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ACCUMULATION OF A LIGHT PETROLEUM PRODUCT LAYER ABOVE A WATER TABLE

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A physical experiment on the accumulation of a light petroleum product (LPP) layer in the capillary zone with following formation of a floating lens on the water table (WT) was carried out. The procedure was developed and justified experimentally to calculate the thickness and the location of a LPP layer in the capillary zone and on WT, the distribution and the volume of LPP from the measurements of LPP levels in the observation well. The thickness and the location of a LPP layer on WT, contents of water and LPP were calculated based on Lenhard and Parker (1987, 1988) and van Genuchten (1980).

Key words: light petroleum product layer, water table, capillary zone, physical experiment, calculations.

НАКОПИЧЕННЯ ШАРУ ЛЕГКИХ НАФТОПРОДУКТІВ НАД РІВНЕМ ҐРУНТОВИХ ВОД

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Виконаний фізичний експеримент з дослідження накопичення шару легких нафтопродуктів (ЛНП) у капілярній зоні з подальшим формуванням плаваючої лінзи на рівні ґрунтових вод (РГВ). Розроблена та експериментально підтверджена методика розрахунку потужності та локалізації шару ЛНП у капілярній зоні та на РГВ, розподілу та об'єму ЛНП за даними вимірів у спостережних свердловинах. Потужність та локалізація шару ЛНП на РГВ, вміст води та ЛНП розраховані на підставі робіт Lenhard and Parker (1987, 1988) та van Genuchten (1980).

Ключові слова: шар легких нафтопродуктів, РГВ, капілярна зона, фізичний експеримент, розрахунки.

НАКОПЛЕНИЯ СЛОЯ ЛЕГКИХ НЕФТЕПРОДУКТОВ НАД УРОВНЕМ ГРУНТОВЫХ ВОД

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Выполнен физический эксперимент по изучению накопления слоя легких нефтепродуктов (ЛНП) в капиллярной зоне с последующим формированием плавающей линзы на уровне грунтовых вод (УГВ). Разработана и экспериментально подтверджена методика расчета мощности и положения слоя ЛНП в капиллярной зоне и на УГВ, распределения и объема ЛНП по данным замеров в наблюдательных скважинах. Мощность и положение слоя ЛНП на УГВ, содержание воды и ЛНП рассчитаны на основании работ Lenhard and Parker (1987, 1988) и van Genuchten (1980).

Ключевые слова: слой легких нефтепродуктов, УГВ, капиллярная зона, физический эксперимент, расчеты.

Introduction

LPPs released to the subsurface environment move down through the unsaturated zone, accumulate in the capillary zone and descend on WT forming a floating lens. Both LPP levels and the thickness of a mobile LPP layer observed in wells do not correspond to the true levels and thickness within the surrounding porous medium. A number of papers [Blake, Hall, 1984; CONCAVE..., 1979; Hall et al., 1984] studied a LPP layer on WT to found correcting coefficients to determine a true LPP layer thickness in soil (T) using an apparent thickness in an observation well (T^w). Laboratory experiments [Hampton and Miller, 1990] showed that in fact there is no calculating coefficient between LPP thickness in sand and in the well. T.P. Ballestero [Ballestero et al., 1994] obtained the relationship between T and T^w for the capillary zone when the weight of a single LPP column $\rho_o g T < 2\sigma_{ao}\cos\varphi/r_{max}$ (ρ_o is LPP density, g is gravitational acceleration, σ_{ao} is surface tension at an air–LPP (a–o) boundary, φ is a wetting angle, and r_{max} is a maximum pore radius):

$$T = (1 - \gamma_o)T^w - h_a, \quad (1)$$

where $\gamma_o = \rho_o/\rho_w$ is specific gravity; ρ_w is water density; h_a is a distance between the bottom of a LPP layer and WT corresponding to an active capillary height (it is not indicated there how to receive it).

This equation has two unknown variables, therefore only the sum ($T + h_a$) can be determined. Moreover, it is not known how to determine the location of a mobile LPP layer (either in the capillary zone or on WT) using the values of T^w.

