An Insight on Gas Migration in Cement Slurry

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Abstract. The fluid invasion basically gas in the cement column is a worldwide problem. This is one of the main challenges of oil well industries to protect the wellbore from fluid invasion. This problem has recognized in the mid of 1970 and basic technologies associated with it has not changed significantly. The leakage of gas can cause to the catastrophic events such as blow out and contamination of adjacent aquifer layers leading to environmental concerns. Although much effort has been put forth on gas migration issues, but no efficient solutions have been established to control it. The main reason for this is some lack of understanding the phase behavior of cement slurry. This may be the reason for that there is no standard available till now for gas migration. This study reviews the various causes of occurrence of gas migration in the cement column. Moreover, this study provides a comprehensive insight on gas migration control additives, which is generally be used in oil well industries to protect the fluid invasion in cement slurry.

1. Introduction
Primary cementing operation requires placing of cement in the annular region between the metal casing and rock formation. A major issue after completion of the cementing operation is the invasion of gas from the formation into the cemented annulus resulting in uncontrolled flow of gas or fluid through the wellbore. The problem was first highlighted to industry by Carter and Slagle [1] in 1970 where they discussed the inability of a cement column to effectively maintain full hydrostatic pressure. Since then, several attempts have been made to study the gas flow in cements to achieve effective zonal isolation. Once the cement slurry is placed in the annulus, several processes begin to take place. The slurry begins to dehydrate due to a reduction in the liquid phase resulting in the formation of a gel phase. The gelation period is followed by setting process where cement hydration products begin to get packed in the cement matrix. During this process, the slurry gradually loses its ability to transmit hydrostatic pressure [2]. The pore pressure decreases and may lead to a situation where gas from the surrounding rock formation invades the cemented annulus. There are some other key properties of oil well cement (i.e., fluid loss, cement shrinkage, gel strength development, permeability, free-fluid, mechanical and chemical failure of cement sheath) which affect the invasion of gas migration. Some solutions for gas migration control have been proposed. Chritsian et al. [3] proposed using cement slurries with good fluid loss control property in order to mitigate gas migration. This may be achieved by the use of special fluid loss control additives that hold the liquid phase within the cement matrix during setting process thereby maximizing the slurry’s ability to transmit hydrostatic pressure. Griffin et al. [4] suggested the use of expansive cements that enable superior bonding and zonal isolation. Sabins et al. [5] indicated that the cement gelation period can be a crucial factor in preventing gas invasion into the annulus. A slurry with a shorter gel transition time changes from a fluid to a gel and finally to a solid state quick enough to prevent formation of gas channels in the
cement matrix. In this study, causes of occurrence of gas migration is briefly described. Further, an insight on the gas migration additives used in oil well industries is presented.

2. Causes of gas migration
The one of the main reasons for invading the gas migration in the cement column is imbalance hydrostatic pressure [6]. The hydrostatic pressure falls below the formation pore pressure due to gel strength development, fluid loss, and cement shrinkage [7]. Several researchers [8-11] also reported another reason for gas migration in the cement column are: cement permeability, free fluid, mechanical and chemical failure of cement sheath. The schematic diagram of occurrence of gas migration in typical oil well is shown in figure 1.

![Figure 1. Schematic diagram of gas migration problem in typical oil well [12].](image)

2.1. Gel strength development
The signal of development of gel strength start from the point at which the cement slurry begins to change from a true hydraulic fluid that transmit full hydrostatic pressure to a solid material that has measureable compressive strength [13]. Figure 2 shows the gel strength development of typical oil well cement slurry. As shown in figure 2, the slurry has sufficient fluidity in the fluid stage, and it maintains the higher hydrostatic pressure which is greater than the formation gas pressure. The hydrostatic pressure of cement slurry gradually decreases in the second stage (called gelled stage) with a simultaneous increase in static gel strength. The gas migration may occur if the hydrostatic pressure reduces below the formation gas pressure at point ‘A’ [14]. The static gel strength at point ‘B’ is generally about 50 Pa and when this value reach to about 240 Pa at point ‘C’, gas migration can be reasonably mitigated [14]. Once the second stage is complete the slurry starts to develop compressive strength at point ‘E’. The time taken by cement slurry to reach point ‘C’ from the point ‘B’ is distinct as gel transition time. Thus, the potential of gases to invade in cemented annulus can be reduced by decreasing the gel transition time. However, the effect of gel transition time on gas invading is still not fully understood.

