Modelling viscous fluid filtration to select optimal bottom-hole filter designs

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Abstract. Determining the resistance value of filters with a filtering surface of mesh and block type is difficult mathematically. This is because many parameters affecting the shell filtration capacity. As for the mesh filters, depending on the type of weaving, the different thickness of weft and warp, the different size in the horizontal and vertical planes, the frame structure which is integral with the mesh have critical influence. As for block constructions, it is the size and uniformity of the composition of the particles, the thickness of the filter shell, the geometry of the filtration channels and other features that play the role. It is, therefore, more convenient for such filters to assess their permeability. The most promising filters are the frames with horizontal slots which have considerably less resistance and interference of the holes. In addition, the features of the frame-rod filter device make it easy to realize a greater inlet area than in other designs, with the same minimum size of the slots. Recommendations for choosing the inlet areas and the size of the filter slots should consider factors related to well production rate, the formation fluid viscosity, particle size distribution of the formations, granulometric composition of the formation, consolidation factor of the bottom-hole zone, clodding and bridging of the deposits.

1. Introduction

There is a shortcoming in quarrying wells equipped with filters, both in the degree and the nature of the formation exposing which depends on the filter construction installed in the formation [1-3]. According to [4], in the filtration calculation, the total filtration resistance is divided into private, corresponding to different filtration zones. If the well bottom construction does not affect the nature of the flow in the zone sufficiently far from the well, additional hydraulic losses appear in the filter zone and on the filter itself and must be seen as dimensionless parameters affecting the total resistance to the flow of produced fluid.

According to the common flow schematization, additional resistance shall be presented according to [4] as:

\[ \zeta = \zeta_1 + \zeta_2, \]  

(1)

where \( \zeta_1 \) and \( \zeta_2 \) are the resistance due to the degree and nature of the formation exposing.

Assessment of the well imperfection influence according to the formation exposing degree with the inflow to it depending on the ratio \( \lambda/m \) (where \( \lambda \) is the filter length and \( m \) is the total power of the
productive formation) and graphs for determining the resistance $\zeta_1$ are given in [5].

The resistance $\zeta_2$ is a complex characteristic depending on the quality of well completion, the hydraulic features of the filter caused by construction as well as the filter shell clogging and the breakdown of the linear filtration mode. Therefore, the value $\zeta_2$ can be determined in this way:

$$\zeta_2 = \zeta_{2f} + \zeta_{2d} + \zeta_{2dt},$$

where $\zeta_{2f}$, $\zeta_{2d}$, and $\zeta_{2dt}$ are the resistances caused by the filter, deposit character, and deviation from the linear filtration mode.

The process of filtering a viscous fluid through a model of a porous medium with relatively small pore sizes obeys the Darcy linear law [5] and then the value of the generalized resistance can be determined by the formula:

$$\zeta_2 = \zeta_{2f} + \zeta_{2d}.$$

From here it is clear that when choosing optimal constructions of filters and their elements, their hydraulic parameters play a decisive role. They are determined by the resistance of the filter itself, and the placement of filters in weak and soft formations or gravel package well leads to significant contact pressure losses in the filter-rock zone and the sand-holding ability of the filter shell.

2. Results and Discussion

The hydraulic parameters of the rock-filter system (under other conditions) are a consequence of the geometric parameters of the filtering shell forming the mutual position of the slots and influencing the resistance to movement of the produced fluid due to the breakdown of flow linearity, its diffraction, etc.

Increasing the inlet area of the filter shell with the same size of slots affects on reducing contact losses in the filter-rock interface by increasing porosity in the near filter zone. Also, the form and mutual position of the elements of the filtering shell influencing the creation of stable bridges from large fractions of sand or gravel packing ensures the retention of particles that make up the formation matrix with the simultaneous passage of the colmatant.

Various filter constructions are currently in use. There are filters with round holes, slotted, located in the vertical or horizontal plane, with different lengths, which can reach the size of the formation thickness, as well as with a filtering surface of meshes and block-type filters. For filters with round holes V.I. Shchurov [6] studied similar solutions of M. Mason and, as a result, constructed refined graphs of the dependence (Figure 1) $\zeta_{2f}$ on the parameters:

$$\alpha = d_0/D and \beta = nD,$$

where $d_0$ is the diameter of the filter openings; $n$ is the number of filter openings per unit length; $D$ is the diameter of the filter.

So $\alpha$ and $\beta$ parameters are indicators of relative inlet area, the graph shows that increasing the inlet area leads to decreasing the filter resistance $\zeta_{2f}$.

M.R. Harris’ theoretical research [7] shows that the total efficiency of the formation of round holes group in terms of flow coefficient depends on their mutual position. The graph (Figure 2) shows the results of some conclusions.
Figure 1. The dependence of $\zeta_{2f}$ on parameters of $\beta = 0.01nD$ and $\alpha$ for filters with round holes: 1 - $\alpha = 0.03$; 2 - $\alpha = 0.04$; 3 - $\alpha = 0.05$; 4 - $\alpha = 0.06$; 5 - $\alpha = 0.07$; 6 - $\alpha = 0.08$; 7 - $\alpha = 0.09$

Graphic dependencies are built considering the following conditions:
- supply contour radius is 200 m;
- outer radius of the cement column 76 mm;
- perforated channel length is 30.5 cm;
- perforated channel diameter is 12.7 mm;
- perforator bullet penetration behind a cement column is 300 mm.

