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Review Article

Comprehensive Review on Gas Migration and Preventative Strategies through Well Cementing

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ABSTRACT

Hydrostatic pressure less than pore pressure and the existence of a path to gas migration are two major factors that must be stopped simultaneously to prevent migration. Understanding the mechanisms of cement hydration in early times is necessary to investigate these factors. Cement hydration can lead to swelling and shrinkage at the same time. At the beginning of cementation chemical shrinkage occurs, followed by swelling and autogenously shrinkage, and the degree of hydration, the water-cement ratio and the fineness of cement. The most important factors that make the annulus pressure less than the pore pressure are: cement placement, Cement hydration in liquid state, and Cement hydration in solid-liquid state.

Keywords: Well Cementing; fluid migration; Rheology; preventing strategies; Nano-silica

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Introduction

Regarding the drilling operation, the cement slurry is prepared through combining raw cement along with water and required additives which is injected down the casing and then up to the annulus space [1]. Supporting and holding the casing, isolate the formation are some of main purposes of well cementing [2]. Additionally, it hinders unfavorable formation fluids migration through annulus space [2, 3]. The majority of hydrocarbon fields throughout the world have experienced traces of gas migration through annulus which may lead to many detrimental challenges to the well health [4]. The main provoker which causes gas phase to intrude into the annulus space is attributed to the channeling mechanism within the cement which is caused as a result of improper cementation operation [5]. Cement is utilized in ranges of temperature between 0 ^oC in Permafrost and 100 ^oC in some secondary recoveries [6, 7]. The cement quality behind the casing implements a significant role both through primary cementing and also through stimulation and work-over jobs [7]. The cement strength which is employed in oil wells mainly rely on some parameters including time and curing conditions [8, 9],environmental factors [10, 11], slurry and additives design program [12] and any extra treatments in which the formed cement mixtures are exposed [13, 14]. To make more appropriate cement slurry, both calcium chloride and sodium chloride are mainly employed as accelerator agents so as to lower the cement setting time. Moreover, Barite or Hematite as weighting agents are extensively utilized to improve cement slurry density [11, 12]. Considering the deep wells in which temperature is very high, early cement hydration occurs which leads to quick setting of cement and subsequently undesirable cementation and channeling throughout the cement [15, 16]. The major challenges of cementing is migration of fluids throughout the annulus after well cementing has brought many problems, ignoring or failing in migration control will lead to catastrophic happenings including blowouts [17]. Gas migration involves a quarter of failures pertinent to the primary cement operations.[18]. Therefore, as the purpose of saving the well and refraining operationally hazardous and challenging remedial cementing, the slurry had better to be optimized and resistant rather gas migration issues [19].

Theory and reviews

Conditions for gas migration: The most important conditions to occur annular gas migration are: **1.**The annulus hydrostatic pressure has a less or an equivalent value compared to the pore pressure **2.** Annulus space allows the entrance of gas and **3.** A path is available through the annulus in which gas migration occurs. If one of the conditions is eliminated, gas migration will stop [15, 20-24].

Gas migration types: Generally three sorts of gas migration have been classified in literature:

Immediate gas migration: This type of migration is primarily observed during cement placement, between commence of the cementing job and the final step of cement placement. The best solution to mitigate the challenges is to employ preventive actions [7, 21 and 25].

Short-term gas migration: This type of migration which is usually referred to as post-placement migration, is observed between the final step of the primary cementing job (usually highlighted by the plug landing) and the cement setting step. However, the procedure which triggers the migration is assumed to be the annular pressure decay [7, 22].

Long-term gas migration: This type of migration is normally observed after the complete setting of cement, which might happen within several hours after the cement job accomplishment. Long-term migration is now attracting much more interest because of soaring number of Plug and Abandonment operations[17].

Effective parameters of gas migration

Different parameters implement various roles regarding gas migration issue. It must be regarded that we are not able to control some of these factors through the optimization of slurry phase [19]. The most important factors affected on gas migration are shown in table 1.

