INTERMITTENT GAS LIFT PERFORMANCE ASSESSMENT THROUGH SIMULTANEOUS AND COUPLED DYNAMIC SIMULATION

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Resumo – A avaliação do Gas Lift Intermitente (IGL) através de cálculos computacionais usando os modelos mecanicistas encontrados na literatura geralmente aproxima o ciclo operacional do IGL por uma seqüência de estágios independentes, sem interação uns com os outros, ocorrendo sucessivamente sem superposição no tempo; esta aproximação restringe a análise do sistema a uma faixa limitada de condições operacionais na qual este comportamento particular existe. Na realidade, fora desta faixa, alguns estágios do ciclo de IGL podem ser simultâneos, e não seqüenciais como anteriomente assumido. Este artigo apresenta um novo modelo mecanicista de IGL com um esquema de simulação para considerar a possível ocorrência de estágios simultâneos e seqüenciais ao longo dos ciclos de IGL. A dinâmica dos ciclos de IGL é determinada por um sistema variável, simultâneo e acoplado, de equações algébricas não-lineares e equações diferenciais temporais, definidas interativamente ao longo da simulação e resolvidas de acordo com os estágios em ação do ciclo de IGL. Um estudo de caso para um típico poço equipado com IGL, produzindo a partir de um reservatório de baixa produtividade e parcialmente depletado, em diferentes condições operacionais, mostra como o simulador computacional de IGL pode ajudar o operador de campo a ajustar os parâmetros do IGL de modo a maximizar a produção do poço ou o seu ganho econômico.

Palavras-Chave: petróleo, gás, produção petrolífera, elevação artificial, gás lift

Abstract – The assessment of Intermittent Gas Lift (IGL) by computer calculations using the mechanistic models found in the literature usually approaches the IGL's operating cycle as a sequence of independent non-interacting stages, occurring back-to-back, without overlapping in time; that approach restricts the system analysis to the limited range of operational conditions when such particular behavior indeed exists. In fact, out of such range, some stages of the IGL cycle may be rather simultaneous than sequential, as previously assumed. This paper presents a new IGL mechanistic model and simulation scheme to consider the possible occurrence of both sequential and simultaneous stages throughout the IGL cycles. The dynamics of the IGL cycles is assessed through a simultaneous and coupled variable set of non-linear algebraic and time-differential equations, interactively defined on the run and solved according to the ongoing stages of the IGL cycle. A case study for a typical IGL well, producing from a low productivity reservoir partially depleted, at different operational conditions, shows how the IGL computer simulator can help the operator to set up the IGL parameters to maximize the well production or its economic gain.

Keywords: petroleum, gas, petroleum production, artificial lift, gas-lift

1. Introduction

The Intermittent Gas Lift (IGL) is an artificial lift method employed to produce oil when the reservoir is somewhat exhausted or its productivity is too low to use a higher producing method. A high-pressure gas supply provides the supplement of energy necessary to intermittently lift the reservoir's liquids (oil and water) up to the surface. The IGL cyclic operation is controlled by setting up the cycle period and the gas injection period on the timer controller of the injection motor valve at the surface, and by pressure-charging the dome of the operating lift-valve located inside the tubing string, near to the casing bottom. The IGL assisted wells can produce within a somewhat wide range of flow rates provided that the operator sets the aforementioned control parameters to achieve the goals designated by the company, which may be maximizing the oil production or the financial profit.

The operator must understand the behavior of an IGL well and how sensitive is the well response to its control parameters. The complexity of the calculations involved in the optimization of IGL cycles often encourage the use of simplistic correlations, lacking in generality, and of questionable validity. Hence a good computer simulator would be a helpful aid to the operator.

2. Literature review

The early works on IGL modeling were presented by Brown and Jessen (1962), White et al. (1963), Brill et al. (1967) and Neely et al. (1973). Those authors described the main patterns of the IGL, based on field measurements of test wells. Semi-empirical models were derived to predict some variables of the IGL operation. The simplicity of such models for handy calculations is advantageous. Nevertheless, most of them are based on results recorded just for the first IGL cycle, still under the influence of transient effects. Those models also lack generality and lead to a fragmented analysis of the IGL behavior, since some aspects of the IGL are not considered.

