Algorithmic support of automatic yield control system of a gas well cluster

M U Prakhova, A N Krasnov and E A Khoroshavina

Ufa State Petroleum Technological University, 1, Kosmonavtov Street, Ufa, 450044, Russia

E-mail: prakhovamarina@yandex.ru

Abstract. Gas wells operation is associated with the problem of regulating their yield. Debit value must provide for meeting various criteria with some of them being mutually exclusive. Initial debit value is set under a deposit development project and then is adjusted periodically at best based on the results of quarterly hydrodynamic well exploration. However, in order to enhance operation yield of a gas well cluster debit regulation must be carried out in real time. This problem hasn't been solved yet. The article offers a yield control algorithm for a gas well cluster consisting of three separate units: yield enhancement, yield decreasing and yield distribution among wells. Transfer from one unit to another is carried out based on the results of measuring current gas consumption rate in wells and the pressure on isolation valve building’s plumes. The gap between the allowed values of well consumption (maximum and minimum) is identified on the basis of the research of a well's operation. Algorithm approbation was carried out in a program package for simulation, design and analysis of the operation of above-ground infrastructure and PipeSim pipeline system. The results confirmed the feasibility of the proposed algorithm and the possibility of managing operation regime of every well independently.

1. Introduction

The majority of gas and gas-condensate deposits in the Russian Federation are situated in the regions of the Far North. This makes it especially pertinent to introduce systems of automatic gas field control systems taking into account the harsh climate conditions. Automatic process control system of a gas field (GF) as a rule unite local systems of automatic control (ACS) of individual facilities, such as gas treatment plants (GTP), gas booster stations (GBS), etc. The development of an ACS for the yield of gas wells and the whole gas-collecting system is a rather complex and still unsolved problem. This is determined by the very complexity of the object of control.

A gas or gas-condensate well cluster is a group of wells (usually 3-10) situated in 10-100 meters one from the other and incorporated into one cluster collector with one pipe (plume) connecting it to the industrial gas collecting network (IGCN). The distance between clusters is usually between one and several kilometers.

The debit of each well depends on a significant number of factors: geological and industrial, technological and economic. [1] The identification of technological regimes of gas well operation is done for every well on an individual basis depending on the factors that are the most important for that particular well and on the demand for gas. The possibility of destroying the bottom-hole formation zone because of excessive removal of sand and rock bending materials in case of elevated debits are the main geological factors as well as the creating of water cones and the possibility of premature flooding of the
well. [2] The debit of a well also influences thermodynamic balance that if upset can lead to the formation of hydrates thus causing serious trouble during the operation of wells: their output is changed and the outflow of gas from wells stops because of hydrate jams, equipment frosting, etc. Technological factors are associated, firstly, with the desire to provide optimal conditions for industrial gas treatment (for example, to make pressure higher at the entry to the low temperature separator) or avoid stronger vibration of the flow head. Economic factors help to take into account the demand for gas as well as deposit-associated expenses. In summer gas consumption rate is lower which leads to reduced development by lowering the debit of wells with some of them being completely shut down for the summer. Real technological regime is set by the geological service every quarter or once in 6 months in accordance with the project data, research results and operation experience.

2. Relevance. Overview of existing solutions

Thus control over well output is a complex multi-aspect task that must take into account mutual influence of wells through the gas bearing formation. Optimization criteria for well debit distribution can be, for example, smoothing of non-dimensional coefficients in pressure loss in wells (in the bottom hole zone - well bore - positive choke system), in other words, debit is reduced in the well with the higher coefficient (within the geological norm), and the other way round, where the coefficient is smaller, the debit is increased. [3] This can be explained by the fact that increased coefficient of pressure loss shows (most likely) that the bottom-hole zone of a gas bearing well is flooded that is why the debit must be reduced (and consequently, bed depression in it) by increasing it in neighboring wells. Moreover, neighboring wells can partly take the excess of water from the flooded well.

Many research papers are dedicated to the problem of regulating gas wells, for example the works [4-8]. Yield control is analysed from the point of view of preventing liquid jams from forming and the subsequent reducing of debit and, in the end, well self-kill. [5] Lower well head parameters in comparison with the established value is the criteria that forms controlling impact. The elimination of a liquid column can be done by supplying compressed gas from the unit compressing plant to the casing string-borehole annulus. Gas is dispersed in the technological pipeline to the gas flashing device and the operation of the gas well cluster can be continued. Actually, both the unit compressing plant and gas dispersion to the gas flashing device are serious drawbacks of the offered solution.

