Thermo-aerodynamic efficiency of non-circular ducts with vortex enhancement of heat exchange in different types of compact heat exchangers

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Abstract. Experimental studies of thermo-aerodynamic characteristics of non-circular ducts with discrete turbulators on walls and interrupted channels have confirmed the rational enhancement of convective heat transfer, in which the growth of heat transfer outstrips or equals the growth of aerodynamic losses. Determining the regularities of rational (energy-saving) enhancement of heat transfer and the proposed method for comparing the characteristics of smooth-channel (without enhancement) heat exchangers with effective analogs provide new results, confirming the high efficiency of vortex enhancement of convective heat transfer in non-circular ducts of plate-finned heat exchange surfaces. This allows creating heat exchangers with much smaller mass and volume for operation in energy-saving modes.

1. Introduction
A demonstrative example of the comparison of heat exchangers (HE) with cores based on tube-and plate smooth-duct (TPsm), with ridges and grooves (TPrg) and plate-and-fin interrupted (PFint) heat-exchange surfaces (HES), various possible variants of efficiency comparisons: with smooth ducts (without enhancement of heat transfer) and HE with ducts of identical geometry with artificial turbulence of the coolant flow; heterogeneous HE with smooth ducts and channels of other sizes, forms and methods of enhancement of heat exchange; heterogeneous HE with heat exchange enhancement by different methods in channels of various types; groups of heterogeneous HEs with determining the best and worst HE based on the ranking by the volume of the HE cores. The efficiency comparison, in the most general case, distinguishes the following: a reference HE, presumably less effective (in a particular case, with a smooth-duct heat exchange surface), all characteristics of which are known from the preliminary calibrated heat calculation or the results of thermal engineering tests; compared to HE, with an artificial turbulence of the coolant flow (its characteristics are determined from the design heat calculation). The comparison is carried out at the thermal and aerodynamic boundary conditions of the equality of the thermal loads \( Q_{HE-st}/Q_{HE-cnf} = 1 \), the mass flow rates of the heat carrier \( M_{HE-st}/M_{HE-cnf} = 1 \), the temperature headings \( \theta_{HE-st}/\theta_{HE-cnf} = 1 \) and the ratio \( \Delta p_{HE-st}/\Delta p_{HE-cnf} \geq 1 \) total losses of coolant pressure on friction in HES ducts, input to and exit from HE. In determining the best heat exchanger from a group of all possible analogues, HE can serve as a reference both without and with enhancement of heat exchange in HES ducts. If, in considering the task of comparing the two HE, the deviation from the observance of the thermal and aerodynamic boundary conditions of the realization of the rational enhancement of convective heat transfer (RECH) process at the rationality exponent \( K = [(\text{Nu}_{HE-cnf}/\text{Nu}_{HE-st})/(\zeta_{HE-cnf}/\zeta_{HE-st})]_{Re=ident} \geq 1 \), in the part \( \Delta p_{HE-cnf}/\Delta p_{HE-st} \leq 1 \) [1], it is possible to obtain the comparison result in the form of a decrease in the \( \Delta L \) of the length of the HE in the course of air under the condition \( K < 1 \) with the determination of the calculated value \( \Delta p_{HE-cnf}/\Delta p_{HE-st} > 1 \) or observance of the specified condition for its limitation \( (\Delta p_{HE-cnf}/\Delta p_{HE-st})_{max} \leq [\Delta p_{HE-cnf}/\Delta p_{HE-st}]_{lim} \).

2. Calculations and comparisons of the cores of compact heat exchangers
2.1. Plate- and fin heat exchangers with smooth and interrupted ducts of identical geometry in cross sections

An important case of the general problem of comparing the volumes of the same type of heat exchangers is considered by the example of plate- and fin heat exchangers. This ensures reasonable decisions on the expediency of upgrading the smooth-channel plate-and fin (figure 1, a, below) and tube-plate heat exchangers (figure 1, b) in various engineering facilities, replacing them with efficient designs with artificial turbulence of the coolant in the PFint HES channels (figure 1, a, top) and TPrg HEs (figure 1, b, right) during the RECH process: $K = [(\text{Nu}_{\text{int}}/\text{Nu}_a)/(\zeta_{\text{int}}/\zeta_a)]_{\text{Re=ident}} \geq 1$.

