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Method Article

An advanced scaling model system for non-condensable gas steam assisted gravity drainage recovery process

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ABSTRACT

Physical modeling is critical to study the performance of certain operation in heavy oil reservoirs. A well-designed experiment should guarantee the information gathered from lab would be applied to predict the thermal process in the field. To meet this requirement, the initial and boundary condition similarity between lab and field should be satisfied. It is reasonable to follow certain scaling criteria to fabricate the physical model. In addition to these conventional guidelines, this paper makes following recommendations to ensure a successful thermal recovery experiment,

- To control and mitigate the steam channeling between the sand-pack and apparatus wall, the back wall is designed as it can be pushed enough to increase contact pressure.
- Heat loss should be handled carefully, which impacting steam chamber growing and causing heat accumulation around the model.
- A data acquisition system, based on PXI platform and Labview software, for the thermal recovery experiments had been proved valuable in evaluating the spreading progress of steam chamber.

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Keywords: Scaling model, Thermal recovery, Heat loss control, Channeling, Anisotropic stress condition, Temperature cloud, Intensity graph
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Resource availability:	*The instruments, equipments and software used in our study had been revealed by following links,* https://www.dupont.com/brands/nomex.html https://www.bronkhorst.com/int/products https://www.teledyneisco.com/en-us/pumps https://www.emerson.com/en-us/automation/rosemount https://www.ni.com/en-us/support/model.pxie-1075.html https://www.embarcadero.com/products/rad-studio

*Method details

Background

Thermal recovery is the most important way to unlock heavy oil (or oil sands) reserves worldwide. The performance of certain thermal project varied according to its geological condition and main recovery technology. Physical modeling is critical to ensure a success of the operation. It not only helps operators understand the mechanisms and characterizations of the operation but also provide valuable information for numerical simulation and field deployment. However, running a high quality physical experiment in the lab is not easy as it always involves complex physical process, like heat transfer, multiphase flow in porous media, phase behavior of agents, dissolution and exsolution of gases, viscous fingering, chemical reaction, de-asphalting and so on. Generally, a customized setup, method as well as procedure are needed. So far, many models for this kind of purpose had been built by various affiliations. However, few would deal with the challenges of scaling, heat loss control as well as steam channeling. This work presents an advanced scaling model system, which includes some unique technologies to meet these challenges.

Scaling consideration

As we try to understand the potential performance at field scale from lab scale, a bridge between these two scales should be established first. Scaling theory, based on dimensionless group analysis and controlling equations for physical process, shows the relationship between two in terms of geometry, time and so on. It provides a guideline for model design. Pujol and Boberg [1] made the first effort to bridge the gap between field operation and lab scale experiment in terms of steam flooding process. Kevin Kimber [2] then systematically studied the scaling methods and present five scaling approaches. Yang and Butler [3] proposed a B3 scaling group for Steam Assisted Gravity Drainage (SAGD) process. Yuan et al. [4] deviated another scaling group for Non-Condensable Gas (NCG) SAGD study. Lorimer [5] used reservoir simulation to study scaling groups for hybrid steam-solvent recovery processes. They examined diffusion, dispersion, advection and capillary pressure and proposed a set of scaling groups. Generally speaking, Pujol and Boberg (PB) criteria [1], developed for heat transfer and darcy flow in porous media, is good enough for most steam injection process. It is also successfully applied in simulating SAGD process. Our previous lab experience of SAGD study following PB criteria did produce reliable results. However, it also has some limitations, such as representing capillary force. Since capillary force is generally very low compared to viscous force in recovery super heavy oil, ignoring capillary force would not affect the physical modeling result very much. Another limitation need to mention is that mass transfer is not considered in PB criteria. As far as we know, there is no reliable scaling method dealing with heat transfer, mass transfer and Darcy flow in porous media all at once. Fortunately, solubility of nitrogen in both oil and water is negligible and the mass transfer

Table 1
scaling groups derived from PB criteria.

No.	Scaling groups	Physical significance	Parameters to be scaled
1	$\frac{L_y}{L_x}, \frac{L_z}{L_x}$	Geometry ratio	geometry
2	$\frac{\rho_o}{\rho_R}, \frac{\rho_w}{\rho_R}, \frac{\rho_s}{\rho_R}, \frac{\mu_o}{\mu_s}, \frac{\mu_o}{\mu_w}, \frac{C_o}{C_R}, \frac{C_w}{C_R}$ $\frac{\rho_{rr}C_{rr}}{\rho_R C_R}, \frac{\rho_c C_c}{\rho_R C_R}, \frac{\lambda_w}{\lambda_o}, \frac{\lambda_{rr}}{\lambda_o}, \frac{\lambda_c}{\lambda_o},$	Dimensionless properties	Properties of reservoir
3	$J = \frac{p_c}{\sigma \cos\theta}\sqrt{\frac{k}{\phi}}$	Capillary force to interfacial tension	Capillary force
4	$\frac{k\Delta p}{VL_x\mu_w}$	Driving force to viscous force	Pressure difference
5	$\frac{k\Delta\rho g}{V\mu_o}$	Gravity to viscous force	permeability
6	$\frac{\alpha_o}{VL_x}$	Heat conduction to convection	velocity
7	$\frac{\alpha t}{h^2}$	Fourier number	time

would be insignificant. We still used PB scaling method to design the physical simulation of NCG SAGD in this work. The steam injection temperature, operating pressure and fluid system in the model tests were the same as in the field. Finally, we got a set of scaling groups as showed in Table 1.

