Operating Conditions Optimization of Steam Injection in Enhanced Oil Recovery Using Duelist Algorithm

Totok R. Biyanto, Sonny Irawan, Hiskia J. Ginting, Matradji, Ya'umar, A. I. Fitri

***Abstract*—**Steam injection is the most suitable of Enhanced Oil Recovery (EOR) methods to recover high viscosity oil. This is due to the capabilities of steam to reduce oil viscosity and increase the sweep capability of oil from the injection well toward the production well. Oil operating conditions in production should be match well with the operating condition target at the bottom of the production well. It is influenced by oil properties and reservoir rock properties. Hence, the operating condition should be optimized. Optimization requires three components i.e., objective function, model, and optimization technique. In this paper, the objective function is to obtain the optimum operating condition at the production well. The model was built using Darcy equation and mass-energy balance. The optimization technique utilizes Duelist Algorithm due to the effectiveness of its algorithm to obtain the desirable optimization results at the optimum operating condition.

***Keyword*—**Enhanced oil recovery, steam injection, operating conditions, modeling, optimization, Duelist algorithm.

NOMENCLATURE

A	Area
A_p	Area of heat transfer
Cp_{iw}	Mass heat capacity of injection well
Cp_{pw}	Mass heat capacity of production well
h	Convective heat transfer coefficient
e_{total}	Total error
e_p	Error of pressure
e_t	Error of temperature
k	Permeability
$\mathbf{k}$	Conductivity heat transfer coefficient
L_p	Length of heat transfer
L_r	Length of reservoir rock
m_{steam}	Mass of steam
Nu	Nusselt number
Pr	Prandlt number
q	Volumetric flow rate of steam
Q_{iw}	Heat of injection well
Q_{pw}	Heat of production well
$Q_{totallosses}$	Total heat losses
Re	Reynold number
$R_{conduction}$	Heat resistance by conduction
$R_{convection}$	Heat resistance by convection
T_{iw}	Temperature of injection well
T_{pw}	Temperature of production well
T_{∞}	Temperature of boundary
ΔP	Pressure drop
μ	Viscosity
φ	Viscous dissipation

Totok R. Biyanto is with the Process Design, Optimization, and Control Laboratory- Department of Engineering Physics – Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia (corresponding author, e-mail: trbiyanto@gmail.com).
Hiskia J.Ginting, Matradji, Ya'umar and Fitri A. I. are with the Process Design, Optimization, and Control Laboratory- Department of Engineering Physics – Institut Teknologi Sepuluh Nopember (ITS) Surabaya, Indonesia.
Sonny Irawan is with the Petroleum Engineering - Universiti Teknologi PETRONAS, Malaysia.

I. INTRODUCTION

NOWADAYS, fossil energy is the most frequently used energy in a wide variety of needs. This energy is contained in reservoirs beneath the ground. There are three stages to recover oil, i.e. primary, secondary, and tertiary. In the primary stage, oil production utilizes the natural down-stream reservoir pressure and/or the artificial lift. In the secondary stage, oil recovery uses the improved oil recovery (IOR) method such as water flooding and well pressure maintenance. Starting from the primary stage up to the secondary stage, cumulative oil production is able to recover the oil up to 50% from total content of oil in reservoir [1]. To increase oil production, in the tertiary stage using EOR is needed.

EOR is the implementation of various techniques to increase oil production from a well by introducing the external fluids, substances, and energy into the oil reservoir. Nowadays, the EOR method is able to use thermal, gas, chemical or others such as microbe, acoustic and electromagnetic. EOR has the capability to recover up to 80% of the oil from the total oil content in reservoir [2]. The EOR method selection is based on properties of oil and reservoir rock. The thermal EOR method, such as steam injection, is used to recover heavy oil.

