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Predicting Dynamic Water And Gas Coning Progress

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***Abstract*—Water and gas coning is one of the most important phenomenon that affect the oil production from oil reservoirs having external drive of water and/or gas cap sources.**

Analytical model has been developed which consist of two terms affecting coning; the first term expresses the ratio between gravity to viscous forces; while, the second term that is called the unit response function by the displacing fluid zones, which expresses the decline rate of external drives to support reservoir pressure drops with the production time.

Since, the model reflects the real situations of reservoir-aquifer-gas cap zone systems; in which each of the displacing fluid zones has a specific strength to support the reservoir pressure drops depending on their characteristics and fluid properties. Moreover, the reservoir-aquifer-gas cap zone has been considered as a closed boundary systems, in which the critical flow rates decreases with the production time.

Several hypothetical systems have been suggested to reflect the real reservoirs situation, the critical oil flow rate with respect to aquifer and gas cap zone, and the progress of water and gas cones have been estimated by the presented model. The results show that water and gas coning is a complex phenomenon that depends on all reservoir and displacing fluid zone variables; the dynamic critical flow rates affected simultaneously by both of the displacing fluid zones; the most severe critical flow rate can be selected to control both of cones to hit well vicinity. While, the cone progress with time can be used to determine the best perforated intervals to achieve perfect coning stability.

Keywords—Water and Gas coning; Water and Gas Drive Reservoirs; Oil Reservoir Performance.

I. Introduction:

Water and gas coning is one of the most important phenomenon that affect the oil production from oil reservoirs having external drive of water and/or gas cap sources. Coning can seriously impact the well productivity and influence the degree of depletion and the overall recovery efficiency of the oil reservoirs.

Coning is caused by the imbalance between gravity and viscous forces around the completion interval. The viscous forces drive the oil flow into a wellbore with a pressure drawdown. These dynamic forces tend to move the fluids contact towards the vicinity of the well [1].

[1,2] presented thorough review for the presented correlations; and could be stated briefly that after the research by [3], a number of empirical, analytical and numerical correlations have been developed for predicting the critical rate assume a steady-state, constant pressure condition in a partially penetrated well. [3, 4, 5] derived the critical oil production rate from radial steady state flow equation in an isotropic system. [6, 7, 8]; proposed relationships to estimate the critical rate in anisotropic formations.

However, almost of these correlations assume open outer boundary and/or very strong drive mechanism at steady-state conditions [3-8]; thus, the results provide a constant critical oil flow rate. While, few of correlations [9] solved a closed outer boundary problem in which pseudo-steady-state conditions prevailed, causing a decreasing in critical oil flow rate with time.

Stable system cones may only be “pseudo-stable” because the drainage system and pressure distributions generally change; because with reservoir depletion, the water-oil contact always advance toward the completion interval, thereby increasing chances for coning [10].

For this reason, the coning phenomenon was observed even with the critical oil rate [1], it is because the critical oil flow rate is calculated using a steady state expressions; however, this case has very limited time, but in real situation, the OWC and GOC moves towards the reservoir zone to replace the withdrawal volumes of oil produced (i.e. the net oil column reduces with time causing larger pressure drawdown gradient with time) which led for more progress in coning phenomenon.

In infinite aquifer systems the effect of the pressure changes at the oil/aquifer boundary can never be felt at the outer boundary. Thus a constant pressure equal to initial reservoir pressure can be felt at this boundary. While, in finite aquifer system indicates that the aquifer outer limit is affected by the influx into the oil zone and that the pressure at this outer limit changes with time. Geologically all formations are finite, the outer boundary governs the behavior of the aquifer. Thus, in real sense, all boundary systems are closed, which never reaches the steady state condition, and then the critical oil flow rate is decreasing with time.

Moreover, all correlations assume very strong drive indices, which may not reflect the real reservoir situation in field systems; in reality, the external drive mechanism having specific strengths depend on their zone characteristics, the fluid properties and their communication degree with the reservoir. Thus, the cone progress rate should be affected by the strength degree of external drive indices. The most reliable analytical model to predict aquifer and/or gas cap strength and the communication degree between each other's has already been provided by [11]. The variation in external drive strengths results in different cone speed towards the perforation intervals.
[12] investigated the influence of the gravity and viscous forces of interaction on production performance for well producing oil from bottom water drive reservoirs, they prevailed that the production performance increases as the ratio of gravity to viscous forces increases.

Therefore, with the progress of oil production; both of OWC and OGC moves towards the reservoir zone lead in decreasing the oil column height and vice versa for water and gas columns heights, this causing decreasing in production performance due to decreasing in gravity forces compared to viscous forces. Thus, the critical oil flow rate should be minimized with the production time to keep a high production performance.

In this study, trail is made to formulate more rigorous model which involve all rock and fluid properties of reservoir-aquifer-gas cap system, both of aquifer and gas cap having different strengths to substitute the occurred reservoir pressure drops, the model should also involves the effects of gravity and viscous forces.

