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EXPERIMENTAL DETERMINATION OF THE EFFICIENCY OF RECUPERATIVE HEAT EXCHANGERS

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Abstract. *The paper discusses the efficiency of recuperative heat exchangers. Thermodynamic efficiency has been selected as the measure of efficiency for recuperative heat exchangers. The authors present diagrams of experimental setups designed to investigate energy utilisation efficiency for various heat transfer agents flow patterns in 'tube-in-tube' and shell-and-tube heat exchangers. A methodology and procedure for determining the thermodynamic efficiency of heat exchangers are presented. The authors found that, in a counter-flow configuration, the thermodynamic efficiency is 5–10% higher than in a direct-flow one. At the specified heat transfer fluid flow rates, the thermodynamic efficiency of a tube-in-tube heat exchanger is 25–30% higher than that of a shell-and-tube. The experimental data obtained will subsequently enable the appropriate selection of heat exchanger type and the rational design of heat transfer agent flow patterns. It depens on the specific operating conditions of the heat exchanger, thereby significantly improving process efficiency.*

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Introduction

Energy saving is a key factor in the country's economic development [1]. The issues of increasing energy efficiency and reducing energy consumption in manufacturing are a priority, as technological processes and operations in the oil refining, petrochemical, chemical, food, pharmaceutical, microbiological and metallurgical sectors are characterised by high energy consumption. To assess energy efficiency, it is necessary to have reliable indicators that can be used to compare actual results with the maximum potential for energy savings. In recuperative heat exchangers, heat transfer from the hot medium to the cold medium occurs across a partition wall. Moreover, it is a complex process due to a number of factors [1, 2]. Accurate calculation and assessment of the energy efficiency of heat exchangers are crucial for optimising production processes and reducing operating costs. Recently, the exergetic method of thermodynamic analysis has become widely used in the assessment of heat transfer efficiency.

It enables a more in-depth analysis of the process, improves understanding of the underlying mechanisms, and reduces the costs of heat transfer agents. The exergetic efficiency of a shell-and-tube heat exchanger, as determined by this method, makes it possible to analyse the qualitative aspects of the process of converting heat into energy, identify its causes, calculate losses in thermal efficiency, and propose ways of eliminating them, thereby improving the efficiency of the device [3].

For many years, experimental research has been conducted in the research laboratories of the Department of Chemical Engineering Processes and Equipment at Yaroslavl State Technical University, Yaroslavl, Russia on spray apparatus and gas-liquid reactors utilising ejection gas dispersion. In experimental systems, during studies of hydrodynamics and mass transfer in gas-liquid reactors with gas-liquid ejection dispersion, the liquid was circulated repeatedly through the nozzle bypass line and ejectors by pumps [4, 5]. Indeed, during the process it was heated to high temperatures. Therefore, a heat exchanger (shell-and-tube or 'tube-in-tube') was installed on the recirculation line to cool the fluid. The choice of heat exchanger was based on the heat exchanger currently available in the laboratory.

The purpose of this study is to determine experimentally the thermodynamic efficiency of heat exchangers (shell-and-tube and 'tube-in-tube' types), and compare the two main heat transfer agents flow patterns: direct flow and counter-flow.

Main body

Heat exchangers in chemical and oil refining plants make up about 40% of the total weight of equipment, due to the need to supply or remove heat from the process [6].

The nature of the temperature changes in the heat transfer fluids across the surface of the recuperative heat exchanger depends on their flow pattern. The simplest flow configurations are: direct flow and counter-flow (Fig. 1).

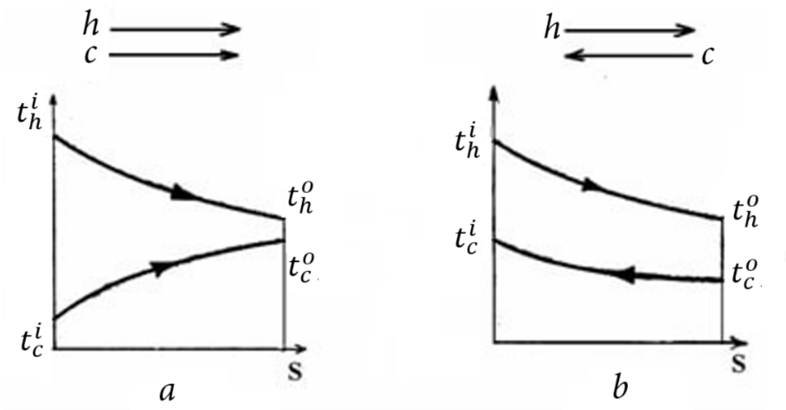

Fig. 1. Heat transfer fluid agent patterns: a – direct flow pattern, b – counter-flow pattern

