Scientific article
UDC 66.045
DOI: 10.52957/2782-1900-2026-7-2-143-149

DETERMINATION OF THE ENERGY AND EXERGY EFFICIENCY COEFFICIENTS OF RECUPERATIVE HEAT EXCHANGERS

V.K. Leontiev[1], O.N. Korableva[1], A.V. Leontiev[2]

Valery Konstantinovich Leontiev, Candidate of Technical Sciences; **Korableva Olga Nikolaevna**, Candidate of Chemical Sciences, Associate Professor; **Leontiev Alexey Valerievich**, Head of the Fire Safety Research and Testing Sector

[1]Yaroslavl State Technical University, 150023, Russia, Yaroslavl, 88 Moskovsky pr.; *korablevaon@ystu.ru*

[2]Forensic Expert Institution of the Federal Fire Service "Fire Testing Laboratory" in the Yaroslavl region, 150539, Russia, Yaroslavl region, Yaroslavsky district, Lesnaya Polyana village, 4; *alex-leontyev@mail.ru*

Keywords:
recuperative heat exchangers, heat, exergy, energy and exergy efficiency coefficients

Abstract. *The article examines methods for determining the energy and exergy efficiency coefficients of heat exchange apparatuses. The experimental dependences of the energy and exergy efficiency coefficients on the value of KS/W for a pipe-in-pipe heat exchanger and a shell-and-tube heat exchanger were obtained. According to the authors' counterflow scheme of coolant movement, the values of both efficiency coefficients are higher than for the parallel-flow scheme. Moreover, at small values of KS/W (less than 0.22–0.24), the values of the energy and exergy efficiency coefficients for the shell-and-tube heat exchanger are higher than those for the pipe-in-pipe heat exchanger. Indeed, at large values of KS/W, the efficiency of the pipe-in-pipe heat exchanger is higher than that of the shell-and-tube heat exchanger.*

For citation:
Leontiev V.K., Korableva O.N., Leontiev A.V. Determination of the energy and exergy efficiency coefficients of recuperative heat exchangers // From Chemistry towards Technology Step-by-Step. 2026. Vol. 7, Iss. 2. P. 143-149. URL: https://chemintech.ru/en/nauka/issue/7273/view

Introduction

Previously, based on experimental data, the thermodynamic efficiency of recuperative heat exchangers was determined. A comparison of the thermodynamic efficiency of recuperative heat exchangers for two flow arrangements of heat transfer fluids, parallel flow, and counterflow was provided. The advantage of the counterflow arrangement was confirmed, resulting in the thermodynamic efficiency 5–10% higher than under parallel flow. At the selected flow rates of the heat transfer fluids, the thermodynamic efficiency of the pipe-in-pipe heat exchanger is higher than that of the shell-and-tube heat exchanger [1].

Main body

The purpose of this study is to compare the efficiency of recuperative heat exchangers based on the energy and exergy efficiency coefficients.

The energy efficiency of heat exchangers is one of the most important indicators of heat exchanger performance [2–6].

A visual representation of the energy and material flows of the heat exchange process is presented in the diagram (Fig. 1).

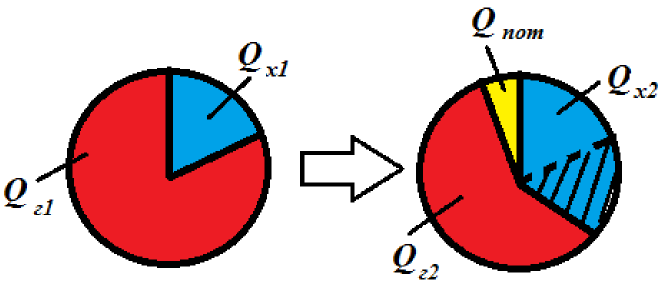


Fig. 1. Diagram for the heat transfer process without a change in the aggregate state of the media.

