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DEVELOPMENT OF DESIGN CRITERIA FOR WELL COMPLETION IN HORIZONTAL WELLS

A well constructed horizontal production well can assure the most advantageous flowing conditions when the fluid content of the yield gas is not separated to a considerable extent in the environment of the bore bottom. However, in case of wells producing a high gas-fluid ratio, the intensive separation of fluid and gas in the horizontal section may cause failures of the well structure.

For the time being, there is a serious uncertainty concerning hole gripping, system pressure and the effect of well structure influencing flow conditions. The clarification of effects influencing the flow conditions in a horizontal well section could be an important step in preventing the expected production problems, as well as from the point of view of the construction of a suitable well structure.

The present study reports on a series of tests for investigating the mixed flow of gas and fluid in a horizontal well section. Conditions of the design and development of the investigation equipment are presented. In the following, the analysis of horizontal well sections is proposed to be a factor to be considered in well design. During the investigation, flow diagrams have been made to analyze the impact of the casing liner - producing pipe on the flow chart.

PROBLEMS CAUSED BY THE SEPARATION OF FLUID AND GAS IN A HORIZONTAL SECTION

The problems of production in horizontal wells appear as a direct result of long open sections or perforation intervals, or of slotted liners. A frequent phenomenon is hereby the failure resulted from an excessive sand sedimentation or the separation of fluid and gas by gravitation.

Szepesi [1] and *Butlin* [2] report in their articles respectively well completion failures and production problems caused by the high rate gas production in vertical and horizontal wells based on their rich experience in well completion and production.

In case of higher gas contents and flow rates, the undesired fluid-gas separation in a horizontal well section may result in a pulsating production associated with high-pressure impulses. Among the harmful effects of the considerable pulsation the most frequent are the repeated failure of production installations and the increasing sand production.

Thus, the investigation of the separation of fluid and gas by gravitation in a horizontal well section, to assure the trouble-free operation of a well producing the mixed fluid and gas flow is an essential matter. For the time being, the most uncertainty in this topic can be found around hole gripping, system pressure and the impact of well structure on the pulsating flow [3].

The present investigation analyzes the relation between pulsating production conditions and the well structure resulted under the above circumstances, looking for such possibilities to construct a well structure which can suitably influence the flow conditions in a horizontal section.

Relations between flow conditions in a horizontal well section and the well construction

The basic categories of horizontal well sections are:

- construction of open hole wells
- construction of wells with pre-perforated casings
- pre-perforated casing with external casing packers
- construction with cemented casing.

The advantages and disadvantages of the various modes of well construction are very different in respect of the conditions provided for inflow, production, production regulation, formation treating and injection.

The basic types of horizontal well constructions are multiplied by variations of the cross section which could essentially influence the development of flow patterns. Taking the typical section changes as basis, the construction of wells can be classified as follows:

- open hole and cemented liner construction
- packed construction with production tubing
- construction with production tubing and without packer.

It is to be determined how the characteristic structures of a construction can influence the development of a flow diagram. The question can be answered by the investigation of flow diagrams created within the construction selected.

Relationships for describing the transition zones in flow charts

The *Kelvin-Helmholtz* instability considers the basic mechanism of the wave formation, i.e. the situation of the vacuum produced by pressure change overcoming the gravitation.

Theoretic relation of the classical *Kelvin-Helmholtz* instability for long waves and waves of small amplitude (see *Milne-Thomson* [4]):

$$k \cdot \rho_L (V_L - c)^2 \cdot coth(k \cdot h_L) + k \cdot \rho_G (V_G - c)^2 \, coth(k \cdot h_G) = g(\rho_L - \rho_G) + \sigma \cdot k^2, \quad (1)$$

where:

k = wave length, k = 2p/a	$\mathbf{V_G}$ = gas velocity
c = wave velocity	ρ_L = fluid density
σ = superficial tension	ρ_L = gas density
$\mathbf{V_L}$ = fluid velocity	$\mathbf{h_L}$ = fluid level.

