Energy Proceedings
Vol 38, 2024
ISSN 2004-2965

A dynamic control technique for improving oil recovery during the in-situ combustion

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ABSTRACT

In-situ combustion (ISC) has excellent potential in the development of unconventional resources such as heavy oil and tar sand. However, a uniform extension process for the combustion chamber is crucial for maintaining efficient and economical oil recovery during the ISC, which should be given more attention. In this work, a dynamic control technique that is achieved by the regular implementation of production well intermittent shutdown (PWIS) with the aim to improve the uneven extension of combustion chamber is proposed. A 3D combustion model with a volume of 214962 cm^3 is utilized in the ISC experiments to study the application effect of dynamic control technique. The variation of effluent gas compositions, spatial distribution of coke zone, swept area of combustion chamber, burning stability, and pressure difference are studied and analyzed. The results show that the PWIS method is able to force the combustion chamber to extend toward the low and medium permeability regions with little influence on the burning state. The volumetric sweep coefficient of combustion chamber in the low and medium permeability zones was improved and the combustion status varied slightly during the PWIS implementation. Final 3D morphology of coke zone is vividly described according to the real size, and its spatial volumes in the low and medium permeability zones enlarge noticeably after the PWIS implementation. Additionally, the cumulative oil production increased from 5586.5 g to 10426 g, and the final oil recovery ratio enhanced from 23.3% to 40.8% after implementing the dynamic control technique. This work provides a practical approach to improving the volumetric sweep coefficient of combustion chamber, which is of great significance in maintaining a higher oil production efficiency during the ISC field application.

Keywords: Heavy oil, In-situ combustion, Dynamic control technique, Combustion stability, Coke zone

NONMENCLATURE

Abbreviations	
ISC	In-situ combustion
SWB	Secondary water body
PWIS	Production well intermittent shutdown
So	Oil saturation
Sw	Water saturation

1. INTRODUCTION

Heavy oil accounts for an essential portion of the unconventional oil and gas resources, its highly efficient and economic recovery is of great significance to meet the increasing requirement for fossil fuels [1]. Thermal EOR techniques are widely used for improving recoveries in the heavy oil reservoirs [2]. Among the many ways of exploitation, in-situ combustion (ISC) has been identified as an effective thermal recovery method [3]. The fire front is then driven from the injection well to the production well by the injection of air in accordance with the injection project. Due to the rise in reservoir temperature and pressure, the combustion front forces fluids toward the production well utilizing a combination of gas, steam, and water drive. ISC can either be forward or reverse and is further classified into dry combustion and wet combustion, depending on the addition of water during or after the combustion [4]. There are many challenges to achieving profitable exploitation for ISC field applications ascribed to the inadequate mechanism investigation into the sophisticated oil displacement and chemical reactions processes [5]. In the past decades, extensive laboratory studies and pilot tests have been conducted to reveal the mechanism and verify the effectiveness of this technique. Among those laboratory

This is a paper for 15th International Conference on Applied Energy (ICAE2023), Dec. 3-7, 2023, Doha, Qatar.

studies, one-dimensional combustion tube has been widely used to obtain the requisite parameters in designing the ISC field application such as the ignition temperature, velocity of combustion front propagation, fuel availability, and air flux requirements [6]. Unfortunately, combustion tube experiments cannot vividly describe the dynamic evolution process of combustion chamber and coke zone in the heterogeneous reservoirs owing to the limited dimensions.

The ISC performance is vulnerable to the formation physical parameters and production operations such as the formation heterogeneity, secondary water body distribution, oil saturation, oil viscosity, air flux, air injection pressure, well spacing, etc. [7-9]. Furthermore, the recognition of synergistic effect of these factors on combustion chamber extension is still underway by virtue of the extremely complex combustion dynamics and chemical reactions [10]. Therefore, dynamic control methods focusing on modifying the unfavorable extension behaviors of combustion chamber needs further exploration and study. Technically, the dynamic control method should be devoted to adjusting the air injection and production procedures with the aims to improve the oil recovery efficiency. Additionally, the burning stability of combustion front should be fully considered in the process of dynamic control technique implementation.

