



## Original Paper

# An analytical model to estimate the time delay to reach spontaneous ignition considering heat loss in oil reservoirs

James J. Sheng<sup>\*</sup>, Er-Long Yang

College of Petroleum Engineering, Northeast Petroleum University, Daqing, 163318, Heilongjiang, China



## ARTICLE INFO

## Article history:

Received 1 September 2023

Received in revised form

29 December 2023

Accepted 10 January 2024

Available online 5 February 2024

Edited by Yan-Hua Sun

## Keywords:

Spontaneous ignition

Time delay

Air injection

Heat loss

Low temperature oxidation

Combustion

## ABSTRACT

During air injection into an oil reservoir, an oxidation reaction generates some heat to raise the reservoir temperature. When the reservoir temperature reaches an ignition temperature, spontaneous ignition occurs. There is a time delay from the injection to ignition. There are mixed results regarding the feasibility of spontaneous ignition in real-field projects and in laboratory experiments. No analytical model is available in the literature to estimate the oxidation time required to reach spontaneous ignition with heat loss.

This paper discusses the feasibility of spontaneous ignition from theoretical points and experimental and field project observations. An analytical model considering heat loss is proposed. Analytical models with and without heat loss investigate the factors that affect spontaneous ignition. Based on the discussion and investigations, we find that it is more difficult for spontaneous ignition to occur in laboratory experiments than in oil reservoirs; spontaneous ignition is strongly affected by the initial reservoir temperature, oil activity, and heat loss; spontaneous ignition is only possible when the initial reservoir temperature is high, the oil oxidation rate is high, and the heat loss is low.

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## 1. Introduction

When oxygen or air is injected into a reservoir, oxygen reacts with the crude oil through low-temperature oxidation (LTO). LTO is an exothermic process. The released heat will heat the reservoir leading to a higher reservoir temperature. When the temperature reaches a spontaneous ignition temperature, high-temperature combustion may occur. If LTO cannot release enough heat, or the heat loss is significant, a spontaneous ignition temperature can never be reached, then combustion will not occur. The oxidation time required for the reservoir temperature to reach the spontaneous ignition is called the delay time.

If spontaneous ignition cannot occur, artificial ignition is implemented down at the wellbore. Then there is an extra cost. Sometimes, artificial ignition may fail, leading to the failure of the air injection project. If spontaneous ignition can occur, it may continue as the reservoir temperature has been raised, making the combustion easy to prevail. Therefore, understanding spontaneous ignition is particularly important. Recently, it has been proposed

that air may be injected into oil reservoirs to produce hydrogen (Seeking Alpha, 2022; Okere and Sheng, 2023). This makes *in-situ* combustion and spontaneous ignition more important than ever.

There is a discrepancy regarding whether spontaneous ignition could happen in reservoirs. When high-pressure air is injected into an oil reservoir, Kumar et al. (2007) observed some thermal benefits. In some cases, spontaneous ignition was observed in the field (e.g., Gates and Ramey, 1958) and in some experiments. However other experimental data and field projects indicated that spontaneous ignition was unlikely to occur.

This paper is first to discuss experimental and field observations regarding the feasibility of spontaneous ignition in oil reservoirs and then provide some theoretical explanations of the observed. An analytical model was proposed by Tadema and Wijdema (1970) about spontaneous ignition under adiabatic conditions (no heat losses). Their model is used to understand the factors that will affect spontaneous ignition. After that, an analytical model is proposed to estimate the time delay to compensate for heat loss to the over- and under-burden rocks. Finally, an analytical model is proposed to estimate the time delay to reach a set reservoir temperature.

<sup>\*</sup> Corresponding author.

E-mail address: [jpsheng@outlook.com](mailto:jpsheng@outlook.com) (J.J. Sheng).

## 2. Field observations

The injection wellbore temperature exceeded 538 °C after 3 months of air injection in the South Belridge field in California in 1956, and spontaneous ignition occurred (Gates and Ramey, 1958). Among 25 air injection projects surveyed by Chu (1982), five projects had evidence of spontaneous ignition. When air was injected in the light oil reservoirs in the North and South Dakota portions of the Williston Basin, the CO<sub>2</sub> content in some production wells exceeded 12%; a high content of halite was shown in thin-section photomicrographs indicating exposure to a high temperature; some rocks had black spots indicating combustion (Gutierrez et al., 2008, 2009). Kumar et al. (2007) reported that thermal effects resulted in more oil production in the Red River zone in West Buffalo. Turta and Singhal (2001) mentioned that spontaneous ignition could occur in reservoirs as low as 30 °C.