Heavy oil is a crude oil with API gravity less than value 22.3 and viscosity of over 100 cp. Since heavy crude oil is trapped in the small porosity and permeability of reservoir rock, this characteristic of the oil in the reservoir rock makes recovery difficult. Therefore, the heat of steam injection is suitable to reduce the viscosity of heavy crude oil, and the pressure of water is able to push the oil toward the well production [3]. According to this practice, the quality of the steam injection should be suitable to the oil and rock properties, and hence, steam injection operating condition optimization is required. This optimization is required due to the operating conditions of the steam injection that affects the efficiency of the process of EOR. The injected steam in the reservoir must be regulated to the specific pressure and temperature condition such that the oil can be swept. One of the consequences of increasing the pressure and temperature of steam cause increase in additional operating costs, however reducing in the pressure and temperature will reduce sweep efficiency. Therefore, the optimization of the EOR operating condition to obtain maximum oil production and lowest energy consumption cost should be performed.

Some researches have been performed in steam injection optimization. Escobar et al. have performed optimization of cyclic steam injection process in horizontal well to optimize the value of cumulative discounted net income (CDNI) [4]. Another research about the comparison of cyclic steam stimulation, steam flooding, and steam-assisted gravity drainage (SAGD) performances have been performed in a horizontal well by Shanqiang Luo [5]. However, thus far, there has not been any research paper which describes the optimization of operating conditions (PVT) in the steam injection process.

PVT optimization in the EOR steam injection required three components i.e. problem formulation, model of the fluids in reservoir rock, and optimization technique. Problem formulation of this optimization is to obtain the effective steam operating condition for the entire reservoir area, by adjusting the PVT steam at injection well inlet. The optimized variables are temperature and the pressure of the steam injection at the inlet injection well. The steam injection model is built by utilizing the mass-energy balances and Darcy equations. Duelist algorithm (DA) optimization techniques were chosen due the ability of the duelist algorithm to find global solutions faster than others evolutionary techniques, such as genetic algorithm (GA), and particle swarm optimization (PSO) [6].

II. Research Methodology

The method of this research is shown in Fig. 1 and is explained in the following sub section.

A. Identification of Steam Target and Reservoir Rock Properties

The target of the steam operating condition in the production well in this research is pressure of 1247 psi and temperature of 93°C. The reservoir rock properties are sandstone with permeability of 1250 mD and porosity of 10%. The model of reservoir rock used is cylinder-shaped with diameter of 2 m and length of 500 m.

B. Determination of Objective Function

The objective function of this optimization is to minimize the difference between the actual operating condition (pressure and temperature) of the steam and targeted operating condition, which is obtained by summing the error of pressure and temperature. Total error can be formulated by using (1) as:

$$\boldsymbol{e_{total} = e_p + e_t} \tag{1}$$

where e_p is error of pressure, e_t is error of temperature, and e_{total} is error total by pressure and temperature.

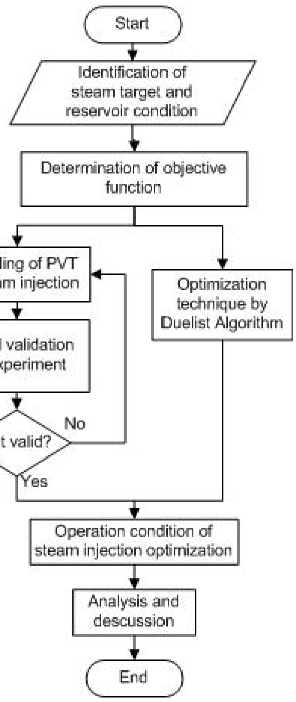

Fig. 1 Research methodology

C. Modeling of PVT of Steam Injection

Modeling of steam injection is performed to simulate the state of steam in the reservoir rock. A lot of research has been performed to model the steam injection either analytically or numerically. Jansen has modeled steam flooding based on data from 15 steam flooding projects [7]. However, the model excludes the process steam through the reservoir rock. Another research has been modeled the steam injection by using vapor-liquid equilibrium [8]. This modeling describes the state of steam, oil and its fraction composition in detail. However, there are many unknown parameters. Another research by Olimpia Banete has modeled heat transfer in porous media using the Lattice Boltzmann Method [9]. The Lattice Boltzmann concept is less representative because it uses lattice domain.