In order to achieve the goal of modifying the unfavorable expansion behaviors of combustion chamber with hardly affecting the burning state. A technique of the production wells intermittent shutdown (PWIS) was proposed and implemented in the heterogeneous porous medium using a 3D combustion model. The variation of effluent gas compositions, spatial distribution of coke zone, final oil recovery ratio, burning stability, pressure difference, and swept area of combustion chamber was studied and analyzed. This work brings forward a way to improve the volumetric sweep coefficient of combustion chamber in the heterogeneous formation, which helps to attain a higher oil recovery in the ISC field application.

2. EXPERIMENTS

2.1 Materials

The heavy oil used in the experiment was collected from the Xinjiang oilfield, China. The density of oil with sufficient dehydration is 0.95 g/cm^3 at ambient conditions and the variation of oil viscosity versus temperature is presented in Fig. 1. The oil viscosity is 6811 mPa·s (shear rate is 10 s^{-1}) at 30℃. The sand samples used in experiment are quartz sand with different mesh ranges (20~40, 40~60, and 60~100). Additionally, the cement with a temperature resistance of 1000℃ was evenly coated on the top of oil sand to prevent the occurrence of air channeling along the inner surface of upper flange.

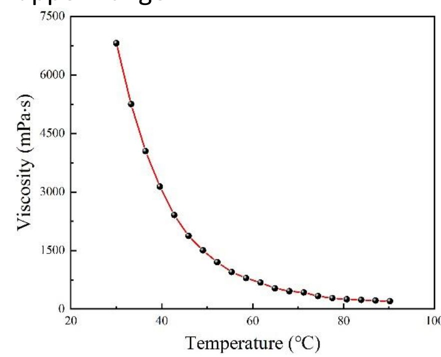

Fig. 1. Variation of heavy oil viscosity versus temperature

2.2 Experimental procedures

2.2.1 Experimental apparatus

A schematic diagram of the 3D combustion model experiment is presented in Fig. 2. The experimental devices consist of a gas injection unit, temperature control, and detection system, data monitoring and acquisition system, and 3D combustion model. The gas injection unit mainly includes gas cylinders (N2 and compressed air), gas pressure regulator valve, gas mass flow meter, and pressure gauge. Temperature control and detection system consists of an electric heater, k-type thermocouples, heating jacket. Data monitoring and acquisition system is composed of temperature sensors, pressure sensors, and an online gas analyzer, which detects and records the temperature variation, effluent gas components, gas injection rate, and pressure difference.

The model is made of Hastelloy, its inner diameter, wall thickness, volume, and weight are 80 cm, 1 cm, 0.215 m^3, and 470 kg, respectively. The maximum pressure and temperature resistance of the model is 1.5 MPa and 800℃, respectively. The upper flange is equipped with an air injection well (H) and chimney wells (G1, G2, G3, and G4). There are three horizontal production wells (N1, N2, and N3) assembled inside the model and located in the same plane (named as production well plane). The distance from the gas injection well (H) to the toe of production wells N1, N2, and N3 is separately 55 cm, 47 cm, and 55 cm. The production well is connected to a gas-liquid separator device, and part of the separated gas is detected and analyzed by the online gas analyzer. There are forty-four temperature detection wells arranged in the model, which makes it able to accurately monitor the temperature variation during the ISC process.