The relation cannot be used but for real wave speeds. In case of a large wave length, i.e.:

$$k \cdot h_L \langle\langle 1; \; k \cdot h_G \langle\langle 1$$

and the superficial speed is negligible, and then the following relation gives the condition of instability:

$$(V_G - V_L)^2 \rangle (\rho_L - \rho_G) \cdot g \cdot (h_G / \rho_G + h_L / \rho_L). \quad (2)$$

As far the gas density is lower and gas velocity much higher than that of the fluid, i.e.:

$p_G \langle\langle p_L \quad \text{and} \quad V_L \langle\langle V_G$

then the relation can be further simplified:

$$\rho_G \cdot V_G^2 \rangle g \cdot (\rho_L - \rho_G) \cdot h_G . \tag{3}$$

Kordyban and Ranov [5] were considering the effect of the pipe upper wall and modified the expression of the Kelvin-Helmholtz instability. According to the authors, the wave stability, i.e. the criterion of formation of a slug flow is given by the relation:

$$\rho_G \cdot (V_G - V_L)^2 \rangle (\rho_L \cdot g / k) / coth(k \cdot h_G - 0.9) + 0.45 \cdot coth^2 (k \cdot h_G - 0.9) . \tag{4}$$

The authors have determined the relation empirically, by following the relation between wave length and amplitude.

Taitel and Dukler [6] have developed relations for determining the outline of three flow patterns which can be seen in flow charts in theoretical way, namely for the outlines known as:

- intermediate
- slug-annular
- slug-bubbling.

In developing the relations they have taken into account the so called Bernoulli-effect appearing between the flowing layers. They supposed that the wave is developed when the difference of pressure is sufficient to overcome the forces of gravitation.

The authors suggested the following relation for the determination of the transitional zone between laminated-stratified wavy and slug ones:

$$V_G \; \rangle \; C \; \left(\frac{(\rho_L - \rho_G) \cdot g \cdot cos\,\theta \cdot A_G}{\rho_G \cdot dA_G / dh_L} \right)^{1/2} , \tag{5}$$

where:

C = A'_G / A_G

A_G = cross section of the flowing gas

A'_G = cross section of the flowing gas at wave peak.

$\frac{dA_L}{dh_L}$ = change of the cross section filled by the fluid in function of fluid level.

The authors have recommended the following relation for determining the values A, C:

$$C = 1 - \frac{h_L}{d} . \tag{7}$$

As a criterion of the transition from slug to annular, *Taitel and Dukler* have indicated the following ratio:

$$\frac{h_L}{D} \langle 0.5 . \tag{8}$$

Barnea at al. [7], considering the gas content of the fluid wave, suggested this relation:

$$\frac{h_L}{D} \langle 0.35 . \tag{9}$$

The conditions of development of the slug flow were also investigated by the authors *El-Oun* [8], as well as *Scott and Kouba* [9]. However, their relations comprise several factors which cannot be approached by well design but with a very considerable uncertainty.

After reviewing the literature it can be stated that the criteria cited in the most important publications for the determination of the transitional zones in a flow chart refer only to pipes of a given diameter. Since the basic relations of the two-phase flow can hardly be solved for this case, without knowing the peripheral conditions, an empirical solution supported by laboratory tests seems to be practical for investigating the problems of exploitation with a system casing-tubing.

The investigation enabled to build equipment for testing the flow chart in a system casing-tubing.

SPECIFICATIONS OF THE EXPERIMENTAL EQUIPMENT

In the investigations related to flow maps, the applicability of theoretic or empirical relations is sometimes confirmed by the researches with tests carried out on their own testing equipment. For such purposes various testing equipment have been built from the most simple laboratory circuits through the very expensive real size installations. Yet they can be classified in two main groups depending on whether they are suitable for testing the flow conditions on pipes [10] or they consider also the inflow conditions of a horizontal well section [11].

The test of systems with a more complex geometry, specific to the types of well construction, cannot directly be measured with the testing equipment found in bibliography. New testing equipment conforming the given peculiarities had to be developed.

Characteristics of the testing equipment

The cross sectional rates of the testing tube in the developed laboratory testing equipment agree with a combination of 7" (29 lb/ft) pipe liner and 2 7/8" (8.6 lb/ft) producing pipe (packer hole), i.e. inner diameters of the testing tubes:

39 mm (like casing)

13.6 mm (like tubing).

Thus, the selected pipe lengths:

- for a tube of 39 mm diameter: 2 m
- for a tube of 13,6 mm diameter: 1,5 m.