However, Huang and Sheng's simulation work showed that the temperature could only reach 150 °C, when the initial reservoir temperature was 99 °C, indicating that spontaneous ignition could not occur. Fassihi et al. (2016) reported the reservoir temperature was increased from 200 to 230 °C in the pilot test in the Holt Sand Unit. Such low temperatures may indicate LTO occurred, instead of spontaneous ignition. Niu et al. (2011) and Greaves et al. (1999) believed that most likely LTO prevailed in light oil reservoirs.

## 3. Laboratory observations

In a series of ramped temperature oxidation tests, Barzin et al. (2010) observed that the system suddenly increased about 60 °C from 180 °C, indicating that spontaneous ignition occurred through light oil LTO. However, in dozens of light oil ARC tests, Christopher (1995), and Yannimaras and Tiffin (1995) found that only 20% of the tests showed continuous exothermic behavior, and the rest did not show the occurrence of spontaneous ignition. In their 22 air injection tests using packed-bed reactors, Abu-Khamsin et al. (2001) found that the maximum temperature rise was about 10 °C, indicating spontaneous ignition did not occur, because the LTO-generated heat was lower than the heat loss. Jia et al. (2012) showed that the core temperature only increased from 80 to 89 °C within 22.2 d of experiments. They attributed the low-temperature rise to heat loss through metal thermocouples. Huang and Sheng (2018) predicted that the temperature increase from the original core temperature of 100 °C was around 10 °C in their simulation model with heat loss, and the increase was around 25 °C in their adiabatic case due to LTO reactions. Their temperature increases are close to those from the experiments by Jia et al. (2012) and Abu-Khamsin et al. (2001).

Clara et al.'s (2000) air flooding experiments under adiabatic conditions showed that the core temperature increased from 134 to 400 °C spontaneously indicating spontaneous ignition, but the temperature could not increase when the initial temperatures were 92–134 °C. Huang et al.'s (2016a, 2016b), and Huang and Sheng's (2017a) DSC experiments showed that the oil exhibited exothermic behavior only after the temperature was heated above 300 °C.

Yang and Sheng (2019) compared the test using cocoa powder, the tests with different hydrocarbons, and crude oil mixed with sand. While the cocoa powder was spontaneously ignited, the other tests with decanal (high volatility), linseed oil (low volatility), and crude oil mixed with sand all failed. They attributed the failure to the vaporization of the fuel and heat loss caused by the vaporization of decanol and the crude oil, and the failure of linseed oil to the blockage of airflow in the bottom of the sample by oil film. Therefore, in a flooding experiment or in an actual reservoir where air displaces oil, it will be difficult to have spontaneous ignition

because air may displace vaporized oil and blow some generated heat, in additional heat loss to the experimental facilities or to the surrounding formation rocks. More discussion and simulation results can be seen in our future publication (Sheng, et al., 2024).

## 4. Theoretical explanation of the observed

The above reviews of both field and laboratory observations indicate the feasibility of spontaneous ignition depends on the balance between heat loss and heat generation. If the heat loss is slower than the heat generation, a local temperature can increase to an ignition point, and spontaneous ignition may occur.

As the temperature increases, a flammable fuel gives off some vapor. When there is sufficient vapor to ignite, the flash point is reached. The fuel vapor is ignited and starts to burn. If it continues to burn for at least 5 s, the fire point is reached. Thus, the flash point of a flammable liquid is lower than its fire point. If there are sufficient fuel and sufficient oxygen, the burn will continue. When the temperature in the reservoir is raised by some reactions to the fire point of a fuel, spontaneous ignition occurs. In other words, for spontaneous ignition to occur, three conditions need to be met: temperature to fire point, sufficient fuel, and sufficient oxygen.

Here are a few examples to explain the conditions required to achieve spontaneous ignition. In a highway covered by asphalt that is a component of high activity, spontaneous ignition does not happen, although a high temperature could reach under strong solar light because there is enough ventilation so that asphalt vapor cannot be sufficiently accumulated. In a real reservoir, spontaneous ignition may not occur even if the reservoir temperature is higher than a fire point if there is not enough oxygen. In an open forest, spontaneous ignition may occur when the low fire point of a flammable material is reached, and more heat is accumulated to make the combustion continue, as there are sufficient flammable trees and air.