A.M. Farr [Farr et al., 1990] and R.J. Lenhard and J.C. Parker [Lenhard, Parker, 1990] described the distribution of LPP in the formation during the accumulation of LPP above the water-saturated zone using oil-air and oil-water interfaces in the monitoring well under the equilibrium state. However, it was not mentioned about a zone from which LPP can flow into a well, i.e. a zone called “true thickness” by previous researchers. It is necessary to determine the size of “true thickness” and the quantity of contained LPP to plan the methods of pumping and the volume of mobile LPP that can be withdrawn.

The purpose of this research was to carry out an experiment on simulation of the formation of a kerosene layer above WT. The results of this experiment were used to justify the procedures for calculations of LPP thickness, distribution and volume at different stages of the accumulation of a kerosene lens.

Experimental materials

In order to study the formation of a LPP lens above WT and represent this process by a well, we carried out the experiment in a plexiglas column (Fig. 1) installed in a pan and filled with sand. A diameter of grains was less than 0.5 mm and porosity was 0.376.

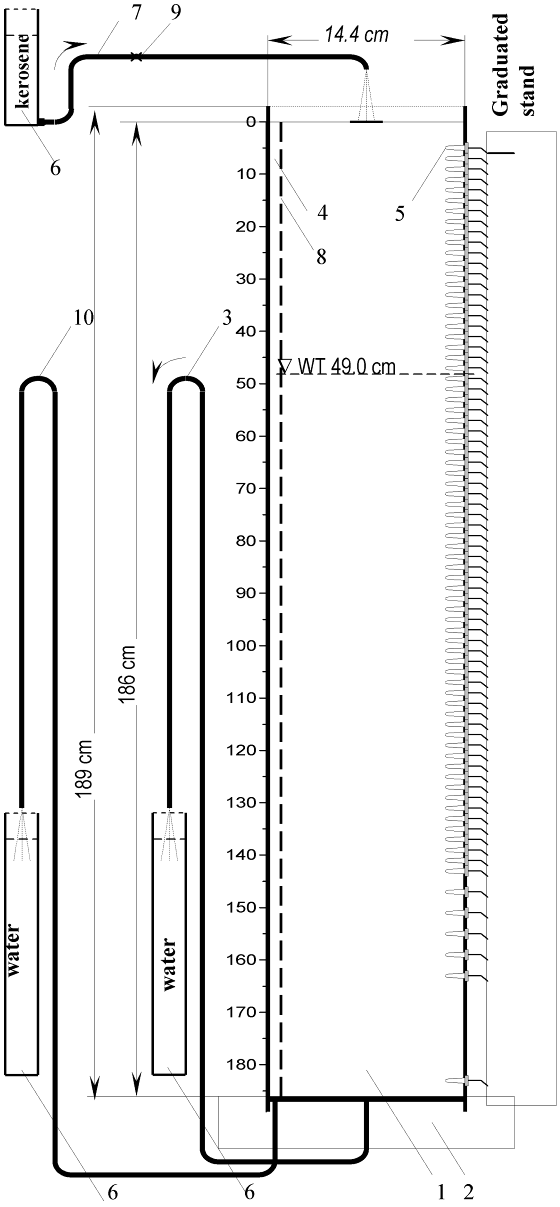

Fig. 1. The equipment for studying of kerosene layer accumulation in sand and its representation by the observation well

1 – a plexiglass column filled with sand; 2 – a plexiglass pan; 3 – a branch line for keep of a column water level; 4 – an observation well; 5 – piezometers; 6 – measuring vessels; 7 – a tube for kerosene input; 8 – a filter; 9 – a tap; 10 – a branch line to specify a boundary condition in the well

Movement of mobile kerosene levels, i.e. H_{ao} (air–LPP) and H_{ow} (LPP–water) in sand along the column was registered by kerosene appearance in piezometers (5) installed into the wall of the column in every two centimeters in the range of level move. An aluminium perforated gauze corner stuck to the wall of the column represented an observation well (4). Location of levels in the well (H_{ao}^{w}, H_{ow}^{w}) was determined visually through the transparent wall of the column by a measuring bar stuck nearby. The initial water level in the column was specified at a 49-cm depth that was considered to be WT. At this level the return tubes imitating boundary conditions were installed from the column (3) and the well (10). It was considered the measured water volume flowing out from the tube during kerosene input on a sand surface represented a relationship between water in the column and the aquifer.

