УДК 66.081.3

INFLUENCE OF GEOMETRIC PARAMETERS OF GRANULAR PARTICLES ON FLUIDIZATION QUALITY

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Annotatsiya. Hozirgi vaqtda energiyaning eng qimmat turlaridan biri bu issiqlik energiyasidir. Uning yuqori narxi nafaqat ishlab chiqarish jarayoni, balki uni uzatish va undan foydalanish samaradorligi bilan ham belgilanadi. Energetika, kimyo, neftni qayta ishlash, oziq-ovqat va boshqa sanoat tarmoqlarida katta o‘lchamlarga ega, tez ifloslanadigan hamda quvur to‘plamining xizmat muddati qisqa bo‘lgan qobiq-quvurli issiqlik almashinuvchilardan keng foydalaniladi. Ma’lumki, issiqlik almashinuvchilarining og‘irligi va o‘lchamlarini kamaytirish yoki bir xil o‘lchamlarda ularning issiqlik quvvatini oshirishning eng istiqbolli yo‘li issiqlik almashinuvini jadallashtirish hisoblanadi. Konvektiv issiqlik almashinuvini kuchaytirishning turli usullari taklif qilingan va tadqiq etilgan. Issiqlik almashinuvini jadallashtirish usulini amaliyotda qo‘llashda faqatgina issiqlik almashinuvi yuzasining samaradorligi emas, balki uning turli bir fazali va ikki fazali issiqlik tashuvchilar uchun mosligi, ishlab chiqarish texnologiyasiga qulayligi, mustahkamlik talablari, sirtning ifloslanishi, ekspluatatsiya xususiyatlari va boshqa omillarni ham hisobga olish zarur. Biroq, eng avvalo, issiqlik almashinuvini jadallashtirishning muayyan usulini tanlashda uning aynan qurilmaning aniq ish sharoitlarida yetarli darajada samarali ekanligiga ishonch hosil qilish kerak. Ushbu talablarga eng ko‘p darajada oqim turbulentligini oshirishga xizmat qiluvchi passiv issiqlik almashinuvi jadallashtirish usullari javob beradi. Quvurlarda bosim yo‘qotilishining o‘rtacha darajada ortishi sharoitida issiqlik almashinuvini kuchaytirish masalasi asosiy issiqlik tashuvchi oqimida qattiq zarrachalarni psevdosuyuqlantirish orqali hal etilishi mumkin. Psevdosuyuqlantirilgan qatlamdagi issiqlik almashinuvi intensivligi bo‘sh quvurdagi yoki qo‘zg‘almas donador material bilan to‘ldirilgan quvurdagi bir fazali gaz oqimiga nisbatan ancha yuqori bo‘ladi. Devor bilan gazli psevdosuyuqlantirilgan qatlam orasidagi issiqlik almashinuvi yetarlicha chuqur o‘rganilgan bo‘lib, issiqlik berish koeffitsienti qattiq zarrachalarsiz apparatga nisbatan ikki martadan ortiq oshishi aniqlangan.

Kalit so‘zlar: Issiqlik almashinuvini jadallashtirish, qobiq-quvurli issiqlik almashinuvchi, psevdosuyuqlantirilgan qatlam, donador zarrachalar, konvektiv issiqlik almashinuvi, passiv jadallashtirish usullari, bosim yo‘qotilishi, issiqlik samaradorligi, gaz–qattiq fazali oqim, issiqlik berish koeffitsienti.

