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SOME PROBLEMS OF LIQUID FLOW IN POROUS MEDIA

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In the paper theoretical considerations and results of experimental investigations into a liquid flow in porous media are presented. Since the first experiments with such a flow, made by Darcy in 1856, much research work in this field has been done. The flow of liquid in a porous medium is essentially nonlinear (with the permeability depending on flow velocity). The author reviews the research into this nonlinearity and experimental investigations into a liquid flow in a pore space made in the last 125 years and reports on the experimental investigations into the velocity field in a pore space carried out at the Strata Mechanics Research Institute in Cracow.

Key words: nonlinearity of flow in porous media, velocity field in pore space

1. Introduction

The flow of liquid in a porous medium occurs on a large scale in nature as the flow of water in porous rock. The essential characterisitcs of this process is the amount of water which can flow within a certain time, i.e. the flow rate.

In 1856 H. Darcy was the first to carry out experimental investigations into a water flow in a layer of fine-grained sand. Basing on the results of these experiments he found that the flow rate is proportional to the pressure difference inducing this flow and derived a formula describing such a flow.

After some transformations this formula can be written in the form most often used in hydrogeology: $v = kI$, where v denotes the filtration velocity [cm/s], i.e. the rate of flow from a unit cross-section, I denotes the hydraulic gradient, $I = Dh/l$, i.e. the ratio of differences between the piezometric water heads at input and output to the flow path length, respectively, and k is the coefficient filtration so-called (measured in cm/s).

Because of its very convenient form such a simple description of filtration has been generally accepted as a law of nature and videly applied as Darcy's law. There were made some attempts to derive Darcy's law from the Navier-Stokes equations in which the porous medium was trated as a continuous medium with certain characteristics of the flow. This led to more general formula

$$v = \frac{K}{\mu}\frac{\Delta p}{l}$$

where

Δp – pressure difference measured at the the input and the output
μ – viscosity of the liquid
K – permeability, $[\mathrm{m}^2]$.

The filtration coefficient or permeability is usually treated as the material constant of a porous medium, e.g. rock.

The criticizm the experimental results of Darcy, attracted for various a couple of next years, especially by Smreker (from 1879 to 1918) (Kleczkowski, 1980), proved, however, limited possibilities of the application of Darcy's law to the description of filtration flow of a liquid in rocks. Smreker found that Darcy's law yielded satisfactory results for the description of water flow in sand filters; it cannot be used, however, even for approximate calculations of water flow in natural rock (not excluding sand), since in such cases the results do not agree with the real values (Kleczkowski, 1980).

The results of many experiments have shown that in real, natural and in artificially induced flows of a liquid in porous media, the filtration coefficient in the above cited Darcy's law or, in general, the permeability in such flows is not constant and does not represent any properties of the medium. It should be noted that permeability, e.g. the filtration coefficient is a characteristic of the process of liquid flow in a porous medium, and not the property of that medium.

There can be distinguished two types of permeability variation in liquid flow in porous media. One group comprises variations occurring in time, in the flow in natural rocks, always after a change of the kind of the flowing solutions. Here variation is caused by changes in the dimensions or, in general, by geometrical changes in the pores occurring as a result of internal swelling or internal shrinking of the rock induced by physico-chemical phenomena appearing in the course of interaction of some components of the rock (mainly clay minerals) with water or with solutions of various salts. Such permeability changes may exceed two orders of magnitude.

The other group of variations comprises permeability variation depending on the velocity of filtration without any change in pore dimensions. The origin of this variation is of a hydrodynamic nature. Permeability changes in this group depend on the geometrical features of the pore space and to a considerable degree on the pores dimensions. The values of these changes, on the whole, do not exceed one order of magnitude. This existing variation of permeability or filtration coefficient and dependence on the filtration velocity has been called the nonlinearity of flow in a porous medium.

Typical examples of such nonlinearity of flow in porous media are shown in Fig.1 and Fig.2.

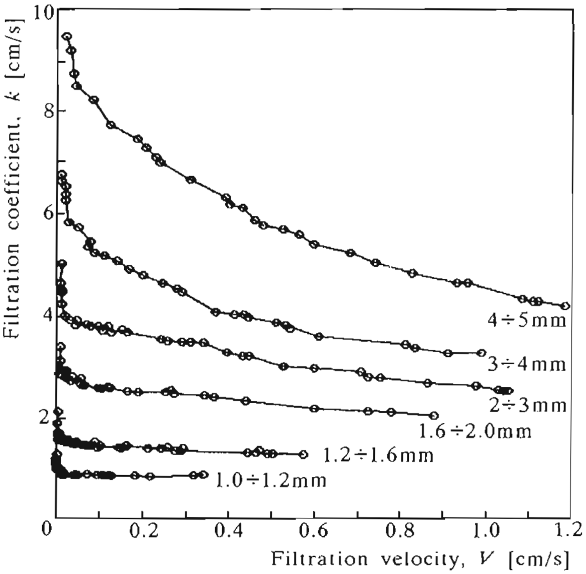

Fig. 1. Change of the filtration coefficient in a water flow in several porous media made of grains of crumbled quartz glass of various grain dimensions (Skawiński and Lasowska, 1974)

