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NUMERICAL MODELLING OF THERMOHYDRODYNAMIC PROCESSES IN FRACTURED OIL RESERVOIR

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Summary. Numerous reasons for the existence of hydrocarbon reserves, as well as the complexity of the processes associated with their formation and extraction emphasize the need for complex scientific approaches in the rational selection and metrological development of exploitation. The most important direction in these studies is the research for the mass transfer of hydrocarbons and the mechanisms of interfacial transition, taking into account changes in pressure and temperature in the collector under the multiphase fluid filtration in a porous medium. In fundamental studies on physical and mathematical modeling in order to predict development it is important to consider all the features of temperature anomalies during the movement of gas-liquid systems in hydrocarbon fields with different thermobaric conditions. In this paper, the problem of determining influential level of temperature anomalies on the distribution of thermodynamics fields during oil exploitation in fractured collector is solved. The algorithm of numerical solution is offered and numerous computer experiments have been conducted by means of software creation. The influence of the specific heat capacity of the liquid, the Joule-Thomson coefficient, wellbore volume influence coefficient, absolute permeability, fluid viscosity and deformation properties of the collector on exploitation process were assessed.

1. Introduction

Experience in the oil fields development shows that the complexity of the physical processes that occur during the exploitation of the fields highlights the need for a comprehensive scientific approach in the creation of technological schemes.

These geological and geophysical methods are more reliable and allow to obtain complete information. In this case, it is possible to address issues such as determining the operational characteristics of the productive layer, the technical condition of wells and control over the operation of pumping equipment. The most important of these issues is the determination of the exploitation characteristics of the layer. The most important direction of these studies is the study of the mechanisms of mass transfer of hydrocarbons and the transition between phases, taking into account changes in pressure and temperature during the filtration of fluid in the formation. It is important to take into account the impact of pressure and temperature changes in the development of hydrocarbon fields on the performance of oil reservoir exploitation. In this case, thermodynamics studies based on the measurement of pressure, flow and temperature in the wellbore play a key role in the complex of geophysical methods.

The study of heat transfer phenomena in the movement of fluids in a porous medium, taking into account the phase transitions and thermodynamics effects, is not only a search for methods of interpretation of thermometric data (especially in multiphase flow conditions), but also a scientific and practical interest in improving non-stationary heat and mass theory.

Measurement of the small changes in fluid temperature due to thermodynamic effects in the process of field development with modern well thermometers also allows to solve a number of diagnostic and practical issues related to the well and reservoir system. Numerous studies have been devoted to the determination of the temperature field in the formation, taking into account the thermodynamics effects of fluid filtration in porous media, and on this basis to the assessment of the performance characteristics of the layers (Чекалюк, 1965; Карачинский, 1975; Алишаев et al., 1985; Abasov et al., 1993; Рамазанов, 2004; Рамазанов, Паршин, 2006; Филиппов, Ахметова, 2011; Джалалов и др., 2018).

In this paper the influence of thermodynamic effects on the change of exploitation parameters of the oil reservoir during the exploitation of the deformed reservoir is examined with central well.

2. Statement of the Problem

Assume that a central well is exploited in a circular oil formation with a fractured collector during development. The following physical assumptions were made in the statement of the problem: The initial pressure and temperature before layer development are p_0 and T_0, respectively. Besides

- The well is entire on the degree and nature of the opening and covers the full thickness of the layer with a sufficiently large radius;
- Oil filtration is subject to Darsy's law and is non-isothermal;
- The pressure at the bed boundary is constant;
- The initial natural distribution of temperature along the layer is stable;
- The temperature of the liquid and porous medium is the same at any point in the layer;
- Heat transfer in the radial direction of the layer is not taken into account in comparison with convective heat transfer.

