



# Physical factors affecting the electrically assisted thermal bitumen recovery

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## Abstract

Known for decades and recently field-tested, the technology of low-frequency heating (LFH) for heavy oil and bitumen recovery seems to regain a second life. It uses electrical conductivity of connate water to propagate an alternating current between electrodes, inducing the Joule heating of the reservoir. The “hot spots” (high temperature zones with boiling connate water) appearance around the electrodes may be relieved by water circulation which enhances also heat transfer inside the reservoir. Moreover, the water circulation may have a significant effect on bulk electric conductivity in case of injection of salty brine. The results of recent 3D field-scale numerical simulations demonstrate that to reach these effects, quite moderate water injection rates and salt concentrations are required.

Taken in whole such a (LFH) process includes many factors that may affect both preheating and production periods. The multiphase heat and mass transfer depends on physical properties of saturated porous medium, fluids flowing between electrodes and producers, and local process parameters. The main objective of our current work is making use of a particular pattern of electrodes, to numerically demonstrate the role of such phase and component transport factors as absolute reservoir permeability, water dispersivity coefficient and relative permeability, reservoir heterogeneity and water vaporization on bitumen recovery from oil sands. Note that few of mentioned physical factors can be influenced by applied LFH operational conditions.

The reservoir simulation of bitumen recovery assisted by low-frequency heating is a challenging multi-physical problem.

The understanding of the physical factors impact on preheating and production provided by this work is an important feature in process design considerations.

## Introduction

Generally the basic idea of thermal recovery processes is to increase the reservoir temperature and thereby to reduce the oil viscosity in order to make mobile the original oil (bitumen) in the reservoir (Fig. 1a). Methods of heating the reservoir oil include well-known fluid injection methods such as cyclic steam stimulation, steam-flooding, SAGD, fire-flooding and newer techniques of in-situ reservoir heating with electromagnetic energy. Steam injection and fire-flooding techniques are now applied commercially to heavy oil deposits, but they are technically difficult and uneconomical in some very viscous oil sand deposits. All fluid-injection methods in oil sand deposits encounter the same problems of very low initial injectivity, poor communication between the wells and poor control of injected fluid movement, reservoir heterogeneity and unfavorable mobility ratio leading to poor sweep efficiency. The shallow depth of Canadian reservoirs is another limitation for the steam drive methods like SAGD destined more for deeper reservoirs. For example, besides the elevated probability of steam leakage there is a likelihood of formation fracture with the use of high injection pressures.

One of the methods of in-situ heat generation that overcomes, at least partially, these difficulties is the electrical heating method that has been developing for about thirty years and was already tested at large scale. To heat the reservoir with this method there is no need for fluid injection. Also shallow reservoir depth and its thickness are not limiting factors for

electrical heating. This method can also be used to mobilize the original oil as a preheating technology for subsequent steam drive process.

From a physical viewpoint the LFH method is based on the Joule effect of the circulating electric current, the conducting path for electrical current being through the continuous connate water enveloping the non-conductive sand particles. Electrical energy is converted into heat along these pathways, because of electrical resistivity of the water, and the heat is transferred to the oil and the sand particles by conduction. The temperature is increased over the reservoir volume due to the heat generation and then the variations of fluid (mainly, water) saturation and temperature affect the bulk electrical conductivity of the reservoir. The subject of this work is to continue the numerical study of the low frequency heating method started recently<sup>3</sup>.

Numerous efforts were made in the last decades to develop reliable laboratory experiments, simulation tools, and pilot tests of recovery processes based on LFH<sup>6,8-10,12-16,20</sup>. The advantages of this approach are the control of electrode temperature to avoid the water evaporation at hot spots in the vicinity of electrodes, the improvement of heating done via enhancement of heat transfer, the modification of bulk electrical conductivity by injecting salt water; the latter results in effective expansion of the elevated conductivity region (eg Ref. 3).

The idea of the heating improvement by increasing bulk electrical conductivity through the use of salty brine was first presented by El-Feky<sup>6</sup> and then by Harvey<sup>8</sup>. They investigated the feasibility of using an electric current for the selective heating of portions of an oil reservoir and have observed that the oil recovery was 13% greater with selective heating than with the waterflood alone.

The summary of mean temperature rise rates done using literature data on LFH is presented in Table 1. These data on temperature rise during LFH reflect the potential of the method from the viewpoint of required and available power and demonstrate that a reservoir volume can be heated up in relatively short time compared to usual production time scale. For more details the interested reader may have a look through the literature review in Ref. 3 and, of course, the papers cited in Table 1.

The important step towards the practical use of LFH was the simulation results reported by McGee and Vermeulen<sup>12</sup> and later the pilot test report<sup>13</sup>. In particular the authors used water injection via electrodes to prevent boiling of water and to enhance the heat transfer by convection. The other advantage of the water circulation, related to reservoir electrical properties, is increasing the bulk electric conductivity in the reservoir especially around the injection well (electrode) according to Archie's law. Reservoir electrical conductivity plays an important role in heat generation at low frequency electrical heating. At similar applied potential input, a reservoir with higher electrical conductivity generates more electric power.

The oil production peak was observed at the beginning of the second stage, and the rate of temperature rise was about 2°C/d. The authors concluded that the recovery factor was comparable with a successful SAGD project.

According to the Table 1 data the rate of temperature rise during the preheating period seems to be consistently in the range of 0.1–1°C/d. On the other hand, the bulk reservoir electrical conductivity depends strongly on water saturation and a solute concentration in the water phase.

Taken in whole such a (LFH) process includes many factors that may affect both preheating and production periods. The multiphase heat and mass transfer depends on physical properties of saturated porous medium, fluids flowing between electrodes and producers, and local process parameters. The main objective of our current work is making use of a particular

pattern of electrodes, to numerically demonstrate the role of such phase and component transport factors as absolute reservoir permeability, water dispersivity coefficient and relative permeability, reservoir heterogeneity and water vaporization on bitumen recovery from oil sands. Note that few of mentioned physical factors can be influenced by applied LFH operational conditions.

## Physical mechanisms and main parameters

Physically the LFH method is based on so-called Joule effect in the original (connate) reservoir water which therefore plays a role of conductor. The electrical current is supplied via electrodes settled directly inside the special wells. An alternating or direct current based power supply can be used for the heating purpose<sup>12,21</sup>. Let's consider now the key parameters for LFH beginning with the bulk electric conductivity of the reservoir and the electric power applied within multiphase thermal flow environment.