The example in Fig.1 is a result of experimental investigations into a flow in porous media carried out at the Strata Mechanics Research Institute (Skawiński and Lasowska, 1974). The flows of water were realized in pure porous media prepared from grains of quartz glass of various dimensions. The influence of pore dimensions on the occurrence of nonlinearity of flow can be easily observed. In a medium prepared from large grains $(4 \div 5\,\mathrm{mm})$ the filtration coefficient undergoes a change in the whole applied range of filtration velocity (from very small to $1.2\,\mathrm{cm/s}$). The range of the occurrence of significant nonlinearity diminishes with the reduction of pore dimensions. In the flow in a porous medium prepared from grains of about $1\,\mathrm{mm}$ in size, strong nonlinearity occurs only at smallest applied flitration velocities (from very small up

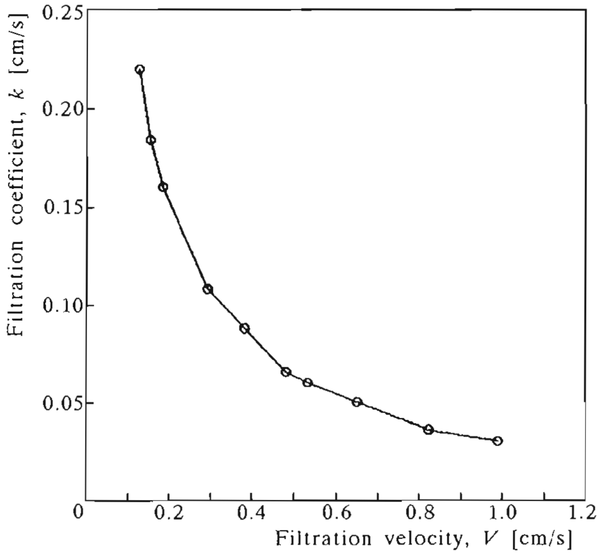

Fig. 2. Change of the filtration coefficient in a water flow in a rock from sulfide ore from Jeziorko (Badawika and Skawiński, 1989)

to 0.02 cm/s). At higher filtration velocities in such a flow the nonlinearity is hardly noticeable.

Another example of the nonlinearity of flow in a porous medium, shown in Fig.2 (Badawika and Skawiński, 1989), was observed in a water flow in natural rock – in a sulfide ore from a sulfur deposit in Jeziorko. The flow of water took place in a core (8 cm in diameter and 10 cm in length), cut out from a lump of rock. Within the range of filtration velocity from 0.1 cm/s to 1 cm/s the filtration coefficient decreased nearly ten times. These are the values which cannot be disregarded in the practice of strip mine.

2. Nonlinearity of flow

The phenomena of nonlinearity observed in all real flows of liquids in porous media have become a basis for the attempts to describe this flow using formulae other than the description of Darcy. One of these has been called the equation of Forchheimer.

In 1901, P.Z. Forchheimer assumed that the permeability in water flow in a porous medium is a sum of two components depending on the filtration velocity to the first and second power

$$\frac{p}{l} = \alpha\mu v + \beta\rho v^2$$

where: μ is the viscosity of the flowing liquid, ρ is its density, while α and β are the coefficients assumed to be constant.

At the first glance it seems that the second power of the velocity v^2 attributes nonlinearity of the flow to the turbulence occurring in it, similarly as in the flow in a pipe, since the pressure gradient in such a turbulent flow in a pipe is also proportional to the second power of velocity and does not depend on viscosity. There are however, substancial differences between the cases of flow in a pipe and in a porous medium, which make insufficient the explanation of nonlinearity of flow in porous media by the occurring turbulence, especially at small velocities. First of all, in the flow in a porous medium, turbulence cannot occur in the entire volume of the pore space at once. The space occupied by the turbulent flow must increase with the increase in flow velocity. This fact changes the coefficients α and β in Forchheimer's formula, which contradicts their constancy. Moreover, the filtration velocities in a porous medium at which the nonlinearity becomes measurable, are at least by two orders of magnitude smaller than the velocities determining the occurrence of turbulence in a pipe.

G. Schneebeli in 1955, C.D. Dudgeon in 1966, D.E. Wright in 1968 and others (Schneebeli, 1955; Bear, 1972) carried out the experiments intended to determine the conditions of the occurrence of turbulence in the flow in a porous medium. The results of these experiments have definitely shown that deviations from Darcy's law cannot be attributed only to occurring turbulence.

E. Linquist in 1933, G. Schneebeli in 1955, M.K. Hubbert in 1956, A.E. Scheidegger in 1960 and many others (Schneebeli, 1955; Bear, 1980) suggested to explain the deviations from Darcy's linear law by taking into consideration the forces of inertia active in the flow in the pore space of a porous medium, and originating in the curvatures of the flow lines.

Decisive experimental investigations into the problem of the turbulence onset in the flow in porous media were carried out for the first time by G. Schneebeli (Schneebeli, 1955). He realized water flows in a porous medium made-up from glass spheres and irregular grains of granite of different dimensions, observing the deviations from Darcy's linear law. The occurrence of turbulence in the pore space was visualized by introducing a colouring agent. Schneebeli observed the loss of linearity at flow rates much smaller (Re $2 \div 5$) than those necessary for the appearence of the first traces of turbulence in the pore space (Re > 60).

