On the pulse pneumatic transportation of metal radioactive waste materials at atomic electric power stations

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Abstract

A problem of metal particles movement in a tube under action of a pulse gas flow was numerically and experimentally solved. Comparison of computational and experimental data was carried out. On the basis of researches the optimum characteristics of the work of pulse pneumatic transportation of metal radioactive waste materials are determined. Modeling was performed within the framework of model of non-stationary two-dimensional motion of ideal compressible media on the basis of laws of conservation of mass, pulse and energy in case of axial symmetry. The thermodynamic flow field has been computed both in gas and solid phases. Processes of particles mutual interactions, coalescence, fragmentation, interaction with a tube walls and motion have been investigated in detail. Interface borders have been considered as contact discontinuity surfaces, where a condition of a continuity of normal to the surface component of a flow velocity vector and the continuity of normal component of tension tensor were satisfied. Modeling was performed numerically on the basis of the method of individual particles. The comparison of the computational and experimental data confirms the reliability of numerical algorithm. The optimum pipeline parameters (optimum nozzle diameter is 37 mm, pressure of gas in receiver chamber is about 8 MPa) are determined, at which the effective pulse cleaning of pipelines from metal wastes with the least expenses is possible. It was found that series of pulses is more effective mode of transportation than a single pulse, having similar total power.

1 Introduction

Significant share in high radioactive waste materials, formed in factories on regeneration of worked off nuclear fuels in nuclear electric power stations, make metal wastes as fragments of constructional materials from processing nuclear reactors. One of labor-consuming and dangerous operations in technological process of processing reactors is the operation on transportation of firm wastes, as it is necessary to take into account the danger of materials to an environment and their harmful influence on health of the attendants and population. The various devices for transportation of high radioactive waste materials are known [1, 2, 3]. Now most widespread is their delivery to a burial place in containers by the specially equipped automobiles

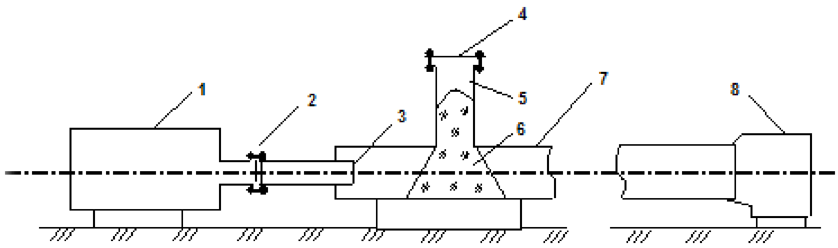

Figure 1: The scheme of experimental installation of pulse pneumatic transportation: 1 - receiver; 2 - valve; 3 - nozzle; 4 - cover; 5 - bunker; 6 - metal pieces; 7 - pipeline; 8 - accumulating chamber.

or railway transportation. Such approach alongside with advantages has essential lacks: in places of loading and the unloadings there are inevitable losses, that can result in jamming the container, and the repair thus is necessary in view of a radioactivity. The best transport of firm radioactive wastes represents pipeline, based on pneumatic transportation and allowing sharply to locate a zone of distribution of radioactive particles, to improve sanitary - hygienic conditions. Such transport has a high degree of automatisation and provides moving a material in a complex line. Here occurrence of emergency conditions is possible as well, in case of a stop of work of the device for pneumatic transportation at blocking, owing to fall of operating pressure values. Especially it is essential for materials with high specific density. However, the latter lack is possible to avoid, using pulsed pneumatic transport [4]. The recent paper is devoted to theoretical and experimental determination of various modes of operations of pulsed pneumatic transport devices, which combines the advantages of usual pneumatic transport and is deprived of the mentioned above lacks. This system is applied now at industrial facilities of "Mayak" groop. The gas was used as an inflator in the pipeline, as the clearing of a liquid is more difficult problem. The scheme of experimental installation for research of parameters of pulse pneumatic transportation is submitted in Fig. 1. A portion of metal pieces was loaded into the bunker and closed by a cover. The gas (air) was pumped into receiver chamber, and after opening of the special valve it penetrates in the pipeline (where the pieces are transported to the accumulating chamber) through a nozzle. In the experiments the simulators of metal pieces of firm wastes with granular structure were used, which were obtained at their mechanical crushing in cutting devices. The size of basic groop of pieces (particles) is about 30-40 mm. A diameter of the pipeline is 250 mm. The purpose of the paper is a calculation of the various characteristics of the process with the subsequent determination of optimum parameters values, ensuring fast and effective clearing off the pipeline: a nozzle diameter, pressure of gas in the receiver chamber and total gas charge.

