Journal of Engineering Physics and Thermophysics, Vol. 71, No. 1, 1998

FILTRATION FLOW IN FILLINGS IN THE PRESENCE OF CAVITIES

V. I. Eliseev, A. P. Tolstopyat, and K. M. Koval'

UDC 532.546

Some results of experimental investigations obtained by visualization are presented that show the effect of hollows on the gas distribution and mass transfer in apparatuses that operate with dense beds.

In investigating and developing new technological processes and apparatuses that operate with dense beds of fillings, problems of the interaction and conjugation of gasdynamic and filtration regions and flows are gaining in importance. This is due to the arrangement of various inserts, chambers, exhaust channels, and perforated pipes in the apparatuses [1, 2], the natural formation of hollows and gas channels in the corresponding operating regimes [3-5], and the various laws of transfer. Similar problems arise when environmental problems (mass transfer in soils with large cracks and lenses or in hydrogeological regions adjacent to channel flows and water basins) [6, 7], issues associated with extraction of raw materials [8], dynamic and mass-transfer processes in the tissues of living organisms [9] are considered. Various theoretical models have currently been developed that describe, to one degree of detail or another, hydrogasdynamic and heat and mass transfer processes. However, in a number of cases, they need to be experimentally tested and supplemented.

Given below are some results of experimental investigations performed on the basis of a visualization method developed by the authors [10, 11]. By using ammonia or hydrochloric acid vapors as an indicator, polystyrene treated with a special solution can be dyed, respectively, blue-green or pink-yellow. This enables us to distinguish different regions of flow and, as a result, establish propagation regions for one or another filtration flow. The boundaries between the regions, for small velocities, are rather thin lines, due to which we can consider them to be streamlines. By altering the flow rates of the supplied flows and obtaining these boundaries, we can construct a series of streamlines and thus show the flow pattern.

Experimental investigations were performed on a special stand a detailed description of which is given in [11]. It is a planar model plotting board, mounted vertically, with a filling in it, a system of gas channels equipped with instruments for measuring the pressure and flow rates of the supplied gas, and a gas-chemical indication system. The system of gas channels provides for independent supply of gas to three of the four sides of the rectangular plotting board (from the lateral sides and from below), variations in the gas flow rates being provided by float rotameters and pointer-type manometers.

The gas-chemical indication system provides for visualization of the filtration flow in a bed of disperse material. It incorporates two vessels filled with an aquecus solution of ammonia and hydrochloric acid. The gas that moves along a gas channel enters one or the other vessel, is bubbled there, and carries away vapors of the dissolved substance.

The effect of inhomogeneities in the bed was investigated by forming them artificially with a prescribed arrangement. The gas (air) was introduced in the bed from two slot nozzles mounted diametrically relative to each other. The air blown via one nozzle was bubbled through the ammonia solution and, interacting with the treated polystyrene, marked the zone of its filtration flow in the bed. The relations among the flow rates of the gases blown via the two nozzles, were varied in the experiments. The overall flow rate was maintained constant, and a fixation time was allowed for a steady filtration pattern of flow to be established, after which photographing was performed.

Dnepropetrovsk State University, Dnepropetrovsk, Ukraine. Translated from Inzhenerno-Fizicheskii Zhurnal, Vol. 71, No. 1, pp. 70-74, January-February, 1998. Original article submitted January 3, 1996.

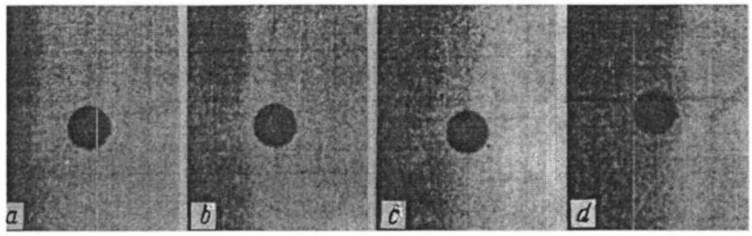

Fig. 1. Plane filtration flow along an impermeable cylinder.

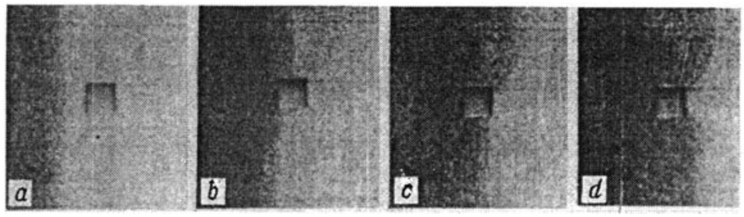

Fig. 2. Interaction of a filtration flow with a square cavity.

