Journal of Petroleum Exploration and Production Technology (2019) 9:1255–1261
https://doi.org/10.1007/s13202-018-0570-0

ORIGINAL PAPER - PRODUCTION ENGINEERING

Mathematical model to predict unsteady-state heat transfer mechanism and economic feasibility in nanoparticle-assisted electromagnetic heating stimulation technique for bituminous extra-heavy oil reservoir

Steven Chandra[1] · **Hadi Winarto**[1] · **Sudjati Rachmat**[1]

Received: 12 June 2018 / Accepted: 8 October 2018 / Published online: 15 October 2018

Abstract

As conventional hydrocarbon reserves have gone into depletion state, oil companies around the world have turned their attention to heavy oil reserves, which were previously overlooked due to their less prolific capability compared to conventional hydrocarbon reservoirs. Bituminous heavy oil resources are known to be plentiful in quantity and size, but not without disadvantages, in which the astronomical viscosity is a troublesome aspect to be considered in exploiting the reservoir. It is not seldom that the viscosity itself is so high that bituminous oil would appear as solid-like substance under reservoir pressure and temperature. Electromagnetic heating has long been touted as the solution to overcome viscosity barrier in exploiting bituminous heavy oil reservoirs. The introduction of heat from electromagnetic wave propagation enables more efficient well stimulation technique compared to resistive heating. However, as sophisticated as the models are, they seem to be lacking a techno-economic model to consider feasibility of the project. This mathematical presentation incorporates technical aspects of heating and EM propagation model to properly model unsteady-state temperature and heat propagation as a function of time. The model is then tested on a sample bituminous heavy oil reservoir with thinly layered production zone and it has been highly reliable to swiftly predict project feasibility of nanoparticle-assisted EM heating.

Keywords Electromagnetic heating · Heavy oil · Nanoparticle · Well stimulation

List of symbols

A	Constant porous media heat capacity
API	American Petroleum Institute
BOPD	Barrel oil per day
c	Speed of light
f	Frequency
h	Reservoir thickness
k	Permeability
kWh	Kilowatt-hour
mD	Milli Darcy
P_e	Reservoir pressure
P_o	Heating power
P_w	Flowing bottomhole pressure
Q_o	Oil flowrate
r	Radius of interest
r_e	Drainage radius
S_o	Oil heat capacity
T	Time
T	Temperature
T_o	Wellbore temperature
α	Attenuation constant
δ	Complex dielectric constant
ε	Permittivity
κ	Dielectric constant
μ	Electric permeability
σ	Conductivity
ω	Angular frequency

Introduction

Conventional hydrocarbon resources in Indonesia used to be one of the most reliable components of revenue that fuels economic growth and government spending on infrastructures and budgeting. However, this period of prosperity is

---

✉ Steven Chandra
steven@tm.itb.ac.id

[1] Petroleum Engineering Department, Institut Teknologi Bandung, Jalan Ganesha No 10, Bandung, Indonesia

not expected to last indefinitely, as conventional hydrocarbon resources have been exploited in long, exhaustive cycles, rendering it uneconomical in the long term. As Indonesia's oil and gas production is deteriorating swiftly, measures must be taken to ensure this downhill does not deteriorate further in years to come.

