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DEVELOPMENT OF COMPACT HEAT EXCHANGERS ACCORDING TO THE RESULTS STUDY OF THE REGULARITIES OF HEAT EXCHANGE ENHANCEMENT ENERGY SAVING

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Abstract. The conditions for the realization of energy-saving heat exchange enhancement are experimentally determined, in which the increase in heat transfer in the investigated surface ducts is equal to the growth of aerodynamic losses. A method for determining the geometric and regime parameters of surface ducts, which determine the energy-saving regimes of heat exchange enhancement, is implemented. Energy-saving enhancement of heat transfer in the interrupted ducts and channels with ridges and valleys allows, respectively, to 2.78 and 1.40 times to reduce the heat exchange surface and the mass of the heat exchanger with the previous energy costs. The results of the research make it possible to eliminate the intuitive choice of the shape and parameters of the ducts of the heat exchanger surfaces and to ensure their operation in energy-saving regimes.

1. Introduction.

In hydrodynamics, there are two methods for generating vortices in the wall layer of heat and coolant flows in ducts: in the case of flow around poorly streamlined bodies; on the sections of diffuser-confuser flows. The first method is realized in plate-finned heat exchangers (HTA) by using interrupted ducts instead of long smooth ones, the second method is implemented in tubular-plate HTA using instead of smooth fins profiled plates with ridges and valleys. The results of studies of the thermo-aerodynamic characteristics of the rectangular ducts of the plate-finned interrupted (PFTint) and tubular-plate in the ridges and valleys (TPrg) of the heat exchange surfaces (HTS) confirmed the realization of the processes of energy-saving (rational enhancement of convective heat transfer-RECH) with high level of achieved estimation $(Nu/Nu_{sm})'_{max}$.

2. Objects of research

Eleven plate-finned (PFTint HTS 1…6, 8…11 and PFTsm HTS 7) and thirty-five tubular-plate (TPrg HTS 1…31 and TPsm HTS 32…35) HTS were designed and manufactured by two methods of artificial turbulence of the coolant flow in rectangular ducts in orderto carry out an experimental study for determining the regularities of the implementation of RECH. Smooth-ducted (PFTsm HTS 7 and TPsm HTS 32...35) heat exchange nozzles provided an opportunity to assess the enhancement of heat exchange by both methods [1].

2.1. Plate-finned heat transfer surfaces

Experienced HTA consisted of interrupted and smooth-ducted HTS with rectangular ducts soldered to the surfaces of flat tubes. The use of all matrices and punches in the manufacture of HTS made it possible to withstand the constancy of the given sizes and shapes of the cross sections of the ducts and to avoid distortion and unevenness in the arrangement of the fins in the HTS. Among the possible variants of fabricating PFTint HTS objects for investigating the effect of the relative thickness of the fin δ/d, a preference was given to a variation in which the change in the δ/d value is achieved by changing the value of the equivalent diameter d of the duct with a constant thickness δ of the fin wall.

