

On the Rational Structure of a Rotating Fluid Flow in Geotechnological Processes

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Considering the present state of the world mineral resources, it is shown out that hightemperature geothermal fluids can he used to extract valuable minerals. For this purpose a technology was devised and experimental vortex equipment was built and tested under laboratory conditions. It was proved that any technological process for concentrating valuable materials (including geothermal fluids) demanded a certain vortex flow structure to optimize heat-and-mass transfer.

INTRODUCTION

Industrial progress entails an increasing demand for products obtained from raw mineral materials, the amount of these products having doubled during the last decade. Using the consumption of some metals as an example one can estimate the growth of this demand (Table 1). At the same time, and in spite of intense

mining, the resources of raw mineral materials available worldwide are increasing owing to discoveries of new deposits, to more careful investigations of those previously known, as well as owing to ore reserve reassessments based on new conditions (Table 2) [4], [5]. However, the increase of mineral resources generally takes place by involving poorer or more complex deposits whose mining was previously regarded as unprofitable; for this reason a close relation exists between the quality of ore resources and prices of metals. For example, as can be gathered from [5], the price of aluminum at the London Metal Exchange increased by a factor of 1.5 during a period of 1970-1994, the price of nickel having increased by a factor of more than 3 for the same 25 years.

Metal	Year	Price, dollars/ton
Al	1993	1206
	1994	1462
Ni	1970	~2000
	1976	4200
	1993	5365
	1994	6490
	1996	7715
	2000	8678

The deterioration of ore grade affects all regions of the world For example, the average content of copper in the deposits of developing countries dropped down to 1.57% in 1971 from 2.35% in 1961, and to 1.2% m 1981 This resulted from having to use porphyry copper ores in which the content of copper is in the range of

0.5 – 0.8% [4]. During the same period the average content of lead in ores declined from 4.1 % in 1961 to 3.3 % in 1971 to 3.0 % in 1981. The average content of tin in lode deposits declined from 1 - 2% in 1952 to 0.5-1% in 1978, the respective values for alluvial placers being 0.04% and 0.02%. The average

extractable content of gold in the U. S. A. decreased by a factor of 1.9 during the period of 1950-1970 [4]. A similar situation [3] took place in the former USSR. Iron ores with 55 58% of iron were mined in the 1960s,

the present-day iron content is 30%. The average ash content of coal mined in the 1970s was 22% the present-day value is as high as 50%.

Table 1 Consumption growth of some metals since 1985 [5]

Metal	Year	Consumption, tons	Metal	Year	Consumption, tons
Bi	1985	3000	In	1985	55
	1986	3500		1986	75
	1987	4000		1987	90
	1988	4300		1988	104
	1989	4400		1989	107
	1990	4500		Zn	1985
V ₂ O ₅	1989	41800	1989		548000
	1990	48700	1992		720000
Cd	1990	15600	Hf	1990	130
	1993	24000		2000	220

Miners have to go to greater depths, mine low-grade deposits and even use waste rock dumps. Valuable components are increasingly extracted from unconventional raw materials; for instance, sulfur started to be derived from natural or associated gases. A number of metals are being extracted from a wider range of raw materials. For example, alkali metals begin to be extracted not from conventional minerals (spodumene pectalite etc.) but from new materials such

as brines, associated petroleum water, geothermal water, lithium-bearing clay, etc., because more than a half of the total explored alkali metal reserves are concentrated in these materials. Much can be done to enhance the output of mineral production by a more efficient use of the reserves: at present the loss of coal underground is 22%, >50% being a value for potash salts up to 20% for iron ore, and up to 10% for refractory materials [1] [2].

Table 2 World reserves of basic nonferrous metals [1], [2], [3], [4], [5], [6].

Metals and ores	Total reserve, millions of tons			
	1961	1971	1981	1991
Bauxite	6600	9500	21900	30600
Al	319	210	481	542
Pb	60.9	94.2	127	145
Zn	117	147	203	223
Ni	29.4	67.5	59.4	59.7
Sn	5.29	6.83	7.36	7.8
W	0.610	0.878	1.650	1.841
Mo	2.29	4.89	9.74	11.6
Co	2.25	2.76	2.86	2.9
Sb	1.53	1.65	1.81	1.9

The deterioration of ore quality is compensated by the exploration and development of new deposits and by integrated ore processing involving the extraction of noble, rare and trace elements as well as of sulfur.

At present low-waste technologies are being devised

by enhancing the multiprocessing of ores along several lines [1] [2] [3], [4], [5], [6]: (1) development of new mining and production processes through the application of dissolving, melting, leaching, underground gasification and other techniques; (2) enrichment of raw materials by on-site anhydrous

techniques; (3) development of uneconomic and substandard mineral deposits; (4) increasing use of useful materials from overburden and host rocks, waste from ore and coal enrichment processes, slime and other wastes for the construction industry and civil engineering building materials manufacture; (5) development of geothermal reserves; (6) development of technogenic deposits; (7) development of new technologies for the enrichment of raw mineral materials using drying, thermal treatment, sorption, and other techniques; (8) recovery and concentration of finely disseminated mineral materials in order to enhance the efficiency and expand the range of resources containing natural and technogenic useful materials.

Enrichment and processing of ores having increasingly lower contents of valuable components entails increasingly wider ranges of deposits to be used by involving ever new types of mineral materials.