ISSN 3030-3907

Аннотация. В настоящее время одним из самых дорогих видов энергии является тепловая энергия. Её высокая стоимость определяется как самим процессом производства, так и эффективностью её передачи и использования. В энергетической, химической, нефтеперерабатывающей, пищевой и других отраслях промышленности широко применяются кожухотрубчатые теплообменники, отличающиеся значительными габаритами, высокой степенью загрязнения и малым сроком службы трубного пучка. Хорошо известно, что наиболее перспективным способом решения задачи уменьшения массы и габаритов теплообменников либо увеличения их теплопроизводительности при тех же размерах является интенсификация теплообмена. Предложены и исследованы различные методы интенсификации конвективного теплообмена. При выборе метода интенсификации теплообмена для практического применения необходимо учитывать не только эффективность самой поверхности, но и её универсальность для различных однофазных и двухфазных теплоносителей, технологичность теплообменной поверхности или способа повышения эффективности теплообменного оборудования, требования к прочности, загрязнение поверхности, особенности эксплуатации и другие факторы. Однако прежде всего при выборе конкретного метода интенсификации теплообмена необходимо убедиться в его достаточной эффективности именно для конкретных условий эксплуатации аппарата. Этим требованиям в наибольшей степени отвечают пассивные методы интенсификации теплообмена, способствующие увеличению турбулентности потока. Задача интенсификации теплообмена в трубах при умеренном увеличении гидравлического сопротивления может быть решена за счёт создания псевдоожижения твёрдых частиц в потоке основного теплоносителя. Интенсивность теплообмена в псевдоожиженном слое значительно выше, чем в однофазном газовом потоке в пустой трубе или трубе, заполненной неподвижным зернистым материалом. Интенсификация теплообмена от стенки к газовому псевдоожиженному слою изучена достаточно глубоко, и установлено, что коэффициент теплоотдачи увеличивается более чем в два раза по сравнению с аппаратом без твёрдых частиц..

Ключевые слова: Интенсификация теплообмена, кожухотрубчатый теплообменник, псевдоожиженный слой, гранулированные частицы, конвективный теплообмен, пассивные методы интенсификации, гидравлическое сопротивление, тепловая эффективность, газотвёрдый поток, коэффициент теплоотдачи.

Annotation. Currently, one of the most expensive types of energy is thermal. Its high cost is determined both by the production itself and by the efficiency of its

ISSN 3030-3907

transfer and use. Shell-and-tube heat exchangers with significant dimensions, high degree of contamination and short service life of the tube bundle are widely used in the energy, chemical, oil refining, food and other industries.It is well known that the most promising way to solve the problem of reducing weight and dimensions, or increasing heating capacity with the same size of heat exchangers is to intensify heat exchange. Various methods of intensification of convective heat transfer are proposed and investigated. When choosing a method of heat exchange intensification for practical use, one has to take into account not only the efficiency of the surface itself, but also its versatility for various single-phase and two-phase heat transfer media, the manufacturability of the heat exchange surface or a method for increasing the efficiency of heat exchange equipment, strength requirements, surface contamination, operational features, etc. But, first of all, when choosing a specific method of heat exchange intensification, you need to be sure that it is effective enough, and not at all, but for specific operating conditions of the device. Passive methods of heat transfer intensification, which contribute to increased flow turbulence, meet these requirements most of all. The problem of heat exchange intensification in pipes with a moderate increase in pressure drop can be solved by creating fluidization of solid particles in the upstream of the main coolant. The intensity of heat transfer in a fluidized bed is significantly higher than in a single-phase gas stream in an empty pipe or filled with a fixed granular material. The intensification of heat transfer from the wall to the fluidized gas layer has been studied in sufficient depth and it has been found that the heat transfer coefficient increases more than twofold compared to an apparatus without solid particles.

Keywords: Heat transfer intensification, shell-and-tube heat exchanger, fluidized bed, granular particles, convective heat transfer, passive enhancement methods, pressure drop, thermal efficiency, gas–solid flow, heat transfer coefficient

Introduction.

