EFFECT OF ELECTROMAGNETIC MIXING ON TRANSPORT PROCESSES IN COLD IMPURITY TRAPS

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UDC 621.039.537.63

Some results of an investigation of the hydrodynamics of heat transfer in the different regions of a flowthrough cold trap with electromagnetic mixing are given.

An important aspect of the technology of sodium, which is used as a coolant in loops I and II of nuclear power plants with fast-neutron reactors, is the removal of impurities, which gain access to the sodium either periodically or continuously during the running of the plant [1]. The commonest devices for sodium purification are flowthrough cold traps [2]. There are a great many designs [2]. In our country the basic design consists of three regions: the nonisothermal sump, the region of final cooling, and the isothermal filter, which consists of two or three parallel sections [3, 4].

Volchkov et al. [3] pointed out the main faults inherent to the above type of trap: the impossibility of having a long sump owing to solidification of sodium on the bottom of it; the formation of a peak of crystallized-out impurities in the initial region of the filter; the precipitation of impurities in the outlet line of the trap at the start of its operation. Moreover, the residence time of sodium in the trap must be at least 5-10 min for the obtention of the impurity retention coefficient $\beta \geqslant 0.6$-0.7. A considerable increase (by a factor of 2-3) in the flow rate of coolant through the trap, i.e., a corresponding reduction of the residence time, is required in the case of contamination of the sodium due to breakdown, when the performance of the trap (amount of impurities removed from coolant in unit time) has to be increased. An increase in sodium flow rate leads to a reduction of β, with the result that the trap performance does not increase in proportion to the flow rate, as might be expected, but much more slowly. The considered faults can be eliminated by, firstly, increasing the length of the sodium flow in the trap and, secondly, creating conditions in it for mass transfer such that precipitation of impurities from the sodium flow is practically complete before the filtering region of the trap.

An effective way of solving all the above problems is intensification of transport processes in the cold trap by electromagnetic mixing. Roy and Pohl [5, 6] gave the results of investigations of the effect of electromagnetic twisting of a desecnding cooling sodium flow in an annular channel. They showed that mass transfer is greatly improved and retention coefficient increases from 0.51 to 1 (for hydrogen) and is doubled for oxygen (the absolute values of the O_2 retention coefficients could not be determined in the experiments in [5, 6]).

The experiments described below were conducted on a section [7] similar in design to the cold traps most widely used in our country [3, 4]. The main dimensions of the section are given in Fig. 1a, and those of the inductor are given in Fig. 2a. The distribution of induction over the radius and height of the internal volume of the inductor, determined with the aid of a measuring loop and tube voltmeter at different currents, is shown in Fig. 2b and c, respectively. It is apparent that the magnetic flux within the quadrupole inductor is concentrated mainly in a 60-mm layer (from its surface).

Rectangular fins in the form of a screw thread with pitch 4.5 mm, fin thickness 1.5 mm, and fin height 3 mm were cut in the wall of the section to improve the heat transfer. Descending flow of the metal in the sump of the section was ensured by a helix, which had 10 rings 2 mm thick, external diameter 158 mm and internal diameter 82 mm. The pitch of the helix was 60 mm. A 1.5-kW nichrome heater was mounted on the axis of the section. Over the whole length of the section at diameters 74 and 146 mm there were two 6 × 1 mm pockets which contained movable thermocouples. The single-section filter of the section consisted of three parts, each 50 mm high, packed with noncorroding cuttings. The density of packing in the

Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 37, No. 4, pp. 620-625, October, 1979. Original article submitted September 5, 1970.

