SPE-177500-MS

Installing Temperature Sensing Fibers into Steel Tubes

W. Griffioen, S. Grobety, and L. Gapany, Plumettaz SA, Bex

This paper was prepared for presentation at the Abu Dhabi International Petroleum Exhibition and Conference held in Abu Dhabi, UAE, 9–12 November 2015.

Abstract

In pipes for oil and gas there is a need to accurately control and monitor temperatures or other parameters. Distributed Temperature or Acoustic Sensing (DTS or DAS) with optical fibers is a technique used for this. In many applications the optical fibres (or small cables) are inserted into small (few mm) steel tubes, pre-installed in or around the pipes. In this paper a technique is decribed where the fibers are floated in with water (or other liquid) under pressure. Optical fibres upcoated to 485 μm have been installed over 3 km with 90 bar water pressure. Higher pressures (and installation lengths) are possible because the fiber pay-off is placed inside a pressure tank connected to the installation equipment. By adjusting the mechanical pushing force exerted on the fiber, it can be installed with extremely low stress.

Introduction

In pipes for oil and gas there is a need to accurately control and monitor temperatures or other parameters. This can be done with optical fibres using Distributed Temperature or Acoustic Sensing (DTS or DAS). Here the fibres can be monitored with e.g. Raman, Brillouin, or Raleigh backscattering [1]. In many applications the optical fibres (or small cables) are inserted into small (few mm) steel tubes, pre-installed in or around the pipes, often over multi-kilometer lengths.

In this paper a technique is decribed where the fibers are floated in with water (or other liquid, like glycol or ethanol, to avoid freezing or cooking problems) under pressure. The Sensojet installation equipment consists of a dividable house with inside drive wheels to propel the fibre, torque limited using an adjustable magnetic clutch. The house is filled with water under pressure and connected to the steel tube, causing water flowing through it, while the drive wheels propel the fibre. To eliminate the force to pull the fibre into the pressure chamber, the fibre pay-off is placed inside a water tank connected to the house, i.e. at the same pressure. This allows much higher pressures (in principle only limited by the steel tube) and installation lengths. Moreover, larger diameter (currently until about 2 mm) fibres or cables can be installed. When cables with more stiffness are used, the installation is assisted by using a semi-open pig (sonic head).

Tests with the first version of the equipment (without tank still) were done with a standard uv-acrylate coated 250 μm optical fibre in a 4.76/2.76 mm steel tube of 900 m long, wound on a drum (80 cm diameter) with 50 bar. The same fibre was installed in the same tube in helical shape (pitch 1.5 m, winding diameter 0.5 m). It was also possible to install the fibre with ethanol instead of water. With the second version of the equipment (now with tank, see Figure 1) a 485 μm buffered optical fibre was installed in a 3.18/2.16 mm tube of 3000 m long, wound on a 80 cm drum again, with 90 bar. It was possible to install the fibre with almost zero stress, as was confirmed by DTS measurements. With the current equipment, where a maximum pressure of 110 bar can be reached, it is expected that about 5 km length can be reached. As steel tubes can withstand much higher pressures, much higher lengths can be reached, in principle.