One of the most feasible solutions, aside from technical difficulties, is turning our sight onto heavy oil reservoirs. Although enhanced oil recovery (EOR) has been a longstanding campaign that has been touted as Indonesia's solution to dwindling oil and gas production, Abdurahman et al. (2018) mentioned that EOR requires time consuming procedures, ranging from 5 to 9 years of rigorous laboratory testing and field trials before field-wide EOR application is considered to be economically and technically feasible for deployment. This situation, augmented by relatively short oil and gas contract in Indonesia, between 20 and 25 years at most, presents a dilemma for companies in low oil price to even consider EOR as one of the options to magnify revenue. Heavy oil reservoirs, as opposed to EOR methods, presents less gamble due to the fact that the main concern in field development lies on exorbitant viscosity, rendering it uneconomical to be produced utilizing conventional methods. Mukhametsina and Martynova (2013) in [9] highlighted well-developed methods to reduce heavy oil viscosity, namely steam injection, in situ combustion, microwave heating, and electric downhole heating. Based on the criterion of EOR screening developed by Taber et al. (1997), in situ combustion is deemed not viable due to the fact that some of Indonesian heavy oil reservoirs are not located in deeper strata, making it prone to contact nearby water reservoir, causing sociological problems. Application of steam injection, although has been reported to be feasible in gigantic heavy oil field in Sumatra Island by Pearce and Megginson (1991), Abdurrahman et al. (2017), and Hidayat and Abdurrahman (2018) requires massive investment in steam generator and sustainable electricity, let alone the capital required to purchase steam with lucrative pricing scheme, as other industries in Indonesia requires massive amount of high quality steam for process and fuel systems. Holis et al. (2014) presented a finding on significant onshore heavy oil reserves on Iliran Basin, Sumatra, where an accumulation of heavy oil deposit is located on less than 1000 ft of reservoir depth, thus making safety issues in steam injection a big concern. It is also an ongoing concern in matters of supply chain management where steam generators are still heavily on demand in Indonesia, where industrial complex are willing to pay a premium for readily available steam generators compared to oil and gas industry.

Santoso et al. (2016) presented a case of microwave and electromagnetic heating of heavy oil as a method of near well stimulation. This method heavily depended on the unique properties of nanoferro fluid, in which nano-sized Fe_2O_3 prepared on brine as colloidal system, to act as highly conductive heat intermediary between EM /Microwave based heat source to nearby heavy oil, lowering its viscosity and mobility ratio during the process. These findings sprouted new interest in application of advanced material in oil recovery, as nowadays the aforementioned advanced materials utilization is revolving around wettability alteration as mentioned by Tola et al. (2017) and sand control acting as nano-sized filler (Angtony et al. 2018).

This publication addresses the addition of nano-sized Fe_2O_3 to enhance the effectivity of electromagnetic heating as a well stimulation method of bituminous heavy oil reservoirs, in which electrical downhole heating has been proven to be economically ineffective. Utilizing conventional electrical downhole heating (EDH), production rate increases significantly, however problems with inefficient heat transmission hinders further implementation due to the fact that high electricity cost is required on a regular basis to maintain heavy oil viscosity below pour point. The novelty on this publication is the presentation of a simple model that can be used to generate transient temperature profile during nanoparticle-assisted electromagnetic heating as a function of time. This method is more suited for highly viscous reservoir fluid in which the generated heat will not reach boundary of the reservoir due to excessive viscosity, dimension of the reservoir or insufficient power provided to generate the EM waves.

Mathematical modeling of electromagnetic heating

Abernethy (1976) proposed a pioneering method in electromagnetic heating application of near well stimulation. Based on the coupling between Maxwell principles and heat transfer mechanisms, the following equations are derived to model temperature and pressure distribution due to the heating effects as follows:

$$T(r,t) = T_0 + \frac{P_0 \mathrm{e}^{\alpha r_e}}{4.18\rho_o q_o S_o}\left\{\mathrm{e}^{-\alpha r} - \mathrm{e}^{-\alpha\sqrt{t^2+2At}}\right\}, \tag{1}$$

$$P_e - P_W = -\frac{q}{2\pi \mathrm{kh}}\int_{r_w}^{r_e} \frac{\mu(r)\left(1-\frac{r^2}{r_e^2}\right)\mathrm{d}r}{r}. \tag{2}$$

The equations above are based on the derivations done in Abernethy's (1976) publication, in which the coupling between Darcy flow, heat transfer model, and principles in electromagnetic wave propagation are investigated. The main problem lies in the determination of attenuation constant, α, in which Abernethy employed the following equations to predict the attenuation constant:

$$\alpha_e^2 = \frac{\omega^2 \mu \int}{2} \left\{ \left(1 + \left[\frac{\sigma}{\omega \int} \right]^2 \right) \right\}^{\frac{1}{2}} - 1. \tag{3}$$

As it is evident on Eq. 3, the attenuation constant is unique for every types of reservoir, and varying degrees of fluid saturation would also influence the calculation. The inevitable implication from this model is that the values of conductivity, electric permeability, and permittivity has to be tested for every well stimulated, which requires steady supply of capital, a very rare phenomenon nowadays due to economic priority.

