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ESTIMATION OF THE EFFICIENCY OF PARTIAL CASE OF HEAT AND MASS TRANSFER PROCESSES BETWEEN HEAT PUMPS AND MOVING SUBSTANCE. PART 4

A theoretical model is presented for estimating the efficiency of a partial case of processes in which there is thermal contact of a moving substance (or at least part of this moving substance) with the heat-absorbing and heat-releasing heat-exchange parts of at least two heat pumps for the case of heating the moving substance in its input flow by all individual heat pumps. Mathematical expressions for the corresponding estimation calculations and examples of the results of such calculations are presented.
Key words: heat pump, moving substance, heat and mass transfer, efficiency, energy efficiency, thermoelectric heat pump, thermoelements.

Introduction

This work (part 4) is a continuation of the previous works [1, 2, 3] (parts 1 – 3). In this part 4 we will use the notations, abbreviations (in particular, word combinations) and acronyms that were introduced in [1, 2, 3], in the same meaning as in [1, 2, 3]. In [3], mathematical expressions were obtained to assess the efficiency of the investigated heat and mass transfer method and examples of corresponding calculations were given for the case of cooling the MS in its input flow by all individual THPs, provided that $T_{1.n}^{PP} = T_{2.n}^{PP}$ according to Fig. 2 [1] (the case of heating the MS in its input flow by all individual THPs is not considered in [3]).

The purpose of this work is to create theoretical prerequisites for an approximate quantitative estimation of the efficiency (primarily energy efficiency) of the *investigated heat and mass transfer method* [1 – 6] using THPs, which can operate in different modes, for the case of heating of the MS in its input flow by all individual THPs according to Fig. 3 [1].

To achieve this goal, the *objectives of this work* are to create an estimation model, obtain mathematical expressions for estimation calculations and obtain examples of corresponding calculations for the case of heating the MS in its input flow by all individual THPs according to Fig. 3 [1], in particular, for the case when $T_{1.n}^{PP} \neq T_{2.n}^{PP}$.

Description of estimation model and equations for estimation calculations

Let us consider the following example of the *investigated processes*. Consider processes involving a MS and at least one THP (all HPs used in these processes are THPs based on thermoelements [7]), in which, according to Fig. 3 [1], the MS in its input flow is heated by all the THPs taken separately. Let the useful effect of these processes be to maintain the temperature difference of the MS in its input flow between positions 1.0 and 1.n according to Fig. 3 [1] (for some inlet temperature of MS in position 1.0). This useful action is carried out due to the total electrical power consumed by all THPs W^{TTH} (and more directly due to the total heat output of all THPs Q^{TTH}_{hot}). In this work (part 4), we will not take into account the energy consumption for creating the MS flow.

Let us consider the *i*-th THP separately.

We use the well-known ratio to determine the heating coefficient μ_i^{TE} of the thermoelements of the *i*-th THP [18]:

$$\mu_i^{TE} = \frac{Q_{hot,i}^{TE}}{W_i^{TE}}, \tag{4.1}$$

where

$$Q_{hot,i}^{TE} = \alpha_i I_i T_{hot,i}^{TE} + \frac{1}{2} I_i^2 r_i - k_i \left(T_{hot,i}^{TE} - T_{cool,i}^{TE} \right); \tag{4.2}$$

$$W_i^{TE} = I_i^2 r_i + \alpha_i \left(T_{hot,i}^{TE} - T_{cool,i}^{TE} \right) I_i; \tag{4.3}$$

$Q_{hot,i}^{TE}$ is general (total) heat productivity of thermoelements of the *i*-th THP; W_i^{TE} is general (total) electric power consumed by thermoelements of the *i*-th THP; α_i is general (total) differential Seebeck coefficient of the material of thermoelements of the *i*-th THP; I_i is the strength of the current flowing through thermoelements of the *i*-th THP; r_i is general (total) electric resistance of thermoelements of the *i*-th THP; k_i is general (total) thermal conductivity of thermoelements of the *i*-th THP; $T_{hot,i}^{TE}$ is temperature of the heat releasing junctions of thermoelements of the *i*-th THP; $T_{cool,i}^{TE}$ is temperature of the heat absorbing junctions of thermoelements of the *i*-th THP.

Heating coefficient of the *i*-th THP operating in the *investigated process* according to Fig. 3 [1] and with regard to assumption 6 [1] ($d = const$) μ_i^{TTH}:

$$\mu_i^{TTH} = \frac{Q_{hot,i}^{TTH}}{W_i^{TTH}} = \frac{T_{hot,i}^{PP} - T_{hot,(i-1)}^{PP}}{\left(T_{hot,i}^{PP} - T_{hot,(i-1)}^{PP} \right) - \left(T_{cool,i}^{PP} - T_{cool,(i-1)}^{PP} \right)}, \tag{4.4}$$

where $Q_{hot,i}^{\mathrm{TTH}}$ is heat productivity of the *i*-th THP; W_i^{TTH} is power consumed by the *i*-th THP; $T_{hot,i}^{PP}$ is temperature of the MS immediately after its TC with the heat releasing HE of the *i*-th THP; $T_{hot,(i-1)}^{PP}$ is temperature of the MS immediately before its TC with the heat releasing HE of the *i*-th THP; $T_{cool,i}^{PP}$ is temperature of the MS immediately before its TC with the heat absorbing HE of the *i*-th THP; $T_{cool,(i-1)}^{PP}$ is temperature of the MS immediately after its TC with the heat absorbing HE of the *i*-th THP.