Currently, one of the most expensive types of energy is thermal. Its high cost is determined both by the production itself and by the efficiency of its transfer and use. Shell-and-tube heat exchangers with significant dimensions, high degree of contamination and short service life of the tube bundle are widely used in the energy, chemical, oil refining, food and other industries.It is well known that the most promising way to solve the problem of reducing weight and dimensions, or increasing heating capacity with the same size of heat exchangers is to intensify heat exchange. Various methods of intensification of convective heat transfer are proposed and investigated. When choosing a method of heat exchange intensification for practical use, one has to take into account not only the efficiency of the surface itself, but also its versatility for various single-phase and two-phase heat transfer media, the manufacturability of the heat exchange surface or a method

ISSN 3030-3907

for increasing the efficiency of heat exchange equipment, strength requirements, surface contamination, operational features, etc. But, first of all, when choosing a specific method of heat exchange intensification, you need to be sure that it is effective enough, and not at all, but for specific operating conditions of the device. Passive methods of heat transfer intensification, which contribute to increased flow turbulence, meet these requirements most of all. The problem of heat exchange intensification in pipes with a moderate increase in pressure drop can be solved by creating fluidization of solid particles in the upstream of the main coolant. The intensity of heat transfer in a fluidized bed is significantly higher than in a single-phase gas stream in an empty pipe or filled with a fixed granular material. The intensification of heat transfer from the wall to the fluidized gas layer has been studied in sufficient depth and it has been found that the heat transfer coefficient increases more than twofold compared to an apparatus without solid particles.

The modern development of the chemical, oil refining, food and metallurgical industries is associated with the improvement of existing and the development of new, more productive types of heat exchange equipment. The thermal efficiency coefficient of shell-and-tube heat exchangers, which make up more than 80% of all heat exchange equipment, often does not exceed 40%. They have significant dimensions and corresponding weight, as well as a high degree of contamination.

One of the most promising methods of heat transfer intensification is the use of a fluidized bed of solid granular material as an intermediate coolant. The main advantages of this method are: high values of heat transfer coefficients due to turbulence of the coolant flow by intensive mixing of the solid phase, a developed specific contact surface of the phases, mobility of the suspended layer and the possibility of continuous circulation of the solid phase, low hydraulic resistance of the fluidized bed, a relatively simple device and the availability of their automation, as well as the possibility of using this method in existing devices.

The selected intensifier should act on the boundary layer with the greatest thermal resistance, destroying it with subsequent turbulence of the flow in the wall layer. The impact only on the wall layer does not cause a significant increase in hydraulic resistance. The efficiency of the heat exchange intensification method is significantly increased if it also helps to reduce surface contamination.

The organization of fluidization of polydisperse granular material of solid particles in the pipes of the heat exchanger eliminates the above disadvantages due to the destruction and turbulence of the wall layer of the liquid flow. However, the intensity of heat transfer from the surface to a liquid fluidized bed of a polydisperse granular material has not been studied in practice. There is no data in the literature on the effect of particle size and concentration, physical properties of granular

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material and liquefying liquid, as well as parameters of the fixed and fluidized bed, such as porosity and layer height on the value of the heat transfer coefficient. In engineering practice, it is especially important to be able to estimate in advance the specific flow rate of the liquid required to transfer particles of a granular layer of various diameters and densities to a fluidized state.

The lack of experimental generalizations on the hydrodynamics, structure, and external heat exchange of fluidized media of polydisperse granular material with heat exchange surfaces makes it difficult to create modules for this interaction, without which it is impossible to develop methods to intensify heat transfer in these media. The development of effective methods for intensifying heat transfer in both mono- and polydisperse pseudo-liquefied media is possible only on the basis of an adequate model of external heat transfer, reflecting the real picture of the structural and hydrodynamic effects that occur when a surface comes into contact with a heterogeneous medium, and the degrees of their impact on processes. These circumstances determine the relevance of the tasks set in the work, which correspond to the main directions of creating energy-saving equipment

The issues of hydrodynamics, structure and external heat transfer in apparatuses with a liquid fluidized bed of polydisperse granular material, which would serve as a scientific basis for the development of engineering calculation methods for this type of heat exchangers and their use on an industrial scale, are insufficiently equipped in the domestic and foreign scientific literature.

The purpose of the study is to develop a method for intensifying convective heat transfer in tubes based on the continuous mechanical action of chaotically moving particles of polydisperse granular material driven into a fluidized state by a liquid coolant flow on the boundary layer of the flow with the greatest thermal resistance. Creation of equipment for heat and mass transfer in fluidized media of polydisperse granular material, aimed at increasing the intensity of heat exchange, reducing the size and metal consumption of equipment during heat exchange processes.

