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MODELING AND PERFORMANCE ASSESSMENT OF INVERTED INTERMITTENT GAS LIFT

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Abstract. The Intermittent Gas Lift (IGL) is an artificial lift method for petroleum production suitable for producing wells from depleted or low productivity reservoirs. In order to enhance the well production, many variants of the conventional IGL have been developed and used worldwide. One of these variants, the Inverted IGL (IGL-I), consists of removing the gas lift valve and reversing the flow paths inside the well: gas is injected through the tubing whereas liquid is lifted through the casing annulus. The oil production is believed to increase with the IGL-I due to the larger annulus storage capacity, at the expense of higher injected gas volumes. Despite of its potential for practical applications, the IGL-I has not been covered by the literature. Aiming to surmount such gap in the literature, this paper presents a model for the dynamical behavior of the IGL-I wells. The complexity emerged from the IGL-I cyclic operation is assessed through a simultaneous and coupled simulation scheme, comprising a variable set of non-linear algebraic equations and non-linear time-differential equations for the flow of oil and gas throughout the injection, transfer, elevation, production, decompression and loading stages of each cycle. The simulator provides the engineer with a valuable tool to investigate the well behavior of several IGL cycles. Based on the observed results, the designer may propose practical recommendations regarding the IGL-I design and operation.

Keywords: Artificial Lift, Intermittent Gas Lift, Petroleum Production, System Simulation.

1. Introduction

The Intermittent Gas-lift (IGL) is among the most employed systems for artificial lift of petroleum; particularly when the reservoir is somewhat exhausted, so that its pressure is not enough to provide a continuous and profitable flow of oil. There are different versions of this system in use worldwide, and there is a continuous effort to improve it. One of this versions is called Inverted Intermittent Gas-lift (IGL-I) – it consists in the inversion of the flow of oil and gas with respect to the conventional mode of operation. During the IGL-I cycle, gas is injected inside the well tubing, displacing the oil, which is lifted through the well casing (the annular space between the well wall and the inner centered tubing). The completion of the IGL-I does not require a gas-lift valve (although one could be used); the flow from the tubing into the annulus occurs through an orifice.

It is expected that the production of oil with the IGL-I would be greater than that of the conventional IGL, thanks to the larger capacity of the casing to store oil, compared to the volume of the tubing per unit length. At the same time, the absence of a gas-lif valve means one less mechanical device to worry about, one less cause for failure of the system, probably diminishing the need for well intervention. The disadvantage of the IGL-I is its large consumption of gas, which may offset the gain in oil production.

Therefore, in order to accurately assess the productivity and profitability of the IGL-I, a numerical simulator is needed to compute the IGL-I cycle, determining the daily flow rates of oil and gas. To the best of the authors knowledge, after researching the literature and consulting world experts in the field of artificial lift, there are not any published previous works dealing with the IGL-I, nor any available simulator. The present paper addresses this gap of technological knowhow, proposing a method to model the dynamical behaviour of the IGL-I cycles. Some results are also presented, showing the behaviour of the IGL-I.

2. Literature Review

Clegg *et al*. (1993) presented an extensive overview of artificial lift design considerations, comparison of methods and their normal operating conditions. Chacin (1994) discussed the state of the art of the design of IGL methods, presented a simplified algorithm for the calculation of the production rate, and a procedure to select the best IGL method – according to his criteria, the one with the greater ratio of produced oil volume to gas injected volume. Brown and Jessen (1962), Brill *et al*. (1967), and Neely *et al*. (1974) did some experimental work on specific field installations of conventional IGL, establishing empirical rules for the setting of the operational parameters. Although they provide useful guidelines, those rules lack in generality. White (1963) developed the first simple mathematical relationships for the conventional IGL and did experiments on laboratory installations. Machado (1988) developed a mechanistic model coupling physical principles and empirical correlations to calculate some variables of the IGL system. Liao (1991) obtained theoretical results that showed good agreement with Brown, Brill and Neely. White (1982) conducted tests with and without a plunger to demonstrate the reduction of liquid fallback in the plunger case. Mower and Lea (1985) used different plungers to study the effect of plunger geometry on the fallback. Chacin *et al.* (1992) developed a mechanistic model, introducing the empirical findings of Mower and Lea into the IGLP model. Brown described the advantages of IGL with chamber for reservoirs with low static head and low productivity index, and provided a simplified procedure to estimate the average flow pressure at the bottom of the well. Winkler and Camp (1956) applied the IGL with chamber to reservoirs of low static head but high productivity index. Bardeja and Mariaco (1971) discussed the principles that should be applied to the analysis of the IGL with chamber, optimization of the method, and listed results of field cases. Acevedo and Cordero (1991) presented field experiments showing an increase of oil production and decrease of gas consumption. The pig-lift was developed in one petroleum company somewhat recently, consequently very few publications exist. Lima *et al.* (1993) developed a simulator to study the potentiality of this new technique. Lima (1996) presented the working principles of the pig-lift, and argued in favor of its advantages over the other IGL methods. Santos, Bordalo and Alhanati (2001) presented the most comprehensive and detailed model for the simulation of the conventional IGL and also the plunger, chamber and pig versions, but they did not cover the IGL-I case.