There can be found in the literature several studies in which the authors produce a mutlinomial description of flow in a porous medium by averaging the Navier-Stokes equations, considering the expression in which the forces of inertia are taken into account (the first authors were: S. Irmay in 1958 and 1964, Y. Bachmat in 1965 and others), (Bear, 1980).

All these theoretical and experimental studies indicate without any doubt that the assupmtion of constant stream lines in the flow in a pore space by changing of the flow velocity contradicts the reality.

Deviations from Darcy's linear law are due to a considerable contribution of the forces of inertia into the velocity field formation in the flow in the pore space, resulting even in separation of the flow lines from the walls and formation of stationary vortices at different places in this space, where expansions and constrictions of the flow occur.

3. Investigations into the flow in models of a porous medium

In view of the above discussion it is obvious that the models of pore space based on capillaries are definitely not applicable to the investigations into flows in porous media. They do not allow for taking into account curvatures of the surface of walls and by neglecting the constrictions and expansions of flow do not reflect the influence of the forces of inertia operating actually in the flow in the pore space, and inducing changes in the course of the flow lines and their separation from the walls. To investigate the phenomena in a porous medium it is necessary to use the models in which consideration is given to the constrictions and expansions of the pore space.

The idea of using constricted capillaries having periodic throat for modelling the pore space in the investigation into the phenomena occurring in a porous medium was suggested for the first time by E.E. Petersen in 1958 (Petersen, 1958).

Such geometrical formations as constrictions and expansions have been used as the main elements in modelling the porous medium by many authors in theoretical as well as experimental investigations. An interesting example of the application of such models was presented by Payatakes (1973) and others, in which the porous medium was treated as a set of geometrically identical elements, representing throats of statistically varying dimensions. Using such a model the flows of a liquid were investigated numerically.

The first experimental investigations into the velocity field in the pore space by means of visualization the stream lines were carried out by G. Chauveteau and Cl. Thirriot in 1967 (Chauveteau and Thirriot, 1967).

These authors investigated first the water flow in natural sands and found considerable deviations of this flow from linearity. Further on, they constructed a two-dimensional model, geometrically similar to the pore space of the examined sand. In this model they realized flows with different Reynolds numbers observing the visualized velocity field. Visualization was obtained by injection of a colouring agent. The results of these experiments can be summarized in the following statement:

> Changes in the flow lines and the presence of stationary vortices in the pore space were observed even at small Reynolds numbers, about Re 2, when the deviations from the linear flow were fully measurable. The traces of turbulence were observed only at Re about 90. (Chauveteau and Thirriot, 1967).

Similar statements about the velocity field in the pore space can be made also on the basis of many other similar, experimental and theoretical studies, which can be found in the literature.

All the above considerations based on the results of experiments and theoretical studies indicate undoubtedly that the flow in a porous medium should be treated as a real viscous flow in a geometrically very complicated pore space, and that the most important geometrical formations in this space are the throates and expansions occupied by the flow. In these studies it has been also established that deviations from the linear description of such a flow are due to the changing velocity field in the pore space. A detailed knowledge of these changes in the velocity field, however, was rather poor.

Here, attention should be paid to the studies on such flows (Friedman, 1970; Stevenson, 1973), since these are the first works where the velocity field was studied in a flow in an axially-symmetrical expansions with the following constriction and a rectangular shape of the longitudinal section of the whole expansion. These investigations consisted in numerical calculations of suitable transformed Navier-Stokes equations with the appropriate boundary conditions. These solutions anticipating the existence of the stationary vortex in the cavities of the expansions are in full agreement with the results of later experimental investigations into such flows (Skawiński and Lasowska, 1987).

To explain the problem of the changes of the velocity field in the pore space and their influence on permability during the flow through a porous medium it is necessary to undertake the research using appropriate models of the pore space and porous medium, and to verify the results in the real flows in porous media.

4. Investigations into the velocity field in models of pore space

Investigations into the velocity field and its changes in the flow of liquid in models of pore space have been undertaken at the Strata Mechanics Research Institute of Polish Academy of Sciences in Cracow.

According to the author's own considerations and the literature data it can be assumed that most important and typical geometrical formations in a real pore space are the constrictions and expansions of this space (Petersen, 1958; Bear, 1972). These geometrical features have been used as a basic model of the pore space. Such models have been realized as axisymmetrical sudden expansions of a pipe of rectangular logitudinal section, with varying ratio of the pipe diameter to the diameter of expansion. The actual models were made of plexiglass.

The investigations into the velocity field in the employed models of a pore space were performed by using the visualization method. The method consisted in illumination of some particles suspended in the flowing liquid and in taking photographs of them at various exposition times. Supposing the flow to be steady in time, by equalizing the density of the particles and the liquid and at moderate velocities, it may be expected the particles to move along the stream lines. Thus the traces of the illuminated particles photographed under these conditions show the stream lines in the examined velocity field. To avoid the deformation of these pictures the refraction index of the flowing liquid had to be equalized with the refraction index of transparent walls of the employed models. The liquid with its proper refraction index almost identical with the refraction index of plexiglass was prepared as a solution of ammonium rhodanide in a mixture of glicerine and water. The velocity field was illuminated with a narrow laser beam.