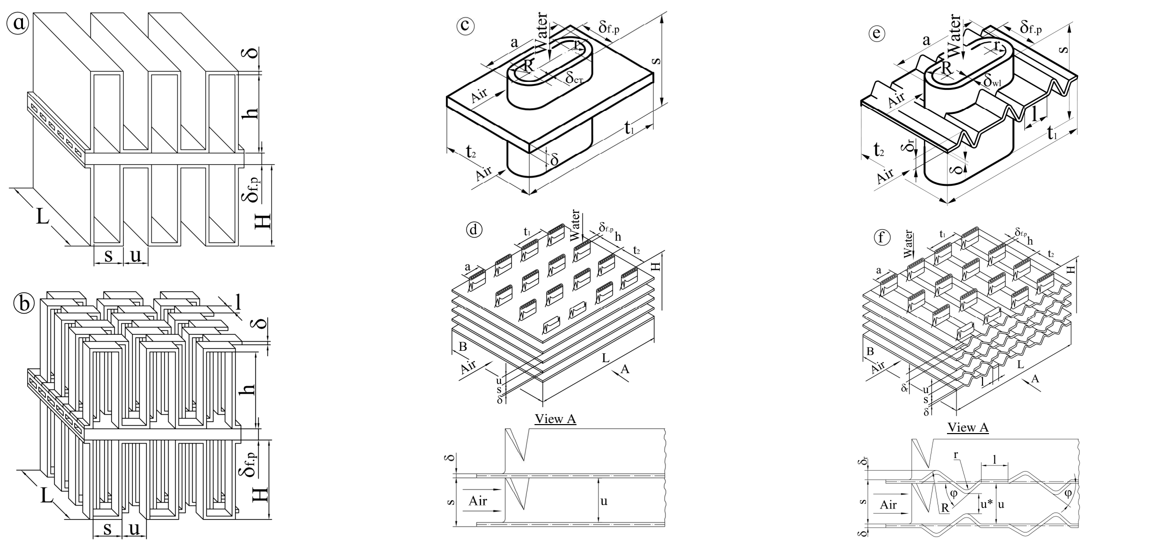

Figure 1. Geometric characteristics of the investigated heat exchange surfaces

2.2. Tubular-plate heat exchange surfaces

The general view of the TPrg HTS, indicating the basic dimensions, is shown in Figure 1, e, f. TPsm HTS 32...35 with L/d = 10.50, 11.63, 13.22 and 15.62 were also investigated to evaluate the probable RECH process in the TPrg HTS 1...31 ducts.

Cooling plates with ridgesand valleys for tubular-plate experienced HTA were manufactured using rotor matrices and punches ensuring compliance with the required dimensions. Twelve versions of corrugated plates were made of copper M3 thickness of $0.1{\cdot}10^{-3}$ m with different combinations of sizes l and δ_r and one option – of smoothed plates. Thirty-one types of HTA with TPrg HTS 1...31 and four – smooth-ducted TPsm HTS 32...35 were prepared by using them when assembling finned heat exchange surfaces with the observance of 4 step values $s = 4{\cdot}10^{-3}$; $5{\cdot}10^{-3}$; $6{\cdot}10^{-3}$; $7{\cdot}10^{-3}$ m. All thirty five types of HTS were divided into seventeen groups: eight for tests at l/d = variable and d*/d = idem; nine for d*/d = variable and l/d = idem. All experienced HTA had the same values for the steps of installing flat-oval tubes (from copper M3 with a thickness of $0.15{\cdot}10^{-3}$ m and invariable overall dimensions of the section $a = 18{\cdot}10^{-3}$ m and $\delta_{f.p} = 3{\cdot}10^{-3}$ m) $a = 18{\cdot}10^{-3}$ m and $\delta_{f.p} = 3{\cdot}10^{-3}$ m) in depth $t_1 = 23{\cdot}10^{-3}$ m and the width $t_2 = 15{\cdot}10^{-3}$ m of the HTA core, the distance along the front between the flat-oval tubes being at $h = 12{\cdot}10^{-3}$ m and the four values of the step s of the installation in the experimental HTA corrugated and smooth edges (see figure 1, d, f): $4{\cdot}10^{-3}$ m – HTS 1…11 and 32; $5{\cdot}10^{-3}$ m – HTS 12…21 and 33; $6{\cdot}10^{-3}$ m – HTS 22…25 and 34; $7{\cdot}10^{-3}$ m – HTS 26…31 and 35.

3. RECH generation of vortices at the entrance to the interrupted ducts

The interruption of long smooth ducts leads to destruction of the boundary layer and an increase in the enhancement of heat transfer under the same conditions for the motion of the gaseous coolant. The smaller the value of the parameter l/d, the more often an artificial disturbance of the boundary layer occurs due to the generation in it of vortices by the turbulent inlet edge of the duct causing additional energy to flow into the thin wall layer with weak subsequent diffusion of the vortices into the core of the flow, the higher the heat transfer coefficient, although at the same time the coefficient of aerodynamic drag increases. At a small length l (compared to L, see figure 1, b) of the short PFTint HTS duct, the largest input value of the Nu criterion is reduced insignificantly. Using such a heat transfer surface, one can make the fins short (l/d << L/d) in the direction of flow of the coolant flow, and by changing the value of the parameter δ/d to control the scale of the generated vortices, achieving very high average values of the heat transfer coefficient with a moderate increase in the aerodynamic resistance of PFTint HTS.

