Detection and Maintenance of Optimum Dynamic Fluid Level in Oil Well

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Abstract*: *This article discusses automation of oil wells equipped with sucker–rod pump assemblies. The control method of such assembly is proposed where variation of dynamic fluid level is selected as controllable parameter, the appropriate information can be obtained by mathematic processing of wattmeter graph signal. Simulation results are presented which confirm operability and efficiency of the proposed method of detection and maintenance of optimum dynamic fluid level.

Keywords*: *sucker–rod pump, dynamic fluid level, control system, wattmeter graph, algorithm.

I. INTRODUCTION

Nowadays petroleum extraction industry has reached such stage of its development when the reserves of light crude oils are depleted and exhausted, thus, it is required not only to develop deposits with unconventional hydrocarbons but also to resume operation of previously suspended wells with exhausted reserves and shutdown due to low economic efficiency. Research devoted to development of control systems of oil extraction units allowing to pump off well fluid from marginal wells with high efficiency is very urgent [1].

II. LITERATURE REVIEW

Sucker–rod pump is the most popular type of equipment (Fig. 1) applied for oil extraction from marginal wells and wells with various complications, more than 70% of Russian wells are equipped with such assemblies.

The main task of control systems of sucker–rod pump assemblies is to adjust pump rate. The existing rate adjustment methods can be conventionally subdivided into three groups: those based on pressure stabilization at pump inlet; those based on stabilization of dynamic fluid level in oil well annular space; and those based on stabilization of amount of extracted fluid [2].

The performed review of relevant publications has demonstrated that the most popular are the control systems based on stabilization of dynamic fluid level [3–5].

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One of the methods to detect dynamic fluid level in oil well is depth sounding of annular space, that is, measurement of depth by transit time of sound wave [6]. This method is the main in oil extraction industry, however, it is characterized by certain disadvantages. Firstly, in the case of insufficient pressure in oil well for level detection, it is required to release annular gas into atmosphere. Secondly, the speed of propagation of sound wave depends on composition of petroleum gas, temperature and pressure, which exerts influence on measurement accuracy [7–9]. Detailed comparison of depth sounding with other measurement methods of dynamic fluid level (dynamometry, wattmetry, and others.) is given in [10]. The existing detection methods of fluid level are expensive or require for complex mathematical models based on accurate measurements and numerous time variables of well and equipment.

III. METHODS

A. Block Diagram

At present sensorless control systems of sucker–rod pump assemblies (SRPA) become more and more popular, they can adjust pump rate only on the basis of mathematical processing of signal of power consumption by SRPA drive. Such systems are more reliable and user friendly since they do not require for calibration and maintenance of numerous sensors of physical properties [11, 12]. Thus, nowadays it is important to study the methods of automatic adjustment of fluid level in oil well annular space on the basis of mathematical processing of wattmeter graph signal [5, 13, 14].

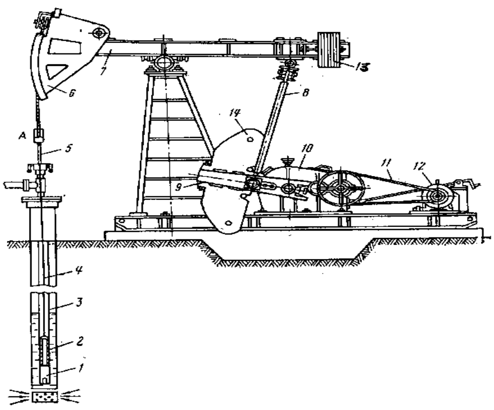


Fig. 1: Sucker–rod pump assembly with conventional pumping unit: 1 – sucker–rod pump; 2 – plunger; 3 – sucker–rod string; 4 – string; 5 – wellhead stem; 6 – horsehead; 7 – beam; 8 – rocker; 9 – crank; 10 – reducer; 11 – V–belt drive; 12 – electric motor; 13 – counterbalance; 14 – crank counterbalance.

Disadvantage of application of signal of power consumption as a feedback signal of control system is the impossibility of numerical measurement of dynamic fluid level in oil well annular space without complex mathematical models of control object, which prevents adjustment on the basis of preset dynamic fluid level. However, the signal of power consumption (wattmeter graph) is interrelated with load variation in SRPA. Increase in dynamic fluid level leads to decrease in pressure at pump inlet and respective load increase in the system and, hence, in power consumption, that is, it is possible to develop control method on the basis of reaction of control object (variation of power consumption caused by variation of dynamic fluid level) to variation of control action (pumping rate of oil well fluid).