## Reservoir electric conductivity and Joule power

At a given electrode pattern the electric conductivity field completely defines the distribution of Joule heating power (Eq. A6) and, hence, drastically influences both the results of preheating and oil production. The complex electric potential field ( $\psi$ ) is defined from stationary field equation which reads as:

$$\nabla \cdot (\sigma \cdot \nabla \psi) = 0 \dots\dots\dots (1)$$

According to the generalized Archie's law<sup>1</sup>:

$$\sigma = \sigma_w \varepsilon^m S_w^n f(T) \dots\dots\dots (2)$$

the bulk electric conductivity  $\sigma$  may vary with local water saturation  $S_w$ , lithology type (the formation factor  $F^{-1} = a^m$ ), temperature  $T$  and also with all factors affecting the water phase (or brine) conductivity  $\sigma_w$ . The latter include mainly the impact of solutes dissolved in connate and injected water. According to experimental data on the temperature dependency<sup>18</sup> one may take as a general rule the nearly linear increase of the conductivity approximately by a factor of 3 for the first 100°C of temperature rise (Fig. 1b). Mention here that colloid properties of clay deposited in separate inclusions and/or layers may affect considerably the bulk reservoir conductivity.

The variation of the water conductivity with the solute concentration depends much on the dissolved mineral. The choice of NaCl was dictated by easy access and its nearly constant solubility within a wide enough temperature range (this can be of crucial importance in view of solid precipitation at variable temperature near electrode). It is worth mentioning that the rate of water conductivity increase with NaCl concentration is nearly constant and its order of magnitude value is 1 S/m per weight percent and more.

To provide necessary heating power in case if initial reservoir conductivity is low, it may be feasible to modify the conductivity via forced brine circulation. It is not difficult to show that among the factors influencing the conductivity according to Archie's law only solute concentration propagation may provide an order of magnitude rise for initial reservoir conductivity.

The mechanisms of such propagation include convective, diffusive and dispersive transport. The convection (via the water circulation) dominates near electrodes and may also become important after opening the production wells at elevated reservoir temperature. Taken in whole the diffusion and especially the convective dispersion may become important mechanisms of the solute propagation (or more precisely, the propagation of an elevated conductivity zone). Notice that the dispersion is proportional to local fluid velocity so that this contribution to the conductivity modification can be controlled to some extent.

## Electro-thermo-fluid-dynamic environment of LFH

The advantage of the salted water (brine) circulation, related to reservoir electrical properties, is increasing the bulk electric conductivity in the reservoir especially around the injection well (electrode) according to Archie's law. Reservoir electrical conductivity plays an important role in heat generation at low frequency electrical heating. At similar applied potential input, a reservoir with higher electrical conductivity generates more electric power (cf. Figs. 3,6a).

The other contribution of the circulation is related to reservoir water evaporation problem. It occurs at hot spots around the electrodes and remains one of the important problems in the electrical heating. This phenomenon cuts the electrical current paths near the electrode and decreases sharply the efficiency of the process. The water circulation can absorb the heat in the electrode's vicinity and prevent evaporation of reservoir water which finally may allow operation at larger energy input level. Water circulation, that is transportation of water away from an electrode, also leads to more homogeneous heat distribution in the reservoir due to convective heat transfer around the electrode.

So the impact of brine injection on bitumen recovery during LFH which can result, for example, from expected lower electric potential applied per unit of power supply, shorter preheating time, and lower heat losses<sup>3</sup>, is evident. Similarly evident is the fact that its study concerns strongly coupled electro-thermo-fluid-dynamic phenomena. It follows that more efforts should be spent on studying and developing adequate means of measurement and control. This includes the control of such variables like temperature, electric power and current distribution in the reservoir or at least in the electrode vicinity (for some more details see Ref. 12).

## Impact of reservoir heterogeneity

Bitumen reservoirs are often very heterogeneous with respect to such measured characteristics as geometrical parameters, transport properties, initial distribution of components including aqueous fluid and bitumen itself<sup>7,11</sup>. As an example mention the Athabasca oil sands where the heterogeneities of reservoir and bitumen properties are under investigation managed by Alberta government which demonstrates the practical importance of the problem.

For oil recovery applications the reservoir heterogeneity may concern different geometrical scales and physical properties. It can influence the flow and hence the components distribution, the power field, the reservoir temperature and finally affect the production history. Generally it is not evident *a priori* which heterogeneity may have most important contribution to production. Moreover this contribution can be either positive or negative (with respect to homogeneous "base" case). To start with this, in the current work the assumption of initially homogeneous medium and fluid properties at the reservoir scale has been made. At the same time the reservoir heterogeneity at

smaller scale is supposed to impact connate water and injected solute transport. In the former case this results in mobile state of connate water or in other words non-negligible initial injectivity which facilitates brine circulation in the reservoir. (The idea came from B.C.W McGee who made a corresponding remark during our discussion in 2010). In the latter case the mechanical dispersion of solute allowing more rapid expansion of elevated conductivity region around each electrode was studied. Theoretically, from the viewpoint of dispersion, the stronger heterogeneity the better, i.e. the propagation of solute from electrode is faster due to higher characteristic dispersivity of the medium.

An opposite reasoning may be valid, however, for early preheating period where medium heterogeneity in the electrode vicinity can result in local overheating and water evaporation there. This local but undesirable event shows one more advantage of pure conductive early preheating discussed recently in Ref. 3; this allows at least to control the electrode temperature *eg* keeping it constant

## Electric heating modeling tools

Simulation of unconventional oil recovery methods may require the development of new numerical tools. This is the case for oil recovery aided by electric heating (in broad sense). Need in technologies of such a kind (*eg* for bitumen deposits in Canada) resulted in development of commercial simulator modules<sup>5,19</sup>, then so-called coupling models<sup>17</sup> because the multi-physical nature of the problems evidently appeals to a simulator coupling approach. In Ref. 17 two models have been used to solve the LFH equations: the CMG STARS based fully integrated model which included the (low-frequency) electric module<sup>5</sup> application, and the coupling model based on the special coupling tool called EMIR which is written in COSMOL Script and MATLAB language. Mention in passing that COMSOL fully integrated models (stationary or transient with simplified convective transport) are feasible for many particular cases.

The main steps during EMIR computations have been organized as following (Fig. 2). After initialization of the model parameters the sequential loop of computations is started. The Joule power density (coupling term between two models) is computed first on finite element (FE) grid (which normally is unstructured) and then integrated over each block of the finite volume (FV) model grid (structured, rectangular or hexahedral<sup>5</sup>). Upon termination of the coupling term computation and its output the next reservoir simulation step begins via launching CMG STARS computations of thermal flow in reservoir (see model in Appendix). The flow pattern and the new electrical conductivity field are computed using respectively Eqs. A1 to A5 and Eq. 2 above. EMIR proceeds now with interpolation of conductivity given on FV grid and required for subsequent computations on FE grid. This loop is repeated at each coupling step until the final time is reached.

In practice the EMIR model is not highly sensitive to coupling time step size; only the relatively strong variation of bulk electrical conductivity due to brine injection, constrains the coupling time step. This is due to the fact that relatively fast evolution of electrical properties changes drastically the electric current and heating power fields around electrodes. In general both models have been in good agreement for considered cases of LFH including 3D case reported recently in Ref. 3.