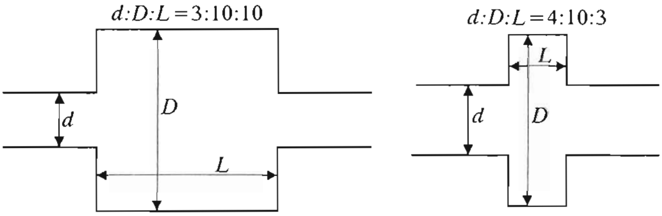

Fig. 3. Scheme of the expansions of the pipe used in experiments as the models of pore space

In the performed investigations into the velocity field in such models of the pore space there have been used various diameters of the expansions and

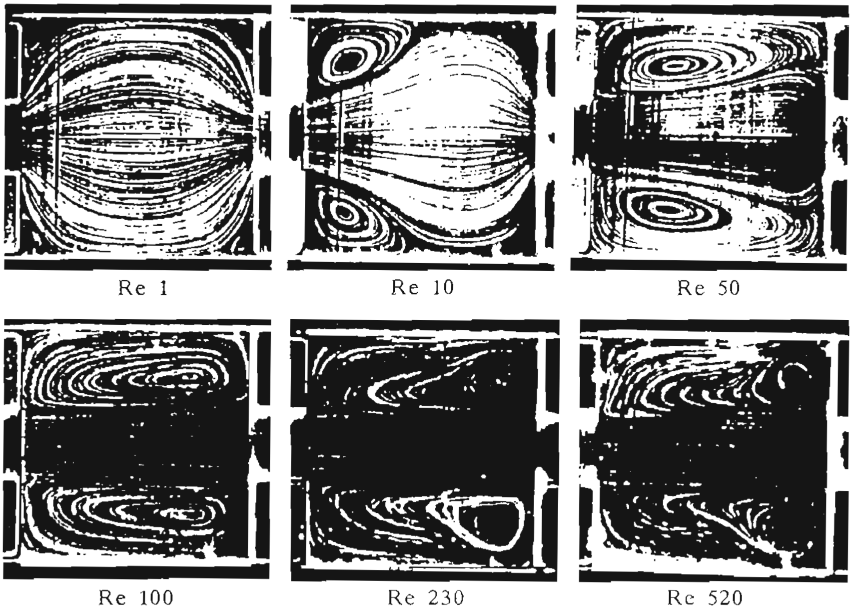

Fig. 4. Velocity field in the model of pore space made as the pipe expansion 3:10:10 (big expansion) (Skawiński, 1992)

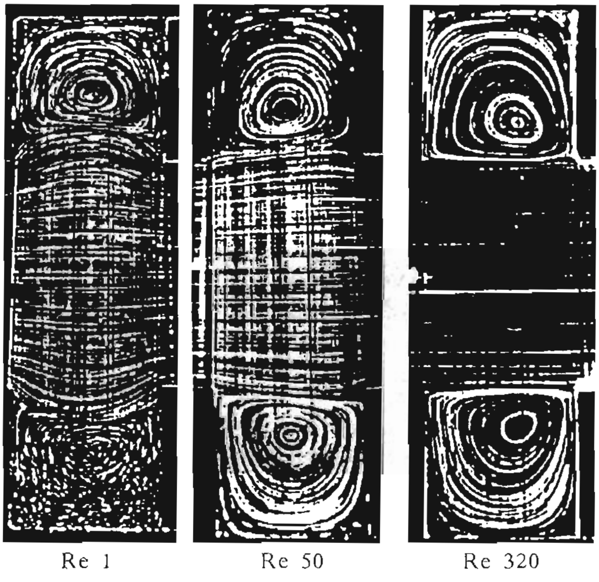

Fig. 5. Velocity field in the model of pore space made as the pipe expansion 4:10:3 (small expansion) (Skawiński, 1992)

various diameters of the input section. In this paper there will be presented the results of investigations conducted using two types of these models, in which the courses of changes in the velocity field are different. In the model of the first type (which may be called "big expansion") the ratio of the input diameter to the expansion diameter and the length of expansion is 3:10:10. In the model of the second type (which may be called "small expansion") this ratio is 4:10:3. This second type of the examined expansion, i.e. the "small expansion", resembles rather a cavity in a pipe. These ratios are shown in Fig.3.

The velocity field in these two types of expansions, resulting from the applied visualization method is shown in Fig.4 and Fig.5. The intensity of flow is given as the Reynolds number (Re), which is based on the diameter of the input throat and the flow rate (taking into account the respective viscosity of the applied solution).

Some basic statements about the velocity field in these two models which can be formulated from the above considerations and experiments are (Skawiński, 1992):

- The velocity field in these models is variable and depends on the mean velocity.
- The velocity field is made up of two formations: the main flow which forms all the discharge of the flow and stationary vortex-flow which does not take part in the discharge formation (Fig.4 and Fig.5).
- There exist two typical courses of the change of the velocity field in the pipe expansions: a change in the great expansion and a change in the small expansion.
- In a great expansion of the pipe, at very low flow velocities the main flow occupies almost the volume of the expansion. With an increase in the flow velocity the region of the main flow becomes smaller and the stationary vortices increase and become prevailing within the expansion (Fig. 4.).
- In a small expansion resembling rather a cavity in the pipe wall, stationary vortices appear at very low velocities. They occupy a prevailig part of the cavity and do not change their volume to any higher degree which causes also the main flow to be little variable (Fig.5).
- The velocity field with changing parts occupied by the main flow and by vortices is stationary, i.e. it does not change in time by very extended

values of the mean flow velocities (Reynolds numbers from the smallest to several hundreds.

