A New Discovery about Inflow Control Devices in Controlling Water and Increasing Oil Recovery

Li Mingjun*[1,2], Ma Yongxin[2], and Yi Xiangyi[1]

[1] Chengdu University of Technology; Chengdu, 610059, Chengdu, China
[2] CNOOC -Ltd Zhanjiang. Zhanjiang, 524057, Zhanjiang, China

ABSTRACT

Inflow control devices (ICD), which prevent water breakthrough by controlling the inflow profile of a well, have been used successfully in many oilfields. This paper will introduce a new discovery and an unsuccessful example. Moreover, this paper investigates meticulously and thoroughly to find the application conditions of the new discovery. Based on permeability rush coefficient and permeability differential, a series of plans are carried out to study ICD application conditions. Finally, a new discovery is developed. There are inflow-control device applications for ICD's, which can work well in heterogeneous reservoirs for controlling water and increasing oil production, but they cannot work well in a homogeneous formation. The effect of ICD on controlling water and increasing oil is very sensitive to the degree of reservoir heterogeneity. The cumulative oil production increases with increasing permeability rush coefficient and permeability differential.

Keywords: Inflow Control Devices, Controlling Water, Increasing Oil Recovery, Application Conditions

INTRODUCTION

ICD, as a sort of completion tools, have been used in many oilfields, in many countries. From these papers, we can understand that the effect of ICD is very good, which can prevent successfully water breakthrough and improve the oil production. In Kristian Brekke's paper [1], ICD's was used to enhance the performance of long horizontal wells producing from high-permeability formations; moreover, ICD increased the plateau rate of a frictionless well by 50% in comparison with a standard completion well. In Augustine's paper [2], the use of ICD can result in increased NPV and increased ultimate recovery. However, neither thick pay zones nor short horizontal wells are good candidates for horizontal wells with ICD. In Michael Lorenz's paper [3], the inflow control technology can balance production inflow and prevent gas or oil coning; also, the inflow control technology can minimize the risk of erosion and achieve sand control without gravel packing. In Henriksen's paper [4], the use of ICD yield the higher volumetric recovery of oil from each well compared to more conventional sand control completion methods in the Troll oil subsea field. In Mclntyre's paper [5], ICD are used successfully in the UK sector of

***Corresponding author**
Li Mingjun
Email: 529145486@qq.com
Tel: +86 75 9391 2596
Fax: +86 75 9391 2596

Article history
Received: October 01, 2015
Received in revised form: January 01, 2016
Accepted: February 10, 2016
Available online: November 15, 2017

the North Sea, which can prevent early water and gas breakthrough, and increase oil recovery. In Henriksen's paper [6], the use of ICD can increase recovery and keep oil rates at higher levels compared to conventional methods. In Cudahy's paper [7], ICD are very effective in improving sustainable well productivity compared to past horizontal completion methods. The combination of ICD design geo-steering calibration with real-time log data, installation procedures, and fluid historical production results through time are also described elsewhere [8]. ICD's show good performance with increased oil production and lower water production in all wells in Ecuador. It is also reported that horizontal producers with inflow controls and NCBF's greatly improve the recovery of oil and reduce the production of water under a water flood scenario [9]. In Zhuoyi Li's paper [10], they investigated how and when an ICD should be used. ICD can be used to improve well performance and increase recovery, but it is not a universal solution for production problems. The application requires a thorough understanding of long-term reservoir behavior and upfront reservoir characterization for implementation. Gualdron reported that ICD's are used in three horizontal wells in Rubiales field, and the performance of the ICD was found to reach the highest cumulative oil production in comparison to neighboring wells [11]. Shad's stated the advantages of ICD-equipped wells over the conventional dual-tubing and slotted liner completions for SAGD operation [12]. The improved well performance, increased bitumen production, and longevity of the wells will compensate for the additional cost of ICD installation in a short period of time.

On the other hand, the oil-field service companies owning ICD technology also publicize that ICD's have an amazing effect on controlling water breakthrough and increasing oil recovery. However, in our work and study, we found a surprising problem that ICD cannot work well in preventing water breakthrough. Thus, a series of deep studies about ICD application conditions have been carried out, and as a result, we have found some new discoveries.

