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NUMERICAL ANALYSIS OF A CYLINDRICAL HEAT SOURCE FOR A NOVEL OIL WELL ABANDONMENT TECHNIQUE

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Abstract.
Oil well abandonment is a mandatory procedure that isolates the reservoir fluids in order to avoid any kind of environmental contamination. However, current techniques used for well plugging are still extremely expensive and difficult to execute. Aiming to overcome these challenges, a new approach in this area has been studied. The method proposes a certain chemical reaction that would generate enough heat to melt the surrounding materials and, after the cooling stage, the solidified mass would plug the well. A numerical analysis was developed to investigate the amount of heat necessary to change the phase of the material at a certain distance. For the model domain, it was considered an infinitely long cylinder to be a heat source. The pipe surrounding the source was defined as being made of stainless steel. In the outer layer, the dolomite sedimentary stone was treated as homogeneous. Simulations were performed in Ansys Workbench software, which discretized the heat conduction equation using the finite element method. The values of internal heat generation were varied and the results were evaluated in function of time and radial distance. Also, the thermal properties of the heat source material were investigated by varying its thermal conductivity and volumetric heat capacity. Increasing the heat generation resulted in higher temperatures profiles and, consequently, faster melting of the rock. However, the continuous increment of the heat might lead to unmanaged temperatures next to the heat source; therefore, the generation must be controlled along with the reaction time.

Keywords: *Oil well abandonment, Numerical analysis, Heat generation, Finite element method*

1. INTRODUCTION

Energy demand has been significantly increasing since last decade, mostly due to the world's population growth coupled with the industrialization advancement. Although the development of renewable and nuclear energy sources, these alternatives produce only a small amount of the worldwide energy. The main role of these sources is to complement and supplement the use of hydrocarbons, instead of replace it. According to the International Energy Agency (2016), in 2016, the oil and gas industry was responsible for more than 80% of the global energy supply.

The most common and applicable procedure to obtain oil and gas is still the exploration of deep-water reservoirs. However, when obtaining these non-renewable energy sources becomes economically unfeasible, because of the low quantity or difficulty in extraction, the well is abandoned (Abshire et al., 2012). Well abandonments techniques have as their main goal the permanent isolation of the reservoir fluids, in order to avoid any leakage that could be harmful to the environment (Mainguy et al., 2007).

One of the main techniques adopted so far is the application of cementing process inside the drilled hole in order to isolate the abandoned well. However, this process requires the employment of high level technology and expertise in a way that is necessary appraise its feasibility. The task has such importance that is decisive in the choice of exploring determined reservoir (Jennings et al., 1996).

Motivated by the foregoing challenges, an innovative approach has been proposed in terms of well abandonment and plugging. This novel method suggests the insertion of a vessel containing a certain chemical substance, which will provide an exothermal reaction. The heat generated by the reaction must be high enough to melt the surround area. This mass amount would solidify and, therefore, permanently plug the reservoir.

The aim of this paper is to serve as a preliminary study by investigating the mandatory heat to melt the surround area of an oil well. The heat transfer was evaluated through a transient numerical analysis with a one-dimensional domain. The exothermal reaction was approached as a solid heat source with a cylindrical shape. Also, materials were considered homogeneous and without porosities. Different heat generations values were used to evaluate the temperature distribution in function of time and radial distance. In addition, thermal properties such as thermal conductivity and volumetric heat capacity were varied in order to find the most suitable material for the heat source.

2. METHODOLOGY

2.1. Model setup

Although this paper is focused on the heat transfer in oil and gas reservoirs, (Gu, 1995) proposed a model to develop an analytical solution for ground-coupled heat pumps that, for this preliminary research, would be extremely useful. Thus, the chemical reaction that would provide energy was approached as a solid cylindrical heat source with an internal heat generation, $\dot{q}_{gen}$. The cylinder had a radius, r_1, and it was positioned inside a pipe with an outer radius, r_2. The area surrounding the pipe was defined as sedimentary rock, which had a radius, r_3, and a surface temperature, T_s. Figure 1 shows a schematization of the model.