Low-grade materials are usually classified into natural and technogenic types in terms of origin. Lode and placer deposits with low contents of valuable components generally arise under natural conditions. On the contrary, various types of low-grade materials in the phase state of aerosuspension and hydrosuspension are of manmade origin; these are various kinds of sand-clay refuse (e. G. crushed gold ore) and technological dusts that contain valuable components. Lean raw materials in the form of liquids, aerosols and gases are generated both under natural and manmade conditions; these are accompanying water, brines, liquid industrial waste low- and high-temperature geothermal fluids, technological gases, etc. As more lean raw materials begin to be exploited, increasingly more important become manmade placers, crushed gold ore from dredges and industrial devices, which contain various fine-grained metals and their compounds such as Ag Au Pt Ge Y and V.

High-temperature geothermal fluids with high contents of valuable components can be a rather promising source of mineral matter.

The experience gained in the development of geothermal fields shows that their use is more profitable than any other methods of steam production, when steam is to be converted to electrical energy. Studies are being conducted in several countries on how valuable components can be extracted from geothermal fluids. For instance, boron and other compounds are extracted from geothermal fluids of the Lardarello fields in Italy. That natural hot fluids are available everywhere in the world was corroborated by drilling through horizons of thermal water during exploration and development of mineral deposits. At the same time a practical use of geothermal fields can only be feasible when certain conditions are met, namely, sufficient reserves, appropriate P - T parameters of the heat agent and profitability of the development [3].

The temperature of the fluid determines its technological use. Hot water below 100°C is used for heating and medical bath treatment (depending on the chemical composition concerned) and is classified as a low-temperature heat agent. Hot waters between 100°C and 300°C are known as medium temperature heat agents, and water above 300°C is classified as a high-temperature heat agent. Because of technological difficulties arising in drilling through hot rocks and building power plants in volcanic zones, the latter is not used in Russia.

As for low-temperature heat carriers their chemical compositions determine their medical applications. High temperature fluids with high contents of valuable components can be regarded as liquid ores or, more exactly, as concentrates of intermediate products where extraction is possible by the method of partial condensation. Studies of geothermal fluid compositions showed the presence of compounds of metals and metalloids, such as B, Br, I, Li, Be, Hg, etc. Many of these components are apparently soluble in steam under high pressures, but they may also be present as aerosols in steam at low pressure. Large amounts of zinc, arsenic, tin and silver were found in the Shov-

Shinzan fumaroles [9], [11].

Based on the concentration of valuable compounds, some of the geothermal fluids can be regarded as raw mineral materials, the extraction of valuable components from which may contribute to a more profitable power production.

Depending on the characteristics of a geothermal fluid, its processing may require separation, condensation, sorption, or evaporation; various processes of chemical technology may be required to deal with the processing of natural brines and dry mineral residue during the geotechnological use of the fluid.

Important aspects of a rational use of geothermal fluids are the recovery and processing of fine dispersed suspensions using high technologies that require the use of special-purpose equipment capable of carrying out simultaneous multifunctional processes.

In particular, considering the high energy resources of heat carriers and, hence, the requirements on these from the viewpoint of power production, a wide use of cyclonic vortex devices is reasonable [7], [8]. Production efficiency can be increased by transferring the processes concerned from diffusion or transition regions to a kinetic region by mixing the reagents, thereby replacing a slow molecular diffusion by a convective diffusion. This results in a turbulent structure, a relatively thick laminar layer near a drop or a particle is destroyed, thereby accelerating the transfer of the reacting components. Besides, mixing generally increases the surface of interacting phases, thus accelerating the reaction. At the same time the increase of turbulent pulsation during the processing of suspensions in technological equipment is caused by an increasing flow velocity, resulting in the increasing entrainment of the material processed and decreasing the time of its residence in the working volume; this unfavorably affects the processing quality, despite the intensification of heat- and-mass transfer.

This effect limits the specific production rate of technological devices. However, when the

technological processes take place in vortex devices, the effect of this conflict on the processing quality can be reduced by the action of centrifugal forces on dispersed drops or particles. The resulting separation of suspended drops toward the walls of the device and the participation of the suspension in longitudinal circulation diminish the entrainment and increase the residence time of the drops in the working volume. In this connection the importance of vortex devices in the processing of dispersed suspensions increases as the fluid extracted from geothermal fields deteriorates. Depending on the thermodynamic and technological features of processes, the optimal implementation of each process requires the use of vortex devices that have appropriate operational and design parameters, which would ensure a rational hydrodynamic structure of the flow in the working volume.

Even though the types of raw mineral materials, technological processes, and vortex structures are very diverse, there exist criteria that can be used to estimate this continuum.

The best criterion seems to be the energy consumption required for the processing of raw materials using different methods in order to obtain high-quality concentrates.

Considering different phase states of the raw material and the technological input- output regulations, a comparison between energy consumption values in processing different raw materials requires subtracting from the total energy consumption the amount that is needed to disperse the suspension and to impart kinetic energy to it during the technological process. Making the resulting quantity dimensionless by referring it to the mass of raw material, we derive a criterion that can be called the specific potential energy of the process E_{spec} :

$$E_{spec} = \sum c_i \Delta T_i + \lambda_j, \quad (1)$$

where c_i , ΔT_i are the respective specific heats and temperature contrasts, λ is the specific energy of phase

transitions.

According to equation (1), $E_{spec} = 0$ for gravitational processes, unless energy is expended for some phase transitions. For sorption and ionic transfer the value of E_{spec} is in the range -100 to 100 kJ/kg. Techniques based on evaporation giving intermediate products in the form of concentrated brines operate in the range of E_{spec} between 200 and 2000 kJ/kg [6].