As an example of operation of the method, we considered the problem of plane filtration flow along an impermeable cylinder. Since the filtration flow that is realized on the setup is potential, the result of the experiment illustrates the well-known problem of plane ideal-liquid flow along a cylinder [2]. Figure 1 gives photographs that provide a visualization of the process. In Fig. 1a, we can see a streamline (a boundary between dark and light fields) away from the cylinder, a small deviation of it being observed on the segment in closest proximity to it. Figure 1b shows another streamline closer to the cylinder, in whose vicinity we also observe a bend. In Fig. 1c, the streamline practically hits the frontal point of the cylinder, passes on its left side, and symmetrically to it leaves the cylinder on the other side. Finally, in Fig. 1d, the streamline passes on the right of the cylinder; therefore we observe a deviation of it to the other side. On the whole, the given pattern is in qualitative agreement with familiar ideas of the flow of an incompressible ideal liquid along bodies. The results shown demonstrate to a certain degree the possibilities of the visualization method. In what follows, it is used for problems of the effect of cavities in loose media on mass transfer in filtration flows.

Figure 2 gives a series of photographs in which an interesting effect is revealed that is associated with filtration flow along a cavity. Here, a square whose side (4.5 cm) is an order of magnitude larger than the grain diameter (0.2 cm) is used as a cavity. In Fig. 2a, we can see a streamline that passes on the left of the square and experiences a bend toward it. In Fig. 2b, the streamline hits the lower left corner of the square, but escape of the dyestuff is observed in a rather wide zone that covers half of the upper side of the square. In this photograph, we can see that the boundary between the dark and light regions, which goes out from the cavity and coincides, in this case, with the symmetry axis of the cavity and the apparatus, is a different streamline now. This indicates an intense process of mixing in the cavity, as a result of which vapors of the dyestuff penetrate into new volumes of the air that moves in the cavity and escape with them, forming a broad mass-transfer trail. Visually (the photograph does not show this clearly), we can note that this trail behind the cavity has different shades: from dark blue in the left portion (the color of the basic region) to a ligher shade. This points to the participation of different concentrations of ammonia vapors in dying different regions of the trail. The same is clearly observed in the next photograph, too (Fig. 2c). In Fig. 2d, it can be seen that the streamline, passing on the right of the square, is completely drawn in by the cavity now. The pure air that flows on the right in close proximity to the streamline also enters the cavity, due to which a portion of the square's right side is in the light region.

From this series of photographs, the effect of hollows on filtration flow is quite evident. The action of this type of cavity can be considered in two ways: as a hydrodynamic sink–source (for the lower region of flow – the sink, for the upper region – the source) that noticeably alters the flow pattern near the inhomogeneity and as the operation of a mixer that intensifies diffusion in the bed. This case pertains to compact hollows that can be characterized by one effective dimension (similar data are obtained in experiments for a circular cavity). The following results pertain to cavities that can be characterized by two effective dimensions, for example, length and width. In

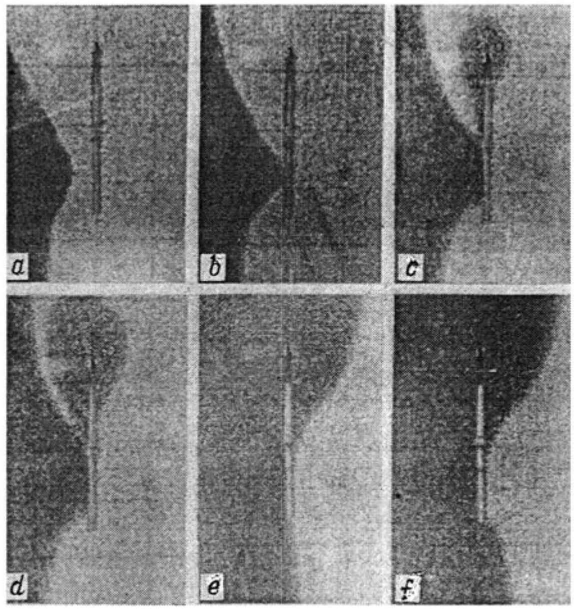

Fig. 3. Filtration flow in a bed with a slot cavity arranged along the stream.

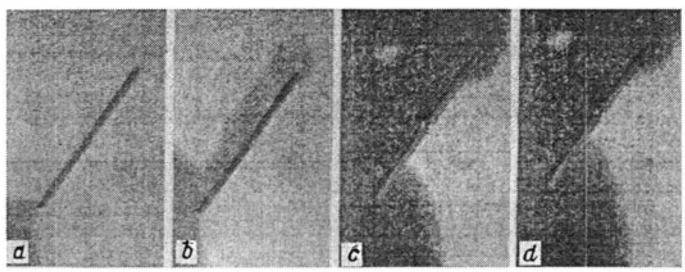

Fig. 4. Filtration flow in a bed with a slot cavity arranged at an angle to the stream.

our experiments, consideration was given to a band whose transverse dimension (1 cm) is much smaller than its longitudinal dimension (30 cm). In real technological apparatuses, various inserts and perforated pipes, using which redistribution of gas in shaft furnaces is attained, act as such cavities, as do gas channels that occur naturally in blast furnaces in critical operating regimes. Under natural conditions, such cavities form various large cracks in the ground; cutting drifts that are realized in shafts for coal or ore mining can be considered as belonging to this category of cracks.

