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Comprehensive Study on Improving Proppant Flow-back Control Using Resin Coated and Rod-shaped Proppant in Egyptian Fractured Wells

Ahmed A. Gawish[1], Said K. Elsayed[1], Ahmed A. Elgibaly[1], and Mohamed A. Heikal[2]*

[1] Suez University, Faculty of Petroleum and Mining Engineering, Cairo-Suez Road, Suez, Egypt
[2] Khalda Petroleum Company, 290 New Maadi, 3rd sector, Cairo, Egypt

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Abstract

Hydraulic fracturing is used as one of the main powerful tools to bypass the formation damage and increase its productivity. One of the most critical problems that faces that treatment is the proppant flow-back production that could lead to failures in surface and downhole equipment. Besides, it reduces severely the fracture width and consequently the fracture conductivity. The use of curable resin to be pumped with proppant or using the rod-shaped or any unconventional type of proppant could be a solution for controlling proppant flow-back and creating more stable fractures. Many models designed for predicting the proppant flow-back and provide measurements about fracture stability. Semi-mechanical model, Free-Wedge model and Stimlab model are utilized in our study on more than 50 wells in the western desert to predict proppant flow-back and showed impressive results. After optimizing case studies and prediction models, the conclusions indicated the effective factors controlling the proppant flow-back that are the drag force, closure stress, critical speed, cyclic stress and fracture width. Besides, the optimized treatment size of unconventional proppant should be about 3-5% of the total main treatment size and coating of 45-50% of treatment size is the optimum percentage for significantly improving the results.

Keywords*: Fracture stability; Proppant flow-back; Resin-coated proppant; Rod-shaped proppant; Semi-mechanical model; Stimlab model.*

1. Introduction

During the life of any production well there is a period when the production rate started to drop due to formation skin which could be the result of any source of damage such as mechanical, chemical or biological as in [1] which easier to be evaluated as it causes reduction of formation permeability despite the water-based fracturing fluid itself might cause damage and decrease the permeability by 11% as well as in [2] specially for low permeability reservoirs. Stimulation treatments -mainly hydraulic fracturing- could be a solution but the presence of the proppant flowback could show severe decline in the fracture conductivity and choke the fracture width which would have negative effect on the productivity of the well in addition to the flowing of proppant grains would erode all the subsurface equipment, production tubing and surface facilities.

Several previous studies like in [3] have been trying to find out the main reason of the proppant flowback and how to minimize the subsequent harmful effects, researchers in their laboratory tried to search for the factors affecting the proppant flowback and what is the major factor controlling the whole operation and Numerical Models has been developed to estimate the critical drawdown pressure to avoid solids flow [4].

Many techniques were used to prevent proppant flowback starting from minimizing or controlling the production rate then using forced closure technique [5] which was not highly effective after that, the using of fibers and deformable particles which construct a network between the proppant and fibrous strands which bridge the perforation and allow only solid-free fluid to flow in addition to reducing the leak-off coefficient of the fracturing fluid as reported in [6] flow but this technique faced the problem of losing the fracture conductivity.

The using of resin-coated proppant (liquid resin system) and the rod-shaped proppant is according to our study could provide higher degree of stability according to the field data results and to the models results themselves.

2. Typical models and techniques used for proppant flow-back control

Models are presented by several studies such as [7-8] trying to demonstrate and clarify the proppant flowback problem and tried to optimize the hydraulic fracture design treatment as a first step to eliminate this problem during the design process, also since 1990 several models are objected to discuss this problem over four main branches, the first one related to the critical velocity in lab using flowback cells, the second one is related to the chemical engineering specifically the flow theory, the third one is the use of mechanical engineering with the proppant transport [9] and placement theories to predict the proppant flowback which is most validated and accountable and the forth one is the numerical methods.