Let $Q_{hot,i}^{\mathrm{TTH}} = Q_{hot,i}^{TE}$ and $W_i^{TTH} = W_i^{TE}$. Then, on the basis of equations (4.1) and (4.4) it can be written:

$$\mu_i^{TE} = \mu_i^{TTH}, \tag{4.5}$$

$$\frac{T_{hot,i}^{PP}-T_{hot,(i-1)}^{PP}}{\left(T_{hot,i}^{PP}-T_{hot,(i-1)}^{PP}\right)-\left(T_{cool,i}^{PP}-T_{cool,(i-1)}^{PP}\right)}=\frac{\alpha_i I_i T_{hot,i}^{TE}+\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)}{I_i^2 r_i+\alpha_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)I_i}. \quad (4.6)$$

We will assume that the heat transfer from the heat releasing junctions of the thermoelements of the *i*-th THP to the MS is carried out through a medium characterized by the corresponding heat transfer resistance (thermal resistance) $R_{hot,i}$, and the heat transfer from the MS to the heat-absorbing junctions of the thermoelements of the *i*-th THP is carried out through a medium characterized by the corresponding heat transfer resistance (thermal resistance) $R_{cool,i}$. We will also assume that there are no other additional factors that could affect the heat exchange between the MS and the *i*-th THP. Then we can write the following equations, which, in particular, reflect the relationship between the junction temperatures of the thermoelements of the *i*-th THP and the MS (in the corresponding positions of its movement):

$$T_{hot,i}^{TE}-T_{hot,i}^{PP}=Q_{hot,i}^{TE}R_{hot,i}, \quad (4.7)$$

$$T_{hot,i}^{TE}-T_{hot,i}^{PP}=\left(\alpha_i I_i T_{hot,i}^{TE}+\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)\right)R_{hot,i} \quad (4.8)$$

(Eq. (4.8) was obtained using Eq. (4.2));

$$T_{cool,(i-1)}^{PP}-T_{cool,i}^{TE}=Q_{cool,i}^{TE}R_{cool,i}, \quad (4.9)$$

$$T_{cool,(i-1)}^{PP}-T_{cool,i}^{TE}=\left(\alpha_i I_i T_{cool,i}^{TE}-\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)\right)R_{cool,i}, \quad (4.10)$$

where $Q_{cool,i}^{TE}$ is general (total) cooling capacity of thermoelements of the *i*-th THP ($Q_{cool,i}^{TE}=\alpha_i I_i T_{cool,i}^{TE}-\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)$ [8]).

Taking into account assumption 6 [1] and the information given above, we write an equation that, in particular, reflects the relationship between the general (total) heating capacity of the thermoelements of the *i*-th THP, the change in the temperature of the MS as a result of its TC with the heat-generating HE of the *i*-th THP, and the heat capacity flow rates of the MS, V_C^{PP} [3]:

$$V_C^{PP}\left(T_{hot,i}^{PP}-T_{hot,(i-1)}^{PP}\right)=\alpha_i I_i T_{hot,i}^{TE}+\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right). \quad (4.11)$$

Taking into account assumption 6 [1] and the information given above, we write an equation that, in particular, reflects the relationship between the general (total) cooling capacity of the thermoelements of the *i*-th THP, the change in the temperature of the MS as a result of its TC with the heat-absorbing HE of the *i*-th THP, and the heat capacity flow rates of the MS:

$$V_C^{PP}\left(T_{cool,i}^{PP}-T_{cool,(i-1)}^{PP}\right)=\alpha_i I_i T_{cool,i}^{TE}-\frac{1}{2}I_i^2 r_i-k_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right). \quad (4.12)$$

Taking into account assumption 6 [1] and the information provided above, we write an equation that, in particular, reflects the relationship between the general (total) power consumption of thermoelements of the *i*-th THP, the total change in the temperature of the MS as a result of its TC with the heat-absorbing and heat-releasing HE of the *i*-th THP, and the heat capacity flow rates of the MS:

$$V_C^{PP}\left(\left(T_{hot,i}^{PP}-T_{hot,(i-1)}^{PP}\right)-\left(T_{cool,i}^{PP}-T_{cool,(i-1)}^{PP}\right)\right)=I_i^2 r_i+\alpha_i\left(T_{hot,i}^{TE}-T_{cool,i}^{TE}\right)I_i. \quad (4.13)$$

In this paper (part 4) we will consider that the values $R_{hot,i}$, $R_{cool,i}$, α_i, r_i, k_i are temperature independent.

Eqs. (4.6), (4.7), (4.9), (4.11), (4.12), (4.13) can be used for estimation calculations of the operating modes of individual THPs and *the investigated processes* in general.

For the example described above, we will use the energy efficiency indicator of the investigated process ω_{hot}:

$$\omega_{hot} = \frac{Q_{hot}^{TTH}}{W^{TTH}} = \frac{\Delta T_{hot}^{PP}}{\Delta T_{hot}^{PP} - \Delta T_{cool}^{PP}} \qquad (4.15)$$

(the right-hand side of this expression was obtained using Eqs. (1), (54) and (55) [1]), where ΔT_{hot}^{PP} – according to the diagram in Fig. 3 [1], is the temperature difference of the MS, which is formed as a result of heating the MS in its input flow by all individual THPs; ΔT_{cool}^{PP} – according to the diagram in Fig. 3 [1], the temperature difference of the MS, which is formed as a result of cooling the MS in its output flow by all individual THPs.