To enable visual survey, the testing tubes are made of transparent plastic, more exactly

- the tubes of 39 mm in diameter: are made of plastic
- the tubes of 13,6 mm in diameter: are made of glass.

Fluid mediums used in the tests: water and air.

Prior to enter into the testing system, there was a possibility to measure the water and airflow rate, separately from one another. The mixed fluid transported into the system through the mixing head is transmitted along a vertical connecting line and the tank attenuating the pulsating current, having also the function of separating fluid and gas by gravitation.

The limit values of the gas and fluid flow rate should be chosen in such a manner that the limit conditions of the slug flow can be measured by means of the testing equipment, i.e. using:

• a gas flow rate of 1-34 mm^3/h and a fluid flow rate of 0,6-60 dm^3/min, flow rates covering the production conditions of a real oil well.

• E.g.: the envisaged minimum fluid flow rate of 0.6 dm^3/min applicable in the test pipe of 39 mm is equivalent to a flow rate of 12,9 m^3/d in the pipe liner of 6 5/8", and that the flow rate of 20 dm^3/min is equivalent to 430 m^3/d in a real pipe liner.

Working pressure of the system is atmospheric and temperature is ambient.

By a simple change in the testing equipment, i.e. by interchanging testing pipes it was possible to make testing circuits suitable for the types of well construction. Figures 1 and 2 illustrate the **A, B, C** and **D** testing circuits in which the combinations of testing pipes conform to the constructions:

- **A** - open hole, with casing or liner
- **B,D** - with packer
- **C** - without any packer

To make this change it was enough to build in a centric intermediary piece with bore diameters of 13,6 mm and 16 m or, respectively, an eccentric piece with a bore

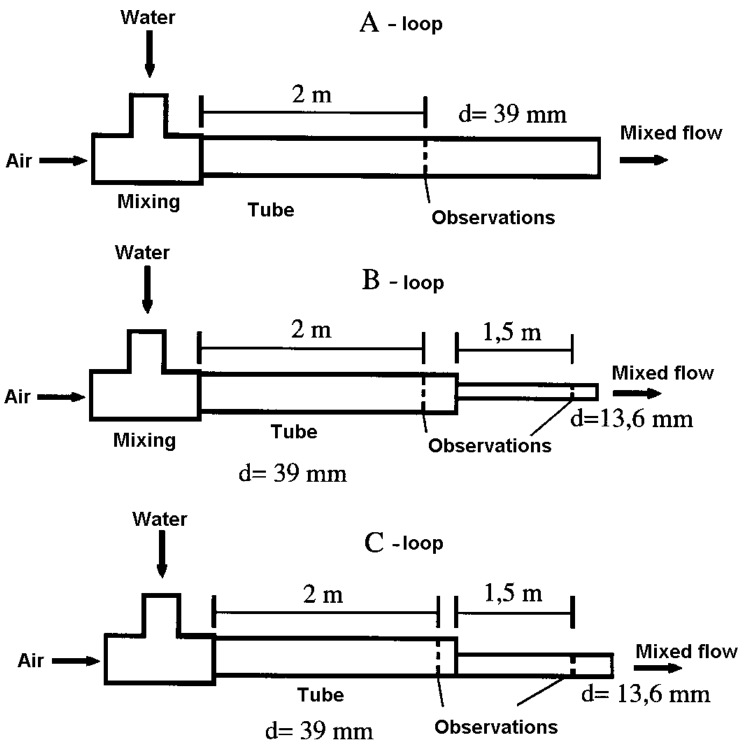

Fig. 1. Experimental loops

diameter of 13,6 mm (see Fig. 2). These pieces served to the connection of two testing pipes of different diameters, as required by testing conditions, to the testing pipe of 39 mm in the equipment 'A'.

Confirmation of the applicability of the testing equipment

By representation in a log-log system of the testing points fixed in a testing pipe of 39 mm diameter (loop 'A'), the flow chart of Fig. 3 can be obtained (case 'A'). V_{SL} and

V_{SG} represent the superficial velocities calculated from the flow rate of the fluid or, respectively, or the gas.