3. Main models for predicting proppant flow-back

3.1. Stimlab model

It is an empirical model that have been conducted by Stimlab consortium in 2002 [10] trying to explain the proppant flowback phenomenon and the parameters that may control this issue, the output was an empirical correlation and a plot between the net closure stress on the x axis and the width to mean diameter ratio (width ratio Wr). It considers the critical fluid velocity is the major parameter. The stability region of this model states that the fracture will be stable when the width ratio is equal to 6 or less. The main disadvantage of this model is that it does not work over range of the closure stress also it was mainly applied on ceramic proppant only. The critical fluid velocity is given by

$$vc = 21.17\left(\frac{SGp\ dp^{2}}{cp\ \mu}\right)Co + Cl \tag{1}$$

3.2. Proppant free wedge model

This model was created by Andrew and Kjorholt [8] and validated by field data. This model focuses on the major two factors affecting proppant flow back which are the drag forces and the closure stress and showed a plot representation between both factors

$$F = \frac{dp}{dx}\left(\frac{dp}{dref}\right)^{3} \tag{2}$$

$$C = \frac{dp}{dx}\left(\frac{dref}{dp}\right)^{2} \tag{3}$$

It is assumed that these forces are related to a reference proppant diameter (while experiment used 0.0284 inches) but it over estimated the drag force (to power 3) as a body force that have major effect. The main disadvantages of this model are the limited range and the single-phase flow assumption but it also valid during the clean-up period which is two-phase flow also, the mechanical destabilization area at width ratio more than 6 is not persuading. The main equation representing the model is Wr max and it represent the maximum stable width ratio is given by

$$Wr,max = 3.2 + 5.51x10^{3}C - 5.47x10^{5}C^{2} + 0.17F + 1.61x10^{2}CF - 6.92x10^{-3}F^{2} - 5.34x10^{5}C^{2}F \tag{4}$$

3.3. Semi-mechanical model

It is a theoretical model was mentioned in [10] consider the concept of minimum fluidization velocity that used in both chemical and mechanical engineering, if the fluid velocity increases the proppant will fluidize under the liquid or gas flow at specific critical porosity called emf from the following Ergun equation.

$$(1-\mathrm{emf})(\rho p-\rho f)g = 150\,\frac{(1-emf)^{2}}{emf^{3}}\,\frac{\left(\frac{\mu f}{1488.16}\right)\mathrm{vf}}{\left[\Phi s\left(\frac{dp}{12}\right)\right]^{2}} + \frac{1.75(1-emf)}{emf^{3}} + \frac{\rho f v f^{2}}{\Phi s\left(\frac{dp}{12}\right)} \tag{5}$$

This model tried to develop good understanding and include for more substantial factors controlling the proppant flow back production and the fracture stability. Such as drag force, net closure stress, fracture width, nominal proppant strength and proppant diameter. The main advantage of this model is that solves the previous problems that pointed out after applying the first two models.

$$F\ stable = WT \exp\left[-0.5\left(\frac{\ln(pc\ net) - a'}{ST}\right)^2\right] + F\ fv \qquad (6)$$

This equation provides the maximum pressure gradient that the proppant pack could handle without failure. But increasing the gradient more than that would unfortunately causes proppant flowback. The width term WT is given by

$$WT = 1422.5 \exp(-1.0483Wr) \qquad (7)$$

As it might be noticed that as Wr is small value that means that WT is larger and its WT increase the fracture will be more stable. Also, the strength term ST is given by

$$ST = 3x10^{-5}Smax + 0.22368 \qquad (8)$$

The strength at which the proppant permeability is reduced to 15% of the non-stressed nominal value and the nominal strength of any proppant is provided by the proppant manufacturers.

$$Ffv = 1.365x10^{7}\frac{vf\ \mu f}{Kf} \qquad (9)$$

The minimum pressure gradient for mobilization of loose cohesionless grains. The idea of this model is similar to the optimization is made to eliminate the sand production by avoid reaching to the critical drawdown pressure [4].

If the actual pressure gradient is smaller than the maximum stable, the fracture will remain stable; otherwise, proppant flowback will be present.

4. Practical and experimental techniques used to control proppant flow-back

4.1. Resin-coated proppant

It was first introduced in 1975 [11] with two types curable resin pre-coated proppant and liquid resin system, the first type was used previously as a proppant flow-back controller and conductivity enhancer also, reduce the crushing percentage and sand production and proppant embedment also improving the crush resistance and preventing the plugging and fine migration. It has impact to face the proppant digenesis [12-13]. The results of using this Type of proppants showed moderate results and insufficient strength and not very good conductivity enhancement also it rises huge problems of storage, environment and safety issues in addition to that it chemically reacts with the fracturing fluid and reduces the effectiveness of the breaker, temperature and curing process.