II. Theory and Work Development:

Prior to production, the reservoirs have a defined fluid contacts, the fluid contacts deform when a pressure difference may occur across their interfaces. However, the pressure difference increases with the progress of production time causing more sever deformation of the fluid contacts which may reach the well perforations, causing production of water and/or gas, as shown in schematic figure (1).

As soon as a well starts producing oil, a pressure drop accrued around the well vicinity; this pulse of pressure drop propagates at specific speed depends on reservoir's rock and fluid properties until reaching the displacing fluids contacts of water and/or gas, causing pressure difference across the fluid contacts, leading to a movement of water and/or gas towards the least pressure region of the reservoir. Hence, the displacing fluid zones will response to that reservoir pressure drop by a reflecting pressure support depends on the displacing fluid zone characteristics and their fluid properties.

Thus, the major cause of coning is pressure drawdown. Therefore, coning can be eliminated by controlling the pressure drawdown around the wellbore. However, the reduction of the pressure drawdown can be performed only by the reduction in the oil production rate. Hence, the reduction in the oil production rate should be determined based on the speed of the fluid contacts to move towards the reservoir to keep the balance between gravity to viscous forces as function of production time.
The fluid contacts move towards the reservoir zone at specific propagation rate depends on the pressure drop magnitude subjected at the fluid contacts, the strength of aquifer and/or gas cap zones to support reservoir pressure drops, and the communication degree between the contacted fluid zones. Therefore, the developed model must involve all rock and fluid properties of reservoir-aquifer-gas cap system.

Therefore, predicting accurate fluid interface movement should be formulated based on the strengths of the unwanted fluid zones (water and/or gas) to support the pressure drop occurred in the reservoir zone.

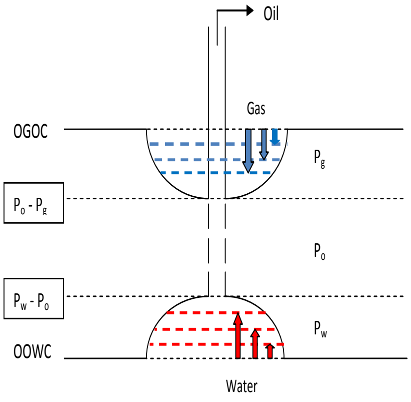

Fig. (1): Schematic drawing shows water and gas cone progress

III. Dynamic Model Formulation:

The coning progress is a result of coning development and the originally fluid contacts movement towards the oil zone. Thus, the evolutions of water and/or gas cones are driven by non-uniform drawdown pressure across the fluid interfaces.

For the elimination of coning, analysts were forced to return to equations governed by the stability between the pressure drawdown and the gravity pressure differential. [12] prevailed that the production performance increases as the ratio of gravity to viscous forces increases. Thus, the critical oil flow rate should be minimized with the production time to keep a good production performance by keeping high rate of gravity to viscous forces.

Hence, the gravity force can be found in critical oil flow rate correlations as the gravity difference between the contacted fluids, while the viscous force is found in Darcy's law. Thus, the ratio of gravity to viscous forces can be written in dimensionless form as follows;

$$Q_{DC} = \frac{Q_{oc}}{Q_o} \qquad (1)$$

Where, Q_{DC}, the dimensionless critical flow rate; Q_{oc} the critical oil flow which can be estimated using any stable cone correlations; Q_o the unrestricted oil flow rate using Darcy equation.

Thus, in more accurate statement, it is very important to predict the cone progress of water and/or gas using a convenient model for estimation the strength of aquifer and gas cap zones and their interaction degree with the reservoir zone. Moreover, it is very important to analyze reservoir performance and coning development according to the degree of magnitude for aquifer and gas cap; in addition to the interaction between the aquifers and the gas cap simultaneously this will help to estimate the instantaneous combined effects for the aquifer and gas cap on reservoir performance.

Changes in fluid withdrawal rates are primarily responsible for changes in the driving indices [3]; thus, the driving forces reduced as a function of producing time. Hence, it can be relate the coning problem which is also a function of withdrawal rates, with the change in the driving indices to construct a rigorous model in predicting the changes in critical oil flow rate without coning problem with the production time. However, [11] pointed out that the unit pressure strength of the displacing fluids always approach the "total pressure strength" that could be provided by the displacing fluids at time goes to infinity ($t = \infty$), indicating that each multiphase system has a specific trend for the interfaces movements and then in pressure supporting the reservoir. This can be used to predict the entire future critical oil flow rate with the production time.

In this study, proper analytical critical flow rate model that include the interaction between the reservoir and the displacing fluid zones could be developed to predict the accurate critical oil flow rate and its progress with production time during the boundary dominated flow period, the model uses the unit response function ($U_{(t)}$) of the displacing fluid zones, which reflect the magnitude of displacing fluids response against a unit created reservoir pressure drop.

$$U_{(t)} = 1 - \frac{P_{Di}}{T_{Di}} \qquad (2)$$

Eq. (2) indicates that, the unit response function ($U_{(t)}$) decrease with time, which can be reaches to zero at time goes to infinity ($t = \infty$).