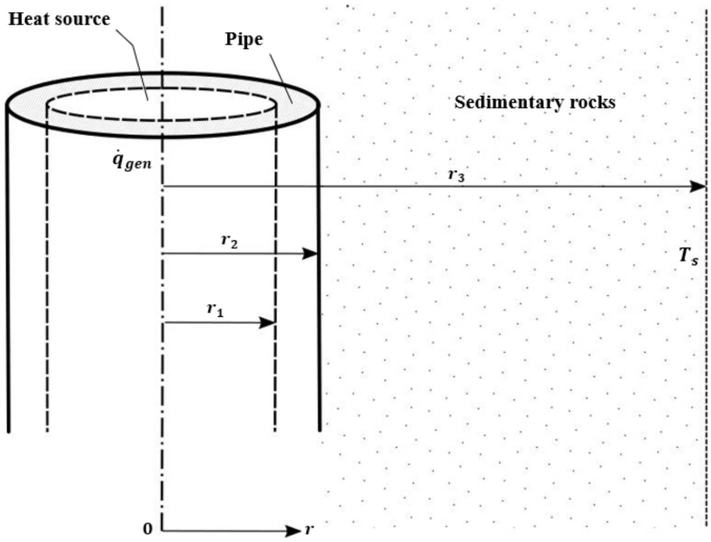

Figure 1. Scheme representing the model.

In order to simplify the model for the numerical analysis, the following assumptions were provided:

(1) The domain was considered infinitely long. This assumption changed the case into a one-dimensional analysis, therefore, the temperature gradient was calculated in function of time and radial distance;

(2) It is well known that sedimentary rocks are mostly heterogeneous and porous, however, in this case, it was considered as homogeneous without any porosity;

(3) Thermal contact resistance between the solids was neglected;

(4) Specific heat and thermal conductivity were constant;

(5) At initial conditions, the temperature was uniform throughout the whole domain;

(6) A far-away boundary was considered with a surface temperature, T_s. Thus, this surface would not be affected by the heat generated in the other boundary unless long periods of time were applied.

Based on these assumptions, the heat conduction equation in cylindrical coordinates can be express by

$$\frac{1}{r_1}\frac{\partial}{\partial r_1}\left(r_1\frac{\partial T_1}{\partial r_1}\right)+\frac{\dot{q}_{gen}}{k_1}=\frac{1}{\alpha_1}\frac{\partial T_1}{\partial t} \qquad 0 \le r \le r_1\ ;\ t > 0 \tag{1}$$

where $\alpha = k/\rho c_p$ is thermal diffusivity. The subject 1 is in terms of the cylinder because this equation governs only the heat source conduction. For both pipe and sedimentary stone is necessary to remove the internal generation term, $\dot{q}_{gen}$. Thus, for these materials the heat conduction is determined by:

$$\frac{1}{r_i}\frac{\partial}{\partial r_i}\left(r_i\frac{\partial T_i}{\partial r_i}\right)=\frac{1}{\alpha_i}\frac{\partial T_i}{\partial t} \qquad r_1 \le r \le r_3\ ;\ t > 0 \qquad i = 2,3 \tag{2}$$

where the subjects 2 and 3 stand for the pipe and the sedimentary rock, respectively.

According to (Carslaw and Jaeger, 1959) and (Özışık, 1989), to solve the governing heat conduction equation for this case, the following initial and boundary conditions are necessary:

$$T_i = T_s \qquad 0 \le r \le r_3\ ;\ t = 0 \qquad i = 1, 2, 3 \tag{3}$$

$T_{i-1} = T_i$ *at the interfaces* $r = 1$ *for* $i = 2$ *and* $r = 2$ *for* $i = 3$; $t > 0$ (4)

$k_{i-1} \frac{\partial T_{i-1}}{\partial r} = k_i \frac{\partial T_i}{\partial r}$ *at the interfaces* $r = 1$ *for* $i = 2$ *and* $r = 2$ *for* $i = 3$; $t > 0$ (5)

$T_3 = T_s$ *at the outer boundary for* $r = r_3$; $t > 0$ (6)

2.2. Thermal properties

One of the main concerns along any thermal study, experimental or numerical, are the materials involved in the problem. Regarding this consideration, the pipe was defined as being made of the stainless steel 304L, which is commonly used in deep water processes due to its corrosive resistance. As mentioned, the sedimentary rock was considered homogeneous; in this case, it was integral compound of dolomite. The thermal properties such as conductivity (k), specific heat (c_p) and density (ρ) of each material are shown in Table 1.

Table 1. Thermal properties of different materials.

Material	ρ (kg/m³)	k (W/m ºC)	c_p (J/kg ºC)
Stainless Steel 304L	8055	13.8	480
Dolomite	2872[(1)]	2.11[(1)]	820[(1)]

[(1)] (Eppelbaum et al., 2014).

