Journal of Engineering Physics and Thermophysics, Vol. 75, No. 5, 2002

HYDRAULIC RESISTANCE OF A RANDOM SPIRAL PACKING FOR REGENERATORS

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UDC 621.51

Results of an experimental investigation of two types of metallic spiral packings for regenerative heat exchangers are considered. They are compared to packings of other types used in regenerators; a method of calculation of the hydraulic resistance of the packings investigated is proposed.

One field of medicine called aerocryotherapy is developing on a large scale at present in Russia and abroad. In the case of practical implementation of this method of treatment, a patient is placed for a very short period of time into a special cryochamber of an aerocryotherapy unit inside which cold gas flows with a temperature in the interval from -110 to -180^{o}C are circulating. The structural features of aerocryotherapy units and the principles of operation are presented in [1, 2].

As a cryoproduct providing the required temperature level of operation of an aerocryotherapy unit one utilizes, in the gas-preparation block, liquid nitrogen, whose consumption largely determines the operating costs associated with the employment of the unit. Investigation of the specific expenditure of cold in the procedure of aerocryotherapy performed in [3] for a domestic KAÉKT-01-KRION unit has shown that only 35% of the total expenditure of cold is utilized efficiently, i.e., is expended on removing heat from a patient. Of the remaining expenditure of cold, underrecuperation in the course of the procedure accounts for 33%, underrecuperation upon completion of the procedure accounts for 18%, and heat supply from the environment through a heat-insulating barrier accounts for 14%.

The above data indicate that much of the cold available in the aerocryotherapy unit is utilized irrationally. To improve the operating efficiency of the unit by increasing the useful component of the expenditure of cold it is appropriate to use the cold of waste gas flows for cooling the subsequent portions of the operating flow in the gas-preparation block. This problem can be solved by incorporating a regenerative heat exchanger into this block, which would "accumulate" the cold of the spent steam of the evaporated cryoproduct and would bring it back into the cycle.

Regenerators have found rather wide use in cryoengineering as heat-exchange apparatuses in large-size air-separation plants of low pressure. In them, one employs regenerators with an aluminum disk packing made of a corrugated tape and with a stony dumped packing manufactured from crushed basalt with a grain size of 8–12 mm. Manufacture of the first type of packings necessitates thin-sheet aluminum and special equipment for its cutting and for manufacture of the tape and its corrugation and subsequent winding of disks from it. All of this involves considerable expenses, which will inevitably lead to a substantial increase in the cost of an aerocryotherapy unit. The use of the second type of packings is not quite favorable in hygienic terms, since the abrasion of basalt in the regenerator because of a periodic change in the direction of motion of the gas flow will lead to the formation of dust and to the necessity of removing it additionally from the gas flow supplied to the working volume of the aerocryotherapy unit. Installation of filtering elements on this flow will produce an increase in the hydraulic pressure of the gas-preparation system.

Of the remaining types of dumped packings mentioned in [4, 5], we can note steel spheres, copper Rashig rings, coiled aluminum rings, etc. However there are virtually no data which would give a comprehensive idea of their hydraulic resistance.

The employment of such packings in the regenerator of an aerocryotherapy unit is rather problematic since the gas flows in the unit are pumped by centrifugal fans, and the head in them is only about 1500 Pa, which is rather low as far as the resistance of regenerators employed in cryogenics is concerned. We have selected a random spiral packing whose manufacture is distinguished by its considerable simplicity and low cost as the most acceptable one.

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1062-0125/02/7505-1022$27.00

TABLE 1. Technical Characteristic of Packings of the SAP Type and Range of Variation of the Basic Parameters of the Experimental Regenerator

Packing	No. of the series of experiments	Compactness S, m^2/m^3	Porosity ε, m^3/m^3	Equivalent diameter $10^3 d_e$, m	Specific mass of the packing ρ_g, kg/m^3	Filtration rate W_f, $kg/(m^2 \cdot sec)$	Pressure loss $\Delta p/h$, Pa/m	Reynolds number Re
SAP No. 1	1.1	1115	0.95	3.4	127	3.2–4.3	980–1310	580–785
	1.2	905	0.96	4.2	103	3.4–4.4	620–860	760–990
	1.3	1855	0.91	2.0	212	3.1–3.9	2330–3280	330–420
SAP No. 2	2.1	825	0.96	4.6	98	3.1–4.1	790–1050	755–1020
	2.2	985	0.95	3.9	117	3.2–4.0	960–1290	670–825