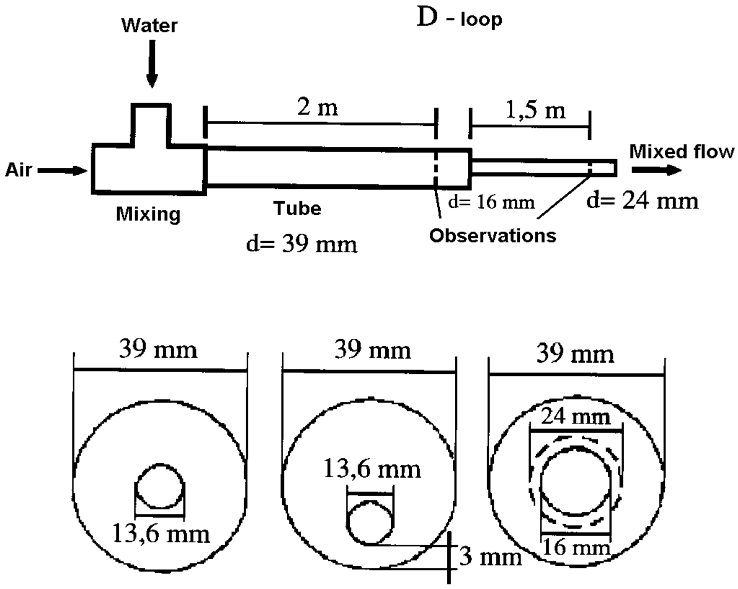

Fig. 3. Testing tube couplings

The flow chart built up covers the areas of the stratified smooth, stratified wavy, elongated bubble and annular flow within the range of 0.03 to 3.6 m^3/h fluid flow rate and 1 to 34 m^3/h gas flow rate. Thus, almost the whole transitional zone of the slug flow, i.e. the elongated bubble-slug, stratified smooth-slug and stratified wavy-slug transitional zones could be plotted. The survey did not include the plotting of disperse-slug transitional zones.

Here are the main flow maps represented in Fig.3:

	Superficial velocity	
	Liquid (m/s)	Gas (m/s)
Stratified smooth-slug	< 0.20	< 5.0
Stratified wavy-slug	> 0.2 < 0.3	> 1.5 < 18
Elongated bubble-slug	> 0.2	> 0.2

Prior to a further application of the testing equipment, the confirmation of the practical applicability of loop 'A' was necessary, since no reference is found in the bibliography on tests similar to connecting two pipes of different diameter to one another. Fig.4 illustrates results of the present tests, comparing the flow maps made with loop 'A' to other flow maps. It is evident that the annular flow border indicated by the present study is close to *Madhane's [12]* flow chart, while the stratified smooth, stratified wavy and slug patterns is close to *Taitel-Duckler's [6]* flow maps.

The conformity is a proof for the applicability of the testing equipment designed and compiled above, as well as for the suitability of the testing method developed.

Flow maps in the casing and in the tubing

It is important to clarify for a well construction what the patterns are that affect the production conditions of a well fitted with tubing among those developed in a horizontal well section of larger diameter (casing, open hole). Thus, besides the results relevant for a pipe of 39 mm large diameter the test series B, C, D comprises also observations pertaining to test tubes of 13,6 and 24 mm diameter.

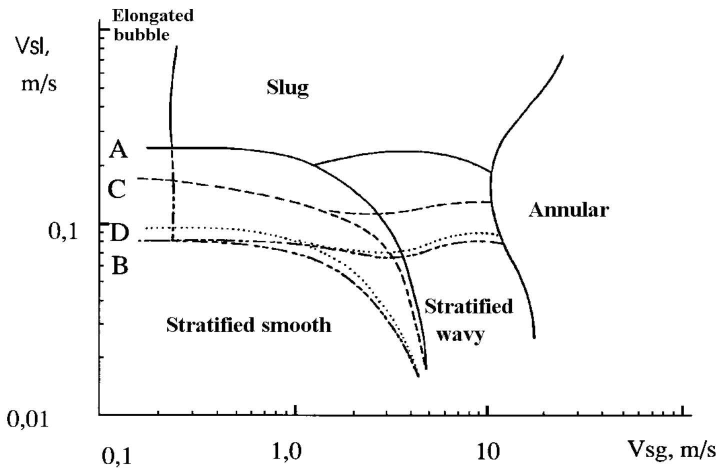

Fig. 3. Experimental flow maps comparison

The following individually tested flow patterns were observed in each of the 39 mm pipe and the connected test pipes of lower diameter:

Test pipe of 39 mm	**Test pipes of 13,6 mm**
Elongated bubble	Slug, annular, mist
Stratified smooth	Elongated bubble, slug, annular, mist
Stratified wavy	Elongated bubble, slug, annular, mist
Slug	Disturbed by waves
Annular	Mist

Following the evaluation of test data the following remarks can be made:

a) As far a elongated bubble, stratified smooth, stratified wavy, annular of mist flow pattern is formed in the tube of 39 mm large diameter, the flow pattern in the connected smaller pipe will follow the regularities of phase arrangement of the gas or fluid in flowing in a horizontal pipe. Accordingly, besides a stratified smooth flow produced in the tube of 39 mm large diameter, in conformity with real superficial speeds of the gas and fluid in the connected small diameter pipe, also stratified smooth, stratified wavy, slug, annular and mist patterns may appear.

b) As far the slug flow pattern is dominant in a pipe of 39 mm diameter, then no clear flow pattern subject to gas and fluid superficial velocity can be formed in the connected small diameter pipe.

The predominantly fluid content of the slugs arriving at regular interval produce an intensive pulsating flow, influencing decisively the flow conditions in the small diameter pipe. Thus, it is reasonable to construct wells, which prevent the formation of a slug flow in the horizontal well section.

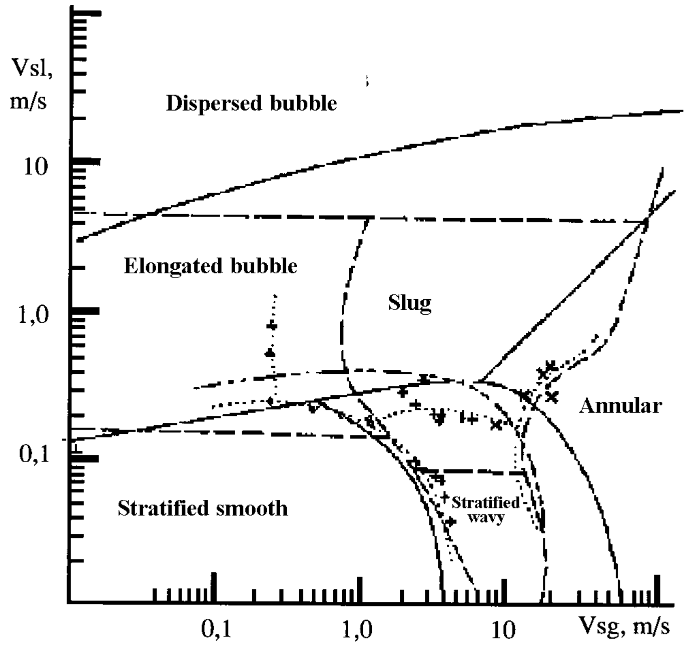

Fig. 4. Comparison between theorics and experiments on flow maps

Theories:

________ Taitel and Dukler
---------- Madhane at al.
____-___-- El-Oun
.... Present study

Analysis of flow patterns formed in various horizontal well constructions

Test 'B' loop is a construction with packer for the case when building in the packer into the horizontal section of a gas and fluid producing well.

The test had the purpose to demonstrate how a system consisted of pipes of two different diameters can influence the formation of flow patterns in the large diameter pipe, i.e. whether production failure can be provoked by changing the well construction only by building in a tubing.

The flow map plotted along the tests is relevant for the joint flow of gas and fluid in a pipe of large diameter. Accordingly, gas and fluid have entered the pipe of large diameter through the mixing head, then they have got out from the testing equipment through the small diameter pipe.

Considering the results obtained with testing loops 'A, B', it is an important change in the flow map (see Fig. 3, case 'B'):

- the slug flow appeared very soon, already at a fluid speed of 0.07 m/s
- the transit zone between stratified wavy and slug became less significant

- the transit of stratified smooth and stratified wavy flows moved towards the lower fluid flow rates. The stratified wavy flow appeared already by a gas speed of 0.3 m/s, with respect to the limit value of 1.4 m/s in a case without any central tubing
- no essential change occurred in the transit between annular and elongated bubble flow patterns.