3.1. Effect on RECH changes in the dissection parameter

The approximations given by power functions of the form $Nu = A \cdot Re^k$ and $\zeta = B \cdot Re^n$ of the experimental dependences Nu = f (Re) and ζ = f (Re) [1] made it possible to construct for the sample values of the Reynolds criterion the $Nu/Nu_{sm} = f(l/d)$ и $\zeta/\zeta_{sm} = f(l/d)$, the coordinates of the points of intersection determine the values of the estimate $(Nu/Nu_{sm})'$ of the RECH process and the dissection parameter $(l/d)'$, which are respectively the largest and smallest values for $(K_\zeta)_{Re=idem} = 1$ [1]. The combination of the graphical definitions of the values $(Nu/Nu_{sm})'$ and (l/d) for sample values of the Reynolds test presented in figure 2, a shows that for the group PFTint HTS 1...6, differing only in the parameter l/d = variable (L/d = 0.65, 0.97, 1.30, 1.94, 2.77, 3.24), with constant values of the remaining geometric parameters δ/d = 0.0777, h/u = 6.93, the RECH process is realized within a fairly wide range of the values of the mode parameter $(Re'_{min} = 600) \leq Re \leq (Re'_{max} = 6000)$, and the value $Re'_{min} = 600$ is defined by the lower limit of the total range of values of criterion $Re = 600...1 \cdot 10^4$ of the study. Compositional figure 3, a shows the dependences $K_\zeta = f(Re)$, $Nu/Nu_{sm} = f(Re)$, $\zeta/\zeta_{sm} = f(Re)$ and $(l/d)' = f(Re)$, the last of which, determines the values of the defining geometric parameter $1.23 \leq (l/d)' \leq 3.23$ and the range of values of the mode parameter $600 \leq Re' \leq 6000$ by the set of points, at which the process $(Nu/Nu_{sm})'$ and the value $(K_\zeta)_{Re=idem} = 1$ realizes the RECH process.

3.2. The effect on RECH of changes in the relative fin thickness

Consideration of the variants of the dependences $\zeta/\zeta_{sm} = f(Re)$ and $Nu/Nu_{sm} = f(Re)$ for different values of Re = idem and the determination of the coordinates of their intersection points (figure 2, b), made it possible to construct the dependences $(\delta/d)' = f(Re)$ и $(Nu/Nu_{sm})' = f(Re)$ for the range of the Re criterion under the condition $(K_\zeta)_{Re=idem}= 1$ of the implementation of the RECH process. The combination of the results of graphical definitions of the values $(Nu/Nu_{sm})'$ and $(\delta/d)'$ for sample values of the Reynolds criterion shown in figure 2, b shows that for the PFT_{int} HTS group 8, 9, 3, 10, 11, differing only in the geometric parameter δ/d = variable (δ/d = 0.1138, 0.0912, 0.0777, 0.0658, 0.0580) with the average values of the remaining geometric parameters $(l/d)_m = 1.30$, $(h/u)_m = 6.95$, the process RECH is also realized in rather wide ranges of values of the mode parameter $(Re'_{min} = 600) \leq Re \leq (Re'_{max} = 4400)$.

To estimate the thermo-aerodynamic efficiency of the studied PFT_{int} HTS 3, 8...11, the dependences $\zeta/\zeta_{sm} = f(Re)$, $Nu/Nu_{sm} = f(Re)$ and $K_\zeta = f(Re)$, are shown in figere 3, b, the last of which helps to determine adherence to the RECH condition. An analysis of these results showed that the effect of the change in the values of the parameter δ/d on the heat transfer is most pronounced in the range of values of the Reynolds test from 550 to 3500, and on the pressure loss coefficient in the range from 1100 to $1 \cdot 10^4$. The values of the Nusselt criterion are increased, and the values of the coefficient of total pressure loss is reducedwith decreasing values of the parameter δ/D in the range of values δ/d = 0.058...0.1138 for $(l/d)_m = (l/d)'_{min} = 1.30$ for Re = idem in the entire range of numbers the core of this

