Guidelines for Conducting Cable Blowing Tests

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Abstract

Guidelines for conducting cable blowing tests are described in this paper. It is argued qualitatively that test trajectories with only subsequent bends without straight sections in between them can be useful to accommodate thermal expansion differences of bundles of microducts in the ducts, but that unwanted speed resonances might occur during cable blowing. It is stated that the cable shall always reach the end of the duct in blowing tests with a not too high pressure (e.g. 10 bar), if not cutting back of duct loops is needed. It is recommended to use the same and low end speed, e.g. 20 m/min, for each test. This shall be anticipated by adjusting the air pressure well before reaching the end, to create a stationary situation.

Keywords: Cable; optical; duct; installation; blowing; test; resonances.

1. Introduction

An important test for the characterization of optical cables is how they perform when blown into a duct. Today, there are many duct trajectories where such blowing tests are performed. They come in a variety of shapes and are installed above ground or buried. In the latter case temperature variations are limited and problems due to undulations in the (micro)ducts as a result of (difference in) thermal expansion are avoided. But, burying a duct trajectory with a length of about 1 km is costly. Different solutions for duct trajectories which are not too costly and where the (micro) ducts can be changed easily are used. Sometimes unwanted resonances in speed occur during blowing of the cables. In this paper the cause of these resonances is searched for. Furthermore, the way in which blowing tests are done differ. Not always the cable reaches the end of the duct. Sometimes high air pressure is used and the speed during the test is evaluated for comparison, and sometimes the pressure is controlled to reach the end of the duct at a certain speed. These topics will be discussed in this paper too.

Cable blowing theory, supplemented by the effect of cable filling on the air pressure gradient, has been used to analyze these resonances in cable speed. The geometry of the duct trajectory plays a role here. The effect of cable filling on the air pressure gradient also plays a role in the blowing behavior in case the cable does not reach the end of the duct. The accuracy of parameters obtained from an installation where the cable does not reach the end of the duct is discussed. Finally the effect of cable speed on an installation is treated. Although the coefficient of friction between cable and duct is assumed to be constant, this is not 100% true, e.g. because of "viscosity friction" of lubricant. Also, the force at which the cable is pushed during blowing is a function of the motor (cable) speed in many blowing machines, for a certain setting of the machine. This means that when tests are done with different end speed, it is also done with a different pushing force.

It was found that resonances in cable speed mainly occur in trajectories where distances of subsequent bends are short, in line with the explanation. When blowing a cable into a duct on a reel the effects are even extreme (the whole reel shaking and making a rattling sound) while the "burst length" going in or coming out are often in exact match with the theory.

2. Resonances

In blowing tests sometimes "resonances" occur in situations where they do not occur in blowing practice. This is an unwanted effect. It looks like the geometry of the test trajectory plays a role. When blowing a cable into a duct on a drum the resonances are very clearly present, and show a quite regular periodic behavior. In this document it is tried to find the cause of these "resonances" and advice measures to avoid them.

2.1 Blowing theory

The pushing force gradient dF/dx for a cable blown into a duct is given by [1,2]:

$$\frac{dF}{dx} = f\sqrt{W^2 + (\mathrm{T}F)^2 + (\mathrm{B}F^2)^2} - \tfrac{1}{4}\pi D_c D_d \frac{dp}{dx} \qquad (1)$$

Here F is the pushing force, f the coefficient of friction (COF) between cable and duct, W the weight of the cable per unit of length, D_c the cable diameter, D_d the duct internal diameter, dp/dx the pressure gradient along the cable (the term with the pressure gradient represents the fluid propelling force), T the effective change in direction of the duct per unit of length and B a parameter indicating buckling of the cable during pushing, the latter given by [1]:

$$\mathrm{B} = \frac{D_d - D_c}{\pi^2 B} \qquad (2)$$

The effects of slopes in the trajectory and the effect of cable stiffness in undulations in the duct are not included, because they usually do not play a significant role in blowing tests and because they do not contribute to the understanding of the resonances. For a duct in a continuous coil (e.g. on a drum) with bending radius R the parameter T is given by T = $1/R$. As a rule of thumb undulations in practical ("free" in trench) installations give an effective bending radius R of about 2000 x D_d [1,2]. So, for a "free" 10/8 mm microduct this is about 16 m. In test trajectories undulations are usually less present, but real bends are present. For the moment the theory of constant T over the entire trajectory is taken, later the focus will be on localized bends