Figure 1. Illustrations of the reduced volume of the HE cores to be compared due to the use of enhancement of convective heat transfer: a – dissection of long smooth ducts into many short ones; B – stamping of discrete turbulators (ridges and grooves) on the walls of ducts.

The results of calculations of the cut-off parameter (l/d)$_x$ and the coefficient $\zeta_x$ of the frictional pressure loss in the HES HE ducts on the calculated values of the Nusselt Nu criterion are selectively presented in Table 1 and Figure 2 (graphical solutions).

Table 1. Results of comparison of the reference HE with the PFsm HES and the matched HE with the PFint HES at $s = 5 \cdot 10^{-3}$ m, $d = 7.66 \cdot 10^{-3}$ m, $h/u = 6.750$, $\delta/d = 0.0783$, $\Omega = 428$ m$^2$/m$^3$

| $W_{a-\infty}$ | 1.90 | 2.64 | 4.70 | 5.20 | 7.50 | 11.22 |
|--------------|------|------|------|------|------|-------|
| $Q_a$        | 23450| 27120| 34700| 36685| 44535| 59255 |
| $Re_a$       | 1069 | 1500 | 2686 | 2973 | 4300 | 6442  |
| $\alpha_a$   | 22.65/49.72 | 24.94/54.94 | 30.26/72.40 | 31.90/66.27 | 38.46/75.47 | 52.25/97.78 |
| $Nu_a$       | 6.33/13.90 | 7.01/16.62 | 8.57/20.50 | 9.04/18.78 | 10.93/21.45 | 14.87/27.83 |
| $V_{fract}$  | -11.413 | -11.333 | -11.816 | -13.018 | -13.947 | -14.127 |
| $\zeta_x$    | 0.108/0.226 | 0.082/0.191 | 0.054/0.120 | 0.051/0.096 | 0.042/0.076 | 0.038/0.066 |
| $\Delta p_a$ | 6.42/6.34 | 9.40/19.71 | 19.39/19.13 | 22.31/21.25 | 38.52/37.09 | 77.09/75.77 |
| $V_{fract}$  | 2.153 | 2.209 | 2.314 | 2.099 | 1.955 | 1.812 |
| $M_{metal}$  | 22.56/10.67 | 22.56/9.97 | 22.56/9.97 | 22.56/11.37 | 22.56/12.06 | 22.56/12.76 |

To observe the dynamics of changes in the values of the main results of the HE comparison and the flow of the coolant in Table 1, etc. are also given (in the numerator for the reference HE, in the denominator for the matched HE): $w_{a-\infty}$ is the speed of the unperturbed airflow before entering the live cross section of the HE core, m/s; $Q_a$ is the thermal load, W; $Re_a$ is the Reynolds criterion; $\alpha_a$ is the heat transfer coefficient, W/(m$^2$·K); $\Delta p_a$ is the resistance of the HE core to the cooled cooling air, Pa; $V_{fract}$ is the ratio of the core volumes of the compared reference $V_a$ (or smooth $V_{sm}$) and the correlated $V_{int}$ HE; $M_{metal}$ is the mass of the metal of the HE core, kg. From Figure 2, it is seen that for
the extended to the side of the lower values of the regime criterion Re of the transition region of the coolant flow (due to artificial turbulence), the minimum value of the argument of the dependences $\Nu_0 = l(l/d)$ and $\zeta = l(l/d)$ at Re = variable, indicating the need to use turbulators with a more enhancing ef

deffect on the flow of the coolant (PFint HES, that is, with smaller values of the cut-off parameter l/d or l) than in the developed turbulent regime [2]. The reduction in the volume and mass of the cores compared to HE with PFint HES is estimated in $V_{HE-cnf}/V_{HE-st} = 1.81... 2.31$ times = $L_{HE-st}/L_{HE-cnf}$.