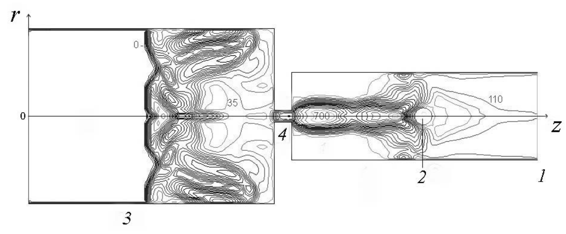

Figure 2: Isolines of gas velocity in the installation.

2 Modeling

Basing on experimental data (obtained with pneumatic transportation device) and knowing its characteristics, we describe the statement of a model problem. The scheme of simulated flow is submitted in Fig. 2. Initially motionless steel particle or conglomerate of particles with diameter d_0 (region 2) is placed within a pipeline having diameter D_0 (region 1). Regions 3 and 4 are the receiver (diameter $2D_0$) and the nozzle correspondingly. The nozzle and the pipeline are initially separated by a diaphragm. All the regions, except for 2, are filled with air. The gas is pumped in regions 3 and 4 for obtaining increased values of initial pressure there. The initial pressure of gas in region 1 is $p_0 = 1$ bar. The whole system is under condition of dynamic balance and has zero value of gas initial velocity in all the regions $u_0 = 0$. At the instant $t = 0$ the diaphragm is removed and propagation of gas pulse from the nozzle within the pipeline starts at constant values of pressure p and gas velocity (equal to sound velocity C_0) at the nozzle. The mathematical model of flow is based on the laws of conservation of mass, pulse and energy for two dimensional non-stationary motion of two-phase compressible medium with obvious allocation of borders between the phases in case of axial symmetry . The basic equations and numerical method are stated in paper [5]. The meanings of characteristic constants correspond to the experimental data described above and are chosen according to [6]. For the firm phase in system of units gram - centimeter-microsecond the following values of characteristic constants have been used: $a_1 = 7,78, a_2 = 31,18, b_0 = 9,591, b_1 = 15,676, b_2 = 4,634, c_0 = 0,3984, c_1 = 0,5306, \phi_0 = 9,0, \rho_0 = 7,86$; for gas $\rho_0 = 0,00122, \gamma = 1,4$. A diameter of the pipeline is $D_0 = 250$ mm, diameter of a particle or their conglomerate is $d_0 = 40$ mm. Let's note, that the problem was solved numerically in dimensionless mode. One of dimensionless combinations of the basic parameters of the problem (determining the flow process) was the ratio $\overline{d} = \frac{D_0}{d_n}$, where d_n is the nozzle diameter. Therefore proportional change of the geometrical characteristics of the problem (at the fixed value of the ratio d_n/d_0) did not change a flowfield of the basic thermodynamic parameters. Due to technological features of pneumatic transportation device [4] the distance l between the particles and the nozzle could not be less than 20 cm. According to computation results, at $l > 20$ cm the main characteristics of the process poorly depend on this parameter, since the losses of a pulse and energy owing to friction of gas at the wall of the pipeline are not

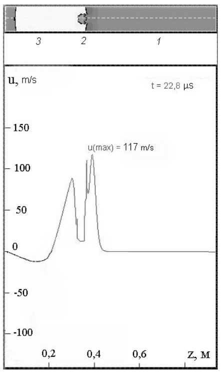

Figure 3: Map of velocity u at the centre of the pipe at $t = 22,8 \mu s$.

taken into account in the model. Therefore the results stated below are obtained at fixed $l = 35$ cm. One of the important technological constants determining characteristic of pipeline transportation, is the velocity of particles starting off U_T. Usually it is considered as lower value of average gas velocity in a cross section of the pipe, at which a particle of definite size is not soared in the flow any more. This hydraulic characteristic of carrying ability of the flow can be considered [3], as the characteristic of some limiting condition, when the frontal influence of a flow on a particle causes its sliding along the wall of the pipe, and the elevating force tries to lift it on some height. According to [3] we have

$$U_T = \sqrt{agd_0/Fr}, \tag{1}$$

$$a = \frac{\rho_2}{\rho} - 1, Fr = \psi_1 + \psi_2 \delta^2 \tag{2}$$

Here, ρ, ρ_2 are density of gas and particles accordingly, g is acceleration of force of gravity, d_0 is a diameter of particles, Fr is Froude number , δ is the ratio of the diameter of a particle to the diameter of a pipe; ψ_1, ψ_2 are experimental constants. For the characteristic geometrical sizes of the problem (as the change of the particle form in course of time from just splintered to smoothed ones was taken into account and $\psi_1 = 0,7 \div 1,35$ according to [3]) the value of U_T varies from 14,4 m/s up to 24,8 m/s. The maximal value of the velocity of particles starting off $U_T = 25$ m/s was taken in the numerical calculations stated below. To minimize the time of obtaining U_T, it is necessary to pick up the optimum size of a nozzle. The necessity of such a nozzle for submission of gas into the pipeline is caused by two main reasons. First, the velocity of a gas flow for steady motion of particles in the pipeline should be $2-3$ times more than the velocity of particles starting off. Secondly, used in experiments the receiver has limited volume.