The blowing or air propelling force is given by the term with the pressure gradient. Because air is a gas, a compressible fluid, the airflow expands towards the end of the duct, where the pressure is lower. Because of this the pressure gradient is non-linear, for a duct without cable or a duct entirely filled with cable given by [1,2]:

$$\frac{dp}{dx} = \frac{p_i^2 - p_a^2}{2\sqrt{p_i^2 - \left(p_i^2 - p_a^2\right)\frac{x}{L}}} \tag{3}$$

Here p_i is the (absolute) air pressure at the injection side of the duct, p_a the (absolute) pressure at the exhaust side of the duct (atmospheric) and L is the total duct length. However, the pneumatic resistance is larger in the part of the duct filled with cable than in the empty part, and therefore the pressure drop over the part filled with cable is larger than for an empty duct (or a duct filled with cable over the entire length). This is especially important for high duct filling factors (diameter ratio of cable and internal duct), as is the case in most installations today [4,5,6,7].

The pressure p_1 at the end of the cable is then found with [1]:

$$p_1 = \sqrt{\frac{L_2 p_i^2 D_h^{19/4} + L_1 p_a^2 D_d^{19/4}}{L_2 D_h^{19/4} + L_1 D_d^{19/4}}} \tag{4}$$

Here L_1 and L_2 are the lengths of the duct filled with cable and empty, respectively, and D_h the hydraulic diameter of the duct filled with cable. The approximation for the latter for geometries differing from cylindrical of 4 x volume divided by wetted surface, leading to a hydraulic diameter $D_h = D_d - D_c$, turned out not to correspond to tests [5,6]. Instead, the following (elliptical) better approximation (but not always 100% accurate) is used [5]:

$$D_h = \frac{2\left(D_d - D_c\right)}{1 + \sqrt{\frac{D_d - D_c}{D_d + D_c}}} \tag{5}$$

In Fig. 1 the pressure gradient is shown for a 1500 m long duct with a pressure of 10 bar (absolute) at the inlet, filled over half its length with a cable with diameter 1/3rd of duct internal diameter (filling factor 1/3rd). The pressure halfway is then 4.94 bar, about half of the applied pressure, but for an expanding airflow this is low (it would be 7.11 bar for an empty duct, or for a duct completely filled with cable). For a 6 mm cable inside a 10/8 mm microduct almost all pressure drop is along the cable part (the red line will show a much lower pressure gradient than the blue line) and the pressure halfway would be 1.34 bar.

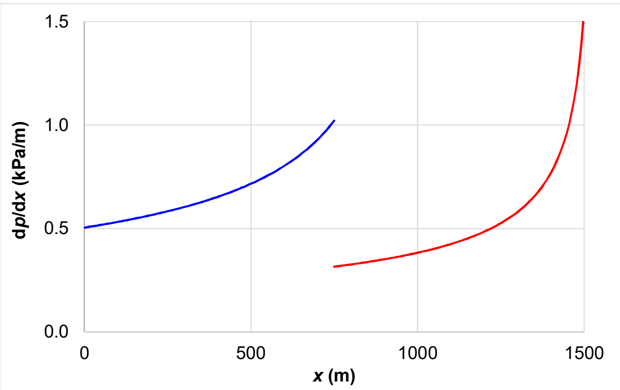

Fig. 1. Pressure gradient d*p*/d*x* as function of position *x* along duct part with cable (blue line) and empty part (red line) for 10 bar pressure (absolute) over 1500 m duct, filling factor 1/3rd and cable halfway in duct.

In Fig. 2 the air propelling force dF/dx is shown produced by blowing (from pressure gradient over cable) for a 6 mm cable into a 10/8 mm microduct (much higher filling factor than in Fig. 1) of 1500 m long for different positions of the cable head and compared to the gravity friction force fW for a coefficient of friction f of 0.06 and a weight W of 0.32 N/m. Note that the part with the empty duct is not shown anymore (no cable, no air propelling force). In [6] theoretical and measured pressure profiles, from which the pressure gradient can be derived by integrating Eq. (3), are shown for different cases.

