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SUMMARISATION OF EXPERIMENTAL DATA ON THE INTENSITY OF HEAT TRANSFER IN A CONTACT DEVICE MADE OF PIPE TURBULATION SYSTEMS WITH SPIRAL TURBULATION GENERATORS

Sadulla Nurmukhamedov [1], ***Elbek Mavlonov*** [1], ***Aynagul Nurillaeva*** [1],
Muzaffar Khayriddinov [1], ***Diyorbek Absattorov*** [2]

[1] Faculty of chemical engineering Tashkent institute of chemical technology

[2] Department of chemical engineering and biotechnology, Karshi State Technical University

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Abstract

This article presents experimental data on heat transfer during contact between the gas and liquid phases using a contact device consisting of a tube bundle with spiral turbulators. It has been established that this method can intensify the heat exchange process and align the temperature along the height of the strengthening section of a distillation column. Experimental data on heat transfer during direct phase contact using an efficient contact device consisting of a tube bundle with periodically arranged turbulators have been obtained. It has been found that turbulators of this design increase the turbulence of the contacting phases, and heat transfer has been intensified by a factor of 1.5 or more. A criterion formula in the form of a highly accurate functional dependence, $Ki = f(Re_{liquid}, Re_{gas}, Pr_{gas}, s/d, t/d, Re_{\kappa})$, has been derived from the experimental data. Its error does not exceed ±5,0%.

Keywords: *column, tubular-lattice packing, spiral turbulator, convective heat exchange, intensification, criteria formula.*

Introduction:

Energy and resource conservation issues directly depend on the intensification of processes and equipment in the chemical, oil and gas refining, and other sectors of the economy of any country. Naturally, addressing these issues requires increasing process efficiency and improving the design of equipment, devices, and machines (Napp, T.A., Gambhir, A., Hills, T.P., Florin, N. and Fennell, P.S., 2014; Mawson, V.J. and Hughes, B.R., 2019). Methods for increasing the efficiency of heat transfer processes can be achieved by: altering the heat transfer surface of pipes (without using external energy); altering the energy of the coolant movement (using external energy); or using both of the above methods (Mawson, V.J. and Hughes, B.R., 2019; Hosseinian, A., Isfahani, A.M. and Shirani, E., 2018; Hashemian, M., Jafarmadar, S., Nasiri, J. and Dizaji, H.S., 2017). Currently, the rapid development of all sectors of the fuel and energy complex is accompanied by an increase in the energy intensity of technologies and equipment. Naturally, this dictates the intensification of technological processes, which will reduce energy costs for pumping the coolant and optimize the design of the apparatus (Voigt, S., De Cian, E., Schymura, M. and Verdolini, E., 2014; Chua, K.J., Chou, S.K. and Yang, W.M., 2010).

Many scientists and researchers in the field of heat transfer intensification have developed pipe designs with developed surfaces and methods for enhancing heat transfer. Most heat exchange tube designs have not found widespread use due to their low manufacturing efficiency and the difficulty of arranging them into densely packed bundles. However, a number of scientists have developed optimal heat exchange tube designs (rolled tubes, spiral-rolled tubes with smoothly defined diaphragms in the channel and similar grooves on the outside, twisted tubes, and tubes with spiral turbulators) that are highly technologically advanced and do not alter the existing assembly technology for devices of this class. It should be emphasized that this design ensures intensified heat transfer on both sides of the heat exchange tube (Norman, B.A., Rajgopal, J., Lim, J., Gorham, K., Haidari, L., Brown, S.T. and Lee, B.Y., 2015; Chorin, P., Boned, A., Sebilleau, J., Colin, C., Schoele-Schulz, O., Picchi, N., Schwarz, C., Toth, B. and Mangini, D., 2023; Balderlou, M.A., Agrawal, M.K., Rao, B.N., El Jery, A., Al Alwan, B. and Sadeq, A.M., 2024; Cohen, Y., Naseraldin, H., Chaudhuri, A. and Pilati, F., 2019; Michalos, G., Makris, S., Papakostas, N., Mourtzis, D. and Chryssolouris, G., 2010; Sayed Ahmed, S.A.E., Mesalhy, O.M. and Abdelatief, M.A., 2015).