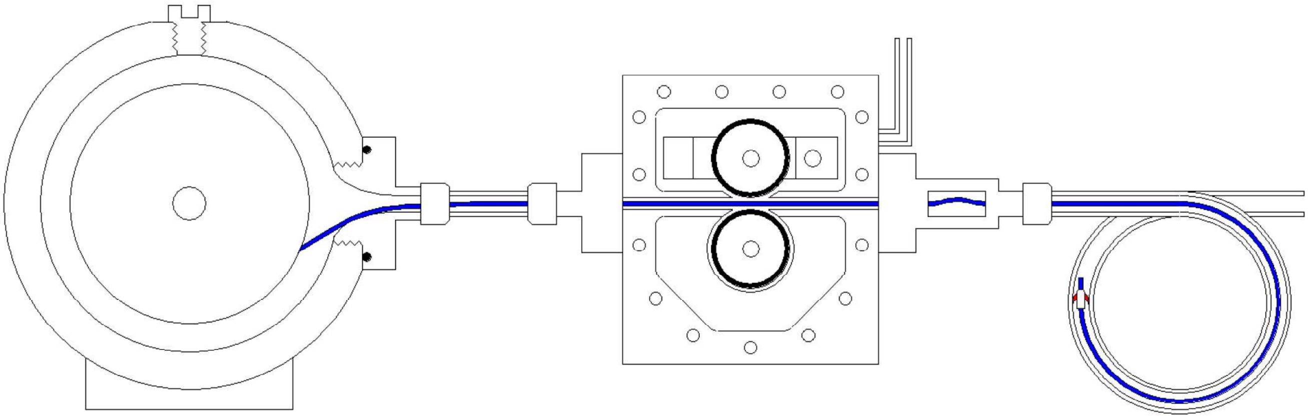


Figure 1—Schematical drawing of equipment to float optical fibers into steel tubes. Left: fiber pay-off in pressure tank, Middle: dividable pressure housing injecting the water into the steel tube and mechanically advancing the fiber, Right: drum with steel tube.

Theory

The force to install a cable into a duct is caused by sidewall forces between cable and duct, resulting in friction. The following effects contribute to the pulling force build-up in the cable [2, 3, 4].

Gravity

In straight ducts only the cable weight (gravity) contributes to the build-up of (axial) pulling force F. The change in force dF per unit of length dx is equal to the gravity friction force (horizontal ducts):

$$dF = fWdx \tag{1}$$

Here f is the coefficient of friction (COF) between cable and duct and W the cable weight per unit of length. Integrating Eq. (1) results in a pulling force that is proportional to the installed cable length x:

$$F = fWx \tag{2}$$

Axial Force

In bends and undulations of the duct, also the axial force in the cable contributes to the pulling force build-up. This force causes a sidewall force dF_n proportional to the local axial force F in the cable and proportional to the (infinitesimal small) change of angle dθ of the bend section [2]:

$$dF_n = fd\theta \tag{3}$$

The friction force per unit of length is found by multiplying this sidewall force by f. Integrating the equation that follows results in a pulling force increasing exponentially with the total change of angle:

$$F_2 = F_1 e^{f\theta} \tag{4}$$

Here F_2 and F_1 are the forces after and before the bend, respectively. This effect is known as the Capstan effect and dominates most cable pulls. In case of a tube coiled on a drum or in a helical shape, this effect makes installation by pulling impossible!

Jetting

In telecommunications, more than 2 decades ago, a trick was found to limit the capstan force build-up: the jetting method [2]. Here airflow is forced into the duct, while at the same time pushing the cable. There is no pig at the end of the cable, so the air can flow at much higher speed than that of the cable. This storm generates a cable propelling force that is distributed over the entire length of the cable. When dimensioning such that the air propelling force locally compensates the friction caused by the cable weight, the local axial force in the cable can be kept low. This eliminates the capstan effect. Even though the air drag forces are an order of magnitude smaller than commonly used forces to pull a cable, installation lengths by jetting usually exceed those obtained by pulling, especially in duct trajectories with many bends and undulations. Today the jetting method is widely used all over the world to install telecommunications cables into ducts. Installation lengths of up to 3.6 km (in one "blow") have been reported, e.g. for the CERN project [5].

Floating

Instead of air also water can be used as a propelling fluid [6]. This additionally causes a reduction of the effective weight of the cable because of buoyancy (Archimedes effect). It would even be possible to tune the density of the propelling fluid and/or the cable such that the effective cable weight becomes zero. Now besides the capstan effect, also the gravity effect is reduced, or even eliminated. This method is called floating and record lengths of up to 10 km have already been obtained. For advancing the cable by floating, the following condition needs to be fulfilled (turbulent flow):

$$\tfrac{1}{4}\pi D_c D_d \, dp \geq f\left(W - \tfrac{1}{4}\pi D_c^2 \rho_w g\right)dx \tag{5}$$

