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CFD Modeling of Dynamic Flow Behavior of Intermittent Gas Lift Components

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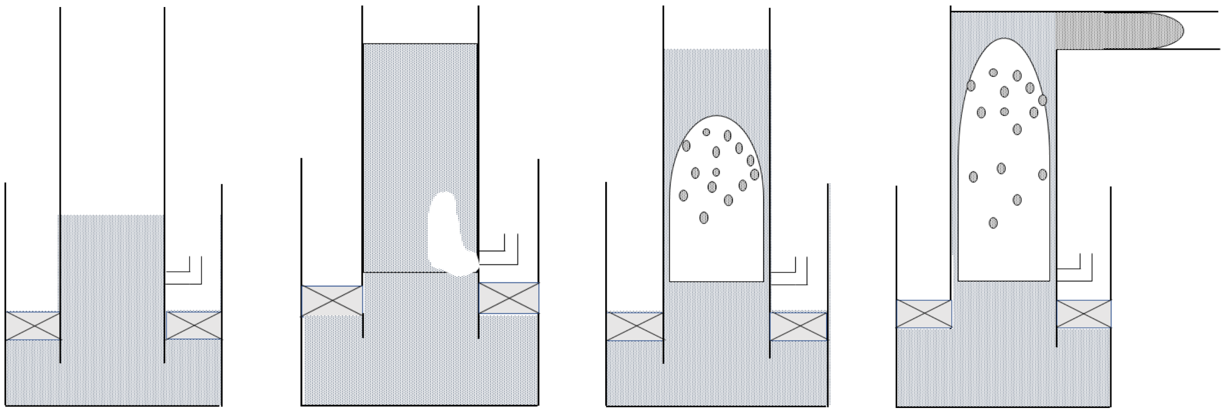
Abstract

The article analyzes the problem of improving the quality of demarcation of rocks, oil as well as gas horizons. The results of theoretical and experimental researches of the backfill materials expanding at hardening on the basis of ash mixes are stated. Clinker heat-resistant autoclave hardening backfill materials that expand during hardening, with high performance properties on the basis of man-made by-products of industry have been developed and studied. The selection of optimal formulations of new heat-resistant backfill materials of autoclave hardening, which expand during hardening, is carried out. The results of the work have practical application in the cementation of oil and gas wells in complex mining and geological conditions in exploration areas and industrial fields of oil and natural gas as well as gas condensate.

Keywords*: Artificial lift; Intermittent gas lift; CFD, Slug flow; Dimensionless analysis.*

1. Introduction

In the most oil field, oil exists in the reservoir under pressure from the natural energy that surrounds it. When a well is drilled into the reservoir, the formation fluids start to flow due to the pressure difference between the reservoir and the producing facilities on the surface. With the continuous natural oil production, the well will lose about 80% of the pressure required to lift the reservoir fluid to the surface and this effect the well deliverability. When the pressures in the reservoir and the wellbore equalize, it becomes very difficult to get the reservoir fluid to the surface without downhole artificial lift processes. In other wells, natural energy is not high enough to drive the oil to the surface at an economic rate; hence, one process of artificial lift must be utilized to sustain the reservoir natural energy. Gas lift is an ideal selection of artificial lift, if gas is readily available on the surface, either from dissolved gas in the produced oil well, or from an outside gas source [1]. Gas lift is a resemblance of the natural flow process with the different that gas is injected as a source of external power to increase the gas oil ratio that helps for decreasing the liquid column weight and lifting reservoir fluid to the well surface. Two types of gas lift are used in the industry one is continuous and the other is intermittent, both share the same principle but with different operation method. Intermittent gas lift is recommended for the mature field when the reservoir pressure is highly decline and continuous gas lift become economically and/or physically not efficient in liquid production. Intermittent gas lift systems have a different configuration includes conventional intermittent systems, configuration that introduce plungers to reduce the fluid fallback and, chamber lift systems to increase the initial accumulated liquid volume. Despite their apparent configuration differences, the fundamental principles for each of these intermittent gas lift operations remain the same. This technique is based on the principle of injection gas at regular time intervals sequentially with the well loading by the reservoir [2]. Intermittent gas lift is achieved by allowing the fluid to build up in the production tube at the bottom of the well (Fig. 1 (a)) and then a large bubble of high-pressure gas is injected periodically under the column of the accumulated liquid into the tube to push the liquid slug rapidly to the surface (Fig 1 (b)). During the slug movement, part of the liquid falls back as liquid film or droplet in the gas phase due to high apparent velocity of the gas (Fig. 1 (c)) When the liquid slug reaches the well head and starts to produce, more gas is injected into the tubing string through the gas lift valve as a result of the high-pressure difference between the tubing and the casing. The valve then close and injection gas stop to flow when the casing pressure drops to the conditions of the valve closing pressure [3] (Fig. 1 (d)). A stabilization time occurs after the slug has been produced, and the liquid fall back from the previous cycle flows down to the bottom of the well and becomes a part of the next cycle [4].