Coupling solutions, such as one presented briefly in this paper, allow relatively fast development of integral (coupling) models and their application to practical problems, and offer an adequate description of the processes under consideration. The

idea of simulators coupling in heavy oil recovery applications seems promising from different viewpoints including that of reliability of modeling results. The EMIR simulations of LFH with water circulation using multi-electrode 3D model of reservoir are envisaged in the nearest future.

## Main results and discussion

The CMG STARS™ reservoir simulator has been used to model LFH for different geometrical configurations, initial reservoir conditions and well/electrode parameters and, particularly, to estimate the oil recovery in case of the LFH application using the so-called electric module. Unless otherwise stated the 2D axisymmetrical model of bitumen reservoir part around single electrode is used (Fig. 4) both for preheating and production period computations. The numerical model has been tested using analytical and numerical results presented recently<sup>2,17</sup>. Few tests which were specific for current study are discussed below. Model governing equations can be found in Appendix while main model parameters used in computations are shown in Table 2.

### Preheating and production

Generally two periods can naturally be distinguished for each case: the preheating and the production one. During the first period the original bitumen is heated, without or with some production, to reach the proper mobility condition for subsequent recovery. The production results depend much on the bitumen viscosity and hence, on the reservoir temperature field at the end of the preheating period. Once the proper condition is reached the production can be started using, for instance, a suitable conventional method of heavy oil recovery. The electric heating however is normally to be continued during production, at least part of its time.

Besides the electric current supply to the reservoir, the preheating process includes also the brine recirculation near the electrodes: the salt water is injected from both ends of the electrodes and is withdrawn in the middle (cf. Fig. 5). The convective heat transfer contributes both to more homogeneous heating and to transporting the dissolved solute destined to modify the bulk electric conductivity around the electrode. This dual effect stipulates more effective and more powerful (per unit of electric potential applied) heating.

The factors affecting the preheating are numerous and include not only the injection well and brine parameters but also the porous medium and fluids properties, especially very near to the electrodes. For example, after the water breakthrough to the electrode middle point, which is relatively fast, the brine will circulate inside a limited volume around electrode. This part of the reservoir, with elevated water phase saturation and the solute concentration corresponding to that in the injected brine, can be called a circulation chamber. Surprisingly, vertical reservoir permeability doesn't take part of valuable parameters even for brine circulation (of course, apart improbable pathological situations).

From a physical viewpoint, the circulation chamber acts like an effective electrode because of the high electric conductivity inside it which is due to three physical factors: water saturation (conventional Archie's law), solute concentration, and temperature (Eq. 2). Obviously, the shape evolution of the chamber will depend on porous medium transport properties, reservoir compressibility, phase mobilities, the physical parameters of phenomena such as capillary imbibition and convective dispersion, etc. Not all of these factors are equally important in each particular case; however, each of them may contribute to the preheating history.

It wasn't our purpose to present here a comprehensive overview of factors influencing the brine assisted electric preheating. Even so there exist among them a few parameters that can be controlled via wells. To define such injection parameters, such as the salt concentration, the solution temperature, and the injector/producer conditions during this period, sensitivity studies have been carried out first. The initial oil viscosity is very high and, obviously, the brine injection is practically possible only after some elevated reservoir temperature is reached and it continues to grow in the electrode vicinity. Subject to reservoir properties and electric power limitations, it may be feasible to start with conductive heating for a very first short period of preheating<sup>3</sup>.

The example of successful preheating and early production is illustrated in Fig. 6. The preheating was carried out under electric potential of 800V until the total power reached 200 kW (see variation of electrode potential and cumulative total electric power in Fig. 6b). The preheating resulted in relatively homogeneous temperature field with the mean temperature of about 130°C at 50days (Fig. 6a); at this time the circulation electrode well has been converted to cold water injection. After 90 days of process the recovery coefficient was about 0.4.

### Water circulation

As the main objective in this stage is the heated (as homogeneously as possible) reservoir, a general indicator of successful preheating is the mean reservoir temperature which is proportional to the total amount of thermal energy generated in the reservoir. The electric power supply can provide the necessary amount of energy within certain limits, which may include applied voltage and/or total current (i.e. total power) limitations. In the "base" case under consideration the electric current is injected to provide a given total power not greater than 200 kW per electrode, or in other words, 15.4 kW per 1 m of the region thickness per electrode. At the given total power the rate of mean reservoir temperature rise is 2.6 °C/d.

After short time of power supply and brine circulation, the magnitude of potential on the electrodes starts to drop with time (cf. Fig. 6b) and indicates a significant and rather fast variation of mean reservoir conductivity. This clearly demonstrates that the brine circulation around electrodes is helpful in the bulk conductivity modification. The injected salt concentration region indicates the approximate circulation chamber boundaries around electrodes which are simultaneously the limits of so-called elevated conductivity zones which physically speaking are "walls" of effective electrodes (Fig. 5). Inside these zones both the potential variation and the mean heating power are relatively small so that the major part of heating power is put outside them.

### Brine properties

The electric conductivity of brine depends crucially on the solute concentration. The injection of such a fluid may lead to locally increasing bulk reservoir conductivity by a factor of hundred or so (Fig. 1b). This effect is also due to the water saturation rise, especially near the electrode. Comparison of preheating temperature fields and of total Joule power supply (time diagrams shown in Fig. 3) demonstrates that the effect of the solute concentration is not linear and at some typical concentration it becomes relatively small. At the same time the hot brine injection doesn't have an effect as significant as might be thought because at conditions under which the injection becomes possible the temperature is already high enough near the electrode. More generally, one may conclude that although the concentration and temperature effect are common, their optimal values depends on many factors and should be

independently defined for each particular case. So all LFH results presented in this paper has been obtained with cold (10°C) water injection from the electrode well.

### Evaporation limit

The water injection for electrode temperature regulation purpose should be kept during total heating time to avoid significant water evaporation. This is especially true for early preheating with deficient injectivity and small heated volume which makes crucial the evaporation problem.

#### Startup

To study the evaporation limit at early preheating the computations have been performed with a sequence of numerical grids under the same physical conditions aimed at determination of initial applied potential and characteristic time to establish a brine circulation. The results were sensitive to grid block size and demonstrated that evaporation may be critical for setting water circulation around electrode as it limits significantly the early time power supply and increases the total time of preheating. Note that constant temperature instead of constant potential would be more relevant condition for startup.

#### Production stage

Although it might be promising under certain conditions to partially evaporate the water<sup>20</sup>, the idea seems technically delicate to realize in complex electro-thermo-fluid-dynamic environment with its advantages still to be proven. In one way or another for being effective the evaporation should take place at a certain distance from an electrode and should not influence the circulation of water. The latter may take place because of pressure rise in the reservoir due steam generation in reservoir. A positive impact on production rate may be envisaged in this case.