As can be seen in the previous table, the thermal properties of the heat source were not listed, since its material was not defined. Thus, this paper also investigated the influence of thermal conductivity and volumetric heat capacity in the temperature distribution. By varying these properties, it would be possible to select the heat source material based on the best results. It was established both thermal conductivity and volumetric heat capacity ratios, involving the heat source and its adjacent material, in this case, the stainless steel pipe. These ratios were defined as:

Thermal conductivity ratio:

$$G = \frac{k_1}{k_2} \quad (7)$$

Volumetric capacity ratio:

$$H = \frac{(\rho * c_p)_1}{(\rho * c_p)_2} \quad (8)$$

As mentioned, the subscripts 1 and 2 stand for the heat source and the pipe, respectively.

2.3. Computational procedure

Numerical simulations were performed using the academic package of the software Ansys Workbench ver.19, which discretized the heat conduction equation through the finite element method. The computational domain was equivalent to the cross section area of the previous model. The radius r_1, r_2 and r_3 were respectively equal to 0.0889, 0.1123 and 0.889 meters. The sedimentary rock radius was ten times bigger than the heat source one to guarantee that the heat generation would not affect the far away surface temperature ($T_s = 20\ °C$). For the heat generation, it was used the values of a) 0.5 x 10^6, b) 1 x 10^6 and c) 1.5 x 10^6 W/m³. The transient analysis used a total time of 100000 seconds and the time steps were set as 1000 seconds each. In addition, the thermal conductivity ratio (G) had the different values of 0.1, 1 and 10. Similarly, the volumetric heat capacity ratio (H) used the values of 0.5, 1 and 2. These variations were studied at radial coordinates of 0 and 0.2 meters.

In general, the mesh was characterized by orthogonal elements whose were more refined next to the interface between materials, as shown in figure 2. The mesh refinement was defined by convergence tests. These tests were proposed to evaluate the independency of the mesh size on the results. Three different mesh sizes were used and they had the following number of elements and nodes: 2100 elements and 6673 nodes; 4480 elements and 14093 nodes; 7382 elements and 23079 nodes. Analyzing different points, the maximum variation found was 0.4 °C; therefore, the coarser mesh was selected to reduce the calculation time. Most elements were PLANE77, which is characterized for having 8 nodes that are well suited to model curved boundaries and transient heat transfer problems (Kohnke, 2015).

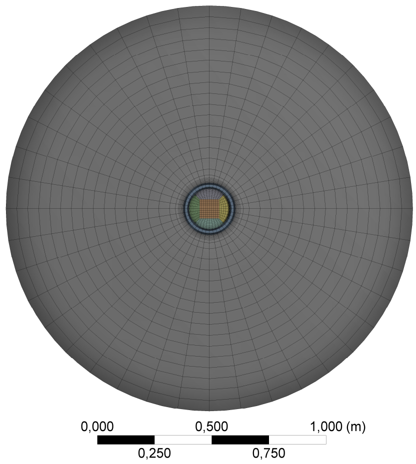

Figure 2. Mesh of the computational domain.

3. RESULTS

3.1. Temperature distribution

Figure 3 shows, at 100000 seconds, temperature gradients for internal heat generations of a) $0.5 \text{ x } 10^6$, b) $1 \text{ x } 10^6$ and c) $1.5 \text{ x } 10^6$ W/m³. The simulations were carried out using both thermal conductivity and volumetric heat capacity ratios equal to one (G = 1 ; H = 1). One can note by comparing the figures that, for the same time, the temperature distribution was different, as its maximum value was observed with higher generations.

Detailing the analysis, both heat generations of $0.5 \text{ x } 10^6$ and $1 \text{ x } 10^6$ W/m³ (Fig. 3.(a) and (b)) displayed reasonable maximum temperature values, reaching 1341.3 and 2662.6 °C, respectively. Nevertheless, for $1.5 \text{ x } 10^6$ W/m³ (Fig. 3.(c)), the temperature reached 3983.9 °C, which can be considered exaggerated for a chemical reaction. This result demonstrates that the continuous increase of heat has to be controlled with time.