Table 1. Factors affecting gas migration

	Annular pressure ≤ pore pressure	Entry space	Migration path
Immediate	Hydrostatic underbalance	Fluid displacement from wellbore	Fluid displacement from wellbore
Short term	Fluid loss	Fluid loss	Slurry permeability
	Gel strength development	Free fluid	Slurry permeability
	Chemical shrinkage of cement	Chemical shrinkage of cement	Filter cake permeability
	Annular bridging	Slurry porosity	Filter cake permeability
	Annular packers	Slurry porosity	Filter cake permeability
Long term	Chemical shrinkage of cement	Chemical shrinkage of cement	Micro annulus
		Mud channel	Mud channel
		Free fluid	Free-fluid channel
	Strength development of cement	Dehydrated filter cake	Dehydrated filter cake
		Bulk shrinkage of cement	Bulk shrinkage of cement
			Low cement tops
			Cement sheath mechanical failure

Fluid loss: Any reduction in the amount of cement in the hydrostatic head reduces entire cement column, which allows gas to enter the slurry. In order to diminish gas penetration and also cement permeability risks, the API fluid volume in high pressure/high temperature should be less than 50 ml for 30 minutes. It is regarded as one of the most important factors which contribute to gas migration. Fluid loss consequences which may impact it are: **1.** Decrease in hydrostatic column height as a result of slurry-volume reduction. **2.** Increase in slurry gelation characteristics as a result of diminished slurry water content. **3.** Annular bridging. **4.** Losses in friction-pressure through the compaction stage as a result of slurry volume reduction. API fluid loss rate reduces to lower than 50 mL/30 min, the invasion risks and consequent hazards would remarkably diminish [24].

Development of Gel Strength: Any decrease in the volume of cement slurry caused by fluid loss and hydration phenomena will be offset by the downward movement of the cement slurry due to the slurry. After pumping the cement into the wellbore and allowing being in static form before setting, the development of gel strength commences. Through various tests pertinent to Static Gel Strength (SGS), it was found that the value of 500 $lbf/100ft^2$ would be resistant against the fluid invasion for gelled type cement. Therefore, the required time for SGS to reach from 100 lbf/100ft^2 to 500 lbf/100ft^2 is referred to as the transition time [7].

Thixotropic Cements: Thixotropic cements with high gel strength are resistant to gas migration. Several experiments show that short transition time and temperature have no effect on strong thixotropic cement slurry so it can eliminate fluid channeling and gas migration in cementing process. Mixture of acid-thixotropic cement tested according to API RP 10B2 in order to evaluate gas migration durability, these evaluations indicate more improvement in gel properties compared with thixotropic cement without acid.

Cement shrinkage: This phenomenon comes from cement hydration process, which is also referred to as chemical contraction of cement. Final chemical shrinkage is often split throughout a matrix internal contraction, which is approximately equal to 2%, also a bulk shrinkage ranging from 4% to 6% by cement slurry volume. Various studies and investigations argue the degree of hydrostatic pressure decline as a result of cement shrinkage. Amongst the most novel researches, one was carried out in which reported that the reduction in annular pressure is not affected by chemical shrinkage. AMPS copolymers fair extent be considered as a very effective substitute to design gas tight slurries and styrene butadiene latex effectively reduce permeability, Baroghel-Bouny et al explained that the cement which has water-cement ratio above 0.40 swells in the first days before shrinkage occurs whereas Horita et.al observed that shrinkage will happen after swelling for water-cement ratio between 0.4 and 0.5. Mounanga et al. indicated that there is a critical point (7% degree of hydration at 0.4 water-cement ratio) to identify type of cement shrinkage it concluded that chemical shrinkage rate will increase after this point and the autogenous shrinkage before this point same as chemical shrinkage, this is due to calcium hydroxide precipitation [23]. When water-cement ratio is equal to 0.6 swelling occurs because of calcium hydroxide, Aft and AFm large scale crystals [11] this is corroborate Barcelo investigations which show lime as main reason of cement swelling [12], while Pichler et al. concluded that swelling phenomena is just because of tricalcium aluminate [9].