2.2. Fluid loss
Fluid loss is the leakage of liquid phase in the cement slurry under static (e.g. during tripping) and dynamic (when mud is circulating in the hole) conditions [15]. Excessive fluid loss decreases the hydrostatic pressure and contribute to provide the space in cement column for gas to enter [16]. American Petroleum Institute (API-10B) standard has described the limit of fluid loss (i.e., 50 mL / 30 min) which is often required to maintain adequate slurry performance. However, the fluid loss in the
cement slurry can be reduced by fluid loss additives such as bentonite, water soluble polymers, cationic polymers, cellulose derivatives, carbonate powder, latex, asphaltenes, thermoplastic resin etc.

![Diagram showing pressure at depth of interest and post-placement time](image)

**Figure 2.** Gel strength development of typical oil well cement slurry [14].

2.3. Chemical shrinkage

The chemical shrinkage in oil well cement is divided into two types; (i) external shrinkage, (ii) total shrinkage. (i) The external shrinkage describes the bulk volume change of the cement slurry leading to a possible micro-annulus between the slurry and borehole wall; (ii) total shrinkage is the sum of contraction pores of the slurry and external shrinkage [17]. Numerous researchers [17-19] investigated the chemical shrinkage of oil well cement and they reported that the total shrinkage is varying from 0.6 to 6 Vol. % at 24 hours in the cement slurry. Backe et al., [17] observed that there is a close correlation between cement content and total chemical shrinkage. A low shrinkage and a short transition period can reduce the risk of gas migration. Pang et al. [19] reported that the total chemical shrinkage increases drastically with increasing the curing temperature, especially during early ages. Vu et al. [20] concluded that first chemical shrinkage occur then, swelling and autogenous shrinkage can occur, and their magnitude depend on degree of hydration, fineness of cement, w/c ratio and additive types.

2.4. Cement permeability

Permeability is the state of material which allow fluid (liquid or gas) to flow through it. The low permeability in the cement is one of the important criterion in the oil industries as permeability governs the flow of any external invading fluid [11]. Many researchers reported that the cement permeability is also a potential factor in gas migration incidents. However, cement permeability can be mitigated by use of additives. Sutton et al. [21] conducted various permeability test and found that the maximum cement permeability of 12 mD and that can substantially reduce by adding polymer fluid loss control additives. Goode [8] reported that permeability is not appeared to be a major factor at low temperatures because no measurable permeability has observed after certain period of time. Researchers [8, 21] emphasized that the other properties of cement particularly the fluid loss, gel strength and flow characteristics should be considered for gas migration properties.

2.5. Free fluid

Free fluid in the slurry pore can make the easy path for formation of gas or fluid. Many researchers [9-10] studied the effect of free water on the gas migration, giving inconsistent statements. Webster and Eikerts [9] observed that the free water in cement column has reduced the effective hydrostatic
pressure which can make a path through the gas may migrate. On the contrary, Tinsley et al. [10] reported that the free water would not be a significant effect on invading of gas migration.

3. Gas migration theory
Several experimental and theoretical models have been presented to determine static gel strength and gas migration in cement slurries. Li et al. [22] attempted to predict gas migration potential based on the static gel strength and hydrostatic pressure reduction. Okoli [23] presented a model to evaluate slurry designs for effective zonal isolation and gas flow mitigation. These models utilize the static gel strength theory to describe gas flow potential at cement/formation or cement/metal interfaces. The hydrostatic pressure is dependent on the gelation tendency of the cement slurry and changes in hydrostatic pressure affects the ability of the cement column to restrict gas flow. Vazquez et al. [24] discussed a methodology in which the main parameters in evaluating gas migration are Flow Potential Factor (FPF) and Static Gel Strength (SGS). FPF is defined as [21]:

\[ FPF = \frac{MPR}{OBP} \]  

(1)

where, MPR: Maximum pressure restriction (psi), OBP: Hydrostatic overbalance pressure (psi)

The MPR is based on the pressure restriction due to SGS. For a general case, the pressure restriction due to SGS is defined as [21]:

\[ P = \frac{(SGS \times L)}{(300 \times D)} \]  

(2)

where, SGS: Static Gel Strength (lbf/100ft²), L: length of cement column (ft), D: Difference between open hole diameter and casing diameter (in).