Particularly noteworthy are “confuser-diffuser” heat exchange tubes, in which heat transfer exceeds the increase in hydraulic resistance and heat transfer is intensified both inside and outside the tubes. The main disadvantage of such tubes is the difficulty of assembling them into a densely packed bundle of shell-and-tube heat exchangers (Konoplev, A.A., Rytov, B.L., Berlin, A.A. and Romanov, S.V., 2023). Enhanced heat transfers during the flow of Newtonian fluids in rotating smooth tube channels has been described in numerous research papers (Hosseinalipour, S.M., Shahbazian, H.R. and Sunden, B., 2018). However, articles devoted to the intensity of heat transfer during the movement of anomalously viscous fluids in rotating efficient tubes with diffuser-confuser turbulators are extremely limited, and those that do exist do not allow for the development of a coherent heat transfer theory. To improve heat transfer in confuser-diffuser tubes, a design modification was implemented by creating an ellipsoidal cross-section in the flow path of the tube. As the tube rotates around its axis, a centrifugal pressure gradient is generated, which promotes vortex motion of the flow and thereby intensifies heat transfer (Bubenchikov, A.A., Bubenchikova, T.V. and Shepeleva, E.Y., 2019). When the coolant flows around the tube, the relief formed by applying an ordered system of spherical depressions to the initially smooth surface is a characteristic of I. G. Kiknadze’s work. (van Nesselrooij, M., Veldhuis, L. L. M., Van Oudheusden, B. W. and Schrijer, F. F. J., 2016).

To determine the heat transfer coefficient K for direct contact between hot and cold coolants at the contact elements of equipment, a relationship can be used in the form (Kasatkin A. G., 2004).

$$Ki = \frac{K \cdot d_э}{\lambda} = 0{,}0011 \cdot \mathrm{Re}_г^{0{,}8} \cdot \mathrm{Re}_ж^{0{,}7} \qquad (1)$$

where K is the heat transfer coefficient, W/m^2·K; d_e is the equivalent diameter, m;

$$\mathrm{Re}_г = \frac{w_{op} \cdot d_э \cdot \rho_г}{V_{св} \cdot \mu_г} \qquad (2)$$

Here wop is the fictitious velocity, m/s; $d_e = 4Vcв/a$ is the free volume of the packing; $Re_{liquid} = 4\Gamma \cdot Vcв/3600\,\nu_{liquid}$·a is the Reynolds number of the liquid phase; Γ is the irrigation density, m^3/(m^2·s); a is the specific surface area of the packing, m^2/m^3; ν_{liquid} is the kinematic viscosity of the liquid phase.

Under similar conditions, Kagan A. M., Laptev A. G. et al. recommended the following formula for calculating the heat transfer in an apparatus with direct contact of both phases.

$$Ki = 0{,}01 \cdot \mathrm{Re}_{\text{г}}^{0{,}7} \cdot \mathrm{Re}_{\text{ж}}^{0{,}7} \cdot \mathrm{Pr}_{\text{г}}^{0{,}33} \qquad (3)$$

Here, $Re_{gas} = 4w_{op} \cdot \rho_{gas} / V_{cb} \cdot \mu_{gas}$ is the Reynolds number of the gas phase; $Re_{liquid} = 4\Gamma / a \cdot \mu_{liquid}$ is the Reynolds number of the liquid phase; $V_{св}$ is the free volume of the packing, m^3/m^3; λ_{gas} is the thermal conductivity of the gas, $W/(m\ K)$; cp is the specific heat capacity, $J/(\mathrm{kg}\ K)$.