Normally, we use the same fluid and matrix in the lab as in the field. Therefore, the properties as porosity, saturation, thermal diffusion coefficient of oil-bearing porous media, density and viscosity of fluid are identical in both system. As Capillary force is quite small related to viscous force, the scaling group 3 is generally ignored with minor impact. Using other scaling groups in Table 1, we could get the following relation,

$$\frac{t_m}{t_f} = \left(\frac{K_f}{K_m}\right)^2 = \left(\frac{L_m}{L_f}\right)^2 \tag{1}$$

Where α is thermal diffusion coefficient, m^2/s; V is velocity of steam, m/s; L is shift distance between wellpairs, m; K is permeability of porous media, m^2; $\triangle\rho$ is density difference between oil and gas, Kg/m^3; g is gravitational accelerate constant, m/s^2; g_c represents gravitational constant; μ is viscosity of oil, Pa.s; t is time, s; m represents model; f represents field;

If we get the information regarding the objective formation, the parameters for lab model would be determined by scaling relation mentioned above. For example, we choose the scaling ratio to be 100. A SAGD formation had wellpair shift distance of 100 m, thickness of 24 m, porosity of 30%, oil saturation of 75%, permeability of 2 Darcy. According to the PB criteria and expressions mentioned above, the model parameters would be determined with width (related to the wellpair shift distance) of 100 cm, thickness of 24 cm, porosity of 30%, oil saturation of 75%, permeability of 200 Darcy. 1 hour in the lab would be 1.4 year at field. Now we have determined the model's height (reservoir thickness) and length (wellpair shift distance). The width of the model represent a fraction of the horizontal segment of SAGD wellpair. For 2D study purpose, this should be considered from the point of heat loss control. If it is too small, the heat loss will take up a large fraction of imported energy and cause failure of the experiment. If it is too large, the model will be big and essentially, it will turn

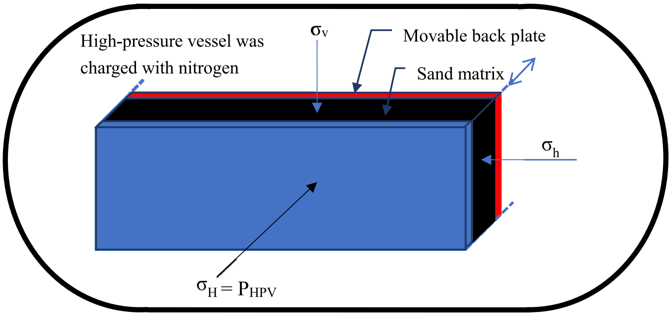


Fig. 1. The unique structure of the 2D model. Movable back plate was in red. Anisotropic Stress condition would be established when HPV was charged with nitrogen.

to be a 3D model. 4 to 10 cm for the width is generally good for a 2D thermal experiment. So far, we have decided the geometry of the model.

Heat loss and channeling control

To better control heat loss of the model, many technologies had been trialed. Putting the model in vacuum to prevent heat convection, covering the surface of the model with special material to reduce heat radiation are among these efforts. Nowadays, there are mainly two sorts of models to meet this challenge. One is using thin wall model, which largely reduce heat conduction along tangential direction inside. As the model is placed inside a high-pressure vessel (HPV), the heat loss due to thermal convection is not ignorable. To undergo extremely high temperature and high pressure during steaming, the model wall had to be made of metal. The merit of this design is that the wall is flexible and always stick to the sand face, which largely impeded gas channeling along the wall. Demerit comes with high cost of fabrication. In addition, heat loss is considerable as high-pressure fluid in the vessel would cause server thermal convection. As an example, Deng et al. [6] from ARC(Alberta Research Council) used a large 2D model to evaluate the performance of SAGD. Its size was 160*24*10 cm, holding multiple well pairs in their thin wall model. The other way is to use thick wall model. It also has to be used with a HPV. As an example, Shin and Polikar [7] from UA investigate Fast-SAGD Process with a 2D model. This model is 87.4*22.7*5 cm. The experiment suffered from serious heat loss issue and got high cumulative steam to oil ratio (CSOR). Zan et al. [8] from PetroChina built a 3D model for steam injection experiment which was a thick wall model. Concerning with this sort includes heat conduction along tangential direction inside, heat sink phenomena and channeling. If the inner surface contacting sand face is made of metal, the first issue will be pronounced. This can be overcome by placing a layer of insulation material, like poly-ether-ether-ketone (PEEK) onto the thick wall. However, Heat sink would be tough if its heat capacity is high. This should be dealt with care by integrating thermal engineering calculation. So appropriate insulation material and thickness of wall and insulation layer would be determined. Due to poor ability to deform, steam channeling was found to be quite common in early experiments with this sort of thick wall models. Therefore, we designed a moveable structure for the plate at backside (see Fig. 1). Once the HPV was pressurized, the back plate would move towards the sand matrix and squeeze it to make it tight. With this structure, we never saw steam channeling in our lab tests any more. This also provided a stress boundary condition and made it possible to include shear dilation effect due to anisotropic stress status. The following equations describe the principle stress,

Model design

According to the scaling theory and formation condition, a customized model was fabricated as Fig. 2 showed. This 2D thick model was 100 cm in length, 25.4 cm in height and 4 cm in thickness.