When high-temperature fluids are processed using methods of partial or complete condensation the specific potential energy is in the range 100 to -3000 kJ/kg, depending on the thermodynamic parameters of the process.

The hydrodynamic structure of a vortex flow is best described using the Rossby criterion (Ro) which gives the energy of the rotating motion of a vortex flow. The aim of this study was to determine the character of relations between these two quantities.

The most characteristic quantities required for calculating the Ro criterion, which can be fairly exactly determined in cyclonic vortex devices are as follows: h , slit height of flow input; a , slit length of flow input; $f_{in} = ah$, area of flow input; L_{ch} chamber length; D_{ch} chamber diameter; d_p pinch diameter; V_{vm} , r_{vm} are the maximum value of the tangential component and its radius, respectively; V_{in} input flow velocity.

The conventional form of the Ro criterion used in the design of cyclonic chambers [12]:

$$Ro_1 = V_{in}^2 \sum \frac{f_{in}}{V_{vm}^2 L_{ch} r_{ch}} \quad (2)$$

$$Ro_2 = V_{in}^2 \sum \frac{f_{in}}{\pi r_{vm} V_{vm}^2 R_{ch}} \quad (3)$$

is not suitable for the design of vortex apparatuses, because the design parameters and the condition of the wall completely control the flow structure in simple cyclonic chambers in self-simulating modes, i. e., as Ro increases according to (2) and (3), so do the resistance and the coefficient of conservation of rotation velocity,

while the exponent k decreases. In the case of vortex chambers this pattern breaks down: the Ro criterion in vortex apparatuses with a concordant flow interaction is lower than that for geometrically equal and similar cyclones, but the resistance and vorticity are higher than in cyclonic chambers [7], [10], [12]; the theoretical Ro criterion for vortex apparatuses with a discordant flow interaction is higher, while the resistance and vorticity are lower, judging by experimental evidence, than in cyclones. A similar discrepancy occurs when the above criteria are compared with the flow structure in the working volumes of vortex chambers. This can be explained by the fact that the flow structure in them is controlled not only by the design parameters but in the first place by flow interaction, and the relation between the operational and design parameters in (2) and (3) are at variance with the real physical process. Moreover, the above formulas include an experimentally measured quantity which is difficult to measure under production conditions or at the designing stage, and the existing empirical relations that can be used to find V_{vm} through $\chi = V_{vm}/V_{in}$ can only be used for certain chamber types.

Based on the experimental study of flow structure in vortex chambers, we found a criterion that depends only on the operational and design parameters and eliminates ambiguities in determining the technological characteristics of vortex chambers:

$$Ro_{exp} = A \frac{1 \pm \frac{V_1}{1 - V_1}}{d} \quad (4)$$

where $A = 4 \sum \frac{f_{in}}{\pi D_{ch} L_{ch}}$ is a dimensionless input

flow area; $V_1 = \frac{Q_1}{Q_1 + Q_2}$ a dimensionless rate for the

first flow; $L = \frac{L_{ch}}{D_{ch}}$ a dimensionless chamber length;

$d = \frac{d_p}{D_{ch}}$ a dimensionless pinch diameter of the vortex chamber.

As the effects of the various operational and design parameters on the flow structure are different, all components in the equation should have their own correction coefficients found experimentally:

$$Ro_{exp} = k_1 A^x k_2 \frac{\left(1 \pm \frac{V_1}{1 - V_1}\right)^y}{k_3 d^i} \quad (5)$$

Even though the form of the Ro criterion proposed here is similar to the forms of the conventional equations for cyclonic vortex apparatuses [12], it has a different physical meaning and allows a satisfactory estimation of the characteristics of any vortex apparatus.

The data reported in the literature on the optimization of operational and design parameters for various technological processes [10], [12] were obtained for specific designs and, hence, are insufficient for fully estimating the effect of the process concerned on the flow structure. The absence of any theory in this line of research prevents mathematical methods to be employed for deriving the desired relationship. Therefore the only feasible way to solve the problem was to carry out a series of comparable experiments in models of vortex chambers.

We studied the aerodynamics of the core of a rotating fluid flow in the working volumes of vortex chambers during various technological processes using an experimental testing unit which is schematically displayed in Fig. 1. The unit functioned as follows: the ventilator ATsS 850 (1) fed air through pipe 3; the air flow rate was adjusted by slide valves 8; the air mainline conveyed air to heating cartridges 6, which could be heated to 500°C when required by the technological regulations, the worm feeder 14 fed dispersed material both to the mainline and to the working volume.

When it was required to model high-temperature processes involving the combustion of a fuel (propane-butane), a mainline gas supply system was switched on to propel the gas to the dead end of the vortex chamber from cylinder 19. To model condensation we switched on the mainline which delivered steam from steam generator 16; if necessary, solutions with mineral admixtures were ejected into the steam from vessel 20. For modeling evaporation there was a mainline which supplied a fluid; the fluid was conveyed by pump 25 from vessel 18 to the working volume of the vortex chamber. Valves 17 were used to select a desired technological process and to switch off unwanted systems. The resulting products were collected in settling tank 21 and removed. Technological gases were removed via the scrubbing system 22 by exhaust fan 23 to pipe 24.

The vortex chamber 2 was assembled from cylindrical units held together with flange joints 9. The internal configuration of the vortex chamber working volume was varied using plane replaceable pinches 12 and 13 with different diameters of the holes; the pinches were used to modify the parameters d_1 and d_2 in the range 0.05 to 1. The mode of a rotating flow generation in the chamber volume was determined by the orientation of the vortex units relative to one another.