### Reservoir heterogeneities

Below are considered two factors capable to enhance the heating due to more rapid spreading of solute inside reservoir. Although the mechanisms are quite different they may have a common reason and originate from intrinsic heterogeneity in reservoir transport properties. In fact as it has been already stated above, the degree of bitumen reservoir heterogeneity and hence its impact on oil recovery remains often an open issue for practical application, and our results are just a small tentative contribution to the problem investigation. Perhaps the general answers we've searched for may not matter much for each particular case but can be useful as a technical guideline.

### Initial water mobility

The mobile connate water facilitates much the circulation of brine and makes possible more rapid preheating. At initial reservoir conditions the water interstitial velocity is close to characteristic solute propagation one and modification of initial conductivity may take rather short time. Fig. 7 illustrates the particular example of connate water mobility influence on LFH. Shown in Fig. 7a are the electric resistance and total instantaneous power supply variations for initially immobile and slightly mobile connate water, while in Fig. 7b - the temperature fields for similar two cases at given constant potential at the electrode. The total power supply reached 300 kW limit value after about 10 days of circulation (more than 3 times faster compared to reference case, red line in Fig. 7a) and consequently the mean temperature is significantly higher after only three weeks of preheating.

### Mechanical dispersion

Despite the significant impact of mechanical dispersivity on salt concentration field around circulation chamber the global effect of dispersion was not strong (Fig. 8). It might be more advantageous in this case to increase the injected salt concentration. Even so it seems to be of limited application, for instance, at startup but certainly not in case of initially mobile water. Remind that dispersion coefficient is proportional to local interstitial velocity of brine and hence may be controlled via brine injection regime.

### Conclusions

- The most important physical properties affecting the LFH results are the bulk reservoir electrical conductivity, the temperature and initial oil viscosity, the fluids and reservoir thermal and transport properties. The main operational conditions are the applied power limit, injected brine electrical properties, the electrode spacing, and the injection pressure limit. All these data were collected carefully from the literature and used as reference in our numerical studies;
- Salt water circulation may improve significantly both the bulk electrical conductivity and the power distribution during the preheating and at least early production periods. The electric power supply can be done at lower electric potential which certainly may facilitate and enhance the LFH application. Furthermore, the water circulation increases the convection heat transfer around the electrodes and also helps to manage "hot spots" in the vicinity of the electrodes;
- A recovery factor of about 40% has been reached after three months of production modeled on single electrode element with bulk reservoir volume about 2600 m<sup>3</sup>. The process time is a function of electric power that can be supplied for heating. The production may be increased by relevant improvement of the preheating period.

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### NOMENCLATURE

$E_s$	=	bulk volumetric matrix internal energy
$E_f$	=	bulk volumetric fluid internal energy
$f$	=	bulk electric conductivity temperature dependency
$h$	=	phase specific enthalpy
$k_r$	=	relative permeability
$K$	=	absolute reservoir permeability
$m$	=	Archie' law constant
$n$	=	idem
$p$	=	phase index
$r$	=	radial distance ( <i>eg</i> from the well/electrode centre)
$S$	=	saturation
$t$	=	time
$T$	=	temperature
$u$	=	Darcy' velocity
$V_0$	=	given electrode potential
$z$	=	axial distance (along vertical electrode)
$\varepsilon$	=	porosity
$\eta$	=	phase relative mobility
$\lambda$	=	bulk reservoir thermal conductivity
$\mu$	=	phase viscosity
$\rho$	=	phase density
$\sigma$	=	bulk reservoir electric conductivity

$\sigma_w$  = water effective electric conductivity  
 $\psi$  = complex electric potential

## REFERENCES

1. ARCHIE, G.E., The Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics; *Petroleum Transactions of AIME*, 146, pp. 54-62, 1942.
2. BOGDANOV, I.I., EI GANAOU, K. and KAMP, A.M. 2008. Study of Electrical Heating Application for Heavy Oil Recovery; *Proc. 2<sup>nd</sup> European COMSOL Conference, Hanover, November 2008*.
3. BOGDANOV, I.I., TORRES, J.A., AKHLAGHI, H.A., and KAMP, A.M., The Influence of Salt Concentration in Injected Water on Low Frequency Electrical-Heating Assisted Bitumen Recovery; *paper SPE129909-PP presented at the Seventeenth SPE Improved Oil Recovery Symposium, Tulsa, Oklahoma, 24–28 April 2010*.
4. CARSLAW, H. S. and JAEGGER, J. C., Conduction of Heat in Solids; 2<sup>nd</sup> edition, Oxford: Clarendon Press, 1958.
5. COMPUTER MODELING GROUP Ltd, CMG STARS; Calgary, Alberta, Canada, 2009.
6. EI-FEKY, S.A., Theoretical and Experimental Investigation of Oil Recovery by the Electrothermic Technique; *University of Missouri-Rolls, PhD Dissertation, 1977*.
7. FUSTIC, M., AHMED, K., BROUGH, S., BENNETT, B., BLOOM, L., ASGAR-DEEN, M., JOKANOLA, O., SPENCER, R., LARTER, S., Reservoir and Bitumen Heterogeneity in Athabasca Oil Sands; *Annual Meeting of the Canadian Society of Petroleum Geologists, 2006*.
8. HARVEY, A. H., AMOLD M.D., and EI-FEKY, S.A., Selective Electric Reservoir Heating; *JCPT*, 18(3), pp. 47-57, 1979.
9. HIEBERT, A.D., VERMEULEN, F.E., CHUTE, F.S. and CAPJACK, C.E., Numerical Simulation Results For the Electrical Heating of Athabasca Oil-Sand Formations; *SPERE*, 1(1), pp. 76-84, 1986.
10. HIEBERT, A.D., VERMEULEN, F.E. and CHUTE, F.S., Application of Numerical Modeling to The Simulation of the Electric-Preheat Steam-Drive (EPSD) Process In Athabasca Oil Sands; *JCPT*, 28: pp. 74-86, 1989.
11. LARTER, S. , ADAMS, J., GATES, I.D. , BENNETT, B. , HUANG, H., The origin, prediction and impact of oil viscosity heterogeneity on the production characteristics of tar sand and heavy oil reservoirs; *Journal of Canadian Petroleum Technology*, Vol. 47, Issue 1, pp. 52-61, January 2008.
12. MCGEE, B. C. W. and VERMEULEN, F. E., The Mechanisms of Electrical Heating for the Recovery of Bitumen From Oil Sands; *JCPT*, 46(1), pp. 28-34, 2007.
13. MCGEE, B.C.W., Electro-thermal pilot in the Athabasca oil sands: Theory versus performance; *World Oil*, 229(11), pp. 47-54, 2008.
14. PIZZARO, J.O.S., and TREVISAN, O.V., Electrical Heating of Oil Reservoirs: Numerical Simulation and Field Test Results; *JPT*, 42(10), pp. 1320-1326, 1990.
15. RICE, S.A., KOK, A.L., and NEAT, C.J., A Test of The Electric Heating Process As A Means of Stimulating The Productivity of An Oil Well in The Schoonebeek Field; *CIM Annual Technical Conference in Calgary, June 7-10, 1992*.
16. TODD, J.C., and HOWELL, E.P., Numerical Simulation of In-situ Electrical Heating to Increase Oil Mobility; *JCPT*, 17(2): 31-41, 1978.
17. TORRES, J.A., BOGDANOV, I.I., DABIR, V. and KAMP, A.M., Analysis of coupled and fully integrated models for low-frequency electrical heating assisted heavy oil recovery; *paper A019 presented at the European Conference on Mathematics in Oil Recovery, ECMOR XII, Cambridge, UK, September 2010*.
18. UCOK H., ERSHAGHI, I., OLHOEFT, G.R., Electrical Resistivity of Geothermal Brine; *JPT*, 32(4): 717-727, 1980.
19. VINSOME, P. K. W., and SHOOK, G. M., Multi-Purpose Simulation; *Journal of Petroleum Science and Engineering*, Vol. 9(1), pp. 29-38, February 1993.
20. WANG, J., MCGEE, B., In-situ water vaporization improves bitumen production during electrothermal processes; *Society of Petroleum Engineers, International Thermal Operations and Heavy Oil Symposium, ITOHOS 2008, "Heavy Oil: Integrating the Pieces", Vol. 2, pp. 899-906, 2008*.
21. WITTLE, J.K., HILL, D.G., and CHILINGAR, G.V., Direct Current Electrical Enhanced Oil Recovery in Heavy-Oil Reservoirs to Improve Recovery, Reduce Water Cut, and Reduce H2S Production While Increasing API Gravity; *Paper SPE 114012-MS presented at the SPE Western Regional and Pacific Section AAPG joint Meeting, Bakersfield, California, USA, 29 March-2 April, 2008*.

