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Smart Expandable LCMs - A Theoretical and Experimental Study

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Abstract

A lost circulation incident can have a heavy financial cost in the form of losing rig time, mud fluid and in severe cases well blowout with serious consequences. Hence, considerable research and experiments have been done to make lost circulation materials that can seal fractures effectively. However, lost circulation materials used today still have limitations such as damaging production zones, plugging tools such as LWD and in worst cases totally failing in sealing the fractures and causing a well to be drilled with total loss. In this work, we introduce a new class of "Smart Lost Circulation Materials (LCMs)" to seal the fractures efficiently without damaging production zones or plugging tools. Our smart LCMs are made out of thermoset shape memory polymers which are activated by the formation's *in situ* temperature to effectively seal the fracture while providing extra compressional forces to strengthen the wellbore. A fully coupled fluid flow and particles model is developed to study the effectiveness of smart LCMs and evaluate their sealing efficiency via different combinations and size distributions. In addition, a series of experiments were conducted using particle-plugging apparatus (PPA) to measure the sealing efficiency of the smart LCMs. The proposed LCM shows promising results in quick and effective sealing of fractures and building stress.

Introduction

Lost circulation has been a problem since early days of rotary drilling. Drilling fluids is supposed to be circulated down to the bottomhole and come back to the surface for cutting transport and cooling the bit (White, 1956). However, when lost circulation occurs, drilling fluids are lost and loss circulation materials (LCMs) need to be added to the mud to stop further fluid loss. A lost-circulation incident may have a heavy financial and environmental cost that justifies the price of LCM products to treat the problem. Rig nonproductive time is another financial burden in these incidents (Whitfill and Hemphill, 2003). In addition, lost circulation leads to the mud levels falling, which can cause the well to be in an underbalance pressure state, and in severe cases, it may lead to a kick or even a blowout (Arshad *et al.*, 2014). Lost circulation events usually occur in cavernous, karst, highly permeable and naturally fractured formations (Al-Saba et al, 2014). Since lost circulation is a very important issue, a lot of studies have been conducted to minimize its impacts. Lost circulation materials are materials that seal the fractures and minimize mud loss. Nygaard et al. (2014) classified LCMs into seven categories, being: fibrous, granular, flaky, acid/water soluble, mixture, high fluid loss LCM squeeze, swellable/hydratable LCM combinations and nanoparticles. Fibrous materials are a type of LCM that is slender, long and flexible and can be in different lengths and sizes of fiber. Fibrous materials may have a small degree of stiffness and when bridging a fracture, forms a mat-like bridge structure. Examples of fibrous materials would be cellulose fibers, mineral fibers and saw dust. Granular materials are "additives that are capable of forming a seal at the formation face or within the fracture to prevent the losses into the formation." Granular materials are rigid with high crushing resistance and are often used for wellbore strengthening applications or preventive treatments. Examples of granular materials would be glisonite, coarse bentonite, perlite, asphalt and sized calcium carbonate. Flaky materials are a type of LCM that has a thin, flat shape with a large surface area. They are not very stiff materials and form a bridge over the permeable formation face. Examples of flaky materials would be mica, cellophane, vermiculite, cottonseed hulls, corncobs and flaked calcium carbonate. Acid or water soluble LCMs are non-damaging LCMs since conventional LCMs could damage the formation when used in the reservoir section. Examples of acid soluble LCMs would be mineral fibers and calcium carbonate while water soluble LCMs would be a mixture of sized salts.

Mixtures occur when two or more LCMs are combined together to yield a better performance in decreasing fluid loss. Swellable/Dehydratable LCMs are a blend of LCMs that contain a highly reactive material such as polymers. The highly reactive materials are activated by chemical reagents or when contacting drilling fluids. Nanoparticles are particles that could be added directly to the mud using an *ex-situ* procedure or could form from the addition of precursors that were added to the mud by the in-situ procedure. Examples of nanoparticles used in the field will be silica, calcium carbonate and iron hydroxide.