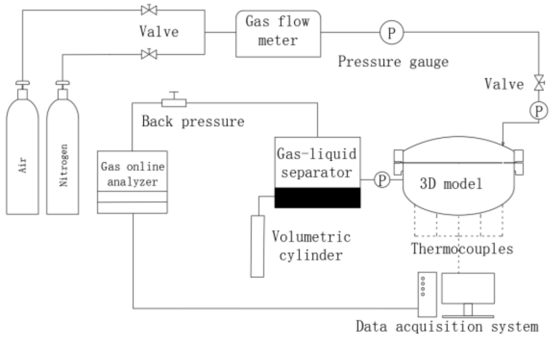

Fig. 2. Schematic diagram of the ISC experiments

<u>2.2.2 Combustion experiments preparation</u>

The quartz sand, crude oil, and kaolin were mixed as the preset mass ratio, and the oil sand that could be used to simulate different permeability regions was obtained after the sufficiently agitate. Table 1 listed the oil sand quality packed in these different zones, and their locations were marked in Fig. 3. By adjusting the mass ratio of quartz sand, oil, water, and kaolin, the model mimicked the oil saturation (So) and water saturation (Sw) in various regions. The high permeability layer (So=39.6%, Sw=6.87%) and the heterogeneous zone were packed on the plane of production well. The left side of heterogeneous area was a low permeability region (So=35.3%, Sw=13.5%), the right side was a medium permeability region (So=42.5%, Sw=15.6%), and the elliptical cylinder in the central part of high-permeability zone was to simulate the secondary water body (So=20%, Sw=60%) formed in the steam injection process. The short axis length of the secondary water body (SWB) was 8 cm, the long axis length was 18 cm, and the thickness was 8 cm. The action of water-saturated zones near the air injection well was to improve the stability of combustion front propagation by enhancing the efficiency of convective heat transfer. Furthermore, oil sands with an oil saturation of 95% were packed below the production well plane to prevent the accumulation of oil in the bottom of the model during ISC process. The permeability of the low, medium, and high permeability zones was approximately 1.5 μm^2, 2.3 μm^2, and 3.6 μm^2, respectively. Additionally, the control experiments without PWIS method implementation were also conducted to compare and analyze the improvement of oil production capability by dynamic control technique. The procedures of experiments are described as follows.

(1) Packing the oil sand in the model and compacting uniformly according to the pre-designed conditions.

(2) cement was brushed on the top layer of oil sand to prevent the occurrence of air breakthrough, then installed on the upper flange of the model.

(3) connected the experimental devices according to the schematic diagram presented in Fig. 2 and checked the sealing tightness.

(4) Injected N2 into the model at a rate of 1.5 L/min and adjusted the backpressure to maintain at 0.5 MPa, then started the heating program for preheating.

(5) Air was injected into the model for ignition after sufficient preheating and the injection rate was increased gradually during ISC process. After the successful ignition, the temperature of heating rod was maintained at 700℃. Meanwhile, recording the compositions of effluent gases, temperature variation, and pressure difference during the experiments.

(6) Two ISC experiments with identical physical parameters were conducted. Experiment A served as the control experiment without implementing the PWIS method, while experiment B implemented the PWIS method in three rounds to enlarge the volumetric sweep volume of the combustion chamber.

(7) Stopping the air injection as the O_2 concentration in effluent gases exceeded 15% or the temperature peak value was monitored by thermocouples near the production well.

(8) After the model was cooled to ambient temperature, removed the upper cap of the model carefully to avoid damaging the oil sand distribution in the model. Then excavated the burned oil sand and measured the actual size of coke zone.

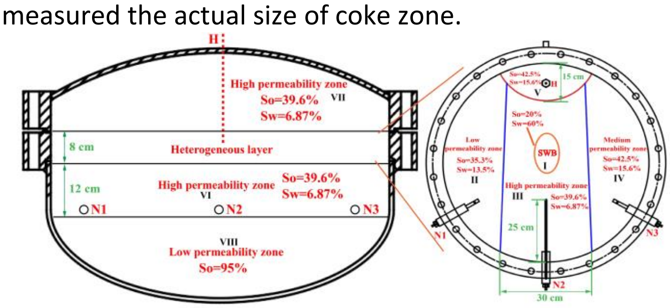

Fig. 3. Physical parameters in the experiments

Table 1. Oil sand quality in different zones of the 3D model.