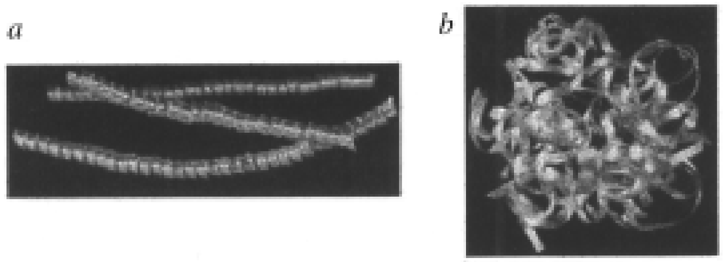

Fig. 1. Experimental packing: 1) SAP No. 1 made of spirals of the same diameter; b) SAP No. 2 made of a tangled tape of the same width and thickness as in SAP No. 1 produced by cutting an aluminum ingot.

We investigated two types of such packings which were the product of turning. Their technical characteristics and range of variation of the basic parameters in experimental study are given in Table 1 and their appearance is shown in Fig. 1. The porosity of the packings was controlled by their compression in the case of placement along the regenerator height.

The investigations were carried out on a special bench consisting of (enumerated in order of their traversal by the gas flow): two fans, a thermometer measuring the temperature at the inlet to the packing, a tube in which the packing was placed between two grids, a differential manometer for measuring the pressure drop on the packing, a differential manometer and a thermometer for measuring, respectively, the excess pressure and the temperature of the gas in front of the counter, and a counter of the gas flow rate. The capacity of the fans which were combined into a network was controlled by valving off the inlet pipes; the height of the packing bed was changed through the movement of the upper grid with fixing screws inside the tube. Blowing-through was carried out using hot atmospheric air. To eliminate the influence of the resistances of the inlet and outlet portions of the regenerator and the metallic grids between which the packing under study was placed the empty regenerator was blown through additionally. Thereafter, in calculating the resistance of the packing, we subtracted the value of the resistance of the empty regenerator from the value of the total resistance with the corresponding flow rate of the gas. The bench is described in greater detail in [6].

To process experimental data we employed the dependences [7] used in studying the passage of a gas flow through a packing bed. According to them, the specific pressure loss per running meter of the packing height is equal to

$$\Delta p/h = \xi \, [W_f^2/(2 d_e \, \rho_g)] \, , \quad (1)$$

$$\xi = (\Delta p/h) \, [\pi^2 \, d_r^4 \varepsilon^3/(2 \rho_g \, S V_{n.cond}^2)] \, , \quad (2)$$

$$\mathrm{Re} = W_f d_e/\mu \, , \quad (3)$$

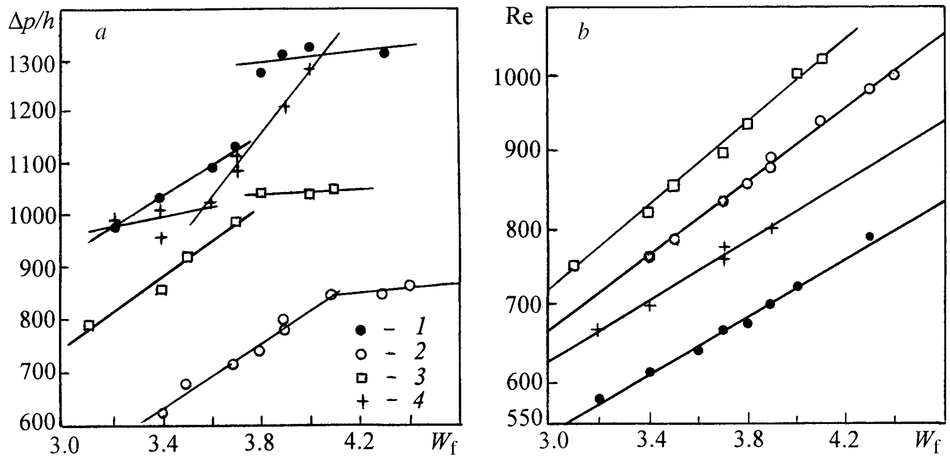

Fig. 2. Dependences $\Delta p/h = f(W_f)$ (a) and $\text{Re} = f(W_f)$ (b) for the investigated packings: 1) series 1.1, 2) 1.2, 3) 2.1, and 4) 2.2.

where $W_f = m/f_r$, $f_r = (\pi d_r^2 \varepsilon)/4$, and $V_{n.cond} = m/\rho_r$.