Under these conditions determination of the pressure and temperature distribution functions in the layer is described by the following system of equations by corresponding initial and boundary conditions:

$$\beta^* \frac{\partial p}{\partial t} = \frac{1}{r}\frac{\partial}{\partial r}\left(\frac{k(p)}{\mu} r \frac{\partial p}{\partial r}\right), r_c \le r \le r_k, t > 0, \quad (1)$$

$$C_{pl}\frac{\partial T}{\partial t} = \rho_f C_f \frac{k(p)}{\mu}\frac{\partial p}{\partial r}\left(\frac{\partial T}{\partial r} + \varepsilon \frac{\partial p}{\partial r}\right) +$$

$$+\eta \rho_f C_f \frac{\partial p}{\partial t}, \quad r_c \le r \le r_k, \quad t > 0, \quad (2)$$

$$p(r,0) = p_0, \quad r_c \le r \le r_k, \quad (3)$$

$$\frac{2\pi k(p) H}{\mu}\left(r\frac{\partial p}{\partial r}\right)\Big|_{r=r_c} = Q + C\frac{\partial p}{\partial t}\Big|_{r=r_c}, t > 0, \quad (4)$$

$$p(r_k, t) = p_0, \ t > 0, \quad (5)$$

$$T(r,0) = T_0, \quad r_c \le r \le r_k, \quad (6)$$

$$T(r_k,t) = T_0, \quad r_c \le r \le r_k, \quad (7)$$

(Чекалюк, 1965; Карачинский, 1975; Алишаев et al., 1985).

Here $\beta^* = \beta_f + m\beta_{\text{col}} -$ elastic capacity coefficient, $k -$ absolute permeability, $\mu -$ dynamic viscosity, $r_c -$ radius of the well, $r_k -$ radius of the layer, $t -$ time, $r -$ radial coordinate, $C_{pl} -$ volume heat capacity of the layer, $C_{sr} -$ specific heat capacity of rock, $C_f -$ specific heat capacity of the liquid, $\rho_f -$ density, $m -$ porosity, $\varepsilon -$ Joule-Tomson coefficient, $\eta -$ adiabatic coefficient, $p_0 -$ layer pressure, $T_0 -$ layer temperature, $H -$ layer thickness, $Q -$ debit of the well, $C -$ coefficient of impact of wellbore volume.

After the substitutions

$$r = r_k \bar{r}, \ p = p_0 \bar{p}, \quad k(p) = k_0 \bar{k}(p), \quad \mu = \mu_0 \bar{\mu}, \ T = T_0 \bar{T} \quad (8)$$

the problem (1)-(7) takes the following form:

$$\frac{\partial \bar{p}}{\partial \tau} = \frac{1}{\bar{r}}\frac{\partial}{\partial \bar{r}}\left(\frac{\bar{k}(\bar{p})}{\bar{\mu}}\bar{r}\frac{\partial \bar{p}}{\partial \bar{r}}\right), r_0 < \bar{r} < r_s, \tau > 0, \quad (9)$$

$$\frac{\partial \bar{T}}{\partial \tau} = \tilde{A}\frac{\bar{k}(\bar{p})}{\bar{\mu}}\frac{\partial \bar{p}}{\partial \bar{r}}\left(\frac{\partial \bar{T}}{\partial \bar{r}} + \tilde{B}\frac{\partial \bar{p}}{\partial \bar{r}}\right) + \tilde{D}\frac{\partial \bar{p}}{\partial \tau}, \quad (10)$$

$$r_0 \le \bar{r} \le r_s, \quad \tau > 0,$$

$$\bar{p}(\bar{r},0) = 1, \quad r_0 < \bar{r} < r_s, \quad (11)$$

$$\frac{2\pi \bar{k}(\bar{p})}{\bar{\mu}}\left(\bar{r}\frac{\partial \bar{p}}{\partial \bar{r}}\right)\Big|_{\bar{r}=1} = \tilde{Q} + \tilde{C}\frac{\partial \bar{p}}{\partial \tau}\Big|_{\bar{r}=1}, \tau > 0, \quad (12)$$

$$\bar{p}(r_s, \tau) = 1, \quad \tau > 0, \quad (13)$$

$$\bar{T}(\bar{r},0) = 1, \quad \bar{T}(\bar{r},t) = 1. \quad (14)$$

Here,

$$\tau = \frac{k_0}{\mu_0 r_k^2 \beta^*} t, r_0 = \frac{r_c}{r_k}, \ r_s = \frac{r_k}{r_k}, \tilde{Q} = \frac{\mu_0}{H k_0 p_k} Q,$$

$$\tilde{C} = \frac{C}{H r_k^2 \beta^*}, \tilde{A} = \frac{\rho_f C_f p_k \beta^*}{C_{pl}}, \tilde{B} = \frac{p_k \varepsilon}{T_k}, \tilde{D} = \frac{\eta \rho_f C_f p_k}{C_{pl} T_k}.$$