(A) Buildup of liquid slug (B) Gas injection (C) Liquid fall back (d) Slug production and valve close

Figure 1. Intermittent gas lift cycle

The need of high-pressure gas is periodic in intermittent process and this gives it the advantage over the continuous gas lift, but on the other hand, intermittent flow is not capable of producing a high-volume rate of fluid compared to continuous flow since gas is injected intermittently over a specific period. Investigation of the characteristics of an oil well during the movement of the liquid slug from the bottom of the well to the surface reveals researchers interesting. For proper design of efficient intermittent gas lift process the relationships of different parameters involve in the system at various points with respect to time should be defined. The unsteady state nature of intermittent flow, the high number of parameters involved, the interfacial instabilities and the different kinds of acting forces into the system increased the complexity of the system [5]. Also, from the open literature, the researches and publications of intermittent gas lift to this time are still few compared to another field of study. Some of the researchers studied intermittent gas lift systems using field test wells and operation conditions similar to real wells. Based on the experimental results, they examined the effect of different parameters on the efficiency of intermittent process [6-9]. Since the experimental work on a large scale that can represent the integrated intermittent gas lift production system is costly and complicated, some researchers tried to describe and determine the impact of different parameters on intermittent gas lift using laboratory-scale experiments [4,10-13]. Another part of researchers developed computer program based on mathematical models [14-16], mechanistic model [5], or numerical model [17-19]. Intermittent gas lift is considered as complex process and contains many interaction parameters that required trial and error procedure to find the best and optimum operation conditions that is good on case by case. The work on the intermittent gas lift should be proceeded to find a good computer model which can accurately describe the whole intermittent cycle and the effects of interaction parameters on the system efficiency.

Nowadays, A Computational Fluid Dynamics (CFD) model has been widely applied to perform the multiphase flow study of all flow regime types [20-29]. Computation simulation is applied in most of engineering fields, but unfortunately these studies are not deal specialty with the conditions found in the intermittent gas lift system. In this study, CFD simulations are developed to study the effect of different interaction parameters on the performance of the intermittent gas lift. To analysis the complex flow process, is important to reduce the actual system to dynamically similar small model by using mechanistic model. In the present study the dimensionless ratio of the variables is used rather than the actual value to reduce the complexity of the model and study a wide range of variable in a less simulation time.

Three-dimension tubing string with diameter of 2 in. and 2.375 in. is used in this paper; the tubing length is long enough (20D) to capture the flow regime and the feature characteristic of intermittent gas lift flow. Natural gas with a specific gravity of 0.7 is used as an injection gas to lift the accumulated liquid in the tubing (saltwater in this study) to the surface. The CFD simulation is developed with a commercial CFD fluent Ansys19, multiphase volume of fraction (VOF) model with standard k – ε turbulent model is used to capture the transient flow of intermittent gas lift. The goals of this study are to physically describe and investigate the slug flow during intermittent gas lift within the production string and to calculate the liquid production percent at different conditions with high accuracy. The results from the model developed in this study are compared with experiment's data from literatures to validate the simulation data.