The model used in optimization requires a valid model, availability of data, and fast response. In order to fulfill the requirements, the PVT model utilizing mass-energy balance to model temperature and Darcy Equation to model the pressure in the reservoir rock are suitable.

Temperature of steam is obtained by utilizing the mass-energy balance in (2):

$$\boldsymbol{Q_{iw} = Q_{pw} + Q_{totallosses}} \tag{2}$$

where Q_{iw} is the inlet energy from the bottom of injection well, Q_{pw} is the outlet energy at the bottom of production well. $Q_{totallosses}$ is the total of heat energy losses to the surroundings of the reservoir rock. The value of Q_{iw} and Q_{pw} is obtained from (3) and (4):

$$\boldsymbol{Q_{iw} = m_{steam} C_{p_{iw}} T_{iw}} \tag{3}$$

$$\mathbf{Q_{pw} = m_{steam} C_{p_{pw}} T_{pw}} \quad (4)$$

where m_{steam} is the mass of steam, $C_p$is the mass heat capacity of steam, and T is the temperature of the steam. The total of heat energy losses to the surroundings of the reservoir rock has occurred by conduction and convection. The total of heat energy losses is obtained from (5):

$$\boldsymbol{Q_{totallosses}} = \frac{\boldsymbol{T - T_\infty}}{\boldsymbol{R_{conduction} + R_{convection}}} \quad (5)$$

where $Q_{totallosses}$ is the total of lost energy, T_∞ is the temperature of boundary, $R_{conduction}$ is the heat lost resistance by conduction, and $R_{convection}$ is the heat lost resistance by convection. The value of $R_{conduction}$ and $R_{convection}$ is obtained from (6) and (7):

$$\boldsymbol{R_{konduksi}} = \frac{\boldsymbol{L_p}}{\boldsymbol{kA_p}} \quad (6)$$

$$\mathbf{R_{konveksi}} = \frac{\mathbf{1}}{\mathbf{hA_p}} \quad (7)$$

where L_p is the length of heat transfer, k is the conductivity heat transfer coefficient, A_p is the area of heat transfer, and h is the convective heat transfer coefficient. The value of the convective heat transfer is obtained from the Nusselt number in the rocks of sandstone [10].

$$\boldsymbol{Nu = (0{,}255/\varphi) Re^{1/3} Pr^{2/3} = \frac{hL_p}{k}} \quad (8)$$

where Nu is Nusselt number, φ is viscous dissipation, Re is Reynold number, and Pr is Prandlt number. For modeling the pressure, Darcy equation is used, as referred to in (9):

$$\boldsymbol{q = k \frac{A}{\mu} \frac{\Delta P}{L_r}} \quad (9)$$

where q is the volumetric flow rate, K is the permeability of reservoir rock, A is the cross section area of the rocks, μ is the viscosity of steam, ΔP is the pressure drop of steam while through the rocks and L is the length of the rocks.

The model requires the properties of steam, which depended on the operating condition of the steam. In any addition of steam distance from the injection well to the production well, the properties will be changing gradually. Hence, it requires a model that can capture the degradation of the pressure and temperature along reservoir rock, segmentally. This process called discretization. The discretization of reservoir rock is shown in Fig. 2 below.

The reservoir rock is divided into the n number of segments. In each segment, the pressure and temperature will change the mass-energy balance and Darcy Equation. The greater number of n will increase the model accuracy. However, it will increase the computational load. At the end of reservoir rock at the bottom of production well, the pressure and temperature can be calculated using:

$$\boldsymbol{P_{outlet} = P_{inlet} - \sum_{i=1}^{n} \Delta P_i} \quad (10)$$

$$\boldsymbol{Q_{outlet} = Q_{inlet} - \sum_{i=1}^{n} Q_{losses_i}} \quad (11)$$

The properties in each of the states are estimated using Aspen HYSYS.