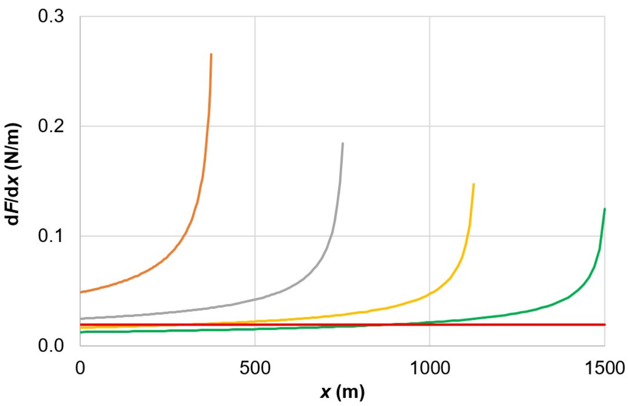

Fig. 2. Force dF/dx as function of position x for blowing along 6 mm cable in 1500 m long 10/8 mm microduct, for 10 bar pressure (absolute) at injection side for cable installed over 25, 50, 75 and 100% of duct length, compared to gravity friction fW (red line). Pressures at cable head are 1.83, 1.34, 1.13 and 1 bar, respectively.

With Eq. (1) the air propelling force and friction force from Fig. 2 can be used to calculate the pushing force build-up along the cable for different positions of the cable head in the duct. Calculation starts with the force F_h at the cable head and is then calculated back along the cable until the cable injection side, where the necessary force can be applied. The force at the cable head is close to zero. But, when the cable head is in a bend or a continuous coil there is a non-zero force resulting from friction and repulsion [1]:

$$F_h = \frac{3fB}{\sqrt{6\left(D_d - D_c\right)R^3}} + \frac{B}{2R^2} \tag{6}$$

Especially when blowing the cable into a duct on a reel, this could have a large effect, because the air propelling forces can have difficulties to fight with the capstan force from the start and continuously upstream. This problem can be solved with a sonic head [3], but this is usually not used during blowing tests.

2.1.1 Example 1. A cable with a diameter D_c of 6 mm, a weight W of 0.32 N/m and stiffness B of 0.16 Nm^2 is blown into a 10/8 mm microduct, in a trajectory according to IEC [8] (see also Fig. 6, bottom) of 1500 m long with effective bend radius R of 8.2 m (undulations with effective R of 16 m over each 50 m, connected by 180° bends with bend radius of 0.4 m) and the COF between cable and microduct is 0.06. The pressure gradient is the same as given in Fig. 2. The force at the cable head from Eq. (6) of 0.012 N is low and the effect is hardly seen for the effective bend radius of 8.2 m. The calculated force build-up from Eq. (1) for the 4 different positions of the cable head is shown in Fig. 3.

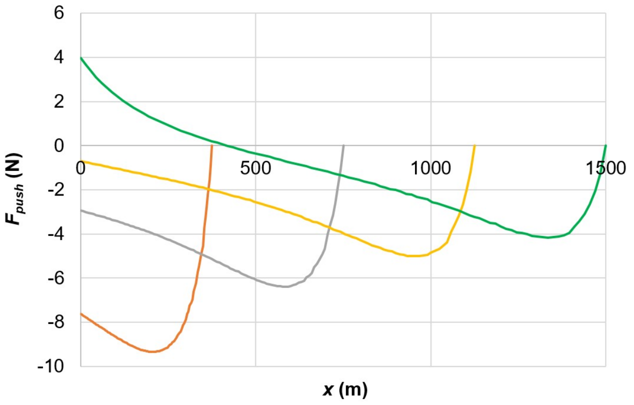

Fig. 3. Force F_{push} build-up as function of position *x* for 6 mm cable (*W* = 0.32 N/m, *B* = 0.16 Nm²) in 10/8 mm 1500 m long microduct, with COF of 0.06, for situations of Fig. 2 and for an effective bend radius of 8.2 m.