The work [6] suggests using adaptive three term controllers of gas consumption that are connected to the wells and attached with its entry to the gas consumption sensors and with the exit to the well execution units. It must be pointed out that the term "adaptive" is considered in a quite narrow sense here. Adaptive regulator provides for the possibility of changing the parameters of the regulator and its structure depending on the changes in parameters of the object of control or external disturbances that impact it [9]. The system of adaptive automatic control of the gas well cluster yield analysed below provides for the system adaptation to the well operation conditions thanks to the tuning parameters adjustment algorithm of only one of three term controllers that is installed at the gas collector and does not affect controllers installed in wells. Thus, gas offtake by GTP changes, only controlling impact on the entries to all gas well three-term controllers becomes different in the system.

According to the patent [6], signals are transferred sequentially to the executive units of every well with a time lag that is necessary to complete all transition processes. Nevertheless, the proposed structure is a multi-connected control system, and it is highly likely that such consecutive signaling to executive units will lead to numerous iterations in the formation of control impact because of the mutual impact of well parameters.

3. Problem statement

The present article reviews the automatic control system of a gas well cluster yield that helps to avoid gas losses in the gas flashing device and control operation regime of every well on an individual basis.

4. Results and discussion

In order to implement the proposed algorithm ACS must include (Figure 1) temperature and pressure
converters, gas consumption sensor, motor-operated regulating valve, methanol supply system to the casing string-borehole annulus in front of the regulating valve and in the cluster's collector with a meter and methanol consumption regulator. In order to assess the hydrate formation conditions in well plumes after the pressure regulator and in gas collector there are surface gas temperature sensors. Collection and processing of initial information with programmed logical controller MOSCAD-M F4570B by Motorola.

Let us consider the algorithm using the example of a gas well cluster No. 11 GTP-1B of Zapolyarny oil, gas and condensate field (OGCF).

The algorithm allows the level of gas consumption in a gas well cluster that is necessary to support the required gas pressure at the entry to the switching valve building (SVB) through insignificant changes in the regulating valves position in the wells. If the algorithm is switched off, then regulators in wells must be left in the same position since their last adjustment.

In case of a fault in the gas consumption sensor in any of the wells or in the regulating valve (if after the completion of a algorithm cycles, the regulator that was influenced by the control impact and is not in the marginal position and does not change the position), the algorithm must be suspended and the operating staff informed.

The main task of the algorithm is to meet the following conditions:
1) pressure in the SVB plume must meet the preset technological minimum and maximum
   \[ P_{\min,SVB} < P < P_{\max,SVB} \]  
\[(1.1a)\]
2) gas consumption in a well must meet the required regulating gap in the well \( Q_{\text{reg},i}^{\min} \leq Q_i < Q_{\text{reg},i}^{\max} \)
   \[ Q_{\text{reg},i}^{\min} \leq Q_i < Q_{\text{reg},i}^{\max} \leq Q_i^{\max} \]  
\[(1.1b)\]

Unlike three term controllers regulation that is currently used, where settings adjustment is necessary, this algorithm does not require regulation range to be preset for every well \( Q_{\text{reg},i}^{\min} \ldots Q_{\text{reg},i}^{\max} \).

Regulation range presetting is done manually by an operator or is calculated automatically. If \( Q_{\text{reg},i}^{\min} \ldots Q_{\text{reg},i}^{\max} \), the operating staff checks if condition 1.1b is met as well as the condition:
\[ \Sigma Q_i^{\min} \leq \Sigma Q_{\text{reg},i}^{\min} \leq Q_{\text{GWC}} \leq \Sigma Q_{\text{reg},i}^{\max} < \Sigma Q_i^{\max}. \]  
\[(1.1c)\]

If the results are positive, then the preset \( Q_{\text{reg},i}^{\min} \ldots Q_{\text{reg},i}^{\max} \) are used in the consumption calculation algorithm, otherwise the data is not accepted by the GWC control system and the following message is produced.

With the calculation method \( Q_{\text{reg},i}^{\min} \ldots Q_{\text{reg},i}^{\max} \), they are calculated automatically after the GWC consumption task is changed \( Q_{\text{GWC}} \) or identified based on the GWC well settings adjustment:
\[ Q_{\text{per},i}^{\max} = (1 + \varepsilon) Q_{\text{p},i}; \]  
\[ Q_{\text{per},i}^{\min} = (1 - \varepsilon) Q_{\text{p},i}; \]  
\[ Q_i = 1 \% \text{ (by default).} \]

The algorithm uses the following parameters (Figure 1).