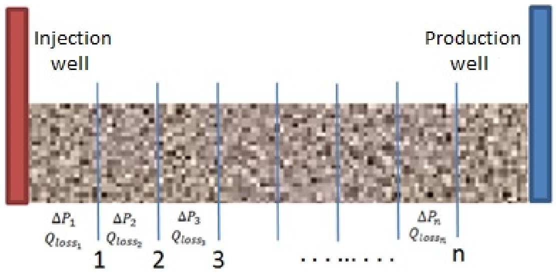

Fig. 2 Reservoir rock discretization

D. Experiment and Validation

In order to validate the model, experimental data is required. The experiment was performed using core holder apparatus as shown in Fig. 3:

Fig. 3 Core holder apparatus

The steam was injected through the core holder in any operating condition and recorded the PVT at the outlet of the core holder. Independent variables of this experiment are pressure and temperature at the inlet core holder, and the dependent variable is pressure and temperature at the outlet core holder. The Taguchi method was used to determine the number of experiments, according to the number of variables (pressure and temperature) and suitable level. In this experiment, Taguchi method L9 was utilize for the design of the experiment. The level values of any variables are shown in Table I.

TABLE I
DESIGN EXPERIMENT

No.	Parameter	Level		
		Low	middle	high
1	Pressure (psi)	1000	1250	1500
2	Temperature (°C)	200	250	300

Experiments with two variables and three levels when viewed on the table orthogonal array selection will show the array of L9. From the array is found the inlet state of the experiment, as shown in Table II.

TABLE II
EXPERIMENT INLET CONDITIONS

No.	Temperature inlet (°C)	Pressure inlet (psi)
1	300	1500
2	300	1250
3	300	1000
4	250	1500
5	250	1250
6	250	1000
7	200	1500
8	200	1250
9	200	1000

Utilizing the inlet conditions tabulated in Table II, the outlet conditions of fluids were observed at the pressure and temperature variables as well as the flow fraction of liquid and vapor.

E. Steam Injection Optimization by Duelist Algorithm (DA)

DA is one of the stochastic optimization algorithms. This algorithm is inspired by the fighting competition system. Participants in the competition represent the solution of the optimization problem. The fighting competition in DA is shown in Fig. 4.

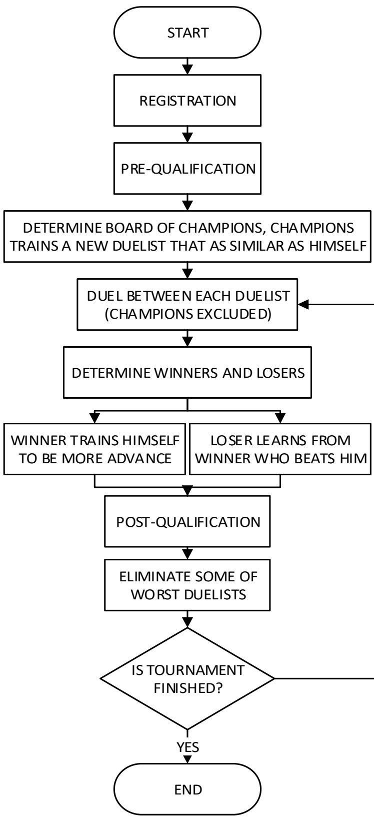

Fig. 4 DA flowchart

The optimization parameters where chosen based on the paper [6]. The best participant of fighter will be chosen as the best operating condition (pressure and temperature).

III. RESULT AND DISCUSSION

A. Model Validation

The steam injection model was performed using Darcy equation and mass-energy balance. It is desirable to validate the model using actual experimental data. The experimental data was conducted using core holder apparatus, as shown in Fig. 3. The experimental design utilized Taguchi method with L9 array. The experimental results are tabulated in Table III.