EXPERIMENTAL PROCEDURES

Problem Finding

This is a thin bottom water reservoir with sufficient bottom water energy in South China Sea. The reservoir thickness is about 5 m. The type of reservoir is single porosity, and reservoir physical properties are very good; the porosity is 30-36%, and the permeability is 655-5242 mD; the reservoir pressure is about 8.9 MPa, and the reservoir temperature is about 67.1 °C. The ground oil is characterized by "three highs and two lows", namely high density (0.9366-0.944 g/cm^3), high viscosity (178.5-237.6 mPa.s), high colloid content (7.96-15.81%), low freezing point (-l8-8.9°C) and low wax content. The underground oil density is 0.8975 g/cm^3, featured by high oil viscosity (70 mPa.s), low solution gas/oil ratio, low saturation pressure (0.8 MPa) and great difference between reservoir pressure and saturation pressure.

In order to improve oil recovery, horizontal wells are used in this oilfield. The simulation results show that all horizontal wells with conventional completion techniques cannot prevent water rising, and water rises fast. Single well cumulative oil production is very low, and the average is less than 5×10^4 m^3; the minimum is about 2×10^4 m^3 with a small pressure drop as shown in Figure 1.

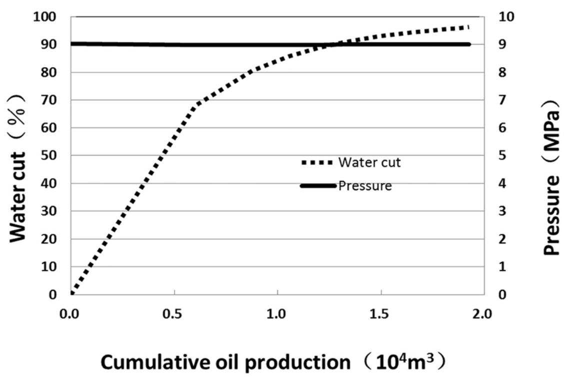

Figure 1: Single well production curve.

As the water rises fast and single well production is low, inflow control devices are considered to control bottom water coning and improve oil production. A low-yielding well, A1H was selected as an experimental well to carry out ICD numerical simulation research. The model plane grid is 50 m×50 m; in addition, vertical grid is 0.6 m. The number of grids in *X*, *Y*, and *Z* direction is 312, 200 and 51 respectively. The main parameters of A1H well are as follows: the wellbore length is 300 m, and the production rate is 500 m^3/d. Because it is a heavy oil reservoir, underground oil viscosity is 70 mPa.s, and Nozzle-based ICD are used (Figure 2), which are independent of oil viscosity. Eclipse simulator is used to carry out the ICD research.

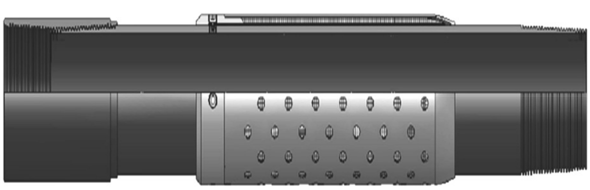

Figure 2: Nozzle-based ICD.

First, every grid is numbered, through which the horizontal section passes from 1 to 6 in the model (Figure 3). By analyzing the PRT file, the part of high water cut is found, which is the heel of the horizontal section (Figure 4).

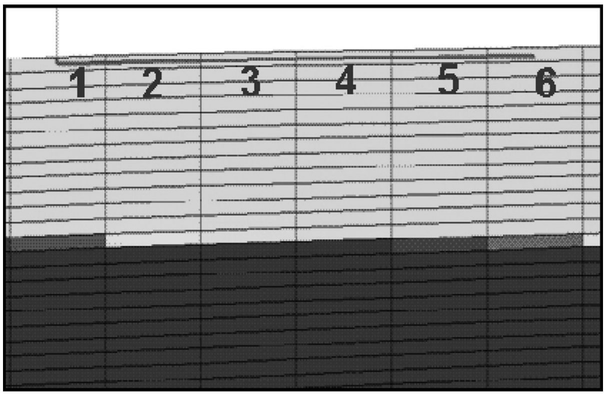

Figure 3: Well (A1H) trajectories.

