Minimized Leak Casing for Shale Gas Exploitation

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Abstract- **The goal of present study is to determine most impermeable structure against shale gas leaks around extraction wells. This rests upon double tubing and the possibility to guarantee the distance in between the two tubes all along their path underground for injecting a protecting sealing cement in the interval domain between the two tubes. Proposed insertion strategy consisting in mounting a four rolling balls ring at the head of each inner tube segment has been discussed. During insertion the balls are rolling (and sliding) on inner surface of outer tube. Most favorable conditions for simultaneous longer rolling contact and buckling and deformation avoidance during inner tube insertion have been set up to establish the proof of principle of present strategy. They are explicitly fixing the acceptable window value of pushing insertion force and the minimum value of inner tube thickness so that the operation can be safely conducted in terms of all other system parameters. Global casing optimization by studying different materials, junction types and full system architecture will be discussed elsewhere.**

Keywords: **Shale Gas Exploitation, Double Tubing, Rolling Inner Tube Insertion, Gas Leaks**

I. INTRODUCTION

Exploitation of conventional energy sources has been bouncing up with technical development of hydraulic fracturing allowing economically viable access to enormous shale and tight gas potential, the first one being mostly found trapped in layers of sedimentary shale rocks, the second one in sandstone or limestone formations with relatively low permeability. Even if some potential sources can be deemed uneconomic at some time, improved recovery techniques and higher commodity prices are causing a re-evaluation of these discoveries and their review by exploiting companies. Practically, shale gas and tight gas sources are found at depths between 2 – 5 kilometers below ground surface. They require sophisticated process for full exploitation such as hydraulic fracturing and horizontal drilling techniques to extract the trapped natural gas due to the particular rock characteristics where the gas is located [1].

Independent of process complexity which has to be driven according to a well-defined sequence with carefully designed proportions of elements in injected hydrofrac fluid and adequate drilling mud [2], a main practical issue in shale gas exploitation is the gas leaks at the origin of possible large groundwater contamination [3]. They are resulting from cracks formation in the casing which generate fissures through which the gas can migrate outside pumping system. The fissures are mainly due to hydraulic fracturing process, used to crack the rocks containing the shale gas, which needs a very high applied pressure, starting at 330 bars, in conjunction with the large stresses on the tubing itself due to the applied flexion-torsion forces [4-6] for following prescribed non rectilinear trajectory to reach the shale source. During exploitation, the constant pressure applied by the ground on the casing, combined with natural ground movements, can also cause stresses on it.

The goal is to find by comparison of already existing ones the casing with best impermeability against horizontal leaks. This is based on a review of preparation operations before exploitation which include three main steps: 1) the drilling phase and the outer tube setting 2) the insertion of (smaller) inner tube through which the fracking fluid is injected underground to the selected location 3) the injection of cement in the annular domain in between the two tubes to seal them and to annihilate the risk of a leak dangerously polluting the outer environment. Of these three steps, the last one is mostly important as it is supposed to "repair" the defects consecutive to inner tube positioning which is submitted to strong stresses in following its curved underground trajectory and can have large deformations and/or cracks and fissures which impair their impermeability [7]. This question will be discussed here by defining a constructive path which will enable reach the configuration where distance between inner and outer tubes is maximized in order to leave largest annular space for cement deposition.

II. SYSTEM MODELING

Schematically, the preparation phase before exploitation consists in drilling vertically to about the depth of the determined layer and to re-orientate horizontally the drilling head to penetrate in the shale source. So there is a right angle change of direction which, on top of torsion effect, creates a periodical tension-compression on (outer) tube in the curved section. It is only when the pumping system is stabilized on site that exploitation, mainly comprising high pressure injection through the tube, can be started. So the tube and its casing have to comply with two very different constraints: a dynamical stress when setting the structure, and an isotropic pressure afterward when filling the tube with injected high pressure fracking fluid.

Then the contained fluid exerts a lateral force on the deflected pipe; the magnitude of the force, acting towards the outside of the curve, is the product of the pressure by the cross-section multiplied by the curvature. If the pipe is not perfectly straight due to an initial bending, this couple

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between the pressure and curvature is present since the very beginning. When the pressure rises inside the pipe, the coupling effects cause the pipe to bend more till a sudden large deflection will be reached at Euler instability value which causes tube deformations and cracks leading to leaks out of the tube in outside environment. To prevent this situation multiple tubing has been worked out with two concentric inner and outer metallic tubes and cement casing in between supposed to "glue" in some sense the two tubes and to forbid leaks due to its elasticity and resistance. The difficulty is then to make sure that during insertion process inside wellbore, inner tube stays right in the middle with its axis coincident with outer tube axis. This does not seem "naturally" possible owing to mechanical and frictional constraints exerted by wellbore internal surface on inner tube dynamics during insertion, especially in the bended section [8, 9]. In other words there will always be localized spots where inner and outer tube surfaces will be in contact after long enough penetration. Other reason is existence of instabilities which deform tube surface under bending by ovalization [10] and buckling modes [11-14]. Possible suggestion would be to screw the inner tube by applying a torsion torque at surface extremity, but this cannot be a realistic solution due to wrinkle deformation on inner side of curved tube [15] and very large required torque for long tubes [16].