Thus, the effect of aquifer and gas cap strengths as function of production time on coning progress can be given as follows;

$$Q_{DC_{(t)}} = Q_{DC}.U_{(t)} \qquad (3)$$

Where; $U_{(t)}$ the unit response function ($U_{(t)}$) of the displacing fluid zones.

While, the unit pressure decline (P_{Di}) in the aquifer or gas cap zone can be defined mathematically by;

$$P_{Di} = \frac{P_{Df} - P_{Do}}{P_{Df}} \qquad (4)$$

And, the unit time interval (T_{Di})in the aquifer or gas cap zone can be defined mathematically by;

$$T_{Di} = \frac{T_{Df} - T_{Do}}{T_{Df}} \qquad (5)$$

Where; P_{Do} the dimensionless pressure drops occurred in reservoir; and P_{Df} the dimensionless pressure drop support provided by the displacing fluid zones, which can be written respectively as follows [3,13];

$$P_{Do} = [2T_{Do} + ln(R_{Do}) - 0.75] \qquad (6)$$

$$P_{Df} = [2T_{Df} + ln(R_{Df}) - 0.75] \qquad (7)$$

While; T_{Do} the dimensionless time of unit pressure drop in reservoir zone; and T_{Df} the dimensionless time of unit pressure support by the displacing fluid zones, which can be written respectively as follows [3,13];

$$T_{Do} = \frac{0.0002637 K_o.t}{\varphi \mu_o C_o re^2} \qquad (8)$$

$$T_{Df} = \frac{0.0002637 K_f.t}{\varphi \mu_f C_f re^2} \qquad (9)$$

Hence, the reservoir exhibit only horizontal fluid movement towards the perforated interval; since, the dimensionless radius taken as given by [13] solution, as follows;

$$R_{Do} = \frac{r_w}{r_e} \qquad (10)$$

While, the displaced fluid zones exhibit both of horizontal and vertical movements towards the reservoir; since, the dimensionless radius taken as given by [14] solution, as follows;

$$R_{Df} = \frac{H_f}{r_e \sqrt{\frac{K_v}{K_h}}} \qquad (11)$$

The methodology used in verifying the dimensionless reservoir radius allows accounting the exact strengths of displacing fluid zones against reservoir pressure drops.

Thus, $U_{(t)}$ unit pressure decline of the displacing fluids across the fluid contact for each unit time interval can be expressed as follows.

$$U_{(t)} = 1 - \frac{\frac{P_{Df}-P_{Do}}{P_{Df}}}{\frac{T_{Df}-T_{Do}}{T_{Df}}} = 1 - [(\frac{P_{Df}-P_{Do}}{T_{Df}-T_{Do}})(\frac{T_{Df}}{P_{Df}})] \quad (12)$$

The term of $U_{(t)}$ indicates that the external drive support drops with time, and approach to zero at time goes to infinity ($t = \infty$).

Meanwhile, the dynamic cone progress towards well vicinity can be estimated using [15] model to predict dynamic capillary pressure, as follows;

$$DH_f = \frac{144\,\Delta P_c}{32.2\,\Delta\rho} = \frac{144\,\Delta(P_f - P_o)}{32.2\,\Delta(\rho_f - \rho_o)} \quad (13)$$

Where, P_c can be calculated using [15] model; but in this case the critical flow rate can be used to calculate the movement of fluids contacts, as follows;

$$P_c = P_f - P_o = 141.2\,\frac{Q_{oc}\mu_o B_o}{K_o H_o} P_{CD} \quad (14)$$

Where, $$P_{CD} = \ln(\frac{K_f \mu_o C_o}{K_o \mu_f C_f}) \quad (15)$$

IV. Sensitivity Analysis of Reservoir and Fluid Parameters:

The effects of reservoir-aquifer and gas cap characteristics on critical flow rate and cones progress have been investigated. Computer program has been prepared to generate sets of figures which show the effect of aquifer and/or gas cap characteristics on coning progress. Different hypothetical reservoir-aquifer-gas cap systems have been proposed to analyze the critical flow rate and both of water and gas cone progress towards the vicinity of oil well.

The specification illustrated in Fig. (2) indicates that the aquifer strength is greater than the gas cap; thus, the system shows rapid water cone progress compared with the gas cone progress, and then the critical flow rate with respect to water will control both of cones. Meanwhile, Fig.(3) show the opposite of the first case, in which the gas cap has greater strength than aquifer, and thus, the system shows rapid gas cone progress compared with the water cone progress, and then the critical flow rate with respect to gas will control both of cones.

While; Fig. (4) shows the effects of fluid gravity difference and reservoir size on coning progress compared with that shown in Fig. (3), it can be notice that increasing the gravity forces decrease cone progress towards the perforated interval and then lead to increase reservoir performance. While, decreasing reservoir size, lead to speed up cone progress; this can be attributed to the greater pressure drop occurred in small reservoir size than bigger ones.

The effect of reservoir permeability variation on cone development has been shown in Fig.(5), it can be notice that increasing of reservoir permeability lead to decease both of water and gas cones progress and then lowers the decline rate on the critical flow with the production time.