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**Figure 2.** To the definition (graphical solution) of the values (l/d), and $\zeta_{xs}$ of the heat exchanger with PFint HES at $s = 5 \times 10^{-3}$ m and $w_{s,s} = 1.90$, 2.64, 4.70, 5.20, 7.50; 11.22 m/s (the corresponding values of the Reynolds test are shown in the figure).

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**Table 2.** Results of comparison of the reference HE with the PFsm HES – $s = 5 \times 10^{-3}$ m, $d = 7.66 \times 10^{-3}$ m, $\Omega = 428 \ m^3/m^2$ and compared HE with the PFint HES – $s = 4 \times 10^{-3}$ m, $d = 6.12 \times 10^{-3}$ m, $\Omega = 524 \ m^3/m^2$ at (h/u)$_{in} = 6.860$ and (\(\delta/d)_in = 0.0799$

| W_s | 1.90 | 2.64 | 4.70 | 5.20 | 7.50 | 11.22 |
|-----|-----|-----|-----|-----|-----|-----|
| $Q_s$ | 23450 | 27120 | 34700 | 36685 | 44535 | 59255 |
| Re$_s$ | 1069/869 | 1500/1219 | 2686/2183 | 2973/2416 | 4300/3495 | 6442/5237 |
| $\alpha$ | 22.65/50.14 | 24.94/60.61 | 30.26/74.06 | 31.90/78.23 | 38.46/86.60 | 52.25/109.3 |
| Nu$_s$ | 6.33/11.20 | 7.01/13.61 | 8.57/16.75 | 9.04/17.71 | 10.93/19.66 | 14.87/24.85 |
| (l/d)$_s$ | -12.348 | -10.525 | -12.655 | -2.589 | -13.240 | -13.240 |
| $\zeta_{xs}$ | 0.108/0.210 | 0.082/0.173 | 0.054/0.116 | 0.051/0.112 | 0.042/0.085 | 0.038/0.076 |
| $\Delta_p$ | 6.42/6.15 | 9.40/8.96 | 19.39/18.78 | 22.31/22.25 | 38.52/38.01 | 77.09/82.32 |
| $V_{nf}/V_{nf}$ | 2.770 | 3.040 | 2.993 | 2.907 | 2.697 | 2.305 |
| $M_{int}$, kg | 22.56/8.92 | 22.56/8.19 | 22.56/8.19 | 22.56/8.19 | 22.56/8.19 | 22.56/8.19 |

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**Table 3.** Results of comparison of the reference HE with the PFsm HES – $s = 5 \times 10^{-3}$ m, $d = 7.66 \times 10^{-3}$ m, $\Omega = 428 \ m^3/m^2$ and compared HE with the PFint HES – $s = 3.5 \times 10^{-3}$ m, $d = 5.39 \times 10^{-3}$ m, $\Omega = 598 \ m^3/m^2$ at (h/u)$_{in} = 6.714$ and (\(\delta/d)_in = 0.0762$