Schmidt et al. (1984) presented a dynamic model for the conventional IGL cycle, based on the conservation equations of mechanics. Comparisons between numerical calculations and measurements in an experimental test facility supported the validity of the model. Liao et al. (1995) developed a comprehensive mechanistic model for the conventional IGL cycle, obtaining results in good agreement with the former experimental works. The conventional IGL cycle was divided into 4 sequential stages, each one with its own complete set of ordinary differential equations. The stages were simulated in a standalone fashion, through an iterative numerical procedure. Santos et al. (2001) improved Liao's modeling approach, and extended it to other variants of the IGL: the IGL with chamber, the IGL with plunger (ideal case) and the IGL with pig (pig-lift); including the gas injection stage on the simulation.

Carvalho Filho and Bordalo (2003) developed a new approach to the IGL modeling. The possible occurrence of overlapping of the stages in the IGL cycle was considered according to the system dynamics. The derived model extended the simulation capabilities to a wider range of operational conditions, including those related to the IGL cycles with strictly sequential stages. Bordalo and Carvalho Filho (2004) used the same approach to model the inverted intermittent gas lift – where gas is injected through the tubing whereas liquid is lifted through the casing annulus – and presented a procedure to optimize the IGL output, maximizing either the oil production or the economic gain.

3. Modeling of the IGL Cycle

The IGL cycle may be described by stages: **injection** (gas input into the casing), **elevation** (gas-lift of the liquid slug inside the tubing), **production** (output of liquid at the surface), **decompression** (gas flow out of the tubing) and **loading** (liquid flow from the reservoir into the well), as shown in Figure 1 (a) to (e); while the physical IGL system can be modeled by dividing it into subsystems – comprising the *casing annulus* above the packer, the *production tubing*, the *perforation chamber* below the packer, the *oil reservoir*, the *source for gas-injection* and *production facilities* at the surface. Those subsystems are connected to each other through flow elements – injection motor-valve, gas-lift valve, production choke, bottom check-valve, lines and the well perforations, which regulate the interaction among the subsystems during the entire IGL operating cycle, according to proper boundary conditions represented by the reservoir and the surface facilities.

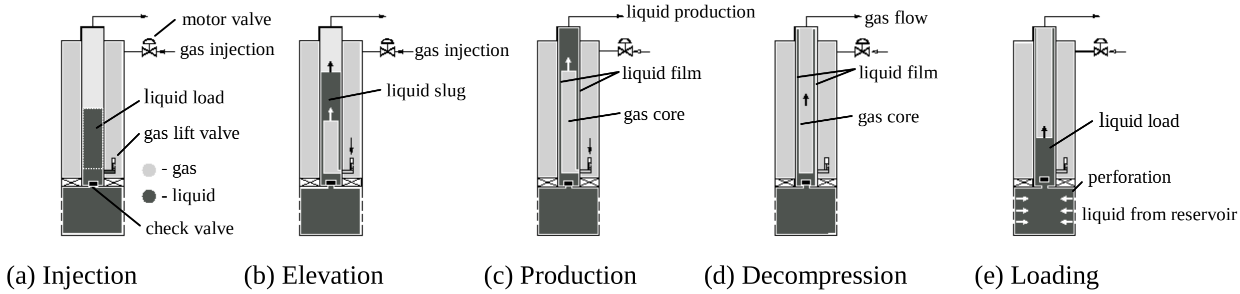


Figure 1 - Stages of the IGL cycle.