When air (oxygen) is injected into an oil reservoir, low-temperature oxidization (LTO) occurs. It releases heat to raise the temperature at the air injection front. Meanwhile, the heat is also lost to the neighbor zone at the front. The oxidation reaction rate increases almost exponentially with temperature, whereas the heat loss rate increases linearly (slower). Therefore, it is possible for the LTO reaction to reach the spontaneous ignition (Gray, 2016). Generally, it is more difficult to have spontaneous ignition in laboratory experiments than in oil reservoirs because heat will be more easily lost through the experimental setup.

## 5. Time delay to reach an ignition temperature without heat loss

Assuming an adiabatic environment in an oil reservoir, Tadema and Wiejdema (1970) derived an analytical solution to estimate the delay time of spontaneous ignition,  $t_{SI}$ , for LTO to release heat to reach a spontaneous ignition temperature:

$$t_{SI} = \frac{(\rho C)_r B}{\phi S_{org} \rho_o H A_o p_{O_2}^n} \left\{ \left[ \left( \frac{T}{B} \right)^2 + 2 \left( \frac{T}{B} \right)^3 \right] \exp \left( \frac{B}{T} \right) \right\}_{T_{SI}}^{T_{ri}} \quad (1)$$

$$t_{SI} = \frac{(\rho C)_r T_{ri} \left( 1 + \frac{2T_{ri}}{B} \right)}{\phi S_{org} \rho_o H A_o p_{O_2}^n} \exp \left( \frac{B}{T_{ri}} \right) \quad (2)$$

where  $\phi$  is the effective porosity, fraction;  $(\rho C)_r$  is the reservoir heat capacity, kcal/(m<sup>3</sup> reservoir °C);  $T_{ri}$  and  $T_{SI}$  are the reservoir initial temperature and the spontaneous ignition temperature,

respectively, °C but in K in the terms associated with  $B$ ;  $B$  is the constant in  $K$  defined by  $-E/R$ ,  $E$  is the activation energy of the oxidation reaction, J/mol, and  $R$  is the universal gas constant equal to 8.3147 J/(mol K);  $S_{org}$  is the residual oil saturation under gas injection, fraction;  $\rho_o$  is the oil density, kg/m<sup>3</sup>;  $p_{O_2}$  is the partial pressure of oxygen, atm;  $A_0$  is the frequency factor, (kg O<sub>2</sub>/kg oil)/(d atm<sup>-n</sup>);  $n$  is the reaction order, dimensionless; and  $H$  is the enthalpy of the corresponding reaction, kcal/kg O<sub>2</sub>.

An alternative form of Eq. (1) is provided by Hou et al. (2011). Eq. (2) is an approximate form as the term of  $T_{SI}$  may be negligible compared to the term of  $T_{ri}$ .

From the above equations, the delay time is inversely proportional to the porosity. Using Eq. (2) and the other data from Tadema and Wiejdema (1970)'s South Belridge case (Base case), the estimated delay time is 361.940 d (about one year) if the porosity is 0.1 for a tight oil reservoir, as presented in Case 1 of Table 1. However, in the South Belridge case presented by Tadema and Wiejdema (1970), the delay time was 97.822 d when the porosity of 0.37 was used. This comparison indicates that it is more difficult for spontaneous ignition to occur in tight reservoirs.

Eq. (2) also shows that the delay time is inversely proportional to the residual oil saturation  $S_{org}$ . The delay time will be 723.879 d presented in Case 2 of Table 1, if  $S_{org}$  is 0.3 and  $\phi$  is 0.1, with other data same as those in Base case.

In the Base case, air is injected at 15.3 atm., and the corresponding oxygen partial pressure is 3.2 atm (20.9% of the air pressure). If the air pressure is increased to 300 atm (4410 psi) corresponding to 62.7 atm, the delay time is 92.070 d (Case 3) using Eq. (2). It indicates that a higher air injection pressure can shorten the ignition time needed.