The energy efficiency characterises the ratio between the heat received by the cold heat transfer fluid and the maximum possible (available) amount of heat that can be transferred to the cold heat transfer fluid. It shows the fraction of the maximum possible heat is actually transferred through the apparatus:

$$\eta_{en} = \frac{Q_{c2} - Q_{c1}}{Q_{h1}}$$

where $Q_{c2}$is an amount of heat leaving the heat exchanger with the cold heat transfer fluid, W;
Q_{c1} is an amount of heat entering the heat exchanger with the cold heat transfer fluid, W;
Q_{h1} is an amount of heat entering the heat exchanger with the hot heat transfer fluid, W.

$$Q_{c2} = Gct_{c2}, \qquad Q_{c1} = Gct_{c1}, \qquad Q_{h1} = Gct_{h1}.$$

where $G$is mass flow rate of the heat transfer fluid, kg/s;
c is specific heat capacity of the heat transfer fluid, J/(kg·K);
t_{c2} is temperature of the cold heat transfer fluid at the outlet of the heat exchanger, °C;
t_{c1} is temperature of the cold heat transfer fluid at the inlet of the heat exchanger, °C;
t_{h1} is temperature of the hot heat transfer fluid at the inlet of the heat exchanger, °C;

The amount of heat transferred to the cold heat transfer fluid is determined as

$$Q_{c2} - Q_{c1} = Q_c.$$

The energy efficiency of heat exchangers is influenced by many factors, including the flow velocity of the heat transfer fluids, which contributes to an increase in heat transfer coefficients; fouling of heat exchanger surfaces; and design parameters of the heat exchangers (helical ridges in tubes, spiral channels, transverse baffles).

To improve the energy efficiency of heat exchangers, methods of heat transfer intensification and reduction of heat exchanger surface fouling are used. However, heat transfer intensification leads to an increase in the energy consumption required to overcome the growing hydraulic resistance. Consequently, the increase in heat transfer intensity should be balanced against the increase in hydraulic resistance [3].

Experimental studies were conducted for recuperative heat exchangers of the pipe-in-pipe type and a single-pass shell-and-tube heat exchanger. Table 1 shows the main parameters of the heat exchangers.

Table 1. Main parameters of the heat exchangers

Pipe-in-pipe heat exchanger	Shell-and-tube heat exchanger
Inner pipe diameter $d_{н}\text{x}\delta_{ст} = 27\text{x}3$ mm; Outer pipe diameter $D_{н}\text{x}\delta_{ст} = 48\text{x}4$ mm; Total length of the heat exchanger $L = 6$ m; Heat transfer surface $S = 0.452$ m^2; Thermal conductivity coefficient $\lambda_{ct} = 46.5$, W/(m·K)	Inner pipe diameter $d_{н}\text{x}\delta_{ст} = 14\text{x}2$ mm; Housing diameter $D_{st} = 200$ mm; Total length of the heat exchanger $L = 0.5$ m; Heat transfer surface $S = 1.34$ m^2; Thermal conductivity coefficient $\lambda_{ct} = 17.5$, W/(m·K)

Thermocouples, 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. The flow rates of the heat transfer fluids were measured with rotameters and were kept the same for hot and cold water.

Table 2 presents the results of experimental and calculated data for determining the energy efficiency.

Table 2. Results of the study on determining the energy efficiency of recuperative heat exchangers.

Heat exchanger type	Flow diagram	Heat transfer agent flow rate, G, kg/s	t_{h1}, °C	t_{c1}, °C	t_{c1}, °C	Q_c, W	Q_h, W	η_{en}	$\frac{KS}{W}$
pipe-in-pipe	direct flow	0.16	66.7	8.9	29.6	13877.28	44715.68	0.310	0.434
		0.32	66.7	8.9	27.3	24670.72	89431.36	0.276	0.35
		0.47	66.7	8.9	25.6	32887.31	131352.3	0.250	0.302
	counterflow	0.16	66.7	8.9	31.8	15352.16	44715.68	0.343	0.434
		0.32	66.7	8.9	28.9	26816.00	89431.36	0.300	0.35
		0.47	66.7	8.9	26.3	34265.82	131352.3	0.261	0.302
shell-and-tube	direct flow	0.16	66.7	8.9	23.5	9787.84	44715.68	0.219	0.478
		0.32	66.7	8.9	22	17564.48	89431.36	0.196	0.296
		0.47	66.7	8.9	20.2	22253.09	131352.3	0.169	0.227
	counterflow	0.16	66.7	8.9	25.2	10927.52	44715.68	0.244	0.478
		0.32	66.7	8.9	23.1	19039.36	89431.36	0.213	0.296
		0.47	66.7	8.9	21.5	24813.18	131352.3	0.189	0.227