While, The effect of aquifer and gas cap zone permeability variation on cone development has been shown in Figs.(6 and 7) respectively, it can be notice that increasing of aquifer permeability lead to increase of water cone progress and then raising the decline rate on the critical flow with respect to water as function of the production time. But, increasing of gas cap zone permeability lead to increase of gas cone progress and then raising the decline rate on the critical flow with respect to gas as function of the production time.

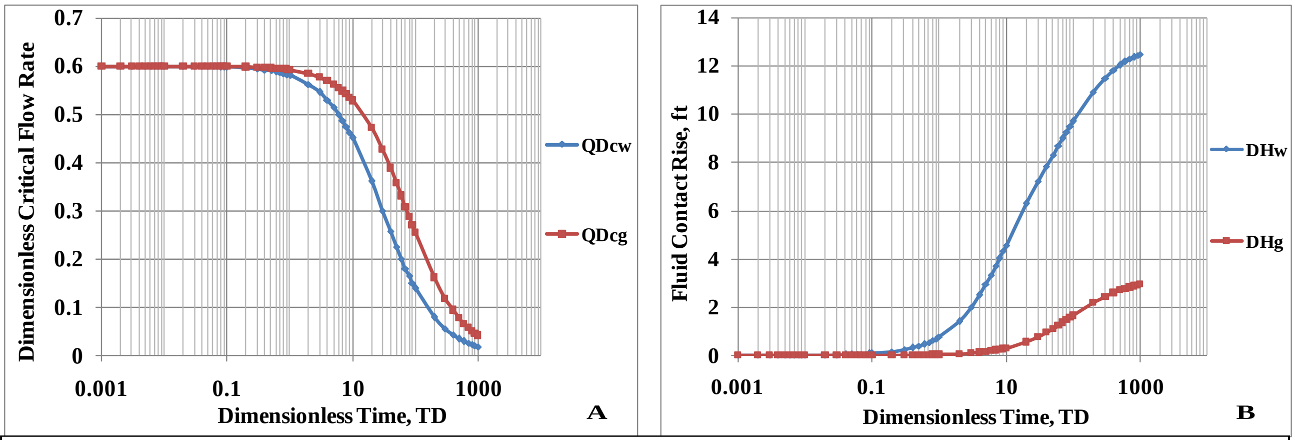

Fig.(2): $R_D = 0.001$, $Q_{DC} = 0.6$, $K_o = 320\ md$, $\boldsymbol{K_w = 250\ md, K_g = 3000\ md}$, $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\Delta\rho_{wo} = 13.5\ Ib/ft^3$; **A**- Critical Flow Rate, **B**- Fluid Contact Rise

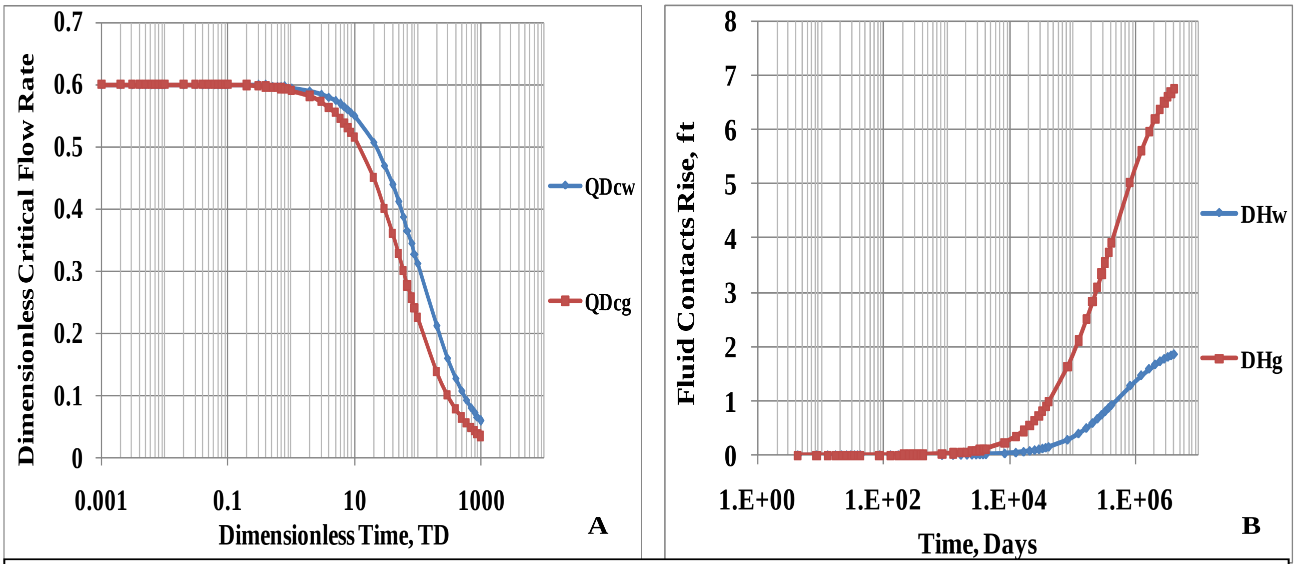

Fig.(3): $R_D = 0.001$, $Q_{DC} = 0.6$, $K_o = 320\ md$, $\boldsymbol{K_w = 75\ md, K_g = 4000\ md}$, $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\Delta\rho_{wo} = 13.5\ Ib/ft^3$; **A**- Critical Flow Rate, **B**- Fluid Contact Rise