As can be seen, equation (9) is not explicitly related to the function $T(r,t)$. Therefore, we can solve this equation separately.

By using of the substitution $x = \frac{\bar{r}^2}{4}$ we transform the problem (9)-(14) as follows:

$$\frac{\partial \bar{p}}{\partial \tau} = \frac{\partial}{\partial x}\left(x \frac{\bar{k}(\bar{p})}{\bar{\mu}}\frac{\partial \bar{p}}{\partial x}\right), x_c \le x \le x_s, \tau > 0, \quad (15)$$

$$\bar{p}(x,0) = 1, \ x_c \le x \le x_s, \quad (16)$$

$$\frac{4\pi \bar{k}(\bar{p})}{\bar{\mu}}\left(x\frac{\partial \bar{p}}{\partial x}\right)\Big|_{x=x_c} = \left(\tilde{Q} + \tilde{C}\frac{\partial \bar{p}}{\partial \tau}\right)\Big|_{x=x_c}, \quad (17)$$

$$\bar{p}(r_s, \tau) = 1, \quad \tau > 0, \quad (18)$$

$$\frac{\partial \bar{T}}{\partial \tau} = \tilde{A}\frac{\bar{k}(\bar{p})}{\mu} x \frac{\partial \bar{p}}{\partial x}\left(\frac{\partial \bar{T}}{\partial x} + \tilde{B}\frac{\partial \bar{p}}{\partial x}\right) + \tilde{D}\frac{\partial \bar{p}}{\partial \tau}, \quad (19)$$

$$x_c \le x \le x_s, \ \ \tau > 0,$$

$$\bar{T}(x,0) = 1, \quad (20)$$

$$\bar{T}(x_s,0) = 1, \quad (21)$$

here, $x_c = \frac{r_0^2}{4}$. $x_s = \frac{r_s^2}{4}$.

The problem (15)-(21) is a mixed problem for partial differential equations with special nonlinearity which makes difficulties in finding its exact (analytical) solution. Obtaining approximate solution describing all physical properties accurate for the considered problem requires effective numerical method. Among extensive of approximate methods the finite differences method is one of the universal tools for obtaining numerical solution of the problem of nonlinear partial differential equations (see, for example, Азиз, Сеттари, 1982; Самарский, 1977; Richmyer, Morton, 1967; Годунов, Рябенький, 1972; LeVeque, 2002; Toro, 1999 et al.).

3. Building a Numerical Solution Algorithm

At first we cover the segment $[x_c, x_s]$ into n equal subsegments and let denote by x_j, $(j = 0,1,2,\dots n)$ points of partitions that $x_j = x_c + j\cdot h_x$, $(i = 0,1,2,\dots n)$, and $h_x = \frac{x_s - x_c}{n}$. By analogy, the $[0,T)$ with points $\tau_k = k\cdot h_\tau$, $h_\tau > 0$, $(k = 0,1,2,\dots,)$ is divided to time layer.

Thus, the following grids

$$\Omega_{h_x} = \left\{x_j = x_c + j\cdot h_x, \ \ h_x = \frac{x_s - x_c}{n},\right\}$$

$$(j = 0,1,2,\dots n)$$

$$\Omega_{h_\tau} = \{\tau_k = k\cdot h_\tau, h_\tau > 0, (k = 0,1,\dots,)\}$$

cover the $[x_c, x_k]$ and $[0,T)$ respectively. Consequently, $\Omega_{h_x h_\tau} = \Omega_{h_x} \times \Omega_{h_\tau}$ that is