Here the left part of Eq. (5) is the water propelling force, with dp the pressure drop over the length dx, D_c the diameter of the cable and D_d the (internal) diameter of the duct, and the right part is the gravity friction from Eq. (1), now with effective weight in water, with ρ_w the density of water and g the acceleration of gravity. From Eq. (5) the length L follows over which the cable can be installed for a pressure p (relative to the atmospheric exhaust pressure) at the beginning of the duct:

$$L = \frac{\pi D_c D_d p}{4f\left(W - \tfrac{1}{4}\pi D_c^2 \rho_w g\right)} \tag{6}$$

This length can also be reached in a continuously coiled duct, on a drum or in a helical shape. The only remaining effect comes from the force to bend the cable, in a continuous coil only at the front end of the cable and at the cable injection point.

Effect Stiffness of Cable (Fibre)

When the cable is relatively stiff and/or an incidental bend in the duct is relatively sharp, the force to bend the front end of the cable can be relatively large. This causes a friction (repulsion) force F_h at the cable head due to bending it in a bend radius R_b and is given by [2,3,4]:

$$F_h = \frac{2Bf}{\sqrt{6(D_d - D_c)R_b^3}} + \frac{B}{2R_b^2} \tag{7}$$

This force can be compared to the gravity friction which an equivalent length L_{eq} would cause, according to Eq. (5):

$$L_{eq} = \frac{F_h}{f\left(W - \frac{1}{4}\pi D_c^2 \rho_w g\right)} \tag{8}$$

In order to compensate for the force F_h, excess fluid propelling forces are required, i.e. a higher pressure or a shorter length is required than would follow from Eq. (6). When the incidental bend is followed by continuous coiling, the Capstan effect is also present, for a part consuming the excess fuid propelling forces. The longer the cable length (L_{eq}) needed for the excess fluid propelling forces to overcome the force F_h, the stronger the Capstan effect will be. The same is true for cable buckling, also causing extra friction, even developing faster than for the Capstan effect [2,3,4]. The conditions for the fluid flow can be calculated by adding to Eq. (5) the Capstan and buckling friction [2,3,4]:

$$\frac{1}{4}\pi D_c D_d dp \geq f\sqrt{\left(W - \frac{1}{4}\pi D_c^2 \rho_w g\right)^2 + \left(\frac{F_h}{R_{coil}}\right)^2 + \left(\frac{D_d - D_c}{\pi^2 B} F_h^2\right)^2}\, dx \tag{9}$$

Here R_{coil} is the effective radius of the coil (when no sharper incidental bend is present in a coil, the bend radius R_b can be taken equal to R_{coil}). This leads to a modified Eq. (6):

$$L = \frac{\pi D_c D_d p}{4f\sqrt{\left(W - \frac{1}{4}\pi D_c^2 \rho_w g\right)^2 + \left(\frac{F_h}{R_{coil}}\right)^2 + \left(\frac{D_d - D_c}{\pi^2 B} F_h^2\right)^2}} \qquad 10)$$

Consider a sharp incidental bend and/or a relatively stiff cable, followed by continuous coiling and/or ″space to buckle″ in the tube (for which a small cable stiffness would be a worst case). The length that follows from Eq. (10) can then be considerably shorter than what would follow from Eq. (6).

Sonic Head

Fortunately, the friction force at the front end of the cable can also be compensated, by using a sonic-head, see Figure 2. This is a suction sealing pig which opens (via a spring mechanism) at a certain pressure, and leaves the excess pressure for the high-speed water flow (without that the Capstan effect would make the installation impossible). Typically the pressure drop over the sonic head is about 1 bar, while tens or hundreds of bars are used for floating the cable.