A SGS value of 500 lbf/100ft² is usually considered to be the strength sufficient to prevent fluid invasion through the cement column. In this situation, the pressure restriction due to SGS is at its maximum and equation (2) becomes [21]:

\[ MPR = 1.67 \times \frac{L}{(\text{dhole} - \text{dcasing})} \]  

(3)

where, dhole: diameter of open hole (in), dcasing: diameter of metal casing (in).

Therefore, the FPF ratio as described by equation (1) can be used to evaluate fluid migration potential and the severity of gas flow potential can be determined from table 1 [25]:

| FPF | Severity Rating |
|-----|----------------|
| < 4 | Minor flow     |
| 4 – 8 | Moderate flow |
| > 8 | Severe flow    |

4. Gas migration control additives
This is the area in oil well industry that required more attentions as there are no specific details are available for use of gas migration control (GMC) additives. However, API STD 65 [26] has briefly described the need of GMC additives but specific details are not given. Researchers have used the following additives for gas migration.

4.1. Bentonite
Bentonite is a clay generated material frequently used in oil and gas industry due to its high swelling properties and low permeability for various applications. Few researchers have used the bentonite to mitigate the gas migration in the cement slurry. Ramadan et al. [27] have used the bentonite with latex additives to prevent the gas migration and reduce the fluid loss in cement slurry and observed that the gas transit time is decreased by 62 % with an increase in temperature.

4.2. Silica fume
Silica Fume is one of the common gas migration additives. A very fine (grey colored) non-crystalline silica produced in electric arc furnace as a by-product of the production of elemental silicon metal or ferrosilicon alloys. Silica fume particles are very small, with maximum particles size less than
1 µm (100 times finer than cement particle) with high specific surface area 20 m²/g [28]. Various researchers [29-30] have studied the application of silica fume for mitigation of gas migration and concluded that silica fume is very effective for gas migration. Skalle and Sveen [29] reported that micro-silica is effective for gas migration for temperature up to 150°C. Daou and Piot [30] observed that only moderately compacted micro-silica with a bulk density of approximately 300 kg/m³ would be helpful in developing a good cement performance.

4.3. Latex
Latexes are aqueous dispersions of polymer particles (such as surfactants) which imparts stability to the dispersion [31]. Latex is most commonly additives used for gas migration. Most latexes, however, can lose their elastic ability and become brittle at higher temperatures (> 160°C) [29]. Latex fills the pores in OWC slurry and decrease the permeability of the cement. The most common latex are vinylidene chloride, poly-vinylacetate, and styrene-butadiene.

4.4. Carbon black
Carbon black is a product of incomplete combustion of coal tar or ethylene cracking tar in the form of paracrystalline carbon which can be used as gas migration additives. The range of the particle size of the carbon black is 10 to 200 nM. Calloni et al. [32] reported that carbon black (4 % by weight of cement) is sufficient to control gas migration in all formulation.

4.5. Hydroxypropyl methylcellulose (HPMC)
HPMC is a cellulose based gelling agent which can be used for gas migration agent. Abbas et al. [33] reported that HPMC can create an impervious barrier for water and prevent the gas migration in the wellbore hole.

5. Conclusions
A comprehensive review on causes of occurrence of gas migration and additives used in oil well industries to control this problem in the wellbore is discussed. The following conclusion is drawn based on review.
1. The invasion of gas can be prevented by keep the cement pore pressure more than the formation gas pressure.
2. The phenomenon of gas migration is believed to occur during the transition state between initial and final set of the cement.
3. The invasion of gas into cement matrix can be prevented by use of suitable polymeric materials and additives in the cement slurry to immobilize the fluid within the pore spaces.
4. The additives such as bentonite, silica fume, and latex are generally used in oil industries to control the gas migration.
5. More research work is required to fully understand the phenomenon behind the occurrence of gas migration in cement column and its solutions.