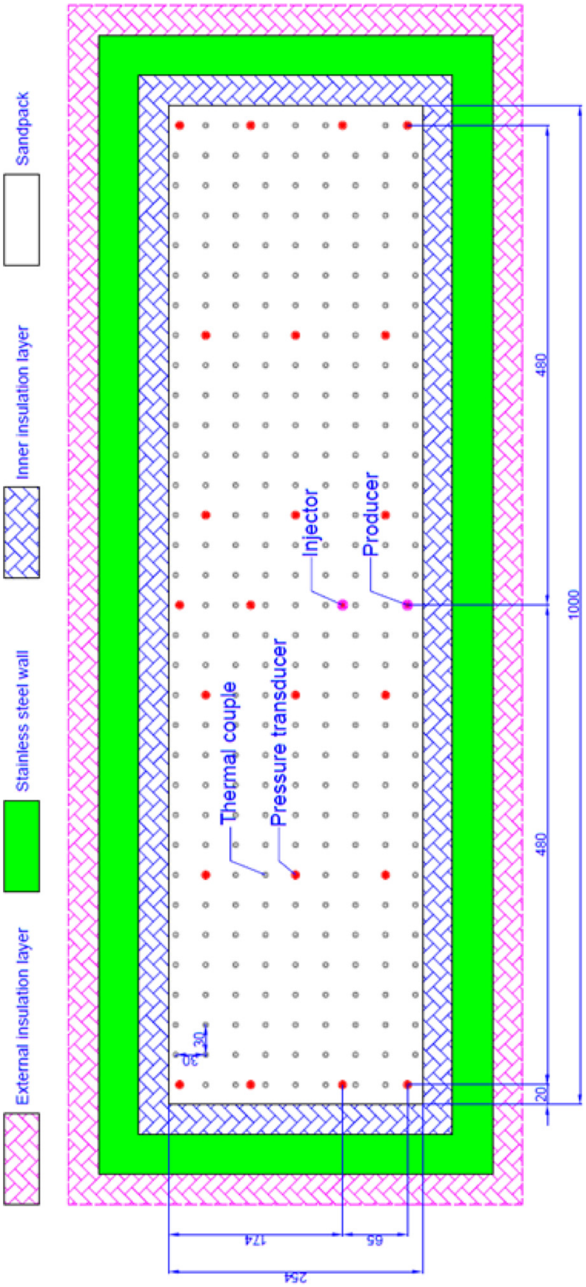


Fig. 2. Deployment of sensors and wells in the 2D model.

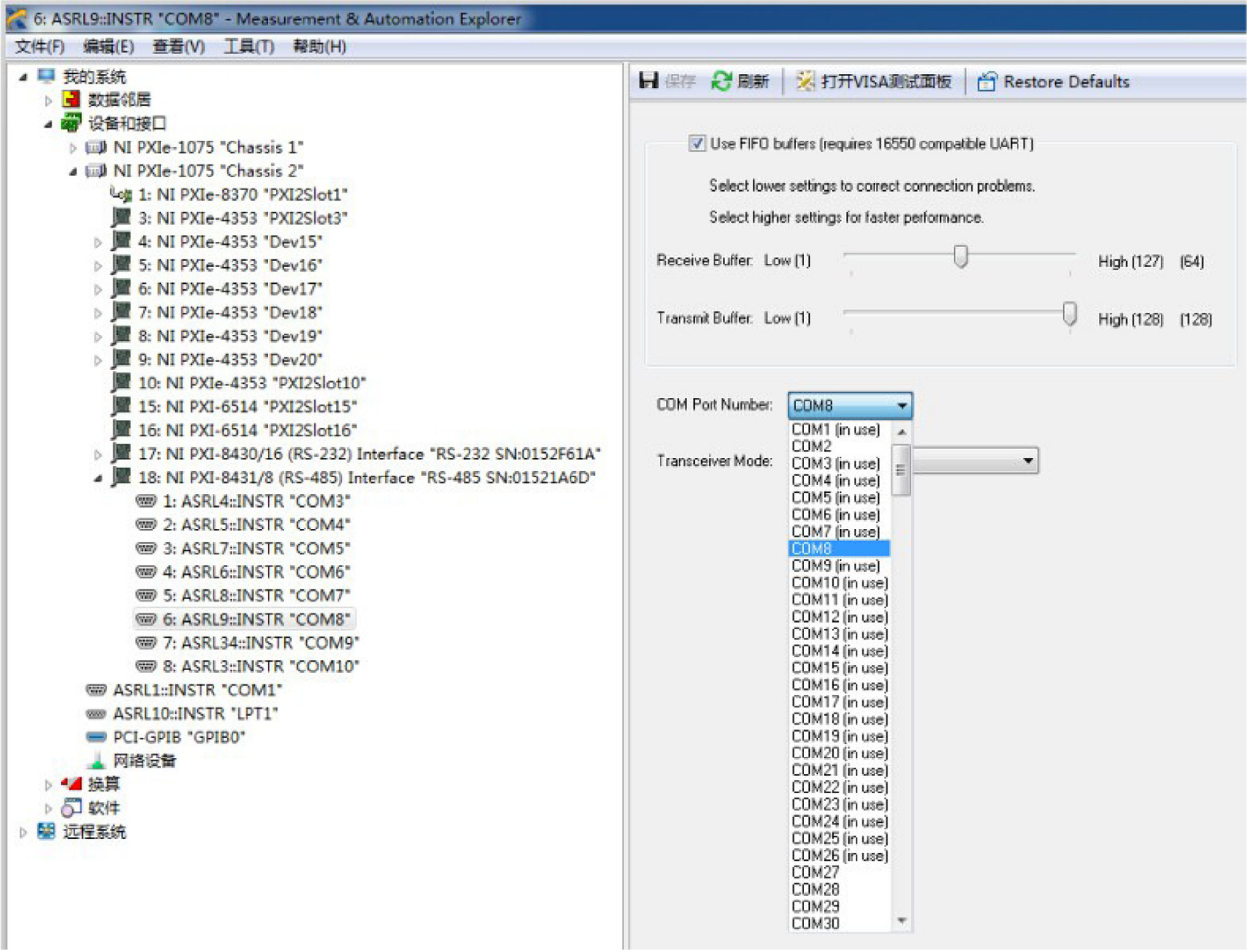
Totally 297 thermal couples (Omega, K type) was deployed with shift distance of 3 cm in each direction. 24 pressure transducers (Wika, 0.1%FS) and 7 differential pressure transducer (Rosemount, 0.065% FS) for collecting temperature and pressure information with time. Considerable efforts had been made to control heat loss during desiring and fabricating this model. There were two insulation layers, inside and outside the model, were installed independently. The inner insulation layer would play the most important role of controlling heat loss. It was 4 cm in thickness. This thickness had been chosen by numerical simulation with the aim of controlling heat loss ratio below 10% at steaming temperature for 8 hours. The inner insulation layer was made of a special material, which was capable to keep heat conductivity below 0.24 W/m·K at steaming temperature and pressure. It also performed well when contacting with water and oil. In contrast, traditional insulation material, mica plate, usually sucked in water and swelled during steam injection. Besides, the external insulation layer (Nomex), with thickness of 3 cm, was applied to the external surface to further prevent heat loss. Lastly, the model would be placed inside a high-pressure vesselwhich was charged with nitrogen. This would mimic overburden pressure and prevent potential steam channeling along the surface of the model.