Permeability: Cheung and Beirute were pioneers of proposing a mechanism for gas migration. They carried out their experiments by conducting some laboratory investigations in which the gas primarily invaded the cement pores and ultimately penetrated the entire cement matrix which greatly hindered and prevented the hydration process and thus a migration path was established [8]. Afterwards, Parcevaux (1984) highlighted the theory by carrying out a research upon cement slurries and investigating the pore-size distribution while thickening and setting periods. It concluded that at beginning of setting time connected pores started to appear. enlargement of pores occurs and pores communication develops after initial invasion of gas [18]. All-Yami at 2009 designed a new cement formulation with high density which can prevent gas migration by permeability reduction. Experiment results show that Hematite and Manganese Tetroxide with equal concentration significantly reduce fluid loss through the cement blocks. Also utilizing latex (in gas block additive form) more than 3.5 gallon per sack improves the results [19].

Mud removal: Mud removal is very important in cementing job for obtaining proper zonal isolation. used a new designed fiber to pre-flush cementing fluids and concluded that nonaqueous removal significantly improve from the well when fiber was used through cementing operations[4]. Chun researched on Nano Emulsion to remove filter cake and non-aqueous drilling fluids. Results of this study indicated that technology of Nano Emulsion able to decrease interfacial tension between oil and water below 0.001 mN/m. which can significantly reduce mud removal problem 6]. It can be use acid with Nano Emulsion simultaneously to eliminate calcium carbonate and filter cake. Advantage of these natural source, easy handling, nontoxic and bio degradable emulsions are free of toluene and benzene [14]. Also Juan used seven surfactants with different formulations of maximum concentration of 10 percent in volume of spacer which achieved to same results [22]. Recently smart unconventional biomaterials used to oil based drilling fluid removal. It is determining bonding strength between casing and set cement to verifying proper cleaning efficiency of mud contaminations [11].

Casing/ Formation Interface (micro annulus): The phenomenon of gas migration may even occur through micro annulus, which is expressed as infinitesimal gaps that might be created between the casing and liner and also around the cement sheath 9]. It also can be formed between cement sheath and formation post setting [17]. Pressure and temperature variations during or after cementing operations can expand or contract the steel casing both in length and diameter values can intense micro-annulus and will cause deformation [19]. The contraction of cement after the primary setting is approximately a few tenths of a percent and it does not seem to establish a remarkable continuous annulus [9].

Latest 270 000 operating wells data review show that, 6% of wells were recognized to contain leaks, 0.5% of them having gas migration and 5.5% having surface casing vent flow in micro annulus. HPT logging coupled with SNL logging assist accurately identifying gas migration in micro annulus and source of fluid leakage [2].An experimental investigation conducted on micro-annuli cell coupled with pressure and strain gauges to evaluating leakage rate in order to improve micro-annulus interpretation, the results show that in linear elasticity regime, test cell radial deformation is proportional to micro-annulus pressure and maximum pressure gradient located in micro-annulus outer part. Size of micro-annulus correlated to rate of leakage by utilizing a model coupling radial deformation to pressure inside the micro-annulus, this modeling and prediction are compared with experimental results [1].

Cement sheath Mechanical failure: In case that compressional and/or tensile stresses violate the maximum possible values designated to prevent the formation of micro cracks in cement or local near casing crushing (shear failure), sufficient space for gas entry or gas migration path will be created [3]. Tectonic stresses, subsidence and formation creep can the key factor which cause cement loading [13]. Shadravan studied on cement fatigue cycle by conducting several experiment on different type of cement blocks. In these experiments, temperature and pore pressure are constant at 330F and 15,000 psi. Experiment results and calculations indicated that primary failure in cement blocks in all cases was radial failure which is implemented in high pressure and temperature conditions [12]. Skorpa et.al designed a setup to evaluate cement sheath integrity in presence of mud contaminations their results show that in cases which have mudfilm, radial cracks not to develop and propagate [9]. It can be used low concentration (less than 5 wt%) gypsum in order to adsorbing energy and reducing mechanical failure [3].