6. References
[1] L. G. Carter, and K. A. Slagle, SPE-3164-PA, 1170-74 (1972).
[2] P. R. Cheung and R. M. Beirute, J. Pet. Tech., 37 (6), 1041-1048 (1985).
[3] W. W. Christian, J. Chatterji, and G. W. Ostroot, J. Pet. Tech., 28 (11), 1361-69 (1976).
[4] T. J. Griffin, L. B. Spangle, and E. B. Nelson, Oil and Gas J., 143-51 (1979).
[5] F. L. Sabins, J. M. Tinsley, and D. L. Sutton, “Transition time of cement slurries between the fluid and set state,” SPE technical conference and exhibition, Dallas, US (1980).
[6] P. M. Mohammad and J. Moghadasi, SPE-105663-MS, 1-8 (2007).
[7] H. Justnes, D. Van Loo, B. Reyniers, P. Skalle, and J. Sveen, Advan. Cem. Res., 7 (26), 85–90 (1995).
[8] J. M. Goode, J. Pet. Tech. 14 (08), 851–54 (1962).
[9] W. W. Webster and J. V. Eikerts, SPE-8259-MS, 1-8 (1979).
[10] J. M. Tinsley, E. C. Miller, F. L. Sabins, and D. L. Sutton, J. Pet. Tech., 32 (8), 1427–37 (1980).
[11] S. Appleby and A. Wilson, Chem. Eng. Sci., 51(2), 251-267 (1996).
[12] K. Muehlenbachs, http://www.frackingcanada.ca/industrys-gas-migration/ (Accessed 9 November 2019).
[13] J. Moon, and S. Wang, SPE 55650-MS, 1-10, (1999).
[14] N. Lee, A. Prabhakar, O. K. C. Gary, J. Moon, M. H. Zhang, C. H. A. Cheng, H. Klaus, and K. K. Hau, Const. Build. Mater., 191, 1093-1102 (2018).
[15] O. John, Amer. J. Eng. Res., 6 (8), 136-151 (2017).
[16] Z. Li, J. Vandenbossche, A. Iannacchione, J. Bringham, and B. Kutchko, SPE Drilling & Comp., 31(2), 145–58 (2016).
[17] K. R. Backe, P. Skalle, O. B. Lile, and S. K. Lyomov, J. Can. Pet. Tech., 37 (1998).
[18] M. E. Chenevert and B. K. Shrestha, SPE Drilling Eng., 6, 37-43 (1991).
[19] X. Pang, C. Meyer, G. P. Funkhouser, and R. Darbe, Const. Build. Mater., 74, 93–101 (2015).
[20] M. H. Vu, A. P. Bois, and A. Badalamenti, SPE-189384-MS, 1-24, (2018).
[21] D. L. Sutton, F. Sabins, and R. Faul, Oil Gas J., 82,1984.
[22] Z. Li, J. Vandenbossche, A. Iannacchione, J. Bringham, and B. Kutchko, SPE Drilling & Comp., 31, 1-14 (2016).
[23] U. Okoli, SPE-193490-MS, 1-12 (2018).
[24] G. Vazquez, A. M. Blanco, and A. M. Colina, SPE-94901-MS, 1-9 (2005).
[25] E. Nelson, “Well Cementing,” Schlumberger Dowell, Sugar Land, Texas, 1990.
[26] API STD 65-2, Standard for isolating potential flow zones during well construction, American Petroleum Institute, (2010).
[27] M. A. Ramadan, S. Salehi, G. Kwatia, C. Ezeakacha, and C. Teodoriu, J. Pet. Sci. Eng., 179, 26-35 (2019).
[28] E. Grabowski and E Gillott, Cem. Concr. Res., 19, 333-344(1989).
[29] P. Skalle and J. Sveen, SPE-23075-MS, 1-12 (1991).
[30] F. Daou and B. M. Piot, SPE-112701-PA, 24, 1-9 (2009).
[31] G. Kwatia, C. Ezeakacha, and S. Salehi, “Literature report of elastomer sealing materials and cement systems,” BSEE Project No.: E17PC00005, 1-78 (2017).
[32] G. Calloni, N. Moroni, and F. Miano, SPE-28959-MS, 1-9 (1995).
[33] G. Abbas, S. Irawan, S. Kumar, M. N. Khan, and S. Memon, SPE-169643-MS, 1-10 (2013).

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