# Progress in Floating Sensor Fibers into Steel Tubes

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## Abstract

Optical fibers have excellent sensing properties. They can be used for e.g. Distributive Temperature Sensing (DTS), finding application in Monitoring Power Cables, Pipes for Oil and Gas, both Wells and Transport, Steam Pipes in Power Plants, etcetera. Often the fibers (or small cables) are installed in (2-6 mm) steel tubes. This can be done by floating with water or alcohol, a technique described in this paper. Extremely long (>10 km) uninterrupted installation lengths are demanded. A challenge in such small tubes, even with high pressures of 100 bar or more. Special equipment has been developed, handling such pressures and allowing accurate control of the installation. Feasibility of installation of 5.2 km with 80 bar has been proven already. Higher pressure and a sonic head will be used to further extend this length.

**Keywords:** Optical fibers; sensor fibers; optical cables; power cables; pipes; oil; gas; distributive temperature sensing; DTS; DAS; microducts; steel tubes; installation; jetting; floating; water; alcohol.

## 1. Introduction

Optical fibers have excellent sensing properties, using e.g. optical techniques like Raman-, Brillouin- or Raleigh- backscattering or Bragg-grating reflection [1]. With these techniques distributive sensing of temperature and fiber strain/stress are possible with high accuracy. Distributive Temperature Sensing (DTS) is a commonly used technique to monitor power cables for optimization of current rating, and is also used widely to monitor pipes in the oil and gas industry, for different applications (transport, wells, etc.). Also Distributive Acoustic Sensing (DAS) becomes increasingly popular, especially when boring wells. In most applications the fibers are installed into small steel tubes, with internal diameter typically ranging between 2 and 6 mm.

In this document progress in installing the optical fibers into the steel tubes by floating with a liquid is described. In most cases the liquid is water, but also alcohol (ethanol, propanol) is used. The latter can be used for high temperature applications, where the critical point is passed and there is no risk anymore for excessive pressures. Trials and installations have been done with 165 µm metal coated fibers, 250 µm standard (uv-acrylate) coated fibers, buffered (uv-acrylate) 485 µm fibers and recently small 2-fiber cables (1.1 mm). Most trials were done with the steel tube wound on a reel, but also helical and straight installations were done, and a deep well installation is planned. Most used are relatively thick-walled steel tubes, e.g. 4.76/2.76 mm, but now also a successful trial was done with a thin-walled (low-cost alternative) welded steel tube of 5.0/4.5 mm, of the kind used in Optical Power Ground Wires (OPGW).

It is a challenge to reach very long installation lengths of optical fiber in the very narrow steel tubes. With jetting (air) optical cables installation lengths of 3.5 km have been reached, and with floating (water) optical and power cables even lengths of 10 km have been reached. These lengths usually matched theory ([2-6] and Appendix). But, for very narrow tubes, like the steel tubes, it looks a bit more difficult to reach such extreme lengths, even though higher pressures can be used.

Further gaining in understanding the theory of floating for these extreme situations has been reached, gradually closing (almost) the gap between theory and experimental results. This is treated in this paper. A sonic head at the foremost end of the cable has been demonstrated theoretically to enhance installation performance, while the effect of an end cap already has proven to work experimentally, both for installation and flushing the fiber out.

Several installation trials are described in this paper, the longest one 3 km (90 bar water pressure), but before presentation of this paper a 5.2 km test is planned (already tested 2 km of fiber with tube open at 5.2 km). The target today is to reach >10 km uninterrupted floating (not just to beat records, but because of applications which need such uninterrupted lengths), which is expected to be possible according to extrapolation of the tests with 1.1 mm cable into 5.0/4.5 mm steel tube (1.8 km reached with a pressure of 25 bar).

## 2. The Challenge

### 2.1 What has been Reached Today?

It is a challenge to reach very long installation lengths of optical fiber (in one shot) in the very narrow steel tubes. With jetting (synergy of blowing and pushing) installation lengths of 3.5 km of optical cable have been reached, in 40/32 mm HDPE ducts (with 17 mm cable) and in 7/5.5 mm microducts (with 3.2 mm cable), with 16 bar. With floating (water instead) even lengths of 10 km have been reached, for optical and low-voltage cables, in 50/40 mm ducts, with 20 bar. Also in microducts (10/8 mm) the technique of floating was possible for 6 mm cables until 6 km, with 25 bar. With these installations there is usually a good match between practical experience and theoretical models ([2-6] and Appendix), with a coefficient of friction (COF) found as low as 0.06-0.08 [7].