To compare the efficiency of recuperative heat exchangers in terms of energy efficiency, the dependences $\eta_{en} = f\left(\frac{KS}{W}\right)$ were plotted. As the argument in this dependence, the quantity $\left(\frac{KS}{W}\right)$ was chosen, where K is the heat transfer coefficient, W s/m2; S is the heat transfer surface area, m^2; $W = G \cdot c$ is the water equivalent, W/K.

Figures 2 and 3 show the obtained dependences for the pipe-in-pipe heat exchanger and the shell-and-tube heat exchanger for different flow arrangements of the heat transfer fluids.

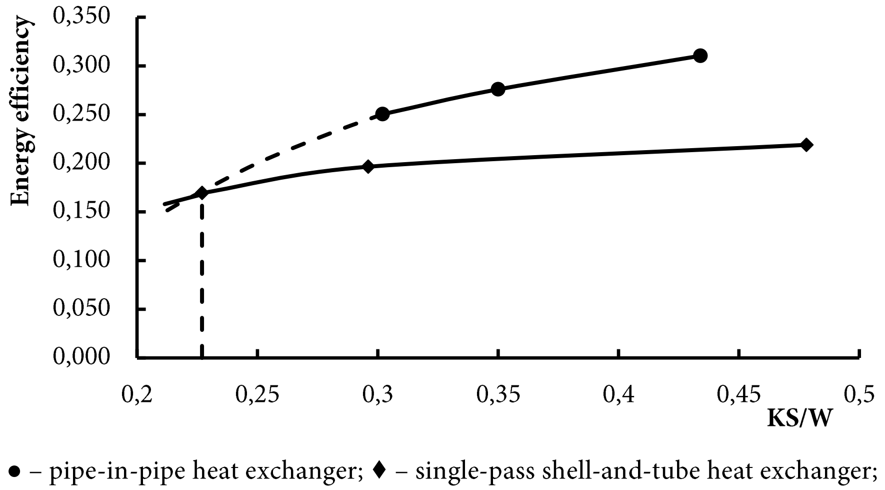


Fig. 2. Dependences $\eta_{en} = f\left(\frac{kS}{W}\right)$for the parallel-flow arrangement of the heat transfer fluids

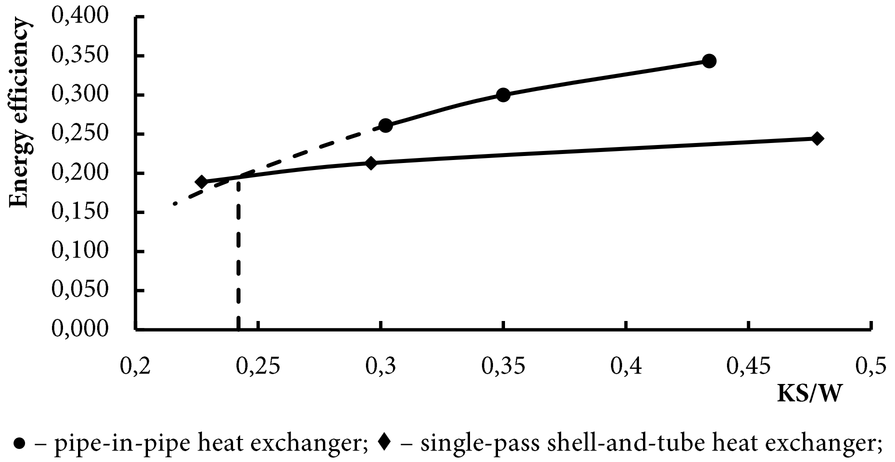


Fig. 3. Dependences $\eta_{en} = f\left(\frac{KS}{W}\right)$for the counterflow arrangement of the heat transfer fluids

In the studied range, the energy efficiency is higher for the pipe-in-pipe heat exchanger, but examining the nature of the dependences, it can be noted that at $\left(\frac{KS}{W}\right)$ values of less than 0.22–0.24, the lines intersect. Therefore, at $\left(\frac{KS}{W}\right)$ values of less than 0.22–0.24, the energy efficiency η_{en} is higher for the shell-and-tube heat exchanger. This means that at high flow rates of heat transfer fluids (G) and small heat exchanger dimensions (S), the shell-and-tube heat exchanger is more efficient one.