- At much ghigher mean velocities (Re above several hundred) the velocity field becomes non-stationary, the instabilities appear and grow succesively till the turbulence in the velocity field is achieved.

Because the expansions and constrictions are most representative geometrical features of the pore space in a porous medium it can be supposed that the change of the velocity field in natural pore space is similar or even identical with the one observed in the examined models of the pore space under analogous conditions (Skawiński, 1992).

To validate the above conclusion some additional experiments have been performed. They consisted in the examination of the velocity field in a real pore space in a porous medium instead of the pore space models.

At first a porous medium was built of spheres in several geometrical arrangements and a variable velocity field in the pore space between these spheres was examined. The method of this examination was the same as that used when examining of the velocity field in the models of pore space described above.

Some results of these examinations are presented in Fig.6 and Fig.7.

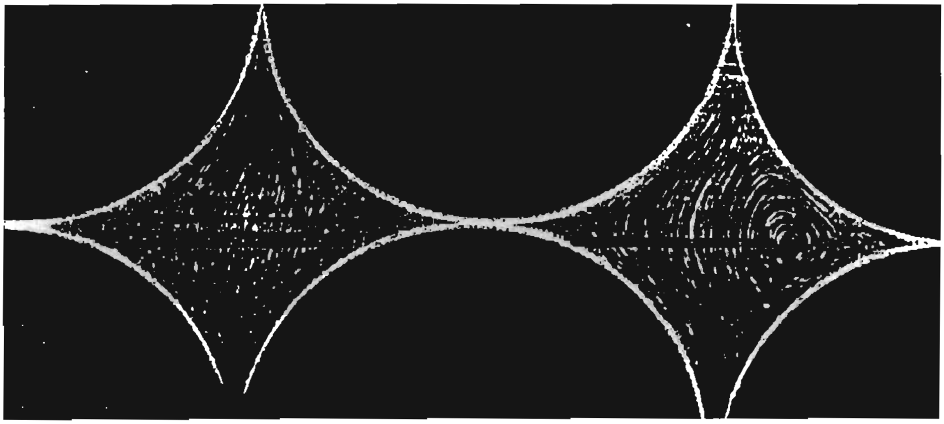

Fig. 6. Velocity field in pore space in the porous medium made of spheres in a cubic arrangement, at Re 0.001 (Skawiński, 1992)

These pictures show definitely and clearly that the velocity field in a real pore space is composed, similar as in the pore space models, of two kinds of flow: the main flow forming the discharge of the flow and the stationary vortex

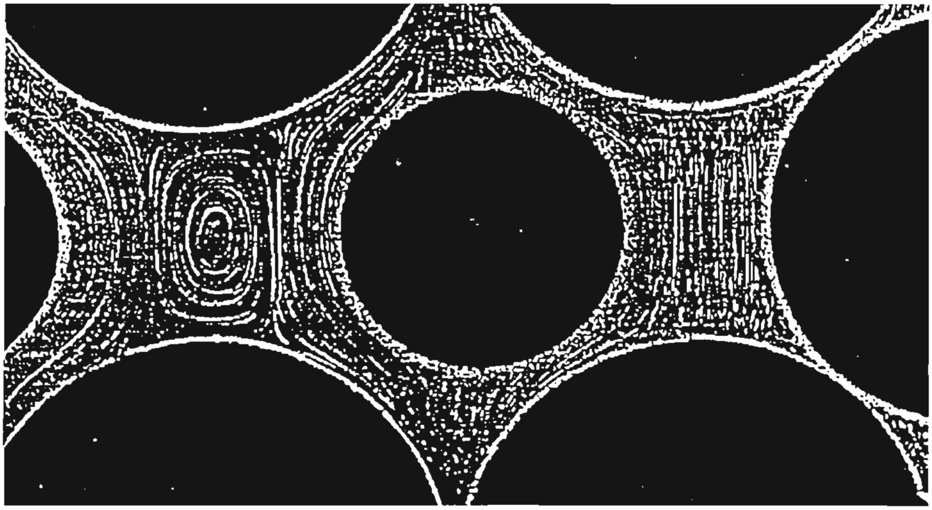

Fig. 7. Velocity field in pore space in the porous medium made of spheres in a hexagonal arrangement, at Re 0.003 (Skawiński, 1992)