2. CFD modeling development

2.1. Governing equations

CFD software FLUENT (Ansys 19) is used in this study to simulate the motion of gas bubble and liquid slug in a vertical tube. In CFD- FLUENT, the control volume method—referred to as sometimes the finite volume method is used to solve the transport equations. Multiphase flow can be numerically calculated in CFD simulator using either Euler- Lagrange approach or Euler-Euler approach. In the present study, the volume of the fluid VOF multiphase model is used which is a type of Euler-Euler approach. VOF model is a surface tracking technique and it is usually used to model more than two immiscible fluids, where interface position is important. The motion of large bubbles in a liquid and the steady or transient tracking of any liquid-gas interface are typical VOF model applications. The tracking of the interface(s) between the phases is accomplished by the solution of a continuity equation for the volume fraction of the phases. For the q phase, the continuity equation has the following form

$$\frac{1}{\rho_q}\left[\frac{\partial}{\partial t}\left(\alpha_q\rho_q\right)+\nabla.\left(\alpha_q\rho_q\vec{v}_q\right)=S_{\alpha_q}+\sum_{p=1}^{n}(\dot{m}_{pq}-\dot{m}_{qp})\right] \quad (1)$$

A single momentum equation is solved in VOF model throughout the domain and the resulting velocity field is shared among the phases. The momentum equation is dependent on the volume fractions of all phases through the mixture properties of density and viscosity $\rho\&\mu$.

$$\frac{\partial}{\partial t}(\rho\vec{v})+\nabla.(\rho\vec{v}\vec{v})=-\nabla p+\nabla.[\mu(\nabla\vec{v}+\nabla\vec{v}^{T})]+\rho\vec{g}+\vec{F} \quad (2)$$ where:

$$\vec{v}=\frac{1}{\rho}\sum_{q=1}^{n}\alpha_q\rho_q\vec{v}_q \quad (3)$$

$$\mu=\sum\alpha_q\mu_q \quad (4)$$

$$\rho=\sum\alpha_q\,\rho_q \quad (5)$$

$$\sum_{q=1}^{n}\alpha_q=1 \quad (6)$$

In the VOF model, the effects of surface tension along the interface can also be included between each of the phases. Surface tension is a result of attractive forces between molecules in a fluid. If we consider an air bubble is moving in liquid, the net force on a molecule within the bubble body is zero. However, at the bubble surface the net force is radially inward, and the surface is contract due to increasing the pressure on the concave side of the surface because of the combined effect of radially force across the entire spherical surface. The surface tension acts to balance the radially inter-molecular attractive force with the radially outward pressure gradient force across the surface. The surface tension model of CSF (continuum surface force) is used in Ansys fluent. A source term is added to the momentum equation to include surface tension to the VOF model calculations. If only two phases are present in a cell, a source term can be expressed as a volume force equation and can be written as below (Ansys fluent 12.0 theory guide):

$F_{vol} = \sigma_{ij} \frac{\rho k_i \nabla \alpha_i}{\frac{1}{2}(\rho_i + \rho_j)}$ (7); where:

$k = \nabla . \hat{n}$ (8)

$\hat{n} = \frac{n}{|n|}$ (9)

$n = \nabla \alpha_q$ (10)

$k_i = -k_j$ and $\nabla \alpha_i = -\nabla \alpha_j$ (11)

The calculation of surface tension effects is more accurate on hexahedral and quadrilateral meshes than on triangular and tetrahedral meshes. Therefore, where surface tension effects are important, the geometry should be meshed with quadrilaterals or hexahedra mesh. Since the flow is turbulent under gas lift condition, standard k – ε viscose model is used for turbulent modeling (for more details refer to Ansys fluent 12.0 theory guide).

2.2. Domain and grid generation

The geometry used in this study represents a tube string with two different diameters of 2 in. and 2.375 in. In intermittent gas well, the liquid accumulates in the tubing string to a certain level before the gas has been injected under the accumulated liquid. To represent the real intermittent gas lift process, at zero time of simulation, the designed tube is patched with liquid to a certain level and the remaining part patched with gas. The gas is injected from an inlet orifice with a diameter of 0.5 in. represent the port size of the gas lift valve. The geometry was created using ANSYS Design Modeler 19, and the mesh was constructed using ANSYS Meshing tool. Hexahedral computation mesh was created with enough mesh resolution near the wall as shown in Fig. 2 to capture the liquid film flow near the pipe wall.