The efficiency of a heat exchanger is determined by a number of factors, including the design of the unit itself, the flow pattern of the heat transfer agents, and the operating conditions. Selecting the optimal heat exchanger design is a complex task. It is resolved by conducting a technical and economic comparison of several unit sizes in relation to the specified conditions or on the basis of optimisation criteria [1, 7].

The heat transfer fluid flow rates are denoted as follows: cold G_c (kg/s) and hot G_h (kg/s). The temperature of the heat transfer fluids changes from the initial temperature (index *i*) to the final temperature (index *o*) as a result of heat exchange.

Heat balance of the apparatus:

$$G_c c_c t_c^i + G_h c_h t_h^i = G_c c_c t_c^o + G_h c_h t_h^o + Q_{loss},$$

where Q_{loss} is the heat loss to the environment, W;

$t_c^i, t_h^i, t_c^o, t_h^o$ is the temperature of the cold and hot heat transfer fluid at the inlet and outlet of the heat exchanger, respectively, °C.

After transforming the equation, we obtain

$$G_h c_h \Delta t_h = G_c c_c \Delta t_c + Q_{loss} \text{ or } Q_h = Q_c + Q_{loss},$$

where $\Delta t_h = t_h^i - t_h^o, \Delta c = t_c^o - t_c^i$.

The last equation shows that the amount of heat released by the hot heat transfer fluid (Q_h) is equal to the sum of the heat absorbed by the cold heat transfer fluid (Q_c) and the heat lost to the environment (Q_{loss}).

In this case $Q_{loss} = 0$, we have $Q_h = Q_c$ and $G_h c_h \Delta t_h = G_c c_c \Delta t_c$.

The thermal load of the unit is equal to the amount of heat transferred from the hot to the cold heat transfer fluid:

$$Q = G_c c_c (t_c^o - t_c^i) = G_h c_h (t_h^i - t_h^o).$$

The thermodynamic efficiency of a heat exchanger is the ratio of the amount of heat transferred to the cold fluid in that heat exchanger to the amount of heat transferred in a heat exchanger with an infinitely large heat transfer surface area and the same inlet conditions. The efficiency of a heat exchanger is determined using the formula [1, 3]:

$$E = \frac{t_c^o - t_c^i}{t_h^i - t_h^o}.$$

The operating characteristics and flow patterns (direct flow and counter-flow) of recuperative heat exchangers can be compared in terms of the heat transfer efficiencies achieved:

$$j = \frac{E_{direct}}{E_{counter}}.$$

I. Determination of the thermodynamic efficiency of 'tube-in-tube' heat exchangers

Fig. 2 shows a diagram of the experimental apparatus. The 'tube-in-tube' heat exchanger is connected to a piping system. Cold water flows through the inter-tube (annular) space in a single direction. Hot water flows through the tube space (inner tube). By opening or closing valves 1–4, direct-flow and counter-flow configurations of the heat transfer fluid flow are achieved. Table 1 presents experimental data. Table 2 presents the properties of the heat transfer fluids at average temperatures of the hot and cold fluids. Table 3 presents the results of calculations to determine the thermodynamic efficiency of the 'pipe-in-pipe' heat exchanger.