$$\Omega_{h_x h_\tau} = \left\{(x_j, \tau_k) \middle| \ x_j \in \Omega_{h_x}, \ \ \tau_k \in \Omega_{h_\tau}\right\}$$

is two dimensional grid which covers of

$$D = \{(x,\tau) | \ x \in [x_c, x_s], \ \ \tau \in [0,T)\ \}.$$

The approximate solution of the problem (15)-(21) found by the following system of algebraic equations which constructed by method of finite differences:

$$P_{j,k+1} = P_{j,k}\left[1 - \gamma\left(R_{j+\frac{1}{2}}(x)K_{j+\frac{1}{2}} + R_{j-\frac{1}{2}}(x)K_{j-\frac{1}{2}}\right)\right] + \gamma R_{j+\frac{1}{2}}(x)K_{j+\frac{1}{2}}P_{j+1,k} + \gamma R_{j-\frac{1}{2}}(x)K_{j-\frac{1}{2}}P_{j-1,k}, \quad (22)$$

$$(j = 1,2,\dots,n-1, \quad k = 0,1,2,\dots),$$

$$P_{j,0} = 1, \ (j = 0,1,\dots,n), \quad (23)$$

$$\gamma_1 \frac{4\pi \bar{k}(P_{0,k})}{\bar{\mu}}\left(P_{1,k} - P_{0,k}\right) - \gamma_1 \tilde{Q} = \tilde{C}\,P_{0,k+1} - \tilde{C}\,P_{0,k}, \quad (24)$$

$$P_{n,k} = 1, \qquad \tau > 0, \quad (25)$$

$$T_{j,k+1} = T_{j,k} + \gamma \tilde{A} x_i \frac{\bar{k}(P_{j,k})}{\bar{\mu}}\left(P_{j+1,k+1} - P_{j,k+1}\right)\frac{T_{j+1,k} - T_{j-1,k}}{2} + \gamma \tilde{A} B x_i \frac{\bar{k}(P_{j,k})}{\bar{\mu}}(P_{j+1,k+1} - P_{j,k+1})^2 + \gamma_1 \tilde{D}(P_{j,k+1} - P_{j,k}), \quad (26)$$

$$(j = 1,2,\dots,n-1; \ k = 0,1,2,\dots,),$$

$$T_{j,0} = 1, \ (\ j = 0,1,2,\dots,n), \quad (27)$$

$$T_{0,k} = 1, \ (k = 0,1,2,\dots, \ ). \quad (28)$$

Here,

$$R_{s+\frac{1}{2}}(x) = \frac{x_{s+1} + x_s}{2},$$

$$K_{s-\frac{1}{2}}(P) = \frac{k(P_{s+1}) + k(P_{s-1})}{2}, \quad (s = i, i-1).$$

3.1. Analysis of Calculated Results

In order to carry out computer tests on the basis algorithm of (22)-(28) we use the relation of absolute permeability $\bar{k}\,(p) = a_k[1 + \alpha_k(p - p_k)]$ suggested by (Джалалов и др., 2018), and another necessary data adduced in the Table too. The graphical presentations of achieved results are shown on Fig. 1-6. It is clear that the change in pressure in the oil reservoir occurs only due to the well, which in turn leads to a change of temperature in the reservoir. The dynamic change in reservoir pressure and temperature over time is shown in Fig. 1 and Fig. 2, respectively. These results show that the change in pressure in the well does not depend on the thermobaric parameters, but only on the parameters of the filtration capacity.

Fig. 3-6 show the time dependence graphs of the thermophysical and filtration capacity parameters of the fluid temperature at the wellbore.

According to Fig. 3 and Fig. 4, we see that a decrease in the permeability values of the collector leads to an increase in the temperature drop, and an increase in the viscosity of the fluid leads to a decrease in the temperature drop.