Zones	Sand quality in E1 (kg)	Sand quality in E2 (kg)
Ⅰ	1.8	1.8
Ⅱ	19.6	20.4
Ⅲ	26.7	29.5
Ⅳ	19.3	20.5
Ⅴ	5.6	5.8

Ⅵ	103.9	112.7
Ⅶ	78.7	80.6
Ⅷ	113.3	108.2

2.3 Implementation of dynamic control technique

The unfavorable extension behaviors of combustion chamber easily occur in the heterogeneous reservoir and normally bring about the oil wells productivity diversities. In attempts to improve the unfavorable state, the production wells intermittent shutdown (PWIS) method was implemented in two rounds. The PWIS method is implemented as the production well closed with high oil production capacity regularly for a period, and the closure time is listed in Table 2. A short-time closure hardly affects the oil production efficiency and the injected air diverts flow to other oilwells, the combustion chamber is correspondingly inclined to extend there. The first round of PWIS was conducted in the time of 1708~1802 min. The production wells N1 and N3 located in the low and medium permeability areas maintain the production status, while well N2 was regularly closed 3 times and with a duration time of 20 min each time. Taking the first time of intermittent shutdown as an example, the well N2 was closed at 1708 min and opened after 20 minutes.

The temperature profiles detected by temperature detection layers indicated that the swept area of combustion chamber in the low and medium permeability regions enlarged obviously after employing the PWIS method. Hence, the second round of PWIS was performed in the time range of 2550~3157 min to further improve the swept volume of combustion chamber. The wells (N1 and N3) maintain the production status, and well N2 was initially closed 11 times with a closure time of 20 min, then closed 3 times with each duration of 40 min. The temperature variation implied that the combustion chamber was inclined to extend in the medium permeability zone after the first and second rounds PWIS implementation process. Additionally, the variations in the volumetric sweep coefficient of the combustion chamber, combustion stability, and displacement pressure difference during the implementation of PWIS were analyzed to investigate the application effect of dynamic control technique.

Table 2. Time span for the production well (N2) shutdown

First round (min)	Second round (min)		
1708~1728	2550~2570	2750~2770	2950~2970
1752~1772	2600~2620	2790~2810	2997~3037
1782~1802	2630~2650	2830~2850	3057~3097
	2670~2690	2870~2890	3117~3157
	2710~2730	2910~2930	

3. RESULTS AND DISCUSSION

3.1 Spatial distribution of coke zone

Coke zone evolution is almost consistent with the combustion chamber extension, which is significantly influenced by the direction of airflow in the reservoir [7]. The spatial distribution characteristics of coke zone are helpful in visually describing combustion chamber development. The variation of final coke zone morphology with the PWIS method implementation is presented in Fig. 4. As is shown in Fig. 4A, coke zone mainly developed in the high-permeability zone without the PWIS method implementation. The spatial volume of the internal and external boundaries finally enlarged to 18486.48 cm^3 and 38114.18 cm^3, respectively. The volumetric sweep coefficients of inner and outer boundaries were separately 8.6% and 17.74%. The features of coke zone distribution indicated that reservoir heterogeneity plays a critical role in the combustion chamber extension. Combustion chamber inclines to extend along the high-permeability region owing to the lower flow resistance, which normally brings about huge diverse production behaviors for oilwells such as the response time and oil production efficiency [14]. Coke zone volume enlarged obviously after implementing the PWIS method (shown in Fig. 4B). The volume of internal and external boundaries expanded to 34639.47 cm^3 and 69989.6 cm^3, as well as the volumetric sweep coefficient was 11.61% and 32.56%, respectively. Thereby, the PWIS method is able to improve the unfavorable expansion behaviors of combustion chamber, which greatly reduces the adverse effects of reservoir heterogeneity, enhances the oil recovery in low-permeability layer, and significantly improves the final oil recovery ratio.