Formula (1) describes the intensity of heat transfer during contact between the gas and liquid phases on the packing or trays of column apparatuses. In addition to the above formula, a number of formulas exist, in particular:

$$K_T = 3 \cdot 10^{-5} \cdot \mathrm{Re}_{\text{г}}^{1{,}705} \cdot \mathrm{Re}_{\text{ж}}^{0{,}03} \cdot \left(\frac{L}{G}\right)^{0{,}3} \cdot \mathrm{Pr}_{\text{г}}^{0{,}33} \cdot \frac{\lambda}{D} \qquad (4)$$

Kovalev O. P. and Ilyin A. K. presented a modified formula for calculating heat transfer by replacing the Kirpichev criterion with a generalized heat transfer coefficient (Kovalev O. P., 2012).

$$Nu = 0{,}007 \cdot \mathrm{Re}_{\text{г}}^{0{,}5} \cdot \mathrm{Re}_{\text{ж}}^{0{,}09} \cdot \mathrm{Pr}_{\text{г}}^{0{,}33} \qquad (5)$$

Kypritzis S. and Karabelas A. J., while studying the contact between the gas and liquid phases in a column apparatus with intensifiers, revealed the simultaneous occurrence of heat and mass transfer processes. They also established the dominant role of the gas phase in increasing heat transfer (Kypritzis S., Karabelas A. J., 2001).

$$Nu = 0{,}34 \cdot \mathrm{Re}_{\text{г}}^{0{,}8} \cdot \mathrm{Pr}_{\text{г}}^{0{,}33} \qquad (6)$$

However, reliable calculation formulas do not exist for tubular packing (or trays). Furthermore, such trays are often made up of tubes in a single row, and when tubular-grid packing in the form of a tube bundle is used, calculation formulas are not available.

Objects and methods:

A laboratory setup for studying convective heat transfer in a column apparatus with a tubular-grid packing consisting of a stack of tubes with spiral turbulators. A hot coolant is fed into the tube space of this packing from a closed, continuously circulating system consisting of experimental tubes with spiral turbulators, a tank with electric heating elements, flow and temperature measuring instruments, pumps, connecting pipes with a bypass line, control valves, and taps.

The liquid phase is directed into the intertube space of the tubular-grid packing from top to bottom, and the gas mixture from bottom to top. The temperature along the column height was measured with a temperature probe, in which Chromel-Copel thermocouples are installed every 50 mm. The tubes of the tubular-grid contact device are made of M1 copper, 1200 mm long, and have a diameter of de = 16 mm. They feature turbulators with a winding pitch of s/d = 5,11–14,2. The coolant in the tube channels of the packing moves in a transient flow regime at Reynolds numbers of 2300–9800. The tube wall temperature was measured at 12 points using Chromel-Copel thermocouples with electrode diameters of 0.1 mm. The first and last thermocouples are installed at a distance of 100 mm from both ends of the experimental tube.

Each series of experiments was calculated for heat balance, with deviations in the range of ±2,5%. Initial processing of the experimental data was performed using well-known methods and formulas.

Results and Discussion:

We conducted experimental studies to ensure isothermal performance of the column's coolant along its height using a tube-and-grate packing consisting of a tube bundle with spiral turbulators (Fig. 1). Smoothly contoured spiral turbulators are discretely placed within each tube, with an oval cross-section at their location. The winding pitch of the spiral turbulators is $s/d = 5{,}11$, the tube spacing on the tube sheet is $t/etd = 1.13$, and the gas phase flow velocity is $w = 1{,}42$ m/s.

Analysis of the graphs shows that the functional relationship $Ki = f(Re_{liquid})$ for both staggered and in-line tube arrangements in the tube sheet is ascending with increasing liquid flow velocity.

As can be seen from Fig. 1a, with a staggered arrangement of pipes, if the Reynolds number for the liquid phase is $Re_{liquid} = 50$, the numerical value of the Kirpichev criterion $Ki = 145$, and at $Re_{liquid} = 100$, the value of the criterion $Ki = 227$.