Air was admitted into the vortex chamber working volume using tangential grooves, each consisting of four 0.08 x 0.05 m slits. The aperture of an input slit was varied using concave cylindrical shutters having a curvature radius of $R = D_a/2$, the positions

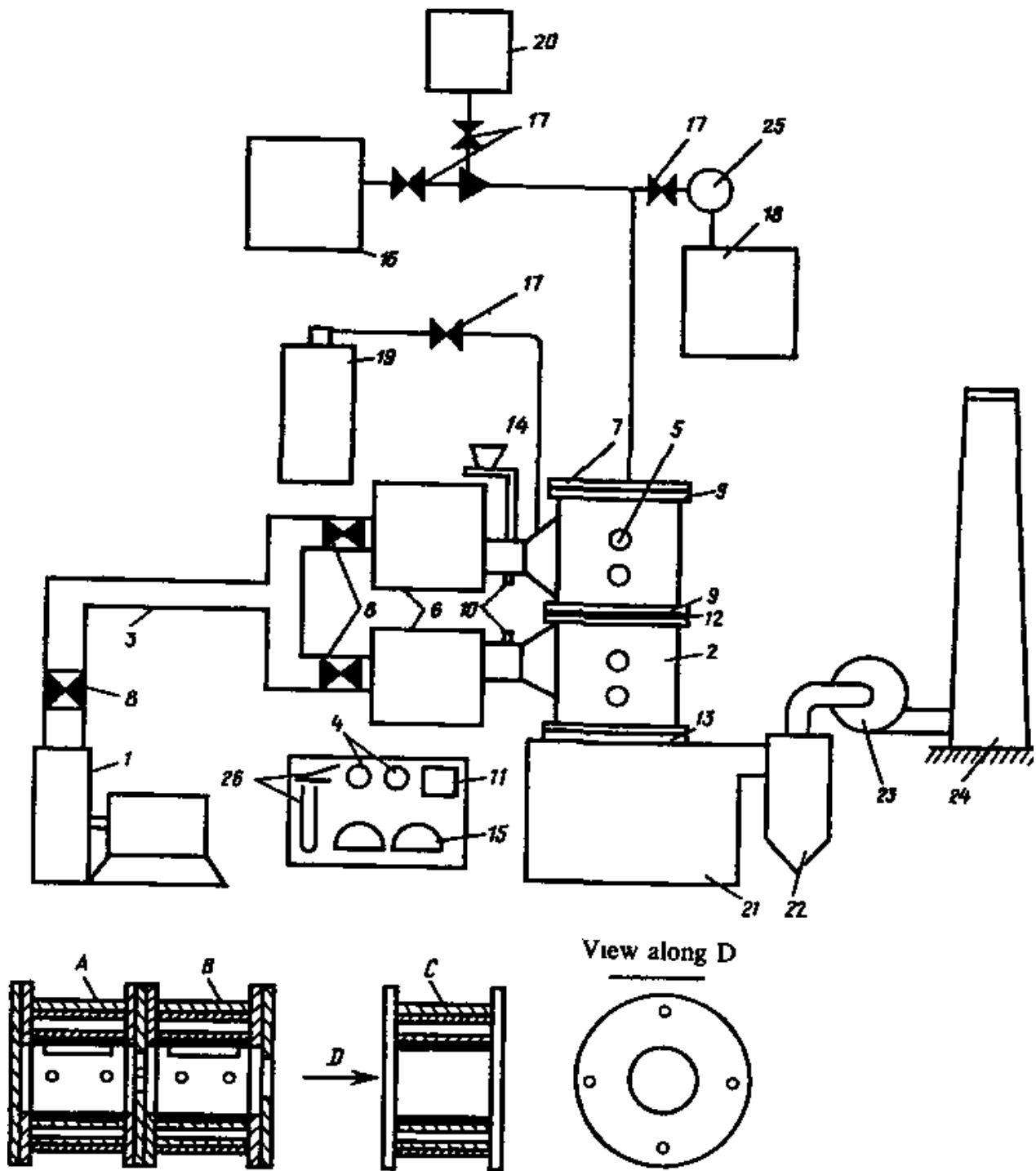


Figure 1 Experimental setup for studying heat- and mass-transfer in models of vortex apparatuses during various technological processes: 1 – high-pressure ventilator; 2 - vortex chamber. 3 - air pipe; 4 – rheostats; 5 - pipe connections for measuring the flow; 6 - air heating units; 7 - dead-end of chamber; 8 - slide valves; 9 - flanges; 10 - units for regulating the characteristics of input flows; 11 - devices for measuring and regulating the consumption of raw material; 12, 13 - internal and external pinches of chambers respectively; 14 – screw-type feeder; 15 – potentiometers; 16 steam generator; 17 – valves; 18 reservoir for solutions; 19 - gas cylinder; 20 - reservoir for mineral additives; 21 – product receiver; 22 – centrifugal separator; 23 – exhaust fan; 24 – pipe; 25 - pump for solution delivery; 26 - micromanometers; *A, B* - vortex chambers, *C* cylindrical inserts for constructing different models of vortex apparatuses.

of these being fixed with a screw stopper. The shutters made it possible to vary the slit area in the range of 0 to 0.04 m², the value of $A = f_{in}/(\beta D_k L_k)$ relative to the inner chamber area being 0 to 10%.

Pipe connections were welded onto the outer cylindrical surface of vortex chambers A and B ; the connections had hermetic lids for introducing probes to measure the structure of the rotating fluid flow. The length of the chamber could be varied using cylindrical inserts C having the inner diameter $D_a = 0.2$ m and length $L_a = 0.2$ m.