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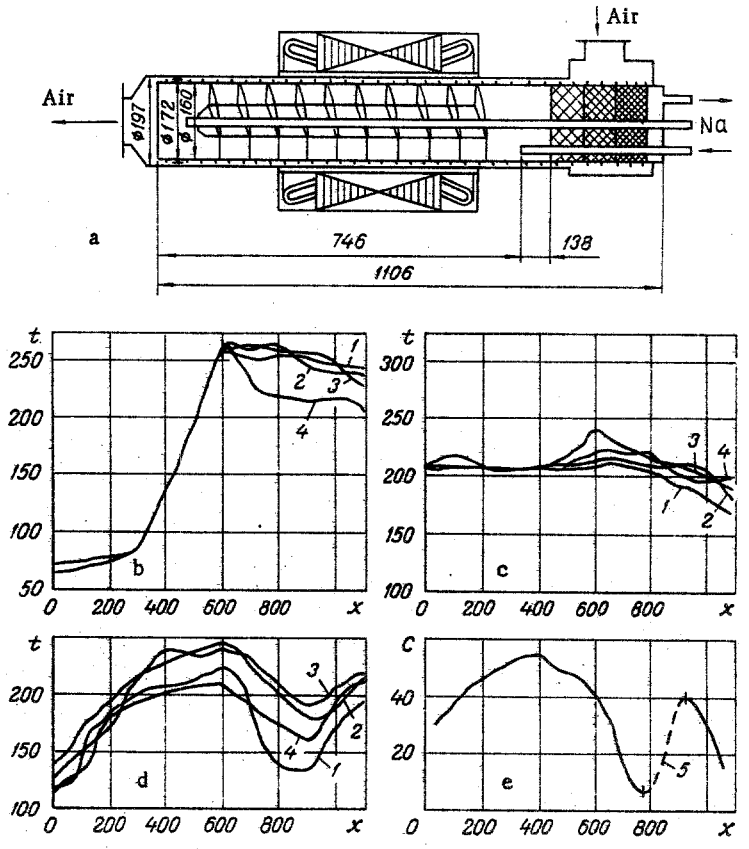

Fig. 1. Design of experimental section, and distribution of temperature and sodium oxide in it: a) experimental section; b) temperature distribution in regime 1 (Table 1); c) regime 2 (Table 1); d) regime 3 (Table 1); e) Na_2O concentration. 1, 4) Thermocouples at distance 73 mm from axis; 2, 3) at distance 37 mm from axis. Portion 5 — interpolation of measurements by γ-ray densitometer at two points. x, mm; t, °C; C, wt.%.

parts was 120, 240, and 480 kg/m^3, respectively. The sodium passed successively through the parts of the filter.

The air and sodium temperatures were measured with Chromel–Alumel thermocouples; the sodium flow rate was measured with a magnetic flowmeter; the flow rate of air pumped through the annular gap of width 12.5 mm was measured with a U-shaped oil manometer calibrated with the aid of an air anemometer. The heat power of the section was determined as

$$Q = G_1 C_p (t_1 - t_2), \tag{1}$$

where C_p was taken at the characteristic temperature, equal to the arithmetic mean of t_1 and t_2. The heat flux was determined also in terms of G_2, t_3, and t_4 (parameters of air flow). The difference in the obtained two values of heat power at air flow rates >0.28 m^3/sec did not exceed ±14%. The mean heat-transfer coefficient for the whole section was found from the expression

$$K = Q/\Delta t S, \tag{2}$$

where

$$\Delta t = t_1 - \frac{t_3 + t_4}{2}. \tag{3}$$

K, defined by (2), is an arbitrary quantity. This method of finding K is due to the complex nature of the temperature field within the section, especially when there is a layer of solidified sodium at the bottom of the section and a layer of impurities on the heat-transfer surface. On the other hand, the use of Δt from (3) allows a comparison of the heat fluxes for the above indicated cases.

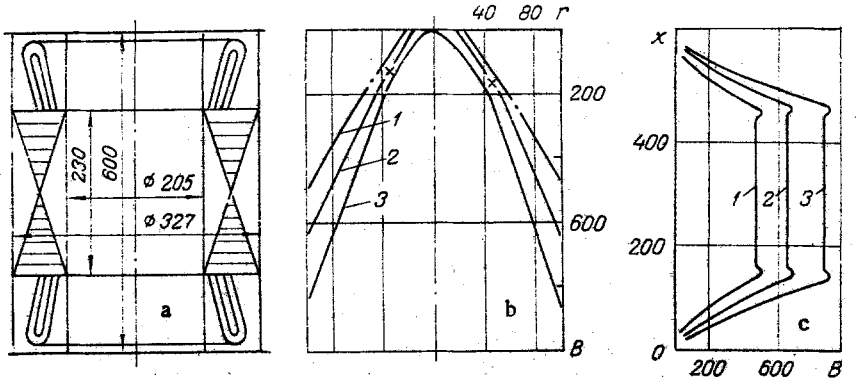

Fig. 2. Dimensions of inductor and distribution of induction within it at different currents: a) inductor; b) distribution of induction over radius; c) distribution of induction over height: I = 1) 10; 2) 20; 3) 40 A, r, x, mm; B, G.

The filtration characteristics of the experimental section were determined by introducing Na_2O_2 powder and gaseous H_2 into the sodium. The O_2 concentration in the Na was determined by a cork impurity indicator [2] with the aid of the equation

$$\lg C_s = 1.14 - \frac{1910}{T}. \quad (4)$$

The H_2 concentration in the Na was measured by a gauge with a hydrogen-permeable membrane [8].