Note that when only one THP is used in the *investigated process*, then ω_{hot} is equal to the heating coefficient of this single THP μ_1^{TTH} [9 – 11].

To implement one of the objectives of this work, some estimation calculations were carried out using the estimation model and equations for estimation calculations described above.

Results of estimated calculations and their features

The initial data and some results of the corresponding calculations, which are relevant to the example of the investigated process considered in this work, are presented (in abbreviated form) in Table 4.1. The column headings of Table 4.1 contain, sequentially, from top to bottom, a text description of the corresponding quantities, their symbolic designation (if any) and dimension (if any), which are separated by dotted lines. In Table 4.1, the initial data and calculation results are marked with different colors (the initial data are in this color, and the calculation results are in this other color).

Also, information about calculations is presented in Figs. 4.1 – 4.7.

For all cases of the considered example, the total temperature difference of the MS in its input flow according to Eq. (54) [1] and the diagram in Fig. 3 [1] is the same and equal to 5 *K*:

$$\Delta T_1^{PP} = \Delta T_{hot}^{PP} = 5\ K\ . \qquad (4.16)$$

Also, for all cases of the considered example, the inlet temperature of the MS is the same according to Fig. 3 [1]:

$$T_{1.0}^{PP} = 298.15\ K\ . \qquad (4.17)$$

In those cases of the considered example when several THPs are used, these several THPs are the same (the values of α_i, r_i, k_i, $R_{hot,i}$ and $R_{cool,i}$ for all these THPs are the same), and also for all these THPs the strength of current flowing through them, I_i is the same.

Let us assume that for the implementation of *the investigated process* according to the diagram in Fig. 3 [1] there is a THP with known given parameters, for example, those given in Table 4.1 for the 1st or 2nd or 5th cases of the considered example of the *investigated heat and mass transfer method.* Fixed temperature $T_{1.n}^{PP}$ and temperature difference $\Delta T_1^{PP} = \Delta T_{hot}^{PP} = 5\ K$ are also specified (4.16). Heat capacity flow rates of MS can change (are not fixed). Examples of calculated results for such cases are presented in Table 4.1 (1st, 2nd and 5th cases) and in Figs 4.1 - 4.6 (for initial data corresponding to the 1st and 2nd cases in Table 4.1).

<u>*Table 4.1*</u>

Initial data and some results of corresponding estimation calculations of the efficiency of the investigated heat and mass transfer method with the use of THP for the case of heating the MS in its input flow by all individual THPs (according to Fig. 3 [1]*; according to assumptions 1, 2, 4-7* [1]*;* $T_{1.0}^{PP} = 298.15\ K$ *)*

Case number of the example under consideration l	Total number of THPs n	Thermoelectric figure of merit of thermoelements of each individual i-th THP z_i, 1/K	Total differential Seebeck coefficient of the material (legs) of the thermoelements of each individual i-th THP α_i, V	Total electrical resistance of thermoelements of each individual i-th THP r_i, Ohm	Total thermal conductivity of the thermoelement legs of each individual i-th THP k_i, W/K	Current flowing through each thermoelement of each individual i-th THP I_i, A	Total resistance of heat transfer from the heat releasing junctions of the thermoelements of each individual i-th THP to the MS $R_{hot,i}$, K/W	Total resistance of heat transfer from the MS to the heat absorbing junctions of the thermoelements of each individual i-th THP $R_{cool,i}$, K/W	Heat capacity flow rates of the MS V_C^{PP}, W/K	MS temperature in position 1.n $T_{1.n}^{PP}$, K	MS temperature in position 2.n $T_{2.n}^{PP}$, K	Temperature difference across thermoelements of the nth THP ΔT_n^{TE}, K	Heating coefficient of thermoelements of the nth THP μ_n^{TE}	Energy efficiency indicator of *the investigated process* ω_{hot}
1(1)	1	0.0026	0.048	2.6	0.34	0.2422	0.1	0.1	0.3917	303.15	303.15	4.8377	9.379 (1)	9.379 (1)
2(1)	1	0.0026	0.048	1.3	0.68	0.4749	0.1	0.1	0.7185	303.15	303.15	5.1074	8.77 (1)	8.77 (1)
3(2)	1	0.0026	0.048	3.082	0.287	0.2245	0.1	0.1	0.3917	303.15	303.15	4.8411	9.436 (2)	9.436 (2)
4(2)	1	0.0026	0.048	1.783	0.496	0.4106	0.1	0.1	0.7185	303.15	303.15	5.1197	8.951 (2)	8.951 (2)
5(1)	1	0.0026	0.048	2.6	0.34	0.2913	0.1	0.1	0.4755	303.15	302.15	5.8103	7.874 (1)	7.874 (1)
6(2)	1	0.0026	0.048	3.692	0.239	0.2227	0.1	0.1	0.3917	303.15	302.15	5.7432	8.013 (2)	8.013 (2)
7(2)	2	0.0026	0.048	3.077	0.287	0.1153	0.1	0.1	0.3917	303.15	303.15	2.5301	17.7	17.923 (2)
8	1	0.0027	0.048	1.008	0.847	0.403	0.1	0.1	0.3917	303.15	303.15	4.7153	7.682	7.682
9	2	0.0027	0.048	1.008	0.847	0.2079	0.1	0.1	0.3917	303.15	303.15	2.4649	14.1	14.443
10	8	0.0026	0.048	3.232	0.274	0.0288	0.1	0.1	0.3917	303.15	303.15	0.6555	67.236	68.748

(1) the value of V_C^{PP} is selected and specified such that the maximum value of ω_{hot} is achieved; (2) the value of r_i (and k_i) is selected and specified such that the maximum value of ω_{hot} is achieved.