Depending on the subsystem, one or two distinct phases (liquid or gas) may flow within it. Each phase is represented by a control volume, over which the conservative mass and momentum balances are applied. Constitutive relations are also needed to accomplish the description of the subsystems, such as state equations for real gases and correlations for oil and water properties, flow friction factors, and mass flow rates through the valves. Combining all these equations results in a set of 25 coupled time-dependent non-linear ordinary differential and algebraic equations, that completely describes the dynamics of the IGL system. The equations may be written in the following general form:

$$dE_j(Y)\big/dt = F_j(Y)\,,\ j = 1,...,m; \quad \text{e} \quad H_j(Y) = 0\,,\ k = m+1,...,25 \qquad (1)$$

The vector Y contains the unknown variables such as densities, pressures, velocities etc; E, F and G are functions of Y. The complete model equations and variables are presented in Carvalho Filho and Bordalo (2003).

3.1 Simultaneous and Coupled Dynamic Simulator

An IGL computer simulator was developed based on the model above. The simulator has special logical features to modify the model "in mid-flight" due to changes in the system configuration, caused by specific events in the IGL operation – for instance, the opening or closing of a valve. To that effect, the equations and variables of the Equation set 1 that remain active at any point during a specific stage of the cycle are controlled by logical functions to keep both the physical and the mathematical consistency of the model. The resulting active equations are solved simultaneously by an iterative numerical procedure. The simulation marches forward in time, using the solution obtained from one time step as the initial condition for the next time step. A comprehensive description of the algorithm of simulation and the solution procedure for the model equation set is given in Carvalho Filho (2004).

4. Comparison with Experimental and Numerical Data

The IGL computer simulator was set to reproduce, as close as possible, the Neely et al. (1973) experimental tests, in order to validate the implementation of the model. Twenty-one cycles of single-point IGL tests were chosen for the comparison. The tests were gathered into four groups, according to their tubing-to-casing pressure ratio at the depth of the gas-lift valve at the time of its opening (P_{to}/P_{co}).

The comparison for the volume of injected gas for one IGL cycle is shown in Figure 2 (a). The difference between the measurements and the predictions are within a ± 20 % range, except for the $P_{to}/P_{co} \approx 0{,}3$ tests. In such cases, a greater volume of gas had to be injected through the motor valve until the gas lift valve opened, in the simulation. The predictions for the volume of produced liquid were also in fair agreement with the experimental data, as shown in Figure 2 (b). Despite of the higher volume of injected gas predicted by the simulator for the $P_{to}/P_{co} \approx 0{,}3$ tests, the predicted amount of produced liquid was within ± 20 % to the measurements in such cases.

The simulator underestimated the production of liquid for the $P_{to}/P_{co} \approx 0{,}8$ tests. The observed differences may be related to the slower liquid acceleration in the beginning of the elevation, when $P_{to}/P_{co} \rightarrow 1$. In those limiting situations, the fall-back of liquid during the lift process becomes high and a considerable volume of liquid can be produced due to the entrainment of the liquid in the gas core after the slug, what is not considered in the model – it assumes as produced the amount of liquid that reaches the surface through the film left behind by the fall-back on tubing inner wall – thus the total production of liquid tends to be underestimated.

Predictions of the IGL computer simulator were also in fair agreement with numerical results presented by Santos *et al*. (2001). According to the comparisons carried out, the IGL computer simulator seems to perform satisfactorily for the range $0{,}45 \leq P_{to}/P_{co} \leq 0{,}62$ – these limiting values agree with the range $0{,}5 \leq P_{to}/P_{co} \leq 0{,}75$ recommended by Winkler (1989) for IGL system design. Since no adjustments were made in the model at this point, higher agreement is expected in a particular case by adequate tunning the model to an experimental data set.