In Base case, the initial reservoir temperature is 30.8 °C. If the temperature is increased to 100 °C, the delay time is reduced to 2.486 d (Case 4) using Eq. (2). In a more realistic case (Case 5), the  $S_{org}$  is 0.45,  $p_{O_2}$  is 62.7 atm., and  $T_{ri}$  is 100 °C, the delay time is 0.843 d. These cases indicate that the initial reservoir temperature is an important parameter. A higher reservoir temperature makes the ignition much easier, as the heat release rate (oxidation rate) is exponentially increased with temperature, and thus the required heat to reach ignition is much less. The high oxidation rate can also be achieved with high-activity oil.

For the kinetic data  $B$  and  $A_0 p_{O_2}^n$ , Huang and Sheng (2017b) surveyed literature data and obtained typical values (median values), with  $B = 3969$  K and  $A_0 p_{O_2}^n = 50000$  s<sup>-1</sup>. If these values are used, the delay time becomes 0 in Case 6, indicating the ignition can occur immediately.

The above calculated results show that the time required to reach spontaneous ignition is strongly affected by the heat release rate from LTO which is a strong function of the initial reservoir temperature and oil activity.

Oddly, the spontaneous ignition temperature does not show up in the approximate solution Eq. (2). In other words, the delay time

**Table 1**  
Effects of some parameters on delay time of spontaneous ignition.

Case #	$t_{SI}$ , d		$\phi$	$S_{org}$	$p_{O_2}$ , atm	$T_{ri}$ , °C	$B$ , K	$A_0 p_{O_2}^n$
	Eq. (2)	Eq. (1)						
Base	97.822	97.820	0.37	0.60	3.2	30.8	8860	5257
Case 1	361.940	361.934	0.10	0.60	3.2	30.8	8860	5257
Case 2	723.879	723.868	0.10	0.30	3.2	30.8	8860	5257
Case 3	92.070	92.069	0.10	0.60	62.7	30.8	8860	5257
Case 4	2.486	2.480	0.10	0.60	3.2	100	8860	5257
Case 5	0.843	0.841	0.10	0.45	62.7	100	8860	5257
Case 6	0.00002	0.00002	0.10	0.45	62.7	100	3969	20668

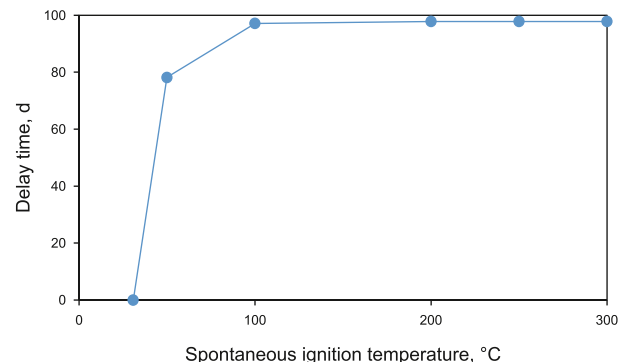
is not affected by the spontaneous ignition temperature. To check that, Eq. (1) is also used to estimate the delay times that are presented in Table 1 as well. In those estimates, the spontaneous ignition temperature is assumed 250 °C. The data are very close to those estimated using Eq. (2). It also indicates that Eq. (2) is a very good approximate solution to Eq. (1).

However, the common sense is that as the spontaneous ignition temperature is higher, the delay time should be longer. Why does Eq. (2) show that the delay time is almost independent of the spontaneous ignition temperature? To answer this question, Eq. (1) is used to estimate the delay times at assumed different spontaneous ignition temperatures, with the initial reservoir temperature being the same at 30.8 °C. The results are shown in Fig. 1. It shows that if the assumed spontaneous ignition temperature is the same as the initial reservoir temperature, the delay time is zero, which should be the case; as the assumed spontaneous ignition temperature increases, the delay time increases exponentially; when the assumed spontaneous ignition temperature is above 100 °C, the delay time almost stops increasing. This is because the oxidation reaction rate or the heat release rate increases with temperature following the exponential function of  $(-B/T)$ . Initially, the heat release rate is low, and the local reaction zone temperature takes some time (delay) to increase; when the temperature reaches a high value (100 °C in this example), the heat release rate becomes very high so that the reaction zone temperature does not need too much time any more to increase to any higher ignition temperature.