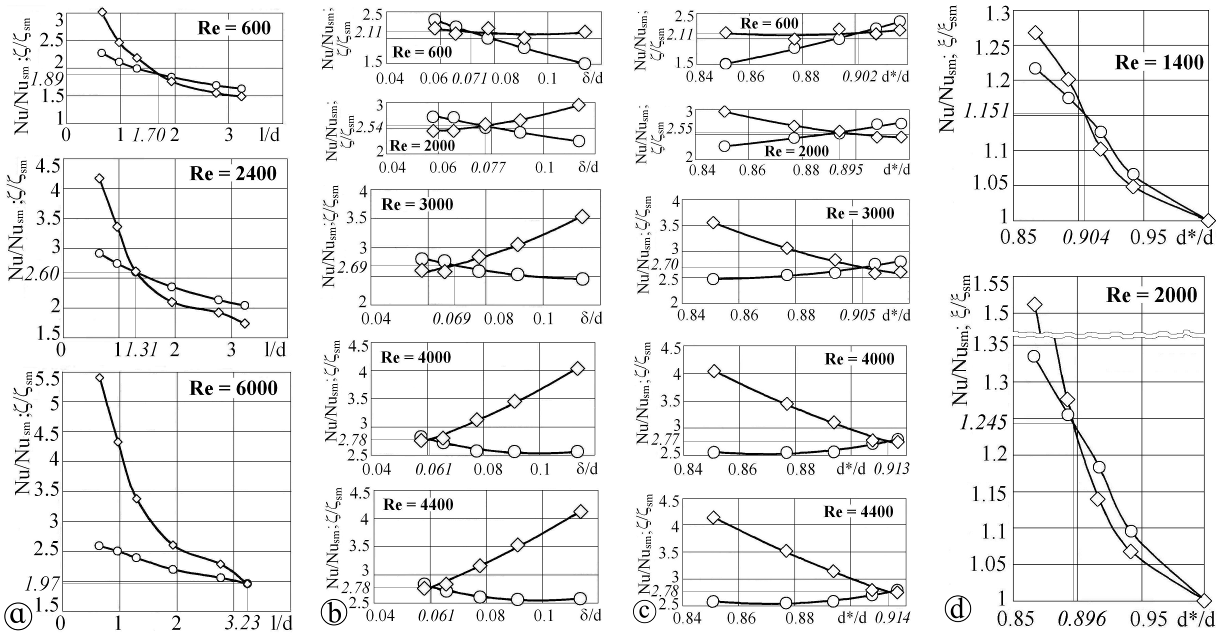

Figure 2. Dependencies (extractions) for Re = idem: $Nu/Nu_{sm} = f(l/d)$ and $\zeta/\zeta_{sm} = f(l/d)$ for PFTint HTS 1…6 at $\delta/d = 0.0777$ – a; $Nu/Nu_{sm} = f(\delta/d)$, $\zeta/\zeta_{sm} = f(\delta/d)$ – b and $Nu/Nu_{sm} = f(d^*/d)$, $\zeta/\zeta_{sm} = f(d^*/d)$ – c for PFTint HTS 3, 8…11 at $(l/d)_m = 1.30$; $Nu/Nu_{sm} = f(d^*/d)$, $\xi/\xi_{sm} = f(d^*/d)$ for TPrg HTS 22…25 at $l/d = 0.202$ – d; ○ – Nu/Nu_{sm}; ◊ – ζ/ζ_{sm} and ξ/ξ_{sm}

flow. As shown in the paper [1], the additional energy supplied to the flow for the formation and propagation of vortices located outside the near-wall layer does not contribute to the increase in the enhancement of convective heat transfer, but leads to an increase in the aerodynamic resistance. A joint analysis of the dependences $Ꝁ_\zeta = f(Re)$, $(Nu/Nu_{sm})' = f(Re)$ and $\delta/d)' = f(Re)$, constructed according to the results of the tests of the PFTint HTS group 8, 9, 3, 10, 11 with parameters $(l/d)_m = (l/d)'_{min} = 1.30$, $(h/u)_m = 6.95$ and δ/d = variable (δ/d = 0.1138, 0.0912, 0.0777, 0.0658, 0.0580) for the conditions $(\delta/d)'_{min} = 0.061$ and achieved with the condition $(Ꝁ_\zeta)_{Re=idem} = 1$ and the value $Re' = 4400$, the value $(Nu/Nu_{sm})'_{max} = 2.78$. A further decrease in the value of the parameter δ/d does not correspond to the RECH condition.