In this work we will try a new smart lost circulation material that not only seals the fracture but strengthens the wellbore. The smart LCM in this case is made out of shape memory polymers and is activated via the temperature of the bottomhole. It then can effectively seal the mouth or the tip of the fracture. The smart LCM can be programmed to be activated at a given formation temperature. Since the fracture needs to be sealed properly, our proposed LCM was made out of thermoset polymers. The high temperature of the reservoirs softens the thermoset polymers a bit and allowing them to stick together and create a bridge that seals the fracture. The high stress released from these polymers ensures the sealing of the fracture mouth and according to the stress cage theory it provides compressional forces to strengthen the wellbore (Cook *et al.*, 2012). It is notable that the release stress should not be very large to prevent the crack from further propagation. Therefore, the stress release for a bundle of thermoset smart LCM is set at 18 MPa. This value is reduced to 8 MPa when applied in the form of particulates.

The smart LCM that we propose here was tested through lab experiments and numerical simulations. The experiment was performed using Permeability Plugging Apparatus with an LCM receiver. This apparatus is composed of a bed that represents the formation and fluid flows through this bed under a specific pressure to try and form a seal to prevent fluid loss. The beds can be slotted or tapered discs that stimulate either natural or induced fractures. The numerical simulations were made using LIGGGHTS, OpenFOAM and CFD-DEM coupling to ensure maximum sealing efficiency at wellbore conditions and to prove that our LCM provides compressional forces and strengthens the wellbore. LIGGGHTS is an improved discrete element code for general granular and granular heat transfer simulations. By solving dynamics equation for particles, LIGGGHTS determines particle interactions, positions and velocities through discrete element method (DEM) in each time step.

Shape Memory Polymers

As mentioned above, our proposed smart LCMs are made out of shape memory polymers (SMPs). Shape memory polymers are smart materials made out of polymers. The SMP has the ability to deform into a temporary shape and return back to its permanent shape when triggered by an external stimulus such as temperature change (Lendlein and Kelch, 2002). SMPs are capable of storing a prescribed shape indefinitely and recover them by specific external trigger, e.g. temperature change. SMPs were used as smart cement additives to prevent cement shrinkage and failure in cement sheaths (Dahi Taleghani *et al.*, 2016). SMPs were also used as smart proppants to increase the fracture's conductivity and permeability (Santos *et al.*, 2016).

Thermoset polymers will be in the form of foam or particles when acting as a lost circulation material. For thermoset polymers, the programming and shape recovery process are well described by the Thermomechanical cycle as seen in **Figure 1** for a pure amorphous SMP and SMP based syntactic foam.

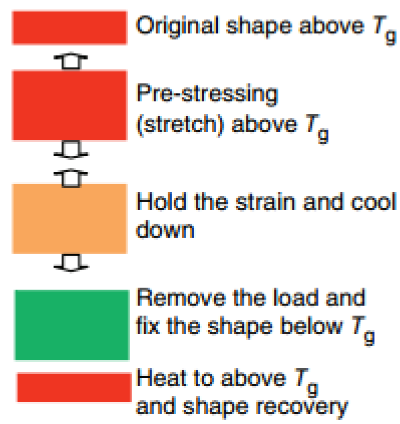

Figure 1- Thermomechanical Cycle for Thermoset SMP (Li, 2014)

In general four steps are included in this cycle: (1) High Temperature Loading: the temperature is elevated to above T_g, i.e., glass transition temperature, where the mobility in the SMP molecular network is surged. The SMP molecular chains in this stage are flexible and can cope with the applied external traction field, (2) Cooling: The SMP is cooled down to below T_g, while the external traction field is maintained. In this step the deformed molecular network retains the induced shape in step 1, (3) Low Temperature Unloading: The traction is removed in this step and this results in the SMP being elastically unloaded and the programming process is completed now and (4) Recovery: In this step the shape is recovered by increasing the temperature to above T_g where the locked molecular chains are able to restore their original configuration and the SMP releases its memory. The stress release in thermoset is generally higher than the stress release in thermoplastic polymers' recovery. Also, thermoset polymers should be very efficient when sealing fractures in HPHT formations since their material properties allow them to withstand high temperatures (Li, 2014). It is very important that we program our smart LCM since programming is the process of storing energy in the polymer network. These properties will be very important when the smart LCM is used to seal the fracture in the bottomhole. The recovery step for the Thermomechanical cycle represents post-programming. The programmed particles will enter the fracture and then recover. Since compressed shape will expand the particles will bridge and seal the fracture. The stress release from these particles will enhance the near wellbore stress and strengthen the wellbore.