The vortex chambers and the inserts (A , B and C in Fig. 1) consisted of an outer and an inner cylindrical shell, water being supplied to the space between them; the model was thereby cooled during nonisothermic processes. The inner surfaces of the shells were lined with a fireproof material, and the outer surface was covered with a heat-insulating layer of frothed polystyrene 30 mm thick.

The total air flow rate was measured using integral pipe combs with a diameter of 0.005 m in the pipes. The air flow rate in each slit was determined using a total pressure pipe and sampling static pressure at the slit walls in the cross-section area where the measuring hole of the total pressure pipe was located. The atmospheric pressure was measured by an M-98 barometer. The air temperature was measured in front of the opening leading to the chamber using a mercury thermometer with a scale division equal to 0.5°C. As the flow structure in the core of the rotating fluid flow is three-dimensional measurements were performed using a five-channel ball probe 0.006 m in diameter. The secondary instruments for probing the flow and determining flow rates were differential manometers and micromanometers 26.

The experiment was conducted for three values of wall roughness $\Delta = h_b/R_{ch}$, the ranges of the wall roughness corresponding to the size of bulges h_b , on the walls of the chambers having radius R_{ch} ($\Delta_1 = 0,5\%$, $\Delta_2 = 1\%$, $\Delta_3 = 2\%$). The hydrodynamics of the chambers with rough walls in the near-wall region was

studied using a three-channel slotting probe and a cylindrical three-channel probe of diameter 6×10^{-3} m with the diameter of input apertures equal to 0.4×10^{-3} m. The core structure was studied using a five-channel ball probe of diameter 6×10^{-3} m, the probe design allowing measurements to be carried out at a distance of 10^{-2} m from the terminal bulges.

Because the hydrodynamic structure of rotating fluid flows in the working volume of a vortex chamber is self-similar, its exact description requires the knowledge of the effect the Ro criterion has on the scale and characteristic quantities of the vortex flow. Moreover, analytical expressions for these quantities enable the exact computation of the flow structure based on existing mathematical models [7], [10], [12].

We derived empirical relations connecting the scale quantities to the Ro criterion for isothermic processes in the temperature range 20 to 80°C; this provided a correction to our computations and enabled the formulas to be related to the design and operational parameters of vortex apparatuses:

$$Ro_{\text{exp}} = 12.5 A^{0.5} d^{-0.75} [1 \pm 4V(1-V)]; \quad (6)$$

$$\varepsilon = \frac{V_{ym}}{V_{in}} = 0.28 (Ro_{\text{exp}})^{1.25}; \quad (7)$$

$$k_{ym} = 0.032 (Ro_{\text{exp}} - 3.5)^2 + 0.8; \quad (8)$$

$$k = (Ro_{\text{exp}} \cdot 10^2)^{-1.13};$$

$$[Ro_{\text{exp}} \approx 10Ro_p \approx 100Ro] \quad (9)$$

where $k_{ym} = r_p/r_{ym}$ is the dimensionless pinch of the

vortex chamber; $V = \frac{Q_1}{Q_1 + Q_2}$ is the dimensionless

flow rate through a unit flow; k is the exponent in the universal equation for the tangential component of flow velocity vector $V_v = [ne^{1-n}]^k$ which was used to compute the flow structure in vortex chambers for constructing mathematical models of technological

processes [7]; the signs \pm denote the flow interaction type; $Ro_p - A\varepsilon/d$ is the criterion form which enables one to incorporate the variation of hydrodynamic flow structure in the working volume of a vortex apparatus, in contrast to equations (2) and (3).

A study of the hydrodynamics of rough-wall chambers permitted a direct evaluation of the effect of wall roughness on the flow for different relations between geometrical chamber dimensions [7]. For comparison experiments were made in cyclonic chambers having the same roughness. As relative roughness increases, vorticity diminishes, its magnitude depending on the method of generating a vortex. A comparison between the hydrodynamical characteristics of chambers with different methods of vortex generation, but with identical geometrical parameters, shows that an increase in wall roughness diminishes the angular momentum both in the flow core and in the near-wall zone of the vortex apparatus.

Despite a certain effect of roughness on the hydrodynamic characteristics, the flow as a whole does not experience any qualitative changes.

Studies of the boundary layer in vortex and cyclone apparatuses show that in the case of concordant interaction, vorticity in a vortex apparatus is more axisymmetrical than that in a cyclone apparatus, and when the interaction is discordant the near-wall zone in a vortex is thicker than in a cyclone.

An analysis of experimental data shows that, as roughness increases, so does the exponent k of vortex chambers, the vorticity χ decreases, and the dimensionless pinch d_{vm} increases:

$$k_{vm} = \frac{0.032(10Ro_p - 3.5)^2 + 0.8}{(1 - \Delta_i)^{0.4}}; \quad (10)$$

$$\varepsilon = \frac{V_{vm}}{V_{in}} = \frac{0.28(Ro_p)^{1.25}}{(1 - \Delta_i)^{0.5}}; \quad (11)$$

$$k = \frac{(10Ro_p)^{-1.13}}{(1 - \Delta_i)^{0.3}}, \quad (12)$$

where $\Delta_{uu} = 10\Delta = 10 \frac{h_{rough}}{R_k}$ is relative roughness of the vortex apparatus wall, and h_{rough} is the height of the bulges on the walls.