Although the present work is based on the model of Santos et al (2001) for the dynamics of the IGL, it includes some original characteristics that make the simulator proposed herein quite different. The most remarkable feature of the new IGL-I simulator is that all the subsystems and its stages are computed in a coupled fashion, i.e., simulating the actual operation in real time of the IGL-I cycle with the stages occurring in parallel, while Santos et al made sequencial calculations. In order to reach this goal, first, the simulator was built to compute the conventional IGL cycle, using a modification of Santos et al equations and employing the new coupled scheme, then it was configured to simulate the IGL-I cycle.

3. The IGL-I System and the Proposed Model

Figure 1 describes the IGL-I cycle – the oil reservoir feeds the well, filling the tubing and the casing (1.a); at some point gas is injected at the well-head through the tubing, displacing the oil (1.b), and soon lifting the oil load, carrying it up through the casing to the surface (1.c), where it is produced (1.d); next, the gas flows out of the well (1.e), and eventually, after the well pressure drops low enough, the reservoir will recharge the well with oil (1.f), so that the cycle may be repeated.

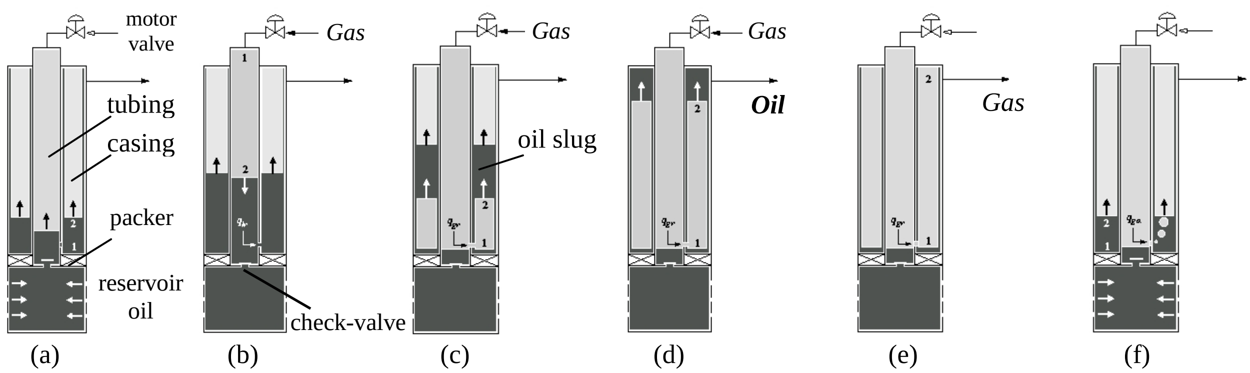

Figure 1. The IGL-I cycle: (a) loading; (b) injection & transfer; (c) injection & elevation; (d) injection & production; (e) decompression; (f) decompression & re-loading

The subsystems interacting are the oil reservoir, the surface line, the well tubing, the well casing and the well-bottom. The connections between them are described by flow equations, which during the simulation are dictated by the status of the ports of these connections (for instance, whether the valves are open or closed). In each subsystem, the fluids – oil and gas – are represented by control volumes, governed by the mass and momentum balances. A set of non-linear ordinary temporal differential equations arise from this model. The model is completed with another set of non-linear algebraic equations for the valves' flow, oil and gas' head loss, gas density etc.

During the simulation, the computer code continuously checks the values of the governing variables and the status of the connections between the subsystems. In this way, as valves open and close, or when pressure dictates, or whenever some crucial event occurs, the set of equations is modified on the run to represent adequately the state of affairs.