## Appendix. Governing model equations

Below is the problem mathematical formulation as it has been used both for fully integrated and coupling models. The model of thermal three-phase two-component flow in bitumen reservoir under LFH conditions is considered. The mass conservation equations are written for the water (index “w” for liquid and “g” for water vapor) and for the oil which is assumed to be uniform non-volatile hydrocarbon liquid (index “h”). Then the equations read as follows

$$\partial_t [\epsilon \rho_w S_w + \epsilon \rho_g S_g] + \nabla \cdot [\rho_w u_w + \rho_g u_g] = 0 \dots\dots\dots (A1)$$

$$\partial_t (\epsilon \rho_h S_h) + \nabla \cdot (\rho_h u_h) = 0 \dots\dots\dots (A2)$$

where  $\epsilon$  is porosity,  $S_p$  phase saturation, the phase flows,  $u_p$ ,  $p=w,g,h$ , are described by generalized Darcy' law

$$u_p = -K \eta_p \cdot [\nabla P_p + \rho_p g_z] \dots\dots\dots (A3)$$

relating phase Darcy' velocity ( $u_p$ ) and local phase pressure ( $P_p$ ) gradient. Here, dropping the common index “p”,  $\rho$  and  $\eta$  are phase density and relative mobility,  $\eta=k_r/\mu$ ,  $k_r$  and  $\mu$  phase relative permeability and dynamic viscosity. As the temperature

is not uniform in the reservoir, the total thermal energy conservation equation which includes solid (index “s”) and fluid phases (index “f”) contributions under assumption of local thermal equilibrium (one-temperature approach), complements the model

$$\partial_t [E_s + E_f] + \nabla \cdot [U_f - \lambda \nabla T] = J, \dots\dots\dots (A4)$$

where E is volumetric internal energy,  $U_f$  total volumetric flow of thermal energy,  $\lambda$  reservoir (bulk) thermal conductivity coefficient, T temperature, J heat source term given by Joule (resistive) heating power definition below (Eq. A6). The total (multiphase) flow  $U_f$  comprises fluid phase contributions,  $U_p = \rho_p h_p u_p$ , where h is phase specific enthalpy. At last, pore volume conservation constraints phase saturations in usual manner

$$S_g + S_w + S_h = 1 \dots\dots\dots (A5)$$

The resolution of stationary electric charge conservation equation (see Eq. 1) enables to calculate the local power source in Eq. A4 as:

$$J = \sigma |\nabla \psi|^2 \dots\dots\dots (A6)$$

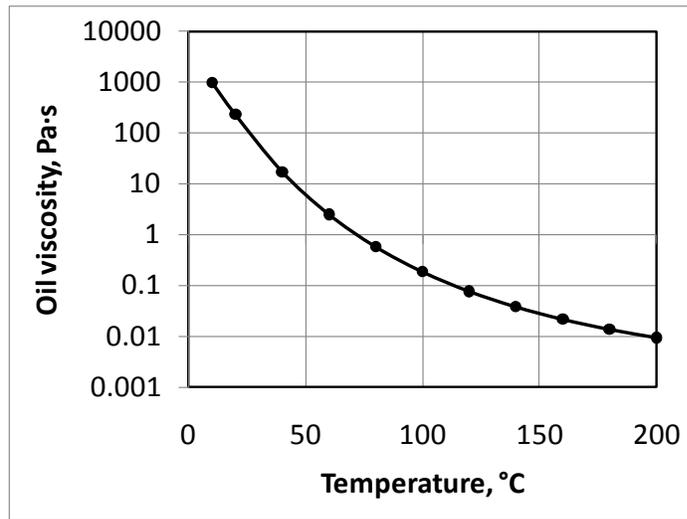
where  $\psi$  is complex electric potential. The constitutive pressure-saturation-permeability relations used for current study together with fluid physical properties variation with temperature and pressure can be found in Ref. 3..

**Table 1. LFH rate according to literature data.**

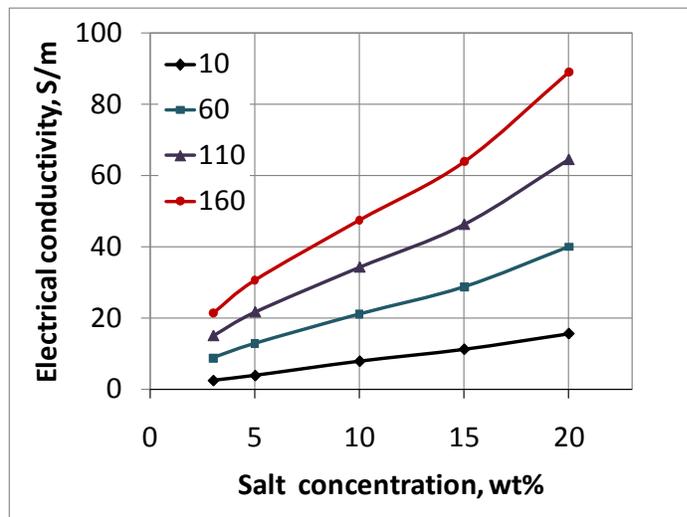
Source	Mean rate, °C/d	Comments
Todd and Howell <sup>16</sup> (1978)	0.2 – 0.3	Numerical model
Hiebert et al. <sup>10</sup> (1989)	0.03 – 1	Numerical simulations
Pizarro and Trevisan <sup>14</sup> (1990)	0.25 – 1.3	Pilot test matched with num. simulations
Rice et al. <sup>15</sup> (1992)	0.10 – 1	Test matched with num. simulations
McGee and Vermeulen <sup>12</sup> (2007)	≤ 2	Numerical simulations of ET-DSP
McGee <sup>13</sup> (2008)	≤ 2	ET-DSP pilot test