So a much easier solution is proposed here, which consists in having each section of inner tube equipped with four spherical rolling balls mounted at right angles on the screwed head onto the previous section, see Figure **1**, and entering with very small compliance into outer wellbore tube. Then obviously inner tube will be in contact through the rolling ball system with outer one at each section head, and its displacement inside the wellbore tube will be by rolling or by rolling and sliding depending on system parameters.

Interestingly, this scheme leaves most of internal space between the two tubes free for cement to be injected later when inner tube is positioned, and, by maintaining the head of inner tube opened enough, for air to be much more easily rejected to the surface inside (free because not operating) inner tube without energetically consuming air pumping out. Once installed with a clipping system to fix it, the inner tube is ready to carry the fracking fluid to specific site at the end of outer tube.

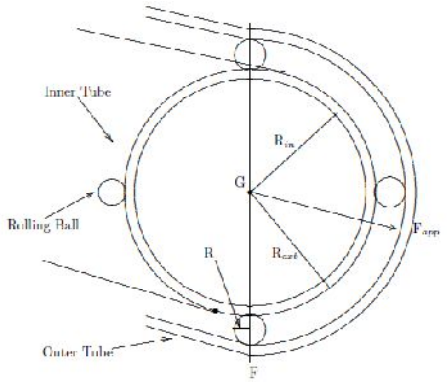


Fig. 1: Sketch of Double Tube Structure with Rolling Balls Ring Fixed to Inner Tube Junction

III. DYNAMIC PARAMETERS DETERMINATION

To give the proposed construction scheme a reality, it is necessary to set from system equations the domain of parameters where required physical properties are indeed satisfied. Here main operation is insertion of inner tube with its rolling contacts inside outer one without deformations so that the distance between the two tubes is always guaranteed to be above a fixed minimum value which corresponds to the minimum cement thickness to forbid possible leakages of very high pressure fracking fluid circulating inside inner tube toward outer environment. Avoiding inner tube deformation during its insertion in outer tube amounts here to control its motion which is driven by exerted force at upper end of each segment and by the rolling contact of the spherical balls on the inner surface of outer tube. For this last problem the equations for ball dynamics are given by

$$Mx'' = F\sin\phi + T\ ;\ My'' = -F\cos\phi + N = 0\ ;\ mk^2\theta'' = RT + \Gamma \quad (1)$$

where (Cxy) is a moving frame following ball contact point on outer tube, ϕ its rotation angle with absolute frame (OXY), M the total mass weighting at contact point including inner tube part, (T,N) the reaction vector at contact point, (F $\sin\phi$, F $\cos\phi$) the force vector at center of gravity (CoG) G of ball, k the gyration radius of ball around perpendicular axis to (Cxy) at G, m the ball mass, Γ the resisting torque to rolling and R the ball radius, see Figure 2.

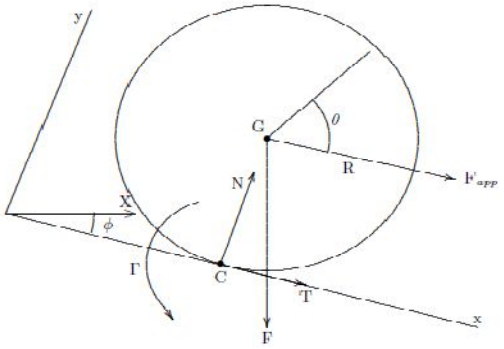


Fig. 2: Sketch of Rolling Ball Parameters

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In general F reduces to the weight along the vertical F = Mg, and T = $T_s + F_{app}$, where F_{app} is the pushing force applied to the inner tube for its insertion. (1) takes also the form

$$N = F\cos\phi > 0; \quad M(x'' + \lambda R\theta'') = F\sin\phi + T(1 + R^2/k^2) + \Gamma R/k^2 \qquad (2)$$

with $\lambda = m/M$. Three types of motion can take place

1) Sliding without Rolling : then $\theta'' = 0$ and $T = \varepsilon f_0 N$ with $\varepsilon = \pm 1$ and f_0 the margin limit. By substitution (2) becomes

$$Mx'' = F(\sin\phi + \varepsilon f_0\cos\phi) \quad ; \quad \Gamma = -\varepsilon f_0 RN \qquad (3)$$

showing equilibrium for $tg\phi < f_0$ and sliding above.