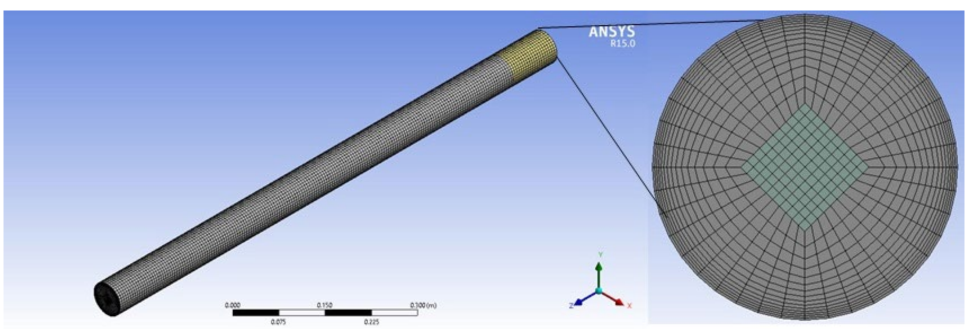


Figure 2. The structured mesh used in this study

2.3. Solution and boundary condition

The multiphase model of VOF is selected with k – ε viscose model for turbulent flow. Pressure inlet and pressure outlet are set at the boundary condition. Pressure inlet and pressure outlet boundary conditions are used. In the industry, the gas injection is ceased when the liquid slug reaches the well surface so, user define function is written to set the pressure inlet based on the liquid volume fraction in the tubing outlet (Appendix A). Three-dimensional transient model using pressure-based solver with time step of 0.001 is performed and the solution data file is automatically saved at defined point during the simulation.

3. Results and discussion

The main objective of this study is to physically study the effect of different parameters on the amount of liquid production percent during an intermittent cycle. The initial variables of injection pressure, tubing pressure, submergence length and valve depth are related to the liquid production fraction for certain tubing size and valve diameter. To minimize the number of the variables and the complexity of the system, the dimensionless ratios rather than the actual value are used to study the system. The dimensionless ratios of the Pi/Pt (injection pressure/tubing pressure) and the S/D (submergence/ injection depth) are related to the dimensionless production ratio N/S (production/submergence). Fig. 3 shows the vertical cross section plane of different geometry used in this study at the initial time of simulation.

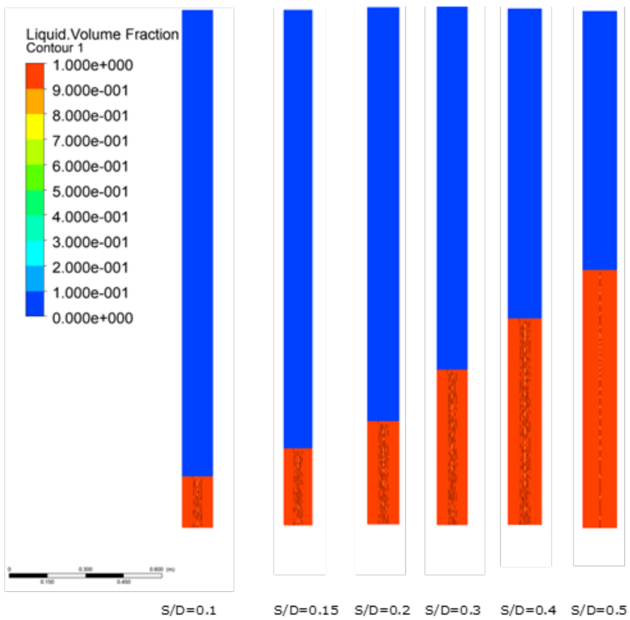


Figure 3. The vertical cross section plane of different geometry used in this study

The gas is injected at certain value under the accumulated liquid through gas lift valve and the injection gas is ceased when the liquid slug reaches the surface of the tubing string. The slug continuous to produce as far as the expansion energy of the gas beneath it is sufficient to produce the entire slug. During the slug production part of the liquid is fall back as liquid film near the wall or/and liquid bubble due to the high slippage velocity of the gas. The liquid film is moving down along the tube wall according to the gravity direction and the liquid fall back accumulates again in the bottom of the tube to join the new cycle.

The liquid produced in the cycle can be calculated from the initial liquid slug volume minuses the liquid fall back in the tube. The dimensionless production ratio N/S is plotted versus the dimensionless submergence depth ratio S/D as shown in Fig. 4 for the tubing size 2.375 in. and 2 in. The results are compared with the production chart of White *et al.* [10] to valid the CFD model.