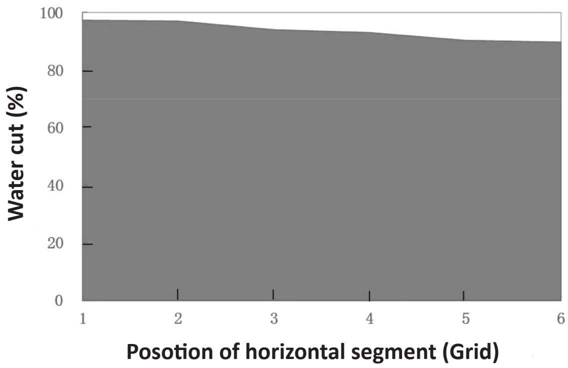

Figure 4: Water cut versus position along horizontal segment.

Finally, ICD's are placed in the heel to control water. The ICD place, the dimensionless flow coefficient for the valve, the cross-section area for flow in the constriction etc. are carefully optimized. The simulation results are shown in Figures 5 and 6.

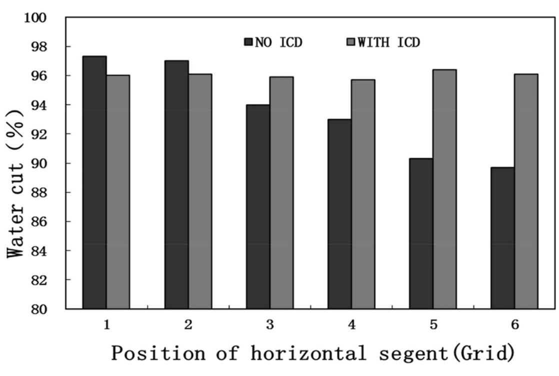

Figure 5: Water cut versus position along horizontal segment for two simulations: No ICD and With ICD.

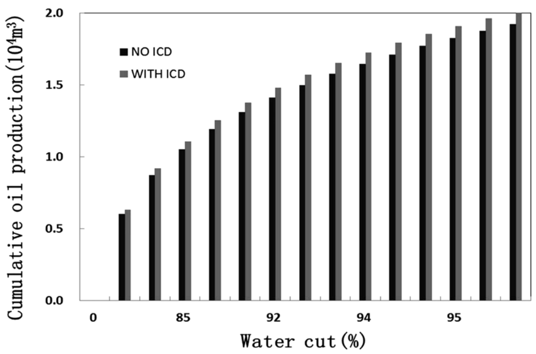

Figure 6: Water cut versus cumulative oil production for two simulations: No ICD and with ICD.

Two simulations, without ICD (symbolized as "No ICD") and with ICD are shown in Figures 5 and 6. Compared the cases of with ICD and without ICD, the water cut along horizontal segment with ICD is adjusted to equilibrium, and heel water is controlled; toe water is increased, and a lower water cut and more oil production are obtained. However, oil production is increased by only 4.6%, which is about 900 m^3. The effect of increasing oil is unsatisfied for ICD.

The Analysis of s Causes of Reservoir Heterogeneity

Why could ICD not prevent water rising and increase oil production in well A1H? Maybe, our simulation method with ICD was wrong; that was our first thought, because all the news about ICD is positive. For this reason, on the one hand, two professional ICD Companies were invited to make an ICD program in well A1H. Unfortunately, the two professional ICD Companies obtained the same result as ours. On the other hand, we thought, perhaps, there are suitable conditions for ICD, so the reservoir physical properties along well A1H were studied deeply. Finally, it was found out that the average permeability along the horizontal segment was close and high (Table 1).

Table 1: Average permeability along the horizontal segment.

Position along horizontal segment (Grid)	Average permeability (mD)
1	1618
2	1575
3	1573
4	1504
5	1476
6	1453

From Table 1, it is clear to see that the reservoir along well A1H is homogeneous. In order to investigate the reservoir heterogeneity degree, the reservoir heterogeneity parameter standards are introduced into the model as shown in Table 2. There are three parameters characterizing reservoir heterogeneity: variation coefficient, rush coefficient, and differential.

Table 2: Reservoir heterogeneity evaluation standard.