2) Rolling without Sliding : then $x'' + \lambda R\theta'' = 0$ and as $\Gamma = \varepsilon h_0 N$, h_0 the margin limit, (2) gives

$$T(1 + R^2/k^2) = -F(\sin\phi + \varepsilon h_0 R/k^2\cos\phi); m(k^2 + R^2)\theta'' = F(\varepsilon h_0\cos\phi - R\sin\phi) \qquad (4)$$

showing equilibrium for $tg\phi < \varepsilon h_0/R$ and motion above, which remains a rolling one as long as $|T| \le f_0 N$ ie when

$$tg\phi \le f_0(1 + R^2/k^2) - h_0 R/k^2 \qquad (5)$$

3) Rolling and Sliding : finally when $\Gamma = \varepsilon h_0 N$ and $T = \varepsilon f_0 N$, (2) transforms to

$$mk^2\theta'' = (\varepsilon f_0 R + \varepsilon' h_0)N \quad ; \quad M(x'' + \lambda R\theta'') = [tg\phi + \varepsilon h_0 R/k^2 + \varepsilon' f_0(1 + R^2/k^2)] \qquad (6)$$

with motion conditions $\varepsilon\theta'' < 0$, $\varepsilon'(x'' + \lambda R\theta'') < 0$, ie $\varepsilon\varepsilon' < 0$ ($\varepsilon' = \pm 1$), which is possible for $f_0 > h_0/R$ and $tg\phi > f_0(1 + R^2/k^2) - h_0 R/k^2$. From these results it follows that most interesting because more controllable situation of Rolling without Sliding (case 2) only occurs in the window angle

$$h_0/R < tg\phi \le f_0(1 + R^2/k^2) - h_0 R/k^2 \qquad (7)$$

Owing to the geometry of curved internal tubular domain in which inner tube is moving from initially vertical position and in necessarily sliding (and rolling) mode, there will always exist a limit angle in bended part for which upper limit of (7) will be reached and last part of the motion will be just rolling. In other words, inner tube motion during insertion starts in rolling + sliding mode (3) in vertical part up to the critical angle value fixed by equality in right part of condition (7), and continue afterward in mixed operation with a rolling mode (2) part after the critical angle. If this last part is controllable by applied pushing force on the head of the tube, it is not necessarily the case for upper part of inner tube in mode (3). For such situation however it is observed that $f_0 = T/N = (T_s + F_{app})/N$ is the larger as F_{app} is itself larger and, from (7), this corresponds to a higher upper limit, in other words to a limit angle closer to (initial) vertical. So increasing the pushing force F_{app} at the rear of inner tube reduces the part of bended sector where its motion is sliding.

There is however a limit F_{def} to F_{app} related to buckling deformation of inner tube portion L in between two consecutive rolling ball rings. In simple straight and vertical cylindrical geometry, the critical buckling force F_{crit} is given by Euler's expression $F_E = k\pi^2 EI/L^2$ with E, I respectively the tube material Young modulus, the tube cross-sectional moment of inertia, and k is a parameter fixed by end conditions. For inclined well one gets $F_{crit} = [4EIW\cos\phi/R_c]^{1/2}$ where W is inner tube effective weight per unit length and R_c the clearance between inner and outer tubes. Other expressions are available for inclined well [17], different buckling shapes [18, 19, 20, 21] and limit conditions [22].

IV. STATIC SYSTEM PARAMETERS DETERMINATION

Finally another constraint is imposed by the condition that, once loaded in step 3 of the process by the high pressure injected fracking fluid, the inner tube does not deform again especially in bended portion [23-26]. This typically leads to condition on inner tube wall thickness which in linear parts is obtained from Tresca condition

$$3Y^2 + m^2(Y - 1)^2 \le K_n^2 \qquad (8)$$

with $Y = (1 - \Delta P)u^{-1}$, $\Delta P = P_{ext}/P_{in}$, $u = 1 - r^2$, $r = R_{in}/R_{ext}$, (P_{ext},R_{ext}), (P_{in},R_{in}) the external and internal pressures and radii, and $K_n = K/P_{in}$ the flowing limit to traction normalized to inner pressure. For a given material, (8) determines the condition on r for stability with various ΔP (here for fixed outer pressure load depending on environment and variable inner pressure load). Solving for Y, (8) becomes finally