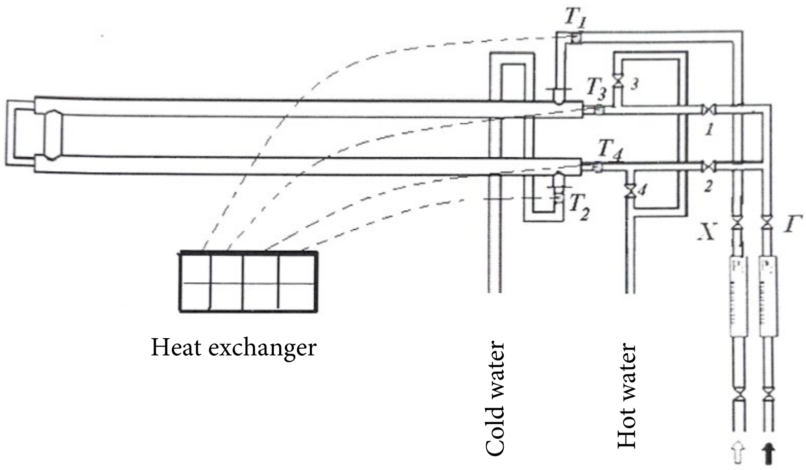

Fig. 2. Schematic diagram of the pilot plant

Thermocouples (T1–T4), connected to a resistance temperature transducer, are used to measure the initial and final temperatures of the heat transfer fluids. The signal from the temperature transducer is fed into the computer programme. Heat transfer fluid flow rates are measured by rotameters P1 and P2. The specific heat capacity of water within the operating temperature range is 4190 J/(kg·K).

Key specifications of the 'tube-in-tube' heat exchanger:

Inner pipe diameter $d_{out} \times \delta_{wall} = 27 \times 3\ mm$;

Outer pipe diameter $D_{out} \times \delta_{wall} = 48 \times 4\ mm$;

Total length of the heat exchanger $L = 6$ m;

Heat transfer surface $S = 0.452$ m^2;

Thermal conductivity coefficient $\lambda_{wall} = 46.5$, W/(m·K)

Table 1. Results of experimental studies to determine the thermodynamic efficiency of a 'tube-in-tube' heat exchanger.

Flow diagram for heat transfer agents	Heat transfer agent flow rate, kg/s	t_h^i	t_h^o	t_c^i	t_c^o	t_h^{av}	t_c^{av}	E
Direct flow	0.16	66.7	49.3	8.9	29.6	58.00	19.25	0.358
	0.32	66.7	50.4	8.9	27.3	58.30	18.10	0.321
	0.47	66.7	51.5	8.9	25.6	59.10	17.35	0.289
Counter-flow	0.16	66.7	50.2	8.9	31.8	58.40	20.45	0.396
	0.32	66.7	51.0	8.9	28.9	58.85	19.00	0.346
	0.47	66.7	51.8	8.9	26.3	59.25	17.60	0.304

The calculations were performed as follows

a) Velocity of the hot heat transfer agent v_h, m/s –

$$v_h = \frac{G}{\rho_h \frac{\pi d_{inn}^2}{4}} = \frac{4G}{\rho_h \cdot 3.14 \cdot 0.021^2}.$$

b) Velocity of the cold heat transfer agent v_c, m/s –

$$v_c = \frac{G}{\rho_h \left(\frac{\pi D_{inn}^2}{4} - \frac{\pi d_{out}^2}{4}\right)} = \frac{4G}{\rho_h \cdot 3.14 \cdot (0.04^2 - 0.027^2)}.$$

c) the Reynolds number of the hot heat transfer agent,

$$\mathrm{Re} = \frac{v_h d_{inn} \rho_h}{\mu_h}.$$

Table 2. Properties of heat transfer agents

Direction of flow	Heat transfer agent	Average temperature, t_{av}	Dynamic viscosity μ, Pa·s	Density ρ, kg/m³	Thermal conductivity coefficient λ, W/m·K	Prandtl's criterion Pr
Direct flow	Hot	58.00	0.4832	983.9	0.5609	3.61
		58.30	0.4810	983.8	0.5612	3.59
		59.10	0.4752	983.4	0.5620	3.54
	Cold	19.25	1.0238	998.1	0.5186	8.27
		18.10	1.0534	998.2	0.5168	8.54
		17.35	1.0736	998.3	0.5156	8.72
Counter-flow	Hot	58.43	0.4801	983.7	0.5613	3.58
		58.85	0.4770	983.5	0.5618	3.56
		59.25	0.4741	983.3	0.5622	3.53
	Cold	20.45	0.9942	997.9	0.5169	8.06
		19.00	1.0300	998.1	0.5182	8.33
		17.60	1.0668	998.2	0.5160	8.66

d) The Reynolds number of the cold heat transfer agent,

$$\mathrm{Re} = \frac{v_f d_e \rho_f}{\mu_f}.$$

The equivalent diameter of the annular space in a 'tube-in-tube' heat exchanger was:

$$d_e = \frac{4\left(\frac{\pi D_{inn}^2}{4} - \frac{\pi d_{out}^2}{4}\right)}{\pi D_{inn} + \pi d_{out}} = D_{inn} - d_{out} = 0.04 - 0.0027 = 0.013\, m.$$

e) Nusselt's criterion Nu [8–10]:

