ADVANCED TECHNOLOGIES AND POWER INSTALLATIONS FOR THERMAL AND ELECTRIC ENERGY GENERATION

6.4. Application of air condensers in power industry

6.4.4. Design of effective configurations of tube bundles of new generation air condensers (NGACs)

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Intensity of transfer processes at flow and heat exchange in transversally washed bundles depends on many factors both regime, and geometrical. For this reason working out and research of new configurations is usually carried out, using a number of approaches. The majority of these approaches is directed to improvement of characteristics of already known configurations.

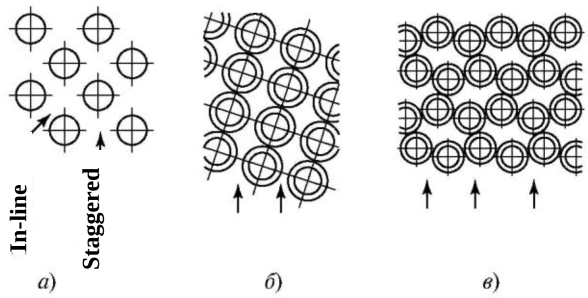
Research directions. Use of transversally washed tube bundles as heat exchange surfaces imposes the certain requirements for them — heat exchange surface should be energetically effective. In this connection, existing techniques of workings out of configurations of tube bundles can be characterized by two directions — "formal" and "power".

Any searching method, not connected and not setting a purpose of working out a physical model of a flow and heat exchange in inter-tube channels, concerns a formal direction. As well, it doesn't contain an estimation of power efficiency of impulse and heat transfer processes in the developing configuration.

It is known that for in-line and staggered, i.e., conventional, traditional layouts of tube bundles, depending on pitches of heat transfer tubes, values of heat irradiation and resistance change in a wide range [12, 13]. Advantages and disadvantages of conventional and staggered configurations of tube bundles are commonly known [12, 13]. By formal varying the values of geometric characteristics of tube bundles and heat carrier parameters, optimization of tube in-line and staggered bundles have been performed [14]. It also shows a scale of distribution of heat carriers according to heat exchange efficiency for staggered and in-line bundles.

Formal direction of the search can also include simple trying of different layouts, adjusting the conventional staggered and in-line configurations, completely technical (mechanical) filling of limited volume with tubes of the bundle, etc.

For example, in [15] a search for an efficient layout of smooth-tube bundle is based on staggered arrangement of tubes by rotating the triangle of staggered layout (Fig. 6.28, a) at a certain angle (relative to the direction of air flow). Experiments have shown that in the intermediate flow diagrams of bundle tubes, heat irradiation is higher and the aerodynamic resistance is less in comparison with the staggered layout. Comparison of the investigated configurations of bundles, considering that energy consumption for pumping and the transferred heat flow are the same, allows to reduce the weight and dimensions of the heat exchange surface by optimal orientation of the bundle relative to a direction of heat carrier flow. Similarly, in [16] data on heat irradiation and aerodynamic resistance of the mixed in-line – staggered bundles from finned tubes are obtained (Fig. 6.28, b). Analysis of energy efficiency of the studied layouts has shown that an efficiency of finned bundle can be increased by changing the direction of flow climbing on the bundle. It was also established an existence of the maximum energy efficiency of heat irradiation in a transitional in-line and staggered bundle of finned tubes.



Pig. 6.28. Effective layouts of tube bundles (formal direction)

Many researchers, selecting the options, modify the geometry of traditional layouts. As a result, there are layouts, essentially similar to the traditional, i.e., staggered and in-line. For example, in [17] a zigzag arrangement of the bundle (Fig. 6.28, в) for air cooling apparatus (ACA) is proposed. The bundle design is obtained from a staggered configuration by converting the straight transverse rows into zigzag tubes, displacing the tubes along the longitudinal axis in a direction of air flow by a certain value. In the zigzag bundles intensification of heat irradiation with simultaneous increase in the bundle resistance is marked. For certain values of geometric relationships, increase in heat irradiation is ahead of the increase in resistance, compared with uniformly passing baseline staggered bundle. Zigzag bundle is compressed at the sides in the "accordion", the compressed cross-section area is increasing at simultaneous reducing the front. This provides greater air cross-section, which can satisfy the low allowable air pressure drop. Developed in [17], a zigzag arrangement of bundle tubes should be considered as a modified staggered layout.