But, for very narrow tubes, like the steel tubes, it looks a bit more difficult to reach such extreme lengths (and still longer lengths are demanded now), even though higher pressures can be used, in the order of 100 bar or more (and the installation length is proportional to the pressure used, at least theoretically). Also the match between practice and theory gets worse when size becomes smaller. This is already the case for optical drop cables used for Fiber to the Home (FttH), e.g. small 1.8 mm cables into 4/3 mm microducts, where a jetting length of 1000 m with a pressure of 15 bar would give a COF of about 0.1. The COF becomes higher for blown fibres, flexible and lightweight Enhanced Performance Fiber Units (EFPUs) [8], and still higher for 485 µm buffered fibers with a weight of only 0.0025 N/m. The latter fiber would result in a blowing length of amply 4.3 km in a 5/3.5 mm microduct for a pressure of 8 bar when the COF would be 0.1. This is an order of magnitude longer than what is reached. Static electric charging (which is minimized by using graphite in the microducts, by controlling the humidity of the airflow and/or by lubrication) is one of the suspects here. But, with floating no static electric charging is expected anymore. Here the even larger theoretical length of 48 km (for 25 bar) is by far not (yet) reached.

### 2.2 Higher Pressures in Steel Tubes

In this paper installation in steel tubes is described, where much higher pressures can be used. With 485 μm (uv-acrylate buffered) fiber a length of 3 km was reached in a 3.18/2.16 mm steel tube by floating with 90 bar, a good result but according to theory the COF must have been 3.6, much higher than for optical cables in (micro) ducts. With 250 μm (standard uv-acrylate coated) fiber almost the same pressure was needed for 2 km, while theory would predict a floating length inversely proportional to the fiber diameter (in the same tube). It looks like the fiber cannot fully pick up the water flow. It could be stuck close to the tube wall, partly in a laminar boundary layer. In fact, for liquids a high pressure is needed to get turbulent flow at all, see Appendix. In a test with a 1.1 mm cable (weight 0.01 N/m) into a 5.0/4.5 mm steel tube, 1.8 km was reached with a pressure of only 25 bar. The most promising until now. But, an even higher effective COF of 8 is calculated, because of the low effective weight of the cable (almost same density as water). Probably cable stiffness, in combination with micro undulations of steel tube and cable, plays a role. It was also noted that a higher pressure of 40-70 bar was needed to start up the cable. Probably the cable was then stuck at the wall. No end-cap was used here. With fibers the effect of an end-cap was shown, helping the fiber to move away from the tube wall. With sonic heads further improvement is expected. Such details will be discussed after presentation of the different test.

## 3. Equipment

The installation equipment consists of a dividable house with inside drive wheels to propel the fiber, torque limited using an adjustable magnetic clutch, see schematic drawing of Figure 1 and picture in Figure 2. The house, with window for buckle detection, is filled with water under pressure and connected to the steel tube, causing water flowing through it, while the drive wheels propel the fiber. To eliminate the force to pull the fiber into the pressure chamber, the fiber 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) fibers or cables can be installed. When cables with more stiffness are used, the installation is enhanced by using a semi-open pig (sonic head).