Heterogeneity standard	Variation coefficient	Rush coefficient	Differential
weak	< 0.5	< 2	< 20
medium	0.5 ~ 0.9	2 ~ 3	20 ~ 30
strength	> 0.9	> 3	> 30

The permeability variation coefficient is the ratio of standard deviation to average given below:

$$K = \sqrt{\sum_{i=1}^{n} \left(K_i - K_{ave}\right)^2 \Big/ (n-1)} \Bigg/ K_{ave} \tag{1}$$

The permeability rush coefficient is the ratio of maximum to average, as reads:

$$K = K_{\max} / K_{ave} \tag{2}$$

The permeability differential is the ratio of maximum to minimum defined by:

$$K = K_{\max} / K_{\min} \tag{3}$$

Based on the permeability rush coefficient and differential, the heterogeneity evaluation of A1H was carried out. The results show that it is a homogeneous formation, and permeability rush coefficient is 1.05, and permeability differential is 1.1. So far, the reason leading to water-control failure is still uncertain, but we speculate that the failure is related to homogeneous formation in well A1H. ICD have application conditions, which cannot work well in homogeneous formation. With the well-founded suspicion, a more in-depth study has been carried out.

Deep Study about Inflow Control Devices Application Situations

Based on permeability rush coefficient and permeability differential, the permeability along horizontal segment are changed to make the formation heterogeneous. The major changes of permeability along horizontal segment are heel and toe. From weak heterogeneity to strength heterogeneity, there are three plans; the brief parameters are shown in Table 3.

Table 3: The brief parameters of the three plans.

Position along horizontal segment (Grid)	Average permeability (mD)		
	Plan 1	Plan 2	Plan 3
1	809.0	64.7	16.2
2	787.5	63.0	15.8
3	1573.0	1573.0	1573.0
4	1504.0	1504.0	1504.0
5	738.0	59.0	14.8
6	726.5	58.1	14.5
Rush coefficient	1.5	2.8	3.1
Differential	2.2	27.1	108.3
Heterogeneity standard	weak	medium	strength

Firstly, the single well production without ICD has been simulated in three plans with Eclipse simulator. Based on the water cut along horizontal segment without ICD, high water cut positions are found. ICD are placed in high water cut positions, and the parameters of ICD are optimized carefully and reasonably in every plan. Finally, the results of two situations, with ICD and without ICD are compared with every plan. The increased proportion of oil in the situation with ICD are compared in three plans to study further ICD application condition and find the relation between the increasing oil effect and heterogeneity degree.

Plan 1

The water cut versus position along horizontal segment and the water cut versus cumulative oil production in plan 1 for the two simulation cases without ICD and with ICD are shown in Figures 7 and 8.

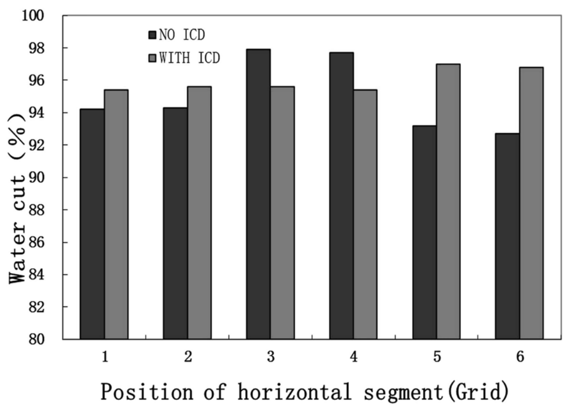

Figure 7: Water cut versus position along horizontal segment (plan 1).

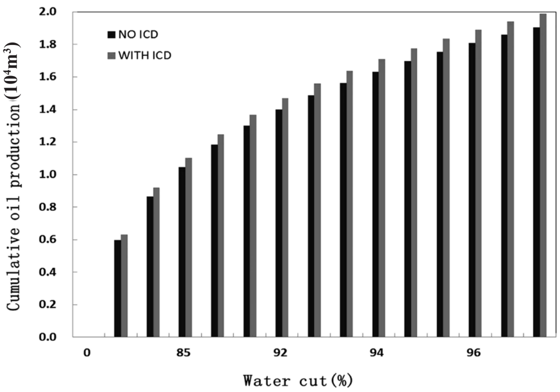

Figure 8: Water cut versus cumulative oil production (plan 1).

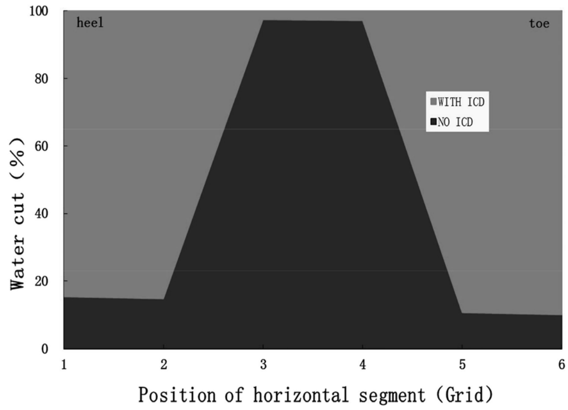

Figure 9: Water cut versus position along horizontal segment (plan 2).