4. RECH generation of vortices by discrete turbulators

Vortices are generated in the wall layer of coolant flows in the sections of the diffuser duct currents TPrg HTS. It is important to note that the scale and enhancement of the generated vortices that determine the values of the turbulent parameters of the coolant flow in the wall layer in the region of reattachment and the development of the boundary layer are determined by the regime and many geometric parameters, among which the most important is the height δ_r of the smoothly rounded profiles of discrete flow turbulence transverse ridges. The effect of δ_r on the change in the values of the thermo-aerodynamic characteristics of TPrg HTS is usually estimated by the geometric parameter d^*/d. Within the limits of a limited volume of the article, it is not possible to bring the whole complex of graphical dependencies, reflecting with full completeness the experimental data obtained for all four groups TPrg and TPsm HTS: 12...15 and 33; 16...19 and 33; 22...25 and 34; 26...28 and 35, in the ducts of which the RECH process is carried out. Let us consider the influence of the change in the value of the parameter d^*/d on the conditions of the RECH process implementation for the example of one group TPrg and TPsm HTS: 22...25 and 34 (figure 3, c). The results of approximating the obtained experimental dependences $Nu = f(Re)$ and $\xi = f(Re)$ by power functions of the form $Nu = A \cdot Re^k$ and $\xi = B \cdot Re^n$ made it possible to construct the graphical dependences $Nu/Nu_{sm} = f(d^*/d)$ and $\xi/\xi_{sm} = f(d^*/d)$ for Re = idem, the coordinates of the intersection points of which for each selected value of the

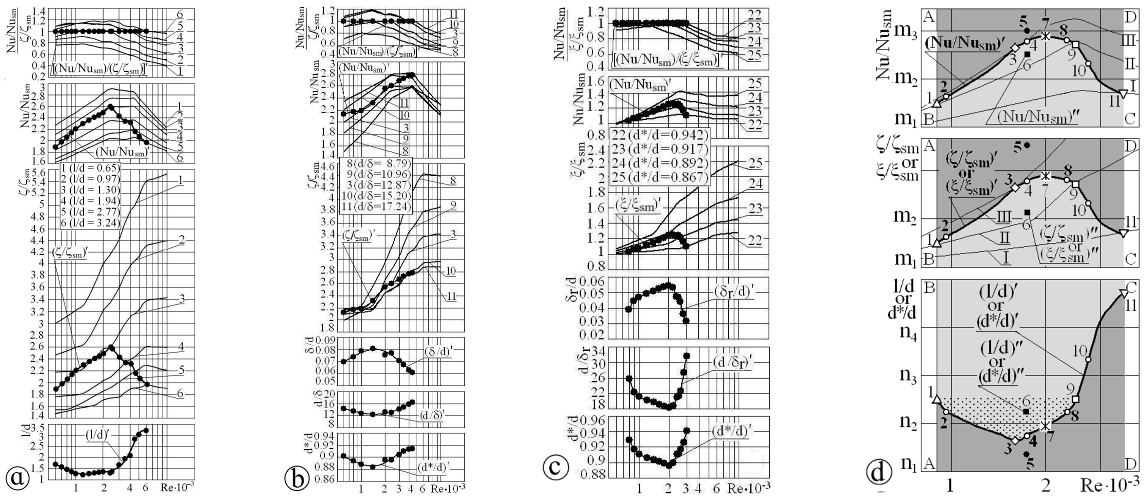

Figure 3. Changes in duct group parameters PFTint HTS 1…6 – a; 3, 8…11 – b; TPrg HTS 22…25 – c and schematization of the parameter change areas that determine the implementation of RECH