Table

Physical quantities	Units of measurement	Numeric values
β^*	$\frac{1}{MPa}$	$1.0 \cdot 10^{-4}$
k	m^2	$0.05 \cdot 10^{-12}$
μ	$MPa \cdot seconds$	$7.0 \cdot 10^{-10}$
r_c	m	0.1
r_k	m	$0.2 \cdot 10^2$
C_{pl}	$\frac{Djol}{m^3 \cdot K}$	1800
C_{sr}	$\frac{Djol}{kg \cdot K}$	$1.8 \cdot 10^3$
C_f	$\frac{Djol}{kg \cdot K}$	$1.5 \cdot 10^3$
ρ_f	$\frac{kg}{m^3}$	$8.5 \cdot 10^2$
m	-	0.2
ε	$\frac{K}{MPa}$	0.4
p_k	MPa	40.2
p_c	MPa	40.2
T_k	C^0	65
H	m	15
Q	$\frac{m^3}{sec}$	$1.157 \cdot 10^{-4}$
$a_k = A + Bp_k - C\,p_{qor}$		A =0.832, $B = 0.8147 \cdot 10^{-2}$, C=0.0023
p_{qor}	MPa	96.6
η	$\frac{K}{MPa}$	$1.5 \cdot 10^{-2}$

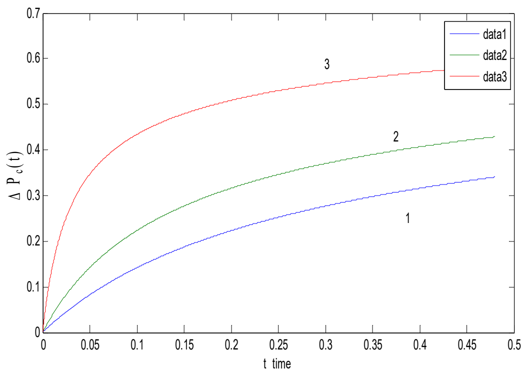

Fig. 1. Graphs of pressure drop distribution at the face of well-bore depending on the fixed value of viscosity $\mu = 0.5 \cdot 10^{-4} MPa \cdot$ sec, and at different values of permeability; 1) $k = 0.005 \cdot 10^{-12}\,m^2$, 2) $k = 0.01 \cdot 10^{-12}\,m^2$, 3) $k = 0.05 \cdot 10^{-12}\,m^2$

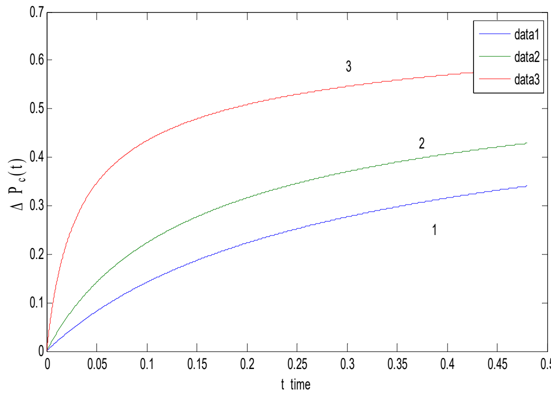

Fig. 2. Graphs of pressure drop distribution at the face of well-bore depending on the fixed value of permeability $k = 0.05 \cdot 10^{-12}\,m^2$ and at different values of viscosity: 1) $\mu = 1 \cdot 10^{-10} MPa \cdot$ sec, 2) $\mu = 0.5 \cdot 10^{-10} MPa \cdot$ sec, 3) $\mu = 0.7 \cdot 10^{-10} MPa \cdot$ sec

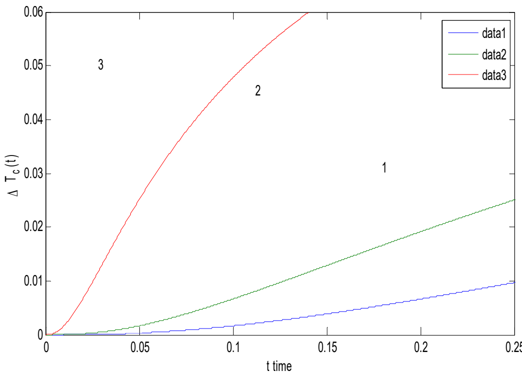

Fig. 3. Graphs of temperature drop distribution at the face of wellbore depending on the fixed value of viscosity $\mu = 0.7 \cdot 10^{-4} MPa \cdot \sec$, and at different values of permeability: 1) $k = 0.01 \cdot 10^{-12}\, m^2$, 2) $k = 0.005 \cdot 10^{-12}\, m^2$, 3) $k = 0.05 \cdot 10^{-12} m^2$