In [15-17] a physical working model of flow and heat irradiation processes in inter-tube channels is not considered. They contain only general physical commentary to positive results, related to the energy gain. In this regard, a search path, selected by the authors, can lead to a need for searching the infinite number of options of tube bundle layouts.

There are also searching formal directions, associated with possibilities of thermal engineering construction technology, containing a tube bundle as a heat exchange surface, bundles from finned tubes of elliptical profile, the unusual fin shapes [18] are developed, etc.

The considered formal searching direction has an objective basis. For example, ACA, whose production started in the 30-ties of the last century, are focused on use of finned tube bundles with the staggered layout. The designers had to develop air-cooled bundle of finned tubes with a compact layout that would have the reduced aerodynamic resistance. Staggered layout with a small number of tube rows (no more than eight rows) satisfies that requirement. In this regard, development of configurations for tube bundles for ACA is traditionally staggered, attached to apparatuses of a standard design. However, in process of design and operation of equipment, problems arise, solution of which may give an energy gain at operation of thermal engineering device. By this, formulation of the problem may have unrealistic demands, since the application of a new layout includes making substantial structural changes.

Meanwhile, it is known that in case of in-line layout, the aerodynamic resistance is much less than in case of the staggered one. Thus, using the advantages of in-line layout of bundle tubes or its modifications, a number of tube rows, keeping the former aerodynamic resistance, can be increased. Such a simplified view needs, of course, the analysis of energy efficiency. However, in terms of setting research objectives at development of highly efficient tube surfaces of heat exchange, a choice of the starting position is important.

The other direction, an energy one, is associated with development of physical flow models in inter-tube channels of bundles. This involves the study of thermophysical characteristics of the local flow and heat exchange processes. Formulation of problems on energy efficiency and synthesis of tube heat exchange surfaces include the development of physical models of flow and heat exchange, as well as application of heat exchange methods in inter-tube channels with the assessment of energy efficiency of heat and aerodynamic processes.

Methods, discussed in [19-21], for improving energy efficiency in heat exchange channels can be realized at development of new highly efficient layouts of tube bundles. In this case, developing the physical model of flow and heat exchange processes, not only the flow processes of separate cylinders should be analyzed, but also large-scale processes in the system of inter-tube channels, formed by groups of tubes, are to be analyzed.

Heat exchange intensification is generally achieved by the impact on boundary layer. By that, a shape of the heat exchange surface creates flowing in channels with a favorable hydrodynamic environment, contributing to the enhancement of heat exchange.

The technique, applied at development of the intensified tube heat exchange surfaces, comes to creation of overflowing through the inter-tube passages, arranged at an angle to the direction of heat carrier flow. This principle is realized in a form of rectangular zigzag channels. Heat carrier passages are formed by rectilinear elements (groups of tubes), which are arranged at an angle to the original direction of flow and are at some distance from one another.

Heat carrier, flowing through inter-tube channels, formed by tube rows, successively washes vortex cavities and confusers. This is one more method of heat exchange process intensification. In [22] the experimental results on heat exchange and resistance at air flowing through the channel with vortex cavities is shown. Increase in heat exchange rate with a moderate increase in resistance is achieved in this case, arranging the flow in a field of longitudinal alternating pressure gradients. This idea in a constructive way is ensured by the channel design in a form of alternating flat and rectilinear diffusers and confusers. The increased level of the flow turbulence, generated in diffusers, is beneficially used in confusers, located behind them. By that, the average heat exchange rate in confusers can be higher than in diffusers.