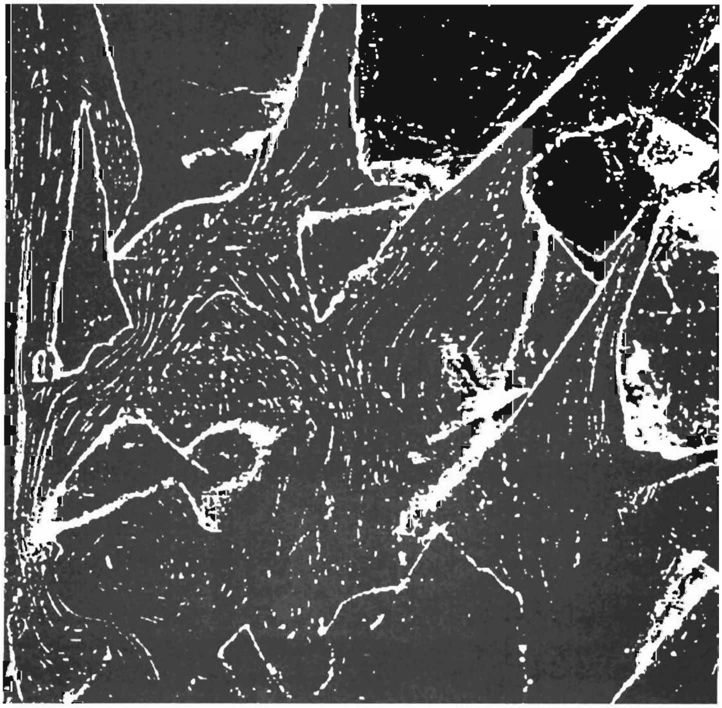

Fig. 8. Velocity field in pore space in the porous medium made of irregular grains in a random arrangement (Skawiński, 1992)

flow, which occupies a part of the pore space and does not take part in the discharge formation. The volume occupied by these two kinds of flow vary depending on the mean flow velocity.

This conclusion is also confirmed by the examination of the velocity field in a real pore space between irregular grains (pieces of crushed plexiglass) in an irregular arrangement. Sample of pictures of such a velocity field are presented in Fig.8. The presence of stationary vortices and variations of the velocity field are also clearly visible.

Undoubtedly, these properties of the velocity field in a pore space are resposible for the nonlinearity of flow in a porous medium. To support this opinion the following experiment has been performed: during the flow in a combination of constrictions and expansions the quantities needed to evaluate the hydraulic conductivity in this flow have been measured simultanously with the observation of the velocity field changes in one of the expansions.

The scheme of this experiment and the results in the form of a dependence of the hydraulic conductivity on the mean flow velocity in the constrictions (in terms of the Reynolds number) and the observed velocity fields are shown in Fig.9.

The correlation between the change of the velocity field and the change in conductivity is distinctly visible in the four ranges *(Skawiński, 1992)*:

- The first range, at smaller velocity (Re up to 100) – a rapid decrease in the cross-section of the main flow and a rapid decrease in conductivity.

- The second range, at medium velocities (Re from 100 to about 800) – a moderate change of the cross-section of the main flow connected with a similar moderate change in conductivity.

- The third range, at somewhat higher velocities (Re from 800 to about 1100) the onset and growth of instability in the velocity field resulting in rapid changes in conductivity, especially at the beginning of this range.

- The fourth range, at highest flow velocities (Re above about 1100) – the turbulence in the flow without any greater influence on conductivity.

In the investigations into changes of the velocity field in various expansions modelling the different character of the pore space (Fig.4 and Fig.5) it has been found that in a greater expansion, e.g. at the ratio $d : D : L = 3 : 10 : 10$, the velocity field changes considerably, starting even from the smallest flow velocities (Fig.4), wheras the velocity field in the small expansion, at $d : D : L = 4 : 10 : 3$ changes only a little, especially at low flow velocities (Fig.5).

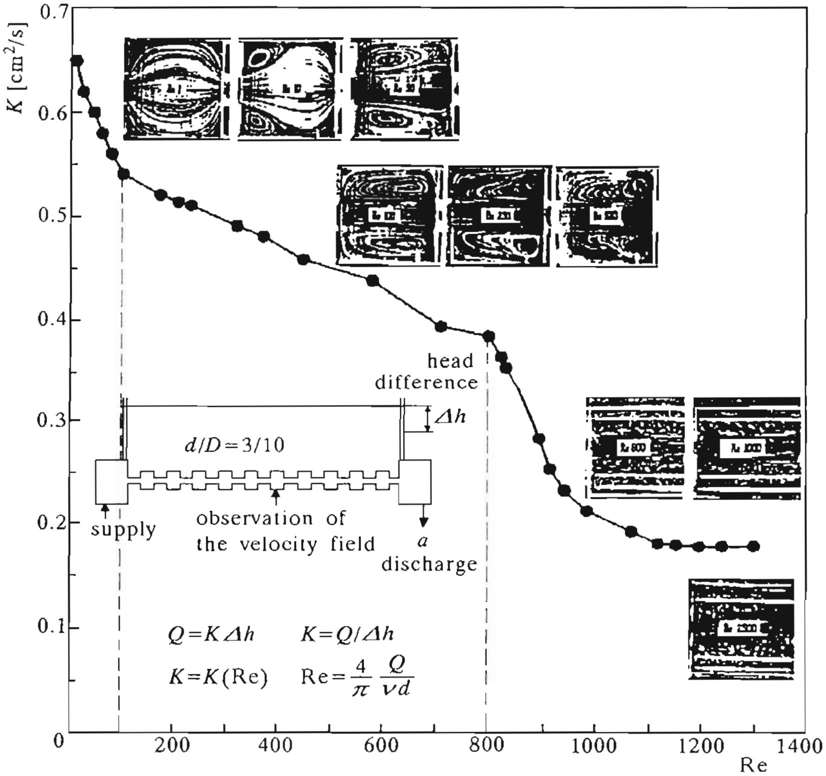

Fig. 9. Correlation of hydraulic conductivity changes with the velocity field changes in the flow in the set of expansions 3:10:10 (Skawiński, 1992)

Further investigations were intended to test how these two courses of changes of the velocity field in the pore space affect the conductivity in the combinations of expansions modelling the porous media with such a different character of pores (Skawiński and Lasowska, 1994). In these experiments the velocity field was not observed, since its variations were known from previous experiments (Fig.4 and Fig.5).