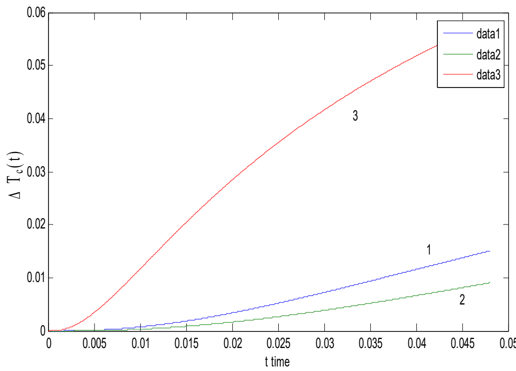

Fig. 4. Graphs of temperature drop distribution at the face of wellbore depending on the fixed value of permeability $k = 0.05 \cdot 10^{-12} m^2$ and for different viscosity values: 1) $\mu = 1 \cdot 10^{-10}\, MPa \cdot \sec$, 2) $\mu = 0.5 \cdot 10^{-10} MPa \cdot \sec$, 3) $\mu = 7 \cdot 10^{-10} MPa \cdot \sec$

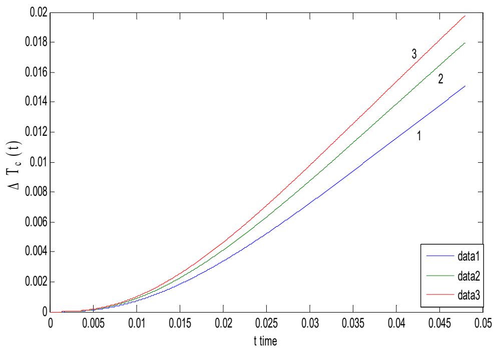

Fig. 5. Graphs of temperature drop distribution at the face of wellbore depending on the fixed value of the Joule-Thomson coefficient $\varepsilon = 0.4\, \frac{K}{MPa}$ and at different values of the specific heat capacity of the liquid: 1) $C_{\text{fluid}} = 1500 \frac{Djol}{kg\cdot K}$, 2) $C_{\text{fluid}} = 1850 \frac{Djol}{kg\cdot K}$, 3) $C_{\text{fluid}} = 2100 \frac{Djol}{kg\cdot K}$

Fig. 5 shows the time dependence of the temperature drop at the face of wellbore depending on the value of the specific heat capacity of the liquid. An increase in the cost of the specific heat capacity of a liquid leads to an increase in the temperature drop over time.

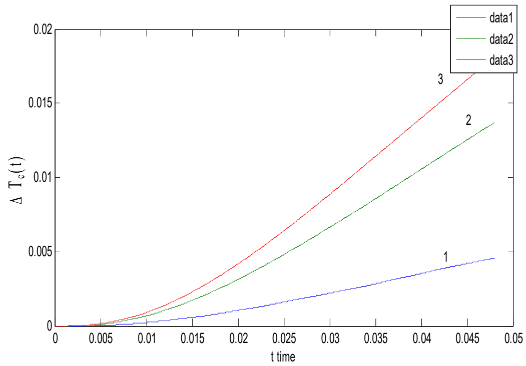

Fig. 6. Graphs of temperature drop distribution at the face of wellbore depending on the fixed value of heat capacity of the liquid $C_{fluid} = 1880 \frac{Djol}{kg\cdot K}$ and at the different values of the Joule-Thomson effect: 1) $\varepsilon = 0.1 \frac{K}{MPa}$, 2) $\varepsilon = 0.3\, \frac{K}{MPa}$, 3) $\varepsilon = 0.4 \frac{K}{MPa}$

Temperature anomaly, which depends on time and is observed when the Joule-Thomson's coefficient changes, dramatically affects the temperature field distribution (Fig. 6). In the variant under consideration, with an increase in the value of the parameter ε, the difference between the temperature drops is about 70-75% compared to $= 0.1 \frac{K}{MPa}$.