Reynolds criterion (see figure 2, d for TPrg HTS 22...25) determine the largest value of the estimate $(Nu/Nu_{sm})'$ of the RECH process and the smallest value of the degree of narrowing of the duct section $(d^*/d)'$. The set of variants of the graphical definitions of the values $(Nu/Nu_{sm})'$ and (d^*/d) for Re = idem presented in figure 2, d shows that the RECH process is implemented within a fairly wide range of the values of the mode parameter $(Re'_{min} = 800) \le Re \le (Re'_{max} = 3000)$ for the group TPrg HTS 22...25, differing only in the parameter value d*/d = variable (d*/d = 0.942, 0.917, 0.892, 0.867) at l/d = 0.202 = idem, h/u = 2.034 = idem, l/d = 11.63 = idem.

5. Physical commonality of the RECH process realized in rectangular ducts by two effective means

The graphical dependencies $(l/d)' = f(Re)$ for the PFTint group HTS 1...6 (figure 3, a) and $(d^*/d)' = f(Re)$ for the groups PFTint HTS 3, 8...11 (figure 3, b), TPrg HTS 22...25 (see figure 3, c) are similar in shapeandare characterized by the same type of dips in the curves and are very similar in character to the behavior of the dependences $(\delta/d)' = f(Re)$ for PFTint HTS and $(\delta_r/d)' = f(Re)$ for TPrg HTS {or $(\delta/d)' = f(Re)$ for PFTint HTS and $(\delta_r/d)' = f(Re)$ for TPrg HTS}. The physical generality of the RECH process, realized by both methods, of artificial turbulence of the coolant flow, make it easy to follow all possible variants of the achieved enhancement of convective heat transfer as shown in figure 3, d. The process along the falling left branch of 1-2-3 dependences $(l/d)' = f(Re)$ and $(d^*/d)' = f(Re)$ is explained by the effect of artificial turbulence on the thicker wall boundary layer in the transition region of the coolant flow if there is a tendency for the growth of the relative thermal characteristic $Nu/Nu_{sm} = f(Re)$ to be higher than that of the relative aerodynamic characteristics $\zeta/\zeta_{sm} = f(Re)$ for PFTint HTS or $\xi/\xi_{sm} = f(Re)$ for TPrg HTS and is accompanied by a decrease in the values $(l/d)' = f(Re)$ or $(d^*/d)' = f(Re)$ to the smallest values $(l/d)'_{min} = (l/d)'_3$ or $(d^*/d)'_{min} = (d^*/d)'_3$. It is equivalent to a decrease of the short fin length along the heating medium to a value l'_{min} and increase the ridge height to the value $(\delta_r)'_{max}$. Then, with the growth of the Re criterion and the onset of a more developed turbulent regime, the leading growth of the ratio being ceased; the Nu/Nu_{sm} ratio grows faster than the ratio ζ/ζ_{sm} or ξ/ξ_{sm}, respectively, the value of the defining complex $(K_\zeta)_{Re=idem} > 1$ or $(K_\xi)_{Re=idem} > 1$ decreases and takes the limiting value for the RECH process $(K_\zeta)_{Re=idem} = 1$ or $(K_\xi)_{Re=idem} = 1$ for $Re'_{11} = Re'_{max}$. The value of the parameter increases to $(l/d)'_{11} = (l/d)'_{max}$ or $(d^*/d)'_{11} = (d^*/d)'_{max}$, which is equivalent to increasing the length of the short fin along the coolant flow to $l'_{11} = l'_{max}$ or decreasing the height of the ridge to $(\delta_r')_{11} = (\delta_r')_{min}$ for the right border region RECH implementation process. Therefore, in the region of incipient underdeveloped turbulence in the transition region of the flow, when the main thermal resistance is due to the thicker wall layer, it is preferable to use discrete turbulators with a more intense effect on the coolant flow (PFTint HTS with lower l/d or l and TPrg HTS values with lower values parameter d*/d or with larger values of δ_r) than with the developed turbulent regime.