The experimental part.

The importance of the fluidization method is especially great for conducting heat and mass transfer processes, since it reduces thermal or diffusion resistance by tens and sometimes hundreds of times compared to processes occurring in a stationary state of granular material. However, the lack of an accurate methodology for calculating hydrodynamics and heat and mass transfer in stationary and fluidized bed devices limits the use of fluidization in industry.

From our point of view, a significant disadvantage of many previous studies is the lack of a reference dependence of the coefficient of resistance on velocity, on the basis of which it would be possible to determine the effect of particle shape

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on the value of the coefficient of friction. In [3], the resistance of a layer consisting of identical particles of regular spherical shape was taken as a reference. Balls of rolling bearings with diameters of 2, 4 and 5 mm were chosen as such particles.

The analysis of the research results [4] allowed us to easily establish a reference dependence, and based on similar experiments, numerical values of the shape coefficient for particles of various geometric shapes and various fractional compositions.

Experimental studies of the hydrodynamics of a fixed layer of polydisperse solid particles with an upward flow of liquid were carried out at a pilot plant, the scheme of which is shown in Fig. 1. The main element of the installation, i.e. the working apparatus, are cylindrical glass tubes with an inner diameter of 20, 36; and 45 mm and a height of 1.0 m. The diameter of the glass tube apparatus was checked by the volume of water in a measuring cylinder. Layers of irregularly shaped particles (particles have almost all oval shapes), gravel particles, rounded glass particles, and lead shot were studied as a working granular material. The characteristics of the studied particles are given in Table 1.

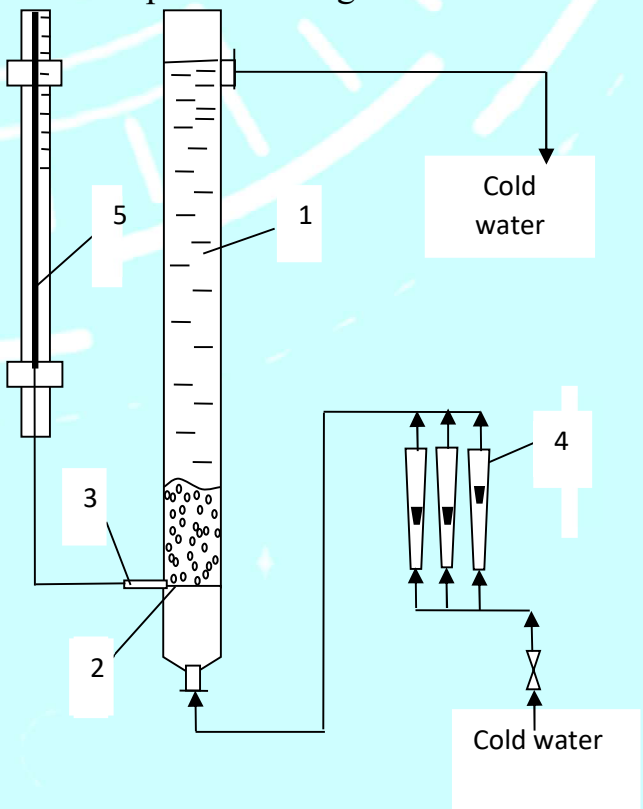


Fig. 1. Scheme of an experimental setup for determining the hydrodynamics of particles.
1–apparatus; 2–distribution grid; 3–pulse pressure extraction tube; 4-rotameters; 5–piezometer.

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The volume of the granular material layer occupied by solid particles was determined by the water displaced in the measuring cylinder. The particle density was found by weighing the counted amounts of grains of a certain volume and size.

The distribution grid of the main unit had slots 4 mm long and 0.2 mm wide and a free cross-section of 5%. The studies were carried out by filtration through a layer of bulk tap water with a temperature of 20-25 ° C. The temperature of the water at the outlet of the apparatus was measured with a glass thermometer with a division value of 0.1 ° C.