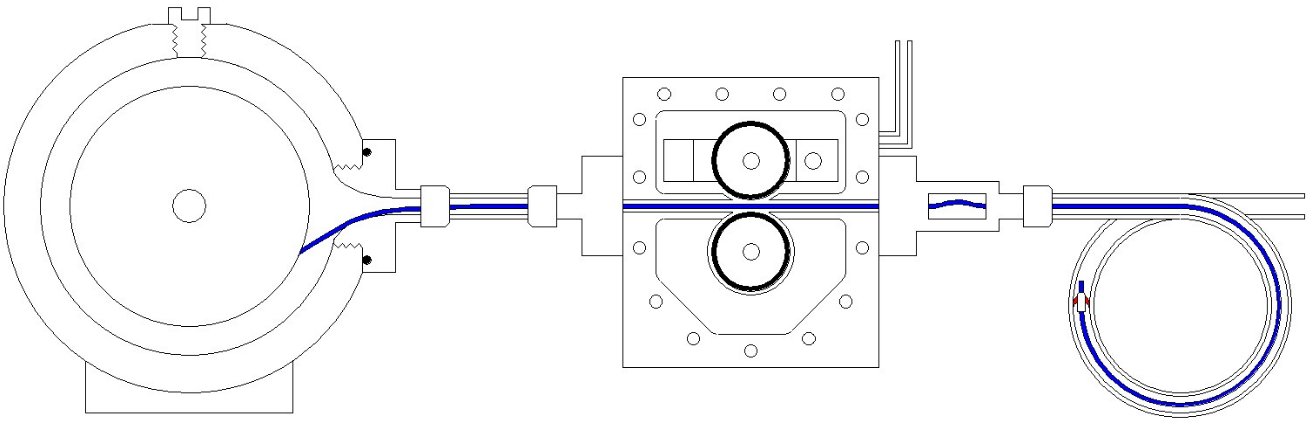

**Figure 1. Schematic drawing of equipment to float optical fibers into steel tubes. Left: fiber pay-off in pressure tank, Middle: dividable pressure housing injecting the water into the steel tube and mechanically advancing the fiber, Right: drum with steel tube and sonic head.**

**Figure 2. 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.**

## 4. Tests in Steel Tubes

A summary is given of trials and installations of optical fibers and cables into steel tubes. Three generations of equipment were used: 1) fiber inserted from outside into pressure chamber, 2) fiber reel placed in small tank and 3) fiber reel placed in large tank, both tanks at same pressure as pressure chamber. Installations were done with water, unless otherwise specified. Most installations were done at the maximum speed of the equipment of 6 m/min, except the test of 2 km in alcohol where the speed was 3 m/min. Recently, the equipment has been modified to reach 13 m/min and was tested for this. Most installations were done with and end-cap at the fiber's foremost end, enhancing the installation (and reproduction).

### 4.1 165 µm fiber in 1.5 km of 4.76/2.76 mm Tube

Several installations with 165 µm metal coated fiber into a 1.5 km long 4.76/2.76 mm steel tube were done at the customer's location, with water of about 100 bar pressure and a speed of 6 m/min. The small fiber diameter allows the fiber pay-off to be placed outside the pressure zone.

### 4.2 250 µm fiber in 4.76/2.76 mm Tube

Installations with 250 µm standard (uv-acrylate) coated fiber into 4.76/2.76 mm steel tubes of 56 m long in coiled and helical shape (diameter 50 cm, helix pitch 1.5 m) were done at the Plumettaz site in Bex, with water and alcohol (ethanol) of about 10 bar pressure. Later the test was done with 800 m coiled tube where the end was reached with 80 bar. The tests could still be done with the fiber pay-off outside the pressure zone.

**Figure 3. Floating 250 µm fiber into 4.76/2.76 m steel tube. No pressure tank used. Here with alcohol.**

### 4.3 485 µm fiber in 1.5 km of 3.18/2.16 mm Tube

The tests at the Plumettaz site were continued with 485 µm buffered (uv-acrylate) fiber into 3.18/2.16 mm steel tubes of 1500 m long in coiled shape (winding diameter 70 cm). The end could be reached with water of 40 bar pressure. Now the fiber pay-off was placed inside a tank (small one, first generation), needed to avoid the higher force to insert the (larger) fiber into the pressure chamber. First no end-cap was used, but then sometimes the fiber got stuck and needed a much higher pressure to start up, especially when flushing out. Using end-caps made installation and flushing out reproducing and successful.