The full set of equations is too extensive to be presented here, as well as the whole complex scheme to modify them as needed for each stage along the IGL-I cycle. The complete inner workings of the simulator have been described in a previous paper concerning the conventional IGL (Carvalho and Bordalo, 2003), as part of the first step in building the computer code for the IGL-I. In the present text, only the main features are shown.

The general form of the set of equations is given by Equation 1, where *E* and *F* are the functions of vector of variables *Y* discriminated in Table 1, while *H* must be referred to Carvalho and Bordalo (2004).

$$\left.\begin{array}{ll} \dfrac{dE_j(Y)}{dt} = F_j(Y) & ; j = 1 \ldots m \\ H_k(Y) = 0 & ; k = 1 \ldots n \end{array}\right\} \tag{1}$$

Table 1. *E* and *F* functions that comprise the set of equations for the IGL-I.

E(Y)	*F(Y)*
$\bar{\rho}_{gt} A_t h_{bt}$	$L_1 \dot{m}_{gi} - (L_4 \vee L_9)\dot{m}_{gv}$
$\rho_l A_t h_{lt}$	$L_3 \dot{m}_{lR} - L_2 \dot{m}_{lv}$
$\rho_l A_t h_{lt} v_{lt}$	$(P_{t2} - P_{gt2})A_t - \tau_{lt} S_{lt} - \rho_l g A_t h_{lt}$
$\bar{\rho}_{gc} A_b h_b$	$(\neg L_9)\dot{m}_{gv} - L_7 \dot{m}_{gP}$
$\rho_l A_{fo} h_f$	$(L_5 \vee L_6)\rho_l v_{rsf} A_{fo} - (L_7 \wedge v_f^+)\rho_l v_f A_{fo} - [L_8 \wedge (v_f < v_{lc})]\rho_l v_{rfl} A_{fo}$
$\rho_l A_c h_s$	$(L_4 \vee L_5)\rho_l v_{rsf'} A_{f'} - (L_5 \vee L_6)\rho_l v_{rsf} A_f + L_4 \dot{m}_{lv}$
$\rho_l A_c h_s v_s$	$(P_{gc2} - P_{s2})A_c - \tau_{sci} S_t - \tau_{sco} S_c - \rho_l g A_c h_s - L_6 K \rho_l \dfrac{v_s^2}{2} A_c$
z_{lt}	v_{lt}
z_{b2}	v_b
z_{s2}	v_s
$\rho_l A_c z_{lc}$	$(v_f < v_{lc})\,\rho_l v_{rfl} A_f + [L_3 \wedge L_8 \wedge (\neg L_9)]\dot{m}_{lR} + (\neg L_8 \vee L_9)\dot{m}_{lv}$
z_{lc}	v_{lc}

$Y = \{\ \bar{\rho}_{gt},\ \rho_{gt1},\ P_{gt1},\ Z_{gt1},\ \rho_{gt2},\ P_{gt2},\ Z_{gt2},\ P_{t2},\ z_{lt},\ v_{lt},\ \dot{m}_{gi},\ \bar{\rho}_{gc},\ \rho_{gc1},\ P_{gc1},\ Z_{gc1},\ \rho_{gc2},\ P_{gc2},\ Z_{gc2},\ P_{c1},\ z_{b2},\ v_b,\ y_f,\ z_{f2},\ v_f,\ z_{s2},\ v_s,\ z_{lc},\ v_{lc},\ \dot{m}_{(l,g)v},\ \dot{m}_{lR}\ \}$

Legend — Variables: *L*, logic flags for the states of flow connections, $\dot{m}$, mass flow rate, *v*, flow velocity, *A*, cross-sectional area of the flow, ρ, fluid density, *P*, pressure, τ, viscous stress, *S*, perimeter of viscous action, *g*, gravity acceleration, *h*, length of a fluid body, *K*, head-loss coefficient, *V*, volume, *z*, height above the perforation zone, *Z*, compressibility factor, *y*, film thickness. First subscripts: g, gas, l, liquid, f, film, t, tubing, c, casing, s, slug body, b, gas body. Second subscripts: c, casing, t, tubing, 2, bow, i, injection valve, v, gas-lift valve, P, production valve, R, reservoir.