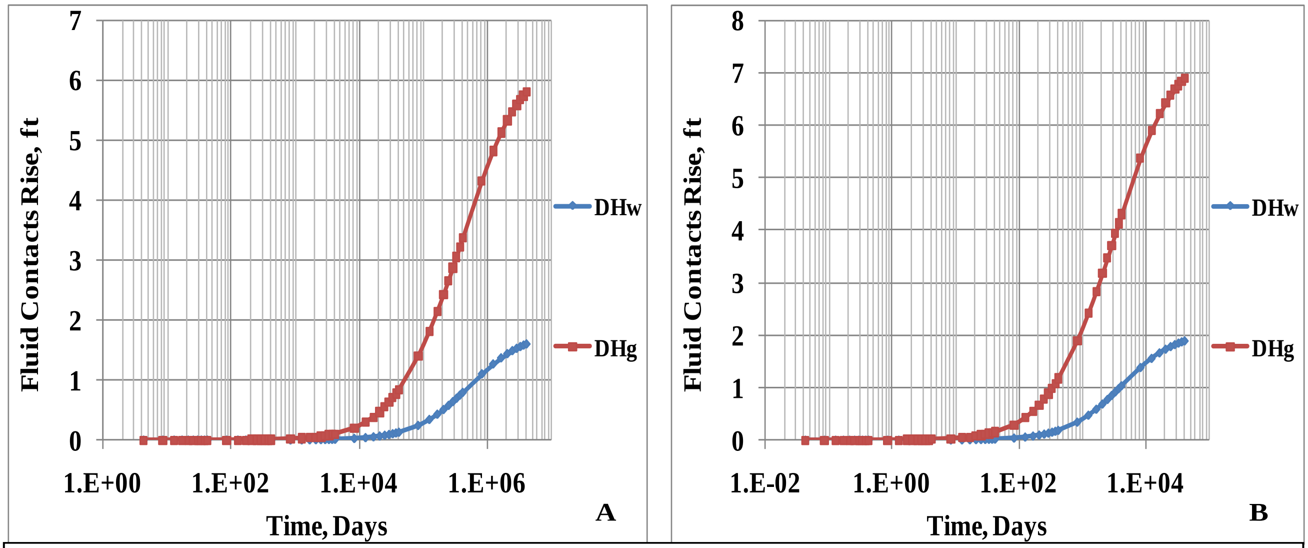

Fig.(4): $Q_{DC} = 0.6$, $K_o = 320\ md$, $K_w = 75\ md$, $K_g = 4000\ md$, $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\boldsymbol{\Delta\rho_{wo} = 15.7\ Ib/ft^3}$ **, A-** $\boldsymbol{R_D = 0.001}$ **B-** $\boldsymbol{R_D = 0.01}$**; A-** Critical Flow Rate, **B-** Fluid Contact Rise