Setup and Data acquisition system

Except the model and HPV, lots of auxiliary equipment are involved in this physical modeling system. This system consisted of 2 pumps (ISCO 260D), 2 steam generators (18KW, 50 ml/min at 375°C), 1 gas flow controller (Bronkhorst F-211cv), 1 gas flow meter (Alicat 20-1), 2 vapor-liquid separators and 1 online viscometer (Cambridge viscopro2000). Nitrogen was pressurized to 45 MPag prior to experiment and stored in 5 accumulators with volume of 2 L. Injecting rate would be controlled by the Bronkhorst flow controller. The operating pressure was set by a backpressure regulator, which would work well at 175 °C. A NI PXIe-1075(see Fig. 3) was used for data collecting. Based on this platform, NI PXIe-4353 modulus was installed for Thermocouple Type K Measurement, NI PXIe-6514 for pressure and pressure difference measurement. NI PXIe-8430 and NI PXIe-8431 are employed as high-performance interface for high-speed communication with RS232 and RS485 devices, such as ISCO pumps, steam generators, Bronkhorst gas flow controller / gas flow meter, vapor-liquid separators, scales and so on. Besides, Labview based software was developed for data processing. It’s quite powerful tool to deal with all kinds of instruments. It is a graphical programming approach that help visualize every aspect of our application, including hardware configuration, measurement data and data processing. The main interface of data acquisition system, developed by Labview software [9], was showed in Figs. 4, 6–8.

Data processing method

Since the temperature as well as the NCG concentration distribution include most valuable information for this study, we made special efforts to plot the 2D cloud with scattered data points. Fig. 5 shows the program. It starts with reading data from thermal couples, which yields a data set. The raw data was then treated and being send to a globe variable TE_Process. X and Y arrays are physical position of thermal couples in X direction and Y direction, which should be input to the program after completing the model design. With these variables, we can interpolate and update the temperature cloud with embedded intensity graph. The resolution of the cloud would be controlled by defining the Interpolation points through the start and end variable. The tricky thing here is that we defined some dummy points, which does not physically exist but serve the purpose of plotting the boundary of the cloud. In our implement, these dummy points were given values from the closest TC. The similar procedure was used to plot the NCG concentration cloud except that the concentration was not directly collected from sensors but from a calculation based on an empirical expression.