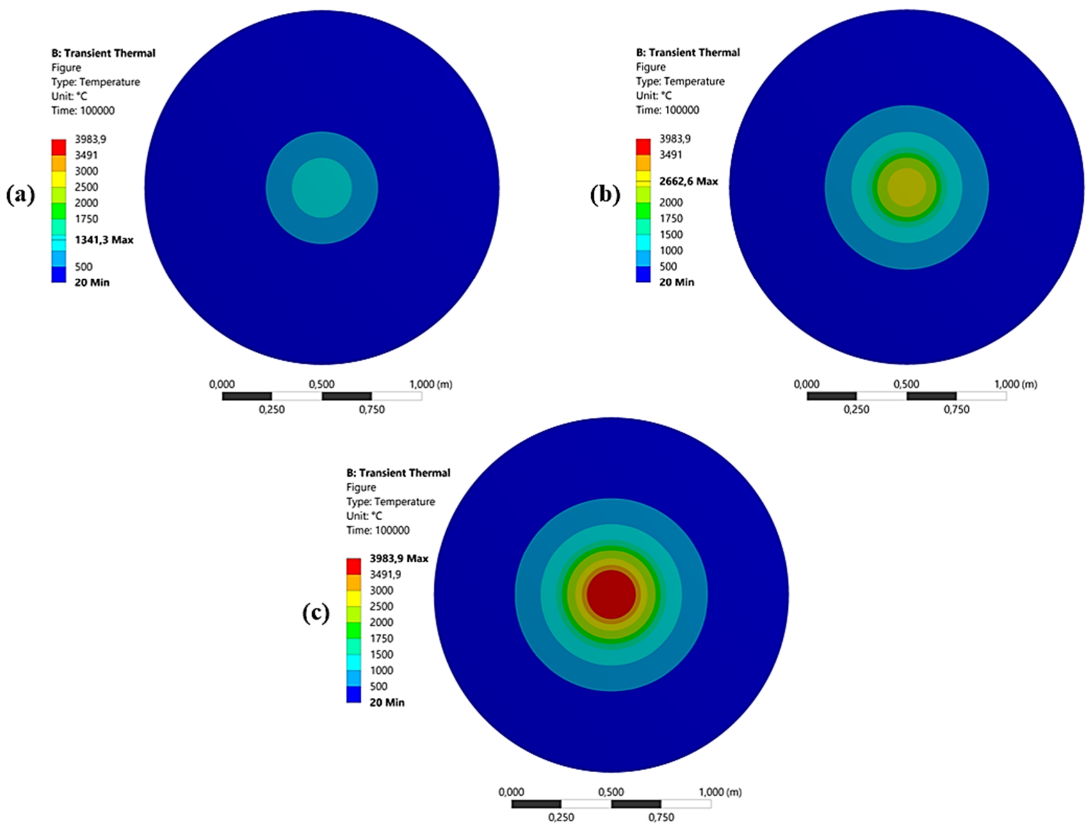

Figure 3. Temperature distribution for heat generations of (a) $0.5\ x\ 10^6$, (b) $10^6$and (c) $1.5\ x\ 10^6$ W/m³ at 100000 seconds.

Figure 4 shows results of temperature profiles measured through the radial distance. For 0.5×10^6 and 1×10^6 W/m³, the analysis time was 10^5 seconds, while a total time of 0.5×10^5 seconds was set for 1.5×10^6 W/m³. As discussed previously, the simulation with higher heat generation presented extrapolated temperatures as results; therefore, its analysis time was reduced.

To determine the amount of material that would be melted, the melting points of stainless steel and dolomite were established. Taking into account that the melting of this rock is an uncommon process, there is an absence of reliable literature estimating its melting point. Thus, it was considered a temperature of 1400 °C, as demonstrated in the phase diagram for high pressures proposed by (Shatskiy et al., 2018). The stainless steel melting point is more consolidated and it is around 1400 °C.

As we can see in the graph, for the stipulated time, a constant heat generation of 0.5×10^6 W/m³ was not able to melt neither the stainless steel pipe nor the dolomite. By increasing the heat generation to 10^6 W/m³, it was possible to melt a circular area with a 0.2 m radius. A slightly less quantity of material was melted in half the time, when a heat generation of 1.5×10^6 W/m³ was applied. Also, the temperature next to the heat source increased almost 400 °C. It is possible to assume that higher generations would melt a certain region in less time, but would reach anomalous temperatures next to the source. These elevated temperatures are not desirable next to the vessel, since they might create instabilities.