For every GWC (i - well number) the following parameters are preset:
- minimum and maximum allowed gas consumption per well \( Q_i^{\min}, Q_i^{\max} \);
- minimum and maximum regulation range \( Q_{\text{reg},i}^{\min}, Q_{\text{reg},i}^{\max} \) (is identified by settings adjustment unit);
- minimum and maximum allowed opening position of the regulating valve \( A_i^{\min}, A_i^{\max} \);
- consumption the hydrate regime \( Q_{\text{hyd}} \).

Measured parameters for every well (i - well number) and GWC:
- gas consumption per well \( Q_i \);
- gas pressure in a well \( P_i \);
- regulating valve position in a well \( A_i \);
- gas temperature in a well \( T_i \);
- gas pressure in GWC collector \( P_{\text{clus}} \).
Figure 1. Algorithmic support of automatic yield control system of a gas well cluster

Table 1. Dependence of the sphericity coefficient of lead inclusions and average sizes of bronze lead inclusions on the modifier concentration

| Designation | Parameter | Parameter characteristic |
|-------------|-----------|--------------------------|
| $Q_{cluster}$ | Necessary consumption | Preset |
| Q | Current gas consumption in a gas well cluster | Calculated |
| $C_{on, pl}$ | Required pressure on SVB plume | Preset |
| P | Current gas pressure on SVB plume | Measured |
| $Q_{GWC, min}$ | Minimal gas consumption per GWC | Preset |
| $Q_{svb, max}$ | Maximum gas consumption per GWC | Preset |
| $C_{on, min}$ | Minimal gas pressure on SVB plume | Preset |
| $P_{max}$ | Maximum pressure on SVB plume | Preset |

Moreover, in order for the algorithm to work, the following parameters and coefficients were preset:
- time lag to allow the next algorithm cycle $\Delta t_1$ и $\Delta t_2$;
- controlling impact on the regulating valve $\Delta A$;
- coefficients to preset relative consumption $a_1$, $a_2$, $a_3$.

Yield control algorithm (Figure 2) is divided into three main units:
- yield increase;
- yield decrease;
- distribution of consumption among wells.
After each unit has stopped working, the algorithm is launched anew (condition meeting check unit). If the necessary gas consumption rate is changed, operational ranges and weight coefficients are checked (if a weight function is used for the distribution). The regulators that have reached marginal minimum position \(A_i = A_i^{\text{min}}\), do not receive controlling impact to close; regulators that have reached marginal maximum position \(A_i = A_i^{\text{max}}\), do not receive controlling impact to open.

**Table 2. Step 1. Yield increase unit**

| Designation | Condition |
|-------------|-----------|
| 1.1         | If there are wells with consumption rate lower than the minimum preset one (for regulating range): \(Q_i < Q_{\text{reg},i}^{\text{min}}\), then proceed to Step 1.2. otherwise proceed to Step 1.4 |
| 1.2         | The well with the minimum current relative consumption is identified: \(\min(Q_i - Q_{\text{reg},i}^{\text{min}})/(Q_{\text{reg},i}^{\text{max}} - Q_{\text{reg},i}^{\text{min}})\) |
| 1.3         | The regulating valve in the well chosen at Step 1.2 receives a controlling impact to open by value of \(2\Delta A\) (if \(A_i + 2\Delta A > A_i^{\text{max}}\), then proceed to Step 1.2) \(A_i = A_i + 2\Delta A\) and a transition is made to the beginning of the algorithm |
| 1.4         | Wells are tested to check for meeting the following condition: \(\min(Q_i - Q_{\text{reg},i}^{\text{min}})/(Q_{\text{reg},i}^{\text{max}} - Q_{\text{reg},i}^{\text{min}})\) in other words the well with minimum relative consumption is identified |
| 1.5         | If in the well, identified at Step 1.4 the relative consumption is lower than 0.9 \((a1=0.9)\) \((Q_i - Q_{\text{reg},i}^{\text{min}})/(Q_{\text{reg},i}^{\text{max}} - Q_{\text{reg},i}^{\text{min}}) < 0.9\), then:  
  a) the regulating valve in the well received controlling impact to open by \(\Delta A\) \(A_i = A_i + \Delta A\) (if \(A_i + \Delta A > A_i^{\text{max}}\), then proceed to Step 1.4)  
  b) transition is made to the beginning of the algorithm.  
  Otherwise:  
  a) transition is made to Step 1.4 to choose the next well, if the testing is not complete;  
  b) if the testing of all the wells is complete, then a message is sent that it is impossible to increase the yield and the algorithm is suspended. |
The algorithm provides for shutting off any of the units. The transition between the units is carried out in the following way. The current gas consumption per wells and pressure in the SVB plumes is checked. If one of the following conditions is met:

- necessary consumption with GWC is higher than the current one
  \[ Q < Q^{\text{clus}}(1-\delta); \]  
  \( (\delta \text{ is calculated based on hydrodynamic well research}); \)  
- necessary pressure in a SVB plume is higher than the current one
  \[ P < P_{\text{min}}; \]  

A transition is made to the yield increase unit (step 1, Table 2).