B. Algorithm

In order to derive laws and control algorithms aimed at detection and maintenance of optimum dynamic fluid level, it is required to formulate a set of tasks which should be performed by control system during its operation.

At initial time the oil well is stopped, fluid inflow is zero due to equalization of reservoir and bottom hole pressures, the fluid level equals to statistic level, that is, the closest to well mouth position. The primary task is to initiate pumping mode of the well, that is, searching for optimum position of dynamic fluid level, as well as coordination of seam fluid inflow rate with pumping rate. When this mode is achieved, it is required to stabilize the selected position of dynamic fluid level during all operation interval of the assembly, therefore, while using the decomposition principle of automatic control systems, it is possible to subdivide the method of detection and maintenance of optimum dynamic fluid level equipped with sucker–rod pump into the stages solving the following problems [15]:

1. Detection of dynamic fluid level providing maximum inflow rate at maximum coefficient of filling of sucker–rod pump cylinder.
2. Selection of pumping rate corresponding to inflow rate of oil well fluid.
3. Stabilization of position of dynamic fluid level.

The only parameters entered by operator into the control system are as follows: the variation range of SRPA beam oscillation frequency and the ratio of V-belt and reducer. On the basis of these parameters, the respective range of motor shaft rotation frequency is predicted [fmin, fmax], which comprises control action for this system.

With the increase in dynamic fluid level, the bottom hole pressure decreases, which leads to increase in abnormally low reservoir pressure and, hence, to increase in inflow rate of well fluid [16, 17]. However, when the dynamic fluid level reaches sucker–rod pump inlet, the amount of gas in fluid increases negatively effecting the coefficient of pump filling due to ingression of high amount of gas into pump cylinder [18, 19]. Therefore, the optimum position of dynamic fluid level in this case is that when maximum inflow rate of oil well fluid is provided at minimum gas ingression into pump cylinder.

Detection of optimum dynamic fluid level providing maximum inflow rate is based on setting current motor shaft rotation frequency fc=fmax corresponding to maximum beam oscillation frequency, hence, to maximum pumping rate of oil well fluid with subsequent measurement of average power consumption W during the time T. Increase in dynamic fluid level is accompanied by increase in power consumption. Nonfilling of pump cylinder as a consequence of gas influence either leads to its decrease (Fig.2) and occurrence of bending point A in the curve or to characteristic curvature of wattmeter graph (Fig. 3).

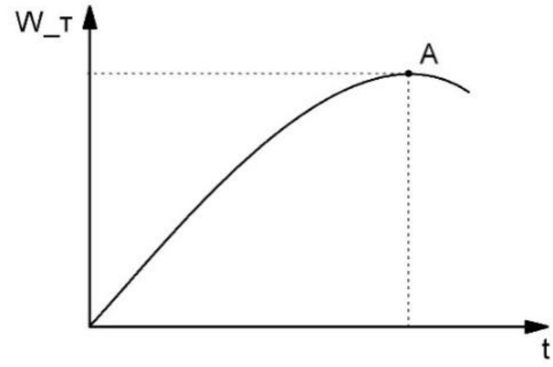


Fig. 2: Drive power consumption as a function of time upon gradual increase in dynamic fluid level to pump suction.

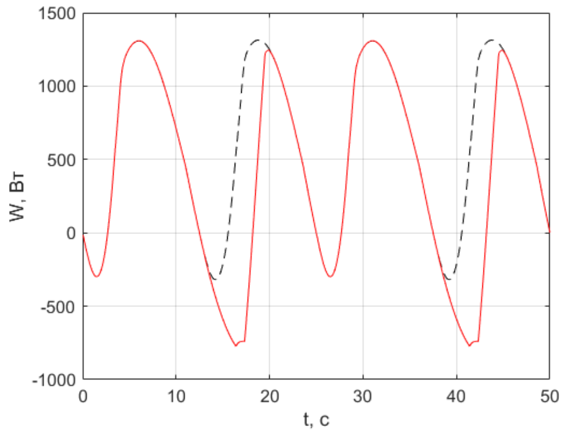


Fig. 3: Variation of wattmeter graph (dashed line: complete filling of sucker–rod pump cylinder; solid line: 70% filling of pump cylinder).