Now let us assume that it is necessary to implement *the investigated process* according to the diagram in Fig. 3 [1], for which a fixed temperature $T_{1.n}^{PP}$, a fixed temperature difference $\Delta T_1^{PP} = \Delta T_{hot}^{PP} = 5\ K$ (4.16), fixed heat capacity flow rates of the MS, a fixed thermoelectric figure of merit of thermoelements of each individual ith *THP* z_i and a fixed total differential Seebeck coefficient of material (legs) of thermoelements of each individual ith *THP* are given, for instance, those given in Table 4.1 for the 3d or 4th or 6th or 7th cases of the considered example *of the investigated heat and mass transfer method*. At the same time, the values of r_i and, accordingly, k_i are not fixed and cannot be selected (calculated) to achieve the maximum value of ω_{hot}. Examples of calculated results for such cases are presented in Table 4.1 (3rd, 4th, 6th and 7th cases) and in Fig. 4.7 (for the initial data corresponding to the 3rd and 7th cases in Table 4.1; Fig. 4.7 shows, in particular, some calculated results that are not in Table 4.1).

For the 8th, 9th and 10th cases of the considered example of *the investigated heat and mass transfer method* according to Table 4.1, optimization was not carried out.

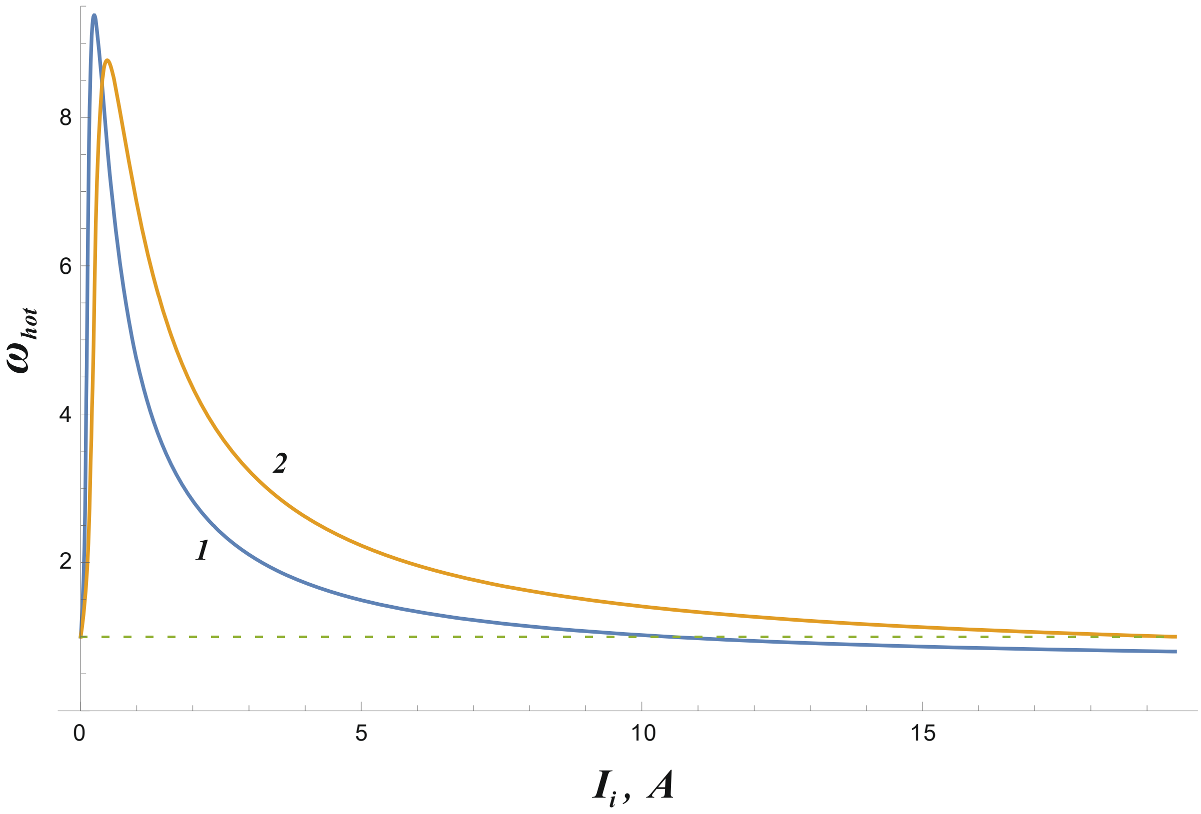


Fig. 4.1. Plots of dependence of ω_{hot} on I_i of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 ($\Delta T_{hot}^{PP} = const = 5\ K$, $V_C^{PP} \neq const$): 1 – for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.