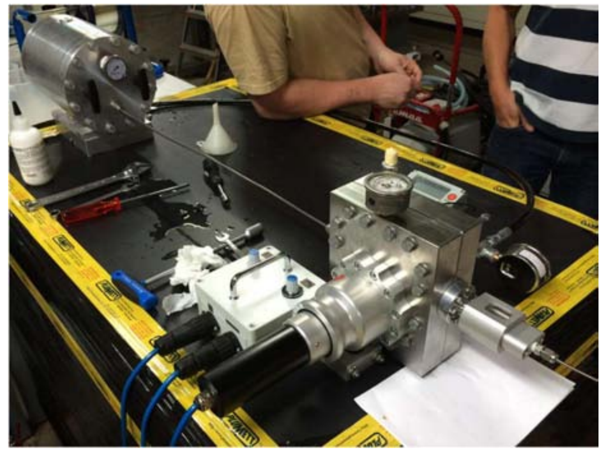

**Figure 4. Floating 485 µm fiber into 3.18/2.16 m steel tube. Small pressure tank used. 1.5 km with 40 bar.**

### 4.4 485 µm fiber in 3 km of 3.18/2.16 mm Tube

At the customer's location installations were done with 485 µm buffered (uv-acrylate) fiber into 3.18/2.16 mm steel tubes, now of 3000 m long, still in coiled shape (winding diameter 70 cm). The end could be reached with water of 90 bar pressure. A larger tank (second generation) was now used for the fiber pay-off. End-caps at the front end of the fiber were used standard, it was also needed to use an end-cap at the rear end of the fiber when flushing out.

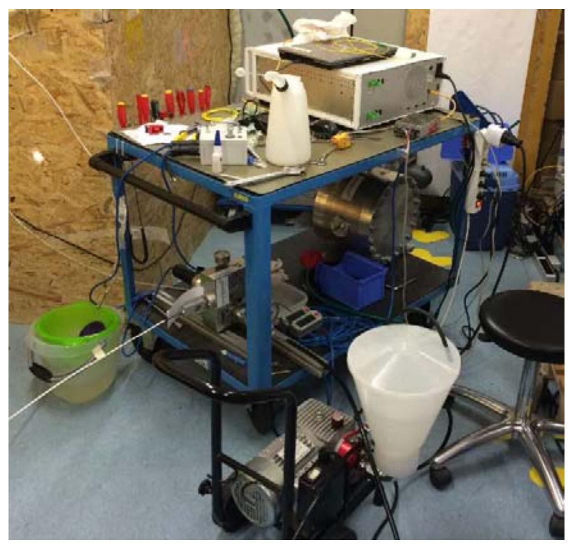

**Figure 5. Floating 485 µm fiber into 3.18/2.16 m steel tube. Big pressure tank used. 3 km with 90 bar.**

### 4.5 250 µm fiber in 2 km of 3.0/2.6 mm Tube

Installations with 160 µm metal coated fiber and 250 µm standard uv-acrylate coated fiber were done at customer location in a coiled 3.0/2.6 mm steel tube of 2 km long. The 160 µm fiber was installed successfully with water of 60 bar (end-cap used). The 250 µm was installed successfully with alcohol (propanol) of 85 bar (no end-cap used), with a speed of 3 m/min. It was found that low temperatures (5 °C) made it difficult to reach high velocity. The equipment was moved to a warmer location (18 °C).

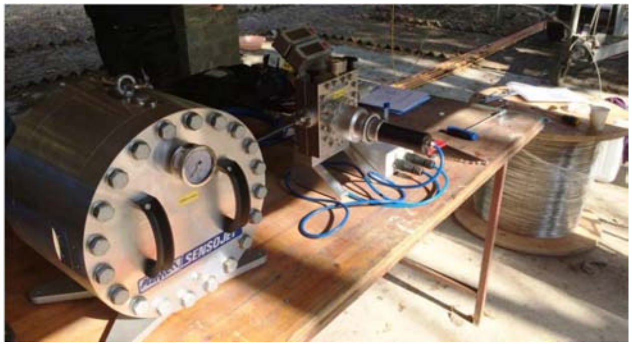

**Figure 6. Floating 160 µm fiber and 250 µm fiber into 3.0/2.6 m steel tube, with water and with alcohol. Big pressure tank used. 2 km 160 µm fiber with 60 bar and 2 km 250 µm fiber with 85 bar.**

### 4.6 1.1 mm cable in 1.85 km of 5.0/4.5 mm Tube

The 1.1 mm cable could be installed into the 5.0/4.5 mm steel tube with water of 25 bar over 1854 m, but the start-up pressure was between 40 bar and 70 bar (no end-cap used). When a connection was made to a total length of 5175 m, and the entire steel tube was filled with water, the 1854 m of cable already installed could run further with 50 bar, while a start-up pressure of 70 bar was needed (now with end-cap). The flow would not change much when the remaining part of the tube would be filled with cable. It is estimated that a start-up pressure of 80 bar is sufficient for 5.2 km of steel tube.