Ovalles (2002) based on several field data obtained from Lake Maracaibo and Orinoco Belt heavy oil system, which have been known for their highly viscous properties, derived an equation to easily calculate attenuation constant of electromagnetic heating, using the following equation:

$$\alpha = \frac{\ln 2}{\frac{c}{2\pi f}\sqrt{\frac{2}{\kappa\left(\sqrt{1+(\tan\delta)^2}-1\right)}}}. \tag{4}$$

The calculation presented above, however much simpler, is still inconvenient to be used for well stimulation process, which requires swift decisions to be made on daily basis. Hascakir and Akin (2010) resorted back to Abernethy's original solution for transient heat flow with no-flow system, a condition where the constraint of no flow can be done from coreflood studies, to find the value of α, using the following equation:

$$T(r,t) = T_0 \frac{\alpha P_0 e^{\alpha(r-r_w)}}{4.18 \rho_o q_o S_o} t. \tag{5}$$

In smaller systems, such as sandstone core utilized in laboratory experiments, such no-flow condition can be obtained up until $r = r_w$, modifying the equation to become

$$T(t) = T_0 \alpha \frac{P_0}{4.18 \rho_o q_o S_o} t. \tag{6}$$

It can be inferred easily that the attenuation constant, α, can be obtained from calculation of gradient of a plot between temperature against time in no-flow condition. The determination of attenuation constant should be enough to determine pressure and temperature profile of the well of interest. However, as reservoir pressure profile and flowrate are linked heavily to viscosity, this problem has to be solved in trial and error method, mostly due to the handling of viscosity change as a function of temperature.

One of the biggest problems appearing in electromagnetic heating utilizing nanoparticle is the idea of incorporating attenuation constant as heat transfer parameter as noted by Carrizales (2008) and Santoso et al. (2016). The problem with defining attenuation constant is in the property of wave propagation itself, where it is a naturally occurring phenomenon that waves of EM and or microwave will travel to every direction, regardless of the media. Experiments done by Indriani et al. (2017) were conducted in a closed, highly monitored system in coreflooding system where transmissions of the aforementioned wells can be reduced into small cluster of core holder system, as the propagation in air is not significant. It is also worth noting that currently there is no commercially available software to model heat transfer caused by electromagnetic heating on the context of heavy oil stimulation. Therefore, this manuscript is addressing the matter by employing numerical model as a solution to the trial and error method, explained in the following flowchart where the shapes filled with green are laboratory experiments and shapes filled with blue are numerical components of this research.

Methodologies

Oil sample obtained from Field *X* in Indonesia is used in this experiment. The oil itself is characterized as having the density of 22° API, however the heptane plus content, combined with the presence of asphaltene, rendering it to become bituminous like in room temperature, as seen in Fig. 1. Further characterization was performed to map oil viscosity profile vs temperature, by heating the oil sample to 1100 C, yielding the viscosity profile plotted in Fig. 2. The viscosity profile is then fitted to power law curve type, rendering a new equation