It can be concluded that in the certain submergence ratio, the recovery percent increases as the injection pressure increases. Also, it can be noted that as the submergence high increases, the production percent also increases at given injection pressure. The current developed model shows a good agreement with the literature data.

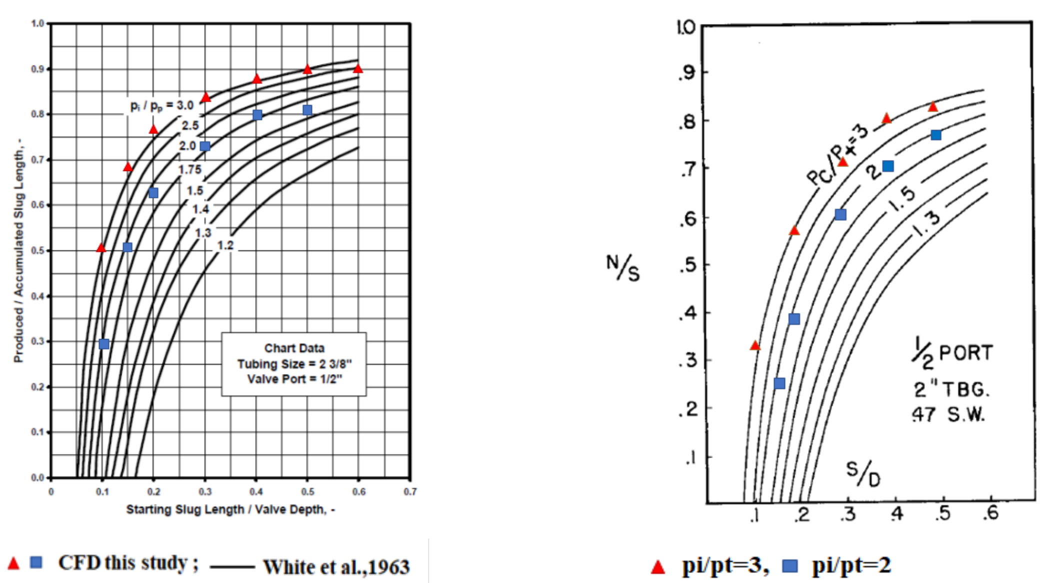


Figure 4. Liquid production percent for two different injection pressure and tubing size

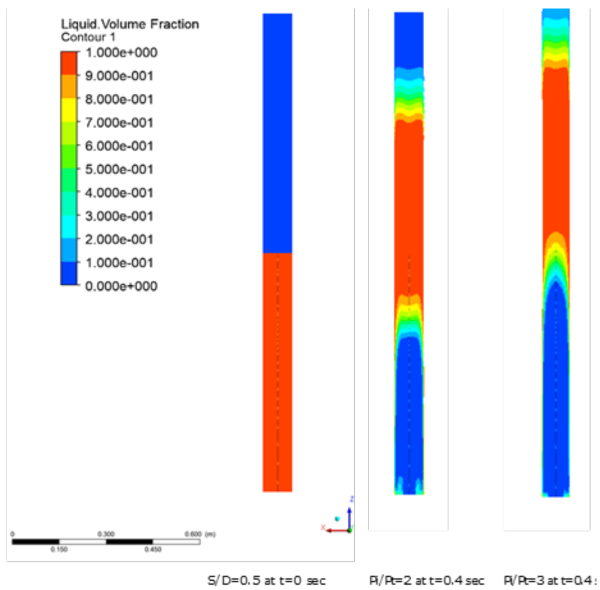


Figure 5. Slug proceeding for two different injection pressure at same tubing size 2.375

Fig. 5 shows an example of the slug proceeding for two different injection pressures at the same injection time, tubing size and initial submergence high. It can be concluded that as the injection pressure increases, the slug velocity increases and reach to the surface faster so that, the liquid production would be increased.

Study the pressure profile during intermittent gas lift cycle is an interesting topic in the oil industry that received a special attention from the researchers for the efficiency and proper design of the system [30]. The pressure gradient along the pipe length at different injection time can be plotted using CFD simulation and a sample of pressure gradient is shown in Fig. 6.