The lines in Fig. 3 can be understood as follows. Take e.g. the line at 25% of duct length. At the cable head the air propelling forces are much higher than the gravity friction, see Fig. 2, so a pulling force (negative pushing force) is building up rapidly, see Fig. 3. At some point a max pulling force is reached, where the capstan effect has become large while the air propelling force decreases when going upstream. So, the pulling force becomes less, but will not become zero, because the air propelling force remains larger than the gravity friction. For the cable head at 75% of the duct length the air propelling becomes less than the gravity friction in the first part of the duct, but the force remains tensile (pulling) at the cable injection side, because of the remaining action of the built-up pulling forces downstream. However, for the cable head at 100% of the duct length the force in the cable becomes a pushing force below 420 m from the cable injection point. When this pushing force is supplied mechanically the cable can still continue, comparable to a push-pulling installation (only the pulling not done with a winch at the end, but as a result from excess air propelling forces, and the pushing force at the injection side partly assisted by air propelling forces). This is the synergy of pushing and blowing as we know it from the blowing theory [1], except that the cable filling effect is now taken into account.

2.1.2 Example 2. In Fig. 4 the force build-up is shown for the same example as Example 1, but now with the microduct on a reel with effective bending radius of 0.6 m. Here the synergy of pushing and air propelling forces is not successful, when the cable head is at 75% of the duct length and a bit earlier. The pushing force explodes before the injection side is reached. This can be explained by a strong capstan effect, making it difficult for the pushing force to work in synergy with the air propelling force. However, it is known that blowing cables (or microduct bundles) into ducts on reel is not much more difficult than installation in the field or in a test trajectory (while the absence of the synergy of pushing and blowing would reduce the blowing distance by a factor of about 2 [1]). Furthermore also a weird phenomenon can be observed when blowing cables or bundles of microducts into ducts on a reel. Installation starts as usual, but after a while (usually after 100-200 m) the feeding stops and goes with periodic intervals, while at the same time a rattling sound is heard and the whole reel is shaking. This rattling can be heard to go zig-zag through the layers in the drum, as is shown in Fig. 5. This is caused by the cable hopping from the outside facing wall to the inside facing wall of the duct, winding by winding. At the end the cable comes out of the duct with the same period, but in counter phase with the feeding. This period often turns out to be exactly the difference in length for the cable at the outside and inside facing wall (often over the full length of the duct, i.e. all turns), respectively, so the model seems to work.

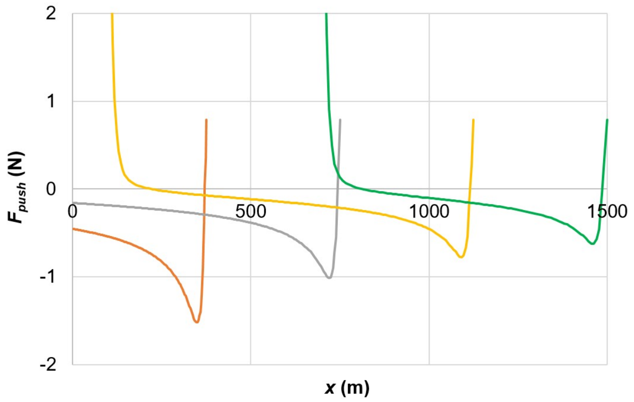

Fig. 4. Same graph as Fig. 3, but now for an effective bend radius of 0.6 m (microduct on reel).

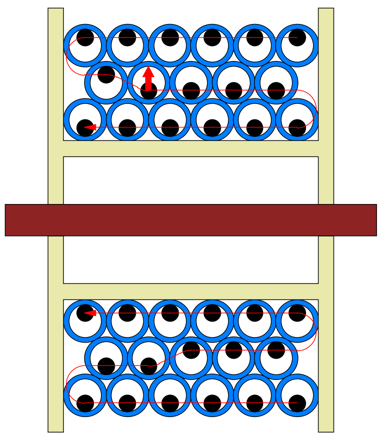

Fig. 5. Cable blown into duct wound on reel, here going from inside to outside facing wall of duct in zig-zags.