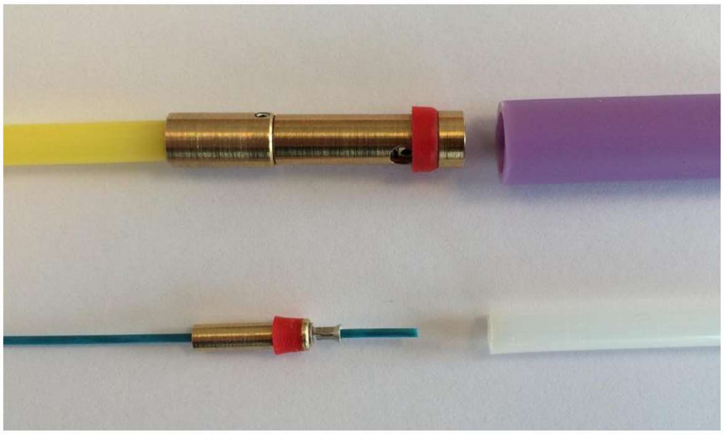


Figure 2—Sonic heads for ducts (steel tubes) with internal diameter of 8 mm (top) and 4.5 mm (bottom) and with cables of 5 mm and 1 mm diameter, respectively.

Examples

A 485 μm uv-acrylate upjacketed fibre, with weight of 2.5×10^{-3} N/m and stiffness of 1.4×10^{-6} Nm^2 is floated into a 4.76/2.76 mm steel tube of 3 km long. For a COF of 1 this length can be reached with only 20 bar, according to Eq. (6), still for the situation that the stiffness does not play a role. In tests (see further) a more than 4 times higher pressure was needed, while the COF was lower than 1. The stiffness friction F_h at the foremost end of the fibre in the coiled tube (bend radius $R_b = R_{coil}$ of 30 cm) of this flexible fibre, calculated with Eq. (7), is 1.5×10^{-4} N, equivalent to the friction of a length of 22 cm of fibre, as follows from Eq. (8). The extra friction on such a short length is not much, as follows from Eq. (10), where only 23% more pressure is required than for Eq. (6), mainly caused by Capstan friction. So, the mismatch with the tests is not explained.

In case an incidental bend with bend radius R_b of 10 cm is present in the previous example (e.g. a small undulation in the coil), the force F_h becomes 8.3×10^{-4} N, equivalent to the friction of a length of 120 cm of fibre. Over this length the Capstan friction (still dominant) and buckling friction will considerably limit the floating performance. For this case indeed a 4 times higher pressure would be needed, which could explain the mismatch with the 90 bar from the test. A sonic head could be the solution here.

For micro cables, with a much higher stiffness, the stiffness friction at the foremost end is much larger, also when less tight bends are present. A micro cable with diameter of 1.1 mm, weight of 0.015 N/m and stiffness of 2.5×10^{-5} Nm^2 is floated into a 6.35/4.5 mm steel tube of 3 km long. For a COF of 1 this length can be reached with 44 bar. The stiffness friction F_h at the foremost end of the cable in the coiled tube (bend radius $R_b = R_{coil}$ of 30 cm) is 2.2×10^{-3} N, equivalent to the friction of a length of 40 cm of cable. The Capstan friction (mainly) would reduce the length already considerably, and a pressure of 73 bar would be needed to reach 3 km. When an incidental bend with radius of 15 cm is present, the stiffness friction F_h at the foremost end of the fibre is 6.6×10^{-3} N, equivalent to the friction of a length of 116 cm of fibre. Now a pressure of 175 bar would be needed to install 3 km (again mainly Capstan friction responsible). Really, a sonic head is needed to float in the cable.

Equipment

A schematic drawing of the equipment for floating optical fibres into steel tubes is shown in Figure 1. At the right side the steel tube can be seen into which the fibre (cable) has to be inserted. In the picture also a sonic head is attached to the front end of the fibre, to assist in passing relatively sharp bends. The fibre is propelled by means of water which is injected under pressure, via the (dividable) pressure housing (middle of Figure 1). At the same time the fibre is advanced by means of a set of wheels (one mechanically driven) inside the pressure housing, pulling the fibre from the fibre reel (left in Figure 1). When the fibre reel is placed outside the pressure housing (as was the case in the first generation of the equipment), a force is required to pull the fibre into the pressure housing. Said force can be quite high, e.g. about 10 N for a 900 μm buffered fibre which is installed with a pressure of 110 bar. At this force, the fibre would buckle into the steel tube when this force is not balanced by the water pressure. For that reason the fibre reel is placed inside a pressure tank, connected to the pressure housing by means of a steel tube. Now, it is enough for the set of wheels to supply the force to pull the fibre from the reel. This force can be fine-tuned by means of a magnetic clutch between the drive motor and the drive wheel. In the window seen right from the pressure housing (see also Figure 3), the slightest excess pushing forces can be recognized by means of a transparent window. This all makes it possible to install the fibre with the lowest thinkable stress.