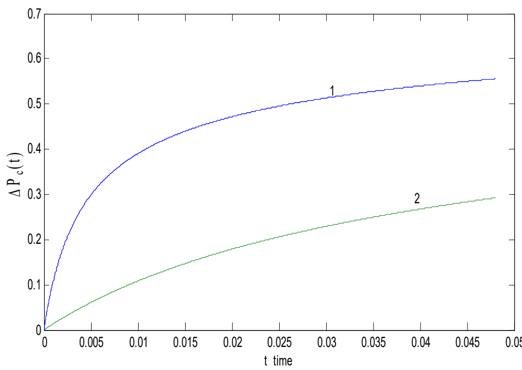

Fig. 7. Graphs of pressure drop distribution at the face of wellbore depending on the deformation factor of collector: 1 – the case $\alpha_k = 0$; 2 – the case $\alpha_k = 1$

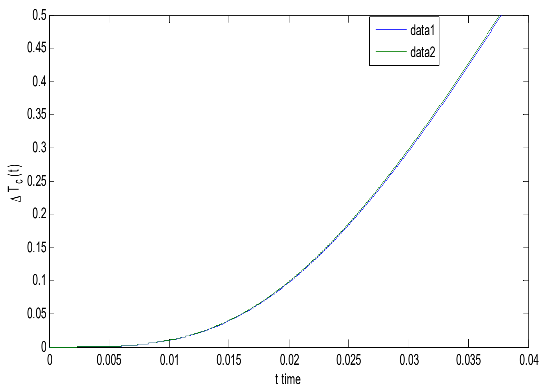

Fig. 8. Graphs of temperature drop distribution at the face of wellbore depending on the deformation factor of collector: 1) the case $\alpha_k = 0$, 2) the case $\alpha_k = 1$

As can be seen from the graph, negligible change of the deformation coefficient slightly affect the overfall temperature at the outlet of the collector (Fig. 8), during the exploitation of the oil reservoir.

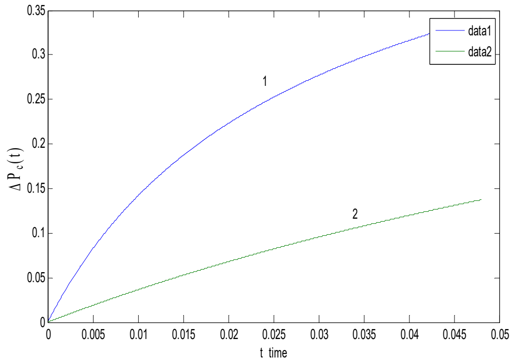

Fig. 9. Graphs of pressure drop distribution at the face of wellbore depending on the coefficient of impact of the wellbore volume: 1 – the case $C = 0$; 2 – the case $C = 1$

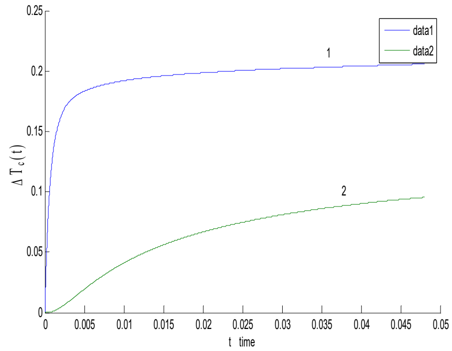

Fig. 10. Graphs of temperature drop distribution at the face of wellbore depending on the coefficient of impact of the wellbore volume: 1 – the case $C = 0$; 2– the case $C = 1$

Conclusions

- A hydro-thermodynamics model of the process of heat and mass transfer formed in the conditions of nonstationary filtration of a liquid in a porous medium layer with a fractured collector is proposed and a numerical solution algorithm is developed. The effect of the parameters included in the model on the process has been studied.
- Based on the results of the numerical calculations, it was found that the thermophysical and filtration-capacity parameters have different effects on the distribution of pressure and temperature field in the porous medium, which is important to consider in solving practical problems related to field development, including well thermometry.