Another important aspect noted was the temperature drop located next to the interface between both materials. The reason for this occurrence is related to the thermal resistance. Since the thermal conductivity of the sedimentary rock is way smaller when compared with the same property of the stainless steel, the heat flow passing through the interface encounters an elevate thermal resistance and, therefore, the temperature significantly decreases. In addition, this circumstance was more evident when source produced more heat, resulting in a higher temperature and, consequently, a greater gradient.

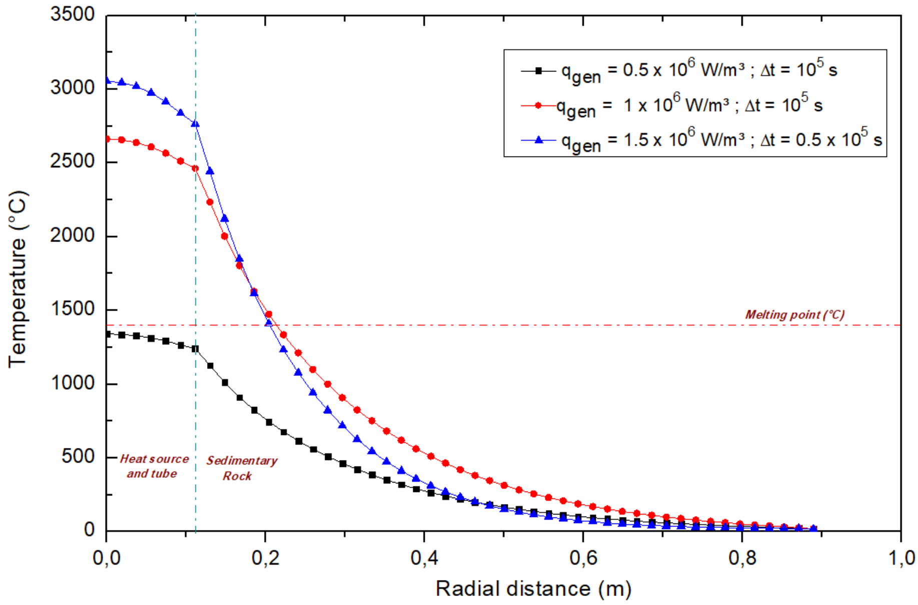

Figure 4. Temperature distribution through the radial distance for different heat generation and time values.

3.2. Effects of G and H

Figure 5 displays the thermal transient analysis for different thermal conductivity and volumetric heat capacity ratios at the heat source center (r = 0). Based on the previous results, the most desirable temperature profiles were obtained with 10^6 W/m^3 and, therefore, the same internal heat generation was applied for this case. One can note that higher temperature values were found with lower thermal coefficient ratios, reaching temperatures between 3500 and 4000 °C. By increasing G, the temperature decreased and started to have close values for different thermal conductivities. These results are in accordance with the study of (Gu, 1995). Thus, it is possible to presume that a material with a low thermal conductivity would increase the temperature next to the heat source. A similar behavior was found in terms of volumetric heat capacity, since higher temperatures were found for lower values of H. However, the changes in its values were less significant when compared with the thermal conductivity ratios. If a longer simulation time was used, the curves of H would stabilize and the only notable changes would be in terms of G.