The height of the layer of polydisperse solid particles was measured using a scale with a division of 1 mm fixed on the working tube. During the experiments, the liquid flow rate was measured with rotameters, and the pressure drop in the layer was measured with a piezometric tube and a micromanometer. The rotameters were calibrated by measuring the amount of liquid flowing from the upper end of the apparatus into a measuring vessel of known capacity with a stopwatch counting the time required to fill the latter. The pulse tube for measuring the pressure drop in the layer was located at the level of the distribution grid under the layer of bulk material.

Table 2.1.

№	Granular material	Average diameter, d, mm	Bulk density, ph, kg/m^3	Density, p, kg/m^3	Porosity , ε0	Shape factor, F	Shape coefficient , φ
1	Gravel	1,4	1460	1840	0,4	0,8	1,4
2		1,9	1440	…..	0,4	0,79	1,6
3		2,5	1330	…..	0,4	0,77	1,7
4		3,04	1300	…..	0,42	0,7	1,8
5	Lead	1,8	6730	11400	0,4	0,87	1,3
6	shot	2,3	6680	…..	0,4	0,83	1,5
7		4,0	6600	…..	0,42	0,75	1,9
8	Glass	0,6	1440	2500	0,4	0,82	1,5
9	rounded	2,3	1400	…..	0,41	0,7	1,8
10	particles	4,4	1360	…..	0,41	0,6	2,3

* - in a swollen state.

First, dry particles of polydisperse granular material were poured into the working tube onto the distribution grid with a certain volume and the height of the fixed layer of granular material was measured to determine the porosity of the layer. The volume occupied by the particles of a certain portion was determined in advance by increasing the volume of water in the measuring cylinder. Then the

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device was slowly filled with water and the height of the stationary layer in the resting liquid was checked again. After that, the required operating speed of the liquid was set using a needle valve, at which the necessary parameters were measured. The pressure drop in a layer of polydisperse granular material was measured with a piezometric tube both with increasing and decreasing fluidization flow velocity. The speeds of the liquefying medium in the apparatuses varied from 0 to 1.0 m/s, and the height of the fixed layer of granular material from 50 to 250 mm.

Experimental data processing methodology

The experimental data was processed and the necessary parameters were determined in the following order.

1. The equivalent particle diameter was determined according to the data of sieving materials into fractions as follows. If the mixture of bulk material is a narrow fraction (for example, passing through a sieve with a cell size d_1, but remaining on a sieve with a cell d_2 close in size to d_1), then the determining particle size is their equivalent diameter d_e (equal in this case to the diameter of the narrow fraction of the mixture d_1), assumed to be equal to the geometric mean of the cell sizes of adjacent sieves:

$$d_e = (d_1 \cdot d_2)^{0,5}, \text{ м} \quad (1)$$

Note that for a narrow fraction, the grain dispersion range is $n=dmax/dmin<2$, and the geometric and arithmetic mean determining sizes are very close.The dispersion of irregularly shaped particles with conventional sieving methods actually fluctuates around the nominal average size of ±30% [38].

When using wide fractions, the value of the equivalent diameter, i.e., the determining particle size, was calculated using the formula:

$$d = 1/\sum(x_i/d_i), \text{ м} \quad (2)$$

where x_i is the volume fraction of particles of this fraction with a diameter di = 0.5 $(d_1 + d_2)$;

d_1 and d_2 are, respectively, smaller and larger particle sizes of this fraction, m

2. Porosity (fraction of free volume) of a fixed layer of polydisperse granular material was determined by the formula

where x_i is the volume fraction of particles of this fraction with a diameter d_i = 0.5 $(d_1 + d_2)$;

d_1 and d_2 are, respectively, smaller and larger particle sizes of this fraction, m

2. Porosity (fraction of free volume) of a fixed layer of polydisperse granular material was determined by the formula

$$\varepsilon_0=(V_l-V_p)/V_l \quad (2.3)$$

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where V_l is the volume of the granular material layer, m^3; V_p is the volume occupied by solid particles, m^3.

