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INCREASE OF ENERGY EFFICIENCY OF DIRECT-FLOW HEAT EXCHANGERS

Abstact. *The article is devoted to the development of a method for determining the minimum interaction surface in a system of heat exchangers. A comparative analysis of direct-flow and counter-current types of heat exchange is carried out in relation to the creation of systems for ensuring temperature conditions, for which weight and size characteristics are decisive. It is shown that the main characteristic of efficiency in the design and simulation of heat exchangers, based on the temperature representation, is not applicable for devices with a phase transition. The definition of efficiency as the energy characteristic of the energy exchange process of interacting flows is proposed. Comparison of the energy received by the heated stream from the heating stream made it possible to determine the energy potential in the heat exchanger. The introduction of energy efficiency made it possible to substantiate the relationship between the efficiency of once-through and counter-flow heat exchangers with access to structural and thermophysical requirements. The analysis of analytical relationships showed that in assessing the thermal stresses arising in the apparatus, the determination of average values over the surface of the temperature of the coolant plays a significant role. It is shown that the countercurrent heat exchanger represents the limiting case of minimizing the heat transfer area. The increase in the efficiency of once-through heat exchangers due to sectioning is analyzed and the possibility of increasing the efficiency of once-through heat exchangers is shown. The research results indicate not only the topological equivalence of the direct-flow apparatus system to one counter-current, but also the possibility of constructing a partitioned apparatus system with the serial connection of its elements with an efficiency equal to the efficiency of counter-current apparatuses. A recursive algorithm is proposed for constructing a partitioned system of direct-flow apparatus. The developed method can be used to create computer-aided design systems for heat exchangers of complex chemical plants.*
Keywords: *heat transfer; countercurrent flow; direct flow; energy efficiency; sectioning*

Introduction

A necessary component of internal combustion engines, turbines, power stations, chemical technologies, heating and cooling systems, DATA centers are heat exchangers. The significance of energy loss during heat exchange in the total cost of operating industrial and transport systems leads to the importance of reducing these losses. According to the scheme of mutual flow of heat carriers, heat exchangers are divided into countercurrent, direct-flow and cross-flow, as well as their combinations [1]. When solving a constructive problem with known parameters of heat carriers and their costs, the required heat exchange surface and the mass-dimensional and reliability parameters resulting from it are determined, the requirements for which can be very strict, for example, for movable products. Since the efficiency of countercurrent heat exchangers is higher than direct flow, and in solving some heat exchange problems, only direct flow is possible, optimization becomes an obligatory design stage.

Analysis of literature data and problem statement

In modern literature the majority of researches is devoted to development of a design of heat exchangers [2; 3]. Results of influence of hydraulic resistance on effectiveness of heat exchange in heat exchangers of various types are presented [4]. The designs of heat exchange equipment were investigated, including: tubular apparatuses with innovative heat exchanging elements, coil-in-tube heat exchangers “pipe in a pipe” type with changing and unchanging bending radius of the helical helix of the flowing part of the heat exchanging elements, as well as heat exchangers with a rotating heat exchange surface [5; 6]. The rise in temperature stresses of modern technology required taking into account dynamic loads when designing heat exchangers and cooling systems for gas-turbine and combined plants [7-8], creating advanced heat exchange surfaces [9] to increase the heat transfer intensification [10]. A special place is occupied by heat exchangers for the chemical industry, a feature of which is the presence in the course of internal reactions the release or absorption of heat [11]. When creating miniature heat exchangers in refrigeration [12], heat surfaces of utilization plants

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for electronic components [13-15] the polymer nanocomposites which have advantages over traditional counterparts are used. A common approach to all the above studies is a parametric approach to improving the quality indicators of one or several components of heat exchange and not enough attention to the development of methods for calculating heat exchangers and systems of such devices [16]. One of the attempts to improve the efficiency of heat exchangers is their division into sections [17]. Such an approach assigns the apparatus system to a single apparatus, allowing the direction of flow movement determined by the technology to be preserved. In our opinion, the reason for the widespread use of partitioning heat and cold flows with costs G and U with initial T_0 and Θ_0 final T_1 and Θ_1 temperatures, respectively, is subject to the condition: $-G\frac{\partial T}{\partial F} = U\frac{\partial \Theta}{\partial F}$. An important task in the design of heat exchangers is to increase the efficiency of heat transfer φ while minimizing the required area F, which determines its weight and size characteristics. The main parameters of the mathematical description of heat transfer processes are the water number $\alpha = G/U$, heat transfer coefficient k and $NTU = \frac{kF}{G}$, which characterizes the ratio of the largest temperature difference along the length of the apparatus to the average temperature difference of the flows.