There have been constructed the sets of identical constrictions ($d = 3\,\mathrm{mm}$, $L = 10\,\mathrm{mm}$) and three different expansions of a legth $2\,\mathrm{mm}$, $10\,\mathrm{mm}$ and $30\,\mathrm{mm}$, i.e. sets of elements with $d : D : L$ equal to $3 : 10 : 2$ (named E02), $3 : 10 : 10$ (named E10) and $3 : 10 : 30$ (named E30). These three sets (numbering from 24 to 99 elements) modelled porous media of three different geometrical characters of pores. In these three models of porous media and additionally in a capillary of $3\,\mathrm{mm}$ diameter ($100\,\mathrm{cm}$ in length) there were realized water flows with different velocities.

The flow intensity was described in terms of the Reynolds number, basing on the flow rate and the diameter of the constriction (as given in Fig.9). The conductivity was defined as K [cm^2/s], basing on the flow rate (as given in Fig.9). The measurement results in these flows are given in Fig.10.

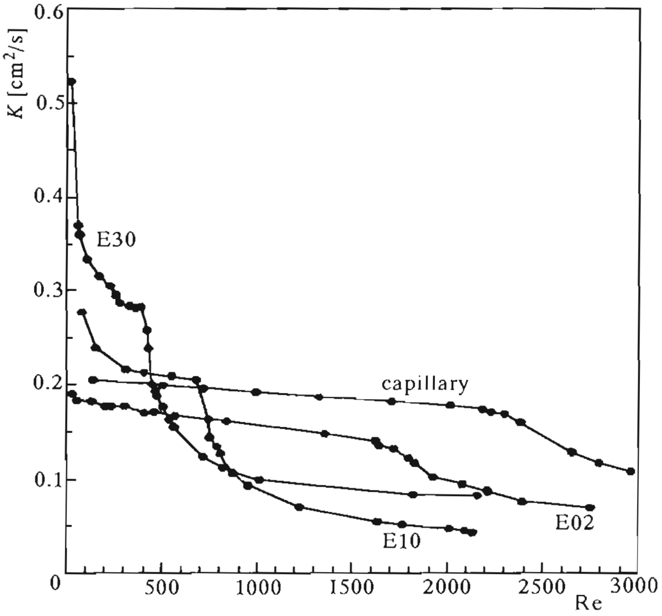

Fig. 10. Change of the hydraulic conductivity in the flow in the sets of expansions 02, 10, 30 and in a capillary (Skawiński and Lasowska, 1994)

Very great changes in the conductivity occur in flows in the set E30 (more than five fold in the examined range of Re), and rather small changes, not differing greatly from those in a capillary, take place in the set E02.

From the results of the above investigations conducted using models of porous media it can be concluded that in a porous medium with no great differences between the pore dimensions and where the dimensions of the pore expansions are smaller than the dimensions of the channels, the nonlinearity of flow is rather small. In a porous medium with more different pore dimensions the nonlinearity of flow is high.

The onset of instability of the velocity field in pores depends also on the character of the pores. By more different dimensions of pores (model E30) the instability of the velocity field appears much earlier (at Re 400) than in the case of more smooth pores (in model E02, at Re 1700).

5. Commentary

All the cited references, considerations and results of experimental investigations indicate that for the flow of liquid in porous media to be consistent with reality it has to be treated as a real internal flow, i.e. the flow in a closed space of various geometrical shapes. The geometrical shape of a pore space is very complicated, hence the investigations into the velocity field and its changes in this space must be performed using suitable models. Sufficiently adequate models of the most important elements of the pore space i.e. the expansions and constrictions, has been found to be expansions of the pipe. Extensive qualitative examinations of the velocity field and its changes have been made in various expansions of a pipe as a model of the pore space and are reported in this paper. The dimensions of the used models of pore space, of the order of a few or some dozens of millimeters, minimized the effect of interaction of the flowing water with the pore space walls, which may be also the origin of the nonlinearity of flow, e.g. in natural porous media (rocks) with small pore dimensions.

The results of these experimental investigations were the basis for drawing the following conlusions concerning the internal flow which models the flow in porous media and their relations to the flow in a real porous medium:

1. In all these flows, variation in the hydraulic conductivity (filtration coefficient) is observed, that depends on the velocity of flow (e.g. expressed as Reynolds number).

2. For the examined range of flow, comprising Re from a few to 2000, the change in hydraulic conductivity takes place in the three characteristic courses:

   (a) considerable changes in conductivity at very small and small Re,

   (b) reduced rate of conductivity changes at intermediate Re,

   (c) renewed great decrease in conductivity at great Re (Fig.9 and Fig.10).