In vortex cavities the standing vortices are formed, leading to a decrease in the outer vortex flow, and hence, energy dissipation in the downstream direction. Vortex cavities with the standing vortices act as diffusers of short-extension and impact the flow, entering the confusers. To assess the flow hydrodynamics in [22] the flow visualization was carried out. Behind the crescent protrusions the standing vortices are formed. The stream flows around the vortex, reaches the wall, and then is divided into two streams, one of which is directed to the vortex zone, and another – along the confuser. Comparison of heat exchange and resistance data for these channels showed an increase in their energy efficiency.

Thus, if we consider the tube bundle in crossflow as a system of adjacent channels, then there can be implemented the idea to improve energy efficiency of heat exchange system through the creation of the flow pressure inhomogenuity and formation of closed vortex zones.

Synthesis of efficient layout of the tube bundles. Design of tube bundle layouts, in which methods of convective heat exchange intensification are implemented, is based on the data on local heat and aerodynamic characteristics at heat exchange surfaces. Considering the experimental data on heat and aerodynamic characteristics, when flowing around a single tube [12, 13] and a group (system) of tubes [15], by forming inter-tube channels in the flow inhomogeneous pressure occurs. In the inter-tube cavities the attached vortices are formed (Fig. 6.29) that, as it's known, can result in the improved energy efficiency of heat exchange systems.

For a single longitudinal row of tubes at their flow by the heat carrier, there is a critical value of the longitudinal pitch,

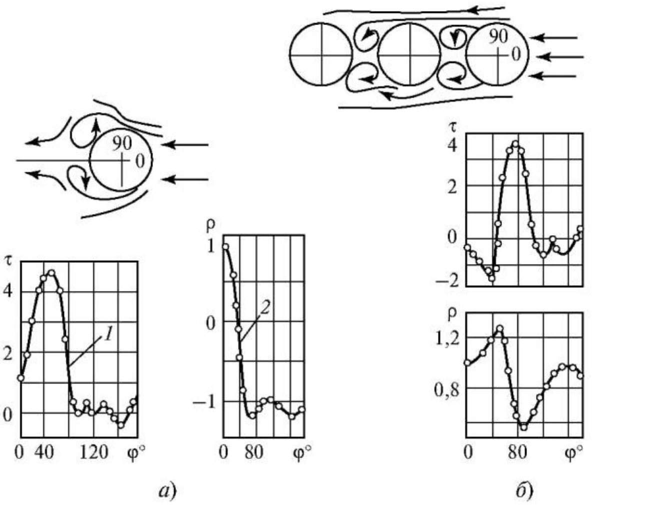


Fig. 6.29. Schematic representation of the cylinder flow (s) and the system of cylinders (b) according to results of observations: curve *1* - distribution of static friction, curve *2* - the same

b = 3,8 [13], which defines two flow patterns. At large longitudinal pitches, i.e. at b> 3,8 vortices coming-off from each of two cylinders at a time can be seen. In this case, frequency synchronization of vortex forming is observed [13], that is, Strouhal number has a single value for a pair of cylinders. Joining of the separated flow occurs in a zone of the front stagnation point of the downstream cylinder; there is only one p_{max} – maximum static pressure in this area. For values $b \leq 3,8$, i.e. at subcritical values of b, there is no coming-off the large-scale vortices from the inter-tube area. At the same time, between the pipes of longitudinal row, the closed circulation vortex cavities are formed. In this range of longitudinal pitches of a group of pipes in the form of a single longitudinal row, Karman vortex path is not formed. This is due to the mechanism of coming-off the vortices, workability of which implies a presence of free inter-tube spacing. In this case, large-scale turbulence of the external flow is not formed, i.e. there are no "useless" energy losses for heat carrier pumping.