The results of a calculation from Eqs. (1)–(3) with the employment of the experimental data obtained for SAP (spiral aluminum packing) Nos. 1 and 2 packings are presented in Figs. 2 and 3. It is seen that all the dependences can quite satisfactorily be approximated by straight lines.

On the plot of the dependence $\Delta p/h = f(W_f)$, we observe a sharp increase in $\Delta p/h$ for $W_f \cong 3.7$ kg/(m^2·sec) for the series of experiments 1.1, which also occurs for other series of experiments (Fig. 2a). For each of them the dependence can be subdivided into two portions approximated by straight lines with different slopes. For the series of experiments 1.1 it is seen (Fig. 2b) that the abrupt change in the hydraulic pressure for the same rate corresponds to Re ≅ 660–670. Analysis of the data given in Figs. 2 and 3 allows the assumption that in these cases we have the transition from the laminar regime of flow to a turbulent one. An analogous phenomenon has been observed by researchers in other works where the critical values of the Reynolds number for disk packings were from 250 to 400 [8], from 400 to 700 [9], and from 500 to 800 [10] respectively. In this case the most substantial abrupt changes in $\Delta p/h$ and ξ occurred for the series of experiments 1.1 and 2.2 corresponding to $\varepsilon = 0.95$.

Approximation of each of the linear portions of the dependence $\xi = f(\text{Re})$ for the series of experiments 1.1 enables us to obtain the following design equations for the coefficient of hydraulic resistance:

for $570 < \text{Re} < 660$

$$\xi_1 = 1.284 - 9.39 \,\text{Re}\, 10^{-4} , \tag{4}$$

for $670 < \text{Re} < 800$

$$\xi_2 = 1.694 - 1.428 \,\text{Re}\, 10^{-3} . \tag{5}$$

In the range of Re numbers 660–670, we have

$$\xi = (\xi_1 + \xi_2)/2 . \tag{6}$$

By employing the analogous system of approximations for series 2.2, we obtain

for $660 < \text{Re} < 730$

$$\xi_1 = 2.963 - 3.144 \,\text{Re}\, 10^{-3} , \tag{7}$$

for $730 < \text{Re} < 830$

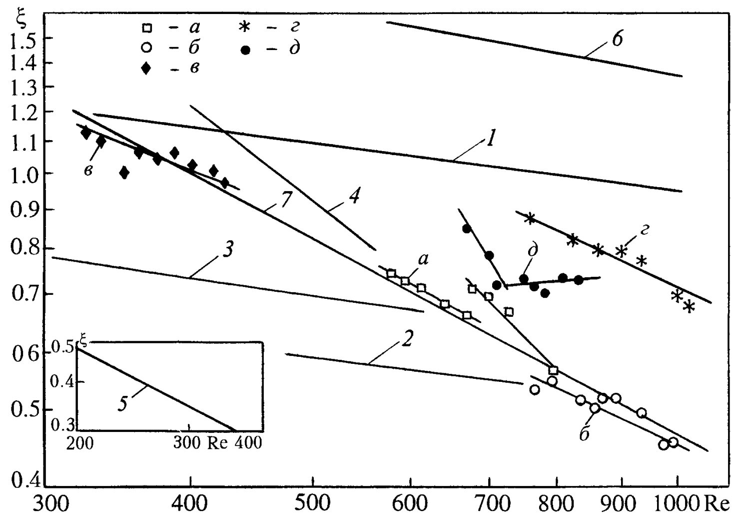

Fig. 3. Comparison of the dependences $\xi = f(\mathrm{Re})$ for different types of packings: 1) Zhavoronkov's experiments [13]; 2) coiled aluminum rings [4]; 3) fine chopped steel chips [4]; 4) disks made of a corrugated aluminum tape at $\beta = 45^{\circ}$ [8]; 5) the same, at $\beta = 60^{\circ}$; 6) coiled tubes with wire fins [12]; 7) universal dependence $\xi = 45\ \mathrm{Re}^{-0.65}$. The investigated packing: a) series 1.1, b) 1.2, c) 1.3, d) 2.1, and e) 2.2.