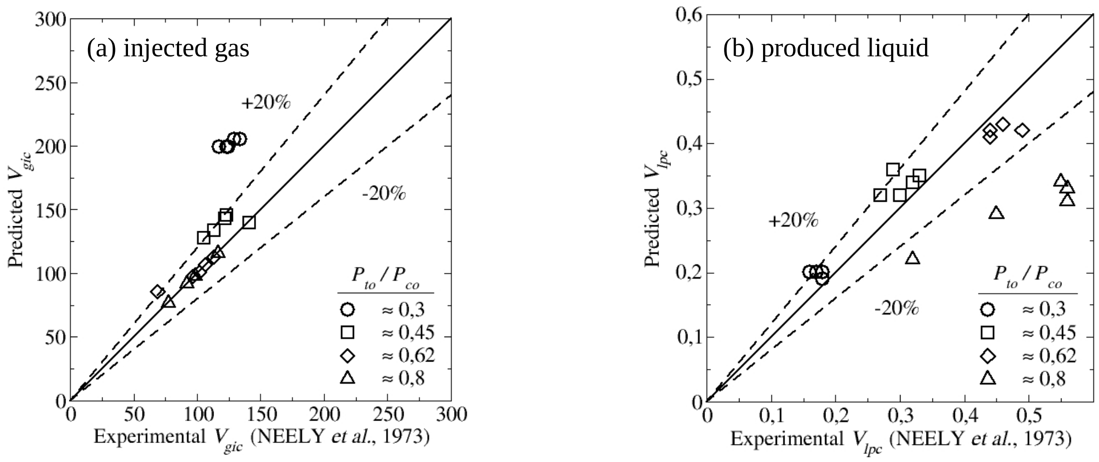


Figure 2 - Comparisons between the model predictions and the Neely et al. (1973) experimental data for one IGL cycle.

5. Assessment of IGL Cycles

A virtual vertical well producing liquid from a partially depleted and low productivity reservoir was considered to assess the IGL cycle patterns through simulation. The main characteristics of the virtual well and reservoir, listed in Table 1, are typical of certain fields in Brazil, which will remain undisclosed for the present.

Table 1. Main characteristics of the virtual well and the oil reservoir

average well perforation depth	1500 m (4921 ft)	reservoir static pressure	7,22 MPa
internal casing diameter (nominal)	127 mm (5 $^1/_2$ in)	productivity index	15 m³/d.MPa
internal tubing diameter (nominal)	50,8 mm (2 $^3/_8$ in)	surface temperature	15 ºC
gas-lift valve port size	11 mm (7/16 in)	underground thermal gradient	36 ºC/km
depth of the gas-lift valve	1475 m	relative density of the oil to water	0,876 (30° API)
dome pressure at 15 ºC (60 ºF)	4.8 MPa	relative density of the gas to air	0,7
port to bellows area ratio	0,2	water fraction	50 %
surface line pressure	686,5 kPa	injection gas pressure	6,86 MPa

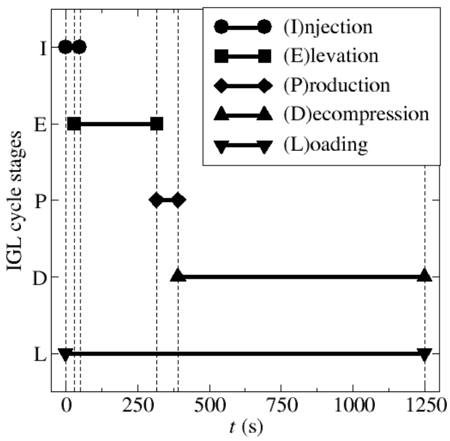
For the example presented in this paper, the motor valve was set at 1250 s and 50 s for the cycle period and the injection period, respectively. The simulation was performed with a time-step of 0.1 s, and a maximum tolerance of 0,001 % for the correction of the variables. Seven IGL cycles were simulated until a stationary regime was attained. Thereafter, the cycles repeated themselves without noticeable changes on the IGL outputs. The residues for global gas and liquid mass balances over the well were 0,1 % and 0,2 %, respectively. Only the results for stable IGL cycles are considered for analysis hereafter.

The time-line of the IGL stages is shown in Figure 3 (a); where simultaneous stages are observed along the cycle. The injection ended after the elevation began, and the liquid continued to flow from the reservoir to the well throughout the whole cycle, because the bottom-hole pressure was sufficient to keep the tubing check valve open. Figure 3 (b) displays a typical pressure record downstream of the motor valve and at the well-head, similar to those obtained from the field registers. The gas injection and the casing decompression signals shown at the top plot, together with the production peaks indicated at the bottom plot, attest the the stability of the IGL cycles.