The distribution of the Na_2O over the height of the section was determined by measuring the γ-ray transmission [3]. The relation between the change in thickness of the aluminum screen and the Na_2O concentration is given by the equation

$$C = \frac{\mu_s \rho_s \rho_2 k \cdot 100}{(\rho_2 - \rho_1)\mu_s \rho_s k + \rho_1 l_* (\mu_2 \rho_2 - \mu_1 \rho_1)}. \quad (5)$$

The ratio of the length of the sump of the experimental section to its diameter is ∿5. This is much larger than the values for the cold traps of experimental rigs and industrial plants (1.5-3). Hence, the use of air as a coolant without preheating led to solidification of the sodium at the bottom of the section. Figure 1b shows (regime 1 in Table 1) the region of solid sodium. When the inductor was switched on, a portion of the descending sodium flow with a temperature close to that of the sodium leaving the section was formed at the cooled wall. Thus, the temperature field was leveled out (Fig. 1c), which led to an increase in the effective air–sodium temperature difference and, hence, to an increase in the heat power of the section. Table 1 indicates that the use of the inductor increased the heat flux by a factor of ∿1.5.

The value of the electric current has practically no effect on the heat transfer when the temperature field in the section is leveled out. This is due to the fact that the main thermal resistance occurs at the wall–air boundary and an increase in the sodium velocity at the cooled surface has almost no effect on the heat-transfer coefficient. Only a very approximate estimate of the sodium velocity at the wall can be made. For the considered geometry at current ∿45 A the mean axial velocity over the width of the helix blade in the space between adjacent turns of the helix is ∿0.4 m/sec. This means that the sodium flow rate in the flow produced by the electromagnetic forces and circulating in the closed space is many (up to ∿30) times greater than the flow rate through the section.

Thus, favorable conditions are created for the crystallization of impurities from the flow by an increase in the sodium residence time in the section — stagnant zones are eliminated — and by the creation of rapid motion at the cooled surface. This is manifested in the value of ∿1 for the retention coefficients for O_2 and H_2 in the presence of electromagnetic mixing; this value is attained when the residence time of Na in the section is ∿1.6 min, which is much lower than the value usually recommended for cold traps. This means that the use of electromagnetic mixing of the flow allows a sharp increase in the coolant flow rate through the trap, i.e., in its performance. Moreover, the obtention of $\beta = 1$ leads to practical completion of the mass-transfer process before the flow leaves the section. Hence, in the experimental conditions, we observed no precipitation of impurities in the output line when electromagnetic mixing was used.

TABLE 1. Heat Regimes of Experimental Section

No. of regime	Electromagnetic mixing	G_1, kg/sec	G_2, m^3/sec	t_1	t_2	t_3	t_4	t_5	h, mm	Q, W	K, W/deg·m^2	P, kg
1	No	0,19	0,40–0,46	312	232	5,2	47,8	65	350	19840	128	0
2	Yes (I=45 A)	0,19	0,40–0,46	312	195	—9,2	52,8	205	0	29100	186	0
3	Yes (I=45 A)	0,19	0,40–0,46	301	207	—2,0	49,7	120–140	0	23450	157	12,8

The accumulation of sodium oxide in the section, as was to be expected, leads to distortion of the temperature field and to a change in heat power (regime 3 in Table 1, Fig. 1d). The radial and axial temperature gradients become greater, particularly in the filter, where the cooling-air inlet and, hence, the region of maximum heat flux are situated. The accumulation of sodium oxide on the cooled surface leads to reduction of the sodium flow rate in the bottom region of the section, which is manifested in a reduction of the temperature in this region. The heat power of the experimental section after the accumulation of 12.8 kg of Na_2O in it was reduced by a factor of $\sim$1.25.

The distribution of sodium oxide over the height of the section is shown in Fig. 1e. The accumulation is greater approximately in the middle of the sump. The second peak was formed in the first part of the filter. The presence of this peak accounts for the increase in hydraulic resistance of the section. The formation of the peak in the filter can probably be explained in the following way. The incoming sodium flow breaks against the first blade of the helix. As a result, part of the flow entering the section is not subjected to electromagnetic mixing and passes directly into the filter.