Figure 3—Window of transparent glass to visually detect fibre buckling when pushing too hard.

Tests and Installations

The equipment has been used in some installations at different places in the world, e.g. using 155 μm metal coated fibres (1500 m reached) and using 250 μm uv-acrylate coated fibres with Bragg gratings (40 m installation at a refinery laboratory). In this paper tests are described which were done in a laboratory environment (Bex, Switzerland), with full control of the parameters. It shall be noted that in the different tests a learning curve was made, and that the water pressures used in the first tests could have been lower when a better knowledge of the equipment settings and procedures was known by then.

Tests with first generation equipment

Feasibility tests have been done with the first generation equipment (see Figure 4) with different combinations of fibre (cable) and tube:

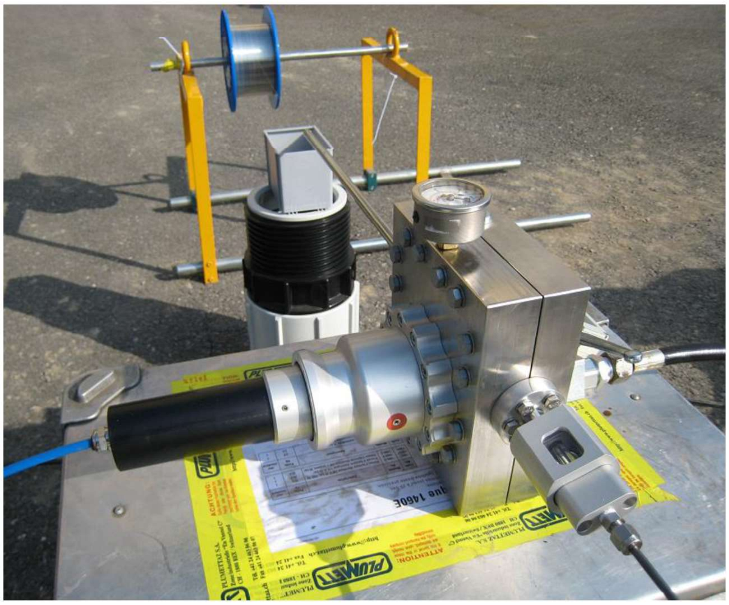


Figure 4—Equipment to float optical fibers into steel tubes, first generation.

1. Inserting a bare (standard) optical fibre (250 μm uv-acrylate coated) with water into a steel tube 4.76/2.76 mm of 56 m long, on a reel. This was done with 50 bar pressure. A first try to jet the

fibre through the steel tube with air was not successful.

2. Inserting a standard optical fibre with water into a steel tube 4.76/2.76 mm of 56 m long, wound in a helix with winding diameter of 0.5 m and pitch of 1.5 m. This was done with 10 bar pressure (but also here first attempt was with 50 bar). In [7] it was found that in a helix of this geometry there is no difference between a coil and a helix when their effective bend radius is the same.
3. Inserting a standard optical fibre with ethanol (to avoid freezing problems, can also be used in supercritical state in hot oil wells) into a steel tube 4.76/2.76 mm of 56 m long, on a reel. The test was done outside, to avoid explosion. This could be done with 10 bar pressure.
4. Inserting a 1.5 mm micro cable with water into a steel tube 4.76/2.76 mm of 56 m long, on a reel. This could be done with only 4 bar pressure. It shall be noted that for longer lengths (and higher pressure) the force which can be applied by the set of wheels is not enough to feed the cable into the pressure housing (with the second version of the equipment this is not a problem).
5. Inserting a standard optical fibre with water into a steel tube 4.76/2.76 mm of 720/900 m long, on a reel. This could be done with 25/50 bar pressure (two tests with two different results).
6. Inserting a standard 250 μm optical fibre with water into a 1.5/1.2/0.8 mm micro tube (plastic inner tube) of 54 m long, on a reel. Even though the tube was very small the installation could be done with 16 bar.