If $\mathrm{Re} < 2320$

$$\mathrm{Nu} = 1.55\left(\mathrm{Re} \cdot \mathrm{Pr} \cdot \frac{d}{L}\right)^{1/3} \left(\frac{\mu}{\mu_{wall}}\right)^{0.25}.$$

If $2320 < \mathrm{Re} < 10000$

$$\mathrm{Nu} = 0.008 \cdot \mathrm{Re}^{0.9} \cdot \mathrm{Pr}^{0.43}.$$

If $\mathrm{Re} > 10000$

$$Nu = 0.021 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.43} \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_{wall}}\right)^{0.25}.$$

e) The heat transfer coefficient is calculated using the following equations:

$$\alpha_h = \frac{\mathrm{Nu}_h \lambda_h}{d_{inn}},$$

$$\alpha_c = \frac{\mathrm{Nu}_c \lambda_c}{d_e}.$$

f) Thermal resistance of the wall [9]:

$$\sum r_{wall} = \frac{\delta_{wall}}{\lambda_{wall}} + r_{load1} + r_{load2} = \frac{0.003}{46.5} + 2\frac{1}{11600} = 0.000237\ \frac{m^2 \cdot K}{W},$$

where r_{load1}, r_{load2} is the thermal resistance on the hot and cold heat transfer agent side, respectively.

g) The heat transfer coefficient is calculated using the following equation:

$$K = \frac{1}{\frac{1}{\alpha_h} + \sum r_{wall} + \frac{1}{\alpha_c}}.$$

i) The value

$$\frac{K \cdot S}{W} = \frac{K \cdot 0.452}{G \cdot 4190}\ \frac{\mathrm{W}}{\mathrm{K}}.$$

Table 3. Results of calculations to determine the thermodynamic efficiency of a 'tube-in-tube' heat exchanger.

Heat transfer agent flow rate, kg/s	Velocity of the hot heat transfer agent v_h, m/s	Velocity of the cold heat transfer agent v_c, m/s	The Reynolds number of the hot heat transfer agent Re_h	The Reynolds number of the cold heat transfer agent Re_c	The Nusselt's number of the hot heat transfer agent Nu_h	The Nusselt's number of the cold heat transfer agent Nu_c	Heat transfer coefficient of the hot heat transfer agent α_h	Heat transfer coefficient of the cold heat transfer agent α_h	Heat transfer coefficient K, W/(m²·K)	Parameter $\frac{K \cdot S}{W}$, W/K	j
0.16	0.470	0.234	20097	2971.4	101.0	26.5	2697.2	1057.3	643.7	0.43399	0.904
0.32	0.940	0.469	40375	5775.8	176.1	48.9	4705.5	1942.9	1037.1	0.34963	0.928
0.47	1.381	0.689	60016	8323.6	240.4	68.5	6433.8	2718.1	1315.2	0.30187	0.951

II. Determination of the thermodynamic efficiency of a shell-and-tube heat exchanger

The diagram of the experimental apparatus is similar to that of used to study the 'tube-in-tube' heat exchanger (Fig. 2). A shell-and-tube heat exchanger has been installed to replace the tube-in-tube heat one. Table 4 presents experimental data. Table 5 presents the properties of the heat transfer fluids at average temperatures of the hot and cold fluids. Table 6 presents the results of calculations to determine the thermodynamic efficiency of the 'pipe-in-pipe' heat exchanger.

Key parameters of the shell-and-tube heat exchanger:

Inner pipe diameter $d_{out} \times \delta_{wall} = 14 \times 2\ mm$;

Housing diameter $D_h = 200\ mm$;

Total length of the heat exchanger $L = 0.5$ m;

Heat transfer surface $S = 1.34$ m²;

Thermal conductivity coefficient $\lambda_{wall} = 17.5$, W/(m·K)

Table 4. Experimental data from studies on the determination of the thermodynamic efficiency of a shell-and-tube heat exchanger.