- 我的系统
  - 数据邻居
  - 设备和接口
    - NI PXIe-1075 "Chassis 1"
    - NI PXIe-1075 "Chassis 2"
      - 1: NI PXIe-8370 "PXI2Slot1"
      - 3: NI PXIe-4353 "PXI2Slot3"
      - 4: NI PXIe-4353 "Dev15"
      - 5: NI PXIe-4353 "Dev16"
      - 6: NI PXIe-4353 "Dev17"
      - 7: NI PXIe-4353 "Dev18"
      - 8: NI PXIe-4353 "Dev19"
      - 9: NI PXIe-4353 "Dev20"
      - 10: NI PXIe-4353 "PXI2Slot10"
      - 15: NI PXI-6514 "PXI2Slot15"
      - 16: NI PXI-6514 "PXI2Slot16"
      - 17: NI PXI-8430/16 (RS-232) Interface "RS-232 SN:0152F61A"
      - 18: NI PXI-8431/8 (RS-485) Interface "RS-485 SN:01521A6D"
        - 1: ASRL4::INSTR "COM3"
        - 2: ASRL5::INSTR "COM4"
        - 3: ASRL7::INSTR "COM5"
        - 4: ASRL6::INSTR "COM6"
        - 5: ASRL8::INSTR "COM7"
        - 6: ASRL9::INSTR "COM8"
        - 7: ASRL34::INSTR "COM9"
        - 8: ASRL3::INSTR "COM10"
    - ASRL1::INSTR "COM1"
    - ASRL10::INSTR "LPT1"
    - PCI-GPIB "GPIB0"
    - 网络设备
  - 换算
  - 软件
- 远程系统

☑ Use FIFO buffers (requires 16550 compatible UART)

Select lower settings to correct connection problems.

Select higher settings for faster performance.

Receive Buffer: Low (1) High (127) (64)

Transmit Buffer: Low (1) High (128) (128)

COM Port Number: COM8

COM1 (in use)
COM2
COM3 (in use)
COM4 (in use)
COM5 (in use)
COM6 (in use)
COM7 (in use)
COM8
COM9 (in use)
COM10 (in use)
COM11 (in use)
COM12 (in use)
COM13 (in use)
COM14 (in use)
COM15 (in use)
COM16 (in use)
COM17 (in use)
COM18 (in use)
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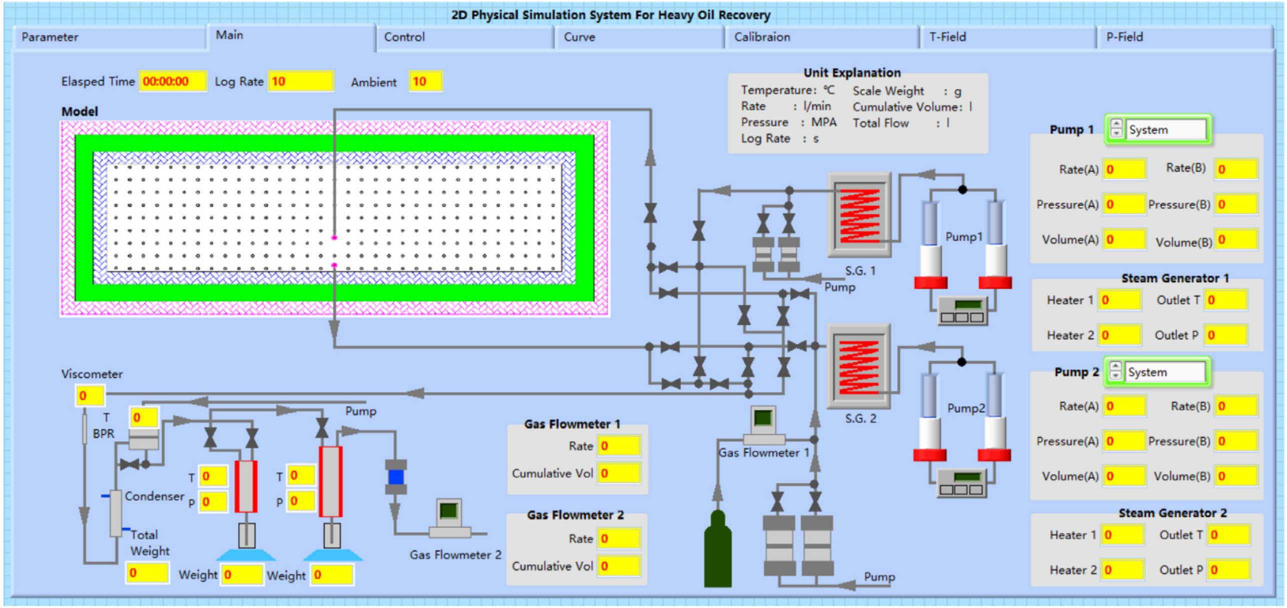
COM21 (in use)
COM22 (in use)
COM23 (in use)
COM24 (in use)
COM25 (in use)
COM26 (in use)
COM27
COM28
COM29
COM30

Transceiver Mode:

Fig. 3. Hardware used for data acquisition system.



Elasped Time 00:00:00
Log Rate 10
Ambient 10

Unit Explanation
Temperature: ℃
Rate : l/min
Pressure : MPA
Log Rate : s
Scale Weight : g
Cumulative Volume: l
Total Flow : l

Viscometer 0
T 0
Total Weight 0
T 0
P 0
T 0
P 0
Weight 0
Weight 0

Gas Flowmeter 1
Rate 0
Cumulative Vol 0

Gas Flowmeter 2
Rate 0
Cumulative Vol 0

Pump 1 System
Rate(A) 0
Rate(B) 0
Pressure(A) 0
Pressure(B) 0
Volume(A) 0
Volume(B) 0

Steam Generator 1
Heater 1 0
Outlet T 0
Heater 2 0
Outlet P 0

Pump 2 System
Rate(A) 0
Rate(B) 0
Pressure(A) 0
Pressure(B) 0
Volume(A) 0
Volume(B) 0

Steam Generator 2
Heater 1 0
Outlet T 0
Heater 2 0
Outlet P 0

Fig. 4. Flow chart showed in the main interface of data acquisition system.