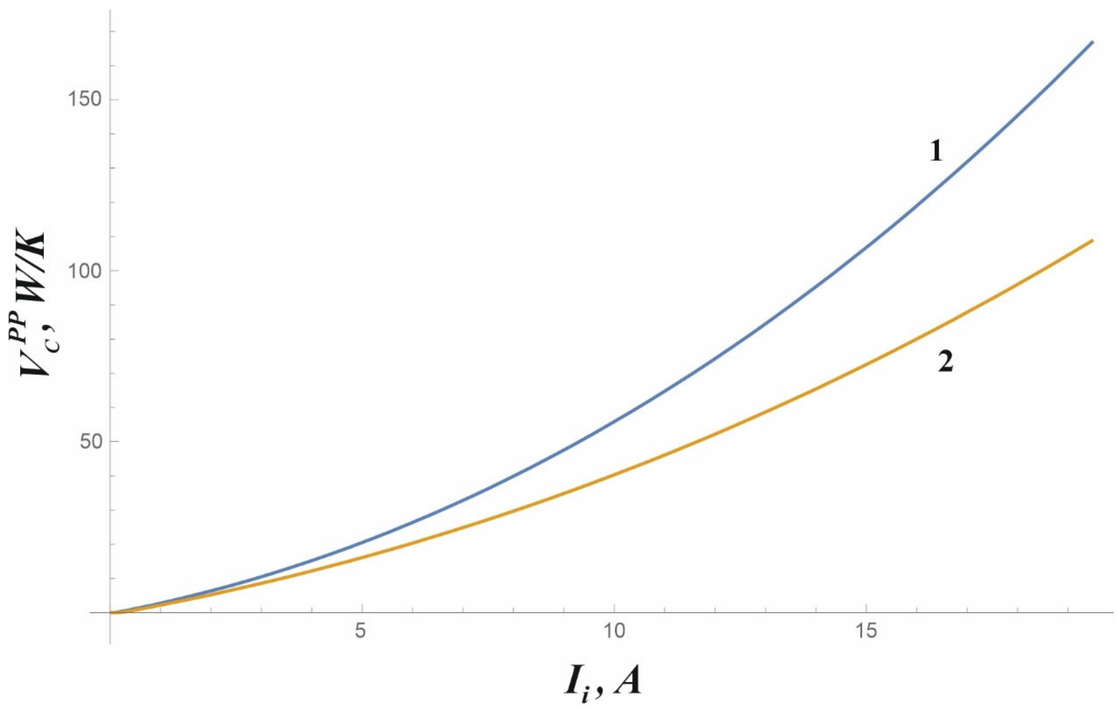


Fig. 4.2. Plots of dependence of V_C^{PP} on I_i of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 ($\Delta T_{hot}^{PP} = const = 5\ K$): 1 –for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.

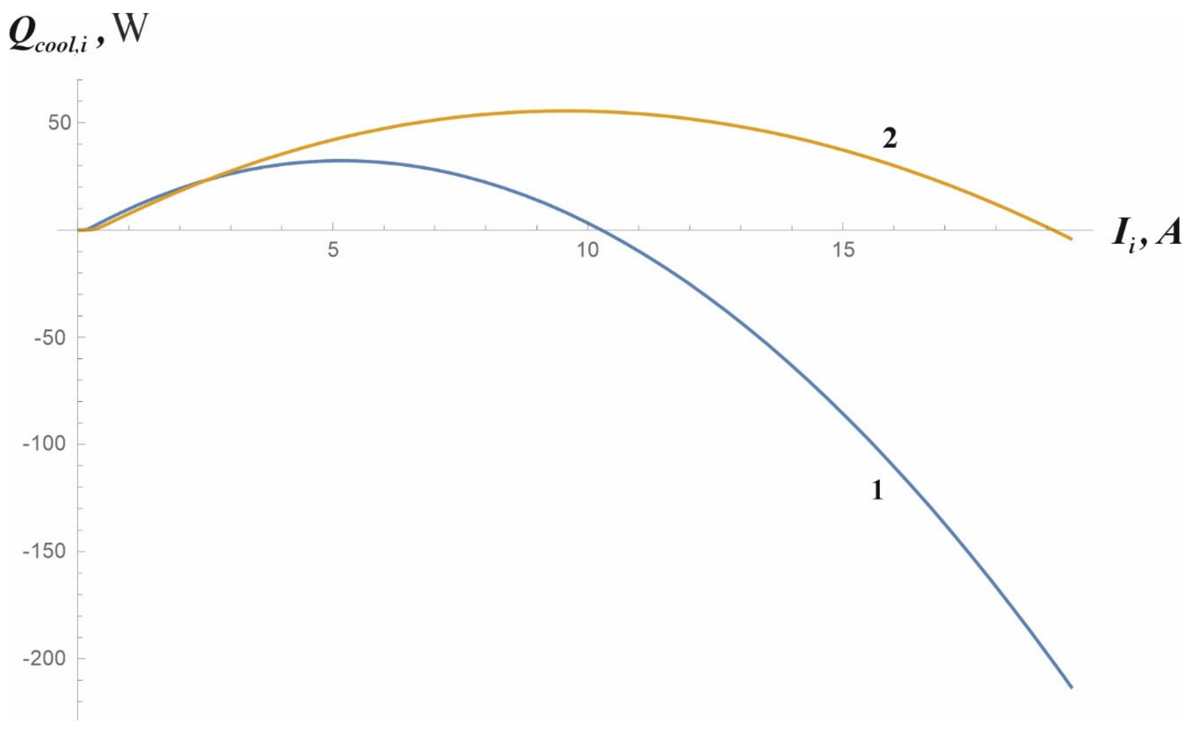


Fig. 4.3. Plots of dependence of heat flow from the MS to the heat absorbing junctions of thermoelements of the ith THP $Q_{cool,i}$ on I_i of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 ($\Delta T_{hot}^{PP} = const = 5\ K$, $V_C^{PP} \neq const$): 1 – for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.