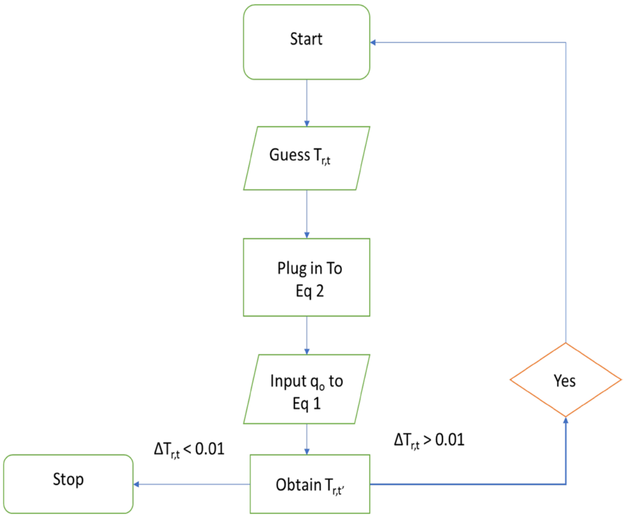

Fig. 1 Trial and error calculation flowchart

Fig. 2 Oil sample from Field *X*

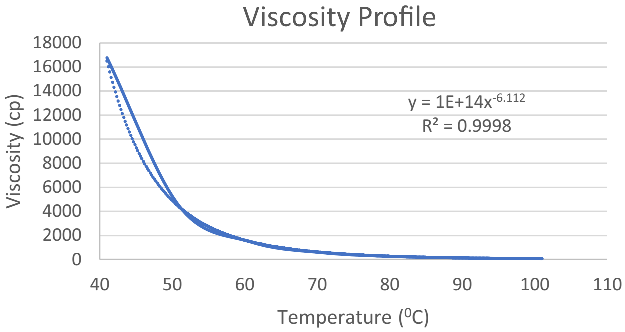

Fig. 3 Viscosity profile of oil *X* vs temperature

that can be used to quickly predict viscosity if temperature values are known or in reverse (Fig. 3).

In order to calculate the attenuation constant of nanoparticle-assisted electromagnetic heating, it is imperative to construct a laboratory tool to perform heating process, the authors also added 14 ppm of nano-sized α-Fe_2O_3 (hematite) with mean particle size < 50 nm. In order to propagate nanoparticle to heavy oil system, it is imperative that nanoparticle is then diluted into brine, forming a colloidal system, with the optimum concentration obtained from Santoso et al. (2016).

A sandpack is then employed as a reservoir to contain both target hydrocarbon with nanofluid, and a platform to place EM emitter device, in which the schematic is shown as follows, with the following specification utilized based on studies in Field *X* (Fig. 4; Table 1).

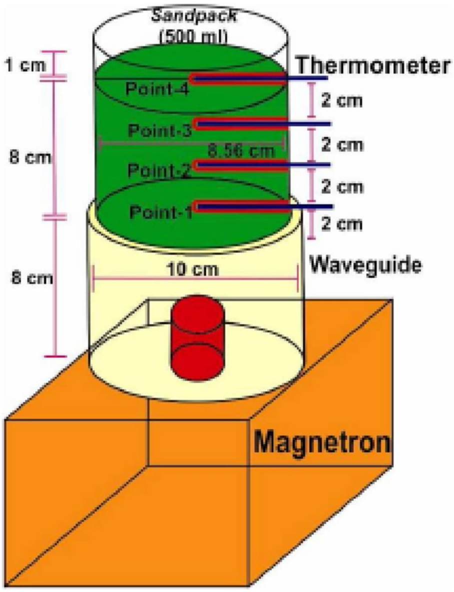

Fig. 4 Sandpack configuration. Reproduced from Indriani et al. (2017)

Table 1 Sandpack design parameter. Reproduced from Indriani et al. (2017)

Parameter	Value
Sandpack volume	500 mL
Sandpack mass	850 g
Porosity	32%
Fluid volume	150 mL
Nanoferro fluid saturation/volume	20%/32 mL
Oil volume/saturation	77%/132.2 mL
Emulsifier saturation/volume	3% / 4.8 mL

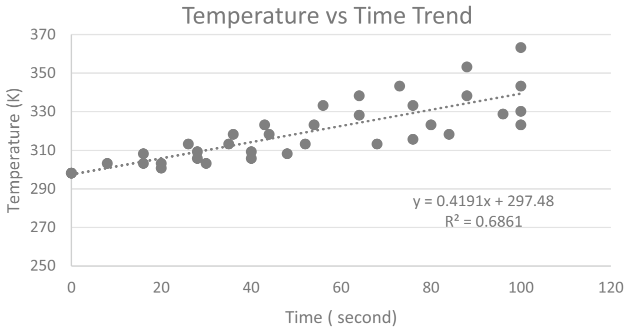

Fig. 5 Temperature alteration vs time at several observation points

The heating process is then performed using commercial grade magnetron of 2.45 GHz wave with maximum output power of 900 W. Several experiments are then performed using variety of emitted power ranging from 180 to 900 W to obtain more reliable data to be processed into attenuation constant calculation. However, the process utilizing low-powered system presented unusable data, mainly due to low viscosity change, therefore only the value of 900 W is used with 4 different measurements done as shown in the sandpack configuration (Fig. 5).

The following additional data are used as an intermediate to attenuation constant, yielding the value of attenuation constant for heavy oil sample in Field X as 0.074 m^{-1} (Table 2).