The concentration of sodium oxide at the bottom of the section was $\sim$30 wt.%. This value can be greatly increased by the successive accumulation of impurities over the height of the section in a direction away from the bottom by moving the inductor. The concentration of the bulk of the impurities accumulated by the trap in the sump before its capacity is exhausted is the main advantage of a trap in which electromagnetic mixing is used.

Thus, the use of electromagnetic mixing improves all the transport processes in the different regions of a flowthrough cold trap: hydrodynamics, heat transfer, mass transfer. The length of the cooled sump and the heat power of the trap can be simultaneously increased; completion of mass transfer within the trap can be achieved with residence times of <2 min. The last property allows a severalfold increase in the trap performance, which is particularly important in emergency situations.

NOTATION

G_1, sodium flow rate, kg/sec; G_2, air flow rate, m^3/sec; t_1, t_2, sodium temperature at inlet and outlet of section, °C; t_3, t_4, cooling-air inlet and outlet temperatures, °C; t_5, sodium temperature at bottom of section; h, height of solidified sodium at bottom of section, mm; x, axial coordinate, mm; r, radial coordinate, mm; B, induction, G; I, current, A; Q, heat flux, W; K, heat-transfer coefficient, W/m^2·deg; P, mass of sodium oxide accumulated in section, kg; C, impurity concentration, wt.%; β, retention coefficient for impurity in trap; C_p, specific heat at constant pressure, J/kg·deg; S, heat-transfer surface, calculated from internal diameter of section, m^2; Δt, temperature difference, °C; C_S, sodium impurity saturation concentration, wt.%; T, temperature of saturation of sodium with impurity, °K; μ_1, μ_2, μ_S, mass coefficients of absorption of sodium, sodium oxide, and aluminum, cm^2/g; ρ_1, ρ_2, ρ_S, density of sodium, sodium oxide, aluminum, g/cm^3; k, change in thickness of aluminum shield, cm; l, length of transirradiated region, cm.

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INSTABILITY OF A VIBRATIONAL FLUIDIZED BED

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UDC 532.546.6

The causes of fine- and large-scale instabilities of a vibrational fluidized bed are discussed and simple models are constructed; the reasoning presented is confirmed experimentally.

With vertical vibration of finely dispersed loads the free surface of the vibrationally fluidized bed very often proves to be nonhorizontal and the distribution of material over a cross section of the apparatus is nonuniform. This has been noted repeatedly in reports on vibrational fluidization, starting with the earliest ones (see [1-5], for example), but clearly insufficient attention has been paid up to now to the analysis of the causes of the nonuniformity phenomenon. At the same time, with the transition to large-scale installations this nonuniformity grows, and under certain conditions part of the vibrating bottom can prove to be entirely uncovered, which leads to instability in the operation of the installation and sometimes to its getting out of order prematurely.

Earlier the nonhorizontal nature of the free surface was connected with the vibrations not being vertical and with the amplitudes of vibrations of individual parts of the bottom being unequal [1, 2]. Special tests showed, however, that only loads of sufficiently large particles react to a change in the direction of the vibrational axis, but even for them the motion of the material is always directed toward the inclination of the axis in the lower part of the bed and in the opposite direction in the upper part, and it cannot be enlisted for an explanation of the observed nonuniformity. Loads of fine particles ($\sim$0.1 mm in diameter) do not react at all to a small inclination of the vibrational axis, which agrees with the well-known data of [6] on vibrational transport and vibrational bunkering.

It seems obvious that the bias of the free surface and the nonuniformity of vibrational fluidization are due to the ordinary "hydrodynamic" instability of the "average" (unperturbed) state of a vibrational fluidized bed, formed under the action of complicated fields of gasdynamic and viscoelastic forces arising in the process of the separation of the bed from and its falling onto the bottom as a result of the combined action of the relative motion of the gas and of waves of elastoplastic deformation propagating through the material of the load. The initial instability relative to small perturbations in the shape of the free surface leads to the formation of relatively slow secondary gas flows and to motion of the particles entrained by them, and this untimately causes the appearance of the observed nonuniformity. The decisive role of gas flows in the development of large-scale instability of a vibrationally fluidized bed is confirmed by the tests in [7], according to which the evacuation of the apparatus, the replacement of the closed bottom by a permeable porous one (which promotes a decrease in the swelling of the bed), and a transition to larger particles (for which the specific force of interaction with the gas is smaller than for fine ones) lead to leveling of the free surface and the disappearance of the nonuniformity.

Investigation of the stability of the average state of a bed is hindered by the fact that a theory which would permit an analytical description of the characteristics of this state

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 0022-0841/79/3704-1162$07.50