The liquid resin system [14-16] is used commonly used since that time, it differs from the first type in the way of pumping unlike the first type, the liquid resin system is pumped on the fly to coat the proppant, this liquid resin coating provides higher consolidation strength for proppant pack to support the proppant pack even at higher drawdown and under higher cyclic stress.

Lower bottom-hole temperature causes the liquid resin system not to work properly as it needs curing process to be implemented in order to show the consolidation strength and the proppant flow-back prevention. If the formation exhibits lower temperature it might need an activator to shorten the curing time.

The capillary pressure between the proppant grains covered by resin pulls the resin to contact point and helps to prevent the resin from occupying the pore spaces, after complete curing process is provided; the shape of resin-coated proppant is become like in Figure 1.

Figure 1 Resin-coated proppant after complete curing process

Figure 2 Rod-shaped proppant typical cylindrical shape

One disadvantage of the liquid resin is that it might still lose percentage of the resin because of the chemical reaction that it might take place between the fracturing fluid and the liquid resin.

4.2. Rod-shaped proppant

This type of unconventional proppant (cylindrical shape) was first introduced in field recorded in our study in 2010 [17-18], as a proppant used to improve the hydraulic fracturing conductivity than the conventional (spherical) proppant also the elongated rod shaped and high strength particles to control the flowback as shown in rod-shaped proppant Figure 2.

It almost avoids the weakness points that were noticed on the previous type of proppant flow-back controller which is resin coated proppant, as there are no any chemical reactions, no need for curing time or to add any chemicals to adjust fracturing fluid PH and no need for a specific forced closure operation.

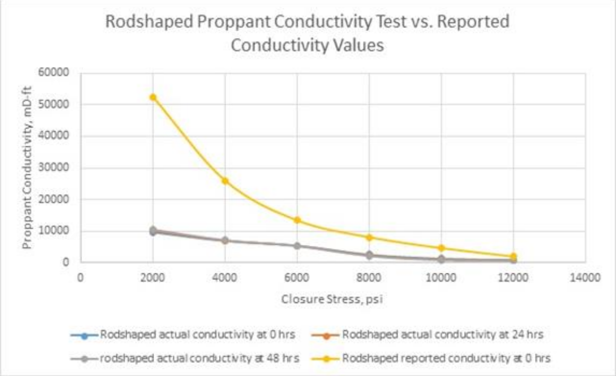

Fig. 3 API conductivity test for rod-shaped proppant

The concept of changing the particle shape and packing enhancement and the mechanical interlock between proppant pack grains that provide the key factor for preventing proppant flow-back with nearly coarser cylindrical proppant, also it is obvious that as the cylindrical shape has higher moment of inertia than sphere it acquires higher resistance to rotate or to move out of the fracture.

There are variations in diameter and length of the proppant pellets and it is very important criteria as if the diameter or the length are too large bridging could occur and if the diameter or the length are too short, then proppant flow-back could occur and cause reducing of the fracture conductivity.

Rod-shaped proppant was presented as a solution for proppant flow-back with conductivity enhancement but after performing standard conductivity test API RP 19D (ISO 13503-5) in the lab under different points of stress it shows that it loses considerable percentage of conductivity after the application of the stress for amount of time. These results are contradicting with the reported data and previous studies [19,17] that assured that the fracture conductivity will be improved after proppant placement in the fracture. Our conductivity test graph in comparison with the reported conductivity data is presented in Figure 3.

5. Results and discussion

5.1. Resin-coated proppant (liquid resin system)

The results after the application of the resin-coated proppant (liquid resin system) was adequate but not very satisfactory despite assuming that the resin is curing properly and the strength is acquired after consolidation is increasing the proppant pack strength by 2000 psi [14]. When treatment size is completely coated by resin, it provided good results but it was cost prohibitive after performing many treatments the success ratio is increased and better results could be provided with almost 45 to 50% coating of the total treatment mass after conducting more than 25 treatments.

Previous studies [14] have been conducted on the liquid resin system to provide the minimum curing time required to have strong consolidation strength after executing the hydraulic fracturing job and showed that the time is almost 7 hours with nearly 190°F, which is the formation temperature of the study.