One important feature of the proposed model is the inclusion of the fallback of liquid left behind from the liquid slug in the form of an oil film around the gas during the elevation stage. This means that not all the oil initially at the bottom of the well will reach the surface and be produced after each cycle.

The daily production correlates with the volume of oil inside the well but it also depends on the possible number of cycles executed per day, therefore the periods of the stages of the cycle add up to affect adversely the net productivity. For instance, a larger liquid load means more oil to be produced, but it takes more time to recharge the well; also, more gas injected allows for more oil production, but it takes more time to decompress the system. The lesson to be learned is that there is nothing obvious or straightforward in the design of the operation of the IGL cycles. The optimum operational points must be determined by running the simulator for the prevailing reservoir properties and depletion condition, fluid properties and well geometry.

The reservoir and fluid parameters are fixed by nature, while the well geometry does not permit a fair latitude of control. Apart from these governing parameters, usually the engineer is left with two variables under his control – the cycle period and the injection period, which can be adjusted at the motor valve's timer. Accordingly, these are the main variables under the focus of the present work.

4. Results of the Simulation

The following results were drawn from simulations of a fictitious well, configured with properties that closely resemble a real onshore well (Table 2). At this time there is a lack of empirical data on IGL-I, but the results reported for this simulator (Carvalho and Bordalo, 2003) were fairly good when applied to the conventional IGL, and also there was a close match to the calculations of Santos et al. Since both the conventional IGL and the IGL-I are governed by the same equations, which are modeled in the exact same fashion, it is reasonable to use the simulator to compare the performances of this two systems to each other.

Table 2. Main characteristics of the case under analysis.

Parameter	Value
average depth of the well perforations	1500 m
internal diameter of the casing (nominal)	127 mm (5 1/2 in)
internal diameter of the tubing (nominal)	50.8 mm (2 3/8 in)
orifice diameter	25.4 mm
depth of the orifice	1475 m
surface line pressure	686 kPa
reservoir pressure	7.22 MPa
productivity index of the reservoir	15 m^3/d.MPa
surface temperature	15 ^oC
underground thermal gradient	36 ^oC/km
relative density of the oil to water (API degree)	0.876 (30)
relative density of the gas to air	0.7
water fraction	50%
injection pressure of the gas	6.86 MPa

For the plots showing the behavior of a single timing setup, the cycle and injection periods are 2000 s and 150 s, respectively. In the comparison of the IGL-I to the conventional IGL, the following data was used for the gas-lift valve (GLV): depth of the GLV – 1475 m, dome pressure at the test rack – 4.8 MPa, port diameter – 11 mm, port to bellows area ratio – 0.2.

Figure 2.a presents the behaviour of the liquid volume produced per cycle from the reservoir V_{lRc} and at the surface V_{lPc}, as well as the liquid fallback; while Figure 2.b displays the injected gas volume per cycle and the gas-to-liquid ratio (IGLR). There is a start up transient after which the cycles become steady, i.e., they repeat themselves. Therefore any experimental procedure must await to gather data until the steady cycles are reached; data from a one-shot cycle should not be used to draw generic conclusions.

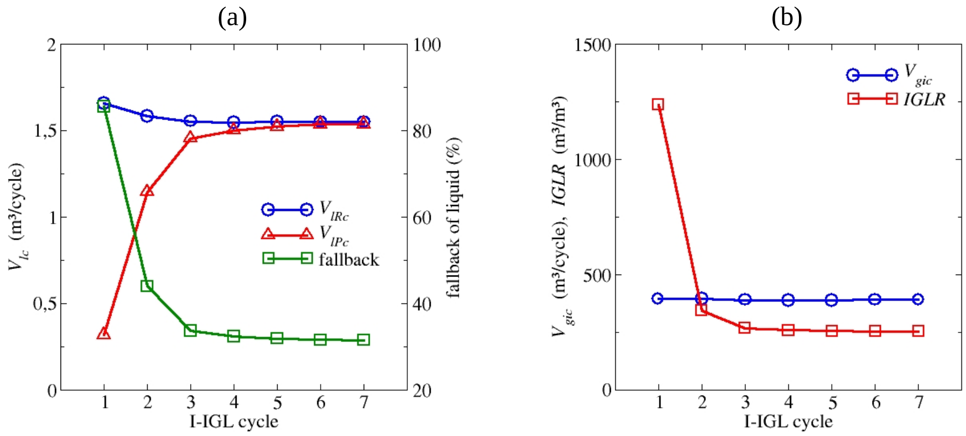

Figure 2. Transient behaviour

Figure 3.a presents a typical schedule for the stages of a IGL-I, where the simultaneity of some stages is clearly observed, justifying the need for the coupled scheme of the proposed simulator. Figure 3.b displays a typical pressure record for steady cycles, similar to the ones that can be obtained in the field – P_{t1} is the pressure in the tubing at the well-head, downstream of the motor valve (control valve); P_{wh} is the pressure output delivered by the well upstream of the surface production line. The injection and decompression are easily noted on the top plot, while the production peak