Figure 3, d shows that the dependencies $(l/d)' = f(Re)$ for PFTint HTS or $(d^*/d)' = f(Re)$ for TPrg HTS, together with their points, determine the values of the corresponding geometric parameters $(l/d)'$ or $(d^*/d)'$ and the range of the Re criteria for which with the estimate $(Nu/Nu_{sm})'$ and the value of the defining complex $(Ꝁ_{\zeta})_{Re=idem} = 1$ for PFTint HTS or $(Ꝁ_{\xi})_{Re=idem}$ for TPrg HTS, the RECH process is implemented.

6. Conclusion

It is established that the RECH process reliably controlled by changing the values of the basic geometric parameters of the ducts is realized in a wide range of values of the regime parameter of the transition mode region: $(Re'_{min} = 600) \le Re' \le (Re'_{max} = 6000)$ for PFTint HTS; $\{Re'_{min} = (800\ldots900)\} \le Re' \le \{Re'_{max} = (3000\ldots4000)\}$ for TPrg HTS.

For the group PFTint HTS 1...6 with the parameters $\delta/d = 0.0777$, $h/u = 6.93$, $L/d = 19.43$ for l/d = variable (l/d = 0.65, 0.97, 1.30, 1.94, 2.77, 3.24) we established: the value of the estimate $\{(Nu/Nu_{sm})'_{Re=2400}\}_{max} = 2.60$ at $(Ꝁ_{\zeta})_{Re=2400} = 1$; the conditions for implementing the process RECH – $600 \le Re' \le 6000$ and $1.23 \le (l/d)' \le 3.23$; the ranges of the values of the RECH process RECH $1.89 \le (Nu/Nu_{гл})' \le 2.60$ at $600 \le Re' \le 2400$ and $2.60 \le (Nu/Nu_{sm})' \le 1.97$ at $2400 \le Re' \le 6000$.

For the group TPrg HTS 26...28 with the parameters $l/d = 0.183$, $h/u = 1.74$, $L/d = 10.50$ for d^*/d = variable (d^*/d = 0.893, 0.913, 0.953) we established: $\{(Nu/Nu_{sm})'_{Re=2000}\}_{max} = 1.38$ at $(Ꝁ_{\xi})_{Re=2000} = 1$; the conditions for the implementation of the process RECH – $900 \le Re' \le 3500$ and $0.893 \le (d^*/d)' \le 0.953$; the ranges of the values of the RECH process RECH – $1.10 \le (Nu/Nu_{sm})' \le 1.38$ at $900 \le Re' \le 2000$ and $1.38 \le (Nu/Nu_{sm})' \le 1.14$ at $2000 \le Re' \le 3500$.

For the extended in the direction of lower values of the regime criterion Re of the transition region of the coolant flow (due to artificial turbulence), there is a dip in the curves of the graphical dependences $(l/d)' = f(Re)$ and $(d^*/d)' = f(Re)$, (PFTint HTS with lower values of l or the parameter l/d and TPrg HTS with larger values of δ_r or with smaller values of the parameter d*/d) than with the developed turbulent regime.

A graphical method for reliable determination of the values of the basic geometric parameters that determine the conditions for the realization of the RECH process, based on the result of an experimental study of a group of a very limited number (4...6) of experimental heat exchangers, is required for the design of HTA.

The informativeness of the picture of the achieved results of the enhancement of convective heat transfer, traditionally reflected by the dependencies $(Ꝁ_{\zeta}) = f(Re)$ or $(Ꝁ_{\xi}) = f(Re)$, $(Nu/Nu_{sm}) = f(Re)$, $(\zeta/\zeta_{sm}) = f(Re)$ or $(\xi/\xi_{sm}) = f(Re)$, is substantially supplemented by the dependences $(l/d)' = f(Re)$ or $(d^*/d)' = f(Re)$, which allow to determine and observe a continuous change in the values of the estimate $(Nu/Nu_{sm})'$ and the main geometric parameters within the entire implementation area of the RECH process with the value of the defining complex $(Ꝁ_{\zeta})_{Re=idem} = 1$ or $(Ꝁ_{\xi})_{Re=idem} = 1$.

The obtained experimental results can be used in the design of new heat exchangers for various purposes using the established ranges for changing the values of the regime and basic geometric parameters of the ducts of the type investigated that determine the realization of the RECH process.

7. References

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