If any of the following conditions are met:

- necessary consumption with GWC is lower than the current one
  \[ Q > Q^{\text{clus}}(1+\delta); \]  
- necessary pressure in a SVB plume is higher than the minimum preset one
  \[ P > P_{\text{max}}; \]  

A transition is made to the yield decrease unit (step 2, Table 3).

If the condition is met:

\[ P_{\text{min}} < P_{\text{pl}} < P_{\text{max}} \]  

A transition is made to the yield distribution unit (step 3, Table 4).

### Table 3. Step 2. Yield decrease unit

| Designation | Condition |
|-------------|-----------|
| 2.1         | If there are wells with consumption rate higher than the minimum preset one (for regulating range):  
\[ Q_i > Q_{\text{reg}_i}^{\text{max}}, \]  
then proceed to Step 2.2,  
otherwise proceed to Step 2.4 |
| 2.2         | The well with the maximum current consumption is identified:  
\[ \max (Q_i - Q_{\text{reg}_i}^{\text{max}})/(Q_{\text{reg}_i}^{\text{max}} - Q_{\text{reg}_i}^{\text{min}}) \]  
The regulating valve in the well chosen at Step 2.2 receives a controlling impact to open by value of \( 2\Delta A \) (if \( A_i - 2\Delta A < A_i^{\text{min}} \), then proceed to 2.2) \( A_i = A_i - 2\Delta A \) and a transition is made to the beginning of the algorithm |
| 2.3         | Wells are tested to check for meeting the following condition:  
\[ \max (Q_i - Q_{\text{reg}_i}^{\text{min}})/(Q_{\text{reg}_i}^{\text{max}} - Q_{\text{reg}_i}^{\text{min}}) \]  
in other words the well with maximum relative consumption is identified |
| 2.4         | If in the well, identified at Step 2.4 the relative consumption is bigger than 0.1 (\( a_2 = 0.1 \))  
\[ (Q_i - Q_{\text{reg}_i}^{\text{min}})/(Q_{\text{reg}_i}^{\text{max}} - Q_{\text{reg}_i}^{\text{min}}) > a_2, \]  
then:  
  a) the regulating valve in the well received controlling impact to open by \( \Delta A \), \( A_i = A_i - \Delta A \) (if \( A_i - \Delta A < A_i^{\text{min}} \), then proceed to Step 2.4)  
  b) transition is made to the beginning of the algorithm  
Otherwise:  
  a) transition is made to Step 2.4 to choose the next well, if the testing is not complete;  
  b) if the testing of all the wells is complete, then a message is sent that it is impossible to decrease the yield and the algorithm is suspended. |
Table 4. Step 3. Yield distribution unit