3. The fictitious (related to the total cross-section of the apparatus) velocity of the liquefying agent (water) was calculated from the flow equation

$$w=V_l/S, \quad m/s \qquad (4)$$

where V_l is the volumetric flow rate of the liquefying agent, m^3/s; S is the cross-sectional area of the apparatus (tube), m^2;

4. Experimental value of the hydraulic resistance of the layer

$$\Delta p_э=9,81 \cdot h_p, \text{ Pa} \qquad (5)$$

where h_p is the level of the liquefying agent in the piezometric tube, m

5. Porosity of the fluidized bed of polydisperse granular material

$$\varepsilon=1-(H_0/H)(1-\varepsilon_0) \qquad (6)$$

where H_0 and H are, respectively, the height of the fixed and fluidized layers, m; ε_0 is the porosity of the fixed layer of granular material.

6. The calculated value of the hydraulic resistance of the fluidized bed

$$\Delta p=Hg(\rho_p-\rho)(1-\varepsilon) \qquad (7)$$

where H is the height of the pseudo-liquefied layer, m; ρ_p- is the particle density, kg/m^3; ρ is the density of water, kg/m^3; ε_0 is the porosity of the granular material layer.

The features inherent in the granular layer make it difficult to directly measure the velocity field in it, and the only easily measurable value is the pressure drop in the layer. The data on the hydraulic resistance of the granular material layer makes it possible to determine the flow rate at which the layer enters the fluidized state, or the so-called fluidization rate. In this regard, the study of the pressure drop in a fixed layer of granular material is of great practical importance.

A layer of loose solid granular material may become mobile as it passes through the liquid. Such a heterogeneous system goes through at least three stages: the static state of the layer when liquid is filtered through it, the fluidization of grains in the liquid stream, and, finally, the removal of grains with the liquid stream. With the same size and shape of the grains of the layer (monodisperse layer), no other states of the system are observed. The uneven grain size (polydisperse layer) is the reason for the appearance of transition regions in particle motion, in particular the transition region between the filtration and fluidization states. The study of the hydrodynamic features and conditions of similarity of the fluidization transition region has shown the need for an experimental study of hydrodynamic resistance in it.

We conducted experiments with twelve samples of various granular materials. In order to increase the degree of heterogeneity of the layer, characterized by the ratio $\eta=d_{max}/d_{min}$, experiments were also conducted with binary

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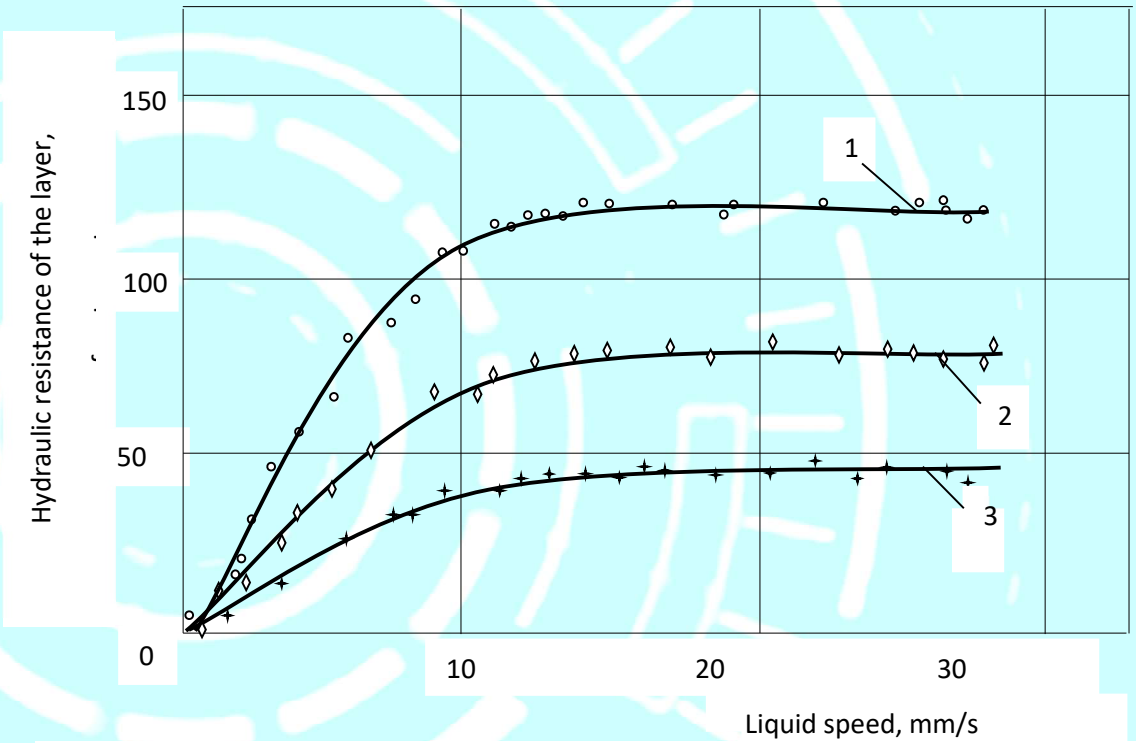
layers, which consisted of particles of different materials and densities, since such layers are adjacent to polydisperse [38].