In plan 1, the reservoir has weak heterogeneity; moreover, permeability rush coefficient and permeability differential are 1.5 and 2.0 respectively. As shown in Figure 7, there is a little change for water cut along horizontal segment, the water cut in center is slightly greater than the water cut in heel and toe for the situation that no ICD’s are used (the permeability of center is bigger than the permeability of hell and toe). With ICD, the water cut along horizontal segment is adjusted to a balanced state. As can be seen from Figure 8, the water rising with ICD is slower than that of without ICD, and the oil production with ICD is higher than that of without ICD. However, oil production is increased by about 1000 m^3 and the increased proportion is only 5%.

Plan 2

The water cut versus position along horizontal segment and the water cut versus cumulative oil production in plan 2 for two simulation cases of without ICD and with ICD are shown in Figures 9 and 10.

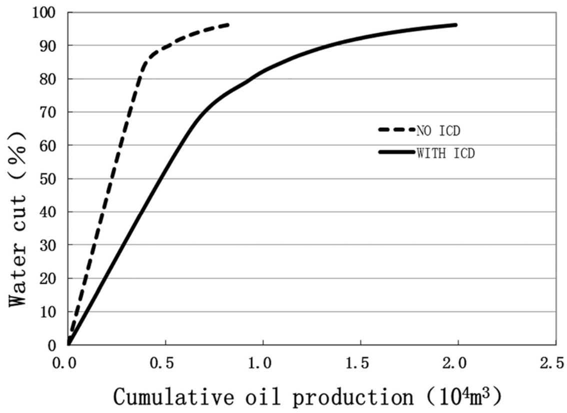

Figure 10: Water cut versus cumulative oil production (plan 2).

In plan 2, the reservoir has medium heterogeneity, and permeability rush coefficient and permeability differential is 2.8 and 27.0 respectively. As shown in Figure 9, there is a great change for water cut along horizontal segment; the water cut in center is greater than the water cut in heel and toe for the situation of without ICD. With ICD, the water cut along horizontal segment is adjusted to a balanced state. As can be seen from Figure 10, with ICD, the water rising is slower than that of without ICD, and the oil production with ICD is higher than that of without ICD. The increased oil production is about 1.15×10^4 m^3 and the increased proportion is 139%.

Plan 3

The water cut versus position along horizontal segment and the water cut versus cumulative oil production in plan 3 for two simulation cases without ICD and with ICD are shown in Figures 11 and 12.

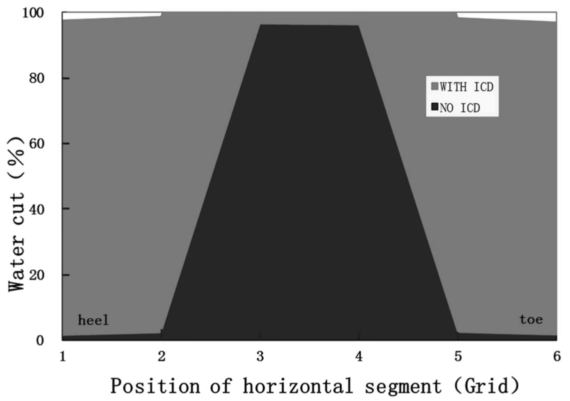

Figure 11: Water cut versus position along horizontal segment (plan 3).

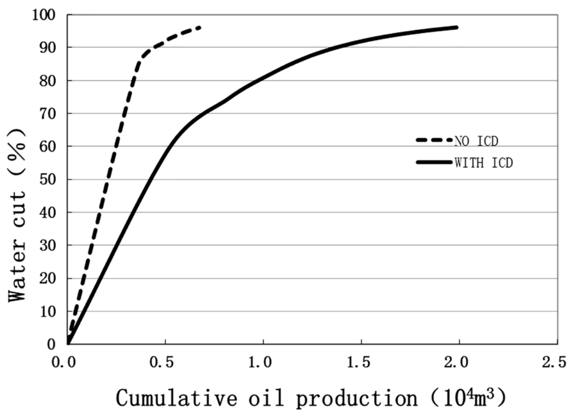

Figure 12: Water cut versus cumulative oil production (plan 3).