appears on the bottom plot. These pressure charts are common diagnosis tools for the engineer and a “must have” feature of the simulator; also they may be used when checking the physical modeling against experimental data. Figure 3.c is an important operational map generated by the simulator, indicating the timer settings that will guarantee stable cycles – shaded area. A timer setting is defined by the pair (t_{cycle}, t_{inj}), respectively the cycle period and the injection period. Unstable operations may occur due to insufficient IGLR to elevate the liquid load, or to the breakthrough of gas across the body of the liquid slug. Both events can be predicted with the simulator. The sample IGL-I cycle presented in this paper is represented by the dot in Figure 3.c – corresponding to (2000 s, 150 s).

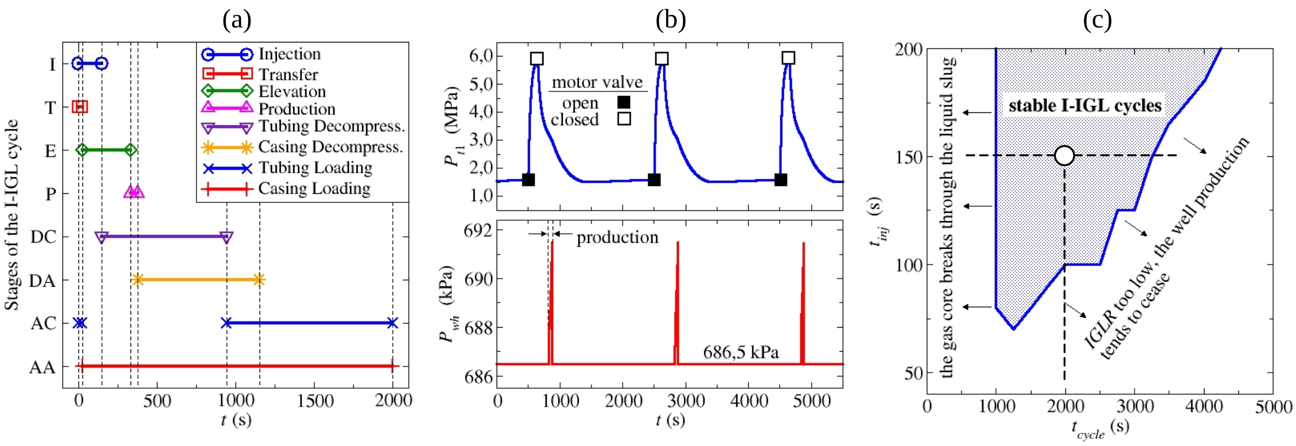

Figure 3. Stages’ schedule for the IG-I (a); pressure signature (b); operation map (c).

Figure 4 shows the levels of liquid in the casing (z_{lc} in blue) and tubing (z_{lt} in red) above the position of the orifice (z_{gv}) during the recharge of the well by the reservoir for one timer setup – z is measured with respect to the perforation zone. The lower level of liquid in the tubing, due to the compressed gas above it, leads to a little reduction of the total volume load; although this is seldom significant, it may become relevant for tubings of larger diameter.

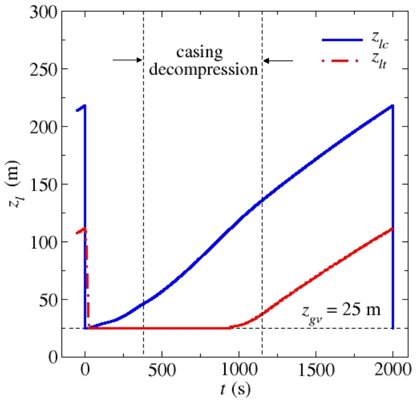

Figure 4. Well loading.