| W_s | 1.90 | 2.64 | 4.70 | 5.20 | 7.50 | 11.22 |
|-----|-----|-----|-----|-----|-----|-----|
| $Q_s$ | 23450 | 27120 | 34700 | 36685 | 44535 | 59255 |
| Re$_s$ | 1069/766 | 1500/1074 | 2686/1923 | 2973/2129 | 4300/3079 | 6442/4614 |
| $\alpha$ | 22.65/52.48 | 24.94/64.60 | 30.26/89.34 | 31.90/83.33 | 38.46/101.3 | 52.25/112.2 |
| Nu$_s$ | 6.33/10.32 | 7.01/12.78 | 8.57/17.80 | 9.04/16.61 | 10.93/20.24 | 14.87/22.47 |
| (l/d)$_s$ | -12.546 | -12.073 | -11.682 | -2.622 | -12.506 | -13.500 |
| $\zeta_{xs}$ | 0.108/0.225 | 0.083/0.188 | 0.054/0.145 | 0.051/0.117 | 0.042/0.104 | 0.038/0.075 |
| $\Delta_p$ | 6.42/6.25 | 9.40/9.06 | 19.39/19.50 | 22.31/21.62 | 38.52/39.84 | 77.09/78.10 |
| $V_{nf}/V_{nf}$ | 3.264 | 3.663 | 3.947 | 3.647 | 3.420 | 2.865 |
| $M_{int}$, kg | 22.56/7.08 | 22.56/6.39 | 22.56/5.70 | 22.56/6.39 | 22.56/6.39 | 22.56/7.77 |
The effectiveness of reducing the volume of the surfaces to be compared with the interrupted ducts
decreasing the equivalent duct diameters of their surfaces is very significant (see Tables 2 and 3).
The reduction in the volume, mass of the cores and the surface length along the air of the matched HE
with the PFInt HES is estimated with respect to HE with a smooth-channel PFsm HES – s = 5·10⁻³ m,
d = 7.66·10⁻³ m, Ω = 428 m²/m³; \( V_{HE-st}/V_{HE-cnf} = 2.30 \ldots 2.99 \), \( s = 4·10^{-3} \) m, \( d = 6.12·10^{-3} \) m, \( Ω =
524 m²/m³ (see table 2); \( V_{HE-st}/V_{HE-cnf} = 2.86 \ldots 3.95 \) times – \( s = 3.5·10^{-3} \) m, \( d = 5.39·10^{-3} \) m, \( Ω =
598 m²/m³ (see table 3).

2.2. Plate-and fin heat exchangers with interrupted ducts of similar cross-sectional geometry
Reducing the equivalent diameter of the channel heat exchange surface increases its compactness.
However, when using plate-and fin heat exchange surfaces in unclosed systems, the operational
limitations imposed by the danger of clogging and expressed by the smallest step-edges – \( s_{min} \approx
(4 \ldots 3.5)·10^{-3} \) m are imposed on the reduction in the dimensions of their ducts. The results of
calculations in table 4 and 5 for comparing parameters of the same type heat exchangers with

| \( W_{he-co} \) | 1.90 | 2.64 | 4.70 | 5.20 | 7.50 | 11.22 |
|---|---|---|---|---|---|---|
| \( Q_A \) | 23450 | 27120 | 34700 | 36685 | 44535 | 59255 |
| \( Re_A \) | 1069/869 | 1500/1219 | 2686/2183 | 2973/2416 | 4300/3495 | 6442/5273 |
| \( α_A \) | 49.72/46.15 | 54.94/60.61 | 72.40/74.06 | 66.27/78.23 | 75.47/79.48 | 97.78/100.8 |
| \( Nu_A \) | 13.90/10.31 | 16.62/13.61 | 20.50/16.75 | 18.78/17.71 | 21.45/18.04 | 27.83/22.47 |
| \( (l/d)_x \) | 1.413/3.240 | 1.333/2.052 | 1.816/2.655 | 3.018/2.586 | 3.947/4.050 | 4.127/4.350 |
| \( ζ_{Q,x} \) | 0.226/0.196 | 0.191/0.173 | 0.120/0.116 | 0.096/0.112 | 0.076/0.076 | 0.066/0.065 |
| \( Δp_A \) | 6.34/6.20 | 9.71/8.96 | 19.13/18.78 | 21.25/22.25 | 37.09/36.87 | 75.77/75.66 |
| \( V_{he-st}/V_{he-cnf} \) | 1.180 | 1.376 | 1.293 | 1.372 | 1.312 | 1.286 |
| \( M_{he-kg} \) | 10.67/9.66 | 9.97/8.19 | 9.97/8.19 | 11.37/8.19 | 12.06/9.65 | 12.76/10.38 |

interrupted rectangular ducts of differing sizes \( s_A = 5·10^{-3} \) and \( s_{cut} = 4·10^{-3} \) m – table 4 and \( s_A =
5·10^{-3} \) and \( s_{cut} = 3.5·10^{-3} \) m – table 5) of the similar geometry of the cross-sections \( (h/u) \approx \) idem, \( (δ/d)_m \) \approx idem)