It is clear that not every combination of fibre (cable) and tube behaves the same. The length that can be reached does not always follow simply from Eq. (6) or (10). There are effects larger than the difference in coefficient of friction. The condition of the flow is important: is it laminar or turbulent (usually the latter)? It looks like that playing with materials (plastic inner wall of tube instead of steel, cable with nylon, PBTP, HDPE,. jacket instead of uv-acrylate coating) can make a big difference. And, increasing the cable diameter also seems to help (although not expected theoretically). There is still a lot to test. Anyway, it would be good to have the fibre reel placed under pressure, to be able to freely vary the water pressure and cable size.

Tests with second generation equipment

The improvement made for the second generation equipment is that the fibre (cable) reel is placed into a pressure tank which is connected to the pressure housing, see Figure 5. Now the only force the set of wheels has to supply is pulling the fibre from the reel. In the steeltube the fluid flow propels the fibre. With this equipment the fibre can be installed with a stress close to zero, by tuning the pressure to just advancing the fibre and the force on the wheels to just not buckling the fibre (in the window). Another advantage is that there is, in principle, no limit to the size of the cable: it does not require a higher force on the wheels. Also there is no limit to the pressure (except for the maximum pressure on the steel tube, which is much higher than the pressures which are used now). This makes it possible to reach much longer lengths.

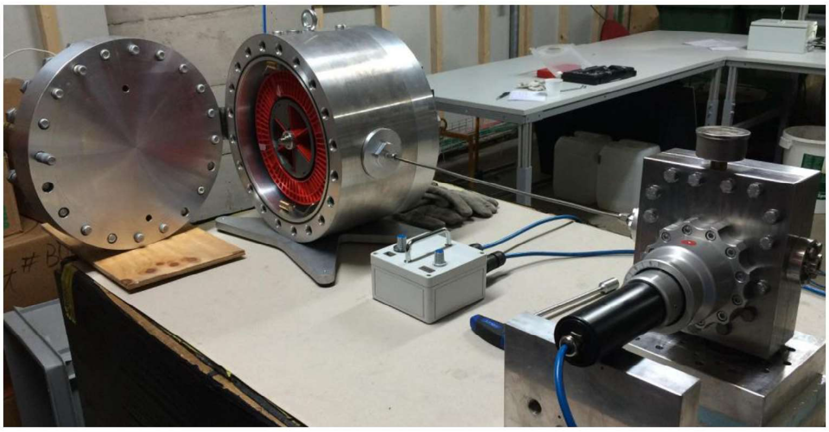
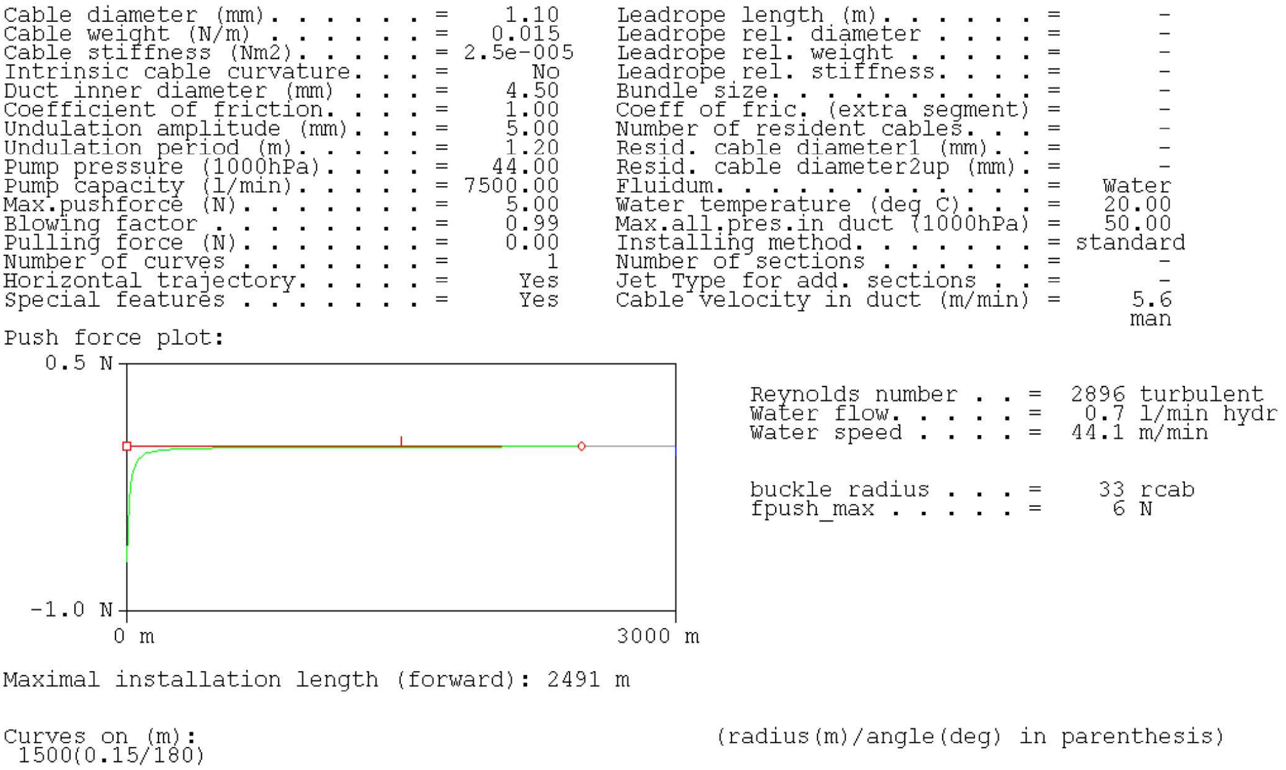