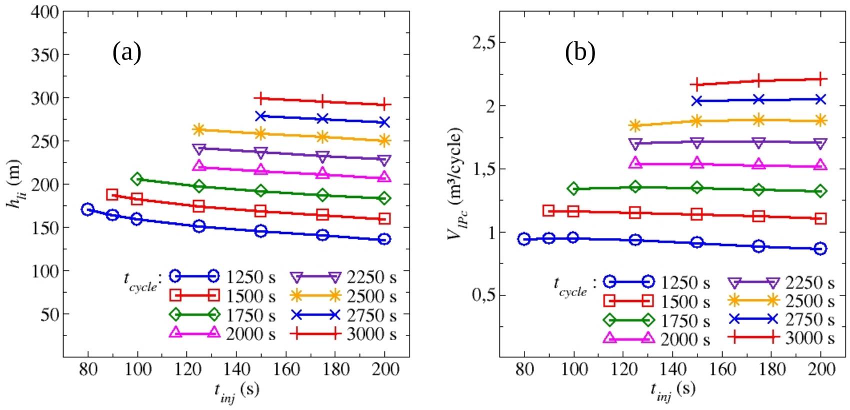

Figure 5. Liquid load (a) and produced liquid volume (b).

Figure 5 presents the variation of the load h_{li} (a) and the produced liquid volume V_{lpc} (b) as a function of the timer setup, indicating the control sensitivity on the hands of the well operator. In Figure 5.a, it is visible the effect of the higher volume of injected gas when t_{inj} increases – it causes an increase in the bottom-hole pressure that reduces the inflow from the reservoir and, consequently, reduces the load. It is also clear that increasing t_{cycle} allows for more time to recharge the well, generating a larger load.

The results on Figure 5.b are a consequence of the fallback (Figure 6.a), which express the effective yield of the liquid loads of Figure 5.a. In order to produce the values displayed on Figure 5.b, a certain amount of gas is required as input (the IGLR is plotted on Figure 6.b), which represents a cost to be deducted from the profit when calculating the actual gain. The complexity of the impact of the dynamics of th IGL-I system on such important economic variables is difficult to assess without the help of the simulation, as it is evident from these graphs. Usually, there are conflicting trends caused by different parameters – a sort of tug-of-war, with outcomes that lean toward the opposing sides depending on the values of the parameters; so that none parameter alone has the upper hand absolutely.

(a) (b)

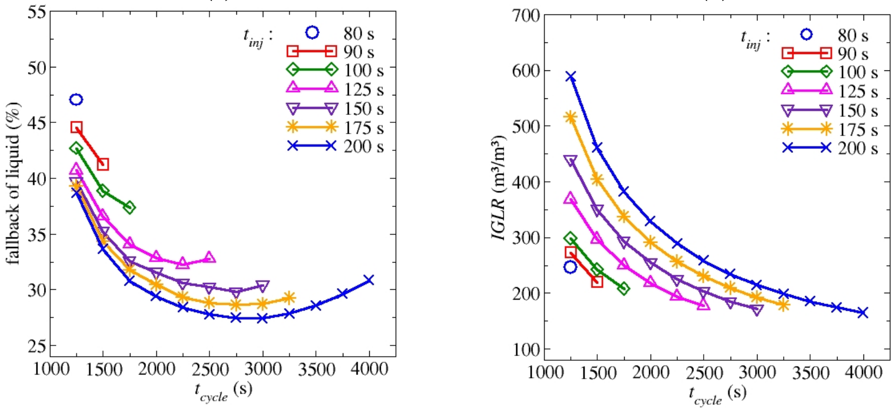

Figure 6. Fallback (a) and injected gas-to-liquid ratio (b).

The liquid daily production is obtained multiplying the produced volume per cycle by the daily cycle rate, which is inverse to the total cycle period, resulting in the curves shown in Figure 7.a, that have points of maximum. To the left of the maximum, the well operates with more shorter cycles producing smaller volumes, while to the righ of the maximum, the well produces larger volumes per cycle but operates with fewer longer cycles. When there is plenty and cheap available gas, the field manager may consider that his priority is the optimization of the production. In such case, the field engineer must strive for the maximum points on Figure 7.a, hinted by the results of the simulator. When the cost of gas is an issue, the simulator also helps in the determination of the economic gain (Figure 7.b). Although a more general equation is employed by the proposed algorithm, a simpler example will suffice for the sake of the argument. Neglecting the cost of treatment and disposing of the water, the gain G^* may be expressed by Equation 2, in units of equivalent volume of oil (thus avoiding the influence of eventual fluctuations on the price of oil), as a function of the *IGOR* (injected gas-oil ratio – R_{igo}), the specific revenue of the oil (in any 'reference monetary unit' per volume – L_o), the specific cost of gas (in the same 'reference monetary unit' per volume – C_g), and the oil daily production q_{op}.