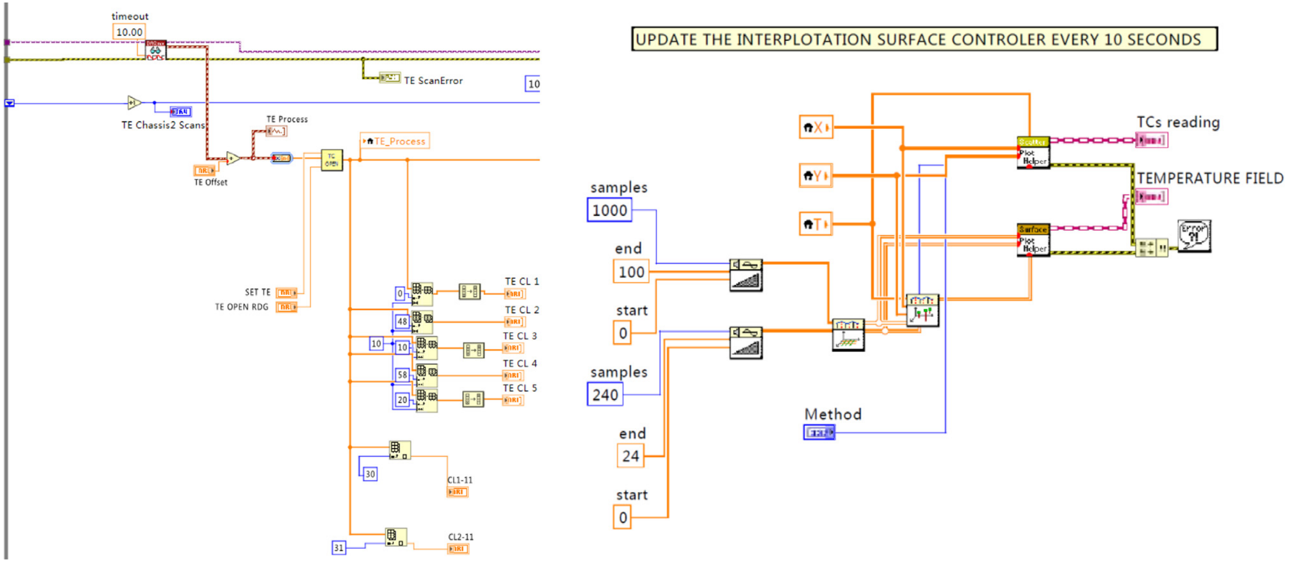
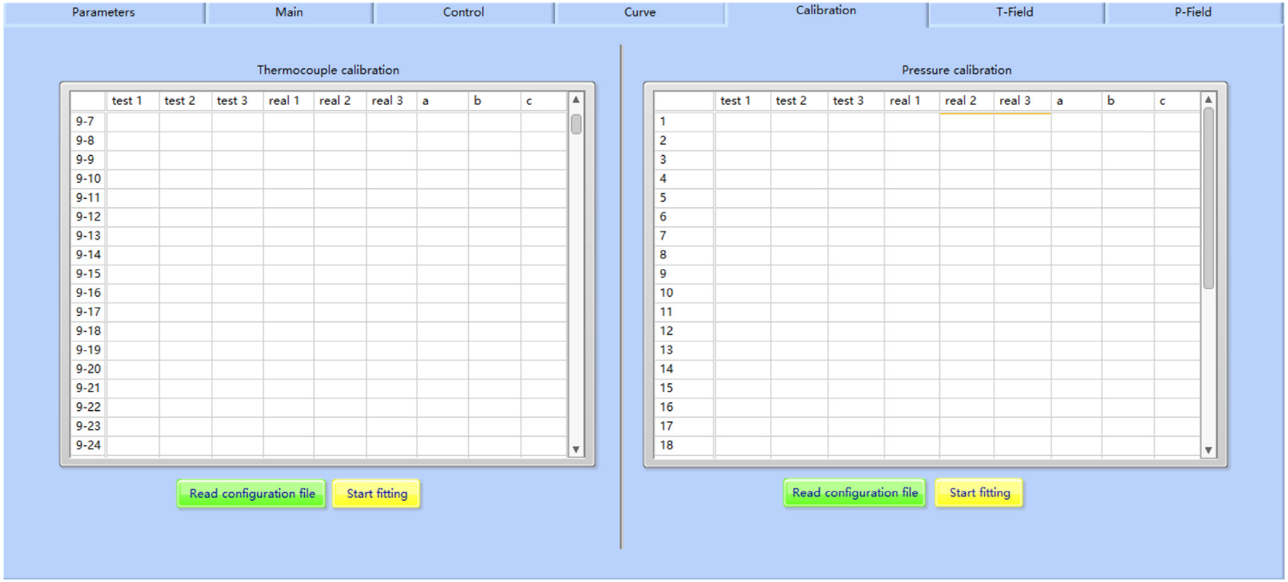


Fig. 5. Diagrams of the data processing program. (Left is the diagram for collecting data from data source. Right shows the program to update the temperature cloud.)