**Table 2. Main model parameters.**

Reservoir length	8	m
Reservoir thickness	13	m
Electrode length	7	m
Electrode radius	0.1	m
Electrode potential	240-800	V
Production pressure	8	bar
Injection pressure	12-15	bar
Initial reservoir temperature	10	°C
Initial reservoir pressure	10	bar
Initial water saturation	20	%
Initial oil saturation	80	%
Injected salt concentration	5.0	% wt
Initial electrical conductivity	0.005	S/m
Initial oil viscosity	1000	Pa·s



(a)



(b)

Fig. 1. Fluid properties used in computations: bitumen viscosity temperature dependency (a) and water conductivity variation with NaCl concentration at different temperature (b).

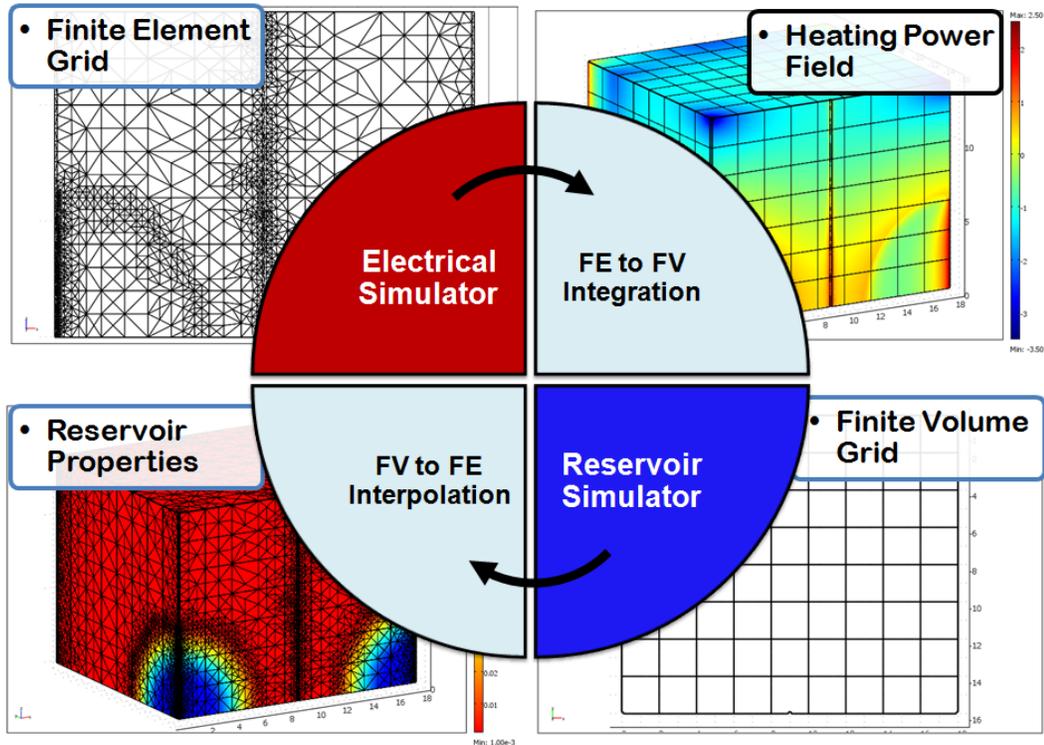


Fig. 2. Schematic diagram of EMIR general loop for LFH coupling model; FE grid is used by the electric simulator (COMSOL) while FV grid by CMG STARS.

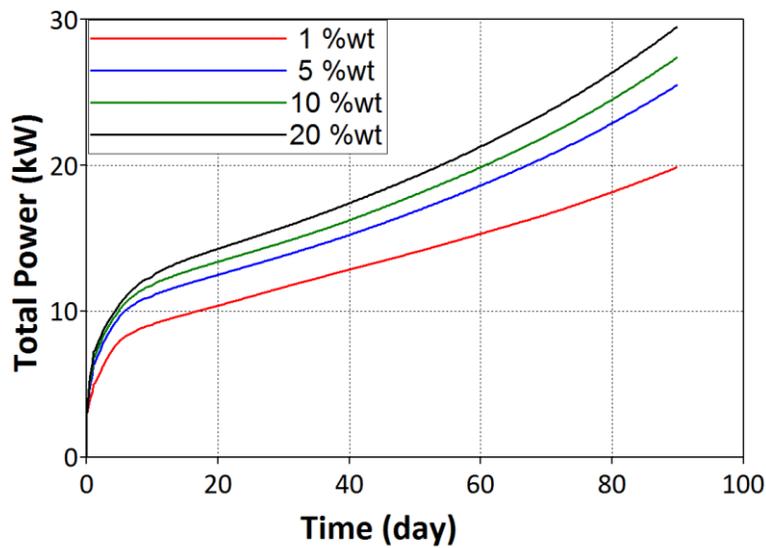


Fig. 3. Total power supply at given (constant) electrode potential,  $V_0=312V$ , for different brine concentration. Note that there is no sharp criterium here for optimal concentration choice.

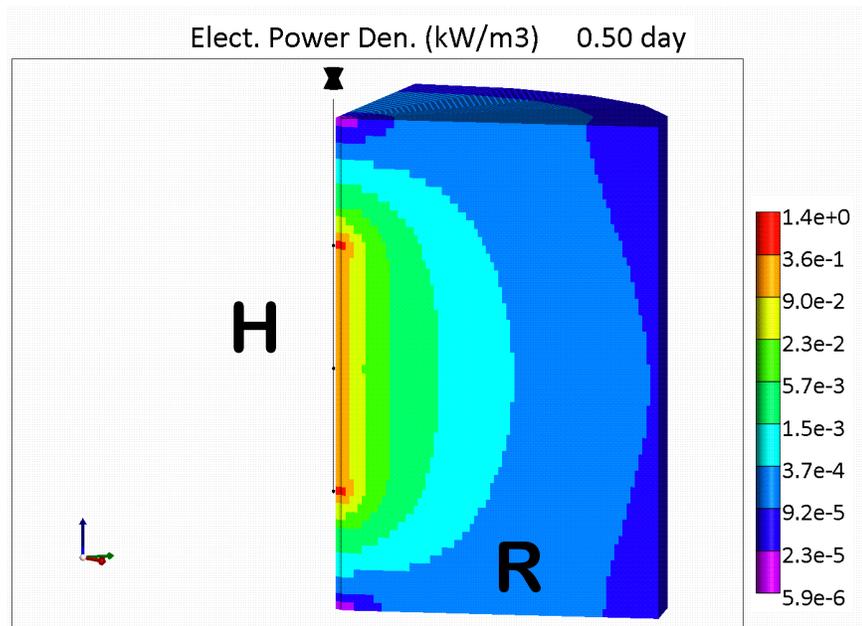


Fig. 4. Single electrode model used for major part of computations.