Infiltrating through the unsaturated zone, kerosene wetted pores in which the a-w interface was replaced with the o—w interface with a much less surface tension. This resulted in decrease of the capillary water height in pores wetted with kerosene and the water output from the column was observed.

The accumulation of kerosene started at the elevation $h_{a}^{max} = h_{d}^{ow}$ above WT [Brooks and Corey, 1964], which corresponded to the head of water displacement into kerosene until interfacial tension (σ_{o-w}) held the weight of the kerosene column, T_c. The level H_{ao} rose in the capillary zone filling free pores while the bottom of the mobile kerosene layer (H_T) descended displacing water from capillaries with a radius $r > \frac{2\sigma_{ao}}{T_c g \rho_o}$ until it reached WT, then $T_c = T_c^{max}$. After this, we observed the accumulation of the kerosene layer under WT for ten days. Fig. 2 demonstrates changes of water and kerosene levels in the well and in the column (a) during the input of kerosene volume, V_o and the output of water volume, V_w (b).

A difference between kerosene thickness in the column (T) and in the well (T^W) was maximal when the kerosene layer accumulated in the capillary zone. As the kerosene layer reached WT, the difference decreased. Below WT the difference $(T^W - T)_{av}$ fluctuated about 50.9 cm due to atmosphere pressure changes with the value of correlation coefficient 0.84 and the displacement on one day (Fig. 2, c).