With the band, we performed a number of experiments that revealed some features of filtration flow that depend on the band's position in relation to the direction of the flow. When it was positioned horizontally (across the flow) nothing important was noticed, due to which we do not give photographs of these experiments here. The streamline, which came from below, crossed the cavity and without smearing (the band width is comparable to the grain diameter) extended upward from the slot almost strictly vertically.

For a vertically positioned band, results are given in Fig. 3. The first four photographs of this series illustrate the dynamics of dyestuff propagation in a bed. The flow patterns are substantially unsteady. Figure 3a and b shows the formation of a streamline that hits the slot, while Fig. 3c and d shows further dynamics of ammonia vapor propagation. The streamline enters the slot from the left, while from the upper portion of the band the dyestuff appears as a torch. Later on, this region expands, which is indicated by Fig. 3d, in which we can see a narrow section of still undyed material.

Steady-state flow patterns are given in Fig. 3e and f. From these photographs it is evident that the slot first absorbs the gas, which, accelerating, flows along the slot; then the resistance in the cavity increases sharply and the gas begins to escape from it. In this portion of the slot, the flow is apparently similar to the flow formed in jet introduction of gas in a stationary granular bed [13]. It is of interest to note that the same pattern is also observed when the upper end of the slot faces the upper level of the filling. In this case, the band is a plane channel exposed to the ambient space. But here, too, first we observe suction of filtered gas in the lower portion of the channel and then rather intense blowing of it out to both sides of the slot. Thus, a slot that is positioned longitudinally in the flow has a substantial effect on filtration and mass transfer in the bed.

The inclined slot of Fig. 4 (its dimensions are the same as in the previous case) has an even greater effect. The first two photographs of this series indicate unsteady development of the flow. Figure 4a shows the streamline that, at this moment, reached the lower end of the band. Figure 4b shows substantially unsteady flow at the moment the ammonia vapors are brought into the slot. Here practically at once the dyestuff vapors propagate over the entire width of the bed. Figure 4c and d gives steady filtration patterns. In the photographs, the streamlines that enter the cavity and leave it can be viewed clearly, which also indicates the presence of a rather strong outflow of the gas from the upper portion of the band. Blowing out takes place even against the mainstream flow, which indicates the appearance of a considerable resistance in the slot that hinders gas motion in the cavity.

The authors did not pose the problem of a quantitative description, required in developing mathematical models of the process. This work seeks to reveal effects that are associated with the interaction of filtration flows with local inhomogeneities, in particular, hollows, and have failed to receive the required experimental coverage and mathematical development in the literature. The results presented are thus of a qualitative character. They show, first, the efficiency of a visualization method, second, a pronounced effect of cavities on filtration flow, especially in their vicinity, and, third, a substantial effect of hollows on mass transfer.

REFERENCES

1. M. É. Aérov and O. M. Todes, Hydraulic and Thermal Principles of Operation for Apparatuses with a Stationary and Fluidized Granular Bed [in Russian], Leningrad (1968).
2. B. I. Kitaev, Yu. G. Yaroshenko, E. L. Sukhanov, et al., Heat Engineering of the Blast-Furnace Process [in Russian], Moscow (1978).
3. V. P. Myasnikov and V. D. Kotelkin, Aeromechanics [in Russian], Moscow (1976), pp. 307-316.
4. V. A. Ostapenko and M. G. Slin'ko, Aerodynamics of Chemical Reactors [in Russian], Novosibirsk (1976), pp. 5-31.
5. Standard Technological Instructions for the Blast-Furnace Process [in Russian], Dnepropetrovsk (1977).
6. V. M. Gol'dberg and S. Gazda, Hydrorheological Principles of Pollution Control for Underground Waters [in Russian], Moscow (1984).
7. L. Lukner and V. M. Shestakov, Modeling of Underground-Water Migration [in Russian], Moscow (1986).
8. G. I. Barenblatt, V. M. Entov, and V. M. Ryzhik, Motion of Liquids and Gases in Natural Seams [in Russian], Moscow (1984).
9. S. A. Regirer and N. Kh. Shadrina, Izv. Ross. Akad. Nauk, Mekh. Zhidk. Gaza, No. 6, 177-124 (1992).
10. A. P. Tolstopyat, K. M. Koval', and V. I. Eliseev, "Visualization method for a gas flow in beds of dispersed or porous material," USSR Inventor's Certificate No. 1675783, Byull. Izobret., No. 33 (1991).
11. V. I. Eliseev, K. M. Koval', and A. P. Tolstopyat, Inzh.-Fiz. Zh., 58, No. 6, 946-953 (1990).
12. L. G. Loitsyanskii, Fluid Mechanics [in Russian], Moscow (1978).
13. G. A. Minaev and S. I. Tatarenko, Inzh.-Fiz. Zh., 57, No. 1, 10-15 (1987).