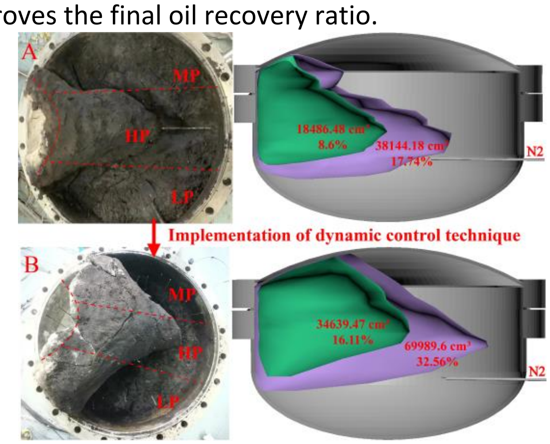

Fig. 4. Variation of final coke zone morphology

3.2 Effect of dynamic control technique

3.2.1 Performance of the first-round implementation

In order to enlarge the swept volume of combustion chamber in the low and medium permeability regions, the first round of the PWIS method was implemented in the time of 1708~1802 min. The variation of produced gas compositions, pressure difference, and air injection rate versus time during the PWIS application are presented in Fig. 5. The closure and the opening time of production well N2 is marked by black dotted lines and blue dotted lines, respectively. The O_2 and CO_2 concentrations in effluent gas exhibited a slight variation with an increase of 0.21% and a decrease of 1.26%. The CO concentration was maintained at around 1.47%, and CH_4 concentration showed a slight reduction of 0.78% as well. The O_2 concentration varied from 9.49% to 9.71%, and CO_2 concentration decreased from 10.38% to 9.12%. The CO concentration was maintained at around 1.47%, and CH_4 concentration showed a slight reduction tendency, it dropped from 1.77% to 0.99%. The slight variation of effluent gas compositions indicated the combustion state varied a little in the PWIS implementation process. The pressure difference sharply decreased from 140 kPa to 70.2 kPa and the instantaneous air injection rate decreased from 20 L/min to 15.4 L/min during the well (N2) first-time closure. The noticeable reduction of pressure difference and instantaneous air flux could be largely explained by the airflow disturbance and unstable multiphase seepage in the porous media during the well shutdown. Additionally, the oscillating points that appeared in the pressure difference curve were induced by the data noise.

The sweep area variation in the low and medium permeability zones was calculated and listed in Table 3. The enlargement of swept area distributed from the first layer to the fourth layer in the low-permeability zone was separately 4.90 cm^2, 12.72 cm^2, 3.24 cm^2, and 7.06 cm^2 after the PWIS method was employed. The combustion chamber inclined to expand in the medium permeable zone and the swept area enlargement in the medium-permeability zone were 4.90 cm^2, 12.72 cm^2, 3.24 cm^2, and 7.06 cm^2, respectively. The second thermometric layer monitored a slight areal variation in the medium permeability region, which was attributed to the small extension of combustion chamber in this layer. In this stage, combustion chamber did not expand to the fifth layer in the low-permeability zone and the swept area was undetected. In summary, the information on effluent gas compositions, pressure difference, instantaneous air injection rate, and swept areas explicitly demonstrated that the PWIS method was able to improve the swept volume of combustion chamber in the heterogeneous formation with little influence on the burning state.

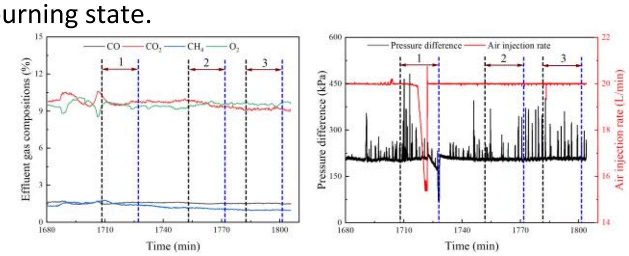

Fig. 5. Variation of produced gas compositions, pressure difference, and air injection rate during the first-round implementation of PWIS