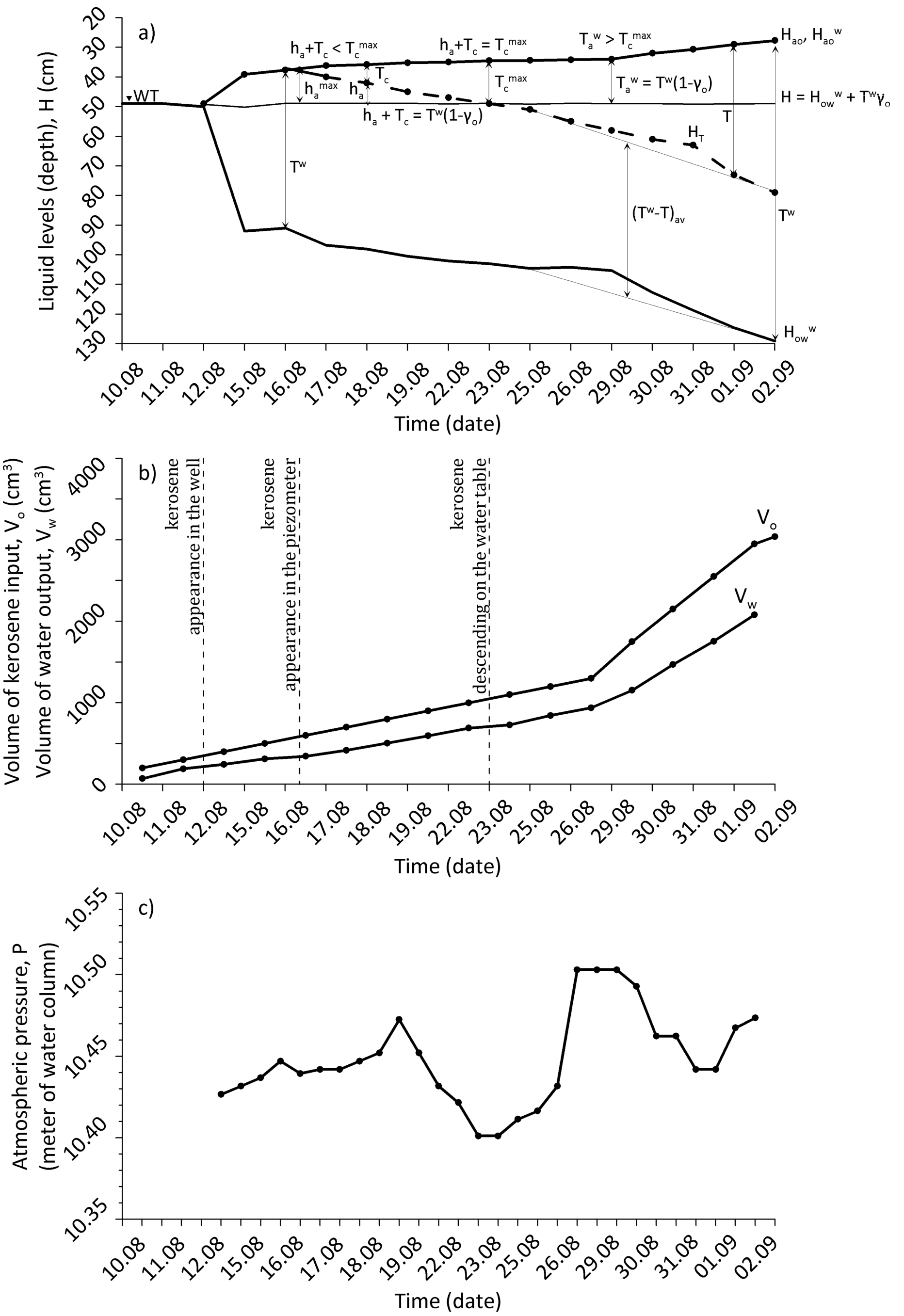

Fig. 2. Changes of water and kerosene levels in the well and in the column filled with sand (a) during kerosene input and water output (b) in correlation to atmospheric pressure (c)

In the field, if the accumulation of a mobile LPP layer discontinues in the capillary zone due to a small leakage, LPP levels and thickness in a well do not provide correct information about the location of a LPP layer and LPP levels. Therefore, calculations of distribution of LPP contents in the formation under such conditions by A.M. Farr [Farr et al., 1990] and R.J. Lenhard and J.C. Parker [Lenhard, Parker, 1990] seem to be noncompletely correct.

For correct interpretation of monitoring data, it is necessary to determine the location and thickness of the mobile LPP layer in the capillary zone or on WT, which will be described in the next section. Proposed calculations are verified with experimental data.

Calculations of LPP layer location, thickness, and LPP content

As we can see in Fig. 2, the location of the LPP layer is in the capillary zone for $T_c + h_a < T_c^{max}$. In case of $T_c + h_a = T_c^{max}$, the LPP layer reaches WT. If the o–w interface locates below WT, the following condition takes place: $T_a^w > T_c^{max}$, where T_a^w is a part of LPP layer thickness in the well above a piezometric surface (H).

Based on (1) and J.P. Hughes [Hughes et al., 1998], we have the following:

$$T_c + h_a = T_a^w = T^w(1-\gamma_o). \qquad (2)$$

T_c^{max} stipulates on LPP thickness, which makes a pressure h_d^{ow} i.e.:

$$T_c^{max} = \frac{h_a^{max}}{\gamma_o} = \frac{h_d^{ow}}{\gamma_o}. \qquad (3)$$

In this experiment $h_a^{max} = h_d^{ow} = 11.4$ cm. Then, according to (3) when $\gamma_o = 0.790$ and $h_a^{max} = 11.4$ cm, $T_c^{max} = 11.4$ cm, which corresponds to the measured value.

In the process of kerosene movement through the capillary zone the magnitude ($T_c + h_a$) changes from $h_a^{max} = h_d^{ow}$ at $T_c = 0$ up to $T_c^{max} = \dfrac{h_d^{ow}}{\gamma_o}$ at $h_a = 0$. Therefore, the magnitude ($T_c + h_a$) changes in direct proportion to:

$$T_c + h_a = \frac{h_a^{max} - h_a}{\gamma_o} + h_a, \qquad (4)$$

$$T_c + h_a = \frac{h_d^{ow}}{\gamma_o} - \frac{h_a}{\gamma_o} + h_a = \frac{h_d^{ow}}{\gamma_o} - h_a\frac{(1-\gamma_o)}{\gamma_o}$$