For the study wells which have been stimulated with hydraulic fracturing and liquid resin system was used to control the flow-back of the proppant, the typical wells condition included bottom hole temperature about 190-200°F and closure stress up to 5000 psi, the treatments were pumped at 25-30 bbl. /min and the typical proppant mass 130,000 to 140,000 lbs of proppant at concentration reach to 7 lb/gal. The concentration of the liquid resin system used to coat the proppant volume (volume by volume) was about 2-3%.

5.2. Application of resin-coated proppant on treated wells

When applying the liquid resin-coated proppant treatments in the presented three models, as mentioned in an early study that the resin coating adds from 1500 to 2000 psi to the nominal strength. Of more than 20 wells the Semi-mechanical model, free wedge model and Stimlab model have predicted about 70% induced fractures after the treatment and using liquid resin system as stable fractures. In addition, it shows that the degree of stability for the resin-coated proppant is moderate and the abrupt increase of drag force or lowering the proppant size would lead to proppant flow-back. Results are based on the data provided by the service companies and properties of proppant provided by proppant manufacturer. The proppant characteristics and results comparison are summarized in tables 1 to 3 respectively.

Table 1. Proppant characteristics of resin-coated proppant treated wells

Wells	Kf (mD)	Proppant type	Proppant mass	Porosity Φ	Proppant size	Proppant S.G.	Proppant diameter
Well 1	240,000	Premium sand Prop	134,400	0.34	20/40-16/30	3.45	0.035
Well 2	250,000	Intermediate strength Proppant ISP	121,600	0.40	20/40-16/30	3.22	0.0255
Well 3	250,000	Premium sand prop	124,800	0.32	20/40-16/30	3.50	0.0255
Well 4	260,000	Premium sand prop	150,400	0.3	20/40-16/30	3.50	0.0255
Well 5	220,000	ISP	123,800	0.3	20/40-16/30	3.22	0.03
Well 6	280,000	ISP	119,900	0.16	16/30	3.22	0.025
Well 7	290,000	ISP	112,000	0.31	16/30	3.22	0.026
Well 8	320,000	Premium sand prop	121,600	0.30	16/30	3.45	0.0245
Well 9	230,000	Premium sand prop	112,000	0.3	16/30	3.45	0.026
Well 10	380,000	ISP	138,100	0.4	20/40	3.22	0.0255
Well 11 A	334,560	Premium sand Prop	140,800	0.41	20/40-16/30	3.50	0.031

Table 2. Design results calculations of resin coated proppant treated wells

Wells	hp (ft) Net pay	hf (ft) design	Pc, net (psi)	V_f placed (ft^3)	C_{fd} Dimension-less conduc-tivity	J_d Dimensionless PI	Wp (inch) average width	Wp, max (inch) max width
Well 1	14	82	5861	79.46	3.57	0.6	0.25	0.41
Well 2	54	123	5136	224.74	2.76	0.52	0.18	0.28
Well 3	12	110	5840	45.76	4.359	0.74	0.145	0.23
Well 4	14	75	6200	97.22	1.494	0.76	0.256	0.40
Well 5	12	115	7605	52.94	31.15	1.42	0.177	0.28
Well 6	36	46	4803	262.84	2.78	0.87	0.27	0.43
Well 7	14	47	6851	113.76	4.36	0.87	0.291	0.46
Well 8	15	121	7100	50.81	6.66	0.86	0.124	0.2
Well 9	10	95	3600	42.10	1.85	0.82	0.12	0.2
Well 10	20	74	5370	153.38	2.84	0.55	0.36	0.57
Well 11 A	24	83	4944	173.44	7.71	0.71	0.38	0.61

Table 3. Results of stability models for resin-coated proppant

Wells	Free wedge model	Semi-mechanical model	Stimlab model
Well 1	Stable	Stable	Stable
Well 2	Stable	Stable	Stable
Well 3	Stable	Stable	Unstable
Well 4	Stable	Stable	Stable
Well 5	Stable	Unstable	Stable
Well 6	Stable	Stable	Stable
Well 7	Stable	Stable	Unstable
Well 8	Unstable	Stable	Stable
Well 9	Stable	Stable	Stable
Well 10	Stable	Unstable	Unstable
Well 11 A	Stable	Unstable	Unstable

5.3. Application of rod-shaped proppant on treated wells

The field implementation for this technique showed better results concerning the proppant flow-back prevention, it was first induced 8 years ago in our field, as an engineering practice to reduce cost for this technique as well, and optimization for the mass of proppant was highly considered.