TABLE III
EXPERIMENT RESULT

No.	Inlet Condition		Experiment Outlet Condition		Model Outlet Condition	
	Temp (°C)	Press (psi)	Temp (°C)	Press (psi)	Temp (°C)	Press (psi)
1	300	1500	288.7	1494.5	259.74	1499.94
2	300	1250	275.7	1248.2	282.37	1249.83
3	300	1000	283.9	992.3	298.5	999.79
4	250	1500	210.6	1495.2	236.64	1499.95
5	250	1250	228.4	1248.8	241.82	1249.85
6	250	1000	236.3	993.1	248.12	999.83
7	200	1500	182.8	1497.7	184.2	1499.96
8	200	1250	187.3	1249.1	191.1	1249.87
9	200	1000	194.1	998.4	197.68	999.86

The proposed model of validation is to make sure the built model can produce the output as well as experimental research. The model validation result for temperature and pressure is shown in Figs. 5 and 6, respectively.

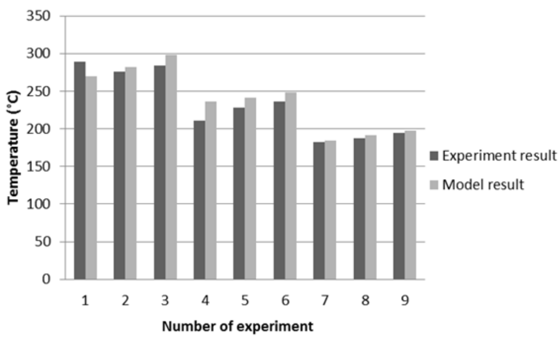

Fig. 5 Temperature validation

From the validation, the average error of the outlet temperature is 0.89% or 2.12°C, meanwhile the average error of outlet pressure is 0.29% or 3.39 psi. In general, the steam injection model exhibits good prediction and is ready-to-use in the optimization model.

B. Optimization Result

In order to obtain the best operating conditions at the reservoir inlet, some of the recent stochastic algorithms were utilized, i.e. GA, PSO, and DA. The purpose of these optimization techniques is to solve the optimization problem in (1). The objective function is to minimize error of pressure and temperature. The objective functions of the optimization iterations for the mentioned algorithm techniques are shown in Fig. 7.

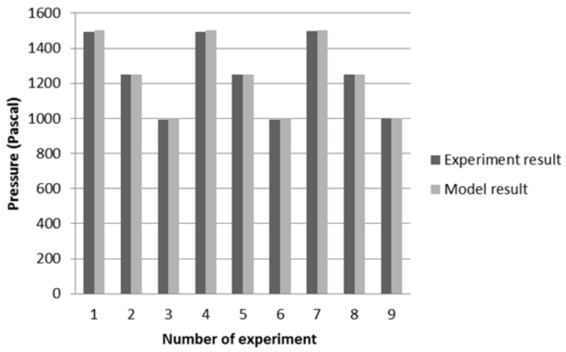

Fig. 6 Pressure validation

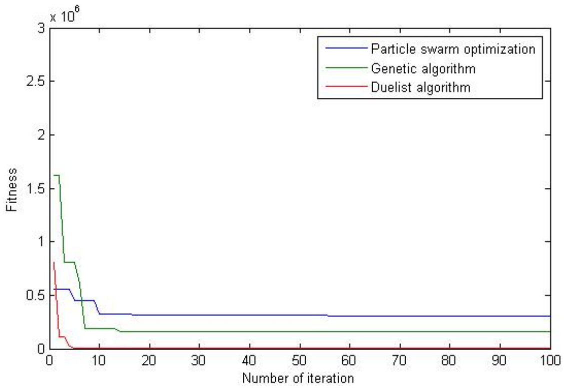

Fig. 7 Optimization techniques result

Since DA has the best performance in this optimization problem, the optimization results will be provided by DA in the rest of the discussion.

C. Optimized Operating Condition

In DA, the best fighter will be represented as the best of operating condition. The iteration of each optimization variables i.e., pressure and temperature to obtain targeted variables are shown in Figs. 8 and 9, respectively. In this case, to obtain targeted pressure during the reservoir length of 500 m, the optimum pressure and temperature operating conditions at the inlet reservoir are 8986 kPa and 303.75°C for pressure and temperature, respectively.