For two transversely adjacent cylinders with relative pitches

$$a = \frac{s_1}{d} \geq 1{,}5$$

an independent coming-off the vortices from each cylinder is observed, i.e. mutual influence of the cylinders is insignificant. In this case, separate longitudinal rows of tubes behave independently, i.e. when they are flowed by the heat carrier stream, there will be no vortices coming-off from the cylinder surface.

Of longitudinal tube rows with a number of tubes $Z_2 \geq 2$ in each row, tube bundles can be formed from both the smooth and finned tubes. It is possible to form inter-tube channels of confuser and diffuser type, with a small number of rows as well as multi-tube bundles.

Flow and heat exchange in the developed bundles is arranged as follows. At crossflow of longitudinal rows of tubes between them the separated zones are formed. When $b \leq 3{,}8$ the flow, separated from the cylinder surface, is attached to the underlying cylinder surface in two points. The resulting circulation between the tubes (attached pair of vortices) is experiencing the impact of periodic cross-pressure fluctuations. From the cavity periodically, at a certain frequency f (Hz) heat carrier mass is flushed, which interaction with the main flow leads to the flow turbulence [24]. As it's noted in [25], the energy spectrum of pressure pulsations is broadband in nature (increased turbulence level), where pulsation peaks of vortex zones fluctuations are observed. In [25] experimental results on estimation of Strouhal numbers are given

$$\mathrm{Sh} = fd/w,$$

where d, m, and w, m/s is the cylinder diameter and the flow velocity, accordingly.

The first study of local heat and aerodynamic characteristics [26-28] were carried out with the layout of the tube bundle in a form of paired groups of smooth tubes of "confuser-diffuser" and "tortuous" types [27]. The pair of tubes that was used in the configuration, as it is well-known [13, 29, 30], can significantly reduce the aerodynamic resistance of the tube bundle, as a pair of cylinders, arranged one after another, are flowed without large-scale vortex formation.

Geometrical ratios, that is, longitudinal and transverse pitches of bundle tubes, various displacement of cylinder pairs Δ (a degree of diffuser and confuser) were chosen on the basis of the above provisions. The average relative transverse pitch of smooth tubes (D = 30,85 mm) of the bundle of the tandem pairs - $S_1 = 2{,}0$; relative longitudinal pitch - $S_2 = 1{,}1$; displacement of the cylinder pair $\Delta = 0$ (in-line tube bundle); $\Delta = 0{,}5R$; $\Delta = R$; $\Delta = 1{,}5R$.

Studies of the physical behavior of flow and heat exchange were based on experimental data on distribution of local and average heat and aerodynamic characteristics along the cylinder perimeter.

Experiments with smooth tube bundles included the following measurements:

- surface friction (using a method of counter ledge);
- static pressure (static pressure selection);
- heat exchange (electrocalorimeter at q = const).

In Fig. 6.30, a, schemes of the investigated smooth tube layouts of confuser-diffuser, and tortuous types, formed from the paired cylinders, are presented. Visualization, conducted in flow channel, showed that at flow in the inter-tube spacing of the confuser-diffuser bundle, large-scale vortices are formed. In the tortuous arrangement, vortices can be similarly seen, but they are smaller, which results in reduction of hydrodynamic resistance.

Analysis of energy efficiency showed that the developed bundles are more efficient compared to in-line and staggered under otherwise equal conditions (Fig. 6.30, б). This means that from separate tube groups parallel inter-tube channels, arranging the flows with transverse pressure drops can be formed. In addition, inter-tube vortex zones act as turbulence promoters [12], i.e. maintain an increased level of turbulence of the flow, washing a system of tubes.

Further studies [28] demonstrated a possibility to improve the energy efficiency of confuser-diffuser bundles from the paired tubes by moving the even longitudinal rows of tubes towards the heat carrier flow (Fig. 6.30, *в*). In this case an intermediate assembly with the improved energy efficiency, compared to the others, was revealed.