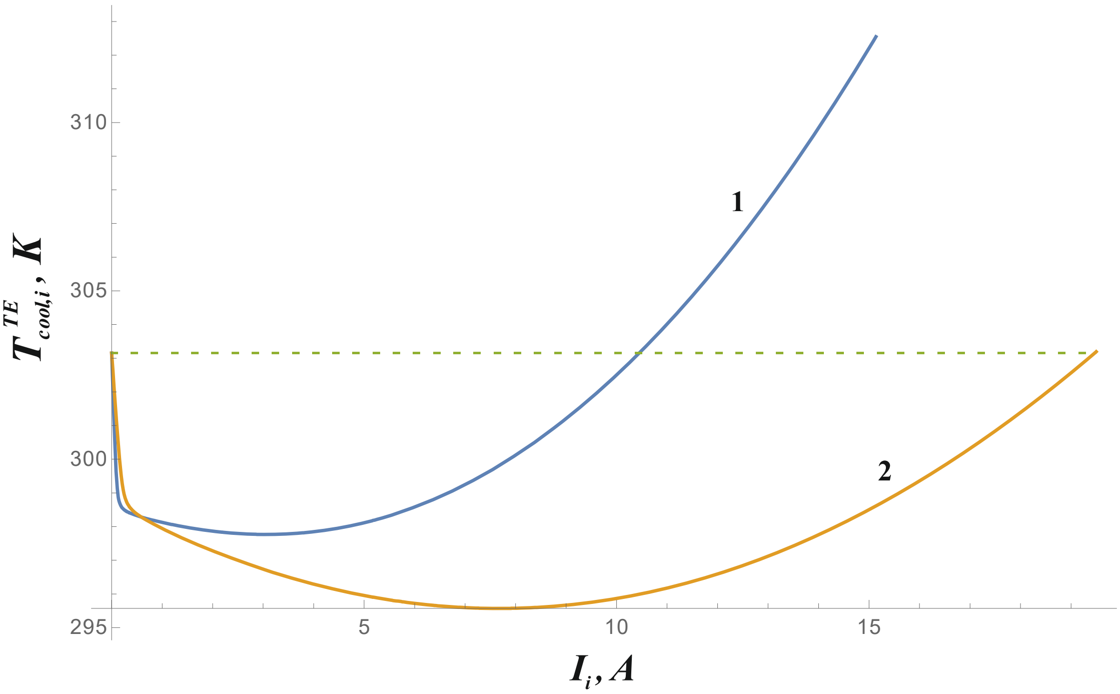


Fig. 4.4. Plots of dependence of $T^{TE}_{cool,i}$ on I_i of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 ($\Delta T^{PP}_{hot} = const = 5\ K$, $V^{PP}_C \neq const$): 1 – for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.