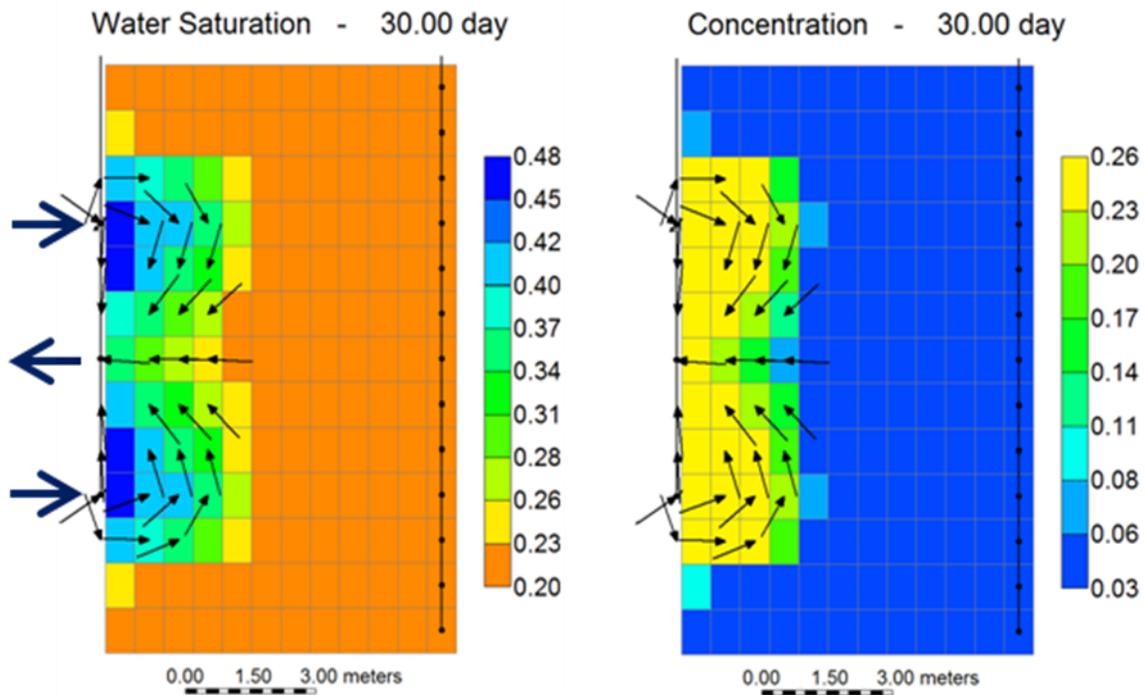
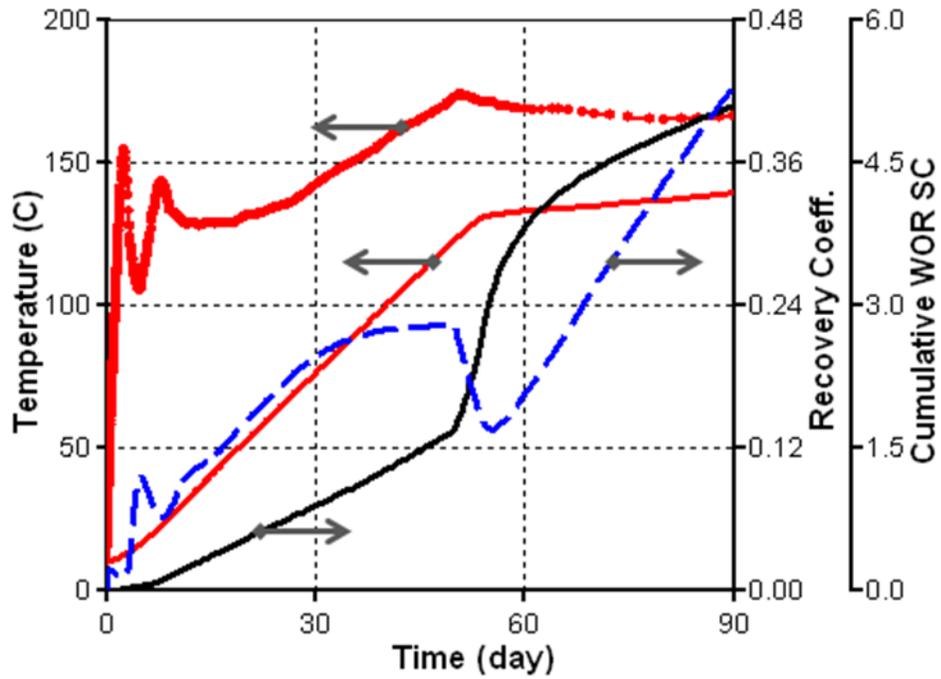
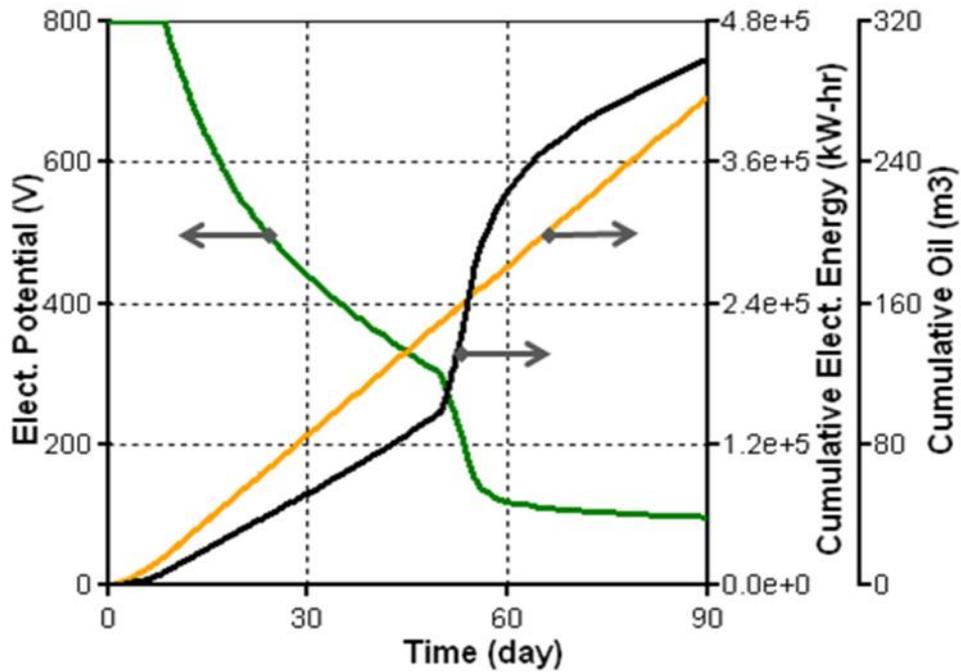


Fig. 5. Brine circulation chamber at 30 days of preheating; two injection points (at top and bottom of electrode) and production point are indicated by large arrows to left (left graph). Total power limit is 15 kW per 1m of thickness. Black arrows show local water velocity direction (cf. Ref.3).