Table 3. Swept area variation of the first-round implementation for the PWIS method

layers	Low permeability zone		Variation	Medium permeability zone		Variation
	1708 min	1802 min		1708 min	1802 min	
1st	187.62 cm^2	192.53 cm^2	4.90 cm^2	396.49 cm^2	410.08 cm^2	13.59 cm^2
2nd	6.34 cm^2	19.06 cm^2	12.72 cm^2	26.10 cm^2	33.63 cm^2	7.53 cm^2
3rd	86.59 cm^2	89.84 cm^2	3.24 cm^2	442.79 cm^2	465.67 cm^2	22.88 cm^2
4th	25.19 cm^2	32.26 cm^2	7.06 cm^2	399.50 cm^2	429.50 cm^2	30.01 cm^2
5th	/	/	/	126.04 cm^2	131.38 cm^2	5.34 cm^2

3.2.2 Performance of the second-round implementation

Given the desirable results for the PWIS method implemented in the first round, the second round was conducted in the time range of 2550~3157 min to further modify the expansion process of combustion chamber. The variation of effluent gas compositions, pressure difference, and air injection rate in the PWIS implementation process are presented in Fig. 6. The closure and opening time for the production well (N2) are labeled by black and blue dotted lines, respectively. The CO_2 and O_2 concentrations in effluent gas fluctuated at around 9.5% and 7.3%, respectively. Whereas the CO and CH_4 concentrations were kept at about 1.5% and 0.6%, respectively. The gentle fluctuation of the CO_2 and O_2 concentrations demonstrated that the burning state of combustion zone varied a little. The pressure difference varied from 219.71 kPa to 292.12 kPa and the instantaneous air injection rate exhibited fluctuation during the well shutdown. The slight variation process was mainly induced by the airflow disturbance and unstable multiphase seepage. To sum up, the ISC performance varied slightly during the PWIS implemented process.

The swept areas of combustion chamber in the low and medium permeability zones are listed in Table 4. The enlargement of swept area from the first layer to the fifth layer in the low-permeability zone was separately 14.26 cm^2, 17.11 cm^2, 37.14 cm^2, 17.35 cm^2, and 12.38 cm^2. Whereas the swept area variations in the medium-permeability zone were 81.49 cm^2, 64.98 cm^2, 11.81 cm^2, 12.66 cm^2, and 69.67 cm^2, respectively. The enlargement of swept area detected in the first, second, and fifth thermometric layers in the medium permeability region was larger than that in the low permeability zone, yet the opposite trend was exhibited in the third and fourth layers. The enlargement of combustion chamber volume and gentle variation of burning status demonstrated the great application performance of the PWIS method.

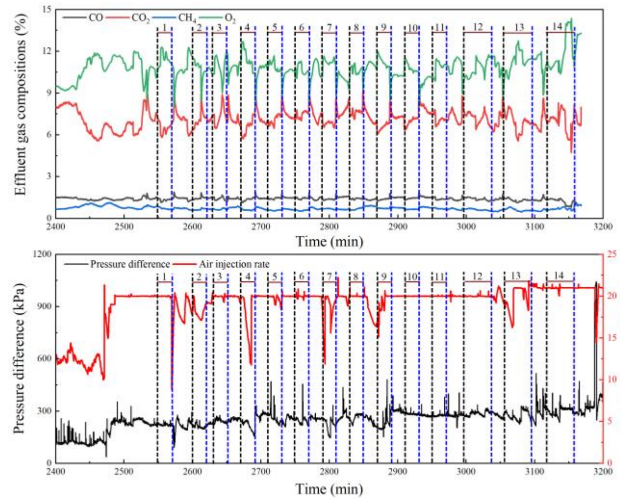

Fig. 6. Variation of effluent gas compositions, pressure difference, and air injection rate in the PWIS implementation period