Thermocouple calibration

	test 1	test 2	test 3	real 1	real 2	real 3	a	b	c
9-7									
9-8									
9-9									
9-10									
9-11									
9-12									
9-13									
9-14									
9-15									
9-16									
9-17									
9-18									
9-19									
9-20									
9-21									
9-22									
9-23									
9-24									

Pressure calibration

	test 1	test 2	test 3	real 1	real 2	real 3	a	b	c
1									
2									
3									
4									
5									
6									
7									
8									
9									
10									
11									
12									
13									
14									
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18									

Fig. 6. User interface for sensors calibration.

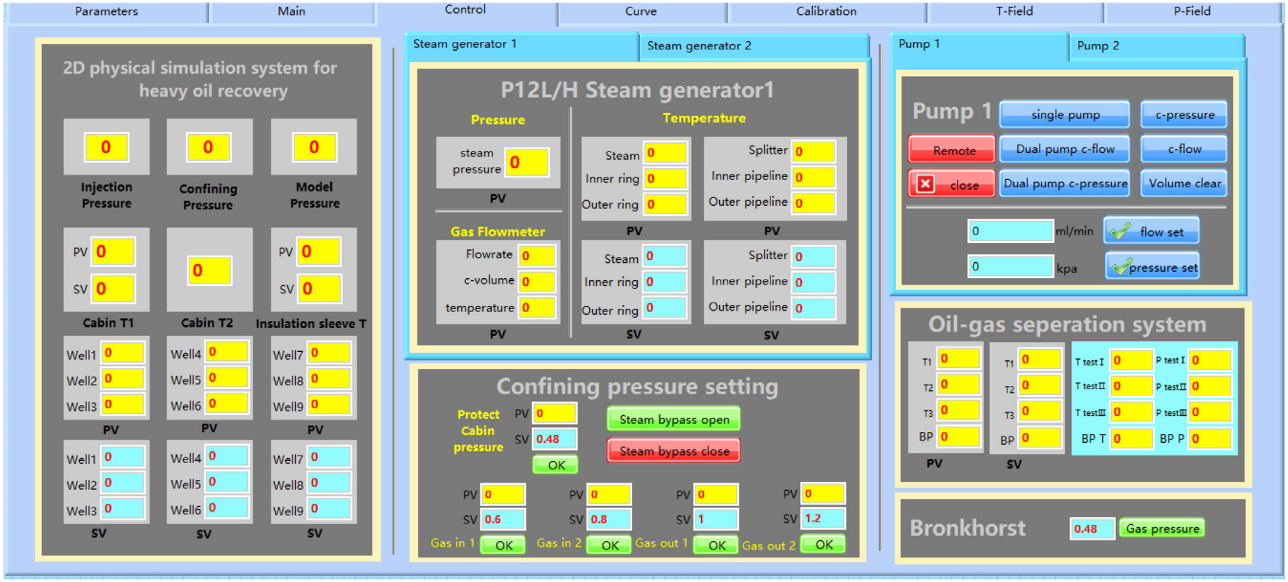

Fig. 7. The control panel of data acquisition system.

Acquisition interval(s) 0.5

Fig. 8. User interface showing real time and processed curves.

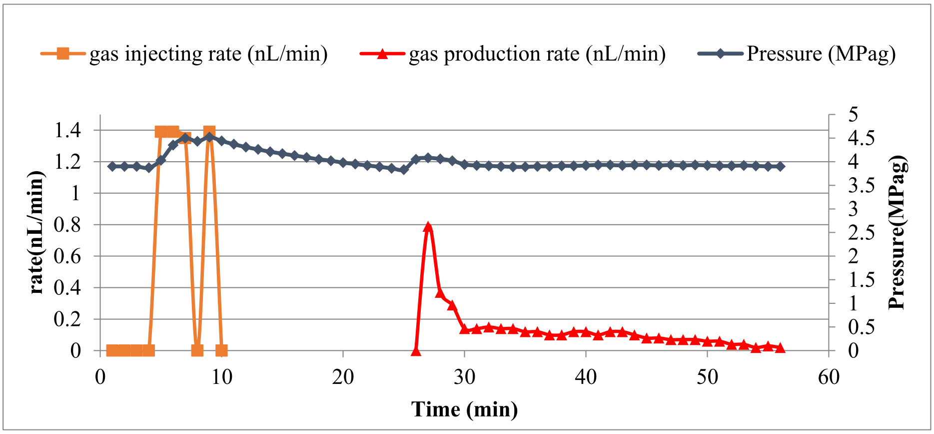

Fig. 9. NCG injection and production during one NCG slug cycle.

Operating procedure

The normal operating procedure of an experiment starts with sand packing, followed by leak detection, porosity/permeability measurement, oil saturation, aging. Then it comes to the formal experiment and data analysis.