A comparison of direct-flow and counter-flow heat exchangers shows that their circuits are equivalent only at very large and very small values of the ratio of water equivalents (products of mass and heat capacity of the stream). This occurs in a situation when the temperature change of one of the outlet; Θ_0- temperature of the cold stream at the outlet.coolants is small, or when the temperature head is large compared to a change in the temperature of the working fluid. In all other cases, ceteris paribus, more is transferred during countercurrent heat than during direct flow. exchangers is not only the mathematical difficulties that arise in solving such problems, but also the absence of a system formulation of such problems.

The purpose and objectives of the study

The purpose of the study is to increase the efficiency of direct-flow heat exchangers.

To achieve this goal it is necessary to solve the problems:

1. To develop a model of the relationship between the efficiency of direct-flow and counter-flow heat exchangers;

2. To determine the maximum achievable efficiency of a direct-flow heat exchanger.

Main part

Heat transfer through the surface F of hot However, there is a class of applications that requires a direct-flow heat transfer circuit.

The main characteristic adopted, both in the design and in the simulation of heat exchangers, is the temperature efficiency [4]:

$$\Phi = \frac{T_0 - T_1}{T_0 - \Theta_0}\ , \qquad (1)$$

where: T_0 is the temperature of the hot inlet stream;

T_1 – temperature of the hot stream at the outlet;

Θ_0 – temperature of the cold stream at the outlet.

This characteristic has found wide application for two-line heat exchangers and is not applicable for devices with a phase transition or in the presence of a chemical reaction. It seems to us more practical to define efficiency as the energy characteristic of the process of energy exchange of interacting flows.

The mean-enthalpy temperature of the flows in the apparatus determines the ratio:

$$T_\Sigma = \Theta_\Sigma = \frac{T_0 G + \Theta_0 U}{G + U}, \qquad (2)$$

where: G is the heat consumption of the hot stream; $x = \Phi_n$- consumable heat capacity of the cold stream.

The temperature distribution in the apparatus with countercurrent flow movement is shown on Fig.1.