$$G^* = q_{op}\left[1 - \frac{C_g}{L_o} R_{igo}\right] \qquad (2)$$

(a) (b)

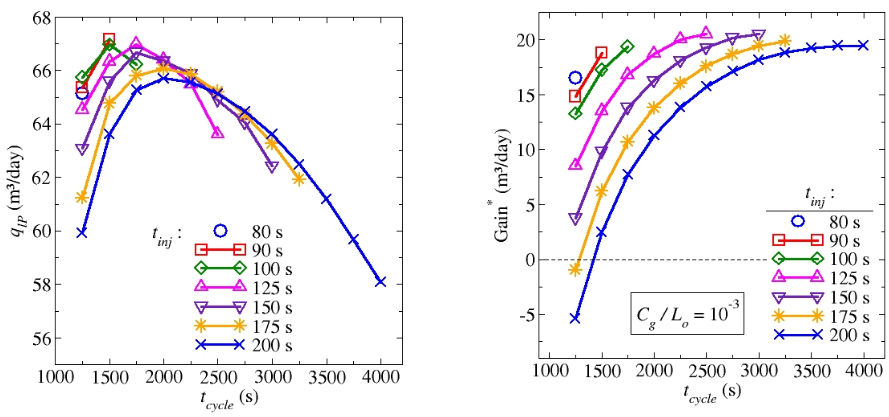

Figure 7. IGL-I – daily liquid production q_{lp} (a) and daily gain G^* (b).

In Figure 7.b, an example of gain calculation is shown for a rate of oil to gas equivalence of 1000 in volume – a reasonable assumption in some petroleum provinces of Brazil. It is interesting to notice the different optima for each priority: for instance, with t_{inj} = 200 s, the optimal t_{cycle} is about 2000 s at approximately 65.5 m^3/d of liquid (with an effective gain of 11 m^3/d of oil), if the priority is production, but it swings to around 3500 s at 61 m^3/d (less production) with a gain of 19 m^3/d, if the priority is shifted to the profit. Once the simulator computes the flow variables, a post-processing module can generate as many different economic scenarios as required, without recalculation of the cycles. Variations of C_g/L_o have a remarkable effect on Figure 7.b (Carvalho and Bordalo, 2004), leading to different timer settings to provide the best economic operation point. One should also take heed of the possibility of negative gain. The post-processing module may quickly aid in such assessments.

Other variations may be studied with the help of the proposed model; for the sake of examples, Figure 8 presents a short study on the effect of the tubing diameter D_t (8.a) and the injection pressure of the gas P_{inj} (8.b) on the volume produced per cycle V_{lpc}. For tubings with a diameter smaller than the optimal, the fallback in the casing reduces the produced volume, while for broader tubings the storage capacity of the casing is smaller, thus, reducing the load. An increase in the energy of the injected gas (higher P_{inj}) imparts greater acceleration and speed to the liquid slug, with a favorable effect on the fallback; but this trend is somewhat limited buy the negative effect on the size of the slug, because of the increase in the bottom-hole pressure that acts against the reservoir inflow.