$$R_{ext} > [1 - P_{ext}/(P_{in}Y_+(P_{in}))]^{-1/2} R_{in} \qquad (9)$$

with $Y_+ = Y_+(K_n) = M^2 + [\langle K\rangle^2 + M^4 - M^2]^{1/2}$ and $M^2 = m^2/(m^2 + 3)$, $\langle K\rangle = K_n/(m^2 + 3)$. As $M^2 << \langle K\rangle^2$, $\eta = P_{ext}/(P_{in}Y_+(P_{in})) \cong P_{ext}/[M^2 P_{in} + K/(m^2 + 3)^{1/2}]$ is in general small up to a depth of 1km depending on the expression of outer pressure P_{ext}. For steel for instance $K = 2400 kg/cm^2$ and for $P_{in} = (330 + .1z)\ kg/cm^2$, $m \cong 1$, z the depth in meters, one gets $\eta = 4P_{ext}/(5130 + 5.1\ 10^{-2}z) = .15$ for $z = 10^3 m$ and $P_{ext} = 200\ kg/cm^2$, leading to inner tube thickness of .77cm for inner radius $R_{in} = 10cm$.

To test the robustness of proposed strategy, more accurate conditions are required with better system description by combining axial compression and global bending [22]. The results can be summarized by the expression

$$a(M/M_p)^{\alpha} + b(\sigma/\sigma_p)^{\beta} = 1 \qquad (10)$$

with M the bending torque and σ the axial compressive stress normalized to their respective instability values, and a,b,α,β empirical parameters obtained from experimental observations, see Figure **3**. It is again verified that higher pushing force F_{app} leads to tighter limit on tube bending possibility, so there is

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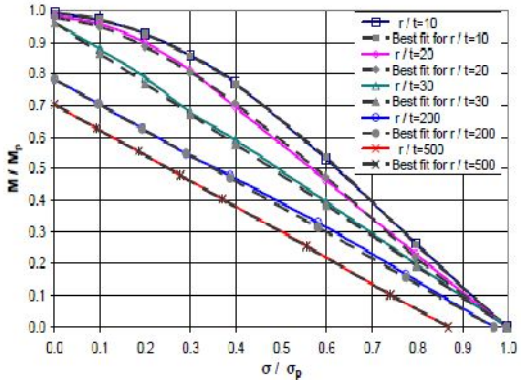


Fig. 3: Collapse Envelopes for Cylinders under Combined Axial Compression and Global Bending for Different Thickness [21]

some advantage to work with lower F_{app} to benefit from a higher bending limit (to move to the left of the diagram on Figure). But this is itself limited by the rolling without sliding condition (7) which gives best possible conditions for insertion realization. Observation of upper two curves for tube thickness of 10% and 20% indicates that with this model it is when F_{app} is about half of its critical value that the spacing between the two curves is largest ie that the tube is the less sensitive (however less than 10%) to a change of bending torque. This in turn implies a maximum limit for bending deformation of inner tube during its insertion, which is expressed by a minimum global curve radius of outer wellbore tube and a maximum length of inner tube segment between rolling ball rings. This shows the strict intermix of the three steps discussed in Introduction and the needs to consider the system globally as a whole with respect to combined forces acting on it [23-26].

V. CONCLUSION

The problem of constructing a minimum leak tubing for shale gas extraction has been discussed. An analysis has been developed here which rests upon the realization of a double tube structure such that the annular distance between inner and outer tubes is guaranteed to be as constant as possible for sealing them by injecting cement in this space to forbid leaks of fracking fluid toward surrounding environment. This implies equipping each inner tube section head with a ring of four spherical rolling balls distributed at right angles which gives the segment the possibility to roll (and/or slide) on inner surface of outer tube during its insertion. It is shown that proposed insertion strategy can be worked out successfully with respect to fixed initial requirements by respecting two explicit very important conditions on applied pushing force and design of adapted geometric size and elastic characteristic properties of inner tube material.

Independent of their formulation, they are the necessary ones for application of present strategy. Other system parameters such as the length of segments in between rolling ball rings, the elastic deformation inner tube characteristics and curvature radius and diameter of outer tube have been considered as given data in present analysis but it is always possible to proceed in a reverse way by searching “best” constitutive material and structure satisfying all operating constraints as it will be discussed elsewhere.

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[2] A large number of chemical and physical agents are injected during fracking action with each a specific role. Some agents are hazardous to the environment and to human health, and can lead to severe risks of contaminating surface or underground water shale critical for human drinking water supply or with important ecological functions if wells cementing and casing have been improperly done. After fracking operation the fluid complex flows back to the surface and can mix with water present in the deep target formations and thus transports back to the surface further potentially toxic or radioactive chemicals. The disposal of this mix of chemicals is generally done by re-injection into deep geological formations. Treatment and recycling is a major challenge, both technically and economically. The amount of water required for fracking is a further area of concern depending on regional water availability and water demand based on specific geological situations

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