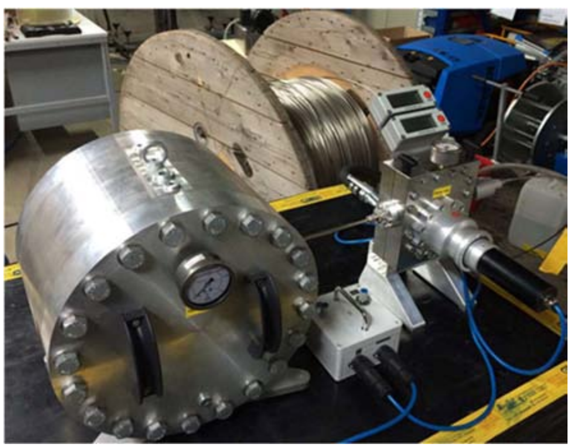

**Figure 7. Floating 1.1 mm cable into 5.0/4.5 m welded steel tube. Big pressure tank used. 1.85 km reached with 25/40 bar, moves with 50/70 bar when connection is made to 5.2 km (completely water filled).**

### 4.7 250 µm fiber in 5.2 km of 5.0/4.5 mm Tube

This installation was done to test the higher speed of 13 m/min of the modified equipment. The larger 5.0/4.5 mm tube was selected on purpose (allows larger flow velocity of the liquid). Alcohol (ethanol), was used as a worst case (because of its higher viscosity the flow will be at lower velocity). A standard 250 µm (uv-acrylate coated) fiber was used for the test. The pressure was set at 80 bar at the start, the fiber velocity set at 6 m/min. After 30 minutes the pressure was increased to 100 bar and the speed increased and maintained all the time at 13 m/min. After the fiber was installed over 1430 m, the alcohol came out at the end of the tube at 5.2 km, indicating that the flow velocity of the alcohol was indeed amply larger than the speed of the cable. The test was stopped when the fiber was installed 2 km.

**Figure 8. Floating 485 µm fiber into 5.0/4.5 m welded steel tube of 5.2 km long, with alcohol. Big pressure tank used. 2 km was installed with 100 bar alcohol coming out at end of tube. Fiber speed 13 m/min.**

## 5. Discussion

It is now tried to explain the observations during the tests and installations. The results of some examples will be compared to theory (see Appendix). The state of the flow (laminar or turbulent, the latter assumption made in the theory of jetting and floating) will be checked. Also the effect of an end-cap in general and a sonic-head for small cables with non-negligible stiffness will be explained.

### 5.1 Example 1: 485 µm fiber in 3.18/2.16 mm tube

A 485 µm uv-acrylate buffered fiber, with weight of $2.5 \times 10^{-3}$ N/m and stiffness of $1.4 \times 10^{-6}$ Nm$^2$ is floated into a 3.18/2.16 mm steel tube of 3 km long, with water under a pressure of 90 bar. According to (6) the COF would be 3.6, a much higher value than for jetting and floating telecom and power cables. Although the stiffness of the fiber is small, it has an effect in the continuously coiled (70 cm diameter) steel tube, mainly because of the capstan effect (not so much the buckling). From (10) a COF of 2.2 would follow (with $F_h$ of $1.5 \times 10^{-4}$ N), still high. According to (20) a hydraulic diameter of 2.91 mm would be required for turbulent flow (tube internal diameter even higher), so the tube is a bit too small (however, so close to the transition condition that the status of the flow can hop between laminar and turbulent, hysteresis). This could be the explanation between the mismatch between theory and praxis. Although the velocity profile of the fluid flow is constant in turbulent flow, the fiber with its small diameter could be "drowned" in a laminar boundary layer at the tube wall. In case of laminar flow, the flow has a parabolic velocity profile, so there will be much less flow to pick up the fiber at the tube wall than in the middle of the tube. It is difficult to make an exact estimate of the length that can be reached in such cases. But it explains why an end-cap at the foremost end of the fiber can pull the fiber from the outermost tube route (where it is pushed by the equipment) towards the innermost part, crossing the center and picking up the flow. In the same way a rear end-cap can enhance propelling of the fiber (taking over the pushing from the equipment) when flushing out the fiber.