The results show that the holes located evenly around the circumference in the horizontal plane lead to the lowest pressure drop at a given flow rate, and holes located vertically along one generating line lead to the largest pressure drop.

The resistance values $\zeta_{2f}$ for filters with a length that is equal to the formation thickness located vertically along the generating line of the pipe, have very similar results in various methods of determination. V. T. Cordwell and S.K. Dodson [8] proposed the expression:

$$\zeta_{2f} = \frac{2}{n} \cdot \ln \frac{2}{\pi \eta}, \text{ with } \eta = 0.3,$$

where $n$ is the number of slots; $\eta$ is inlet area.

V.P. Pilatovsky [9] obtained the expression of dimensionless hydraulic resistance in the form:

$$\zeta_{2f} = \frac{4}{n} \cdot \ln \sin \frac{n^t \alpha}{2},$$

where $n^t$ is the number of impermeable partitions; $\alpha$ is the central angle determining the size of the slot.

Graphic dependences (see Figure 1) performed according to the results of calculating formula (6) allow finding the value $\zeta_{2f}$ of rod frames and filter structures similar to them.

The work [10] confirms that the graphical dependencies (Figure 1) allow determining the resistance value for filters with a limited length of vertical slots. These dependencies are valid for filters with holes made in the form of a circle. For rectangular holes, it is possible to interpolate to round holes considering the equivalent total cross-sectional area.
Figure 2. The dependence of the productivity coefficient (K) on the perforation pattern and the number of perforations (m) in the plan

3. Experiment
Recommended radii of reduction depend on the ratio of the length of the slot $l$ to its width $b$. With the ratio $l/b \leq 3$, the reduction is preferable to produce on the area, and the radius of the reduced hole is expressed by the following dependence:

$$r_{\text{red}} = \frac{b}{\sqrt{\pi}} \cdot l,$$

and with $l/b > 3$ (long and narrow slots):

$$r'_{\text{red}} = \frac{b}{2\pi} \cdot l,$$

i.e the radius is determined along the perimeter.

Graphical dependences (Figure 3) show that the resistance of filters with vertical slots decreases significantly both with an increase in the inlet area and with a decrease in the width of the slot with the same inlet area of the filter surface.

For filters with slotted holes located in the horizontal plane, A.L. Hein gave a similar solution, with relatively large $r/d$ values:

$$\zeta_{zf} = \frac{d^3}{\pi^2 r_{c} b^2} \left[ 6.835 \cdot \frac{b}{d} \left( 1 - \frac{b}{d} \right) - 2L \cdot \left( \pi \cdot \frac{b}{d} \right) + \chi \left( \frac{b}{d}, \frac{2r_{c}}{d} \right) \right],$$

where $d$ is the distance between the centres of adjacent slots; $b$ is the height of the slot; $r_{c}$ is the current radius; $\chi (\frac{b}{d}, \frac{2r_{c}}{d})$ is a tabulated function whose values are given in [4].

The work [10] gives solutions according to which the resistance value of filters with horizontal slots is approximately 20% less than that of filters with cylindrical openings shown in the graphical dependencies (Figure 1).

Determining $\zeta_{zf}$ of filters with a filtering surface of mesh and block type is difficult mathematically. This is because many parameters affecting the shell filtration capacity. As for the mesh filters, depending on the type of weaving, the different thickness of weft and warp, the different size in the horizontal and vertical planes, the frame structure which is integral with the mesh have critical influence. As for block constructions, it is the size and uniformity of the composition of the particles, the thickness of the filter shell, the geometry of the filtration channels and other features that
play the role. Therefore, for such filters it is more convenient to evaluate their permeability according to the Darcy formula [5].

Figure 3. Graphic dependences $\zeta_{zf}$ of on inlet area $\eta$ for the entire reservoir thickness for filters with slots with a diameter of 168 mm: slot width: 1 - 10 mm; 2 - 5 mm; 3 - 3 mm; 4 - 1 mm; 5 - 0.5 mm

For radial filtration through an annular sample:

$$K = \frac{\mu_g Q_g}{20 \pi h (P_{out} - P_{in})}$$

where $Q_g$ is the flow rate, cm$^3$ / s; $\mu_g$ is the dynamic viscosity, MPa $\cdot$ s; $P_{out}$, $P_{in}$ is the pressure difference between the outer and inner surfaces, MPa; $r_{out}$, $r_{in}$ - outer and inner radii in cm; $h$ is the height of the test sample in cm.

The formula shows that the permeability functionally depends on the differential pressure, which in turn is due to the filter resistance $\zeta_{zf}$.

The work [6] studied the hydraulics of filters of various constructions. Figure 4 presents the results of the filter permeability assessment based on their inlet area.
Figure 4. Graphic dependencies of filter permeability on inlet area according to Klotz: 1 - wire-frame; 2 - with bridge-shaped holes; 3 - slotted holes with open perforation; 4 - mesh filters with galloon weaving nets

4. Conclusion

As seen, the most perspective filters are filters - frames with horizontal slots which have significantly less resistance and the influence of an interference of the holes. In addition, the features of the frame-rod filter device make it easy to realize a greater inlet area than in other designs, with the same minimum size of the slots.

Recommendations for choosing the inlet areas and the size of the filter slots should consider factors related to well production rate, the formation fluid viscosity, particle size distribution of the formations, granulometric composition of the formation, consolidation factor of the bottom-hole zone, clodding and bridging of the deposits. Only the result of experimental studies in the laboratory and natural models will determine these parameters, as well as losses at the filter-rock contact.

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