The dispersed suspension was fed through a tangential inlet. The flow was measured in one cross-section $l = 0.5$ using one pipe connection with $\varphi = 90^\circ$. The outlet and intermediate pinches were varied during the experiments, as well the ratio between the air flow rates in the interacting rotating flows and the concentration of the dispersed phase in the flow. We measured static pressure at the inlet and outlet nozzles and the velocity of the input flow, the relation between gas flow rate and the amount of dispersed material supplied was used to determine the flow charging. The flow was measured using a three-channel cylindrical probe of diameter 0.005 m; measurements were made only in the flow core to avoid the damage of the measured area by the dispersed material and the addition of more holes in the probe. There was a system for blowing through the probe capillaries using a compressed-air cylinder. Air was passed through a filter filled with graded zeolite before it came to the probe; the air was then conveyed to the capillaries through a system of three-way cocks. Before the start of an experiment the measuring area of the probe was set at the center of the chamber, the blow-through system was switched on, and the working air was conveyed to the apparatus. Then a screw-type feeder was switched on to deliver the material, a time lag of 60 s was held, the blow-through system was switched off, and the probe capillaries were switched over to the micromanometers. After the experiment was over, the probe was scavenged with compressed air and the filter zeolite was removed to be dried. When a series of experiments has been terminated, the probe was calibrated in a taring device.

An analysis of experimental data showed that the falloff of a tangential velocity component in the working volume of the chamber, as the flow charging increases, has the form

$$W_{vmsusp} = \frac{W_{vm}}{(1+C)^{0.5}}, \quad (13)$$

where C is the concentration of suspension by volume in the flow; W_{vm} is the maximum tangential velocity component in a rotating suspension-bearing flow.

The radius of the maximum tangential velocity component obeys the equation

$$r_{vmsusp} = \frac{r_{vm}}{(1+C)^{0.3}}, \quad (14)$$

where r_{vm} is the radius of the maximum tangential velocity component in a suspension-bearing flow.

The exponent varies as

$$k_{susp} = \frac{k}{(1+C^{0.66})}, \quad (15)$$

where k_{susp} is the exponent in the equation for a gas flow that carries dispersed suspension.

A flow with temperature below 400°C was measured using ordinary cylindrical probes with a cooled coordinate spacer. The structure of high temperature burning flows was studied in models and enlarged technological apparatuses; the flow structure was measured using three-channel water-cooled probes. Flow structure was also studied using probes in enlarged models to examine heating, evaporation and condensation processes.

As the temperature increases, the value of ε decreases and particle velocities increase. Lighter particles are increasingly faster entrained by the flow, the time of particle separation toward the chamber wall decreases, the height of the particle ascent increases, and so does the critical size of the particles removed from the

apparatus, while the entrainment efficiency and the residence time of particles in the apparatus decrease. The qualitative restructuring of the flow in the working volume of a vortex reactor under variation of gas temperature can be explained by variations of its physical characteristics, namely, density and viscosity. Changes in flow structure occurring in the working volume affect the movement of particles in the flow. The flow temperature and the presence of the suspension in it affect the value of the Rossby criterion. This effect can be roughly evaluated using a correction coefficient k_{exp} :

$$Ro_{pr} = k_{exp} Ro_{exp};$$

$$k_{exp} = \left(\frac{273+T_0}{273+T_{pr}} \right)^{0.5} (1+C)^{-1}, \quad (16)$$

where Ro_{pr} is the Rossby criterion for a vortex flow during a technological process; T_{pr} and T_0 are the temperature of the process and the ambient temperature, respectively.

When water is evaporated in the rotating fluid flow, the axial output velocity increases in due proportion, provided the water-fluid mass ratio is below 10%, while the tangential component drops very slightly. As the water content increases beyond 10%, the flow vorticity begins to fall off rapidly. During steam condensation, the axial velocity component and the tangential component decrease in due proportion, provided steam makes not more than 80% of the amount of the working air; accordingly the pressure contrast in the apparatus decreases.

Attempts at relating the structure of a vortex flow to flow temperature alone for different processes did not give unambiguous results. This can be explained by the fact that phase transformations affect both the flow temperature and the flow structure. For example, an increase in the amount of evaporating fluid in the rotating fluid flow causes a decrease in the fluid temperature, but this is also accompanied by a decrease in vorticity. In the case of an ordinary vortex flow without evaporation, a decrease in the flow temperature

causes an increase in vorticity.

An analysis of various technological processes in models of vortex apparatuses with certain operational and design characteristics showed the effect of the specific potential energy of the process E_{spec} on to flow structure.

Experiments in three identical and geometrically similar models of vortex chambers were conducted by generating several different vortex flow structures: (1) concordant interaction of two vortex flows, (2) an ordinary vortex flow, and (3) discordant interaction of two vortex flows. The flow structures in these models blown through with air of temperature 20°C ($E_{spec} = 0$ kJ/kg) were characterized by different Rossby numbers: $Ro_{p1} = 5.25 \times 10^{-1}$ for (1), $Ro_{p2} = 3 \times 10^{-1}$ for a cyclone (2), and $Ro_{p3} = 0.75 \times 10^{-1}$ for (3). The next step was to test various technological processes in each model characterized by different E_{spec} values.

During the experiments we measured the maximum tangential flow velocity components V_{vm} , using a three-channel cylindrical probe, and also the output mean flow rate using an integrating pipe. The results are presented in Fig 2. As the specific potential energy of a process increases, the Rossby number decreases, and so does the vorticity. When the energy output is diminished while remaining positive, the Rossby

number increases because of the increasing vorticity. When E_{spec} is negative while increasing in absolute value, this criterion value decreases because of the declining flow through the apparatus. This pattern shows that the amount of specific potential energy of a technological process controls the structure of the vortex flow in the working volume of the vortex apparatus. It should be noted that the absence of an unambiguous relationship between E_{spec} and Ro may give rise to certain difficulties of using the above relation in designing technological vortex apparatuses.