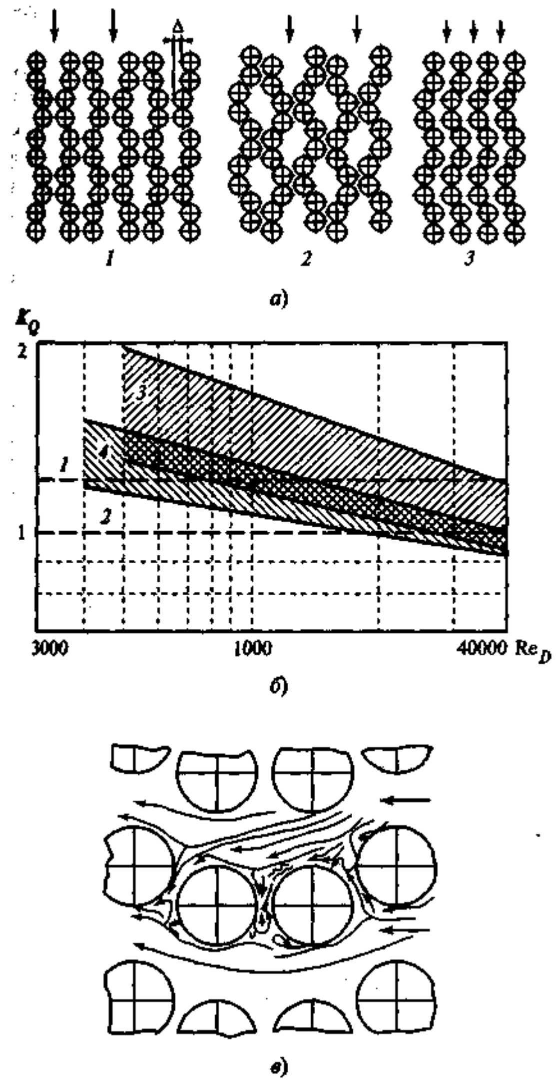


Fig. 6.30. Configuration of paired smooth cylinders: *a* — layouts (1 — confuser-diffuser, *2* — intermediate, *3* — tortuous types); *б* — layout energy efficiency K_Q (1 — staggered, *a*/*b* = 2/1,1; *2* — in-line, *a*/*b* = 2/1,1; *3* — confuser-diffuser and tortuous, Δ = 1,5*R*; *4* — Δ = 0,5*R* and Δ = 1*R*); *в* — diagram of the flow in inter-tube channels of tortuous bundle

Flow visualization in channels of the investigated layouts of paired cylinders with intermediate layouts [28] also showed their weaknesses, that is, a presence of a large-scale turbulence. Reducing the scales of vortices leads to a decrease in energy losses for the flow pumping, i.e. to reduction of aerodynamic resistance.

The consequence of that can be an increase in the energy efficiency of the studied layout of the tube bundle.

Consideration of local characteristics on a surface of the flowed cylinder [12, 13], located in the tube bundle, allows to mark the areas with confuser and diffuser flow nature (front and back areas). This flow pattern, characteristic to interaction between the individual cylinders, has a scale that matches the cylinder diameter. In this case, the cylinders, located in series with local confusers and diffusers, can be combined by the middle flow of diffuser or confuser type. The layout of tube rows under the same principle allow to apply a positive large pressure gradient to local gradients, flowing around individual cylinders. As it is known, for diffuser-type flow, an intensity of turbulence increases [13]. In confuser-type flow, on the contrary (negative pressure gradient) turbulence and disturbances are suppressed. Articulation of diffusers and confusers into the serial channels can improve heat exchange characteristics of the whole tube bundle.

Further development of tube bundles were conducted on this basis, i.e. under a model of flow and heat exchange in adjacent channels with standing votices and large-scale positive-pressure gradient.