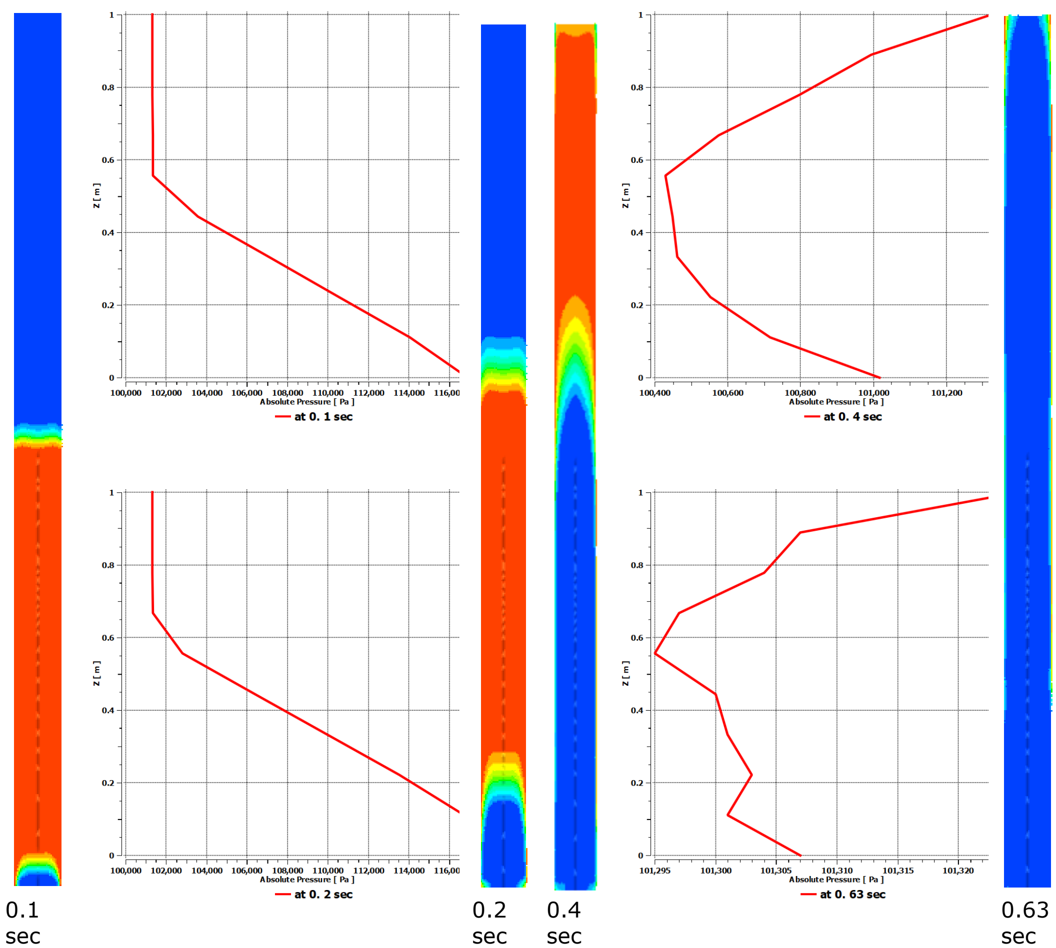
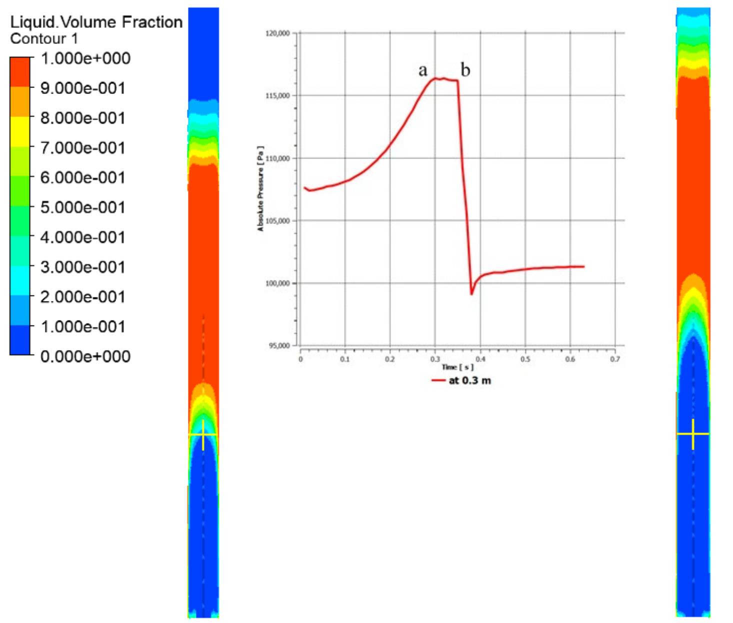