Flow diagram for heat transfer agents	Heat transfer agent flow rate, kg/s	t_h^i	t_h^o	t_c^i	t_c^o	t_h^{av}	t_c^{av}	E
Direct flow	0.16	66.7	55.8	8.9	23.5	61.25	16.20	0.253
	0.32	66.7	57.0	8.9	22.0	61.85	15.45	0.227
	0.47	66.7	58.2	8.9	20.2	62.45	14.55	0.196
Counter-flow	0.16	66.7	56.0	8.9	25.2	61.35	17.65	0.282
	0.32	66.7	57.6	8.9	23.1	62.15	16.00	0.246
	0.47	66.7	59.2	8.9	21.5	62.95	15.20	0.218

The calculations were performed as follows

a) Velocity of the hot heat transfer agent v_h, m/s –

$$v_h = \frac{G}{\rho_h \frac{\pi d_{inn}^2}{4} n} = \frac{4G}{\rho_h \cdot 3.14 \cdot 0.01^2 \cdot 61}.$$

b) Velocity of the cold heat transfer agent v_c, m/s –

$$v_c = \frac{G}{\rho_h \left(\frac{\pi D_h^2}{4} - n\frac{\pi d_{out}^2}{4}\right)} = \frac{4G}{\rho_h \cdot 3.14 \cdot (0.2^2 - 61 \cdot 0.014^2)}.$$

c) The Reynolds number of the hot heat transfer agent

$$\mathrm{Re} = \frac{v_h d_{inn} \rho_h}{\mu_h}.$$

d) The Reynolds number of the cold heat transfer agent,

$$\mathrm{Re} = \frac{v_f d_e \rho_f}{\mu_f}.$$

The equivalent diameter of the inter-tube space in the shell-and-tube heat exchanger was:

$$d_e = \frac{4\left(\frac{\pi D_h^2}{4} - \frac{\pi d_{out}^2}{4} n\right)}{\pi D_{inn} + \pi d_{out} n} = \frac{D_h^2 - d_{out}^2 n}{D_h + d_{out} n} = \frac{0.2^2 - 0.014^2 \cdot 61}{0.2 + 0.014 \cdot 61} = 0.0266\, m.$$

Table 5. Properties of heat transfer agents.

Direction of flow	Heat transfer agent	Average temperature, t_{av}	Dynamic viscosity μ, Pa·s	Density ρ, kg/m³	Thermal conductivity coefficient λ, W/(m·K)	Prandtl's criterion Pr
Direct flow	Hot	61.25	0.4601	982.3	0.5635	3.4210
		61.85	0.4560	982.0	0.5644	3.3850
		62.45	0.4520	981.7	0.5654	3.3500
	Cold	16.20	1.1054	998.4	0.5138	9.0145
		15.45	1.1270	998.5	0.5126	9.2121
		14.55	1.1540	998.5	0.5111	9.4605
Counter-flow	Hot	61.35	0.4594	982.3	0.5637	3.4147
		62.15	0.4540	981.8	0.5649	3.3674
		62.95	0.4486	981.4	0.5662	3.3197
	Cold	17.05	1.0817	998.3	0.5151	8.7989
		16.00	1.1110	998.4	0.5135	9.0654
		15.20	1.1342	998.5	0.5123	9.2764

e) Nusselt's criterion Nu_h:
If $\mathrm{Re} < 2320$

$$Nu = 1.55\left(\mathrm{Re} \cdot \mathrm{Pr} \cdot \frac{d}{L}\right)^{1/3} \left(\frac{\mu}{\mu_{av}}\right)^{0.25}.$$