| \( W_{he-co} \) | 1.90 | 2.64 | 4.70 | 5.20 | 7.50 | 11.22 |
|---|---|---|---|---|---|---|
| \( Q_A \) | 23450 | 27120 | 34700 | 36685 | 44535 | 59255 |
| \( Re_A \) | 1069/766 | 1500/1074 | 2686/1923 | 2973/2129 | 4300/3079 | 6442/4614 |
| \( α_A \) | 49.72/52.48 | 54.94/64.60 | 72.40/78.90 | 66.27/83.33 | 75.47/90.47 | 97.78/112.2 |
| \( Nu_A \) | 13.90/10.32 | 16.62/12.78 | 20.50/15.72 | 18.78/16.61 | 21.45/18.08 | 27.83/22.47 |
| \( (l/d)_x \) | 1.413/2.550 | 1.333/2.080 | 1.816/2.680 | 3.018/2.586 | 3.947/3.490 | 4.127/3.700 |
| \( ζ_{Q,x} \) | 0.226/0.226 | 0.191/0.188 | 0.120/0.123 | 0.096/0.112 | 0.076/0.085 | 0.066/0.072 |
| \( Δp_A \) | 6.34/6.27 | 9.71/9.09 | 19.13/18.54 | 21.25/21.62 | 37.09/36.90 | 75.77/74.97 |
| \( V_{he-st}/V_{he-cnf} \) | 1.512 | 1.653 | 1.597 | 1.722 | 1.739 | 1.648 |
| \( M_{he-kg} \) | 10.67/7.08 | 9.97/6.39 | 9.97/6.39 | 11.37/6.39 | 12.06/7.08 | 12.76/7.77 |

uniquely determine the advantages of the heat exchangers compared to the RECH process for K \approx 1:
the reduction in the volumes and masses of the cores in \( V_{he-st}/V_{he-cnf} = L_{he-st}/L_{he-cnf} = M_{he-st}/M_{he-cnf} =
1.18 \ldots 1.37 \) times – see table 4 and 1.51…1.74 – see table 5.
2.3. Group of different types of heat exchangers

A variant of calculations and comparisons of a group of heat exchangers of different designs is considered: with a reference tube-plate smooth-dust surface – PFsm HES (Figure 1, b on the left); with comparable effective tube-and plate surface with ridges and grooves – TPrg HES (Figure 1, b on the right) and plate-and fin with interrupted duct surface – PFint HES (Figure 1, a top). The initial data package contains all values of the values with index "st" (or "sm"), the parameters of the elements of the all-welded multi-channel flat tube, the dimensions of the constructive front of the HE and the results of studies of the thermal Nu = f(Re) and aerodynamic characteristics ζ = f(Re) HES cores of the reference HE with TPsm HES and matched HE with TPrg and PFint HES [3]. Thermal load HE Q = 52.82·10³ W (\(Q_{\text{HE-PSm}} = Q_{\text{HE-PSm}} = Q_{\text{HE-PSm}}\)). Values at entry to HE are: air velocity \(w_\infty = 4.70\) m/s; air temperature \(t_\infty = +30\) °C; water flow rate \(V_{\text{en}} = 0.004167\) m³/s; water temperature \(t_{\text{en}} = +90\) °C. Core heat exchanger – reference with TPsm HES and correlated with TPrg and PFint HTS (see figure 1): \(B = 645\)·10⁻³ m; \(H = 635\)·10⁻³ m; \(L_{\text{TPsm}} = 138\)·10⁻³ m (6-digit HE), \(L_{\text{TPrg}} = 115\)·10⁻³ m (5-row HE) and 92·10⁻³ m (4-row HE). The air paths of the HE cores: with PFint HES (see figure 1, a) – \(H = 30.3\)·10⁻³ m, \(h = 29.7\)·10⁻³ m, \(s = 5\)·10⁻³ m, \(d = 7.66\)·10⁻³ m; \(c\) TPsm and \(c\) TPrg HES (see figure 1, b) – \(h = 12\)·10⁻³ m, \(s = 5\)·10⁻³ m, \(t_1 = 23\)·10⁻³ m, \(t_2 = 15\)·10⁻³ m, \(u = 4.9\)·10⁻³ m, \(d = 6.99\)·10⁻³ m.