Strategies and solutions to prevent and combat the migration of gas

Thousands of research and millions of dollars spent on understanding the mechanics of fluid (specially gas) migration and developing solutions, it leads to a wide range of different strategies that describe different aspects of gas migration phenomena. Experimental investigation and case studies to provide practical advice [20], technical solution development [3], application of different cement additives in cement slurry [1] and prediction technique for cement quality [2] are number of strategies are studied by researchers. For example Use of nanoparticles additives of cement slurry, especially Nano silica in some condition has mitigated gas migration through modification in cement setting profile, gel strength development ,hydration process and cement microstructure [1]. Another effective additives for this purpose which produced by Halliburton are D-series additives, include D-193, D-700, D600, D-500 and D-400 which used for low- and medium-temperature, high temperature, medium temperature, low temperature and cold environments respectively. Also an innovative additive for fluid loss prevention and weighting the cement slurry is UNIFLAC. This fluid-loss additive is a cost-effective and universal solution for fluid-loss control for all cementing applications. The additive is a custom-made third-generation solid polymer that can be pared solved in the mix water or dry blended with the cement. Its robust properties make slurry design very simple and produce predictable results in the field from the surface casing to the liners [3]. All the approaches and strategies utilized to minimize the gas migration risks primarily rely on targeting one or multiple gas migration conditions, including the control of annular pressure decline, reduction of gas entry space, and ultimately minimizing the migration path. As a result, techniques and approaches to mitigate the mentioned challenges are typically categorized in three different classifications regarding the target conditions during the timeframe of different types of gas migration, as brought in Table 2.

Low Permeability cement slurries

This strategy primarily highlights declining the cement matrix permeability while liquid-to-solid transition period and mainly focuses on the third condition. Normally, low permeability is met by blending certain additives with the slurry of cement. CMC and some other additives added to G class cement in one of south Iranian oil field which show proper reduction in cement permeability [4]. In order to prevent CO_2 corrosive effect on set cement an acid-base calcium cement prepared for the first time in china. After 7 days of exposure to an solution with 700 psi and 212F CO_2 the yield is equal to 0.63% while class G cement under similar conditions has yield equal to 16.54% of carbonation rate [5]. Micro silica exhibit much more rigorous bonding properties, and thus smoothly increases the cement strength and less strength retrogression [6]. It must be denoted that similar gas migration prevention characteristics are introduced for Gas Con additive [2].

Table 2. Technique and approaches to prevent gas migration

	Annular pressure ≤ pore pressure	Entry space	Migration path
Immediate	**Fluid density**	**na**	**na**
Short term	**Right-angle-set cement**	**Low porosity cement**	**Packers**
	Sandwich squeeze	**Low porosity cement**	**Sandwich squeeze**
	Compressible cement	**Compressible cement**	**Low permeability cement**
	Fluid density	**Compressible cement**	**surfactant**
	Thixotropic cement	**Low fluid loss cement**	**Thixotropic cement**
	Low fluid loss cement	**Low fluid loss cement**	**Thixotropic cement**
	Back pressure	**Zero free water cement**	**Low permeability filtercake**
	Annular pressure pulses	**Zero free water cement**	**Low permeability filtercake**
Long term	**na**	**na**	**Packers**
	na	**na**	**Compressible cement**
	na	**na**	**Expensive cement**
	na	**na**	**Flexible cement**
	na	**na**	**Mud removal**
Na: not applicable			