An analysis of the results obtained from the experimental studies of the structure of vortex flows during various technological processes demonstrates that better parameters could be used (e. g., the parameter La , which is related in an unambiguous way to E_{spec} see Fig. 2):

$$La = \rho V_{vm} \sum \frac{f_{in}^2}{(m_{in} - m_{pr}) L_k r_n}, \quad (17)$$

where m_{in} and m_{pr} , are mass flow rates per second of a multiphase flow which is fed to the technological apparatus, and of the product obtained during the technological process and conveyed from the apparatus in the form of a condensate, melt, or simply a dispersed material, respectively.

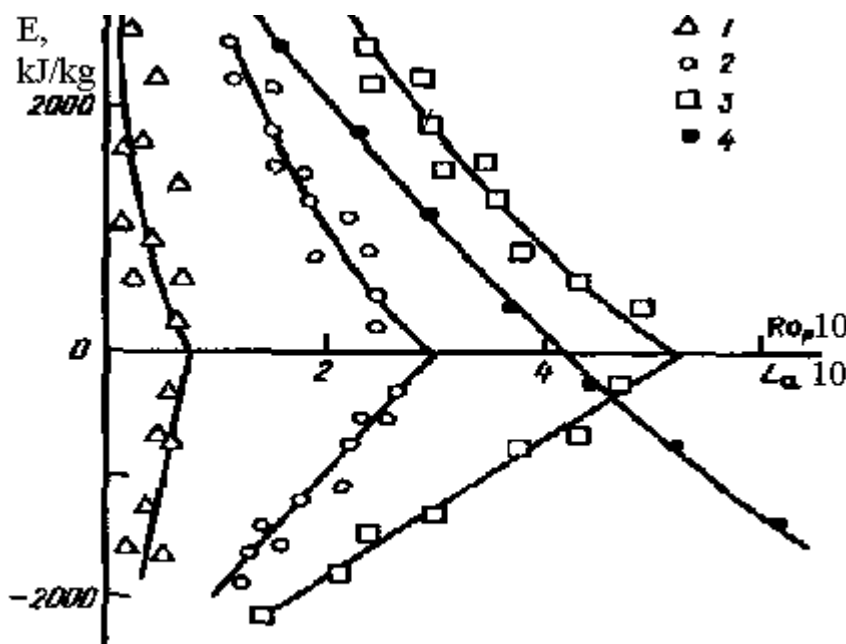


Figure 2 The effect of specific process energy on vortex flow structure in technological vortex devices having different operational and design parameters. Functions of Ro for: 1 - discordant vortex; 2 – cyclone; 3 - concordant vortex (CV); 4 - CV = f(La).

However, in spite of the advantages of this parameter, its application in this study was meaningless, because adequate relations for the design of technological parameters could only be derived by modifying the technique of technological experiments. This parameter is mentioned here as a good example of possible further improvement and new lines of further research.

An analysis of the results presented in Fig. 2 shows that any technological process characterized by a certain value of specific potential energy can be conducted using a variety of vortex apparatus and in a wide range of operational and design parameter modification.

The study of heat- and -mass transfer in vortex devices of different designs revealed that, as the Ro criterion increased for certain types of apparatus, or as the La criterion did for all types, hydrodynamic resistance increased and intensive abrasive wear of the walls took place, especially in high temperature processes. The decrease of these criteria diminishes the entrainment capacity of the apparatus and the residence time of dispersed material in its working volume. An efficient technological process requires in this case the installation of additional devices in the technological chain. Generally, both of these processes can be represented as functions of dimensionless energy quantities \overline{E}_1 and \overline{E}_2 normalized by specific potential energy of the process E_{spec} or by the maximum energy consumption E_{mec} (Fig.3). The summation of these values and the determination of a maximum for each particular process can help optimize the design and operational parameters of a vortex apparatus. We carried out a study to determine the optimal values of the criteria for processes with a

specific potential energy of 2000, 1500, 1000, 500, 200, 5, -200, and -500 kJ/kg. As a result, we got eight pairs of curves which characterize different processes:

$$1) \overline{E}_1 = 0.81Ro^2, \quad \overline{E}_2 = (0.13 / Ro) + 0.92 ;$$

$$2) \overline{E}_1 = 0.63Ro^2,$$

$$\overline{E}_2 = (0.91 / Ro) + 0.81 ;$$

$$3) \overline{E}_1 = 0.51Ro^2, \quad \overline{E}_2 = (3.44 / Ro) + 0.62 ;$$

$$4) \overline{E}_1 = 0.4Ro^2,$$

$$\overline{E}_2 = (22.8 / Ro) + 0.48$$

$$5) \overline{E}_1 = 0.32Ro^2,$$

$$\overline{E}_2 = (100 / Ro) + 0.32$$

$$6) \overline{E}_1 = 0.21Ro^2,$$

$$\overline{E}_2 = (170 / Ro) + 0.15$$

$$7) \overline{E}_1 = 0.15Ro^2,$$

$$\overline{E}_2 = (153 / Ro) + 0.11$$

$$8) \overline{E}_1 = 0.1Ro^2, \quad \overline{E}_2 = (146 / Ro) + 0.08$$

where $\overline{E}_1 = E_1 / E_{spec}$, $\overline{E}_2 = E_2 / E_{spec}$. It is more convenient to use E_{spec} rather than E_{mec}

as a scale quantity for comparative judgements on the processes (Fig. 3).