Economic Value of LCMs

In terms of economic perspective, it is notable that mud loss to the formation is one of the most costly and undesired encounters in the petroleum industry. It could be induced by drilling or could occur to the natural features of the reservoir itself. It causes a large amount of nonproductive time that includes all services that support the drilling operation as well as the cost of the rig time. Therefore, the industry has been developing new techniques in minimizing lost circulation, since a lost circulation incident costs more than the treatment.

It was estimated that lost circulation alone accounted for two to four US billion dollars annually due to lost time. It is not just non-productive time that lost circulation accounts for but uncontrolled loss of fluid can damage the reservoir's formation and have a negative effect on its production potential and therefore, even more future losses (Cook *et al.*, 2012). In the Gulf of Mexico, lost circulation, stuck pipe, sloughing shales and wellbore collapse account for 44% of the total non-productive time. The reason behind this is that they use synthetic-base muds that range from $100 to $200 per barrel and therefore, losing these fluids can be extremely costly. The more the non-productive time, the higher the cost.

According to Baker Hughes, LCM prices can range from $50 per 50 lb. sack to $800 per 50 lb. sack. Usually, the expensive LCMs are the plug types that are used as pills while the cheap LCMs are the ones that are kept on added every time the mud is pumped into the bottomhole. With cases where the LCMs need to be added continuously to the mud, it is estimated according to Halliburton that between 15 lb. to 30 lb. of LCM per barrel of mud should be pumped on every stand. The US Energy Information Administration website monitored the costs of drilling from 2002 to 2007. It was reported that the cost per well in 2002 for all wells was about 1 million dollars and by the end of 2007 the cost per well was about 3 and a half million dollars. This means that the cost increased more than triple the amount in just 5 years. The administration also reported the cost of drilling per foot for these 5 years and in 2002 it was $187.46/ft. and almost quadrupled in 2007 to be $574.46/ft. This increase in the cost per foot was probably due to horizontal drilling, lost circulation problems due to fractured formations and other drilling-encountered problems.

The costs of most LCMs used today as seen above are very expensive and they could also not work properly in certain formations. This is why we propose our new smart LCM which is much cheaper than the LCMs used now and is almost equivalent to the price of resin which ranges from 0.01 $/lb to 0.9 $/lb. Having an effective LCM at this cost will save companies even more money specially when the oil prices are about 40 $/bbl in 2016.

Unaddressed Issues and Disadvantages of Current LCMs

A lot of research and experiments have been done to make sure that LCMs can seal fractures effectively to minimize loss and non-productive time. However, LCMs still have disadvantages like limited application in high-pressure and high-temperature (HPHT) formations or causing damage to producing zones (Brandl *et al.*, 2011). Some LCMs that are made out of polymers fail to deform and change back in shape once activated and this may be due to their dissolving in the drilling fluid. Some LCMs especially the ones used in naturally fractured reservoirs work only for specific formations while fail in others. Therefore, it is important to find a material that can supplement a LCM or be used as an LCM without facing the problems mentioned above to save losses and non-productive time. Drilling engineers have reported clogging of drilling equipment from LCMs due to their large sizes. They used large sizes of LCMs because the small ones could not seal the fracture efficiently.