After the optimization procedure applied on the range of study. Percentage of rod-shaped to the treatment size was initially reduced to (25% per mass) and (50-60% per volume) and then in the following treatments, it was optimized and decrease the volume of the rod-shaped proppant to reach (15% per mass) and (40-50% per volume) to be limited to be used in the tail-in stages. It was noticed that the clean out time is dropped and it showed better stable production and improvement in the artificial lift (Electrical submersible pumps and sucker rod pumps in our study) Performance as it avoids the plugging and the wearing of the internal parts or the pipeline leakage.

Using the rod-shaped proppant enhanced the well's life and the artificial lift sustainability, which provide substantial reduction of the cost that, would be spent on work over rigs for investigating the problems and applied remedial work technique to control or minimize the problems.

More than 95% of the hydraulic fracturing treatments utilizing the rod-shaped proppant implementation in the wells were successful. Applying the preceding models on the wells utilizing rod-shaped proppant provide higher values of stability as the rod-shaped (cylindrical-shape) proppant has equivalent large diameter and it was used with coarser grains and modeled as diameter = 0.079 inches with normal spherical proppant with diameters between

0.0248 and 0.0351 inches for our study mesh sizes proppant size besides the elevated nominal strength and all these factors enhances the stability value and reduce the width ratio and increase the width term WT regarding the semi mechanical model.

More than 75% of the wells data applied to the Stimlab model, free wedge model and Semi-mechanical model showed higher degree of stability, the proppant characteristics and output results from these models are listed through Tables 4 to 6 respectively.

Table 4. Proppant characteristics for rod-shaped proppant treated wells

Wells	Kf (mD)	Proppant type	Proppant mass	Porosity Φ	Proppant size	Proppant S.G.	Proppant diameter
Well 11 B	585,448	ISP& Rod shaped	132,245	0.39	20/40	3.45	0.055
Well 12	780,000	ISP & RS	173,700	0.42	20/40	3.45	0.055
Well 13	600,000	ISP & RS	148,000	0.40	20/40	3.45	0.051
Well 14	740,000	ISP & RS	83,600	0.41	16/30	3.45	0.056
Well 15	640,000	ISP & RS	131,900	0.42	20/40	3.45	0.056
Well 16	740,000	ISP & RS	138,700	0.43	20/40	3.45	0.054
Well 17	340,000	Sand prop & RS	113,823	0.34	16/30	3.25	0.026
Well 18	350,000	Sand prop & RS	122,300	0.31	16/30	3.25	0.0255
Well 19	330,000	Sand Prop & RS	116,000	0.30	16/30	3.25	0.0255
Well 20	340,000	Sand prop & RS	106,300	0.23	16/30	3.25	0.025
Well 21	340,000	ISP & RS	67,700	0.25	20/40	3.45	0.056
Well 22	350,000	ISP & RS	103,527	0.22	20/40	3.45	0.055
Well 23	360,000	Sand prop & RS	96,800	0.30	16/30	3.25	0.025

Table 5. Results of the design calculations for rod-shaped proppant treated wells

Wells	hp (ft) Net pay	hf (ft) design	Pc, net (psi)	V_f placed (ft^3)	C_{fd} Dimensionless conductivity	J_d Dimensionless PI	Wp (inch) average width	Wp, max (inch) max width
Well 11 B	13	303.7	5058	21.7	2.78	0.82	0.04	0.064
Well 12	40	262.2	5027	105.3	2.69	0.68	0.08	0.126
Well 13	13	207.4	6724	38.20	8.81	1.34	0.06	0.09
Well 14	10	127.3	7606	26.21	0.34	0.83	0.05	0.078
Well 15	44	87.9	5953	274.21	7.48	1.41	0.116	0.185
Well 16	40	245.7	6800	92.02	7.67	1.11	0.062	0.10
Well 17	20	181.4	4247	47.68	0.94	0.64	0.045	0.072
Well 18	20	195.7	4100	41.70	1.83	0.52	0.084	0.13
Well 19	10	169.9	3560	22.42	2.62	0.70	0.056	0.09
Well 20	10	170.5	6450	19.05	1.24	0.57	0.047	0.075
Well 21	18	114.5	3860	35.47	0.43	0.46	0.05	0.088
Well 22	38	171.9	4424	71.12	0.38	0.54	0.036	0.058
Well 23	28	154.3	4100	61.62	3.9	0.65	0.086	0.137