Before running the formal SAGD experiment, all pressure sensors and thermal couples are calibrated as showed in Fig. 6. Then auxiliary equipments are preconditioned by the control panel of data acquisition system (Fig. 7). Steam generator was set at 250 °C and pump at constant rate of 10 ml/min. Steam line was wrapped with heating tracer and set at 260 °C. This provided a little degree of superheating. Operating pressure was maintained at 3.9 MPag by backpressure regulator. Therefore, the steaming temperature would be 250 °C and the oil viscosity at this temperature was around 15 mPa·S. Real time data and processed curves were produced and showed in user interface (Fig. 8). The operating procedure for NCG SAGD was a little bit complex. NCG slug operation was conducted every 53 minutes (1 year at field). During one typical slug cycle, steam injection line was closed and the nitrogen supply line was opened. Meanwhile, the producer was shut in. The volume of the steam chamber was determined online by the image-processing software, which computed the size of steam chamber from temperature field. This was then used to calculate the volume of produced oil by assuming that oil saturation declined from 0.98 to 0.3 (residual oil saturation). The volume of NCG in the each slug cycle was chosen to be 20% of the volume of produced oil. Once desired volume of nitrogen had been injected at scheduled rate, the nitrogen supply line would be closed. The next step was shut-in, in which both injector and producer would be closed till chamber pressure dropped to the operating pressure of SAGD. Then steam line would be opened for a short time to displace nitrogen around injector by steam. After that, the producer would be opened and the whole process came back to the normal SAGD operating procedure.

Method validation

By combining this systematic model design method and NI product based data acquization and processing system, we would get the NCG SAGD experiment done with a success. Fig. 9 shows the results of pressure and gas rate. From there we would see the pressure ossilation in this operation. This phenomena had been observed by field trail too. Also the gas production data from this work provide evidence of gas coning which was not well understood before. Fig. 10 exhibits the evolution of steam chamber. It clearly shows a perfect SAGD chamber in inversed triangle shape, which generally present in a typical SAGD operation in this sorts of reservoir. The temperature cloud is made by the method mentioned before. So we know the absolute temperature close to boundary of model

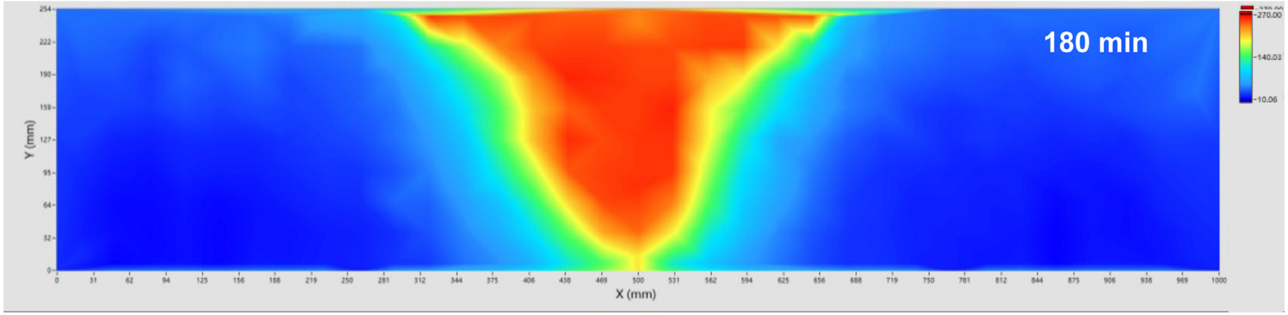

Fig. 10. Steam chamber growth in baseline test, obtained at 180 minutes after first steaming in the experiment.

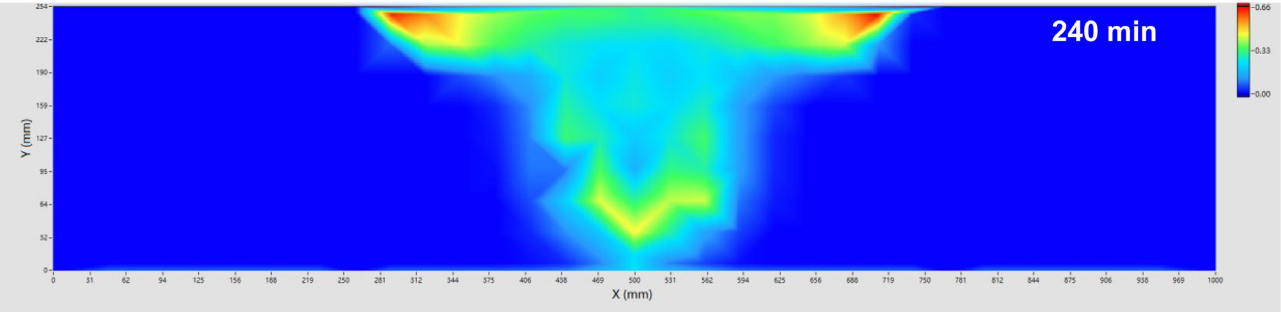

Fig. 11. Evaluation of NCG concentration distribution in the 2D model after shut-in in the same cycle. The concentration in area occupied by original steam chamber was evaluated by partial pressure effect of NCG (or Dalton's Law). It was in the unit of mole fraction.

is uncertain. In the future, this method will be improved by deploying additional thermal couples to the surface. Fig. 11. Presents the NCG concentration distribution in the 2D model after shut-in. This is the first time that the NCG distribution was vividly exhibited, all owe to the dense thermal couple deployment and cloud processing technology. This result could be used to calibrate those numerical simulations and predict the movements of NCG in a steam chamber.

Declaration of Competing Interest

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.

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