Have a closer look at Fig. 5. The initial state was with the cable at the inside facing wall of the duct, in rest. Then the cable is pushed to the outside facing wall from the feeding side. This goes by hopping turn by turn, where the cable just crosses over to the other wall. This is a process where no sliding friction occurs. That’s why the hopping continues also when out of reach of the pushing force. The air drag force, although too small to overcome gravity friction in the first length (and capstan friction is also not there, because in this process there is hardly any pushing force), is strong enough to make the cable hop over. This process continues winding by winding and layer by layer, also when the air propelling force is large enough to overcome gravity friction. Now a longer length of cable wants to move. But, it cannot get more cable length than the accumulated difference in length of cable between outside and inside facing wall of the duct. The hopping wave front also moves faster than the cable can restart from stop (inertia). But, when the hopping front reaches the duct end, where the cable is then locally at rest, **the front end of the cable sees excess air propelling forces and starts to move forward, the wave front moving from the exhaust end upstream**. Now the wave travels the other direction and hopping is from outside to inside facing wall. When reaching the feeding end of the duct a new period of over-length can be inserted by the pusher, etcetera. This process is enhanced by a combination of inertia of the cable and the fact that a cable has usually more friction when moving faster (static electric charging) while the air propelling force is smaller then (difference between airflow and cable speed smaller). Note that a test where this hopping occurs might give wrong blowing performance info.

2.1.3 Example 3. A test trajectory with loops of 100 m long consisting of a continuous sequence of left and right smooth bends with bend radius R and angles γ and $\pi + \gamma$, see Fig. 6, top. For a bend radius R of 6 m an angle γ of 74.4° follows and a total angle per loop of 955°. This is comparable to Example 1, but here there is continuous curvature (no straight sections), so hopping can take place easily. Blowing length becomes longer, but resonances may also occur (in practice seen in such trajectories when cable is about halfway). When the trajectory is made with straight sections of enough length (several tens of meters), like the IEC trajectory [8], see Fig. 6, bottom, the gained length in hopping in the short bends cannot "hop over" to a next bend such a straight length away, where gravity friction is hindering this. Also, there is less curvature in those trajectories, 180° and 360° over 100 m for the IEC trajectory with leg lengths of 100 m and 50 m, respectively.

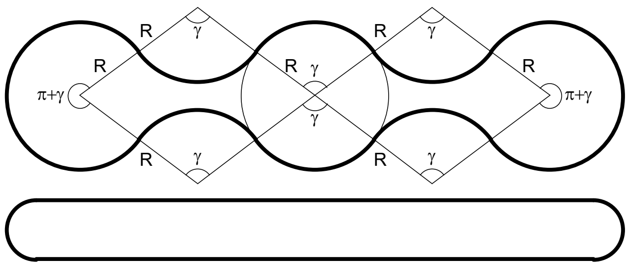

Fig. 6. Tests trajectory with continuous sequence of smooth left and right bends (top) and with sharper bends separated by straight sections (bottom).

The advantage with trajectories like in Fig. 6 (top) is that there is some margin to absorb thermal expansion differences of microducts installed in larger ducts. This is important when the test trajectory is built above ground. But, as a drawback these unwanted resonances might occur. This problem is not seen in test trajectories according to IEC, where friction in the straight sections slow down the hopping. But, when the trajectory is above ground and the temperature is high the microducts might show undulations because of overlength that is not "pushed" into the bends at the end (if this limited amount of bending degrees would absorb enough overlength anyway), which cannot be seen from outside. A solution is using "microduct spanners" at the ends of the trajectory (at the bends), see Fig. 7. The duct with coupling is mounted on a sliding profile and can be stretched by means of lorry straps. The length of max 100 m of the straight sections allows pulling the microduct undulations out.

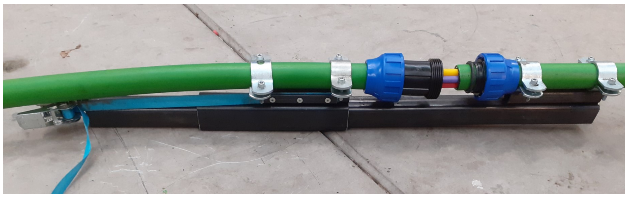

Fig. 7. "Microduct spanners".