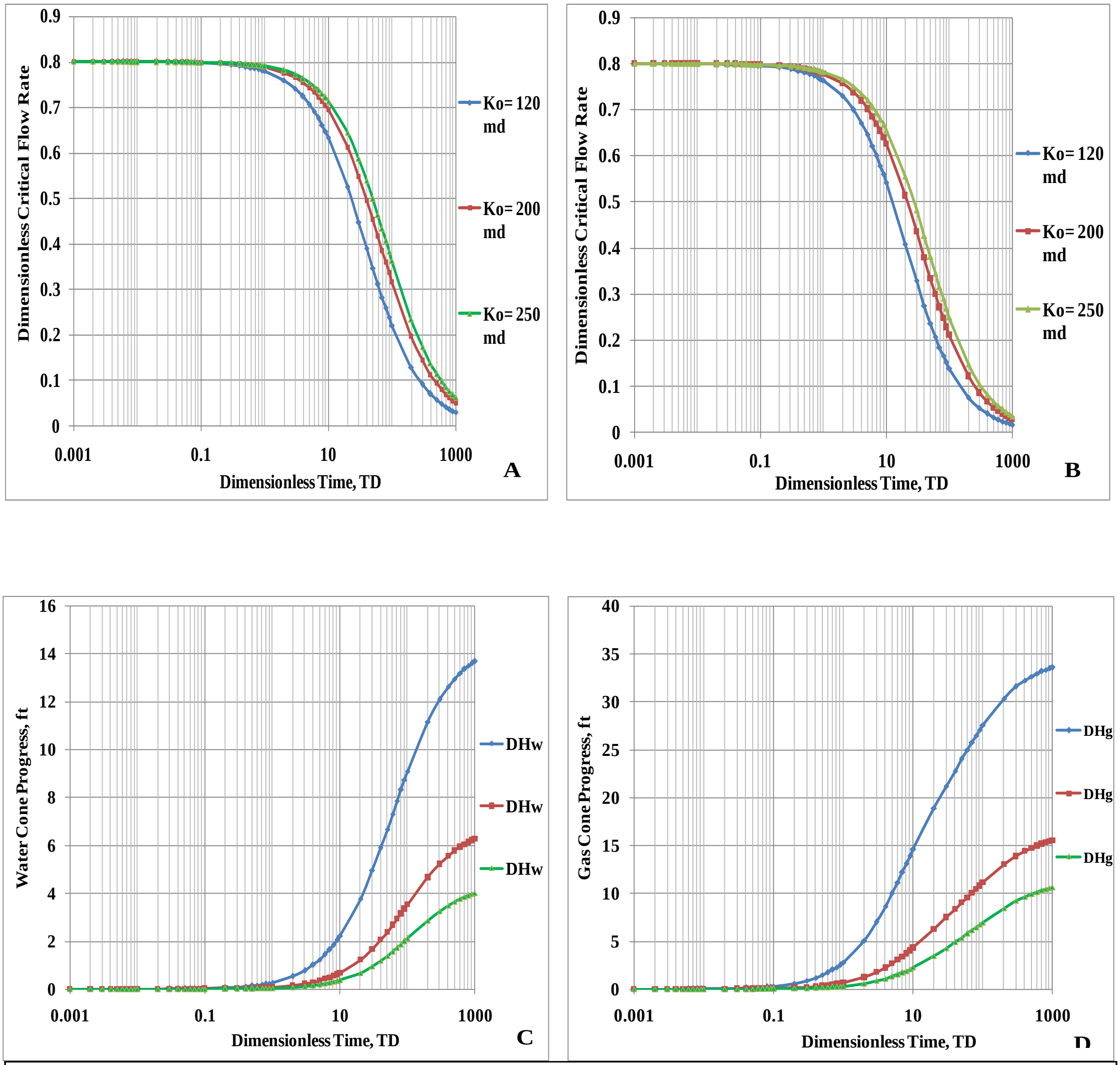

Fig.(5): $R_D = 0.001$, $Q_{DC} = 0.8$, $\boldsymbol{K_o = Variable}$, $K_w = 75\ md$, $K_g = 4000\ md$, $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\Delta\rho_{wo} = 13.5\ Ib/ft^3$; **A&B**- Critical Flow Rate w.r.t. water and gas respectively, **C&D**- Fluid Contact Rise w.r.t. water and gas respectively