The results shown in Fig. 1 also suggest that the initial reservoir temperature is very important to spontaneous ignition. If the reservoir temperature is high, close to 100 °C in this example, the heat generation rate is high. Even though the spontaneous ignition temperature is much higher than the initial reservoir temperature, a very short time (delay time) is needed to reach that high ignition temperature. Turta (2013) mentioned that spontaneous ignition may be expected when the reservoir temperature is higher than 60–70 °C.

### 6. Oxidation time to reach a temperature with heat loss

The preceding section discusses the oxidation time required for the oxidation system to reach an assumed ignition temperature under an adiabatic condition. However, the adiabatic condition cannot be satisfied in real conditions. In a reservoir, the heat generated from LTO may be partly lost to the over- and underburden rocks. In a laboratory experiment, the heat will be lost through the experimental system. This section is to discuss the oxidation time required to reach a temperature when heat loss is included. Note that the arbitrary temperature reached may not be



**Fig. 1.** Delay time at different ignition temperatures.

high enough so that ignition may occur. First a heat loss model is presented.

### 6.1. Heat loss model

Vinsome and Westerveld (1980) worked out analytical solution to calculate the heat loss ( $E_b$  in kcal/(m<sup>2</sup> °C)) to the over- and under-burden formations of a unit interface area (m<sup>2</sup>) with the reservoir:

$$E_b(t, T) = 2 \frac{\lambda}{\kappa} d \left( T + pd + 2qd^2 \right) \quad (3)$$

where  $\lambda$  is the over- and under-burden rock thermal conductivity, kcal/(m d °C);  $\kappa$  is the thermal diffusivity, m<sup>2</sup>/d;  $d$  is the diffusion length in m that is equal to  $\frac{\sqrt{\kappa t}}{2}$ ; and  $t$  is the diffusion time, d;  $T$  is the temperature at the interface and is equal to the reservoir temperature at any time, °C;  $p$  in °C/m and  $q$  in °C/m<sup>2</sup> are intermediate parameters:

$$p = \frac{\frac{\kappa(\Delta t)T}{d} + I^N - \frac{d^3(T-T^N)}{\kappa(\Delta t)}}{3d^3 + \kappa(\Delta t)} \quad (4)$$

$$I^N = T^N d^N + p^N (d^N)^2 + 2q^N (d^N)^3 \quad (5)$$

$$q = \frac{2pd - T_r + \frac{d^2(T-T^N)}{\kappa(\Delta t)}}{2d^2} \quad (6)$$

The superscript  $N$  means the parameter at the preceding time step.

### 6.2. Oxidation time required to compensate heat loss

In the beginning of oxygen or air injection, the oxidation rate is low, the heat released from the oxidation cannot compensate the heat losses to over- and under-burden rocks. The time required to compensate the heat losses can be analytically derived as follows.

During the early time  $\Delta t$  from  $t = 0$  to  $t = t_c$  (compensation time for heat loss), the corresponding reservoir temperature or the interface temperature is  $T_{ri}$ . Assume the temperature is increased by very small percolation  $\Delta T$ , the heat losses due to this temperature percolation is

$$E_b(\Delta t, T_{ri} + \Delta T) = 2 \frac{\lambda}{\kappa} d \left( (T_{ri} + \Delta T) + pd + 2qd^2 \right) \quad (7)$$

with

$$d = \frac{\sqrt{\kappa \Delta t}}{2}$$

$$p = \frac{\frac{\kappa(\Delta t)(T_{ri} + \Delta T)}{d} + I^N - \frac{d^3(\Delta T)}{\kappa(\Delta t)}}{3d^3 + \kappa(\Delta t)} \quad (8)$$

$$I^N = 0 \quad (9)$$

$$q = \frac{2pd - (T_{ri} + \Delta T) + \frac{d^2(\Delta T)}{\kappa(\Delta t)}}{2d^2} \quad (10)$$

$$pd = \frac{4}{7} \left( T_{ri} + \Delta T - \frac{\Delta T}{16} \right) \quad (11)$$

$$\begin{aligned} E_b(\Delta t, T_{ri} + \Delta T) &= 2 \frac{\lambda}{\kappa} d \left( 3pd + \frac{d^2(\Delta T)}{\kappa(\Delta t)} \right) \\ &= \frac{\lambda}{7\kappa} \sqrt{\kappa(\Delta t)} (12T_{ri} + 13(\Delta T)) \end{aligned} \quad (12)$$