The thermal expansion coefficient of HDPE ducts and microducts is quite high, and not the same for each duct. Differences in thermal expansion coefficients between ducts and microducts of 2 x 10^{-4} K^{-1} are no exception, i.e. when a (black) duct is heated up by 25 °C on a hot summer day the expansion will be 0.5% (50 cm on a loop length of 100 m). When a bundle of 7 microducts 10/8 mm is installed into a 50/40 mm duct the free space Δ is about 10 mm for a round bundle and about 12 mm when the bundle reshapes to the duct. For an effective bend radius R of 6 m the difference in length of outside and inside facing wall is equal to Δ/R, or max 0.2%. So, to accommodate for thermal differences a smaller bend radius would be needed (2.4 m).

3. Blowing until end of duct

Cable blowing (also called jetting) is in fact a synergy of blowing and pushing, where most of the force comes from pushing, while the "clever" air propelling forces have the largest effect because they are distributed over the cable length, locally compensating friction and therefore limiting axial forces in the cable. Because of that the exponential force build-up in bends, the notorious capstan effect which is normally the effect which limits traditional cable pulls, is eliminated, or at least minimized.

The synergy of blowing and pushing was already explained in Example 1 with Fig. 2. Air is a compressible fluid and expands towards the end of the duct, where the pressure is lower. Because of this the air velocity, and hence the air drag force per unit of length, is increasing towards the end of the duct [1]. For the duct entirely filled with cable, the drag force per unit of length typically looks like the green line in Fig. 2. And for a typical long length installation the (gravity) friction looks like the red line in Fig. 2. Existing software to calculate blowing lengths uses this green and red line in Fig. 2. At the cable entry side there is not enough air drag force to overcome the friction. Fortunately, here the pushing force assists. Pushing force action normally drops rapidly, because of the capstan effect and buckling friction. But, the pushing force only needs to assist for about 50% of the total force at the cable entry point, and further in the duct the required assistance decreases, until the air propelling forces fully takes over where the green line crosses the red line. For this reason the pushing force assistance has a very long action, usually over more than 50% of the duct length. This is what we call the jetting synergy of blowing and pushing.

Using the green line in Fig. 2 for the blowing calculation assumes that the duct is open at the end of the green line. Existing software to see how far blowing can be successful calculates with the duct open at the end of the cable, because that is the relevant blowing distance. However, a possibility exist to fix the duct length and hence the green line. But, the green line is not taking into account the filling effect of the cable. Correct calculation would need to also use the lines with different colors for the different positions of the cable head. This has not yet been implemented in the software. Reason for that is that the treated theory to calculate the filling effect is not always 100% accurate. Different results have been obtained for different cases [4,5,6]. Therefore it is recommended to always blow the cable until the end, making it possible to estimate the effective coefficient of friction, which can be used in software when the blowing length for an arbitrary trajectory is calculated. A blowing test result where the cable did not reach the end is meaningless (because of the above arguing, and because no software exists to "back-calculate" the coefficient of friction from such a test), not even for comparison of different cables (with usually different cable diameters and different filling effects). It is therefore recommended to cut back the length of the duct (disconnect couplings between loops) in which the cable blowing tests is done when it looks like the cable cannot reach the end with acceptable speed or pressure (when a cable just reaches the end at the highest pressure and with a low speed the cable cannot be blown out anymore, at least not without the help of e rear sonic head [7]).

The following example illustrates which kind of errors can be made. In general a small cable blows better than a larger cable in the same duct. That is because the weight of the cable is proportional to the square of the cable diameter (assuming constant density) while the air drag forces are linearly increasing with the cable diameter. Nevertheless, a large cable can sometimes blow better than a small cable in the first part of the duct, because it takes a bigger part of the pressure drop. But, further in the duct the bigger cable loses. As all cables you install in practice need to reach the end, it makes no sense to test a cable not reaching the end.

4. Recommendations for testing

In this section recommendations are given to achieve optimal comparison of blowing properties of different (micro duct) cables. With this also the parameters can be obtained needed to "back-calculate" the effective coefficient of friction, so estimations can be made for the blowing performance in practical trajectories differing from the test trajectory.