or

$$\gamma_o(T_c + h_a) = h_d^{ow} - h_a(1-\gamma_o). \qquad (5)$$

Based on (5), the value h_a could be determined as:

$$h_a = \frac{h_d^{ow} - \gamma_o(T_c + h_a)}{1-\gamma_o}. \qquad (6)$$

The magnitude ($T_c + h_a$) is determined by (2), and

$$T_c = (T_c + h_a) - h_a. \qquad (7)$$

The calculated values of T_c differed from the values measured experimentally for 0.35-0.75 cm. We consider that it is sufficient accuracy in case of installation of piezometers in every two cm within the column.

In the process of kerosene movement through the water capillary zone the following zones are formed (Fig. 3): (1) air – water (a–w) unsaturated zone with residual LPP; (2) air – LPP – water (a–o–w) unsaturated zone; (3) saturated zone with a mobile LPP (o–w); (4) water (w) capillary zone.

In the upper zone (1) LPP locates as individual drops and films remained after LPP infiltration. A LPP content ($\theta_{o,r}$) determined by laboratory measurements at the "Mikran" devise was 0.016.

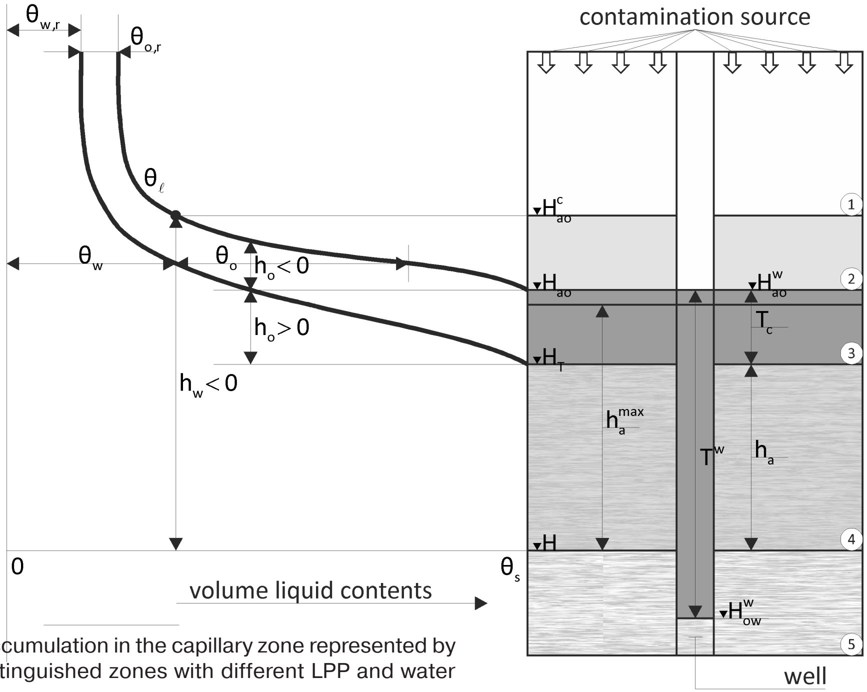

Fig. 3. LPP accumulation in the capillary zone represented by a well and distinguished zones with different LPP and water contents and pressure

The unsaturated zone (2) is formed above the level H_{ao}. The height of this zone reaches a level where capillary pressures h_{aw} and h_{ow} coincide. The capillary pressures are calculated as a difference of the heads of water (h_w), LPP (h_o) and air (h_a) in the point *z*.

