amounts to several seconds. However the time course of the total power of a co-current cooler has the distinct characteristics of inertia of at least order II. The time during which a co-current cooler reaches the value determined is very close to the time during which a counter-current cooler reaches this value in analogical cases. In the cases examined the time ranges from 30 to 50 seconds.

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