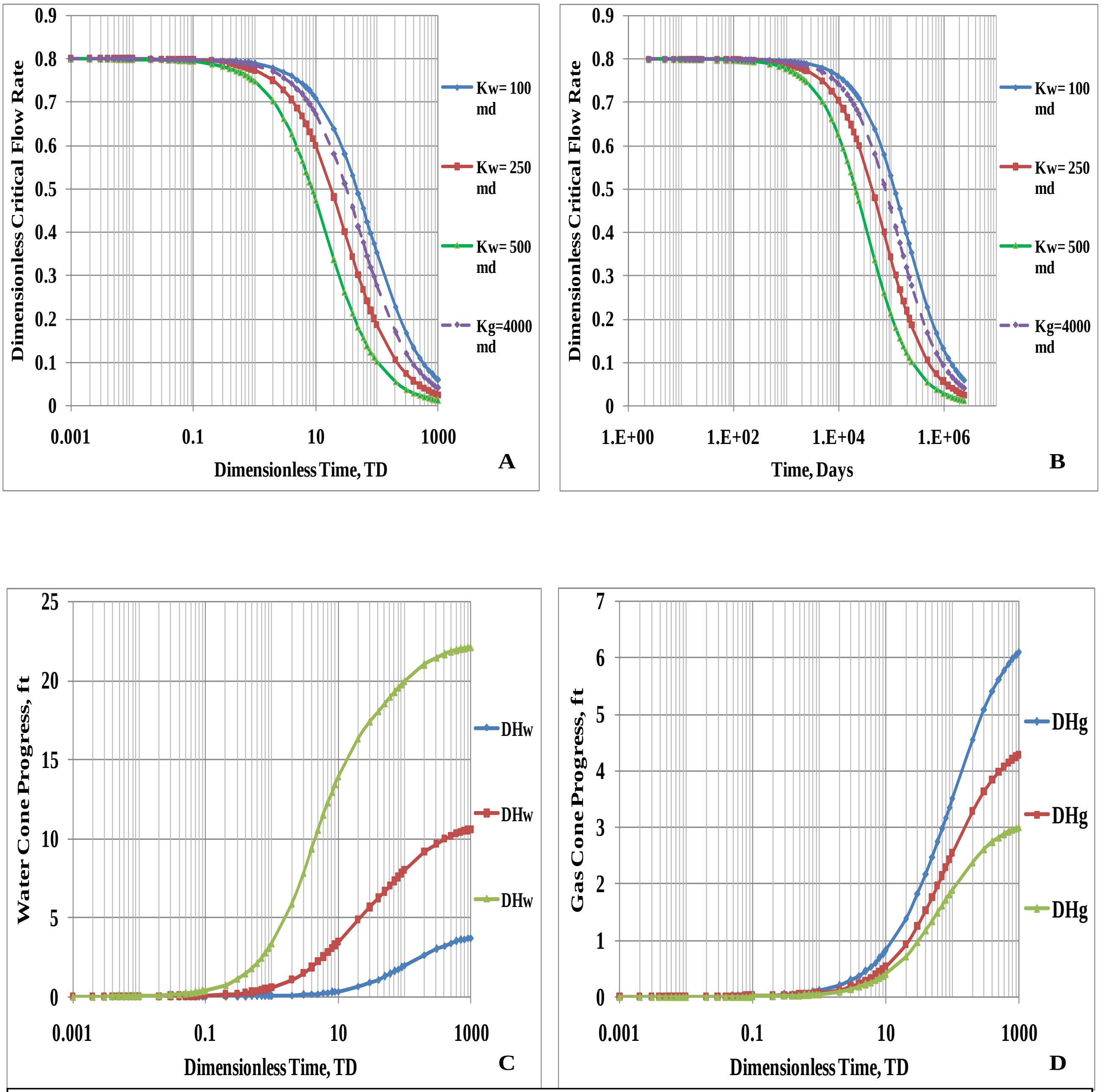

Fig.(6): $R_D = 0.001$, $Q_{DC} = 0.6$, $K_o = 320\ md$, $\boldsymbol{K_w = Variable}$, $K_g = 4000\ md$, $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\Delta\rho_{wo} = 13.5\ Ib/ft^3$; **A&B-** Critical Flow Rate w.r.t. water and gas respectively, **C&D-** Fluid Contact Rise w.r.t. water