When one of the mentioned features occurs, according to the proposed method, the control system transfers to the second stage of searching for optimum dynamic fluid level: detection of pumping rate of oil well fluid equaling to well fluid inflow rate at determined dynamic fluid level. The pumping rate is adjusted by variation of motor shaft rotation frequency.

Near the optimum point (point A, Fig. 2), the shape of wattmeter graph bends, that is, it is possible to interpret erroneously variation of its signal, hence, it is necessary to decrease the dynamic fluid level to a certain level allowing to adjust the pumping rate with full cylinder. With this aim, the current shaft motor rotation frequency is decreased to minimum fc=fmin. Fluid is accumulated in oil well annular space. Then, according to the proposed method, the well fluid pumping rate is selected using dichotomy. The algorithm of rate selection is illustrated in Fig. 4.

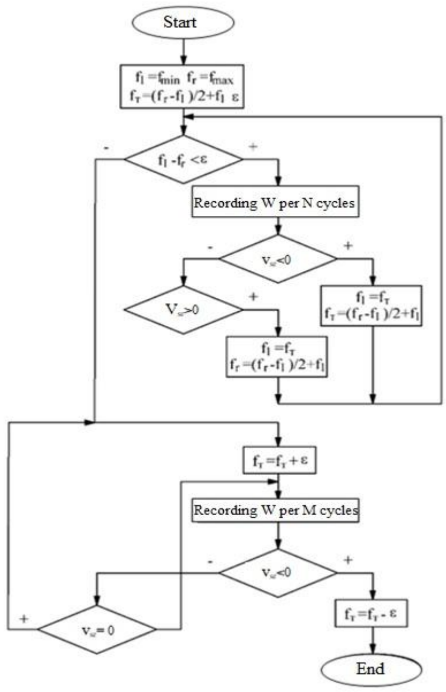


Fig. 4. Selection of pumping rate of well fluid: [fl, fr] – interval boundaries of searching for motor shaft rotation frequency, [fmin, fmax] – minimum and maximum motor shaft rotation frequency, ε – error of detection of motor shaft rotation rate, fc – current motor shaft rotation frequency, W – average power consumption during T period.

Initial boundaries of interval of motor shaft rotation frequency are preset [fl= fmin, fr= fmax] as well as current rotation frequency equaling to one half of the preset interval fc= (fr – fl)/2+ fl. The error of frequency determination is introduced ε. Then the fluid is pumped at selected rate during several cycles N together with simultaneous recording of average power consumption W. After expiration of N cycles, the variation rate of average power υavg is calculated with subsequent variation of boundaries of searching interval and current shaft rotation frequency. If the variation rate of power is lower than zero υavg<0, then, the power consumption by the assembly decreases, which evidences decrease in dynamic fluid level, hence, the current fluid pumping rate is lower than its inflow rate, thus, the interval boundaries of searching for motor shaft rotation frequency and its current value vary as follows:

[fl =fc, fr], fc= (fr – fl)/2+ fl;

If the variation rate of power is higher than zero υavg>0, then, the power consumption by the assembly increases, which evidences increase in dynamic fluid level, hence, the current fluid pumping rate is higher than its inflow rate, thus, the interval boundaries of searching for motor shaft rotation frequency and its current value vary as follows:

[fl, fr=fc], fc= (fr – fl)/2+ fl;

If the variation rate of average power consumption during the time T is zero υavg =0 or the interval range of searching for frequency is lower than the error (fl– fr)<ε, the required rate is assumed to be determined, and the algorithm of searching for well fluid pumping rate is terminated.

During selection of fluid pumping rate there occurs variation of dynamic fluid level, hence, insignificant variation of well fluid inflow rate. After termination of selection of well fluid pumping rate, the position of dynamic fluid level is somewhat lower than the optimum. Hence, it is required to obtain once more the optimum point of the system. With this aim, the current motor shaft rotation frequency is increased by the error fc= fc+ε. The average power consumption during the time T in several pumping cycles M is recorded with subsequent calculation of average power consumption υavg. Decrease in υavg rate to zero evidences equalization of reservoir and bottom hole pressures, and the system again increases the frequency fc= fc+ε. Drop of power increase rate υavg below zero or distortion of wattmeter graph characteristic for incomplete filling of pump cylinder shape evidence that the dynamic fluid level overrides the optimum point. The current motor shaft rotation frequency decreases fc= fc–ε, the well fluid pumping rate corresponding to this rotation frequency is considered to be optimum. The control system transfers to the third stage: stabilization of the selected position of dynamic fluid level for long time. At the selected well fluid pumping rate, the dynamic fluid level can vary as a consequence of well pressure variations, inflow rate, or its operation state. In the mode of stabilization of dynamic fluid level, in oil well annular space the average power consumption for the time T in M cycles is recorded with subsequent calculation of power variation rate υavg. If power consumption decreases in time, the pumping rate is increased fc= fc+ε. When the pump nonfilling due to gas ingression into pump cylinder becomes evident, the well fluid pumping rate is lowered fc= fc–ε.