The smart LCM we propose in this paper has a lot of competitive advantages when compared to the LCMs used today in the field. Firstly, the smart LCM does not only seal the fracture but also provides some compressional circumferential stress like a stress cage around the wellbore to further strengthen the wellbore. Secondly, the developed smart LCM will be adjusted through its chemical composition and has the ability to withstand HPHT formations since its shape memory effect is activated through phase transformation by temperature and pressure. Therefore, the smart LCM will be activated at a specific temperature based on knowing the temperature profile of the wellbore. This will therefore, lower the cost of producing different LCMs for different types of formations. Thirdly, the smart LCM here will be able to work well with all types of muds and it will not fail to change shape while activated. Fourthly, the smart LCM has a volumetric change ability that would prevent the equipment used in the field from clogging and at the same time will ensure efficient sealing of the fracture. The smart LCM is planned to work with all formations, especially naturally fractured carbonate reservoirs in the Middle East, and depleted zones in the United States such as the formations in the Gulf of Mexico.

Experimental Method and Results

The objective of running this experiment is to create a field environment of lost circulation at a small scale and see how effective our smart expandable LCM will seal it. The experiment done to test the smart LCMs was permeability plugging apparatus (PPA) shown in **Figure 3**.

Figure 3- HPHT PPA with LCM Receiver

The particle plugging apparatus that will be used is a high-pressure high-temperature instrument that has a maximum operating temperature of 500 degrees Fahrenheit and a maximum operating pressure of 5000 psi. The PPA assembly consists of a hydraulic hand pump assembly to supply pressure, a 5000 psi stainless steel PPA cell where the fluid and LCM will be placed, a PPA Heating Jacket to heat up the apparatus to specific temperatures, a dial thermometer to measure the temperature, a LCM PPA Receiver- without this receiver the PPA will get plugged and it will be very hard to run the experiment, a backpressure receiver which is used only if the temperature exceeds bubble point of the fluid, a carbon dioxide pressurizing assembly or nitrogen pressurizing assembly to work with the backpressure receiver, a graduated cylinder to measure the fluid loss and finally, slot discs and tapered discs to represent fractures.

The smart LCMs were in two diameter sizes, 2.5mm and 5mm. The smart LCMs activation temperature is 70 Degrees Celsius. **Figure 4** shows the smart LCMs before and after activation.

Figure 4- (a) Smart LCM before activation (b) after activation.

The LCM receiver was filled with 170 ml of water-based mud mixed with a mixture of the sizes mentioned for the smart LCMs. One slotted disc and one tapered disc with descriptions described in **table 1** were used to represent the fracture.

Table 1

Type	Length (Inches)	Width (Inches)
Slot Disc	0.279	0.1
Tapered Disc	1.700	0.04 to 0.1

For each disc, the experiment was done at 3 temperatures of 60, 70 and 80 Degrees Celsius. The fluid loss and the maximum pressure the seal can hold were recorded at each temperature. The fluid loss was measured by pumping hydraulic fluid in the cell until pressure started to build up. The fluid that came out before the pressure build up is the fluid loss. The maximum pressure build up is the maximum pressure the seal can hold before the seal is broken and fluid is lost again. **Table 2** shows the results that were obtained from this experiment.

Table 2

TYPE	Temperature (Degrees Celsius)	Pressure (Psi)	Fluid Loss (ml)
Slot Disc	60	100	47
	70	2000	22
	80	4500	7
Tapered Disc	60	0	58
	70	2500	18
	80	5000	0

It can be seen from the results that when the smart LCM got activated the fluid loss decreased significantly. By the time the PPA cell reached 80 Degrees Celsius all the smart LCMs were activated and the fracture was effectively sealed. The particles bridged together as seen in **Figures 5** and **6** and were able to withstand extremely high pressures.

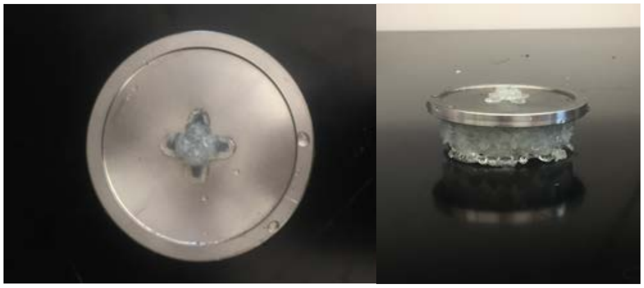

Figure 5- Effectively Sealed Slot Disc by the smart LCMs.