If $2320 < \mathrm{Re} < 10000$

$$Nu = 0.008 \cdot \mathrm{Re}^{0.9} \cdot \mathrm{Pr}^{0.43}.$$

If $\mathrm{Re} > 10000$

$$Nu = 0.021 \cdot \mathrm{Re}^{0.8} \cdot \mathrm{Pr}^{0.43} \left(\frac{\mathrm{Pr}}{\mathrm{Pr}_{av}}\right)^{0.25}.$$

e) The heat transfer coefficient is calculated using the following equations:

$$\alpha_h = \frac{Nu_h \lambda_h}{d_{inn}},$$

$$\alpha_c = \frac{Nu_c \lambda_c}{d_e}.$$

f) Thermal resistance of the wall

$$\sum r_{wall} = \frac{\delta_{wall}}{\lambda_{wall}} + r_{load1} + r_{load2} = \frac{0.003}{46.5} + 2\frac{1}{11600} = 0.000237\ \frac{m^2 \cdot \mathrm{K}}{W}.$$

g) The heat transfer coefficient is calculated using the following equation:

$$K = \frac{1}{\frac{1}{\alpha_h} + \sum r_{wall} + \frac{1}{\alpha_c}}.$$

i) The value

$$\frac{K \cdot S}{W} = \frac{K \cdot 1.34}{G \cdot 4190}\ \frac{\mathrm{W}}{\mathrm{K}}.$$

Table 6. Results of calculations to determine the thermodynamic efficiency of a shell-and-tube heat exchanger.

Heat transfer agent flow rate, kg/s	Velocity of the hot heat transfer agent v_h, m/s	Velocity of the cold heat transfer agent v_c, m/s	The Reynolds number of the hot heat transfer agent Re_h	The Reynolds number of the cold heat transfer agent Re_c	The Nusselt's number of the hot heat transfer agent Nu_h	The Nusselt's number of the cold heat transfer agent Nu_c	Heat transfer coefficient of the hot heat transfer agent α_h	Heat transfer coefficient of the cold heat transfer agent α_c	Heat transfer coefficient K, W/(m²·K)	Parameter $\frac{K \cdot S}{W}$, W/K	j
0.16	0.0340	0.0073	726.2	174.9	5.7	66.5	321.1	1283.7	239.2	0.4782	0.879
0.32	0.0681	0.0146	1465.5	343.1	7.2	83.8	405.0	1614.8	296.3	0.2961	0.923
0.47	0.1000	0.0214	2171.5	492.1	8.2	95.3	460.9	1832.0	333.1	0.2266	0.960

Based on the results of experimental studies to determine the thermodynamic efficiency of heat exchangers, the following relationships $j = f\left(\frac{K \cdot S}{W}\right)$ have been plotted (Figure 3).

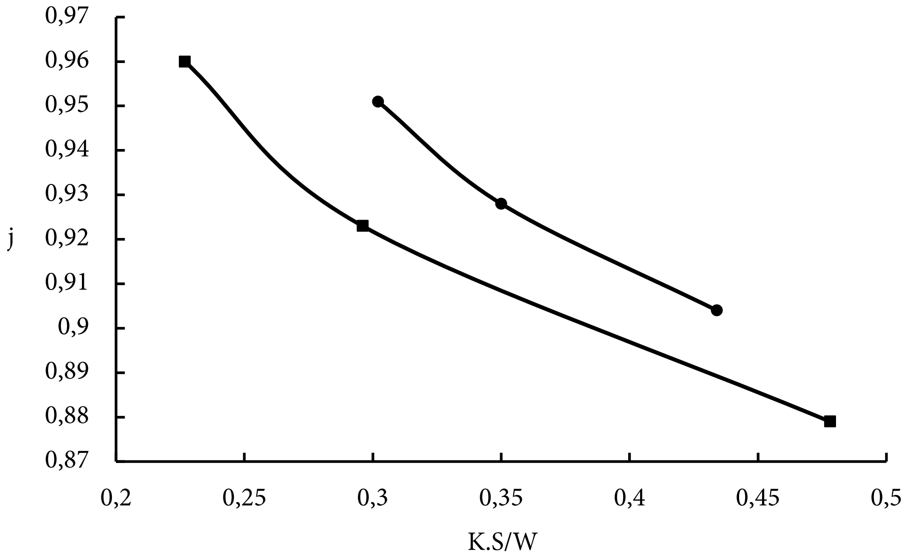

Fig. 3. Experimental data for determining the thermodynamic efficiency of heat exchangers: ● – 'tube-in-tube' type; ▪ – shell-and-tube heat exchanger.