The flow-field of gas velocities in the pipeline at instant $t = 2$ ms from a beginning of diaphragm breaking at the initial pressure value in the receiver $\overline{P} = 7$ MPa is submitted in Fig. 2. Twenty ranges of velocities in an interval from 0 up to 750 m/s are represented here. The length of receiver is 70 cm. In experiments the duration of a gas pulse τ, acting from the nozzle into the pipeline, is sometimes adjusted with the help of a latch in the nozzle. The results of such a numerical modeling in the pipeline are submitted in Fig. 3 at $\tau = 0,8$ ms for longitudinal velocity u at the instant 1,1 ms from the moment of diaphragm break ($\overline{P} = 8$ MPa). Here region 1 is gas at initial pressure $p_0 = 1$ bar ($\rho_0 = 0,001225 g/cm^3$), region 2 is for particles of steel, 3 is a pulse, moving to the left hand side from the nozzle into the pipeline, with compressed air at $\overline{P} = 8$ MPa ($\rho = 0,098 g/cm^3$). We name an interval between the beginning of interaction of a particle with the pulse and moment of reaching the meaning of U_T as the time of obtaining of the velocity of particles starting off. Its meaning was determined from the generated slides with a step of 0,2 ms, showing the further stages of the process. For the recent variant such time is equal to $22,8 \mu s$. Here readout of z coordinate is conducted from the nozzle. The required velocity of particles starting off was determined from a structure of longitudinal velocity at the centre of the pipe. As it is visible from the figure, by this moment the particle velocity begins to exceed the meaning of the velocity of particles starting off.

Table 1. Time dependence of achievement U_T from pressure of working gas.

number of calculation	initial pressure of gas, MPa	time for achievement U_T
1	1	-
2	3	46,00
3	4	34,00
4	5	26,00
5	6	23,60
6	7	23,20
7	8	22,80
8	9	22,40
9	10	21,80

Variations of time of reaching U_T meanings are represented in Tab. 1. As it is visible from the table, at the fixed nozzle diameter $d_n \in [10, 200]$ mm and $\overline{P} > 6$ MPa the time of reaching the velocity of particles starting off begins poorly to depend on growth of initial pressure values. As is clear from numerical simulations, at the fixed pressure of gas in the receiver for meanings presented in Tab. 1, the least time of achievement of the velocity of particles starting off corresponds there the meaning $\overline{d} = 6,8$. With the reduction of $\overline{d}$, the gas in the pipeline has the velocity insufficient for steady motion of particles, and at the very large diameter of nozzle, the pulse of gas is short, i.e. the time of its influence on the particles is insignificant. If $d_0 = 40$ mm, then the optimum diameter of nozzle is 37 mm, that is close to experimental data [4], where it is equal to 35 mm. In Fig. 4 we can see the time diagram of reaching the value of the velocity of particles starting off U_T from the initial pressure of gas. It is visible from the diagram, that the time has radical changes at pressure values diapason from 3 MPa up to 6 MPa, but at the further increase of pressure its change are insignificant. Optimum parameter value for the present scheme is pressure $\overline{P} = 8$ MPa, the further increase is inexpedient, since it will result in the over-expenditure of energy. In subsequent simulations we use this meaning of pressure. Now we must determine the optimum charge of gas