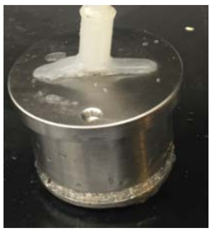

Figure 6- Effectively Sealed Tapered Disc by the Smart LCMs.

Numerical Simulation Method and Results

The objective of the numerical simulation was to validate the pressure buildup caused by the smart LCMs in the experiment and to estimate the concentration of SMPs needed to successfully plug and seal a fracture. A fully coupled CFD-DEM simulation was made to measure the pressure buildup against time when the SMPs bridge and seal the fracture.

The main steps to complete a DEM simulation are listed as: first, “Initialization” and this is the step defining the initial configuration of the particles, boundary conditions and geometry. Second, “Application of Forces” and this is when forces such as gravity, friction caused due to neighbor particles, pressures etc. are calculated for each particle. Third, “Force Calculations” and this is when the velocity and acceleration of each particle is calculated based on the forces mentioned in step 2 using momentum balance. Fourth, “Integration” and this is when the position and velocity of each particle are calculated and updated according to a time step defined by the user. Fifth, “Analysis” and this is when the thermal and mechanical parameters are computed based on each time step. Each step from 1 to 4 is then repeated until the solution is solved and is complete. Finally, “Post Processing” and this is the part where its output data is processed to be graphically visualized.

OpenFOAM is a computational fluid dynamics (CFD) simulator. Computational fluid dynamics is the study of fluid flow, heat transfer and associated fluid phenomena through computer-based simulations. There are three steps needed to successfully complete a CFD simulation. First is “Pre-processing” and this is the part where the user needs to enter the input data. Input data could be grid size, geometry, fluid properties, etc. The physical and chemical phenomena are defined. Second is “Solving” and this part used finite volume method to evaluate partial differential equations in the form of algebraic equations. These equations are then solved using an iterative method. Each value is calculated based on a discrete space according to the mesh geometry. Finally, “Post Processing” and this part is where the solution can be graphically visualized.

Finally, the CFD-DEM coupling can couple solid particle and fluid system simulations together. The particles’ motions are modeled using the discrete element method and the fluid flow is modeled using the CFD approach previously described. Both of these approaches are coupled and a system of solid particles and fluids is formed where the conservation of momentum and mass is achieved (Zhu *et al.*, 2007).

A fracture shape was built using SOLIDWORKS and imported to LIGGGHTS to test the smart LCMs. The fracture was of an elliptical shape with one side having radiuses of 40mm and 12mm and the other side has radiuses of 20mm and 6mm. The length between both sides was 30 cm. The particles in the simulation had the exact same properties as the Smart LCMs and they expanded by up to 25% of their original size when exposed to a temperature of 70 Degrees Celsius or above. The fluid used has a viscosity of 40cp and a density of 10 ppg. The velocity that the mixture of fluid and particles entering the fracture is 1.2 m/s. The time step used for this simulation was 0.00001 seconds and the simulation lasted 3 seconds. Pressure at the outlet was set to zero and the pressure at the inlet was set to 87 psi or 600 KPa.