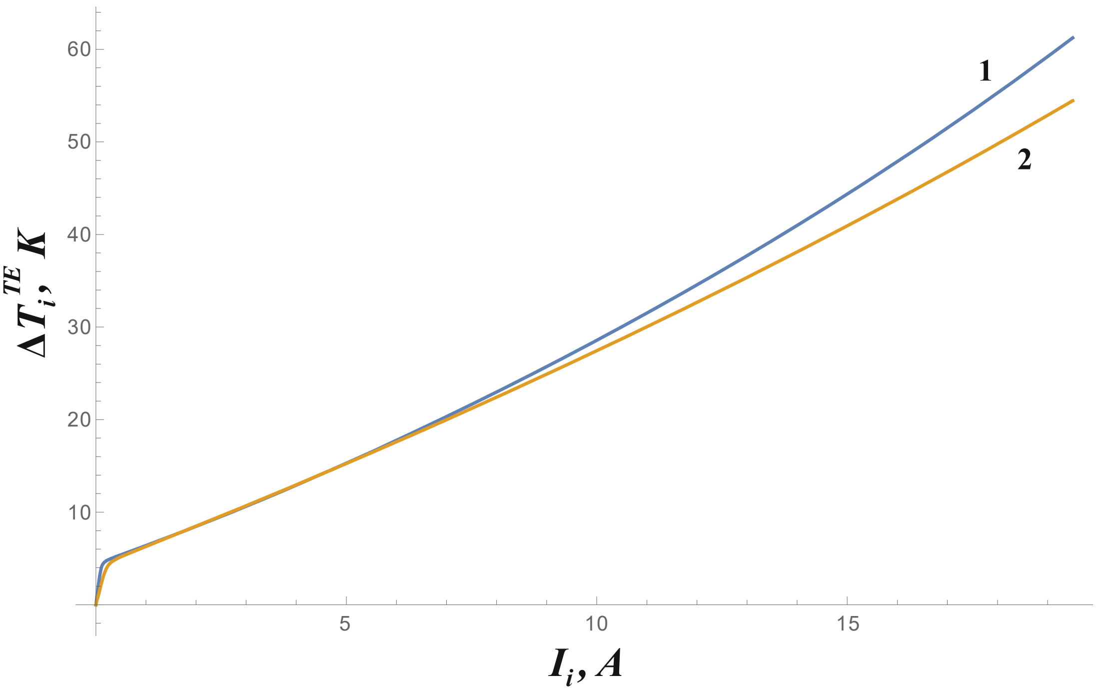


Fig 4.5. Plots of dependence of ΔT^{TE}_i on I_i of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 ($\Delta T^{PP}_{hot} = const = 5\ K$, $V^{PP}_C \neq const$): 1 – for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.

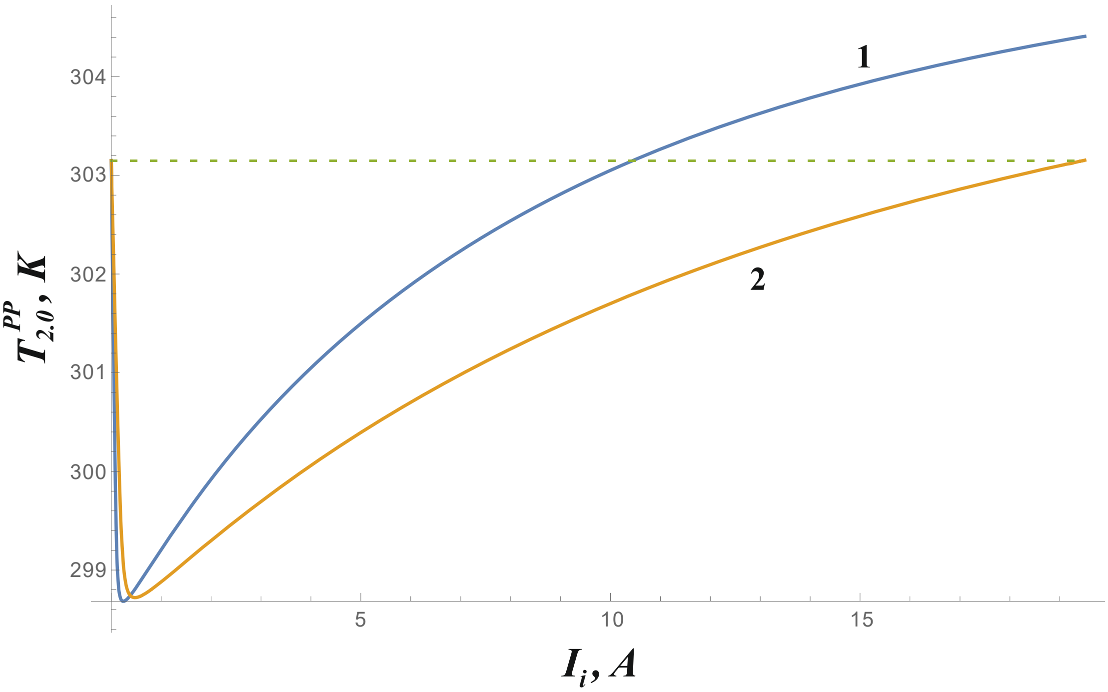
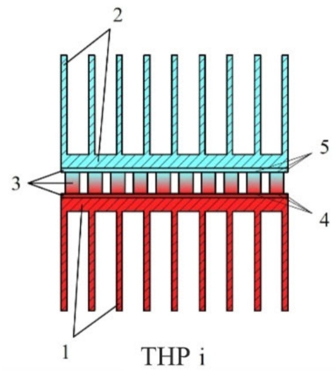
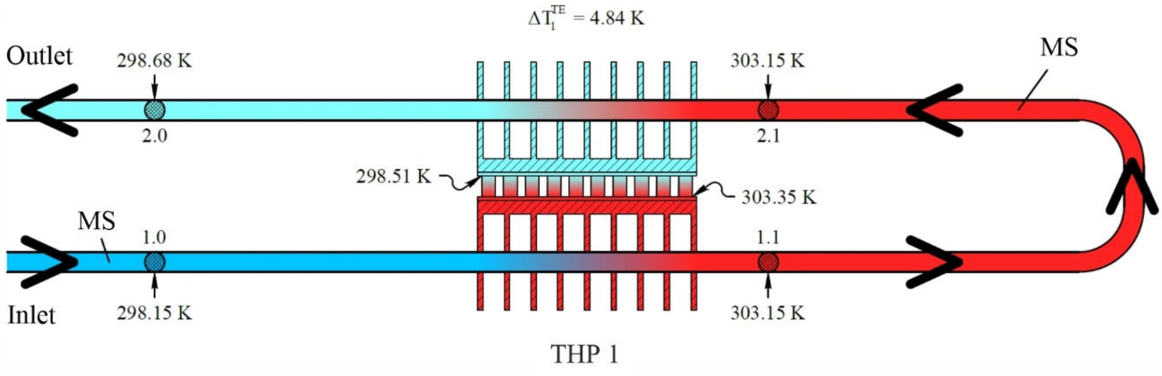