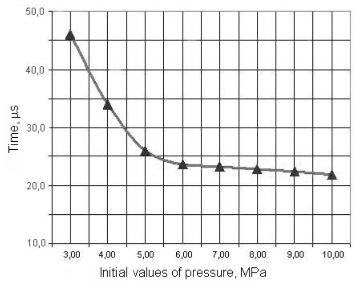

Figure 4: Time dependence of achievement of U from initial pressure of gas

that is necessary for the pipeline cleaning. The distance of particles motion (at fixed nozzle diameter and variating pressure and the receiver volume) is important factor here. Let's note, that as the distance of transportation we consider one from initial place up to the position of the inertia centre for the conglomerate of particles after their motion under action of the pulse of gas. In technological installations that distance is about tens meters. Such range is achieved, if average gas velocity in cross section is 2-3 times higher than the velocity of particles starting off. For the comparison with experimental data it was assumed in numerical simulations, that the value of gas velocity $u = 2,5U_T$ provides such a distance. The comparison of experimental and numerical (continuous lines) data is presented in Fig. 5. The deviations of numerical curves from experimental data do not exceed 7 percents. It is visible from the figure, that with growth of the receiver volume at fixed initial pressure of gas in it, the distance of particle motion initially grows linearly and at achievement of some critical volume remains practically constant. At the increase of initial pressure of gas in the receiver this curve moves above. Thus, there exists an optimum technological volume of the receiver (about $0,078m^3$), and its further increase becomes inexpedient. In Tab. 2 the computation of the charge of gas is presented at the fixed initial pressure $\overline{P} = 8$ MPa. It is visible from the table, that there is an optimum technological volume here as well, that at its further increase the time of achievement of the velocity of particles starting off varies poorly. As well as in the previous problem we determine the time of achievement of the velocity of particles starting off U_T . In experiments for breadboard models of pulse pneumatic device [4] not a single pulse was used, but alternation of pulses. For the checking of efficiency of such an approach, the simulations with two pulses were performed, when the total duration is equal to one submitted in Fig. 3. All other values

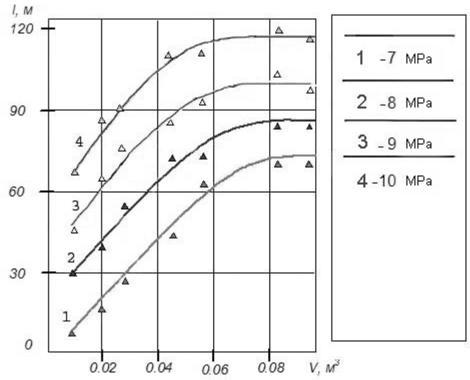

Figure 5: Influence of the receiver volume and initial pressure of gas on the distance of particles motion.

of a flow parameters of these problems are similar. As numerical study reveals, the alternation of the phases of compression and rarefaction, that is usual for the complex of two pulses, results in strong distortion of the form of the conglomerate of particles owing to instability of interface border that promotes the development of the splitting phenomena. Therefore alternation of pulses is more effective means of clearing of the pipeline, than having pulse at fixed velocity and pressure that proves to be true by the experimental data [4]. The numerical simulations confirm that with increase of gas volume its duration of action is increased as well, but the meaning $V_{opt} = 0,095m^3$ is optimal, since at smaller volume the object exposed to influence of a wave of compression, has not necessary velocity for steady motion. The results of modeling on revealing of parameters for the optimum mode of transportation, well coincide with parameters obtained by experimental way.

Table 2. Determination of the optimum charge of gas.

number of calculation	time of achievement U_T, μs	time of action, μs	volume of gas in a pulse, m^3	the charge of gas, kg
10	-	26,0	0,088	8,624
11	30,0	32,4	0,095	9,31
12	26,4	36,8	0,106	10,388
13	22,8	38,2	0,15	14,7
14	22,4	42,2	0,176	17,248
7	22,0	46,0	0,196	19,208

3 Conclusions

The problem of metal particles motion in a pipe under action of a pulsed gas flow is numerically solved in the paper. The comparison of the numerical data with experimental ones testifies about reliability of the numerical algorithm. The optimum value of device parameters are determined (optimal nozzle diameter is about

37 mm, pressure of gas in the receiver is about 8 MPa and appropriate gas charge corresponds to the values), at which the effective pulse clearing of pipelines from metal wastes with the least expenses is possible.

References

[1] Ginniff M. A burial place of radioactive wastes // Nuclear engineering abroad. - 1984. N 7. - P. 42.

[2] Borisov G.B., Saveliiev V.F. Processing and storage of metal wastes from regeneration of the worked out nuclear fuel // Nuclear engineering abroad. - 1978. N 8. - P. 23.

[3] Smoldyrev A.K. Pipeline transportation. - Moscow: Nedra, 1970, 272 pp.

[4] Istomin V.L. Pulse pneumatic transportation of metal radioactive wastes at nuclear power stations // Atomic Energy. - 1994. - V. 77. - N. 3. - P. 231.

[5] Voronin D.V., Istomin V.L. Modeling of pulse pneumatic transportation of metal radioactive wastes from processing at nuclear power stations // Problems of radioactive safety. - 2011 - 4 - P. 61.

[6] Loytsianskiy L.G. The mechanics of a liquid and gas. - Moscow: Nauka, 1987, 840 pp.

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