Since  $\Delta T$  is a small percolation,  $T = T_{ri} + \Delta T$  is approximately equal to  $T_{ri}$ , we have

$$E_b(\Delta t, T_{ri}) \cong \frac{12\lambda T_{ri}}{7\kappa} \sqrt{\kappa(\Delta t)} \quad (13)$$

Assume a reservoir is a cubic box with a unit interface area (1 m<sup>2</sup>) and a thickness  $h$  (m), the heat generated  $H_{gen}$  within  $\Delta t$  from the oxidation is

$$H_{gen} = h\phi S_{org}\rho_o HA_o p_{O_2}^n \exp\left(\frac{-B}{T_{ri}}\right) (\Delta t) \quad (14)$$

When  $E_b(\Delta t, T_{ri})$  is equal to  $H_{gen}$ , we estimate the compensation time  $t_c = \Delta t$ :

$$t_c = \left\{ \frac{12\lambda T_{ri}}{7\sqrt{\kappa}} \left/ \left[ h\phi S_{org}\rho_o HA_o p_{O_2}^n \exp\left(\frac{-B}{T_{ri}}\right) \right] \right. \right\}^2 \quad (15)$$

Using the Base case data of Table 1 and the data  $\kappa = 0.0929$  m<sup>2</sup>/d,  $\lambda/\kappa = 560.6$  kcal/(m<sup>3</sup> °C) from Vinsome and Westerveld (1980), and  $h = 10$  m,  $t_c$  is 205.18 d. Note that when the heat loss is not considered,  $t_c$  is zero! Therefore, in some cases, the heat loss can significantly affect the feasibility of spontaneous ignition. That explains why spontaneous ignition was not observed in some experiments and in some field tests.

As Eq. (15) suggests,  $t_c$  is inversely proportional to  $h^2$ . If the reservoir becomes thinner, the heat generated will be relatively small, but the heat loss surface remains the same; then the heat loss will be relatively large; as a result, the time to compensate the heat loss will be long. For example, if the reservoir thickness is 1 m,  $t_c$  will be 20,518 d! Alternatively, if  $h$  is 100 m,  $t_c$  will be 2.05 d.

### 6.3. Oxidation time including heat loss

To estimate the oxidation time required to reach an arbitrary interface temperature  $T$  from the initial interface temperature  $T_{ri}$ , assume a reservoir is a cubic box with a unit interface area (1 m<sup>2</sup>) and the reservoir height  $h$  m, and the heat balance for the reservoir is that the heat ( $H_{gen}$ ) generated or released from the oxidation period  $\Delta t$  minus the heat increase ( $H_{in}$ ) within the oxidation zone for  $\Delta T$  should be equal to the heat loss ( $E_b(\Delta t, T)$ ) to the over- and under-burden formations. The mathematical equation is

$$H_{gen} - H_{in} = E_b(\Delta t, T) \quad (16)$$

$$H_{gen} = h\phi S_{org}\rho_o HA_o p_{O_2}^n \exp\left(\frac{-B}{T}\right) (\Delta t) \quad (17)$$

$$H_{in} = h(\rho C)_r (\Delta T) \quad (18)$$

$$E_b(\Delta t, T) = E_b(t, T) - E_b(t^N, T^N) \quad (19)$$

The above equation has two unknowns,  $t$  and  $T$ . The unit of  $T$  and  $B$  is K in the exponential term, but  $T$  is in °C elsewhere. From Eq.

(16), we wish to find the oxidation time required when the reservoir temperature or interface temperature is raised from  $T_{ri}$  to  $T$ . The following procedures are used.

Step 1: Set a reservoir temperature that is slightly higher than the initial reservoir temperature. Use Eq. (2) to calculate the oxidation time ( $t_{SI}$ ).

Step 2: The oxidation time  $t$  including the heat loss should be longer than  $t_{SI}$  from step 1. Assume  $t = t_{SI} + \delta_0$ , here  $\delta_0$  is initially an arbitrary incremental time.

Step 3: Use  $t$  to calculate  $d$ ,  $I^N$ ,  $p$ ,  $q$ ,  $E_b(\Delta t, T)$ ,  $H_{in}$ , and  $H_{gen}$ .

Step 4: Calculate the heat ratio  $R_H = (H_{gen} - H_{in})/E_b(\Delta t, T)$  within  $\Delta t$ .