In plan 3, the reservoir has strong heterogeneity; additionally, permeability rush coefficient and permeability differential is 3.1 and 108.0 respectively. As shown in Figure 11, there is also a great change for water cut along horizontal segment; moreover, the water cut in center is greater than the water cut in heel and toe for the situation of without ICD. With ICD, the water cut along horizontal segment is adjusted to a balanced state. As can be seen from Figure 11, with ICD, the water rising is slower than that of without ICD, and the oil production with ICD is higher than that of without ICD. The increased oil production is about 1.31×10^4 m^3 and the increased proportion is 203%. As can be seen from the three plans described above, there are application situations for ICD, which can work well in heterogeneous reservoirs, controlling water and increasing oil production. The failure reason for ICD in well A1H is that the reservoir is homogeneous. As can also be seen from the three plans, the water cut along horizontal segment is related to the reservoir heterogeneity degree; the more the heterogeneous is a reservoir, the more different the water cut along horizontal segment becomes.

Sensitivity Research

Based on the three plans, a further study about ICD has been carried out to find out the relation between the effect of controlling water, increasing oil and heterogeneity degree. The result is shown in Figures 13 and 14.

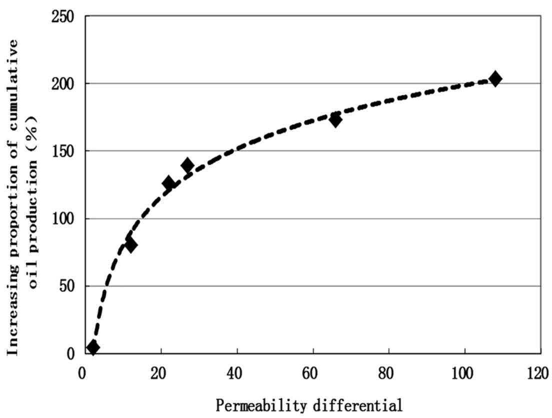

Figure 13: Increased proportion of cumulative oil production versus permeability rush coefficient.

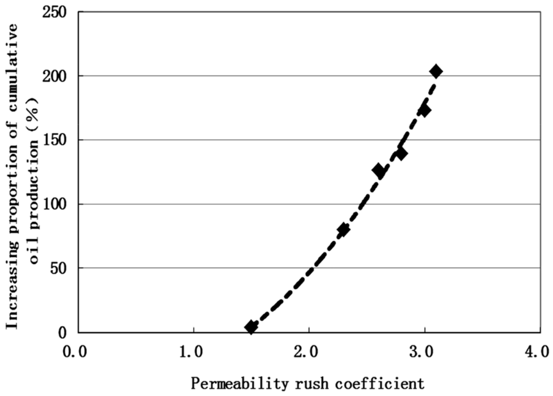

Figure 14: The increased proportion of cumulative oil production versus permeability differential.

As can be seen from the two above figures, the effect of ICD on controlling water and increasing oil is very sensitive to the heterogeneity degree of reservoirs. The cumulative oil production increases with an increase in permeability rush coefficient and permeability differential. The relation between the increasing proportions of cumulative oil production which increases with the permeability differential is a logarithmic relationship. The relational expression is as follows; its correlation coefficient is about 0.992.

$$Y = 51.281\ln(X) - 37.86 \quad (4)$$

where, Y (%) is the increasing proportion of cumulative oil production, and X is permeability differential.

It has a multinomial relationship between the increasing proportion of cumulative oil production and increasing permeability rush coefficient. The relational expression is as follows; its correlation coefficient is about 0.991.

$$Y = 31.62X^2 - 25.94X - 27.79 \quad (5)$$

where, Y (%) is the increasing proportion of cumulative oil production, and X is permeability rush coefficient.

CONCLUSIONS

(1) ICD can adjust the water cut along the horizontal section, but they cannot solve all problems. Based on a series of studies, the application situation of ICD is found, which is suitable for heterogeneous reservoirs; in other words, ICD can work well in heterogeneous reservoirs, but it is powerless in homogeneous reservoirs.