IV. Conclusion

Operating condition of steam injection in the reservoir has modeled by mass-energy balance and Darcy equation. The model was validated using experimental data conducted in the core holder apparatus. The model exhibits high accuracy performance. The DA provided the best solution compared to GA and PSO. The optimization results provide the optimum inlet operating conditions of reservoir rock.

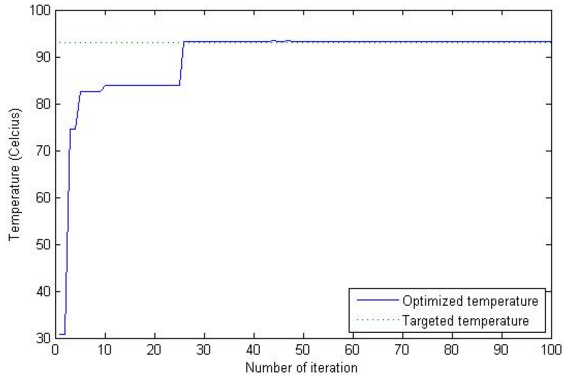

Fig. 8 The Results of pressure optimization on reservoir

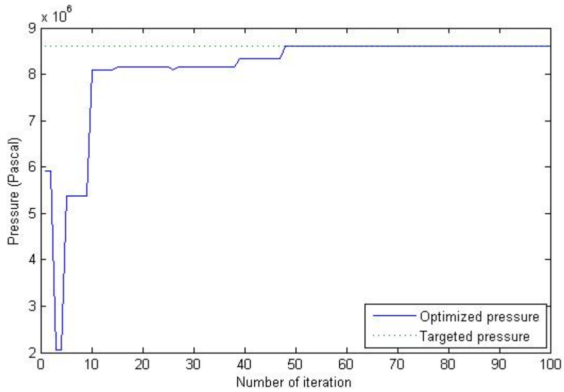

Fig. 9 The Results of temperature optimization on reservoir

Acknowledgment

The authors gratefully thank to Sepuluh Nopember Institute of Technology (ITS) Surabaya, Universiti Teknologi Petronas, Malaysia and DIKTI for providing the facilities for conducting this research.

References

[1] L. L. Schramm and K. Mannhardt, "The effect of wettability on foam sensitivity to crude oil in porous media," *Journal of Petroleum Science and Engineering,* vol. 15, pp. 101-113, 1996.

[2] S. Kokal and A. Al-Kaabi, "Enhanced oil recovery: challenges & opportunities," *World Petroleum Council: Official Publication,* pp. 64-68, 2010.

[3] V. Alvarado and E. Manrique, "Enhanced oil recovery: an update review," *Energies,* vol. 3, pp. 1529-1575, 2010.

[4] E. Escobar, P. Valko, W. Lee, and M. Rodriguez, "Optimization methodology for cyclic steam injection with horizontal wells," in *SPE/CIM International Conference on Horizontal Well Technology*, 2000.

[5] S. Luo and A. L. Baker, "Optimizing horizontal-well steam-stimulation strategy for heavy-oil development," in *SPE Eastern Regional Meeting*, 2006.

[6] T. R. Biyanto, H. Y. Fibriyanto "Duelist Algorithm: An Algorithm in Stochastic Optimization Method," Springer, Advances in Swarm Intelligence: The Seventh International Conference on Swarm Intelligence, June 25-30, 2016, Bali.

[7] T. B. Jensen, M. Sharma, and H. G. Harris, "An improved evaluation model for steam-drive projects," *Journal of Petroleum Science and Engineering,* vol. 5, pp. 309-322, 1991.

[8] O. Cicek, "Numerical Simulation of Steam Injection Using Compositional Formulation," Pennsylvania State University., 1994.

[9] O. Banete, "Towards Modeling Heat Transfer Using a Lattice Boltzmann Method for Porous Media," Laurentian University of Sudbury, 2014.
[10] D. A. Nield and A. Bejan, *Mechanics of Fluid Flow Through a Porous Medium*: Springer, 2013.