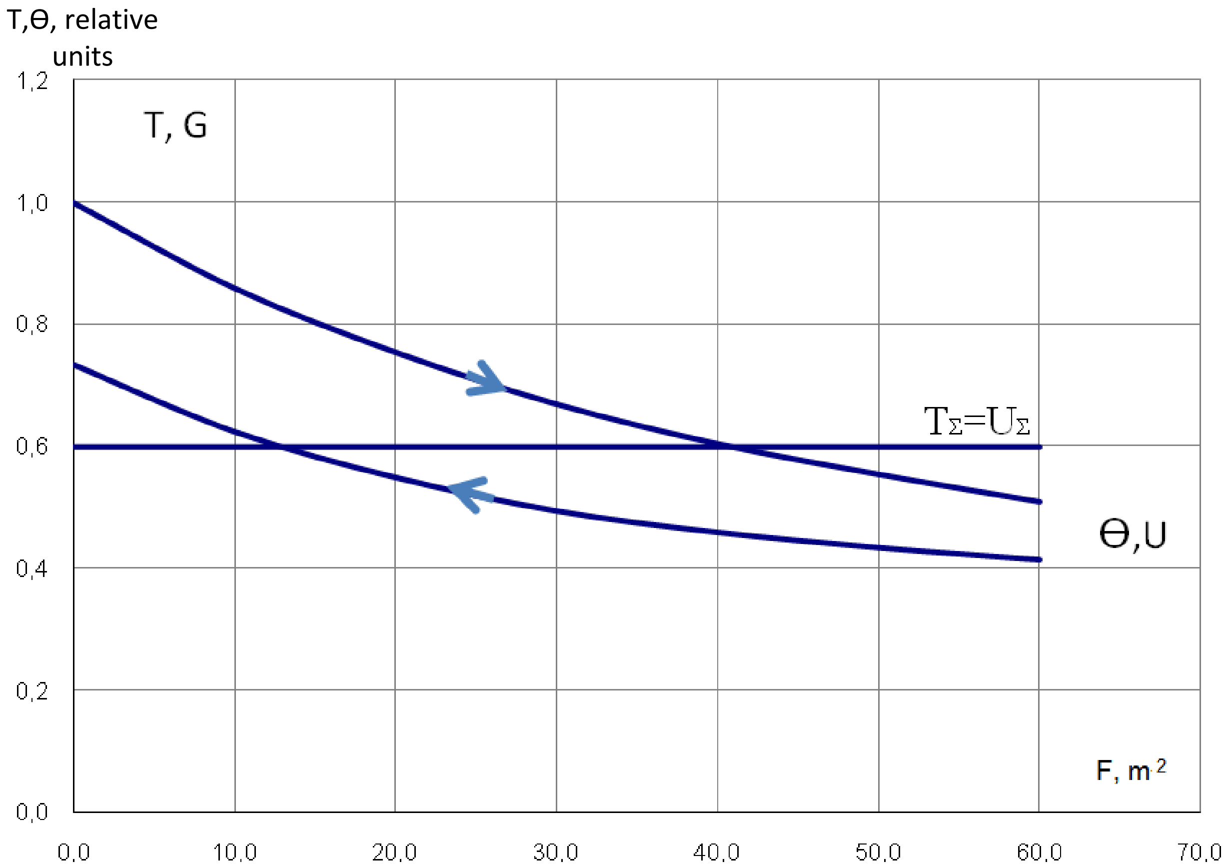

Fig. 1. Temperature distribution in the apparatus with countercurrent flow (one dimensional representation)

The amount of energy Q_2 received by the heated stream in the temperature range $(\Theta_\Sigma - \Theta_0)$:

$$, \; Q_2 = \frac{T_0 G - \Theta_0 U}{G+U} - \Theta_0 U \,, \qquad (3)$$

where: Θ_Σ is the mean-enthalpy temperature.

The amount of energy Θ_Σ transmitted by the heating flow in the interval $(T_o - T_\Sigma)$

$$Q_1 = T_0 G - \frac{T_0 G + \Theta_0 U}{G+U} G \quad . \qquad (4)$$

We define the sum (Q_1 and Q_2) as the energy potential used in the apparatus:

$$\Delta\Phi = Q_1 + Q_2 = 2GU \frac{T_0 - \Theta_0}{G+U} = 2G \frac{1}{1-\alpha}(T_0 - \Theta_0)\alpha = \frac{G}{U} \quad .$$

The ratio of the amount of energy transmitted in the apparatus to the injected energy potential is defined as its energy efficiency:

Defined as its energy efficiency:

$$E = \frac{Q}{\Delta\Phi} = \frac{G+U}{2U} \cdot \frac{T_0 - T_1}{T_0 - \Theta_0} = \frac{1+\alpha}{2} \cdot \frac{T_0 - T_1}{T_0 - \Theta_0} = \frac{1+\alpha}{2} \cdot \Phi \qquad (5)$$

From the existing solution for final temperatures [4], it is not difficult to obtain a connection between the efficiency for direct-flow and counter-flow heat exchangers and the parameters (NTU and α).

NTU is the number of transfer units, defined as: $NTU = kF($, where k is the heat transfer coefficient, F is the heat exchange surface in the element.

Forward flow

$$NTU = \frac{1}{1+\alpha} \ln \left[\frac{1}{1-\Phi(1+\alpha)} \right] \; . \qquad (6)$$

Countercurrent

.

$$NTU_0 = \frac{1}{1+\alpha} \ln \left[\frac{1-\alpha\Phi_0}{1-\Phi_0} \right] \quad . \qquad (7)$$

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Both when assessing the efficiency of technological processes, and when assessing thermal stresses arising in the apparatuses, the determination of the values of the average surface temperature of the coolants plays a significant role.

Forward flow, heating coolant:

$$T_m = \int_0^1 T dS = T_0 - \frac{T_0 - \Theta_0}{1+\alpha} \times \left[1 - \frac{\exp\{-NTU_m(1+\alpha)\}}{NTU_m(1+\alpha)}\right]. \quad (8)$$

Forward flow, heated coolant:

$$\Theta_m = \int_0^1 \Theta dS = \Theta_0 + \alpha \frac{T_0 - \Theta_0}{1+\alpha \left[1 - \frac{1-\exp\{-NTU_m(1+\alpha)\}}{NTU_m(1+\alpha)}\right]}. \quad (9)$$