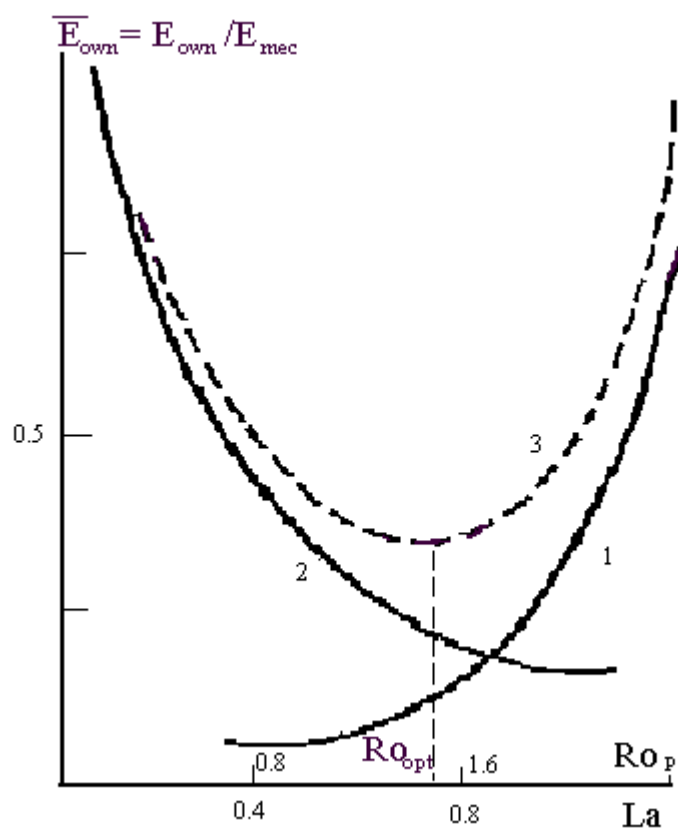


Figure 3 Relation between energy consumption for own needs during a technological process and the operational and design parameters of vortex apparatuses for E_{spec} constant; E_{own} is energy for own needs; E_{mec} is maximum energy consumption; 1,2,4 curves showing dimensionless energy loss for own needs due to increasing resistance of vortex device and to decreasing quality of processing, respectively, as functions of flow structure; 3 – total energy loss.

The solution of these equations gave a relation between the specific potential energy of a process and the optimal values of Ro (Fig. 4). Analysis shows that an evaporation process is more efficient in vortex apparatuses with low vorticity, a separation process is better conducted in apparatuses with high vorticity, and a condensation process is itself the cause of higher vorticity.

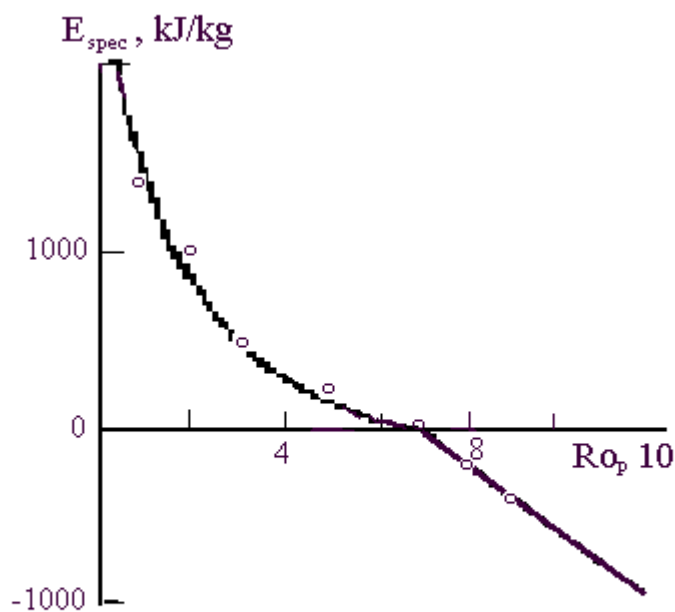


Figure 4 Specific potential energy of technological processes as a function of Rossby criterion.

This regularity allows one to find the optimal flow structure in the working volume during various technological processes, which is extremely important for developing appropriate design methods. However,

the relationship between the potential energy of the process and the vortex flow structure, as well as the theoretical relations for scale and characteristic quantities, were derived from experimental studies in simplified models of vortex apparatuses. For this reason the data presented in this paper are qualitative in character and need be improved (for more exact calculations) by carrying out similar studies in larger models and prototypes of vortex apparatuses during technological processes.

CONCLUSIONS

The mining of low-grade mineral deposits and unconventional raw materials poses the problem of

using geothermal fluids as a promising source of raw mineral materials and semi-products; for the development to be profitable one needs low-waste technologies using both mineral and energy components. A rational use of the mineral component of geothermal fluids calls for new technologies, while the energy requirements call for high pressures and discharges at the heads of water wells. This requires

the use of multifunctional vortex apparatuses. Based on the experimental studies of various technological processes conducted in models of vortex apparatuses, the following conclusions were derived: (1) the quality of raw mineral materials (in particular, geothermal fluids) not only dictates the technological techniques to be used for the processing of these materials, but also controls the aerohydrodynamic structure of the flow in the working volume of the technological apparatus; (2) the specific energy of the technological process controls and shapes the hydrodynamic structure of the flow in the working volume of the vortex apparatus; (3) there exists an optimal flow structure in the working volume for each technological process, the structure ensuring rational conditions of external diffusion processes.

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