Studies of local heat and aerodynamic characteristics of in-line and diffuser smooth tube bundles (Fig. 6.31) with positive-pressure gradient were performed on a model of six-rowed smooth tube bundle [31, 32]. Relative transverse *a* (at the inlet) and longitudinal *b* tube pitches of diffusion bundles made, respectively, a/b = 1,065/1,065. Configuration of such a bundle can be obtained by rotating the longitudinal rows of tubes around the axis of the first row at a certain angle φ. However, centers of tubes of the first row can be arranged in a straight line (in-line type) or displaced (staggered type). Local research program corresponded to the program for the paired tube bundles. Fig. 6.31 demonstrates results of the averaged characteristics of heat irradiation and aerodynamic resistance, which shows that aerodynamic resistance is significantly less (for the paired bundle of tubes up to 5 times) than for the usual line bundle. In this case, heat irradiation is reduced insignificantly (up to 25%). Energy efficiency evaluation of the method [35] at “Other things being equal" provides a significant power reduction for pumping the heat carrier (70%).

Further studies were carried out on the staggered-diffuser and staggered-confuser bundles of cross-finned tubes [33]. In Fig. 6.32 a diagram of design of the developed bundles is shown. In process of experiments the reduced heat irradiation by the local thermal modeling method with security heaters was measured. The data obtained on the average heat irradiation and aerodynamic resistance was evaluated by the method of energy efficiency [34, 35] at “other things being equal”.

For the confused bundle of finned tubes the gained results indicate that heat irradiation rate is much lower than that of the diffuser one. In this case, the aerodynamic resistance is reduced to the same extent as in the diffuser bundle.

It is natural to assume that, since for the confuser bundle less heat irradiation is characteristic, therefore, turbulence suppression due to negative gradient pressure of the mean flow occurs. Since air resistance is reduced to the same degree, we can conclude that there’s no large-scale turbulence in bundles of the considered types. Analysis of energy efficiency of confuser layouts showed an ineffectiveness of flow arrangement of the confuser type.

Thus, synthesis of tube bundles with the increased energy efficiency both of smooth tube and finned ones can be made, forming flat inter-tube channels with the bounding surfaces of tube groups. Fig. 6.33 demonstrates a layout and configuration of the synthetic heat exchange surface in a form of a tube bundle with spiral wire fins. Heat and aerodynamic researches were conducted using a local thermal modeling method for individual layers, i.e. individual tube groups (Fig. 6.33). According to comparative evaluation results of heat irradiation coefficients and specific power for air pumping, there can be concluded that energy efficiency (Fig. 6.34) of the synthesized layout confuser and diffuser air-cooled bundle of finned tubes (model 1) exceeds in efficiency compared to the staggered bundle (model 2).

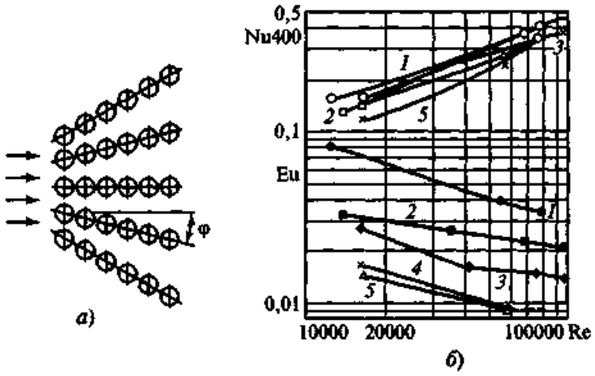


Рис. 6.31. In-line and diffuser smooth tube bundle:
а — bundle configuration; *б* — heat irradiation and aerodynamic resistance: *1* — φ = 0 (in-line bundle); *2* — φ = 0,5°; *3* — φ = 1°; *4* — φ = 5°; 5 — φ = 10°