### 5.2 Example 2: 1.1 mm cable in 5.0/4.5 mm tube

Now a larger 1.1 mm cable, with weight of 0.01 N/m and stiffness of $2.5 \times 10^{-5}$ Nm$^2$ is floated into a 5.0/4.5 mm steel tube of 1.8 km long, with water under a pressure of 25 bar. According to (6) the COF would be 8, much higher value than for jetting and floating telecom and power cables. The stiffness of the cable is larger than for the fiber, so a big effect is expected. In a continuously coiled (again 70 cm diameter) steel tube a COF of 1.0 would follow from (10), with $F_h$ of 1.8x10$^{-3}$ N and again reduced length because of capstan effect, not buckling. According to (20) a hydraulic diameter of 3.6 mm would be required for turbulent flow. With a tube internal diameter of 4.5 mm this condition is fulfilled, so now we really have turbulent flow. Also the cable diameter is probably large enough to stick out of the laminar boundary layer close to the tube wall. 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), a COF of 0.36 would follow from (20), with a force $F_h$ of 5x10$^{-3}$ N. Now the gap between practice and theory almost closes. Important, if such incidental bends really limit so much the installation length, a sonic head would increase the installation distance by a factor of almost 8 (coil) to 22 (coil + bend) in this case! But, the numbers in this example are very critical, better to do a test (planned)!

### 5.3 Cable Velocity

In both examples the velocity of the fluid is much larger than that of the cable, certainly for a cable velocity of 6 m/min, but also for the new cable velocity of 13 m/min. For the 3.6/2.0 mm tube the fluid speed might be sufficient, but the flow is laminar, while the flow needs to be turbulent. For this the steel tube internal diameter shall be large enough, related to the tube length and pressure.

### 5.4 Longer Lengths

Longer lengths can be obtained by using higher pressures. No problem for the steel tubes, also not for the equipment, in principle. But, the tank must be larger and the maximum pressure higher.

## 6. Conclusions

Special equipment has been developed for floating optical fibers and small cables with water or alcohol into small (2-6 mm) steel tubes. High pressures (order of 100 bar), needed to reach the demanded extremely long (>10 km) uninterrupted installation lengths, can be handled. The pay-off reel can be placed in a tank at the same pressure. This allows accurate control of the installation, keeping the stress in the fiber negligible (needed for accurate temperature sensing). Feasibility of installation of 5.2 km with 80 bar has been proven already. Higher pressures will be used to further extend this length. It was found that a small cable performs better than a fiber, while theory forecasts the opposite. Larger diameter simply gives a better match with theory. The state of the flow is important, it shall be turbulent. For this larger diameter (4-6 mm) steel tubes are required when lengths > 10 km are demanded. The use of an end-cap at the foremost fiber end already has proven to enhance the installation performance, keeping the fiber in the flow. It is expected that a sonic head (produced now) can help to reach longer installation lengths, especially for small cables, by pulling the "stiff" cable end through the continuous curve and incidental bends.

## 7. Acknowledgments

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## 9. Appendix: 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 [3,4].

### 9.1 Gravity

In straight ducts only the cable weight (gravity) contributes to the build-up of (axial) pulling force $F$. The change in force d$F$ per unit of length d$x$ 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 $x$:

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

### 9.2 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 d$F_n$ proportional to the local axial force $F$ in the cable and proportional to the (infinitesimal small) change of angle d$\theta$ of the bend section [2]:

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

The friction force d$F$ per unit of length is found by multiplying d$F_n$ 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!

### 9.3 Jetting

In telecommunications, more than 2 decades ago, a trick was found to limit the capstan force build-up: the jetting method [4]. 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 [9].

### 9.4 Floating

Instead of air also water can be used as a propelling fluid [5]. 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 d$p$ the pressure drop over the length d$x$, $D_c$ 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 $\rho_w$ 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:

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

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.

### 9.5 Effect Stiffness of Cable (Fiber)

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 $R_b$, given by [2,3]:

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

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

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

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 fluid 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]:

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

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):

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

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).

### 9.6 Sonic Head

Fortunately, the friction force at the front end of the cable can also be compensated, by using a sonic-head (patented), 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.