Table 4. Swept area variation of the second-round implementation for the PWIS method

layers	Low permeability zone		Variation	Medium permeability zone		Variation
	2550 min	3157 min		2550 min	3157 min	
1st	264.23 cm^2	278.48 cm^2	14.26 cm^2	471.18 cm^2	552.67 cm^2	81.49 cm^2
2nd	46.16 cm^2	63.27 cm^2	17.11 cm^2	9.77 cm^2	74.75 cm^2	64.98 cm^2
3rd	49.57 cm^2	86.72 cm^2	37.14 cm^2	455.28 cm^2	467.10 cm^2	11.81 cm^2
4th	50.15 cm^2	67.68 cm^2	17.53 cm^2	447.07 cm^2	459.72 cm^2	12.66 cm^2
5th	25.47 cm^2	37.85 cm^2	12.38 cm^2	54.96 cm^2	124.63 cm^2	69.67 cm^2

3.3 Dynamic liquid production

Cumulative liquid production versus time in the experiments is presented in Fig. 7, and the A and B are represented without and with implementation of dynamic control technique. After the dynamic control technique was implemented, the time of liquid and oil production was 710 min and 942 min, respectively. The cumulative liquid production was 18024 g and the cumulative oil production was 10426 g. The final oil recovery factor reached 40.8%. Whereas the cumulative oil production was only 5586.5 g and the oil recovery factor was merely 23.3% in the experiment without implementation of dynamic control technique. The final oil recovery factor increased by 73.8% after implementing dynamic control method, which demonstrates a better field appliance prospect. Furthermore, a dramatic increment for the cumulative liquid production was observed as the time varied from 3350 min to 3530 min, which was induced by the displacement effect of high temperature and residual pressure inside the model. The liquid production was still in progress even after the air injection operation was terminated. Additionally, the average oil production rate was 1.09 g/min after implementing the PWIS method, while the average rate was 1.16 g/min without implementing the PWIS method, which indicated that the implementation of the dynamic control technique had little impact on the oil production rate during the ISC.

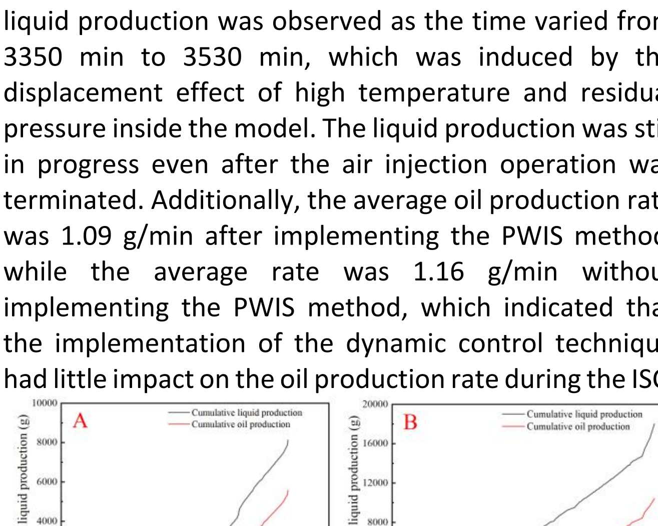

Fig. 7. Cumulative liquid production versus time

4. CONCLUSIONS

A dynamic control technique to improve oil recovery in the heterogeneous formation was proposed and implemented, which was achieved by the implementation of production well intermittent shutdown (PWIS) method. The conclusions are summarized as follows.

(1) Coke zone final morphology in the low and medium permeability zones enlarged noticeably after implementing the PWIS method, which confirmed the improvement of volumetric sweep efficiency of combustion chamber.

(2) The PWIS method greatly reduced the adverse effects of reservoir heterogeneity by improving the unfavorable expansion behaviors of combustion chamber, and the final oil recovery factor was enhanced by 73.8%.

ACKNOWLEDGEMENT

The authors sincerely thank the foundation provided by the National Natural Science Foundation of China (General Program): Study on the prediction of fire front propagation and the mechanisms of fire chamber evolution in three-dimensional space (grant number 52274052)

DECLARATION OF INTEREST STATEMENT

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. All authors read and approved the final manuscript.

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