$$h_a = 0;\ h_o = \frac{(z - H_{ao})\rho_o}{\rho_w};\ h_w = z - H; \qquad (8)$$
$$H = H_{ow}^{w} + \gamma_o T_w,$$

$$h_{aw} = h_a - h_w;\ \ h_{ao} = h_a - h_o;\ h_{ow} = h_o - h_w. \qquad (9)$$

Water (θ_w) and LPP (θ_o) contents were determined using van Genuchten function (VG) according to [Lenhard, Parker, 1987; Lenhard, Parker, 1988]:

$$\theta_l = \theta_{w+o} = \theta_o^{ao}(h_{ao}) =$$
$$= [1 + (\alpha_{ao} h_{ao})^{\varepsilon}]^{-m}(\theta_s - \theta_{r,w}) + \theta_{r,w}, \qquad (10)$$

$$\theta_w = \theta_w^{ow}(h_{ow}) =$$
$$= [1 + (\alpha_{ow} h_{ow})^{\varepsilon}]^{-m}(\theta_s - \theta_{r,w}) + \theta_{r,w}, \qquad (11)$$

$$\theta_o = \theta_{w+o} - \theta_w, \qquad (12)$$

where θ_s is total actual saturation, $\theta_{r,w}$ is irreducible saturation, a and e are affecting factors of pore-size distribution, $m = 1 - \frac{1}{\varepsilon}$.

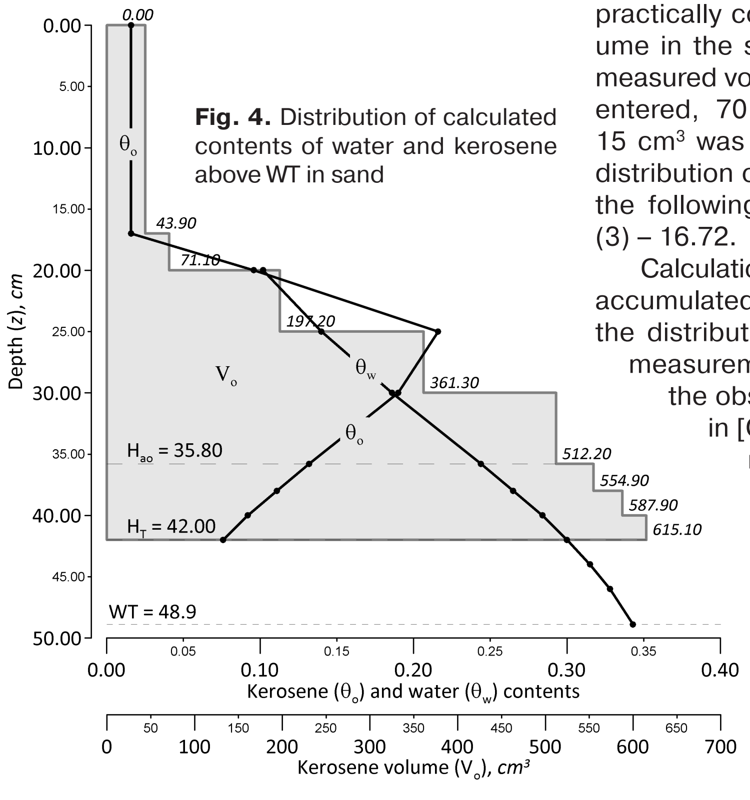

Fig. 4. Distribution of calculated contents of water and kerosene above WT in sand

In order to estimate the parameters of VG function, α and ε, we fitted the experimentally measured magnitude $\theta_w - h_{aw}$ to VG function in the main drainage path for experimental sand. We obtained the following values: $\alpha_{aw} = 0.0287$ 1/cm and $\varepsilon = 7.4552$. The values, α_{ow} and α_{aw} required for calculations were found from the relation: $\alpha_{aw}\ \sigma_{aw} = \alpha_{ow}\sigma_{ow} = \alpha_{ao}\ \sigma_{ao}$ [Lenhard, Parker, 1987]. The values, α_{ow} = 0.072 1/cm and α_{ao} = 0.0812 1/cm were obtained at σ_{aw} = 69.5 din/cm, σ_{ao} = 24.55 din/cm and σ_{ow} = 27.7 din/cm.

In the saturated zone (3) $\theta_{w+o} = \theta_s$, so

$$\theta_o = \theta_s - \theta_w. \qquad (13)$$

LPP and water volumes were calculated for every interval $\Delta z = z_{i+1} - z$:

$$V_{o,\Delta z} = \frac{\theta_{o,i} + \theta_{o,i+1}}{2}\Delta z F;\ V_{w,\Delta z} = \frac{\theta_{w,i} + \theta_{w,i+1}}{2}\Delta z F, \qquad (14)$$

where *F* is the area of the column.