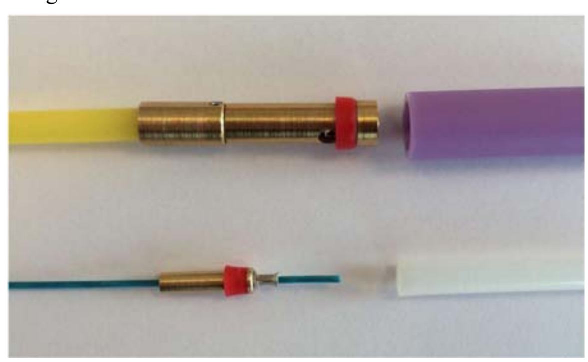

**Figure 9. Sonic heads for ducts (steel tubes) with internal diameter of 8 mm (top) and 4.5 m (bottom) and with cables of 5 mm and 1 mm, respectively.**

### 9.7 Laminar or Turbulent?

The state of a fluid flow is given by a dimensionless number, the Reynolds number $Re$ [10]:

$$\mathrm{Re} = \frac{\rho \bar{v} D_h}{\mu} \tag{11}$$

Here $D_h$ is the hydraulic diameter (for cylindrical tubes this is equal to the inner diameter $D_d$), and $\rho$ the density, $\mu$ the dynamic viscosity and $\bar{v}$ the average velocity of the flowing medium. A criterion for turbulence in pipe flow is a Reynold number which is larger than 2300, with $D_h = D_d$ [10]. When the Reynold number is smaller than 2300, the flow is laminar.

The pipe flow, laminar or turbulent, is described by a unique relation between the dimensionless drag coefficient $C_d$ and Reynolds number *Re*, which is obtained empirically and often shown as Moody charts [10]. The drag coefficient is defined by:

$$\frac{dp}{dx} = -C_d \cdot \frac{\rho \bar{v}^2}{2D_h} \qquad (12)$$

For incompressible flow (liquids) $\rho$ is constant (approximately). In the Moody charts two regions can be recognized, laminar and turbulent, both with their own "fit" to the chart. For laminar flow the drag coefficient is given by the Darcy-Weisbach equation (which can in fact be derived directly, analytically):

$$C_d = \frac{64}{\mathrm{Re}} \qquad (13)$$

With (11) and (12) the Hagen-Poiseuille equation is obtained for the average flow velocity $\bar{v}$:

$$\bar{v} = \frac{D_h^2}{32\mu} \frac{\Delta p}{L} \qquad (14)$$

The volume flow $\Phi_V$ is given by:

$$\Phi_V = \tfrac{1}{4}\pi\left(D_d^2 - D_c^2\right) \cdot \bar{v} \qquad (15)$$

From (14) and (15) it follows:

$$\Phi_V = \frac{\pi\left(D_d^2 - D_c^2\right)D_h^2}{128\mu} \frac{\Delta p}{L} \qquad (16)$$

For turbulent pipe flow (in perfect smooth-walled tubes) the drag coefficient is given by the empirical formula of Blasius:

$$C_d = \frac{0.31}{\mathrm{Re}^{1/4}} \qquad (17)$$

With (11) and (12) then follows:

$$\bar{v} = 2.9 \frac{D_h^{5/7}}{\mu^{1/7}\rho^{3/7}} \left(\frac{\Delta p}{L}\right)^{4/7} \qquad (18)$$

With (15) then follows:

$$\Phi_V = 2.3 \frac{\left(D_d^2 - D_c^2\right)D_h^{5/7}}{\mu^{1/7}\rho^{3/7}} \left(\frac{\Delta p}{L}\right)^{4/7} \qquad (19)$$

Above equation is valid for a perfect smooth-walled microduct. The equation changes when some wall roughness is present. An equation for this was derived by Colebroke [10] to approximate the surface roughness effect, but the equation has to be solved iteratively. Note that the transition from laminar to turbulent flow is not sharp, but a window with jumps and hysteresis.

The hydraulic diameter $D_h$ of a flow channel is defined as 4 times the flow cross-sectional area divided by the wetted surface of the channel. For a cylindrical tube with inner diameter $D_d$ the hydraulic diameter $D_h$ is simply equal $D_d$. For a tube filled with cable with diameter $D_c$ the hydraulic diameter $D_h$ would be equal to $D_d - D_c$. However, the annular shape of the flow channel is deviating too much from a circular channel for the latter expression to be valid, as is found in jetting tests [11]. It has been found empirically (also confirmed by tests with floating) that $D_h$ equal to $D_d - ½D_c$ is a beter approximation.