(2) The effect of ICD on controlling water and increasing oil is very sensitive to the heterogeneity degree of reservoirs, which increases with increasing the heterogeneity degree of reservoirs. Using permeability variation coefficient, permeability rush coefficient, and permeability differential, the heterogeneity degree of the reservoir can be determined to preliminary forecast the result of ICD on controlling water and increasing oil.

ACKNOWLEDGEMENTS

The authors would like to thank anonymous reviewers and the editors for constructive comments and suggestions for improving this paper. The authors also wish to thank their colleagues for their help and suggestions.

REFERENCES

1. Brekke K. and Lien S. C., “New and Simple Completion Methods for Horizontal Wells Improve the Production Performance in High-Permeability,” *Thin Oil Zones, SPE Drilling & Completion*, **1994**, *9*(3), 205-209.
2. Augustine J. R., “An Investigation of the Economic Benefit of Inflow Control Devices on Horizontal Well Completions Using a Reservoir-Wellbore Coupled Model,” *European Petroleum Conference*, Aberdeen, United Kingdom, SPE 78293, **2002**.
3. Lorenz M. D., Ratterman E. E. , and Augustine J.

R., “Uniform Inflow Completion System Extends Economic Field Life: A Field Case Study and Technology Overview,” *SPE Annual Technical Conference and Exhibition*, San Antonio, SPE 101895, **2006**.

4. Henriksen K. H., Gule E. I. , and Augustine J. R., “The Application of Inflow Control Devices in the Troll Field,” *SPE Europe/EAGE Annual Conference and Exhibition*, Vienna, SPE 100308, **2006**.
5. Augustine J. R., McIntyre A., Adam R. J., and et al., “Increasing Oil Recovery by Preventing Early Water and Gas Breakthrough in a West Brae Horizontal Well: A Case History,” *SPE/DOE Symposium on Improved Oil Recovery*, Tulsa, Oklahoma, SPE 99718, **2006**.
6. Henriksen K. H., Augustine J. R., and Wood E. T., “Integration of New Open Hole Zonal Isolation Technology Contributes to Improved Reserve Recovery and Revision in Industry Best Practices,” *SPE International Improved Oil Recovery Conference in Asia Pacific*, SPE 97614, **2005**.
7. Al-Qudaihy D. S., Al-Qahtani H. B., Sunbul A. H., and et al., “The Evolution of Advanced Well Completions to Enhance Well Productivity and Recovery in Saudi Aramco’s Offshore Fields,” I*ADC/SPE Asia Pacific Drilling Technology Conference and Exhibition*, SPE 103621, **2006**.
8. Vela I., Viloria-gomez L. A., Caicedo R., and et al., “Well Production Enhancement Results with Inflow Control Device (ICD) Completions in Horizontal Wells in Ecuador,” *SPE EUROPEC/EAGE Annual Conference and Exhibition*, May, Vienna, SPE 143431, **2011**.
9. Sierra L., East L., Soliman M. Y., and et al., “New Completion Methodology To Improve Oil Recovery and Minimize Water Intrusion in Reservoirs Subject to Water Injection,” *SPE Journal*, **2011**, *16*(3), 648-661.
10. Li Z., Fernandes P. X., and Zhu D., “Understanding the Roles of Inflow-Control Devices in Optimizing Horizontal-Well Performance,” *SPE Drilling & Completion*, **2011**, *26*(3), 376-385.
11. Gomez M., Anaya A. F., Araujo Y. E., and et al., “Passive Inflow Control Device (ICDs) Application in a Horizontal Wells Completions in the Rubiales Area Heavy-Oil Reservoir,” *SPE Heavy and Extra Heavy Oil Conference,* Latin America, SPE 171040, **2014**.
12. Shad S. and Yazdi M. M., “Wellbore Modeling and Design of Nozzle-Based Inflow Control Device (ICD) for SAGD Wells,” *SPE Heavy Oil Conference-Canada*, Alberta, Canada, SPE 170145, **2014**.
13. Sadeghnejad S. and Masihi M., “Water Flooding Performance Evaluation Using Percolation Theory,” *Journal of Petroleum Science and Technology*, **2011**, *1*(2), 19-23.
14. Taheri Nakhost A. and Shadizadeh R., “A Simulation of Managed Pressure Drilling in Iranian Darquain Oil Field,” *Journal of Petroleum Science and Technology*, **2013**, *3*(2), 45-56.