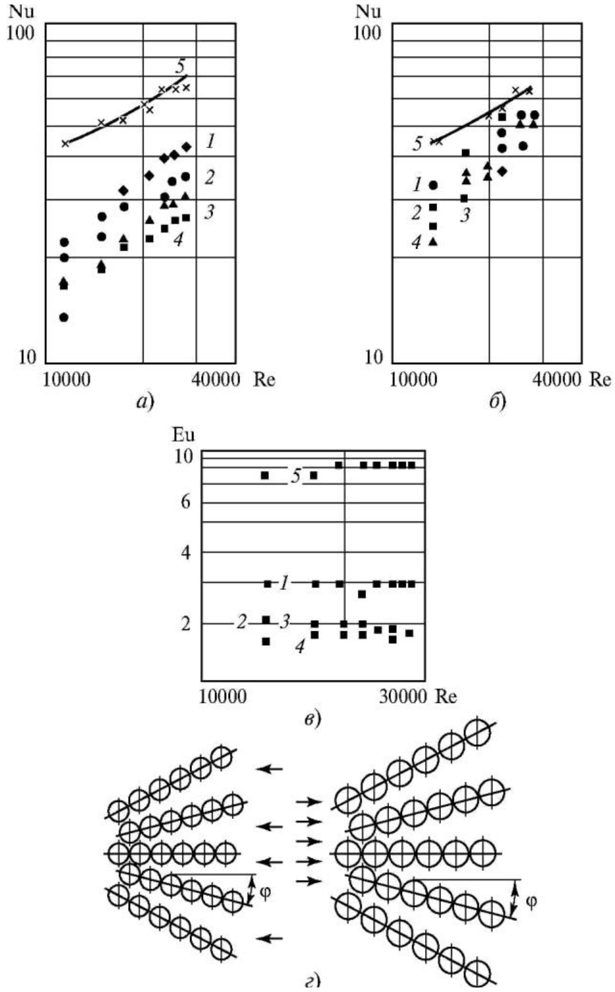


Fig. 6.32. Heat and aerodynamic characteristics of bundles of the finned tubes: *а* — reduced heat irradiation of the staggered-diffuser bundle; *б* — reduced heat irradiation of the staggered-diffuser bundle; *в* — aerodynamic resistance; *г* — layout diagram; *1*—φ= 5°; *2*—φ=10°; *3*—φ=15°; *4*—φ = 20°; *5* — φ = 0

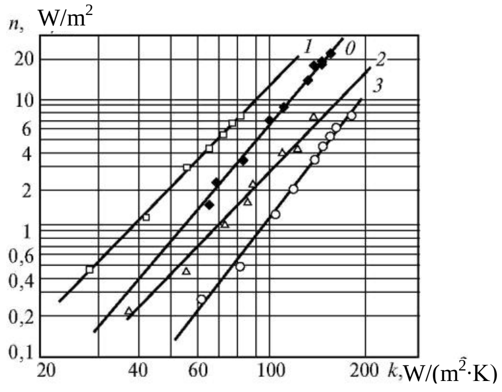


Fig. 6.34. Relationship between heat irradiation factors *k* and specific power for air pumping — *n* for confuser-diffuser bundles: *0* — staggered arrangement; *1* — first layer; *2* — second layer; *3* — third layer

In particular, the following can be noted.

At the same thermal performance of the tube bundle Q, electric power *N*, required for air pumping, can be significantly reduced, compared to the original staggered bundle, as $K_N = (N/N_0) = 0{,}55$. At the same energy characteristics in case of a staggered bundle (*Q* and *N* = idem), the surface area can be reduced, since $K_F = 0{,}44$. Energy efficiency of configurations (model 1 and model 2) is the same, therefore, using a model 1 with a smaller angle (β = 100), tube bundles, comparable by compactness with the staggered bundles, can be developed.

Worked out principles of arrangement of tube bundles allow to improve gas-liquid and air-cooled designs, as well as their technical and economic indicators.