Two common particle sizes were selected to run simulations. The first particle size has a diameter of 2.5mm and the second particle size had a diameter of 5mm. For the first particle size, **Figure 7** shows the amount of particles needed to successfully plug the fracture. Since the particle size are very small compared to the fracture inlet size, the number of particles needed with a diameter of 2.5 mm to fully plug and seal the fracture is 1,060 particles. The closer the particle size is to the smallest fracture inlet radius, the less particles will clog the fracture. As can be seen in **Fig. 8**, the number of 5mm particles needed to plug the fracture are much less than the number of 2.5 mm particles. **Figure 8** shows the particle expansion when the fracture got plugged at the end of the simulation. As can be seen, the closer the particle is to the end of the fracture the more it expands and this is because the particle has been heated for a longer time than the particles close to the fracture inlet and therefore have expanded more. However, expansion will never be more than 25% of the particles actual size. **Figure 9** shows the pressure build up for both the 2.5 mm and the 5 mm particles. It can be seen that the smaller particles sealed the fracture more efficiently than the bigger particles due to a larger pressure buildup. This could be explained due to the high concentration of particles filling up the fracture by the smaller particles and causing better packing than the bigger particles. The pressure for the bigger particle went down at first due to loss of fluid but then the pressure was built due to the fracture being plugged. However, for the smaller particles the pressure was building up as soon as it was applied due to a better sealing of the fracture because of the packing. This is why in the experiment both sizes were used to maximize the packing and decrease porosity.

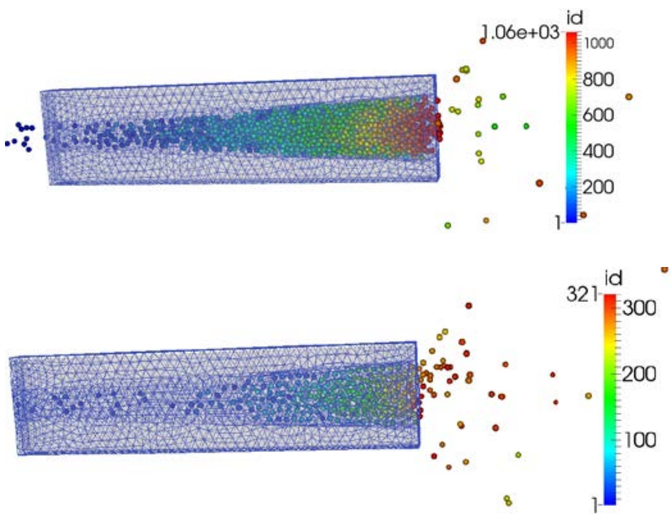

Figure 7- Concentration of 2.5 mm particles needed to plug the fracture (top) vs. Concentration of 5 mm particles (bottom)

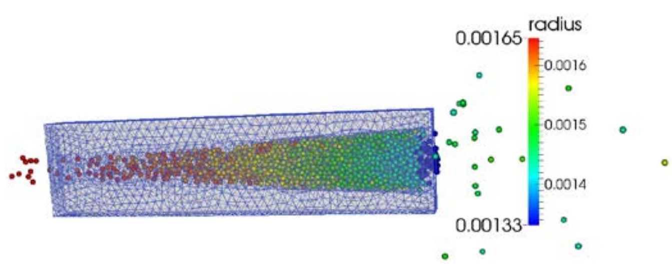

Figure 8- Radius expansion of the smart LCMs.

Conclusions

The smart expandable LCM shows promising results in sealing fractures efficiently and effectively by minimizing fluid loss. The LCM can be synthesized and programmed for any wellbore temperature and any fracture size. Concentration and LCM size should be selected according to the size of the fracture and no damage to production zones will occur since the smart LCM is acid-soluble.

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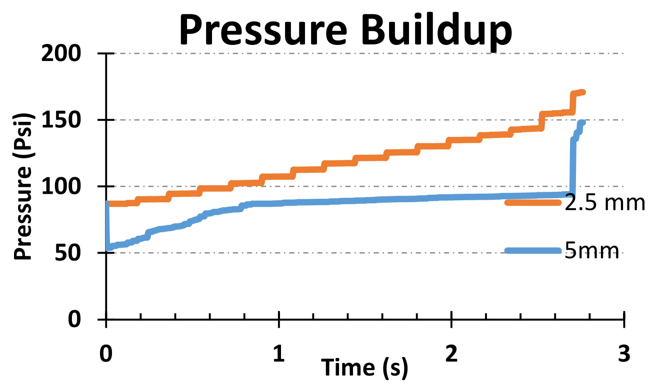

Figure 20- Pressure buildup caused by the fracture seal

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