The well construction with centralized tubing results in much less favorable conditions of production with respect to the situation without any tubing, since the stratified smooth flow appear much sooner, at fluid flow rates much lower.

To test how more favorable production conditions than with a central tubing can be achieved by changing the well construction, i.e. by moving the stratified smooth flow limits towards higher fluid flow rates, there are two possibilities in the practice of well construction. One is to use no centralized tubing (e.g. well without any packer) or to increase the tubing diameter.

Test 'C' represents the situation when tubing with no packer (eccentric tubing) had been built into a horizontal well section with pipe liner. Accordingly, the eccentric production line is situated on the bottom of pipe liner. The axes of both testing pipes do not coincide, they are eccentric (see Figures 1, 2).

According to Fig.3 (case 'C') the improvement of the flow chart with respect to case 'B' is evident:

- The stratified smooth flow appeared only by a fluid velocity of 0,1 m/s even in the most unfavorable situation, i.e. better approaching the case without any tubing
- The transit stratified wavy-slug is higher with respect to test 'B', being more similar to the case without any tubing
- Even the stratified smooth-stratified wavy transit line moved towards higher fluid rates. The stratified wavy flow appeared already at a gas velocity of 0,7 m/s, still being different to the transit limit of 1,4 m/s without any tubing
- The transit between annular and elongated bubble flows did not change essentially.

The flow pattern obtained with test 'C' assures much better production conditions with respect to that obtained with circuit 'B' because the waves appear much later.

Test 'D' is used in the situations when a tubing of enlarged diameter is built into a horizontal well section with pipe liner, using a flow control valve the inner diameter of the tubing. The axes of the test pipes with 39 mm and 26 mm inner diameter in test 'C' have coincided, being connected to each other by a transit piece of 16 mm bore diameter (see Fig.2).

The flow map made with the test circuit ‘D’ hardly shows any improvement with respect to case 'B':

- The limit of the slug flow, i.e. the early appearance of slugs is the reason of bad production conditions
- The transit stratified wavy-slug has perhaps slightly changed with respect to test 'B'
- The flow border stratified smooth-stratified wavy is slightly moved towards the higher fluid flow rates
- The transit between annular and elongated bubble flows coincides with the flow charts previously analyzed.

As a consequence of developing slug flow in the flow pattern pertaining to case 'D', unfavorable production conditions similarly to case 'B' are obtained.

CRITERIA OF STRATIFIED - SLUG TRANSITION ZONES FOR CASING - TUBING SYSTEMS

The development of such designing criteria is necessary which suit with sufficient accuracy for the determination of stratified smooth-slug and stratified wavy-slug transit zones in constructions with or without packer and fitted with a tubing.

On the basis of the research work the author has suggested the following relation for the determination of the transitional zone between stratified wavy and slugs ones:

$$V_G > \left(1 - \frac{h_L + \frac{1}{2}\left(D - d\right)}{D} \right) \left[\frac{\left(\rho_L - \rho_G\right) \cdot g \cdot \cos\alpha \cdot A_G}{\rho_G \left(\frac{dA_L}{dh_L} \right)} \right]^{1/2},$$

where: D = casing ID;
d = tubing OD.

The author recommends substituting in the equation 5 the relation of $\frac{h_L}{D}$ with $\frac{h_L + \frac{1}{2}\left(D - d\right)}{D}$ for the casing - tubing systems.

CONCLUSIONS

The laboratory tests have confirmed that the slug flow pattern formed in a pipe liner is the principal cause of production failures, and that the investigated types of well construction can essentially influence the flow pattern.

Accordingly, when constructing a well it is recommended to prevent the formation of slug flow patterns in the horizontal well section, which could cause a pulsating production.

In publications dealing with this subject only criteria defining transitional zones of the flow map in pipes of similar diameter are available. Thus, such criteria are applicable, among the characteristic well constructions, for open hole well types without any packer and tubing, or for wells with casing and cemented wells.

In case of wells with packer or without packer and fitted with tubing, or in any other construction associated with flow control valves, the relations referring to mixed fluid-gas flows in tubes of similar diameters cannot be applied with sufficient accuracy to the stratified smooth-slug or stratified wavy-slug transitional zones.

In the design of horizontal well constructions the conditions of development for stratified smooth flows should be considered as design factors.

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