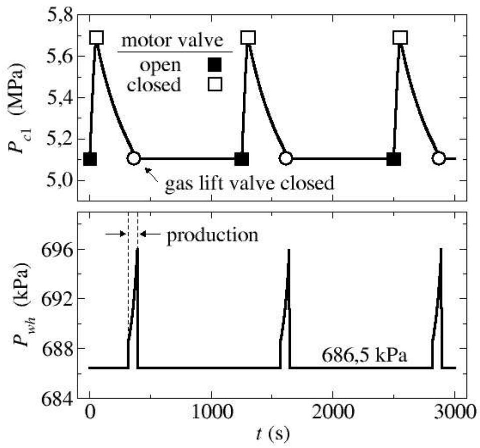
5.1. Maximization of the Well Performance

The IGL cycles can be simulated in a wide range of operational conditions. Based on the simulation results, an operational map for the IGL cycles can be drawn, as shown in Figure 4 (a). The timer settings – defined by by the pair (t_{cycle}, t_{inj}), respectively the cycle period and the injection period – leading to stable IGL cycles are indicated by the shaded area – the IGL cycle corresponding to (1250 s, 50 s) is indicated by a dot in Figure 4 (a). Unstable operation may occur outside of the shaded area. For instance, once the other IGL parameters remain constant, too short cycle periods lead to incomplete liquid loading when the gas injection begins, therefore the gas-lift valve does not open and both the motor and the gas lift valves are out of sync. On the other hand, for too long cycle periods, the load of liquid becomes too big to the volume of injected gas – indicated by $P_{to}/P_{co} \rightarrow 1$ – In such case, the liquid fall-back tends to increase cycle after cycle and the well production may even cease. A new operational map must be generated if the pressure charge in the dome of the gas-lift valve is altered.

For IGL stable cycles, the volume of produced liquid per cycle for different timer settings in Figure 4 (b) reflects the trade-off between two opposite effects. For shorter IGL cycle periods, increasing the volume of injected gas (longer t_{inj}) reduces the liquid volume produced per cycle due to the build up of smaller loads of liquid. For longer cycle periods, and longer injection periods, the larger loads of liquid combined with the reduction of fall-back increases the liquid production per cycle to a small degree.



(a)



(b)

Figure 3 - Patterns of stable IGL cycles from simultaneous and couples dynamic simulation.

According to the variation of the Injected Gas-Liquid Ratio (*IGLR*), shown in Figure 4 (c), it appears that the IGL output should be maximized towards shorter injection times and longer cycle periods. However, one must check the behavior of the oil production rate on a daily basis, and the daily gain, before drawing any conclusions. The daily liquid production is determined multiplying the volume of produced liquid per cycle by the daily cycle rate, which is the inverse of the cycle period, yielding the curves observed in Figure 4 (d). In fact, the daily production increases towards the shorter cycle periods due to the daily cycle rate. Whenever an appropriate gas supply is available at low cost, the operator should choose the timer setting (t_{cycle} = 1000 s, t_{in} = 40 s) to maximize the daily liquid production at 47 m³/d.

When the cost of gas is an issue, the simulator can also help the operator to determine the timer setting that maximizes the economic gain, as shown if Figure 5 (a). The determination of the overall economic gain involves many aspects, and will not be discussed here. Instead, a simple example is sufficient to demonstrate the applicability of the proposed procedure. Neglecting the cost of treatment and disposal of the produced water, the economic gain G^* may be expressed in units of equivalent volume of oil, as follows:

$$G^* = Q_{lp} \cdot \left[1 - WF - \left(c_g \,/\, l_o\right) IGLR\right] \tag{2}$$

The terms on the right side of Equation 2 account for the daily volume of produced liquid (Q_{lp}), the volume fraction of produced water (*WF*), the specific cost of gas – in any reference monetary unit per volume – (c_g), the specific revenue of oil – in the same reference monetary unit per volume – (l_o), and the injected gas-liquid ratio (*IGLR*).