Figure 6. Pressure along the tubing length for different injection time (tubing size 2in. port size 0.5 in. Pi/Pt 3 and S/D 0.5)

The pressure change with time for different position inside the tube can a be plotted using CFD simulation. To describe how the pressure changes at a certain position in the tube with the slug movement progress, an example is described in Fig. 7. Before the gas is injected in the tubing, the pressure at any point along the pipe is equal to the hydrostatic pressure. When the gas is injected into the tube, the pressure began to increase inside the tube until the gas bubble is reached to the studied position (Fig. 7a). Then the pressure remains constant at that position because of the effect of liquid film near the wall. The pressure inside the tube starts to decrease as soon as the gas injection stops when the liquid slug reaches the tube surface (Fig. 7b).



(a) at time 0.3 sec

(b) at time 0.36 sec

Figure 7. Pressure versus time with slug proceeding for 0.3m (tubing size 2in.and Pi/Pt=3)

4. Conclusions

A computation fluid dynamic model is presented in this paper to physically describe the intermittent process and study the effect of different parameters on the dynamic behavior of the system. One of the most useful tools for the study of complex systems in the fluid mechanics is reducing the system to a dynamic similar model. Grouping the well parameters into dimension less ratios have the advantage of minimums the complexity of the system and the time required for the simulation. The percent of the liquid production is related to the injection pressure and the submergence depth at given tubing and valve size. The results obtained from the simulation are compared with the production chart of White *et al.*, [10] to validate the model results. The production rate increase with the increasing of tubing size, length of the initial liquid in the tubing and injection pressure. The maximum rate of production reaches up to 90% for the tubing size of 2 3/8 inch. There is no significant change in the production rate could be observed when the submergence length increase higher than 50% of the tubing length at the same others operation conditions because the liquid fall back increase and the pressure below the liquid slug is not sufficient to lift the liquid to the surface. It is obvious that, the production increase as the injection pressure increase. CFD simulation shows the potential to predict the production ratio at high accuracy and can be used in the future for further development in the researches related to such complex system same as intermittent gas lift. By using the CFD model it can be physically described the slug flow inside the tube and the interaction parameters involve in the system. The pressure profile can be easily obtained for different location and conditions along the production tube. Finally, more effort should be taken in this field of study by applying CFD simulation for further development of the process.

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Nomenclature

F_{vol}	*Volume force*
k	*Curvature*
n	*Surface normal*
∇	*Divergence*
$\hat{n}$	*Unit normal*
σ	*Surface tension coefficient*
$\dot{m}_{pq}$	*Mass transfer rate from phase p to q*
$\dot{m}_{qp}$	*Mass transfer from phase q to p*
S_{α_q}	*External mass source entering phase q (Kg/s/m3)*
μ	*Mixture viscosity*
ρ	*Mixture density*
$\vec{v}$	*Mixture velocity*
$\vec{F}=$	*Gravitational body force and external body forces*
$\vec{v}_q$	*Velocity of phase q*
P	*Static pressure*
Pi	*Injection pressure*
Pt	*Tubing pressure*
N	*Production rate*
S	*Submergence*
D	*Injection depth*
α_q, α_i, α_j	*Volume fraction of phase q, I, j*
ρ_q, ρ_i, ρ_j	*Density of phase q, i, j*

Appendix A

```
#include "udf.h"
#INCLUDE"sg_mphase.h"
DEFINE_PROFILE(pressure_magnitude, thread, i)
{
real pressure_mag;
face_t f;
Thread*t_outlet;
int Zone_ID = 10;/*outlet zone ID*/
Domain*domain;
domain=Get_Domain(2);/*to get liquid phase*/
t_outlet =Lookup_Thread(domain,Zone_ID);
begin_f_loop(f,thread)
{
if (F_VOF(f,t_outlet)<=0)
{
F_PROFILE(f,thread,i) =15600;
}
else
{
F_PROFILE(f,thread,i) =0;
}
}
end_f_loop(f,thread)
}
```

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