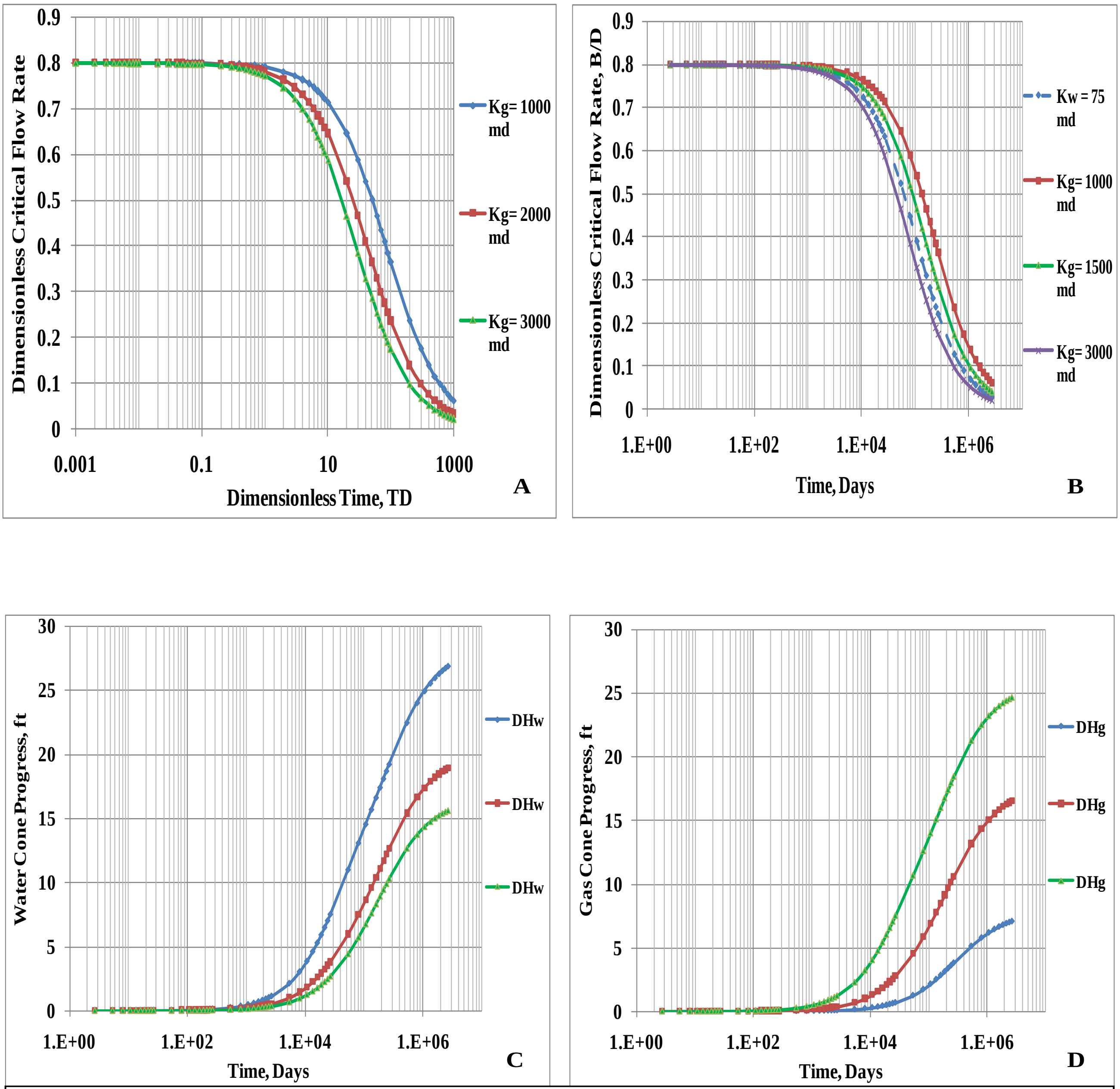

Fig.(7): $R_D = 0.001$, $Q_{DC} = 0.6$, $K_o = 320\ md$, $K_g = Variable$,$K_w = 75\ md$, , $H_o = 50\ ft$, $H_w = 45\ ft$, $H_g = 50\ ft$, $C_o = 8 * 10^{-6}\ psi^{-1}$, $C_w = 3 * 10^{-6}\ psi^{-1}$, $C_g = 5.5 * 10^{-4}\ psi^{-1}$, $\mu_o = 2\ cp$, $\mu_w = 1\ cp$, $\mu_g = 0.016\ cp$, $\Delta\rho_{wo} = 13.5\ Ib/ft^3$; **A&B**- Critical Flow Rate w.r.t. water and gas respectively, **C&D**- Fluid Contact Rise w.r.t. water

V. Results and Discussion:

The sets of figures which are already generated to analyze the effect of reservoir, aquifer and gas cap characteristics on water and gas cone progress and the controlling trend of critical flow rate as function of producing time show that water and gas coning is a complex phenomenon that depends on all reservoir and displacing fluid zone variables.

Figs. (2 and 3) show two opposite cases; the first, Fig. (2) shows the aquifer own more strength than gas cap zone strength, leading for more rapid of water cone progress towards the perforated interval. while, the case given in Fig. (3) shows that the gas cap own more strength than the aquifer, leading for more rapid of gas cone progress towards the perforated interval.

While, Fig. (4) show the effect of both fluid density difference and reservoir size on coning progress; it can be notice the effect of density difference compared with case shown in Fig. (3), it can be notice that increasing density difference lead to improve reservoir performance throughout minimizing coning progress; this observation match the results of [16]. While, part-B shows that decreasing reservoir size lead to speed up the cone progress.

Fig. (5) shows that increasing reservoir permeability lead to reduce the speed of cone progress towards the perforated well intervals, and then lead to lower the decline rate of the critical flow rate with production time, the reason related to the reduction of pressure drawdown occurred in high permeability reservoirs compared with low permeability reservoirs.

However, in this case, it can be notice that the critical flow rate with time as function of gas cone progress is lower than the critical flow rate with time as function of water cone progress; this indicates that the critical flow rate with time as function of gas cone progress will be the controlling flow rate that must be used to avoid hitting the well by both of water and gas cone.

Figs (6) shows that increasing aquifer permeability lead to lower the decline rate of the critical flow rate with production time, the reason related to the speed up of water cone towards the perforated well intervals, which lead to minimize the critical flow rate with production time.

However, in this hypothetical case, it can be notice that the critical flow rate with time as function of water cone progress for aquifer permeability of (250 and 500 md) are lower than the critical flow rate with time as function of gas cone progress of gas cap permeability of (4000 md); this indicates that the critical flow rate with time as function of water cone progress will be the controlling flow rate that must be used to avoid hitting the well by both of water and gas cone. While, the critical flow rate with time as function of water cone progress for aquifer permeability of (100 md) is higher than the critical flow rate with time as function of gas cone progress of gas cap permeability of (4000 md); this indicates that the critical flow rate with time as function of gas cone progress will be the controlling flow rate that must be used to avoid hitting the well by both of water and gas cone.

Meanwhile, Figs. (4 and 5) show both of water and gas cone progress as function of the production time towards the perforated intervals; in this case, it can be notice the high speed of water progress compared to gas cone progress.

Fig. (7) shows that increasing gas cap zone permeability lead to lower the decline rate of the critical flow rate with production time, the reason related to the speed up of gas cone progress towards the perforated well intervals, which lead to minimize the critical flow rate with time.

However, in this case, it can be notice that the critical flow rate with time as function of gas cap cone progress for gas cap zone permeability of (3000 md) are lower than the critical flow rate with time as function of water cone progress of aquifer permeability of (75 md); this indicates that the critical flow rate with time as function of gas cone progress will be the controlling flow rate that must be used to avoid hitting the well by both of water and gas cone. While, the critical flow rate with time as function of gas cone progress for gas cap zone permeability of (1000 and 1500 md) are higher than the critical flow rate with time as function of gas cone progress of gas cap permeability of (4000 md); this indicates that the critical flow rate with time as function of water cone progress will be the controlling flow rate that must be used to avoid hitting the well by both of water and gas cone.

VI. Conclusions:

The following conclusions can be drawn from this work;

- The model predicts the critical flow rate as function of time; since, it reflects the real reservoir situation.
- The model involves all rock and fluid parameters for both of displaced and displacing fluid zones; since, it can be considered a rigor model to investigate coning problem.
- The model takes the exact strengths of the displacing fluid zones on coning progress.

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