4.1 Constant blowing pressure

It is recommended to blow with a constant air pressure, e.g. 10 bar, not too low (because of accuracy, or to keep the flow turbulent in case very small microducts are used) and not too high (well below the maximum pressure of the compressor or duct, to ease blowing out at a higher pressure). This pressure can be set after the first meters of cables have been pushed in, to avoid the risk to blow out the cable (when the pneumatic motor pressure is still zero, or when the electric drive has not yet been powered, the equipment might not hold the cable when air pressure is set on the duct). It is intended to reach the end of the trajectory with a low speed, e.g. 20 m/min, about the same for all tests for a right comparison. It might be needed to shorten or elongate the trajectory (e.g. take out or add loops) if it looks like that such an end speed cannot be met. This shall be done well (e.g. 100 m) before the cable reaches the end, to be sure of a stationary airflow (for which the theory used in the calculations applies) at the end of the test.

4.2 End speed

As was said in the previous sub-section it is intended to end the test with a low speed, e.g. 20 m/min, about the same for all tests. Best is to select the right test length, fixed well before reaching the end (for stationary flow) so installation can be done with a convenient air pressure of e.g. 10 bar. If selecting the right test length is difficult, it is also possible to change the air pressure to a value where the end speed is expected to be around the low value of e.g. 20 m/min. Also this has to be fixed well before the end of the test to enable the airflow to become stationary.

Reaching the end with a same low speed is useful because of:

- Dependency of COF on speed is eliminated. Same for all tests and also nice information to see how far you can blow (no limitation that you need to reach the end at a speed record).
- Often the pushing force of blowing equipment also depends on speed, e.g. a pneumatic motor at a fixed air pressure gives a higher pushing force when the speed goes down.
- The force to pull the cable from the cable drum also varies with the speed.
- Dissipation in drive belts of blowing equipment varies with speed, etcetera.

4.3 Blow until the end

As was said already the cable should reach the end of the test trajectory in order to have meaningful results. In that case the pneumatic resistance is constant over the entire test length and there are no issues with change in pneumatic resistance at the parts where the duct is filled with cable. So, no problem with:

- Inaccuracy of calculation with fill factors.
- Absence of software to calculate with different fill factors.

4.4 Other measures

- Use the same equipment for all tests.
- Take care of using the same kind of ducts.
- Lubricate the same way.
- Take a fresh duct and cable for every combination. A duct or cable can be used another time from dry to lubricated, but not vice versa. An example of testing all conditions:
    - Test with fresh cable and duct, both dry.
    - Take out cable and rewind carefully. Can be used a second time with the duct now lubricated.
    - Take out cable and rewind carefully. Can be used a third time, now also the cable lubricated.
    - In case also a lubricated cable in a dry duct must be tested, it is needed to replace the duct with a fresh one.
    - If all 4 above combinations need to be tested, it is also possible to change the sequence such that instead of a second duct a second cable is needed.

5. Conclusions

In order to perform a cable blowing test, and obtain a good comparison between different cables, as well as a "back calculated" effective coefficient of friction, the following is recommended:

- Preferably bury a (micro)duct test trajectory. If not, then a place in the shade is recommended and/or color black avoided.
- If the test trajectory is above ground and used to blow in (bundles of) microducts for testing microduct cables, and subsequent bends are present without straight sections in between them to accommodate bundles of microduct to expand thermally, then resonances in cable blowing speed may occur. These resonances also might give wrong information about the cable blowing distance in practice.
- If in the above case only a few bends are present (long straight sections in between them), then these resonances are usually suppressed, and microduct spanners can be used to avoid undulations from thermal expansion.
- Perform the blowing tests such that the cable always reaches the end of the duct.
- Perform the blowing test with constant pressure of e.g. 10 bar soon after the start, to be able to estimate the length which can be reached with that pressure, and being in time for cutting back one or more duct loops.
- Once the right duct length is made a pressure must be set well before the cable reaches the end, anticipating the cable reaching the end with a defined and not too high end speed, e.g. 20 m/min.

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7. Authors

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