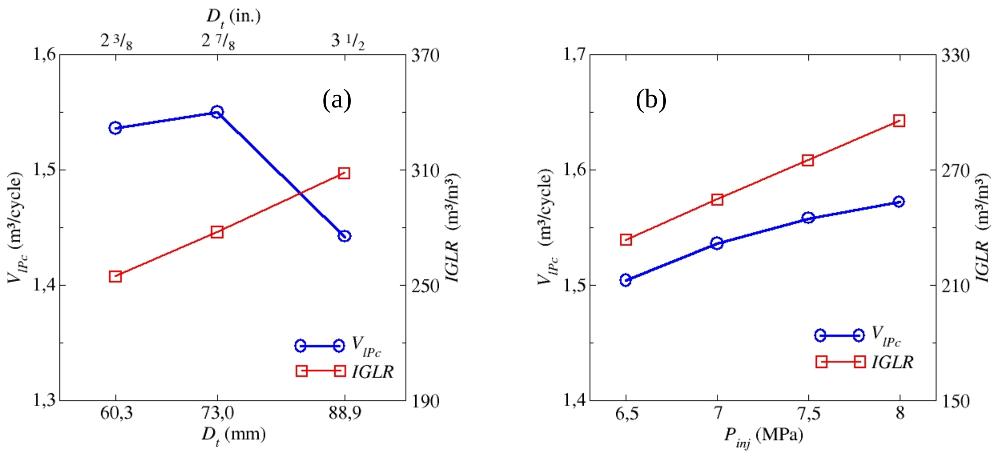

Figure 8. Sudies regarding the sensitivity to the tubing diameter (a) and to the injection pressure of the gas (b).

As mentioned before, the same model applies to the conventional IGL, therefore, many tests may be run to compare both methods for the same well-reservoir field condition. An example is shown in Figure 9, similarly to Figure 7 – in this particular instance, better results are obtained from the IGL-I; however, this is not a general rule. The engineer must compare these methods for each case in question using the simulator. Sometimes small differences in performance may arise, which, under the existing uncertainties, would not be enough to discriminate between the two systems. When such technical ties happen, other criteria of selection will come into play to settle the question.

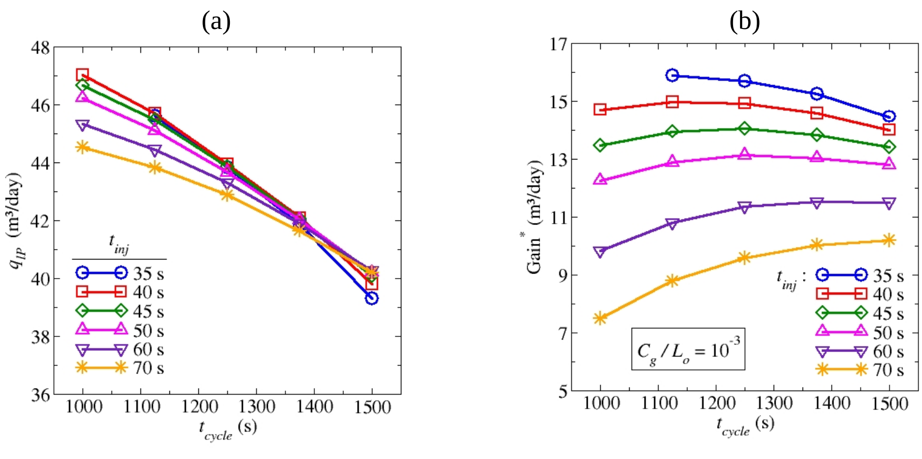

Figure 9. Conventional IGL – daily liquid production q_{lp} (a) and daily gain G^* (b).

5. Concluding Remarks

The simulation results show that the IGL-I may improve oil production at the expense of higher volumes of injected gas, when compared with the IGL. The required IGLR tends to increase due to a higher fallback when the liquid flows through the casing annulus. Nevertheless, it seems that, in many cases, the large capacity of the casing compensates for the gas input with an oil output that pays off.

It is of paramount importance to address the optimization of the timer setup of the motor valve, to settle the trade-off between the volume produced per cycle and the rate of cycles, in order to maximize production or gain.

The general modeling scheme designed for the intermittent gas-lift systems was successfully adapted for the inverted intermitent gas-lift (IGL-I), and a coupled simulator was built for both the IGL-I and the conventional IGL. The model was shown to be sturdy and reliable after running a great number of cases with different values for the configuration parameters. The simulator proved to be very usefull for the study of the dynamics of the intermittent gas-lift systems, for the diagnosis of the operations, and for the optimization of the operational settings. The simulator may also be employed as part of a decision process in the selection of the most adequate artificial lift system for a field application. The modularity and flexibility of the model and the simulator is a valuable asset for its future use as an engineering assistance tool. The present work may be extended to other versions of intermittent gas-lift systems. The physical model and the basic algorithm is in public domain, therefore, lending the present work to further improvement by any interested agents; only a specific realization of the model as a computer code would become a property of the programmer or its rightfull owner.

As a final note of caution, it is strongly recommended that carefull experiments should be performed for both systems, IGL-I and conventional IGL, to further validate the model and to improve the empirical correlations.

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