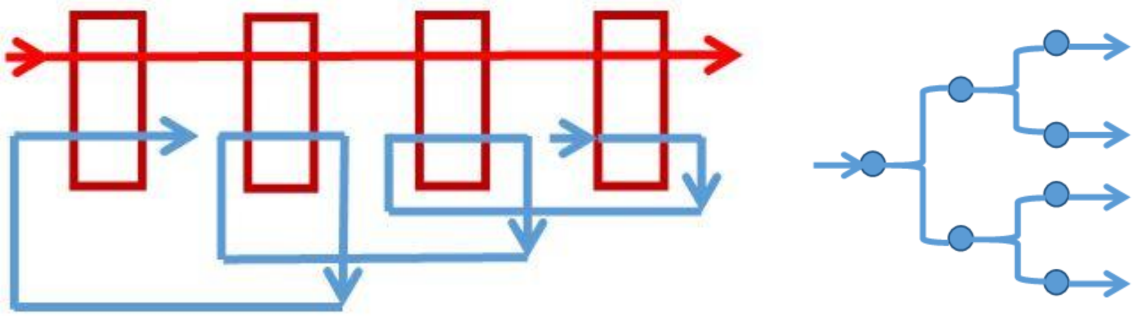
It is not difficult to show that the average values of temperatures along the satisfy the balance

$$G(\Theta_m - \Theta) - U(T_0 - T_{m)} = 0.$$

Using (8) and (9) it is not difficult to get a connection between temperature efficiency and average surface temperatures

$$\Phi = NTU_m \frac{T_m - \Theta_m}{T_0 - \Theta_0}. \quad (10)$$

To achieve greater efficiency without disrupting the technological purpose of heat exchangers (forward flow, cross flow of flows), their sectioning is used. Consider the possibility of sequential integration of direct-flow heat exchangers (Fig. 2).



a b

Fig. 2. Sectioning direct-flow heat exchangers:
a) general scheme; b) the structure of the calculation

Table 1. Comparison of countercurrent and partitioned direct-flow heat exchangers

N / *α*	2	4	8	…	64	…	∞
0.9	-	-	5.004	…	4.496	…	4.489
0.7	-	4.081	3.453	…	3.312	…	3.310
0.5	5.650	2.924	2.739	…	2.688	…	2.687

The given data in Table 1 shows that when partitioning direct-flow heat exchangers, the value NTU tends to a finite limit equal to value NTU_0 of the countercurrent heat exchanger. Consider the difference limit $NTU_0 - NTU_1$. Using relations (6) and (7), denoting $x = \Phi_n$, we can write

$$NTU_0 - N \cdot NTU_N =$$
$$= \frac{1}{1-\alpha} \ln(\frac{1-\alpha\Phi_0}{1-\Phi_0}) - N \frac{1}{1+\alpha} \ln\left[\frac{1}{1-x(1+\alpha)}\right]$$

in the field of variables changes

$$1 > \alpha\Phi > 0 \quad 1 > \Phi_0 > 0$$
$$1 > \Phi_N > 0 \quad 1 > \Phi_N (1+\alpha) > 0 \, .$$

After the obvious transformations we get

$$\ln\left[\left[1 - x(1+\alpha) \cdot \left(\frac{1-\alpha\Phi_0}{1-\Phi_0}\right)^{\Psi} = 0\right]\right],$$

where: $\Psi = \frac{1}{N} \cdot \frac{1+\alpha}{1-\alpha}$.

The following recursive algorithm is proposed for building a partitioned system of direct-flow apparatuses:

INPUT: NTU0 - preset ntu,
E — preset efficiency,
A — flows ratio,
EPS — ntu tolerance,
n_max - maximum iterations
n = 1 # iteration number
Fi0 = E # current efficiency
WHILE n not greater then n_max
N = 2 raised to the n power
Fi = new efficiency value (depends on the Fi0, A)
NTU = new ntu value (depends on the Fi, A, N)
IF NTU deviation from NTU0 less then EPS THEN
 # solution found
STOP

ELSE

Fi0 = Fi
n = n + 1
Results:
N — number of heat exchangers
NTU — totalvalueof NTU

The constructed logic of partitioning of heat exchangers allows achieving the required efficiency with the minimum NTU value approaching the NTU value in a counter-current without violating the process regulations.

Discussion of the analysis results

The results of the analysis indicate not only the topological equivalence of a system of direct-flow heat exchangers (Fig. 1) to one countercurrent, but also the possibility of creating a partitioned system of devices with a series connection of its elements with efficiency equal to the efficiency of countercurrent devices.

Conclusions

1. A mathematical model of communication between counterflow and direct-flow heat exchangers has been developed and analyzed.