The distribution of calculated kerosene and water contents and volumes in sand during the accumulation of a mobile kerosene layer in the capillary zone in the interval H_{ao} = 35.8 cm – H_T = 42.0 cm is shown in Fig. 4.

The total LPP volume within separate zones and in the column in whole was determined by summing $V_{o,\Delta z}$ and was 615.1 cm³, which practically corresponds to the kerosene volume in the sandy column calculated by the measured volumes (700 cm³ of kerosene was entered, 70 cm³ was drained in the well and 15 cm³ was drained with piezometers). The distribution of kerosene within the zones was the following (%): (1) – 7.14; (2) – 76.14; (3) – 16.72.

Calculations of the thickness of mobile LPP accumulated on WT in the sandy column and the distribution of kerosene content by the measurements of LPP and water levels in the observation well justified the theory in [Огняник и др., 2006] and [Парамонова, 2003] based on [Hughes et al., 1988; Lenhard, Parker, 1987; Lenhard, Parker, 1988; Van Genuchten, 1988]. Calculations were carried out in 10 day after kerosene descending on WT by the equation:

$$T = T^w - \frac{h_d^{ao}}{1 - \gamma_o}, \qquad (15)$$

where $\gamma_o = \rho_o/\rho_w = 0.79$, $h_d^{ao} = 10.5$ cm is the head of kerosene displacement into air. At the value measured experimentally, $T^w = 101.3$ cm (Fig. 2), $T = 51.3$ cm, which corresponds to the experimental value. Distribution and volumes of LPP and water contents were calculated using equations (10-14). A difference between the calculated kerosene volume in the column and the true kerosene volume is 8.7%. Kerosene distributed along the column in the following way (%): (1) – 0.7; (2) – 26.2; (3) – 71.8; (4) – 1.3.

Conclusions

The accumulation of LPP above WT including the capillary zone was studied experimentally. Based on the results of the physical experiment, we proposed the procedure for calculations of the location, thickness of a mobile LPP layer, and volume and distribution of LPP and water in depth by the measurements of LPP levels in the observation well.

1. H_{ao}^w and H_{ow}^w are measured in the well; $T^w = H_{ao}^w - H_{ow}^w$ and $H = H_{ow}^w + \gamma_o T^w$ are calculated.

2. T_c^{max} is determined by the equation (3).

3. $T_c + h_a$ is determined by the equation (2). If $T_c + h_a < T_c^{max}$, a LPP layer is above WT in the capillary zone.

4. The value of h_a is calculated by the equation (6).

5. The value of T_c is calculated by the equation (7).

6. $H_T = H + h_a$, $H_{ao} = H_T + T_c$.

7. Capillary heads are calculated by the equations (8) and (9); water and LPP contents are calculated by the equations (10-12), water and LPP volumes are calculated by the equation (14).

If $T_c + h_a = T_c^{max}$, a LPP layer reaches WT: $h_a = 0$, $T_c = T_c^{max}$, $H_{ao} = H + T_c^{max}$.

If $T_c + h_a > T_c^{max}$, a LPP layer lies on WT: $T^w = H_{ao}^w - H_{ow}^w$, T is determined by the equation (15). $H_{ao}^w = H_{ow}^w$, $H_{ow} = H_{ao} - T$, capillary heads, water and LPP contents and volumes are calculated according to the 7 item. It is necessary for calculations: $\gamma_o = \dfrac{\rho_o}{\rho_w}$, α_{aw}, α_{ao}, α_{ow}, h_d^{ow}, according to [Lenhard, Parker, 1988], ε_{aw}, ε_{ao}, ε_{ow}, or α_{aw}, ε_{aw} and σ_{aw}, σ_{ao}, σ_{ow}.

The calculated LPP volume was revised by means of the total kerosene volume in the column determined as the balance of kerosene input and output. It would be more effective to measure distribution of kerosene along the column but it was rather difficult due to the deficiency of the equipment to measure the LPP content without disturbance of porous media.

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