Fig. 4.6. Plots of dependence of the MS outlet temperature according to diagram in Fig. 3 [1] $T_{2.0}^{PP}$ *on* I_i *of the considered example of the investigated process for the initial data that correspond to the 1st and 2nd cases in Table 4.1 (*$\Delta T_{hot}^{PP} = const = 5\ K$ *,* $V_C^{PP} \neq const$ *): 1 –for the initial data of the 1st case from Table 4.1, 2 – for the initial data of the 2nd case from Table 4.1.*

a)



b)



c)

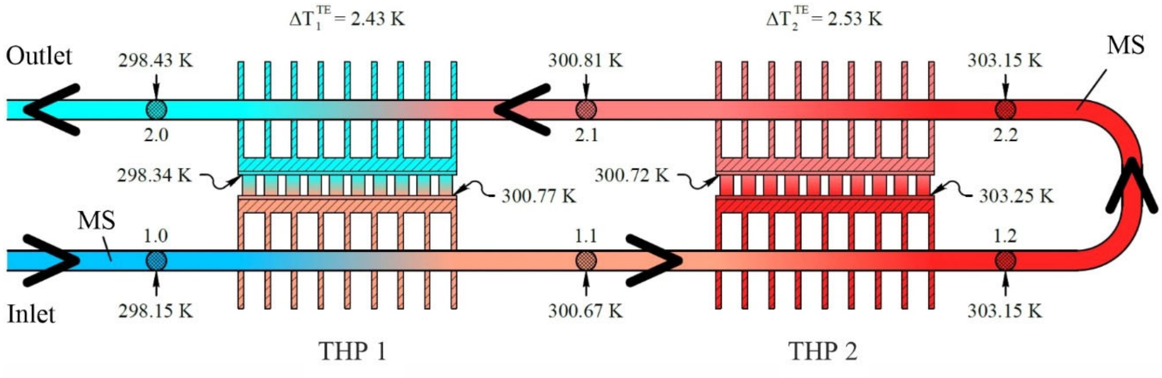


Fig. 4.7. Figure illustrating the calculated results for the 3rd and 7th cases of the considered example of the investigated heat and mass transfer method (according to Table 4.1): a) simplified diagram of individual ith THP: 1 – heat releasing heat exchanger, 2 –heat absorbing heat exchanger, 3 – thermoelectric module, 4 – location of the heat releasing junctions of THP thermoelements, 5 – location of the heat absorbing junctions of THP thermoelements; ***b)*** *simplified diagram of the 3rd case of the considered example of the investigated process with certain corresponding calculated results: 1.0, 1.1, 2.1, 2.0 – successive positions of the MS during its movement (1.0 – immediately before TC of MS to the heat releasing (1st) HE of THP 1, 1.1 – immediately after TC of MS to the heat releasing (1st) HE of THP 1, 2.1 – immediately before TC of the MS to the heat absorbing (2nd) HE of THP 1, 2.0 – immediately after TC of the MS to the heat absorbing (2nd) HE of THP 1; c) simplified diagram of the 7th case of the considered example of the investigated process with certain corresponding calculated results: 1.0, 1.1, 1.2, 2.2, 2.1, 2.0 – successive positions of the MS during its movement (1.0 – immediately before TC of the MS to the heat releasing (1st) HE of THP 1, 1.1 – immediately after TC of the MS to the heat releasing (1st) HE of THP 1, 1.2 – immediately after TC of the MS to the heat releasing (1st) HE of THP 2, 2.2 – immediately before TC of the MS to the heat absorbing (2nd) HE of THP 2, 2.1 – immediately after TC of the MS with the heat absorbing (2nd) HE of THP 2, 2.0 – immediately after TC of the MS to the heat absorbing (2nd) HE of THP 1.*

Conclusions

1. A theoretical model is presented for estimating the efficiency of using the investigated heat and mass transfer method for the case of heating the MS in its input flow by all individual THPs. Mathematical expressions for the corresponding estimation calculations and examples of the results of such calculations are presented.
2. The energy efficiency of the studied process may depend on its features, on the number of THPs used in the process, and on the parameters of the THP thermoelements.
3. Further theoretical and/or experimental studies may be required to make decisions regarding practical applications of the *investigated heat and mass transfer method*.

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Submitted: 15.11.2023.

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ОЦІНКА ЕФЕКТИВНОСТІ ЧАСТИННОГО ВИПАДКУ ПРОЦЕСІВ ТЕПЛОМАСООБМІНУ МІЖ ТЕПЛОВИМИ НАСОСАМИ І РУХОМОЮ РЕЧОВИНОЮ. ЧАСТИНА 4

Представлена теоретична модель для оцінки ефективності роботи частинного випадку процесів, в яких має місце тепловий контакт рухомої речовини (або принаймні частини цієї рухомої речовини) з теплопоглинальною і тепловиділяючою теплообмінними частинами принаймні двох теплових насосів для випадку нагрівання рухомої речовини у її вхідному потоці всіма окремо взятими термоелектричними тепловими насосами. Наведені математичні вирази для відповідних оціночних розрахунків та приклади результатів таких розрахунків.

Ключові слова: тепловий насос, рухома речовина, тепломасообмін, ефективність, енергоефективність, термоелектричний тепловий насос, термоелементи.

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Надійшла до редакції: 15.11.2023.