With a corridor arrangement of pipes, at $Re_{liquid} = 50$, the value of the criterion $Ki = 118$, and at $Re_{liquid} = 100$, the value of the criterion $Ki = 179$ (Fig. 1 b).

An analysis of Fig. 1 a and b shows that in both cases of tube arrangement on a tube sheet, with an increase in the Reynolds number, a significant increase in the Kirpichev criterion value, i.e., heat transfer, is observed; the only difference is in the numerical values of the number. Ki. Thus, for *t*/*d* = =1,13, with a staggered tube arrangement, the heat transfer intensity, depending on the flow velocity, fluctuates within the range of *Ki* = = 112–230, and with a corridor arrangement, in the range of *Ki* = 97–182. A comparison of different types of tube arrangement with spiral turbulators confirmed the well-known pattern for smooth tubes: a denser tube packing promotes an increase in the Kirpichev criterion number, i.e., heat transfer. This is explained by a characteristic feature of the channel shape, which, even at moderate flow velocities, is capable of generating vortices, which are then transformed into a flow with high turbulence, and, as a result, the washing of the heat exchange tube wall is significantly improved. A similar picture occurs when the liquid phase comes into contact with the gas phase on the outer surface of a tube package with smoothly defined turbulators.

A thorough and comprehensive analysis of the literature revealed that numerous criterion formulas have been proposed for calculating the intensity of heat transfer during direct contact between the liquid and gas phases on trays or packing. However, the most suitable formula is that of it (3), which takes into account the velocities of the gas and liquid phases using the Reynolds criterion, as well as the thermophysical properties of the gas phases. However, formula (3) does not take into account the geometry of the spiral turbulators and the pitch of their winding, as well as the degree of turbulence of the coolant in the channel and the gas-liquid flow in the intertube space of the tubular-lattice packing, on which the intensity of convective heat transfer strongly depends.

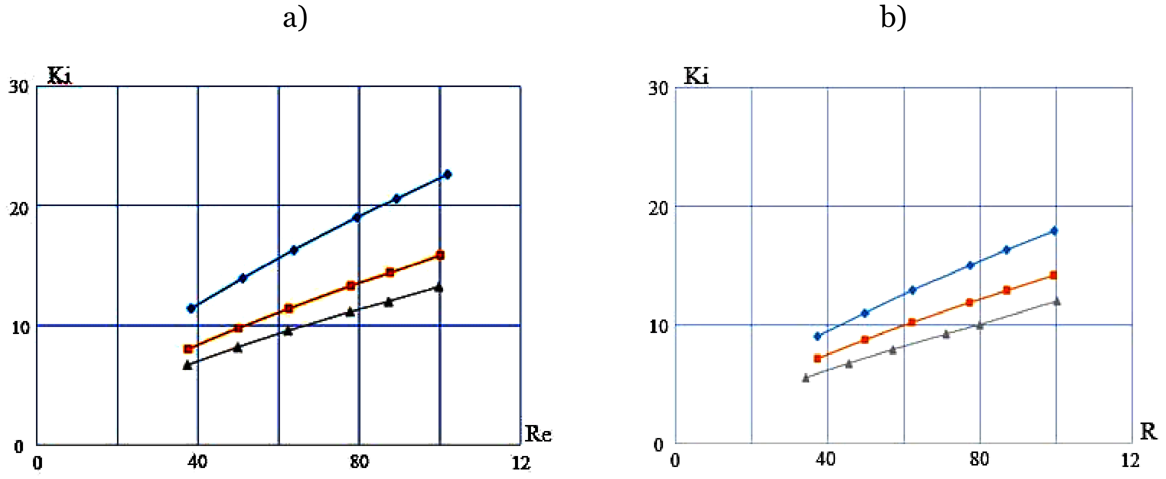
Therefore, we propose to introduce into the formula a correction factor χ, which is a function of the geometric parameters and the flow regime of the coolant inside the pipes:

$$\chi = f\left(\frac{s}{d}, \frac{t}{d}, \mathrm{Re}\right) \qquad (7)$$

and then, the formula for calculating heat transfer during heating of the vapor phase will look like:

$$Ki = 0{,}01 \cdot \mathrm{Re}_{\text{ж}}^{0,7} \cdot \mathrm{Re}_{\text{г}}^{0,7} \cdot \mathrm{Pr}_{\text{г}}^{0,33} \cdot \chi \qquad (8)$$