Numerical techno-economic model

Well $X-1$ in Field X has been employed as test case for this electromagnetic heating study. The well itself has been shut due to unfavorable economic situation, mainly due to excessive pumping power required to lift the produced heavy oil up to surface processing system. The relatively shallow nature of the well, with reservoir pressure only at 1100 psia, provides no incentive on temperature drop during production. It is also important to note that low temperature has halted oil production, as the oil cannot be produced above its bubble point. The company that operates Field X is planning to allocate 20 kW of electricity to support the electromagnetic process, with cycle time decided to be 1 month for well stimulation in 25 m drainage radius. By assuming steady-state process occurs during heat transfer process, the following approximation can be used as a prediction on pressure and temperature prediction on well $X-1$ (Fig. 6).

The above result is almost identical to Santoso et al.'s (2016) work in [13]; however, this result cannot be seen as highly accurate due to the fact that the flowrate is assumed to be constant, without any regard to viscosity change. It is worth noting, however, the above approach of employing constant flowrate can be employed if quick prediction is required.

Realizing that previous methods have been erroneous, the authors provided a new numerical model able to solve the trial and error problem using simple Microsoft Excel Macro VBA, in which the temperature can be plotted dynamically as a function of both time and radius of the well drainage. The numerical scheme itself is divided into 50 segments of the radius ($\Delta x = 0.5$ m) and to preserve heat transfer stability, approximately 20 time-steps ($\Delta t \approx 1.5$ days) are used in the modeling. The resulting model is shown in the "Appendix".

From the calculated numerical scheme, it is worth noting that due to the property of the heated oil, in which it the viscosity reaches astronomical value, the heating method using nanoparticle-assisted electromagnetic heating only reached 5 m of drainage radius after 1 month of heating. This result seems discouraging; however, further calculations indicate that flowrate enhancement due to viscosity reduction provides surprisingly good result, as seen in Fig. 7.

Table 2 Well $X-1$ thermal data

Rock temperature	50.74	°C
Sandstone heat capacity	780	J/kg K
Oil heat capacity	1934	J/kg K
Brine heat capacity	4125	J/kg K
Total heat capacity	1289.504	J/kg K

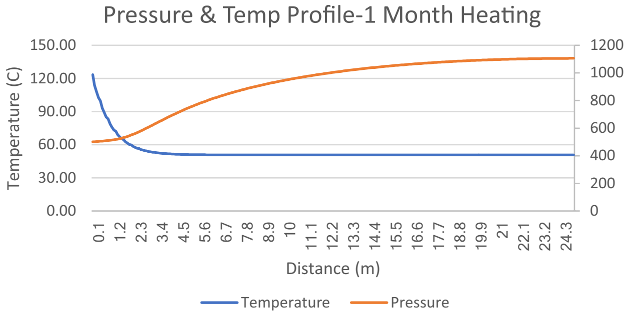

Fig. 6 Constant flowrate pressure and temperature profile

From the figure above, electromagnetic heating has been proven in simulation studies to increase well flowrate by almost thrice of previous peak production before depletion started to reduce temperature and pressure drop. The results of the stimulation, however, is also influenced by pressure drop on the well itself, causing flowrate to peak at about 80 BOPD before decreasing. This presents further challenge in developing new schemes of optimizing stimulation and secondary recovery method, as electromagnetic heating will only provide viscosity reduction mechanism, whilst pressure maintenance should be handled by other mechanisms, mainly waterflooding or cyclic shut-in method.

Economic analysis can be done to provide an insight on the feasibility of the project in varying oil price. The company in charge of the field development, provided some data, mainly on prices of electricity and EM-related tools that was offered by vendors, as seen in Table 3.