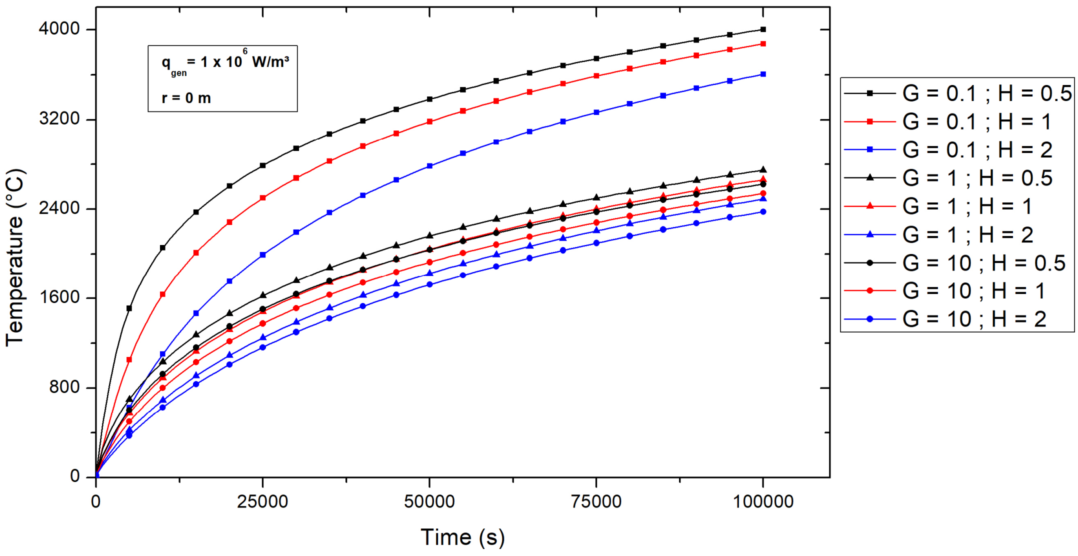

Figure 5. The impacts of G and H on the temperature distribution at the heat source (r = 0).

The behavior of these variables was also evaluated in the sedimentary rock by performing a similar investigation at 0.2 m, as shown in figure 6. It is noted that G have not shown a strong influence in the temperature distribution, since its values were close to be equal for G = 1 and G = 10. For G = 0.1, the temperatures were lower, but did not have a considerable difference. Thus, the temperature dropped when it was used a lower value of G, differing from the behavior at the heat source. The variations in the volumetric heat capacity were more evident, showing that by enhancing H, the temperature would decrease.

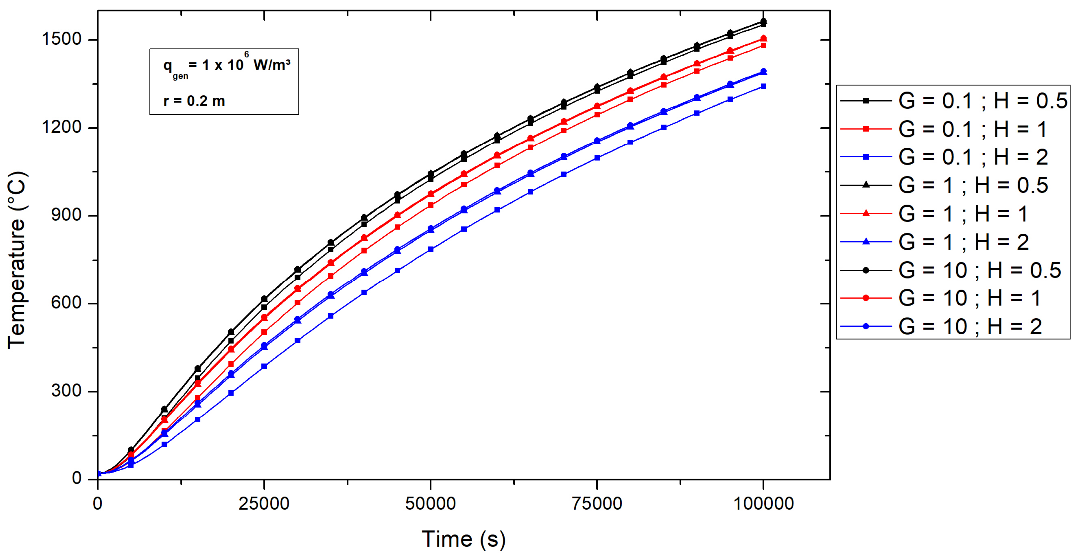

Figure 6. The impacts of G and H on the temperature distribution at the dolomite rock (r = 0.2).

4. CONCLUSIONS

A simplified approach for a new oil abandonment technique was investigated through the numerical analysis of a cylindrical heat source. The model was one-dimensional and the effects of different heat generations were evaluated through the time. Based on the numerical simulations, the herein results indicated a faster melting with higher heat generations. However, the increase of this variable can also be problematic, resulting in anomalous temperatures near the heat source. It is possible to conclude that both the internal heat generation and the total reaction time must be controlled to melt the required amount of material and to not exceed the temperature at the heat source.

In order to select the most suitable material to compound the vessel, this work also evaluated the thermal properties of the heat source. Different thermal conductivities and volumetric heat capacities were adopted and their effects were studied in function of temperature and time. Enhancing the thermal conductivity resulted in lower temperatures next to the heat source and more elevated values at the sedimentary rock. This condition would be useful to reduce the amount of heat at the vessel and to increase the melted area. Increasing the volumetric heat capacity ratio, implied in elevated temperatures at both studied points.

5. ACKNOWLEDGEMENTS

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