Energy efficiency is the ratio of the actually performed work to its maximum possible value, that is, to the exergy of the process under consideration [7–12]. It takes into account energy losses in the heat exchanger: losses due to the irreversibility of heat exchange caused by the temperature difference between the heat transfer fluids; energy losses due to heat transfer to the environment; energy losses due to hydraulic losses during pumping of the heat transfer fluids (however, this component may be neglected when determining energy efficiency).

A significant deviation of energy efficiency from unity indicates the presence of exergy losses. It can be minimized through more rational processes and the use of more advanced equipment. Some factors reducing the thermodynamic efficiency of heat transfer processes in a heat exchanger are as follows:

a) losses due to the finite temperature difference between the heat transfer fluids and hydraulic resistance;

b) losses due to incomplete thermal insulation;

c) low thermal conductivity of the heat exchanger material.

There are losses caused by a change in the flow pattern of the heat transfer fluids. For example, the efficiency of the device decreases with a relative decrease in the hot heat transfer fluid flow rate relative to the cold one and increases with an increase in the former.

The work capacity or exergy of heat Q_h obtained from a heat source with temperature T_{h1} is the maximum useful work that can be obtained from this heat under the condition that the cold source is the environment with temperature T_0. Here, $Q_{\text{г}h} = Q_{h1} - Q_{h2}$.

For recuperative heat exchange apparatuses, the following equation can be used to determine the exergy efficiency [2, 3]

$$\eta_{ex} = \frac{1 - \frac{T_0}{T_c^{av}}}{1 - \frac{T_0}{T_{\text{г}h}^{av}}},$$

where T_0 = 237 °K.

Average temperature of the cold heat transfer fluid: $T_c^{av} = \frac{T_{c2} - T_{c1}}{ln\frac{T_{c2}}{T_{c1}}}$

Average temperature of the hot heat transfer fluid: $T_h^{av} = \frac{T_{h1} - T_{h2}}{ln\frac{T_{h1}}{T_{h2}}}$

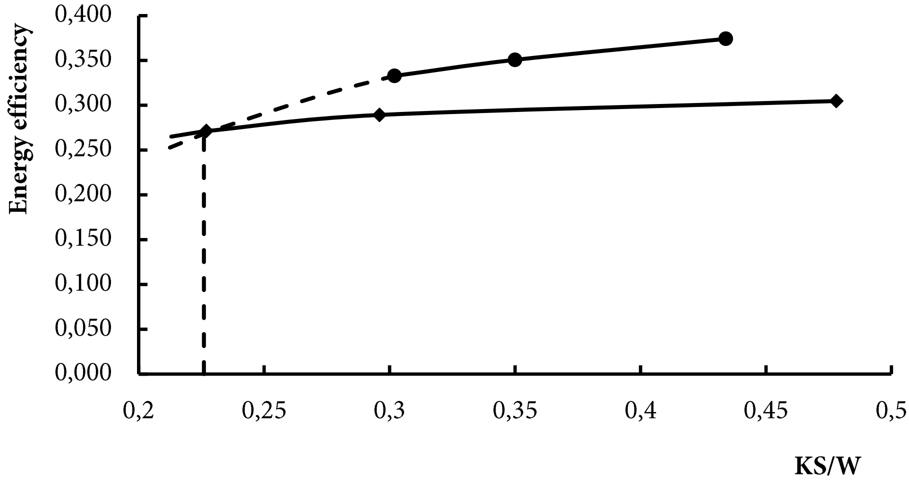
Experimental studies were conducted for recuperative heat exchangers of the pipe-in-pipe type and a single-pass shell-and-tube heat exchanger. Table 1 gives the main parameters of the heat exchangers.