Figure 1. *Dependence of the Kirpicheev criterion Ki on the liquid velocity Re_{liquid} during the separation of an ethanol-water mixture in a contact device of the tubular-grid type with spiral tabulators*



staggered;

b) in-line.

♦ – t/d=1,13; ■ – t/d=1,3; ▲ – t/d=1,5; × – t/d=2; * – t/d=2,5; ● – t/d=3;

Here the parameter χ is determined by the formula:

$$\chi = A \cdot \left(\frac{s}{d}\right)^{b} \cdot \left(\frac{t}{d}\right)^{c} \cdot \mathrm{Re}^{d} \qquad (9)$$

Table 1. *The values of the coefficient A and the powers b, c, and d are given in Table*

Type of accommodation	Speed, m/c	A	b	c	d
Chess	w=1.2	1.13	–0.006	–0.28	0.0001
Chess	w=1.42	0.99	–0.008	–0.26	0.0195
Chess	w=1.8	0.97	–0.022	–0.24	0.0267

Figure 2. *Comparison of experimental data according to the Kirpichev criterion Ki_{exp} with calculated Ki_{calcul} when heating a steam coolant in tubular-lattice packing of rectification columns*

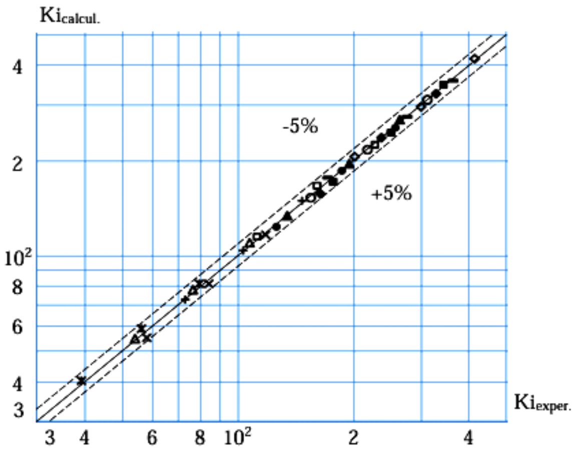


Figure 2. Shows a comparison of the calculated values of the Ki criterion with the experimental results.

t/d=1,13; ● – w=1,2 м/с;
■ – w=1,42 м/с; ▲ – w=1,8 м/с;
t/d=3,0; ♦ – w=1,2 м/с;
* – w=1,42 м/с; – w=1,8 м/с.

Formula (10) is valid in the range of parameter changes: liquid Reynolds number Reliquid = 30–132, gas phase Reynolds number Regas = 4500–20600, Prandtl criterion Pr = 0.55–0.7 and its error is no more than ±5.0% (Fig. 2).

Conclusion

Experimental studies investigating convective heat transfer during direct contact between liquid and gas phases using an efficient contact device consisting of a tubular-grid packing composed of tubes with a developed surface area showed that such packing increases gas-liquid flow turbulence and enhances phase contact, thereby enhancing heat transfer and equalizing the temperature field across the entire column height. The use of the developed contact device has resulted in heat transfer intensification by a factor of 1.5 or more. The derived criteria formula describes convective heat transfer during flow contact in a device consisting of a tube package with spiral turbulators with sufficient accuracy over a wide range of geometric and operating parameters. A distinctive feature of this tube package packing is that the coolant inside the tubes moves in a transient mode, which reduces energy costs for pumping it.

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Contact: haas-bek@mail.ru; elbek8181@mail.ru; anuryllaeva@mail.ru;
newlandtravel@mail.ru; absattorov111@gmail.com