Figure 5—Equipment to float optical fibers into steel tubes. Left: fiber pay-off in pressure tank, Right: dividable pressure housing injecting the water into the steel tube and mechanically advancing the fiber.

With the second version of the equipment a 485 μm buffered optical fibre was installed into a 3.18/2.16 mm tube of 3000 m long, wound on a 80 cm drum again, with 90 bar. It was possible to install the fibre with almost zero stress, as was confirmed by DTS measurements.

Calculation Software

In Figure 6 an example is given of a calculation with software based on [2,3,4]. The 1.1 mm cable from the previous example is floated with 44 bar into a 6.35/4.5 mm steeltube. At 1500 m there is a 180° bend with bend radius of 0.15 m. With normal floating the cable will stop at 1500 m (instead of a helix, undulations with amplitude of 5 mm and period of 1.2 m are programmed). When a ″blowing factor″ of 0.99 (this means that 1% of the pressure is used to generate a pulling force on the sonic head) is programmed, a floating length of 2491 m follows, demonstrating the effect of the sonic head for this case. Note that in the software the installation length is corrected for the non-zero cable velocity (which is not the case for the equations given in this paper), the reason that the 3 km from the example is not reached here.



```
Cable diameter (mm). . . . . . . =    1.10    Leadrope length (m). . . . . . . =        -
Cable weight (N/m) . . . . . . . =   0.015    Leadrope rel. diameter . . . . . =        -
Cable stiffness (Nm2). . . . . . = 2.5e-005   Leadrope rel. weight . . . . . . =        -
Intrinsic cable curvature. . . . =      No    Leadrope rel. stiffness. . . . . =        -
Duct inner diameter (mm) . . . . =    4.50    Bundle size. . . . . . . . . . . =        -
Coefficient of friction. . . . . =    1.00    Coeff of fric. (extra segment) =        -
Undulation amplitude (mm). . . . =    5.00    Number of resident cables. . . . =        -
Undulation period (m). . . . . . =    1.20    Resid. cable diameter1 (mm). . . =        -
Pump pressure (1000hPa). . . . . =   44.00    Resid. cable diameter2up (mm). . =        -
Pump capacity (l/min). . . . . . = 7500.00    Fluidum. . . . . . . . . . . . . =    Water
Max.pushforce (N). . . . . . . . =    5.00    Water temperature (deg C). . . . =    20.00
Blowing factor . . . . . . . . . =    0.99    Max.all.pres.in duct (1000hPa) =    50.00
Pulling force (N). . . . . . . . =    0.00    Installing method. . . . . . . . = standard
Number of curves . . . . . . . . =       1    Number of sections . . . . . . . =        -
Horizontal trajectory. . . . . . =     Yes    Jet Type for add. sections . . . =        -
Special features . . . . . . . . =     Yes    Cable velocity in duct (m/min) =      5.6
                                                                                      man
Push force plot:
   0.5 N
                                                        Reynolds number . . =  2896 turbulent
                                                        Water flow. . . . . =   0.7 l/min hydr
                                                        Water speed . . . . =  44.1 m/min

                                                        buckle radius . . . =    33 rcab
                                                        fpush_max . . . . . =     6 N


  -1.0 N
         0 m                                 3000 m

Maximal installation length (forward): 2491 m

Curves on (m):                                     (radius(m)/angle(deg) in parenthesis)
 1500(0.15/180)
```