$$\xi_2 = 0.626 + 1.219\ \mathrm{Re}\ 10^{-4}\ . \tag{8}$$

Equations (4)–(8) enable us to compute the coefficient of resistance of the indicated types of packings accurate to 10%, which corresponds to the accuracy of obtaining this coefficient from experiment.

The dynamics of change of $\xi = f(\mathrm{Re})$ for the series of experiments 1.2, 1.3, and 2.1 is satisfactorily described using a single straight line:

series 1.2) $\xi = 0.82 - 3.665\ \mathrm{Re}\ 10^{-4}$,

$$\text{series 1.2)}\quad \xi = 0.82 - 3.655\ \mathrm{Re}\ 10^{-4}\ , \tag{9}$$

$$\text{series 1.3)}\quad \xi = 1.587 - 1.423\ \mathrm{Re}\ 10^{-3}\ , \tag{10}$$

$$\text{series 2.1)}\quad \xi = 1.419 - 7.15\ \mathrm{Re}\ 10^{-4}\ . \tag{11}$$

The spread of the experiment points in the coefficient of friction about the approximating straight line is, respectively, ± 3, ± 1.4, and $\pm 2\%$.

The spread of the experimental points of the SAP No. 1 packing for different values of the porosity (ε = 0.91–0.96) about the common approximating straight line in logarithmic coordinates is no more than $\pm 10\%$. In this connection, we can determine ξ with a sufficient degree of accuracy in the corresponding ranges of Reynolds numbers from the dependence of the form $\xi = c\mathrm{Re}^{n}$ which, for this case, is equal to

$$\xi = 45\ \mathrm{Re}^{-0.65}\ . \tag{12}$$

In the experiments of series 2.2 on the SAP No. 2 packing, the constancy of the coefficient of resistance (Fig. 3) with increase in Re from 730 allows the assumption of the onset of a self-similar regime. Evidence in favor of this assumption is the fact that in the NK-25,34 dumped ring packings investigated in [11] the self-similar regime in both the channel shape and the characteristics (d_e, ε) similar to the SAP No. 2 packings was recorded for $\mathrm{Re} > 1000$.

As is clear from Fig. 3, the slope of the straight lines which express the dependence $\xi = f(\text{Re})$ for packings of the SAP No. 1 type for $\varepsilon = 0.95$ and 0.96 is close to such for disk packings made of an aluminum tape with a slope angle of the reefs of 45 and 60°, which can be a consequence of the analogy of the circular arrangement of the elements of the SAP No. 1 packing and the tape in the disk. For a denser packing of this type (when $\varepsilon = 0.91$) the slope of the characteristic $\xi = f(\text{Re})$ is largely similar to the slope of the analogous dependence obtained for the coefficient of resistance of the intertube space of coiled cross-flow heat exchangers manufactured from wire-finned tubes with a close agreement [12].

The comparative data given in Fig. 3 for different types of packings show that ξ in random packings of the type of chopped chips and aluminum coiled rings is appreciably lower than in SAP-type packings Nos. 1 and 2, at least for $500 < \text{Re} < 700$. This circumstance can be explained by the method of placing the packing into the regenerator. The SAP No. 1 packing overlaps most of the flow section, since its elements are arranged across the flow, and in the presence of coiled rings the gas can flow both along the axis and in the gaps between the coils. Furthermore, the decrease in the resistance to the flow can be affected by the lower roughness of the wire from which the rings are wound and its round cross section. The SAP No. 2 packing can be compacted somewhat and form local hydraulic resistances.

Thus, we can infer that, in its hydraulic characteristic, the packing investigated is the closest to a disk packing made of a corrugated aluminum tape and can have values of ξ which are close to those of random packings made of wire and chopped chips only when $\text{Re} > 600$.