| Designation | Condition |
|-------------|-----------|
| 3.1         | If there are wells with consumption rate higher than the maximum preset one (for regulating range): \( Q_i > Q_{\text{reg},i}^{\text{max}} \), then proceed to Step 3.2., otherwise proceed to Step 3.3 |
| 3.2         | a) the well with the maximum current relative consumption is identified: \( \max \left( \frac{Q_i - Q_{\text{reg},i}^{\text{max}}}{Q_{\text{reg},i}^{\text{max}} - Q_{\text{reg},i}^{\text{min}}} \right) \); b) the regulating valve in the well received controlling impact to close by \( A_i \), \( A_i = A_i - \Delta A \) (if \( A_i - \Delta A < A_{i}^{\text{max}} \), then implement 3.2(a) c) otherwise proceed to Step 3.10 |
| 3.3         | If there are wells with consumption rate lower than the minimum preset one (for the regulating range): \( Q_i < Q_{\text{reg},i}^{\text{min}} \), then proceed to Step 3.4., otherwise proceed to Step 3.5 |
| 3.4         | a) the well with the minimum current relative consumption is identified: \( \min \left( \frac{Q_i - Q_{\text{reg},i}^{\text{min}}}{Q_{\text{reg},i}^{\text{max}} - Q_{\text{reg},i}^{\text{min}}} \right) \); a) the regulating valve in the well receives controlling impact to open by \( A_i \), \( A_i = A_i + \Delta A \) (if \( A_i + \Delta A > A_{i}^{\text{max}} \), then proceed to 3.4(a) c) otherwise proceed to Step 3.10 |
| 3.5         | If before the distribution algorithm, the yield increase unit was implemented, then proceed to Step 3.6, otherwise to Step 3.8. |
| 3.6         | a) identify the well with minimum consumption range (weak well): 1. identify the well \( \min \{Q_i^{\text{min}}\} \) 2. if for two wells \( Q_i^{\text{min}} = Q_j^{\text{min}} \), the the weaker one is that with the narrower range \( Q_i^{\text{max}} - Q_i^{\text{min}} \) 3. if the ranges are equal, then the weaker well is the one with the smaller current consumption b) of the current relative consumption for the chosen well is less than 0.9 (a1=0.9), that is when the following condition is met \( \left( \frac{Q_i - Q_i^{\text{min}}}{Q_i^{\text{max}} - Q_i^{\text{min}}} \right) < 0.9 \), then proceed to Step 3.7., otherwise Step 3.6. (a) (if the testing is not complete) - identify the next well according to the hierarchy (one that is stronger). |
| 3.7         | a) exercise controlling impact over the regulating valve in the well chosen at Step 3.6 \( A_i = A_i + \Delta A \) b) proceed to Step 3.10 |
Table 4. Ending

3.8 a) identify the well with maximum consumption range (strong well):
   1. identify the well $\text{max}\{Q_i\}$
   2. if for two wells $Q_i^{\text{max}}=Q_j^{\text{max}}$, the stronger one is that with the broader range $Q_i^{\text{max}}-Q_i^{\text{min}}$
   3. if the ranges are equal, then the stronger well is the one with the smaller current consumption
   b) of the current relative consumption for the chosen well is more than 0.1 ($a_1=0.1$), that is when the following condition is met
   $$(Q_i-Q_{\text{reg},i}^{\text{min}})/(Q_{\text{reg},i}^{\text{max}}-Q_{\text{reg},i}^{\text{min}}) > 0.1$$
   then proceed to Step 3.10,
   otherwise Step 3.8. (a) (if the testing is not complete) - identify the next well according to the hierarchy (one that is weaker).

3.9 a) exercise controlling impact over the regulating valve to close it in the well
   chosen at Step 3.8
   $A_i=A_i'-\Delta A$

3.10 exit from the unit

The gap between the allowed values of well consumption (maximum and minimum) are identified on the basis of the research of a well's operation.

5. Conclusion
The algorithm simulation was carried out in a program package for simulation, design and analysis of the operation of above-ground infrastructure and PipeSim pipeline system. The results confirmed the feasibility of the proposed algorithm and the possibility of managing operation regime of every well on an individual basis.

References
[1] Hodanovich I E and Strizhov I N 2003 Natural Gas Production Available at: https://rucont.ru/efd/301380
[2] 2009 Sloughing of sand prevention 12 5–9 Available at: https://rucont.ru/efd/261897
[3] Ahmedov K S 2014 Complex solution of the gas production optimum planning task Automatization, teleautomation and connection in oil industry [in Russian – Avtomatizaciya, telemekhanizaciya i svyaz’ v neftyanoy promyshlennost] 2 38–40
[4] Mandrik E V, Melnikov S A, Ploskov A A, Shulyatikov V I and Pamuzhak S G 2018 Evaluation of the effect of the liquid and constriction devices on the gas-wells flow-rate Automatization, teleautomation and connection in oil industry [in Russian – Avtomatizaciya, telemekhanizaciya i svyaz’ v neftyanoy promyshlennost] 3 43–7
[5] Antonov M D, Motorin D V, Nemkov A V, Nikolaev O A, Efimov A N, Ageev A L and Degtyarev S P 2019 The way of wet gas well cluster operation Patent RF 2679174
[6] Kononov A V, Stepovoj K V and Moroz S V 2015 The sistem of adaptive automatic control of gas well cluster production rating Patent RF 2559268
[7] Mokhatab S, Poe W A and Mak J Y 2019 Handbook of Natural Gas Transmission and Processing (Principles and Practices Gulf Professional Publishing) pp 103–76
[8] Upchuch E R 1989 Expanding the range for predicting critical flow rates of gas wells producing from normally pressured waterdrive reservoirs SPE Production Engineering 4 321–6
[9] Astrom K J and Wittenmark B 1994 Adaptive Control (Addison-Wesley)