3. The origin of the above changes in the conductivity (or filtration coefficient), i.e. the nonlinearity of flow has been found to be the change of the velocity field in a pore space (Fig.4 $\div$ 8).

4. Two characteristic types of expansions can be distinguished, in which the change of the velocity field and the courses of conductivity changes

differ substantialy from each other: a small expansion with the dimensions ratio approximately $L/d < 2/3$, and a large expansion with the dimensions ratio approximately $L/d > 10/3$ (Fig.3).

In a small expansion $(L/d < 2/3)$ the first course of conductivity changes (according to item 2.) is marked weakly or is almost indiscernible, the second course (slow decrease) is very extended within a wide range of flow velocities; the third course (renewed strong decrease) is also clearly seen (Fig.10).

In a large expansion $(L/d > 10/3)$ the first course of conductivity changes (steep decrease) is very distinct the second course (slow decrease) is short in comparison with other courses, and the third course (renewed strong decrease) is also very distinct (Fig.9 and Fig.10).

The real pore space in a real porous medium may be composed of elements of various geometrical shapes and dimensions, therefore the course of permeability change in the flow of liquids in this pore space is not identical, but similar to those which can be found in the flows in models of porous medium.

Permeability changes in the flow of water in a rock, whose pores have the character of caverns connected by the constrictions, are typical for the flow in large expansions, which is visible in Fig.2 (in a flow in a core cut from a sulfide ore).

In natural porous media, i.e. various kinds of porous rocks, the dimensions of pores in which the flow occurs, are of the order of magnitude from some micrometers to milimeters or even centimeters. In rocks with smaller pores the flow is so insignificant (independent of porosity), that such rocks may be regarded as impermeable. Rocks with pores greater than those of the order of centimeters are found rarely; they are rubbles or gravels.

It is obvious that in the flows of water in a pore space the hydrodynamic similarity is valid, but this is true only with respect to dimensions in which the water layers formed near the walls, bound by the pore minerals, are rather small in comparison with the local dimensions of pores. The thicknesses of these layers of the immovable water or water of various rheological properties are estimated to be of the order of magnitude of some nanometers or at most hundred of nanometers (Grimm, 1962). For this reason it can be expected that the hydrodynamic similarity in the water flow is already no longer valid in pores with the dimensions of some micrometers or even greater. The immovable water layers in the pore expansions of such dimensions can make the pores smooth for the flow, forming small channels with gentle expansions. In such geometrical formations the influence of variable velocity field in minimal. Permeability depends only slightly on the filtration velocity and the flow is almost linear.

The frequently observed nonlinearity of water flow in sedimentary rocks, in which the physico-chemical phenomena play the gratest role, may have its origin just in variable, rheological properties of water in the near-the-wall layers.

Another phenomenon which may occur in the flow of water or water solutions of various salts in sedimentary rocks is the varying in time internal swelling or internal shrinking of the rock. It results from changes in the hydration of certain minerals in the rocks, mainly clay minerals, or the coal substance in coal. These physical-chemical phenomena occurring in rocks may change permeability in the flows of water even by as much as two orders of magnitude (Skawiński and Dyrga, 1986; Skawiński et al., 1991).

In practise in hydrogeology or in industrial applications, the nonlinearity of flow in porous media may be great, important or imperceptible. For these reasons it is impossible to derive a general equation which would describe all types of flow in any porous medium. Therefore to solve many practical problems of flow in porous media one uses various equations and formulae which can describe the flow in porous media with greater or less accuracy in various ranges of the filtration velocity or mean velocity, or Reynolds number, e.g. Darcy's linear formula, Forchheimers binomial formula or other only approximating power formula. The coefficients for these descriptions have to be found from experimental investigations. These formulae can describe the flow or distribution of the filtration velocity or discharge of the flow in porous media with various accuracy which in many cases may be sufficient to solve practical problems.

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Zagadnienia przepływu cieczy w ośrodku porowatym

Streszczenie

W publikacji przedstawione są rozważania i wyniki eksperymentalnych badań przepływu cieczy w ośrodkach porowatych. Od pierwszych eksperymentów H. Darcy'ego w 1856 r. wykonane było wiele prac badawczych tego zgadnienia. Najwazniejsze z tych prac są cytowane i omówione w niniejszym artykule. Wynikiem tych prac jest stwierdzenie, że przepływ cieczy w ośrodkach porowatych jest z natury nieliniowy, to znaczy przepuszczalność w tym przepływie jest zależna od prędkości przepływu.

Hydrodynamiczne przyczyny tej nieliniowości, czyli znaczący udział sił bezwładności w tym przepływie prowadzący do zmian pola prędkości w przestrzeni porowej, omówiony jest w niniejszej publikacji na podstawie badań eksperymentalnych, przede wszystkim wykonanych w Instytucie Mechaniki Górotworu w Krakowie.

W końcowych komentarzach w publikacji zestawione są fakty i poglądy dotyczące przyczyn zmian przepuszczalności w przepływach wody w naturalnych ośrodkach porowatych, czyli w skałach, przede wszystkim w skałach osadowych.

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