At the same time, the value of the hydraulic resistance of the packing is largely affected by the ratio S/ε^3, all other things being equal. Dependence (1) can be represented as

$$\Delta p/h = \xi\,[W_g^2\,\rho_g/(2d_e\varepsilon^2)]\,, \tag{13}$$

and, with allowance for the fact that $W_g = 4V_{\text{n.cond}}/\pi d_r^2$ and $d_e = 4\varepsilon/S$, it can be reduced to the form

$$\Delta p/h = \xi K\,(S/\varepsilon^3)\,, \tag{14}$$

where $K = 2\rho_g V_{\text{n.cond}}^2/(\pi^2 d_r^4)$. Then for the regenerator with a SAP No. 1 packing for the series of experiments with $S = 1115$ m^2/m^3 and $\varepsilon = 0.95$ m^3/m^3 we have

$$(\Delta p/h)_{\text{SAP}} = \xi_{\text{SAP}} K\,(1115/0.95^3) = 1300\xi_{\text{SAP}} K\,.$$

According to [4], for a packing of coiled aluminum rings we have $S = 935$ m^2/m^3 and $\varepsilon = 0.167$ m^3/m^3. In the case of equality of the flow rates of the gas passing through the regenerators and their operation in the same ranges of temperatures and pressures, for the regenerator with a packing of coiled aluminum rings (CAR) we have

$$(\Delta p/h)_{\text{CAR}} = \xi_{\text{CAR}} K\,(985/0.617^3) = 4194\xi_{\text{CAR}} K\,.$$

A comparison of the data obtained shows that, despite the fact that $\xi_{\text{SAP}} > \xi_{\text{CAR}}$ for $300 < \text{Re} < 700$, the resistance of regenerators filled with a SAP No. 1 packing will be lower by approximately a factor of 2 to 3 due to the much larger ratio S/ε^3 for regenerators with a packing of coiled aluminum rings than that of the former.

CONCLUSIONS

1. The investigated types of packings are suitable, from the viewpoint of hydraulic resistance, for use in the regenerators of aerocryotherapy units at least for layer heights of 1–2 m, a mass rate of filtration of 3–4.5 kg/(m^2·sec), and a value of $\varepsilon = 0.95$ m^3/m^3.

2. The hydraulic characteristic $\xi = f(\text{Re})$ of the packings investigated differs from most of the existing random packings mainly because of the features of the geometry of a packing element and its arrangement in the bed. The value of ξ of the SAP No. 1 packing (first series) is close to the value of ξ for disk packings made of a corrugated

aluminum tape with slope angles of the reefs of 45 and 60^{o}, which is, apparently, a consequence of the analogy of the circular arrangement of spirals and the tape in the disk.

3. The empirical dependences (4)–(11) to determine ξ of the packings investigated have been proposed. The universal empirical dependence (12), which can be recommended for Re = 300–1000, has been proposed for rough calculations of ξ of the SAP No. 1 packings when ε = 0.91–0.96.

4. The experiments conducted have shown that it is inexpedient to decrease the porosity ε below 0.95 in view of the considerable increase in the hydraulic resistance.

NOTATION

ξ, coefficient of resistance; W_f, mass rate of filtration, kg/(m^2·sec); d_e, equivalent diameter, m; ρ_g, density of the gas; kg/m^3; m, mass flow rate of the gas, kg/sec; f_r, flow section of the regenerator, m^2; d_r, inside diameter of the regenerator, m; ε, porosity of the packing, m^3/m^3; $V_{n.cond}$, volumetric flow rate of the gas under normal conditions (T = 273.15 K and p = 101 325 Pa), m^3/sec; S, compactness, m^2/m^3; μ, dynamic coefficient of viscosity, Pa·sec; W_g, gas velocity referred to the total cross section of the regenerator, m/sec; $\Delta p/h$, specific hydraulic resistance of the packing bed, Pa/m; β, angle of slope of the reefs of a disk packing to the horizontal, ^{o}. Subscripts: e, equivalent; f, filtration; r, regenerator; g, gas; n.cond, normal conditions; SAP, spiral aluminum packing; CAR, coiled aluminum rings.

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