In most studies devoted to establishing the relationship between the pressure drop and the properties of the layer and the liquefying medium, experiments were carried out with large ratios of the diameter of the apparatus to the diameter of monodisperse grains *(D/d>20)*. At the same time, when carrying out exothermic heterogeneous catalytic reactions with large thermal effects, tubular contact devices are often used in which the catalyst is loaded into pipes with a diameter of no more than 30 mm. In addition, granular material has recently been used as an intermediate heat carrier to intensify heat transfer and prevent scale deposition in tubular heat exchangers [12]. The use of pipes of small diameter and large length (height) makes it possible to approach the isothermal conditions of the process. Therefore, it is of great practical interest to study the hydraulic resistance of a layer of polydisperse granular materials in pipes of small diameter in the range of the ratio of the diameter of the apparatus to the diameter of the particles $D/d = 2 \dots 20$. In the first series of experiments, a layer of gravel of various granulometric composition was liquefied with water. The polydisperse granular mass was dispersed on sieves 1,0-1,7; 1,7-2,3; 2,3-2,8; 2,8-3,3 mm. The resulting mixtures with relatively similar grain sizes were the starting materials for further experiments.

For each initial mixture, the true specific gravity of the grains was determined by the pycnometric method. When composing a polydisperse mixture of a wide composition, its specific gravity was calculated according to the additivity rule. Individual grains of gravel are mostly rounded elements of irregular almost oval shape. The mechanical resistance of the grains was quite high. Special tests did not show much abrasion of the grains during 300 hours of their stay in the fluidized bed at a temperature of 20-30 ° C.

The equivalent diameter of the grain, rather than the diameter of the channels, was taken as the determining size. The transition zone (transition region) was determined from the graphs $lg\Delta p=f(lgw)$ (Fig. 3,4), which most clearly show two characteristic points - the beginning of the transition mode and complete fluidization.

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D=36 mm: 1–H_0=24.6 cm: 2–H_0=14.8 cm: 3–H_0=7.1 cm