Table 6. Results of stability models for rod-shaped proppant

Wells	Free wedge model	Semi-mechanical model	Stimlab model
Well 11 B	Stable	stable	Stable
Well 12	Stable	stable	Stable
Well 13	Stable	stable	Stable
Well 14	Stable	stable	Stable
Well 15	Stable	stable	Stable
Well 16	Stable	stable	Stable
Well 17	Stable	stable	Stable
Well 18	Unstable	stable	Stable
Well 19	Stable	stable	Stable
Well 20	Stable	stable	Stable
Well 21	Stable	stable	Unstable
Well 22	Stable	stable	Stable
Well 23	Unstable	stable	Stable

6. Conclusions

We have studied Proppant flowback prevention techniques to assure the theoretical background for each technique and to be supplied with information for decision making regarding the cost saving and better hydraulic fracturing design consequently better productivity to be achieved. The proppant flowback process is multifactor process. It showed up that all the above-mentioned factors are effective but it is not yet fully understood after all and more discussions and developed simulations and techniques need to be involved.

Cyclic stress is one of the main factors for proppant flowback and it has no presence in the models' formulas. It is recommended for future work to be considered for better simulation of the fracture stability. The rod-shaped proppant does not exhibit higher retained conductivity as it was reported and the proppant pack conductivity drop with time is still under investigation and need further experiments to be confirmed.

Optimization of the treatment size for suitable hydraulic fracturing design is always an important target for economics (lowering the cost of proppant in addition to the clean-up equipment cost). It was succeeded to reduce the rod-shaped proppant mass or the resin coating percentage with providing almost the same results. The addition of resin coating or rod-shaped is increasing the stability value for all models as it increases the nominal strength of the proppant and provides more crushing resistance under elevated closure stresses, furthermore, providing larger proppant diameter (decreasing width ratio Wr) therefore, it was not astonishing to have more stable fractures implementing the preceding techniques.

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Nomenclature

a'	*Constant for Semi-Mechanical Model = 7.7172*
C_{fd}	*Dimensionless Fracture conductivity.*
d_p	*Mean Proppant diameter, inch.*
d_{ref}	*Reference diameter, 0.0334 inch*
dp/dx	*Pressure gradient, psi/ft.*
emf	*Mean voidage at minimum fluidization.*
F	*Drag term, psi/ft*
F_{fv}	*Minimum pressure gradient to destabilize loose proppant psi/ft.*
F_{stable}	*Maximum stable pressure gradient in Semi-Mechanical Model psi/ft.*
G	*Acceleration of gravity = 32.2 ft/s^2.*
h_f	*Fracture height, ft.*
h_p	*Net pay thickness, ft.*
J_d	*Dimensionless productivity index.*
K_f	*Proppant pack permeability, md.*
M_p	*Mass of proppant, Ibs.*
M_{pEB}	*Mass of proppant flowback, Ibs.*
$P_{c,\ net}$	*Net closure pressure, psi.*
S.G	*Specific gravity.*
S_{MAX}	*Maximum proppant strength, psi.*
ST	*Strength term in Semi-Mechanical Model.*
v_f	*Minimum fluidization velocity, ft/min.*
w_r	*Width ratio in Semi-Mechanical Model.*
Wp, avg	*Average propped width, inch.*
WT	*Width term in Semi-Mechanical Model.*
Xf	*Fracture half-length, ft.`*
Mμ	*Fluid viscosity, cp.*
Φs	*Shape factor in Ergun Equation = 0.8 for spherical proppant.*
Φ_{pp}	*Proppant pack porosity, fraction.*
ρ_f	*Fluid density, Ib/ft^3*
ρ_p	*Particle density, Ib/ft^3*

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To whom correspondence should be addressed: Mohamed A. Heikal, Khalda Petroleum Company, 290 New Maadi, 3rd sector, Cairo, Egypt E-mail: Mheikal1@hotmail.com