Therefore, all three stages comprise the method of adjustment of sucker–rod pump rate facilitating detection of optimum fluid pumping parameters and automatic maintenance of operation mode of the system.

IV. RESULTS AND DISCUSSION

The proposed algorithm was verified by mathematical model of SRPA (Fig.5), developed in MATLAB/Simulink environment. Pumping rate of well fluid was varied by variation of motor shaft rotation rate.

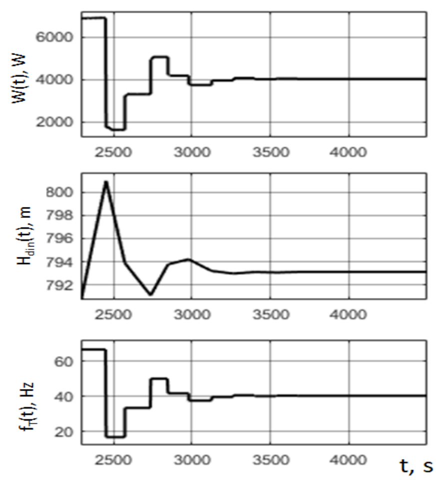
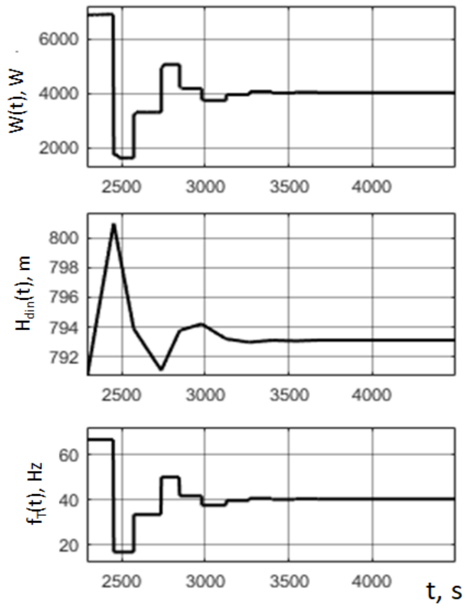


Fig. 5. SRPA model comprised of blocks describing SRPA units: mathematical models of oil well (Oil Well), sucker–rod pump, conventional pumping unit, electric motor (Asynchronous Motor).

Fig. 6. illustrates average power consumption W_t, dynamic fluid level, and motor shaft rotation frequency as a function of time obtained during testing the developed algorithm.

At initial time, the fluid pumping is performed from the depth of 600 m. For this model the optimum fluid level is 800 m, ε = 0.5 Hz, N = 20, M = 400. Control system is activated by pump nonfilling property at the level of 801 m, which corresponds to 95% of pump cylinder filling. At this time the system is switched to selection of pumping rate of well fluid (Fig. 6a), the time interval 2450–2566 s characterizes the interval of accumulation of well fluid. The established dynamic fluid level achieved after adjustment is 793 m. Figure 6b illustrates achievement of optimum dynamic fluid level. During frequency adjustment, the rotation frequency is increased twice by ε = 0.5 Hz with subsequent retiring the frequency by one step. The fixed motor shaft rotation frequency is 40.75 Hz. Total time of system adjustment to optimum level and pumping rate is about 11 h.



b)

Fig. 6. Average power consumption of SRPA per T time: W(t), dynamic fluid level Hdin(t) and motor shaft rotation frequency fc(t) as a function of time.

V. CONCLUSION

The developed method makes it possible to adjust dynamic fluid level on the basis of mathematical processing of wattmeter graph signal without necessity to implement complex mathematical models in control systems, thus permitting quick adjustment of the system for specific control object.

Herewith, well fluid is pumped off at maximum possible rate for specific well and SRPA at minimum harmful impact of gas dissolved in oil, thus permitting to achieve high daily well fluid level.

In addition, this method automatically maintains optimum operation mode of assembly without operator participation, thus allowing to improve automation level of oil extraction.

Operability of the method has been verified by SRPA mathematical model.

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