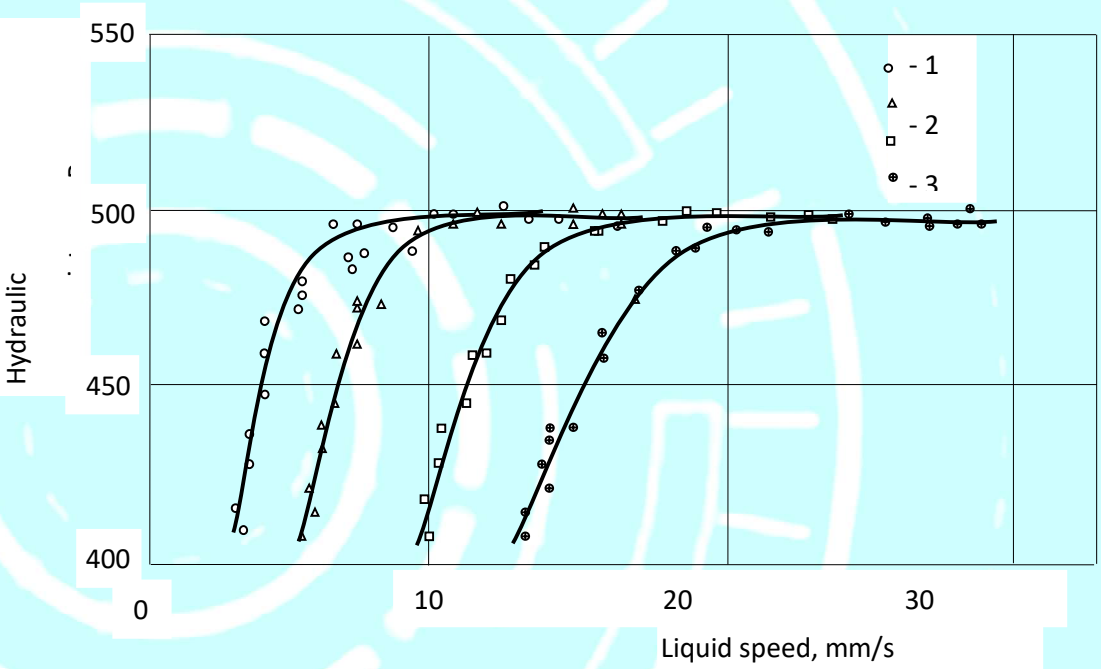
Fig. 3. Dependence of the hydraulic resistance of a gravel layer with an average diameter of 1.98 mm on the water velocity

The equivalent diameter of the web grain was calculated based on the dimensions of the pass-through and non-pass-through sieves and the weight composition of the grains of the initial class.

An analysis of the complex process in the transition region shows that already in its initial period, small grains move in the free volume of the layer between large particles. At the end of the transition mode, all the particles of the layer become mobile. Thus, the idea of a physical process in the transition region allows us to adopt a scheme of particle flow by a liquid flow, rather than a scheme of liquid filtration in the pores of the layer. Computational considerations about choosing the determining size also lead to a similar conclusion.

An essential transition is to replace the actual grain diameter dz with an equivalent diameter de. This transition is purely a calculation technique and has no physical prerequisites. This still expresses the inability to enter the correct defining size for polydisperse.

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D=22 мм; H_0=10 см; $d_э$, мм: 1-1,3; 2-1,98; 3-2,54; 4- 3,04.

Fig. 4. Dependence of the hydraulic resistance of the layer gravel from the speed of the water

In principle, the transition to the calculated equivalent diameter is a rejection of the most significant geometric characteristic of the polydisperse layer - the grain sizes that differ from each other. However, there are currently no other recommendations for calculating the determining grain. In addition, the results of our experiments show a correspondence between the physical processes in the layer and the average calculated grain diameter (de). Apparently, the statistical distribution and averaging of physical phenomena in the process make it possible to enter average calculated characteristics.

Conclusion

The processing of experimental data on the hydraulic resistance of the layer in a logarithmic coordinate system made it possible to clearly identify the behavior of the polydisperse layer during its liquefaction by liquid (Fig. 2.4).

The analysis of the obtained results made it possible to identify the most characteristic features of the polydisperse layer and its difference from the monodisperse layer:

a) the existence of a transitional regime between the filtration and fluidization regions (there is no such region in the monodisperse layer exists;

b) the presence of two characteristic speeds: wh-the initial speed of the transition mode and wk-the critical fluidization rate.

In a layer with particles of continuous fractional composition, the movement of each subsequent class of grains begins before the complete liquefaction of the

ISSN 3030-3907

previous class, i.e. the process of sequential liquefaction occurs continuously throughout the transition region.

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ISSN 3030-3907