2. It is shown that the NTU of the countercurrent heat exchanger circuit is the limiting one, to which the direct-flow system can come as close as desired by an appropriate choice of sections.

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ПІДВИЩЕННЯ ЕНЕРГОЕФЕКТИВНОСТІ ТЕПЛООБМІННИКІВ ПРЯМОГО ПОТОКУ

Анотація. *Стаття присвячена розробці методу визначення мінімальної поверхні взаємодії в системі теплообмінних апаратів. Проведено порівняльний аналіз прямоточного і протиточного видів теплообміну стосовно створення систем забезпечення температурних режимів, для яких визначальними є масогабаритні характеристики. Показано, що основна характеристика ефективності при проектуванні та моделюванні теплообмінних апаратів, що заснована на температурному поданні, не може бути застосована для апаратів з фазовим переходом. Запропоновано визначення ефективності як енергетичної характеристики процесу обміну енергією взаємодіючих потоків. Зіставлення енергії, що прийнята поглинаючим потоком від потоку що гріє дозволило визначити енергетичний потенціал в теплообмінному апараті. Введення енергетичної ефективності дало можливість обґрунтувати зв'язок між ефективністю прямоточних і протиточних теплообмінних апаратів з виходом на конструктивні і теплофізичні вимоги. Аналіз аналітичних співвідношень показав, що при оцінці термічних напружень, що виникають в апаратах, істотну роль грає визначення середніх значень по поверхні температур теплоносіїв. Показано, що протиточний теплообмінний апарат являє граничний випадок мінімізації площі теплообміну. Проаналізовано підвищення ефективності прямоточних теплообмінних апаратів за рахунок секціонування і показана можливість підвищення* *ефективності прямоточних теплообмінників. Результати досліджень вказують не тільки на топологічну еквівалентність системи прямоточних апаратів одному протиточному, але і на можливість побудови секційної системи апаратів з послідовним з'єднанням її елементів з ефективністю рівній ефективності протиточних апаратів. Для побудови секційної системи прямоточних апаратів запропонований рекурсивний алгоритм. Розроблений метод може бути використаний при створенні систем автоматизованого проектування теплообмінних апаратів складних хімічних виробництв.*

Ключові слова: *теплообмін; протитечія; прямоток; енергетична ефективність; секціонування*

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ПОВЫШЕНИЕ ЭНЕРГОЭФФЕКТИВНОСТИ ПРЯМОТОЧНЫХ ТЕПЛООБМЕННИКОВ

Аннотация. *Статья посвящена разработке метода определения минимальной поверхности взаимодействия в системе теплообменных аппаратов. Проведен сопоставительный анализ прямоточного и противоточного видов теплообмена применительно к созданию систем обеспечения температурных режимов, для которых определяющими являются массогабаритные характеристики. Показано, что основная характеристика эффективности при проектировании и моделировании теплообменных аппаратов, основанная на температурном представлении, не применима для аппаратов с фазовым переходом. Предложено определение эффективности как энергетической характеристики процесса обмена энергией взаимодействующих потоков. Сопоставление энергии, принятой нагреваемым потоком от греющего потока позволило определить энергетический потенциал в теплообменном аппарате. Введение энергетической эффективности дало возможность обосновать связь между эффективностью прямоточных и противоточных теплообменных аппаратов с выходом на конструктивные и теплофизические требования. Анализ аналитических соотношений показал, что при оценке термических напряжений, возникающих в аппаратах, существенную роль играет определение средних значений по поверхности температур теплоносителей. Показано, что противоточный теплообменный аппарат представляет предельный случай минимизации площади теплообмена. Проанализировано повышение эффективности прямоточных теплообменных аппаратов за счет секционирования и показана возможность повышения эффективности прямоточных теплообменников. Результаты исследований указывают не только на топологическую эквивалентность системы прямоточных аппаратов одному противоточному, но и на возможность построения секционированной системы аппаратов с последовательным соединением ее элементов с эффективностью равной эффективности противоточных аппаратов. Для построения секционированной системы прямоточных аппаратов предложен рекурсивный алгоритм. Разработанный метод может быть использован при создании систем автоматизированного проектирования теплообменных аппаратов сложных химических производств.*

Ключевые слова: *теплообмен; противоток; прямоток; энергетическая эффективность; секционирование*

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Scientific interests: hydrodynamics and heat transfer in heterogeneous flows, applied mathematics, mathematical programming

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Scientific interests: information technology for high-temperature interactions, the reliability of thermoelectric systems for providing thermal conditions, systems with biological feedback