Conclusions

1. Thermodynamic efficiency has been chosen as the measure of performance for recuperative heat exchangers.

2. There was made a comparison of the thermodynamic efficiency of recuperative heat exchangers for two heat transfer fluid flow patterns: direct flow and counter-flow. In counter-flow systems, thermodynamic efficiency is 5–10% higher than in direct-flow systems.

3. At the specified heat transfer fluid flow rates, the thermodynamic efficiency of a tube-in-tube heat exchanger is 25–30% higher than that of a shell-and-tube heat exchanger. This can be explained by the fact that, in a 'tube-in-tube' heat exchanger, the flow mode of the heat transfer agents in the tube and inter-tube spaces is transitional or turbulent. It provides high heat transfer coefficients.

4. Experimental relationships have been obtained $j = f\left(\frac{K \cdot S}{W}\right)$. When the values $\frac{K \cdot S}{W}$ of the ratio$j$ are small, they tend towards one.

5. The choice of heat exchanger depends on the specific conditions. It is necessary to ensure the flow of the heat transfer agents in a turbulent mode within the tube and shell spaces.

References

1. **Girba, E.A., Leontiev, V.K.** Theoretical Foundations of Energy and Resource Saving: A Study Guide. Yaroslavl: YSTU Press, 2011, 132 pp. (in Russian).
2. **Andrizhevsky, A.A., Volodin, V.I.** Energy Saving and Energy Management: A Textbook – 2nd revised edition. Minsk: Vysshaya Shkola, 2005, 294 pp. (in Russian).

3. **Kruchinin, M.I., Shadrina, E.M.** Theoretical Foundations of Energy and Resource Conservation. Exergetic Analysis of Heat Exchangers: A Study Guide. Ivanovo State Chemical-Technical University: Ivanovo, 2007, 44 pp. (in Russian).
4. **Galitsky, I.V.** A Study of Hydrodynamics and Mass Transfer in Reactors with Ejection Gas Dispersion, Candidate of Technical Sciences dissertation. Moscow, 1978, 202 pp. (in Russian).
5. **Leontiev V.K.** Interphase surface, flow structure and calculation methodology of apparatuses with ejection gas dispersion: Dissertation of Candidate of Technical Sciences. Yaroslavl, 1984. 186 p. (in Russian).
6. **Ivanov, A.N., Belousov, V.N., Smorodin, S.N.** Heat Exchange Equipment for Industrial Enterprises: A Study Guide. Higher School of Technology, St. Petersburg State University of Technology and Design. St. Petersburg, 2016, 184 pp. (in Russian).
7. **Troshin, A.Yu., Naumov, A.M.** Intensification of Heat Transfer in Shell-and-Tube Heat Exchangers: A Study Guide. Voronezh: Voronezh State Technical University, 2016, 132 pp. (in Russian).
8. **Isachenko V.P., Osipova V.A., Sukomel A.S.** Heat Transfer: A Textbook for Universities – 3rd ed., revised and expanded. Moscow: 'Energia', 1975, 488 pp. (in Russian).
9. **Khomenko A.S., Chernov S.K.** Calculation and Design of Heat Exchangers with Finned Surfaces. Kharkiv Aviation Institute, 2005 (in Russian).
10. **Pavlov K.F., Romankov P.G., Noskov A.A.** Examples and Exercises in Chemical Engineering Processes and Apparatus: A Textbook for Universities, edited by P.G. Romankov, Corresponding Member of the Russian Academy of Sciences. – 12th ed., reprint. Reprint of the 1987 edition. Moscow: Alliance Publishing House Ltd, 2005, 576 pp. (in Russian).
11. **Kalinin, E.K., Dreitser, Y.K., Yarkho, S.A.** Intensification of Heat Transfer in Channels. Moscow: Mashinostroenie, 1990, 200 pp. (in Russian).
12. **Kutateladze, S.S., Borishansky, V.M.** Handbook of Heat Transfer. Moscow and Leningrad: Gosenergoizdat, 1959 (in Russian).
13. **Mikheev M.A., Mikheeva I.M.** Fundamentals of Heat Transfer. Moscow: Energiya, 1973 (in Russian).
14. **Isachenko, V.P., Osipova, V.A., Sukomel, A.S.** Heat Transfer. Moscow: Energoizdat, 1981 (in Russian).

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