Table 3 gives the results of experimental studies on determining the exergy efficiency.

Table 3. Results of experimental and calculated data for determining $\eta_{\text{экс}}$

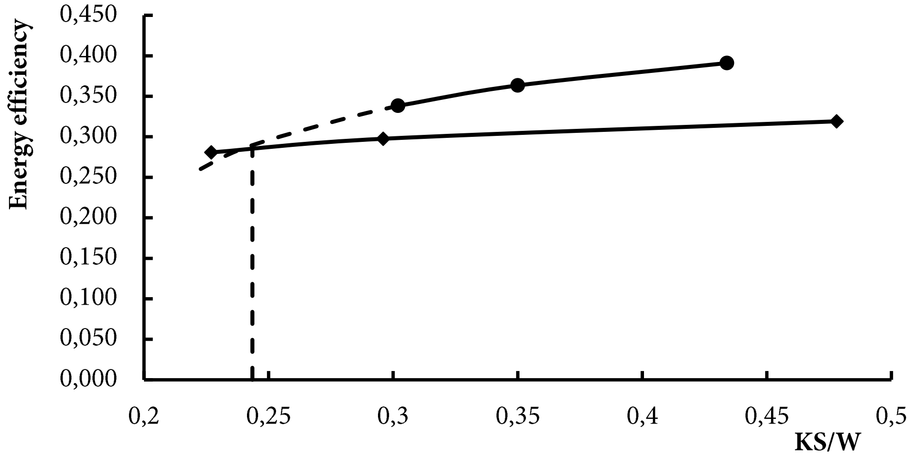
Heat exchanger type	Flow diagram	Heat transfer agent flow rate, G, kg/s	T_{h1}, K	T_{h2}, K	T_{c1}, K	T_{c2}, K	η_{ex}	$\frac{KS}{W}$	K, W/(m²·K)
pipe-in-pipe	direct flow	0.16	339.7	322.3	281.9	302.6	0.374	0.434	643.7
		0.32	339.7	323.4	281.9	300.3	0.351	0.35	1037.1
		0.47	339.7	324.5	281.9	298.6	0.333	0.302	1315.2
	counterflow	0.16	339.7	323.2	281.9	304.8	0.391	0.434	643.7
		0.32	339.7	324.0	281.9	301.9	0.363	0.35	1037.1
		0.47	339.7	324.8	281.9	299.3	0.338	0.302	1315.2
shell-and-tube	direct flow	0.16	339.7	328.8	281.9	296.5	0.305	0.478	239.2
		0.32	339.7	330.0	281.9	295.0	0.289	0.296	296.3
		0.47	339.7	331.2	281.9	293.2	0.271	0.227	331.1
	counterflow	0.16	339.7	329.0	281.9	298.2	0.319	0.478	239.2
		0.32	339.7	330.6	281.9	296.1	0.298	0.296	296.3
		0.47	339.7	332.2	281.9	294.5	0.281	0.227	331.1

Based on the experimental and calculated data, dependences $\eta_{\text{экс}} = f\left(\frac{KS}{W}\right)$ were plotted (Figures 5 and 6).



● – pipe-in-pipe heat exchanger; ♦ – single-pass shell-and-tube heat exchanger;

Fig. 4. Dependences $\eta_{ex} = f\left(\frac{kS}{W}\right)$for the parallel-flow arrangement of the heat transfer fluids



● – pipe-in-pipe heat exchanger; ♦ – single-pass shell-and-tube heat exchanger;

Fig. 5. Dependences $\eta_{ex} = f\left(\frac{KS}{W}\right)$for the counterflow arrangement of the heat transfer fluids

Also, at $\left(\frac{KS}{W}\right)$ values of less than 0.22–0.24, an intersection of the dependences $\eta_{ex} = f\left(\frac{KS}{W}\right)$ is observed. At these values, the efficiency $\left(\frac{KS}{W}\right)$ of the shell-and-tube heat exchanger is higher than that of the pipe-in-pipe heat exchanger.