Right Angle Set Cements: Cements slurries of Right Angle Set (RAS) type are explained as systems which do not exhibit continuous gelation tendency through the placement of slurry which is typically followed by rapid slurry viscosity at the final time of designed pumping schedule. Gel properties of cement with RAS cannot be expanded exponentially and quickly while quickly forms a low permeability matrix that prevents gas infiltration. The design of the RAS slurry is difficult for temperature ranges lower than 250 Fahrenheit since rapid gel development process is mainly dependent upon temperature parameter. Prabhakar experimentally tested sulfur aluminate (CSA) and gypsum cement to evaluate RAS and gel strength properties of new formulation cement slurry, results show in high content CSA cement slurry transition time for gel decreases whereas gel strength development increased [7]. Proper set cement properties can be reached only by using moderately compacted micro silica which has about 300kg/m^3 bulk density. Popular and ease handling micro silica do not provide effective performance to prevent gas migration [6]. Ramirez designed a new Sorel technology cement slurry without utilizing Portland cement which play an important role in cementing operation performance enhancement [8].

Expandable Cements: Small distances between cement and formation can lead to gas migration, expandable cement help to eliminate these distances and prevent gas migration [9]. However, expandable cement cannot remove large channels [8]. The main components of expandable cement include: calcium alumni ferrite-type, sulphur aluminate-type, aluminate-type, and silicate-type [1]. Expanding and hardening of silica expandable cement is slow, however aluminate expandable type is fast [7]. This approach highlights the third condition of gas migration by preventing the formation of micro annulus in long term considerations [2].

Foam cement: Foam cements are made by mixing base cement with one or more foaming agents and adding a gaseous phase (generally nitrogen) to the cement slurry [5]. The purpose of utilizing foam cement is to provide high strength but also low weight cement slurry [6]. Density of this type of cement depends on the density of the components of the cement mixture [8]. Preparation and designing of foam cements is not possible with the addition of just a few additives and requires sophisticated technology. The results of field experiments have shown that foam cement can be used effectively to eliminate the problem of zone isolation [5]. The mechanism of preventing gas migration by foam cement does not exactly cover the specific time frame of gas migration but experience has shown that it can be useful at all three migration times [6]. The primary advantages of foam cementing rather conventional mitigations that might be practical to diminish migration problems are: enhanced toughness, impact resistance eliminating loss circulation and influx controlling of water and gas [3]. Well-dispersed nitrogen bubbles contribute to compensate the adverse impacts of hydration chemical shrinkage. Regarding the conventional design, bulk shrinkage is typically a significant value whereas it is a reduced for foam cement systems [7].

Self-healing cements: One of the recent achievements in cementing operations is self-healing cement (SHC) concept which mainly targets the long term gas migration condition. A hydraulic barrier fast and automatically forms by swelling during exposure to formation fluids [4]. Slurry design and required self-healing substances to optimize it with a regard to target hydrocarbon compositions are the challenges in this strategy [5]. Rheology control agent such as friction reducer, working time controlling agent (retarders) and fluid loss control agents are the most common component to designate self-healing cement [15].

Applied Annulus Pressure: Pressure of pumping fluid that exerted on annulus surface can effectively prevent gas migration. The pressure should be applied immediately after the wiper plug is inserted and at least until the cementing is operational [14].

Surfactants: Surfactants added to the cement slurry and enter the migrating gas and provide a stable foam. This foam withstands the migration of gas from the slurry [16]. The surfactant slows the movement of the gas by converting the gas into a immobile fluid and viscous foam [17]. The addition of surfactant also reduces the slurry surface tension, thereby preventing the bubble from shrinking and moving. The combination of these two mechanisms together with the appropriate slurry design greatly reduces the risk of gas migration after cementation [20].