Using simple techno-economic calculation, NPV can be calculated in accordance to sensitivity analysis of various oil price, ranging from 30 US$/BBL to 70 US$/BBL. No depreciation will occur in this pricing and sensitivity analysis due

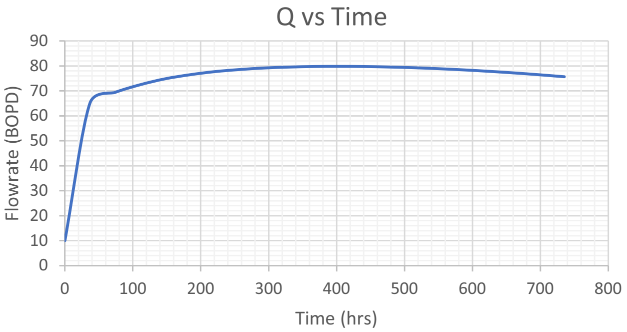

Fig. 7 Flowrate vs time from numerical simulator

Table 3 Economic parameters for EM heating

Item	Value	Unit
Power used	20	kW
Tools	500,000	US$/MW
Electricity price	0.4	US$/kWh
EM fixed cost	10,000	US$

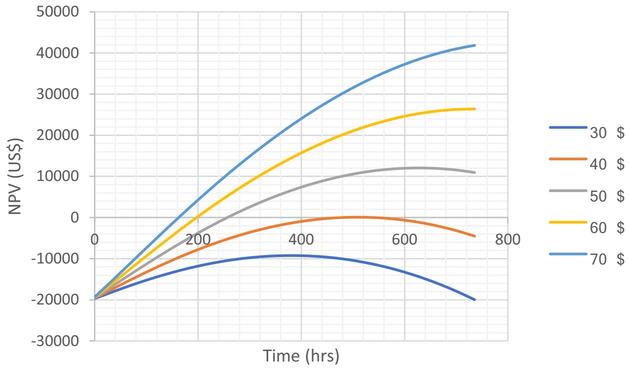

Fig. 8 Oil price sensitivity to project NPV

to the fact that stimulation job would only take 1 month of work. The result is presented in Fig. 8.

It is worth noting that the minimum attractive oil price for companies to start employing nanoparticle-assisted electromagnetic heating is in the range of 50 US$, although the NPV gained is relatively small compared to investments provided. Based on the minimum feasible oil price, the minimum time before this project starts to provide positive revenue is approximately after 10 consecutive days of heating. This is mainly due to the fact oil flowrate build up as temperature rises requiring longer time compared to maintaining presently high oil flowrate. These results provided encouragements for companies to employ electromagnetic heating assisted by nanoparticle to revitalize assets, mainly uneconomic heavy oil reservoirs around the world.

Conclusion

A new techno-economical model has been presented based on numerical trial and error scheme to predict effectiveness of nanoparticle-assisted electromagnetic heating in heavy oil Field *X* in Indonesia. The results have provided more accurate outputs compared to previous studies and the economic model can also present an insight on minimum oil price required to make the project economically attractive.

Appendix

See Fig. 9.