**9.7.1 Example.** A criterion for turbulence "coming from laminar mode" follows from (11) and (14) and for a Reynolds number of 2300:

$$D_h \geq \left[73600 \frac{\mu^2 L}{\rho \Delta p}\right]^{1/3} \qquad (20)$$

The relevant dynamic viscosities $\mu$ and densities $\rho$ are given in Table 1:

**Table 1. Dynamic viscosities $\mu$ and density $\rho$ for water and ethanol**

| Temperature | | Water | Ethanol |
|---|---|---|---|
| 5 °C | $\mu$ (Pas) | 1.5x10$^{-3}$ | 1.7x10$^{-3}$ |
| | $\rho$ (kg/m$^3$) | 1000 | 802 |
| 20 °C | $\mu$ (Pas) | 1.0x10$^{-3}$ | 1.25x10$^{-3}$ |
| | $\rho$ (kg/m$^3$) | 998 | 789 |

In Figure 10 graphs for the minimum hydraulic diameter $D_h$ for turbulence as a function of length $L$ are given for a pressure $p$ of 100 bar (maximum for current equipment). So, for a single steeltube length of 2 km a hydraulic diameter $D_h$ of 3.8 mm would have been needed for installation in turbulent mode with ethanol of 5 °C (in Section 4.5 the internal diameter was only 2.6 mm, and installation was difficult; bringing everything to 20 °C reduced the required minimum diameter to 3.1 mm, still too large, but closer; note that there is a window around the Reynolds number of 2300 where the situation can jump from laminar to turbulent and vice versa, but with hysteresis). When a total tube length of 2 x 5 km is used, a hydraulic diameter of 6.4 mm would have been needed for this. When installing with 20 °C the latter installation would require 5.3 mm. The difference between steeltube internal diameter and hydraulic diameter has to be added too.

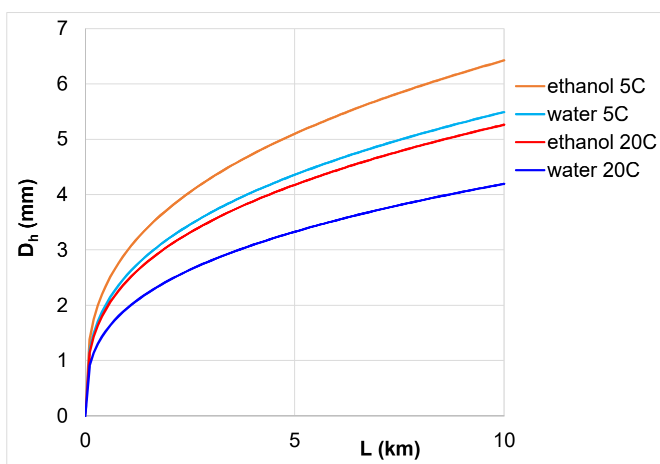


**Figure 10. Minimum hydraulic diameter $D_h$ for turbulence as a function of length $L$ for a pressure $p$ of 100 bar**

The velocity of the fluid flow is only calculated for turbulent flow (this is what we need for good floating installation performance) with Blasius, equation (18), for the worst case of water at 5 °C (not ethanol as a worst case here, because the higher density of the water counts more than the higher viscosity of ethanol). The results are shown in Figure 11. It is good to see that once the flow is turbulent, the flow velocity is higher than the targeted 30 m/min for all the treated cases. But, to really get turbulent flow, large internal steeltube diameters are needed, as stated earlier.

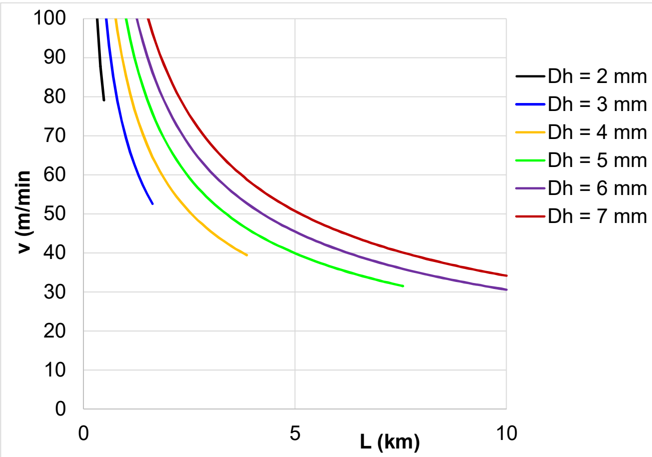


**Figure 11. Flow velocity of fluid (worst case water of 5 °C) as a function of steel tube length *L* for different hydraulic diameter $D_h$ for the turbulent mode for a pressure *p* of 100 bar, calculated with Blasius (19)**

## 10. The Authors

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