Discussion: This section discusses the most important condition and prevention strategies related to gas migration developed by researchers and companies. In order to cope with the gas migration from the conditions mentioned in the preceding sections, it must be ensured that the two main conditions do not occur simultaneously:

1. Hydrostatic pressure in the annular space should be less than or equal to the pore pressure

2. There must be a path to gas migration or must be created.

Investigation of these two conditions requires a good understanding of the initial hydration mechanism of the cement [19]. There is a common view that cement hydration causes shrinkage, but some researchers have suggested that this phenomenon also causes cement swelling, therefore, both of them occur simultaneously [14]. Research results show that at the beginning of cementation chemical shrinkage occurs, followed by swelling and autogenously shrinkage, and their intensity depends on the type and amount of the cement additives, the degree of hydration, the water-cement ratio and the fineness of cement. The results of Baroghel et al. studies indicated that addition of silica fume at water-cement ratios below 0.45 leads to diminish swelling and a remarkable increase in cement shrinkage [3]. There are two main mechanisms for reducing pressure inside the annular space: preventing vertical displacement of cement and reduction of cement volume [21]. The most important factors that make the annulus pressure less than the pore pressure are: 1. cement placement (static and dynamic pressure may be less than pore pressure because of low density cement) 2. Cement hydration in liquid state (height reduction of cement column, bridging in annular space and growth in gelation properties of cement slurry can happen because of severe fluid loss and vertical displacement can be controlled by gel strength development) [2]. 3. Cement hydration in solid-liquid state (In order to counteract vertical displacement of cement, factors such as heterogeneous bonding and cement hydration should be considered). The most reasons is as follows [13]:

1. Cement thickness alteration through the well: (because of tool joints, heterogeneous mud cake, caving etc.), due to the fact that sheath thickness proportional to hydration rate.

2. Locally high rate fluid loss: which lead to form thick cake and prevent vertical displacement of cement slurry.

3. Geothermal gradient: is not uniform so it can affect the cement bonding.

4. Local hydration exposed to formation water: drained or un drained formation near the cement in hydration time can increase and decrease cement volume respectively.

5. Heterogeneity in cement batch

In addition to all the above mentioned conditions, there must be a path for fluid flow (gas migration). There are different type of pathway to migration based on well geometry [4], 1. Cement-casing interface, 2. Formation-cement interface, 3. Channel through the damaged layer and 4. Chanel throughout the time of slurry placement. The main reasons that can form cement channels and their mechanism are shown in table 3.

Table 3. Main reasons for creating cement pathway

Main factors	Causes	mechanism
Hydration in liquid state	**High rate fluid loss**	**Gas expansion and buoyancy effect can creating channels to gas migration**
Hydration in solid state	**a. wellhead pressures changes b. formation fluid density changes c. temperature changes**	**Formation of micro annulus and cracks in the cement**

cement placement	**a. low casing standoff** **b. poor well fluid displacement** **c. shrinkage or dehydration of mud in the cement channels**	**Residual channels created by mud in cement may act as a pathway**

Conclusion

Effective parameters on gas migration are: fluid loss, gel strength development, cement shrinkage, permeability of cement sheath, mud removal, migration pathway, cement sheath mechanical failure and using thixotropic cement. Application of low permeable cement, right angel set cement, expandable cement, foam cement, self-healing cement, annular space pressure control and surfactant are strategies and solution to prevent gas migration.

In order to cope with the gas it must be ensured that the two main conditions do not occur simultaneously: hydrostatic pressure in the annular space should be less than or equal to the pore pressure and there must be a path to gas migration or must be created. Investigation of these two conditions requires a good understanding of the initial hydration mechanism of the cement.

At beginning of cementation chemical shrinkage occurs, followed by swelling and autogenously shrinkage, and their intensity depends on the type and amount of the cement additives, the degree of hydration, the water-cement ratio and the fineness of cement. There are three main mechanisms that control the cement deformation during hydration: chemical shrinkage, structural swelling due do large crystals, and self-desiccation shrinkage. They are in concurrence and the structural swelling is dominant at early time and at high w/c ratios. In other words, the autogenously deformation of cement depends upon hydration degree and w/c ratio.

There are different type of pathway to migration based on well geometry 1. Cement-casing interface, 2. Formation-cement interface, 3. Channel through the damaged layer and 4. Chanel throughout the time of slurry placement.

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