The gain shown in Figure 5 (a) is calculated for $c_g/l_o = 10^{-3}$ – a reasonable assumption for some petroleum provinces in Brazil. Observing both the daily production of liquid and the gain curves, it is interesting to note that the point of maximum of one does not coincide with the point of maximum of the other. The maximum production attained is 47 m^3/d of liquid (23.5 m^3/d of oil) for a gain of a little less than 15 m^3/d of equivalent oil, for a timer setting of (t_{cycle} = 1000 s, t_{inj} = 40 s). On the other hand, the maximum gain is actually 16 m^3/d of oil for a daily production of almost 46 m^3/d of liquid (23 m^3/d of oil), obtained with a timer setting of (t_{cycle} = 1125 s, t_{inj} = 35 s).

Following the aforementioned procedure, the IGL output can be optimized according to the targets of the operator, whether he strives for the maximization of the production or the economic gain. Once the IGL operational map and the production variables are computed by the simulator, different economic scenarios can easily be assessed by a post-processing calculation, which may be required in view of the remarkable effects of the variations of the c_g/l_o ratio on the gain, as shown in Figure 5 (b). Even a negative gain may come off depending on the c_g/l_o ratio.

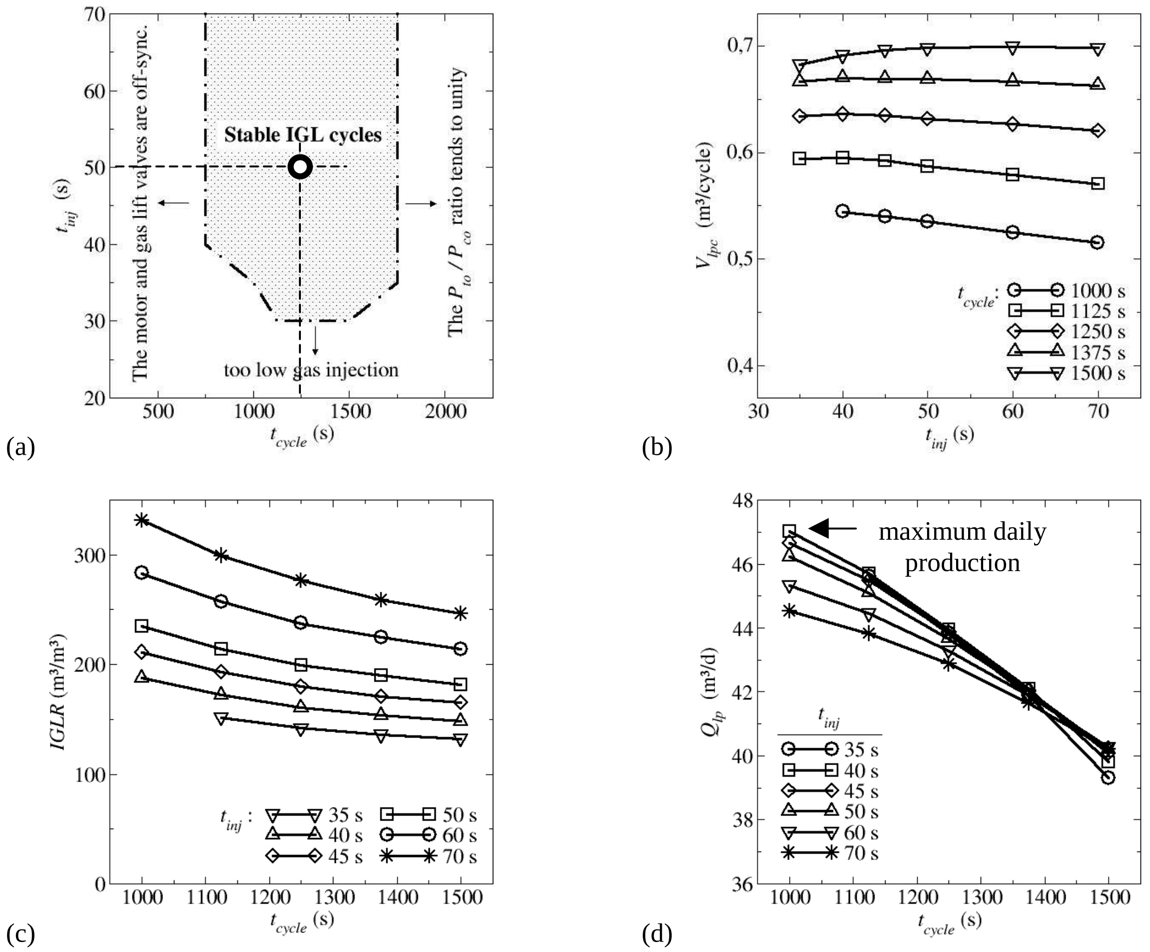


Figure 4 – Operational map and production variables for stable IGL cycles in the well under analysis

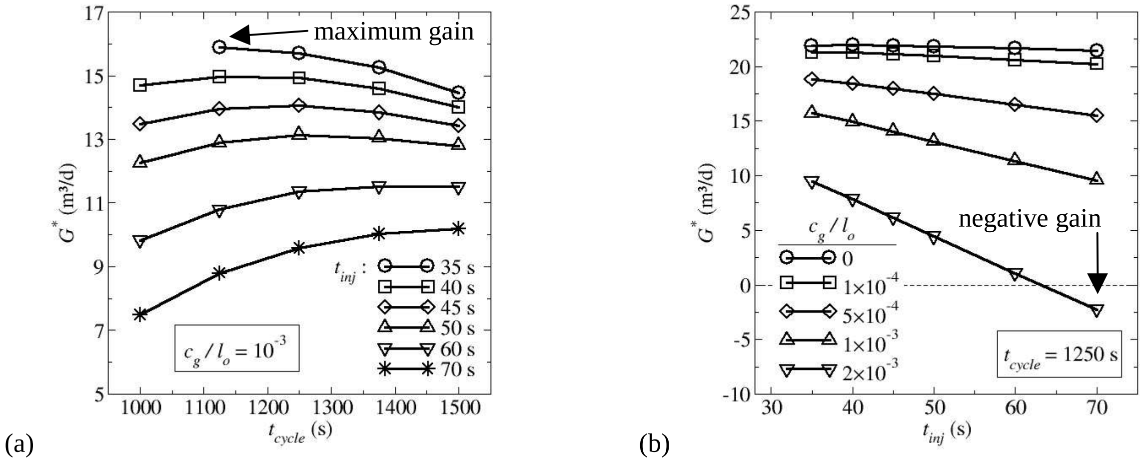


Figure 5 - IGL daily gain for different timer settings at the motor valve

6. Conclusions