Figure 6—Screendump of calculation software for example with 1.1 mm cable in 6.35/4.5 mm steeltube.

Conclusions

In this paper e method is presented to install optical sensor fibres into steeltubes, to monitor pipes for oil and gas using DTS or DAS techniques. The fibres (or cables) are inserted by injecting under pressure a water flow (or other liquid) through the tubes, while at the same time feeding them mechanically from a reel, in pressure communication with the steeltube entrance. The method has been further improved by using a sonic head at the foremost end of the fibre, especially of use when the fibre (cable) is less flexible and/or when sharp bends occur. Optical fibres upcoated to 485 μm have been installed over 3 km with 90 bar water pressure. Higher pressures (and installation lengths) and also larger (cable) diameters are possible with the presented technique. The stress of the installed optical fibre can be made extremely small by accurately adjusted the mechanical feeding force (using a magnetic clutch) and the water pressure (by monitoring the fibre in a transparent window). The theory of the method has been treated and software, based upon this theory, has been confirmed.

Acknowledgements

We would like to express our thanks for the valuable contributions of E. Rochat, F. Ravet and M. Nikles (Omnisens, Switzerland), C. Tzotzi, O. Mesnagne, E. Papore and M. Gainville (Technip, France) and J.L. Berod, F. Kont, V. Goncalves, V. Chaves, Y. Chappuis and Philippe Prat (Plumettaz, Switzerland).

References

1. F. Ravet, C. Borda, E. Rochat, M. Nikles, ″Geohazard Prevention and Pipeline Deformation Monitoring Using Distributed Optical Fiber Sensing″, ASME 2013 International Pipeline Geotechnical Conference, 07/2013.
2. W. Griffioen, *″Installation of Optical Cables in Ducts″,* Plumettaz, Bex, Switzerland, 1993.
3. W. Griffioen, G. Plumettaz, H.G. Nobach, ″Theory, software, testing and practice of cable in duct installation″, *Proceedings of 55th International Wire & Cable Symposium,* 2006, pp. 357–365.
4. Z. Guo, *″Progress in Optical Fibers Research″,* Nova Publishers, New York, USA, 2008 (Chapter 7).
5. W. Griffioen, C. van ’t Hul, I. Eype, T. Sugito, W. Greven, T. Pothof, ″Microduct cabling at CERN″, *Proceedings of the 53rd International Wire & Cable Symposium,* 2004, pp. 204–211.
6. W. Griffioen, L. Gapany, S. Grobety, C. Gutberlet, G. Plumettaz, R. van der Sluis, A. Pijpers, Th. Weigel, ″Floating Cable into Duct: Recent Developments″, *Proceedings of 62nd International Wire & Cable Symposium,* 2013, pp. 11–20.
7. J. Fehlbaum, O. Schuepbach, V. Chaves, W. Griffioen, ″Installing Cables into Continuously Coiled Ducts″, *Proceedings of the 63rd International Wire & Cable Symposium,* 2014, pp. 747–756.