Step 5: If  $R_H$  is negatively deviated from 1, add  $\delta_1$  to  $t$  to increase heat generation, here  $\delta_1$  is an incremental time; if  $R_H$  is positively deviated from 1, deduct  $\delta_1$  from  $t$  to decrease heat generation. This is because as  $H_{gen}$  increases faster than  $E_b$  with time, and  $H_{in}$  is constant with  $T$  being set.

Step 6: Repeat steps 2 to 5 using new  $t$ , until  $R_H$  is approximately 1. Then this  $t$  is the oxidation time required to reach  $T$  when the heat loss is included.

Step 7: Set a higher  $T$ , repeat steps 1 to 6. In step 2, start with  $t = t^N + t_{SI} - t_{SI}^N$ .

Step 8: Repeat step 7 until the ignition temperature is reached.

The above model includes the heat loss to over- and underburden rocks. The model without including heat loss is an energy balance model that is a fundamental model. The heat loss model used in this paper is from Vinsome and Westerveld (1980) and their model is a simple presentation of the solutions of thermal differential equations from Lauwerier (1955). Vinsome and Westerveld's model is widely used, and it is also used in thermal reservoir simulators. The application conditions of the model of this paper rest on the conditions from Lauwerier's model. Some of conditions are homogeneous formations, without considering heat transfer by conduction or radiation in the flow direction, and without considering heat transfer by convection perpendicular to the flow direction.

Using the Base case data of Table 1 and the data  $\kappa = 0.0929 \text{ m}^2/\text{d}$ ,  $\lambda/\kappa = 560.6 \text{ kcal}/(\text{m}^3 \text{ }^\circ\text{C})$  from Vinsome and Westerveld (1980), the initial reservoir temperature is  $30.8 \text{ }^\circ\text{C}$ , and  $h = 10 \text{ m}$ , the relationships between  $t$  versus  $T$  are shown in Fig. 2. With the heat loss, the time is much higher. If the reservoir temperature is low, the oxidation rate is low, thus a long oxidation time is required to increase the reservoir temperature to a higher temperature. When the reservoir temperature is high, the oxidation rate is high, a short time is needed to increase the reservoir temperature to a higher

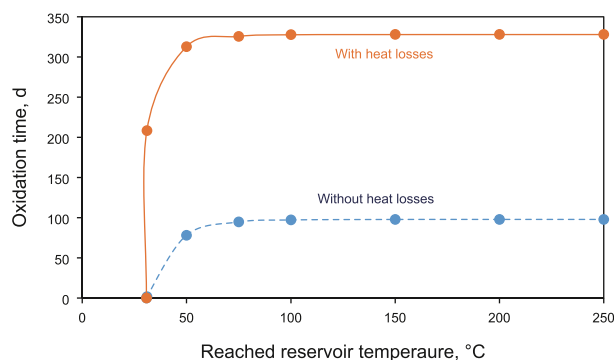


Fig. 2. Oxidation time required to reach different reservoir temperatures with and without heat loss.

temperature. As shown in the figure, the oxidation time is almost flat when the reservoir temperature to be reached or raised is above  $100 \text{ }^\circ\text{C}$ . Note the term oxidation time, instead of time delay for spontaneous ignition is used because at a low temperature, the ignition temperature may not be reached yet.

## 7. Conclusions

Based on the results and discussion from this paper, the following conclusions may be drawn.

- There are mixed results about the feasibility of spontaneous ignition both in laboratory experiments and oil reservoirs reported in the literature.
- It is more difficult for spontaneous ignition to occur in laboratory experiments than in oil reservoirs, probably due to more heat loss in the former.
- Spontaneous ignition is strongly affected by the heat generation rate from LTO that is a strong function of the initial reservoir temperature and oil activity.
- When the spontaneous ignition temperature is high, the delay time is not almost further increased.
- The time required to reach ignition with heat loss could be significantly longer than that without heat loss.

## CRediT authorship contribution statement

**James J. Sheng:** Writing – original draft, Validation, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Er-Long Yang:** Writing – review & editing.

## Declaration of competing interest

The author declares that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Acknowledgements

The work presented in this paper is supported by the National Natural Science Foundation of China (No. 51974334), Hainan Province Science and Technology Special Fund (ZDYF2022SHFZ107), local efficient reform and development funds for personnel training projects supported by the central government, Heilongjiang Post-doctoral Scientific Research Fund (LBH-Q21012).

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