Conclusions

1. Based on experimental studies, the energy and exergy efficiency coefficients of the pipe-in-pipe heat exchanger and the shell-and-tube heat exchanger have been determined.
2. For the counterflow arrangement of heat transfer fluids, the values of both efficiency coefficients are higher than those for the parallel-flow arrangement. As a result, the counterflow arrangement makes it possible to achieve a more uniform distribution of the driving force along the heat transfer surface.
3. Experimental dependences of the energy and exergy efficiency coefficients on the value of $\left(\frac{KS}{W}\right)$ have been obtained both for the pipe-in-pipe heat exchanger and the shell-and-tube heat exchanger.

4. At small values of $\left(\frac{KS}{W}\right)$ (less than 0.22–0.24), the values of the energy and exergy efficiency coefficients for the shell-and-tube heat exchanger are higher than those for the pipe-in-pipe heat exchanger. At large values of $\left(\frac{KS}{W}\right)$, the efficiency of the pipe-in-pipe heat exchanger is higher than that of the shell-and-tube heat exchanger.

References

1. **Leontiev, V.K., Korableva, O.N.** Experimental determination of the efficiency of recuperative heat exchangers // *From Chemistry towards Technology Step-by-Step*, 2026, 7(**1**), 66-75 (in Russian).
2. **Shadrina E.M.**, **Volkova G.V.** Introduction to the course "Theoretical Foundations of Energy and Resource Saving": methodological guidelines, edited by V.Ya. Lebedev. Ivanovo State University of Chemistry and Technology, 2007, 44 p. (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. **Girba, E.A., Leontiev, V.K.** Theoretical Foundations of Energy and Resource Saving: A Study Guide. Yaroslavl: YSTU Press, 2011, 132 pp. (in Russian).
5. **Rakhmanov Yu.A.** Theoretical foundations of energy and resource saving in chemical technology: Educational and methodological guide. St. Petersburg: ITMO University, 2018, 62 p. (in Russian).
6. **Semenyuk L.G.** Thermodynamic efficiency of heat exchangers. *Journal of Engineering* Physics and Thermophysics, 1990, 59(**6**), 935–942 (in Russian).
7. **Sazhin B.S.**, **Bulekov A.P.** Exergy analysis of heat and mass transfer processes in chemical technology. Moscow: MIT named after A.N. Kosygin, 1988, 78 p. (in Russian).
8. **Szargut J.** Exergy. Translated from Polish by Yu.I. Baturin and D.F. Strzhizhovsky; edited by Dr. Tech. Sci. V.M. Brodyansky. Revised and expanded edition. Moscow: Energiya, 1968, 379 p. (in Russian).
9. **Alexandrov A.A.** Exergy of thermodynamic systems. Thermodynamic fundamentals of thermal power plant cycles [Electronic resource]. Available at: http://twt.mpei.ac.ru/TTHB/2/Aleksandrov/Chapter-6/6-1.pdf. (accessed: 01/22/2020) (in Russian).
10. **Tishin O.A., Kharitonov V.N., Gatapova N.Ts., Koliukh A.I.** Theoretical foundations of energy and resource saving in chemical technology: textbook. Tambov: Publishing House of TSTU, 2012, 92 p. (in Russian).
11. **Kalekin V.S.** Theoretical foundations of energy and resource saving in chemical technology – 2nd ed., revised and expanded. Omsk: OmSTU Publishing House, 2006, 92 p. (in Russian).
12. **Dyakonov V.G., Lonshchakov O.A.** Fundamentals of heat and mass transfer: textbook. Ministry of Education and Science of Russia, Kazan National Research Technological University, Kazan: KNRTU Publishing House, 2015, 244 p. (in Russian).
13. Chechetkin A.V.**, Zanemonets N.A.** Heat engineering: textbook for chemical technology specialties. Moscow: Vysshaya Shkola, 1986, 344 p. (in Russian).
14. **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).
15. **Romankov P.G., Frolov V.F., Flisyuk O.M.** Methods for calculating processes and apparatuses of chemical technology (examples and problems): Textbook for universities. – 2nd ed., corrected. St. Petersburg: KHIMIZDAT, 2009, 544 p. (in Russian).

Received 30.03.2026
Approved after reviewing 27.05.2026
Accepted 29.05.2026