The calculated core parameters of the reference HE with TPsm HES are: \(\text{Nu}_{\text{TPsm}} = 12.47\); \(\text{Re}_{\text{TPsm}} = 2500\); \(V_{\text{HE-TPsm}} = 0.056521\) m³; \(\Delta p_{\text{HE-TPsm}} = 58.47\) Pa; \(\eta_{\text{TPsm}} = 0.978\); \(\sigma_{\text{HE-TPsm}} = 0.1355\); \(\sigma_{\text{psm}} = 0.784\); \(\Omega_{\text{HE-TPsm}} = 451.62\) m²/m³; and \(M_{\text{HE-TPsm}} = 17.139\) kg. Comparison of the calculated data shows that for the RECH mode, the core of the 5-row HE with TPrg HES occupies 16.7% less volume than the 6-digit HE with the TPsm HES at practically equal air resistance \((\Delta p_{\text{HE-TPrg}} = 60.26\) Pa) \((\Delta p_{\text{HE-TPsm}} = 58.47\) Pa). An even greater reduction in the volume or length of the HE core in the air (by 40.4%) ensures the use of PFint HES at \((\Delta p_{\text{HE-PFint}} = 58.81\) Pa) \((\Delta p_{\text{HE-TPsm}} = 58.47\) Pa). The obtained results of calculations indicate a sufficiently high thermo-aerodynamic efficiency of tube-and plate heat exchange surfaces with discrete turbulators (ridges and grooves on the fins), and, especially, of plate-and fin HES with interrupted ducts. Comparison of HE core volumes with enhanced heat exchange and smooth-channel HE based on calculations by the proposed algorithm allows determining the decrease in the length of HES channels with artificial coolant turbulence.

All compared heat exchangers with TPsm, TPrg and PFint HES had the same dimensions of the constructive front. Consequently, the changes in the values of the volumes of cores compared to HE were provided by changing the depth of HE in the course of the air with respect to \(L_{\text{TPrg}} = 115\)·10⁻³ m or 83.3% \(L_{\text{PFint}} = 82.3\)·10⁻³ m or 59.6 %. It should be specially noted that compared to HE with TPsm HES, the depth of HE with PFint HES...
decreased noticeably by $\Delta L_2 = 55.7 \cdot 10^{-3}$ m (40.4 %) against HE with TPrg HES by $\Delta L_1 = 23 \cdot 10^{-3}$ m (16.7 %).

The available calculation results show that the volume and depth of HE with PFin HES decreased with respect to HE with intensified TPrg HES by $\Delta L_3 = 32.7 \cdot 10^{-3}$ m or by 28.4 %, which is noticeably better than the decrease in volume or depth of HE with TPrg HES with respect to the reference heat exchanger with TPsm HES.

If you depart from the RECH condition and in the $[(\text{Nu}_{\text{TPrg}}/\text{Nu}_{\text{TPsm}})/(\zeta_{\text{TPrg}}/\zeta_{\text{TPsm}})]_{Re=\text{idem}} < 1$ mode, compare the 6-bit smooth-duct HE 4-row HE with TPrg HES, then the calculations show $L_{\text{TPrg}} = 92 \cdot 10^{-3}$ m or 66.7 % of $L_{\text{TPsm}}$ and $\Delta L_1 = L_{\text{TPsm}} - L_{\text{TPrg}} = 138 \cdot 10^{-3} - 92 \cdot 10^{-3} = 46 \cdot 10^{-3}$ m or 33.3 % of $L_{\text{TPsm}}$. In this case, at the same time, the resistance of the core of the HE to the cooled blowing air is noticeably increased (by 37.8%): $(\Delta p_{\text{HE-TPrg}} = 80.54 \text{ Pa}) > (\Delta p_{\text{HE-TPsm}} = 58.47 \text{ Pa})$.

Efficiency and high accuracy of calculation results allow this method to become a reliable tool when comparing the heat and aerodynamic efficiency of heat exchangers of various types of structures, as well as evaluating the process of enhancement of convective heat transfer in the ducts of heat exchange surfaces.

4. References

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