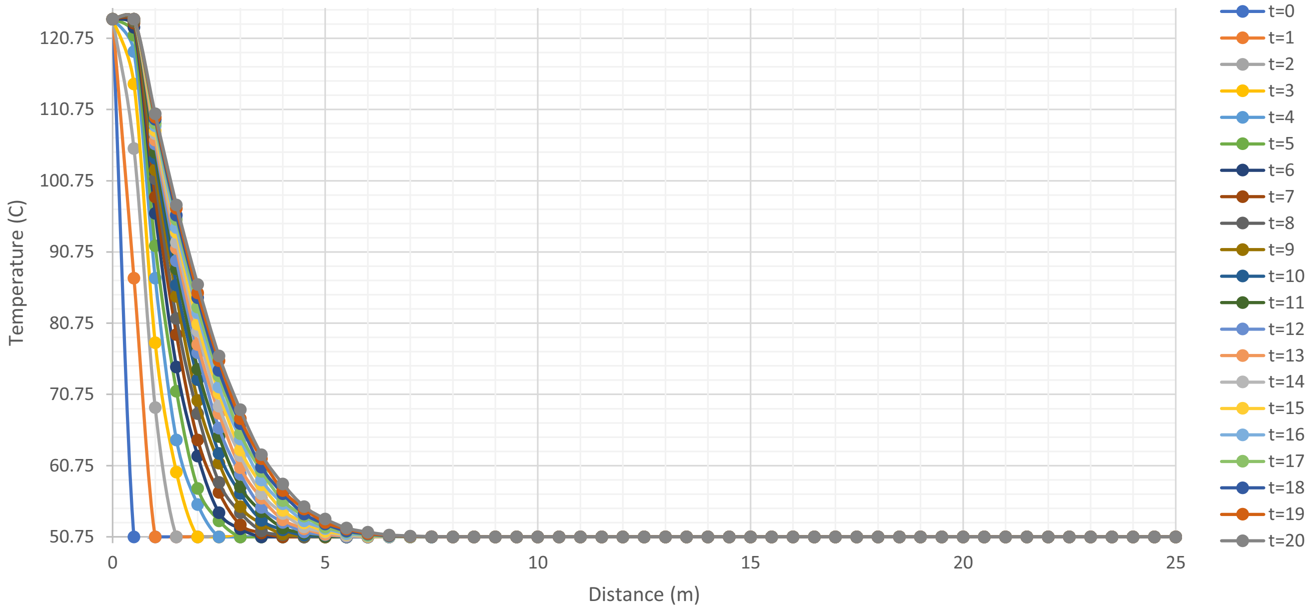

Fig. 9 Numerical result of temperature profile

References

Abdurrahman M, Permadi AK, Bae WS, Masduki A (2017) EOR in Indonesia: past, present, and future. Int J Oil Gas Coal Technol 16(3):250–270

Abdurrahman M, Ferizal FH, Husna UZ, Pangaribuan L (2018) Possibility of wax control techniques in indonesian oil field. In: AIP conference proceedings, 1941

Abernethy ER (1976) Production increase of heavy oils by electromagnetic heating. J Can Pet Technol 3(12):91–97

Angtony W, Winarto H, Chandra S, Herianto H, Nugroho YA, Marhaendrajana T (2018) Application of novel doped nanomaterial resin to increase sand consolidation in a loose sandstone reservoir. In: Proceedings indonesian petroleum association, forty second annual convention and exhibition

Carrizales MA, Lake LW, Johns RT (2008) Production improvement of heavy oil recovery by using electromagnetic heating. SPE annual technical conference and exhibition

Hascakir B, Akin S (2010) Recovery of Turkish oil shales by electromagnetic heating and determination of the dielectric properties of oil shales by an analytical method. Energy Fuels 24:503–509

Hidayat F, Abdurrahman M (2018) A prospective method to increase oil recovery in waxy shallow reservoir. IOP conference series: materials science and engineering, Vol 306

Holis Z, Firmansyah DA, Romodhon W, Kamaludin MK, Damayanti S (2014) Structural evolution and its implication to heavy oil potential in Iliran high, South Sumatra Basin, Western Indonesia. 76th EAGE conference and exhibition

Indriani E, Anugerah A, Rachmat S, Munir A (2017) Microwave heating with nano ferro fluid for heavy oil application. In: Progress in electromagnetics research symposium-fall, 2017

Kumar DH, Patel HE, Kumar VRR, Sundanarajan T, Pradeep T, Das SK (2004) Model for heat conduction in nanofluids. Phys Rev Lett 93(14):1–4

Mukhametsina A, Martynova E (2013) Electromagnetic heating of heavy oil and bitumen: a review of experimental studies and field applications. J Petrol Eng 2013:476519. https://doi.org/10.1155/2013/476519

Ovalles C, Fonseca A, Lara A, Alvarado V, Urrecheaga K, Ranson A, Mendoza H (2002) Opportunities of downhole dielectric heating in Venezuela: three case studies involving medium, heavy and extra-heavy crude oil reservoirs. In: SPE/PS-CIM/CHOA international thermal operations and heavy oil symposium and international horizontal well technology conference

Pearce JC, Megginson EA (1991) Current status of the duri steamflood project in Indonesia. SPE international thermal operations symposium

Santoso RK, Rachmat S, Resha AH, Setiawati O (2016) An investigation of Fe2.3 nanoparticles diffusion into oil for heat transfer optimization and electromagnetic heating for well stimulation and EOR. Presented at the SPE Asia Pacific oil & gas conference and exhibition

Taber JJ, Martin FD, Seright RS (1997) EOR screening criteria revisited-part 1: introduction to screening criteria and enhanced recovery field projects. In: SPE reservoir engineering, 189–198

Tola S, Sasaki K, Sugai Y (2017) Wettability alteration of sandstone with zinc oxide nanoparticles. In: 23rd formation evaluation symposium of Japan