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ЧИСЛЕННОЕ МОДЕЛИРОВАНИЕ ТЕРМОГИДРОДИНАМИЧЕСКИХ ПРОЦЕССОВ В ДЕФОРМИРОВАННОМ НЕФТЯНОМ ПЛАСТЕ

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Резюме. Многочисленные причины наличия запасов углеводородов, а также сложность процессов, связанных с их образованием и добычей, выдвигают на первый план необходимость использования комплексных научных подходов при рациональном выборе и разработке методов эксплуатации. Важнейшим направлением этих исследований является изучение массопереноса углеводородов и механизмов межфазного перехода с учетом изменения давления и температуры в пласте в условиях фильтрации многофазного флюида в пористой среде. В фундаментальных исследованиях по физико-математическому моделированию для прогноза полной разработки важно учитывать все особенности температурных аномалий при движении газожидкостных систем на месторождениях углеводородов с различными термобарическими условиями. В статье решается задача определить степень влияния температурных аномалий на распределение термогидродинамических полей при разработке нефтяной залежи деформируемым пластом. Предложен алгоритм численного решения и проведены многочисленные компьютерные эксперименты путем создания программного обеспечения. Оценивалось влияние удельной теплоемкости жидкости, коэффициента Джоула-Томсона, коэффициента влияния объема ствола скважины, абсолютной проницаемости, вязкости жидкости и деформационных свойств на процесс.
Ключевые слова: *тепломассообмен в пласте, деформируемый коллектор, фильтрация флюидов, метод конечных разностей, коэффициент Джоуля-Томсона*

DEFORMASİYA OLUNAN NEFT YATAQLARINDA TERMOHİDRODİNAMİK PROSESLƏRİN ƏDƏDİ MODELLƏŞDİRİLMƏSİ

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Xülasə. Karbohidrogen ehtiyatlarının mövcudluğunu təmin edən çoxsaylı səbəblər, həmçinin onların əmələgəlmə və çıxarılması ilə bağlı baş verən proseslərin mürəkkəbliyi işlənilmə üsullarının rasional olaraq seçilməsi və yaradılmasında kompleks elmi yanaşmaların zəruriliyini önə çəkir. Bu tədqiqatların ən vacib istiqaməti məsaməli mühitdə çoxfazalı fluidin süzülməsi şəraitində layda təzyiq və temperatur dəyişmələrini nəzərə almaqla karbohidrogenlərin kütlə mübadiləsini və fazalararası keçid mexanizmlərinin öyrənilməsindən ibarətdir.

Fiziki və riyazi modelləşmə üzrə aparılan fundamental tədqiqatlar isə müxtəlif səciyyəli termobarik şəraitə malik karbohidrogen yataqlarında qaz-maye sistemlərinin hərəkəti zamanı yaranan temperatur anomaliyalarının bütün xüsusiyyətlərinin tamlıqla işlənilmə göstəricilərinin proqnozunun təyini zamanı nəzərə alınması vacib və mühüm əhəmiyyətə malikdir. Məqalə bu qəbildən olan işlənilmə məsələsinin həllinə həsr olunduğundan mühüm aktuallıq kəsb edir.

Bu iş deformasiya olunan kollektorda neftin istismarı zamanı temperatur anomaliyalarının termodinamika sahələrinin paylanmasına təsir dərəcəsinin təyin edilməsi məsələsinə həsr edilmişdir. Ədədi həllin tapılması üçün alqoritm təklif edilmiş və proqram təminatının yaradılması yolu ilə çoxsaylı kompüter təcrübələri aparılmışdır. Mayenin xüsusi istilik tutumunun, Joul-Tomson əmsalının, quyu lüləsinin həcmi təsir əmsalının, mütləq keçiriciliyin, mayenin özlülüyünün və kollektorun deformasiya xassələrinin istismar prosesinə təsiri qiymətləndirilmişdir.
Açar sözlər: *layda kütlə-temperatur mübadiləsi, deformasiya olunan kollektor, flüidin süzülməsi, sonlu fərqlər üsulu, Joule-Tomson əmsalı*