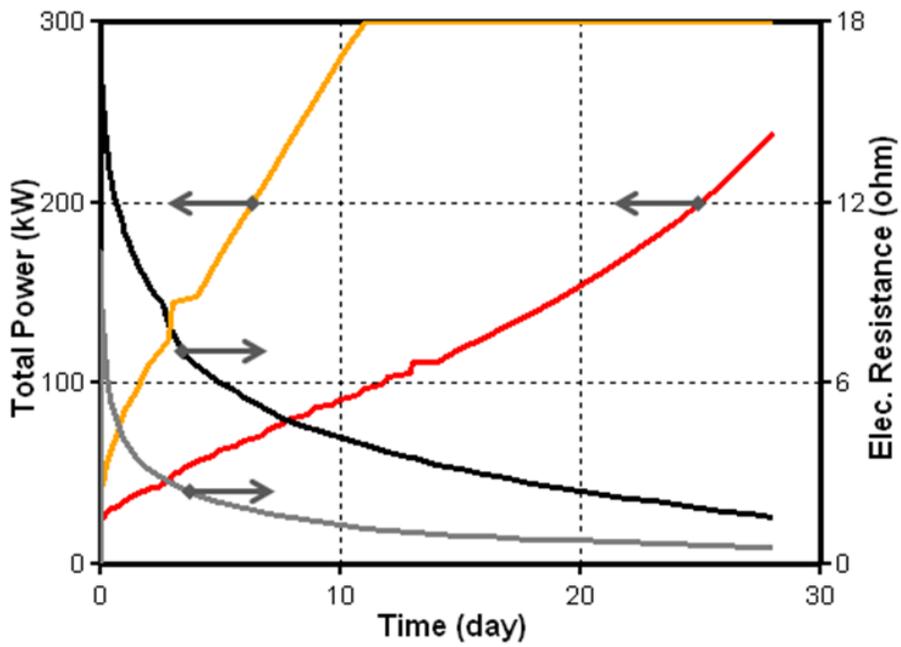


(a)

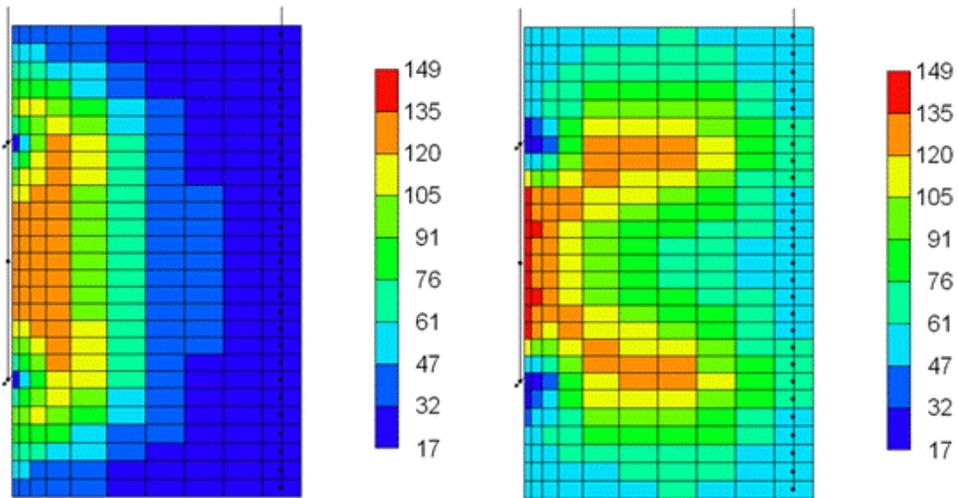


(b)

Fig. 6. Preheating and production with heating over 90 days: maximum and mean temperature (red lines), recovery coefficient (black line) and cumulative WOR (blue dashed line) - (a); applied electric potential (green line), cumulative energy (in orange) and oil production at SC (black line) - (b).



(a)



(b)

Fig. 7. Initially mobile water ( $S_{w,i}=0.25$ ;  $k_{rw}(S_{w,i})=0.0014$ ) impact at constant electrode potential,  $V_0=625V$ : on total power supply (orange to red lines) increased due to faster resistivity drop (gray to black lines) (a); on temperature around electrode (b, right to left graph).

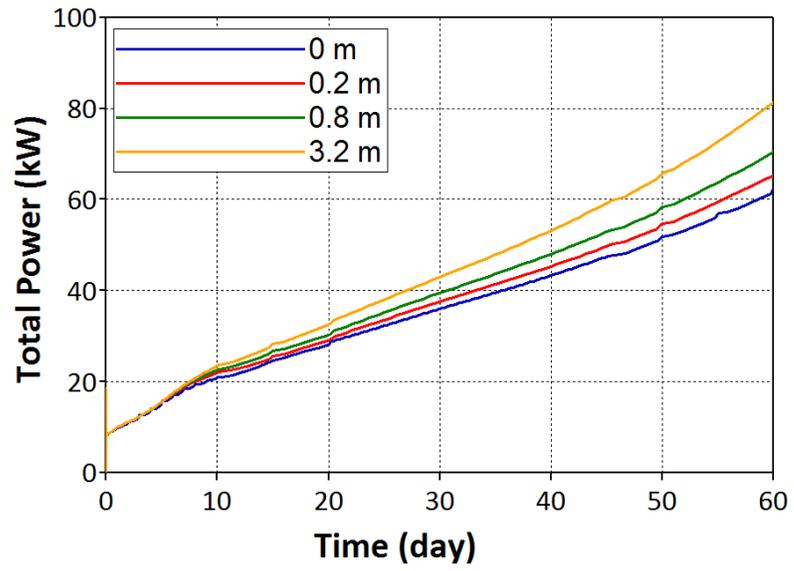


Fig. 8. Mechanical dispersivity (see legends) impact on total power supply at constant electrode potential,  $V_0=400V$ .