An improved model for simultaneous and coupled dynamic simulation of the IGL cyclic operation was presented in this work. The IGL well-system was divided into subsystems and its cycle was split into stages: injection, elevation, production, decompressing and loading. The IGL modeling led to a complete set of 25 coupled time-dependent non-linear ordinary differential and algebraic equations, valid for all stages of the IGL cycle.

An IGL computer simulator was developed based on the model. The simulator is able to numerically reproduce several IGL cycles with both sequential and simultaneous stages, according to the boundary conditions of the well-system and the set up of its control-parameter. The simulation predictions were in fair agreement with the experimental data from Neely *et al.* (1973) within the range $0{,}45 \le P_{to}/P_{co} \le 0{,}62$. The discrepancy observed in the predictions of the volume of produced liquid as $P_{to}/P_{co} \rightarrow 1$ indicates a limit of the IGL model. The assumption of no liquid entrainment does not seem to hold in those cases.

The well response to the IGL control parameters can be assessed through simulation within a wide range of operational conditions. The IGL well performance can also be optimized towards the mazimization of the volume of produced oil or the economic gain of production. The IGL operation maps and its corresponding production charts can be generated from the simulations for different timer settings in the motor-valve and also different dome pressure charges of the gas-lift valve. Hence, with the aid of these maps and charts, the operator can easily determine the timer settings for stable IGL cycles, as well as its corresponding oil outputs, gas inputs and economic gains.

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