Projects with Remote Installation (“Tube Post”) of Energy Cables in Ducts

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ABSTRACT

A method was developed to install energy cables into ducts and then further transport them through coupled ducts, like “tube post”, to any desired location, without the need to go there with material, equipment and labour. There is almost no limit to the FreeFloating distance over which cables can be transported. Many advantageous applications exist, like installing cables into crowded city centres from suburbs and offshore cables from shore. A land project with FreeFloating in Copenhagen is described, and a project in Thyborøn (Denmark), where offshore wind turbines were connected by array cables installed from shore, even at Beaufort wind force 8.

KEYWORDS

Energy cable; HV cable; Installation; Duct; Pipe; FreeFloating; Water; Pressure; Pig; City centres; Offshore; Wind Energy; Remote.

INTRODUCTION

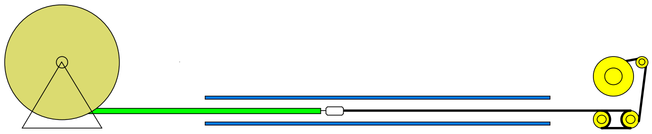
Energy cables can be installed aerial or underground. In the latter case the cables can be direct buried or installed in ducts. Special methods have been developed to install cables into ducts using water under pressure [1,2,3,4]. A typical advantage is that operation is economical, direct installation with all material, equipment and labour at one (entry) side of the duct. Moreover, long lengths can be installed and the methods are friendly to the cable. Maybe the most appealing variant is FreeFloating where the cable, once installed in the duct, is flown further by the sole action of water, like “Tube Post”, from any convenient launch location to any desired destination location, almost without any limit to the distance over which the cable can be transported, the limits discussed in this paper. This technique already proved to work in an installation trial at a test site in Saint-Étienne-du-Grès (France) [3]. In this paper two projects are described with FreeFloating, a land project in Ballerup, a suburb of Copenhagen (Denmark), and the Nissum Bredning offshore wind farm project in Thyborøn (Denmark).

BENEFITS CABLE IN DUCT

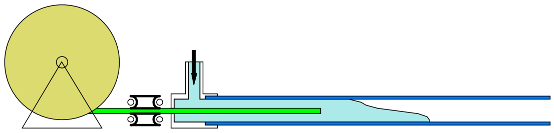
Several advantages can be recognized for cable in duct solutions. In general cables can be removed or replaced without digging up. Protection in the pipe is even better than for direct buried cables [4], because of the free space in the duct, a well-known fact in Telecommunications. There are specific benefits for both land and offshore applications. On land ducts can be laid in short sections and then simply be coupled together. No need to keep trenches open for long lengths and long time, reducing neighbourhood disturbances. For offshore applications no cable armouring is needed, which allows to use standard “land” cables and save a lot on costs. Also AC losses are minimized. Additionally, the risk of cable damage is smaller because they are installed after the pipes (ducts) have safely been laid into the seabed. The position of the pipe (i.e. also with respect to the seabed) can accurately be monitored using intelligent pigging, which has also been done in the Nissum Bredning project.

And last but not least all cables can be installed from a convenient launch location when using the FreeFloating technique, enabling to reach crowded city centres, tunnels, and national parks, without the need to go there with equipment, and even installing offshore cables from shore, also array cables between the offshore wind turbines. The latter enlarges considerably the offshore working window, allowing to keep on installing at bad weather conditions.

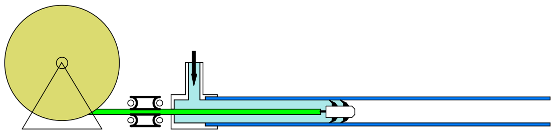
INSTALLATION CABLE IN DUCT (PIPE)



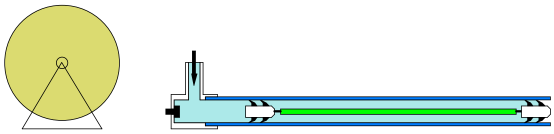
Pulling (winch)



Floating (WATUCAB)



WaterPushPulling (WATUCAB)



FreeFloating (WATUCAB)

Fig. 1: Cable-In-Pipe installation techniques

Pulling (winch)

The traditional way to install cables into ducts is pulling them with a winch, see Fig. 1. For this first a pulling rope has to be installed. Also installation equipment and labour are required at both ends of the duct. Furthermore the capstan effect (friction of the cable under tensile load in bends) limits the cable lengths which can be installed in one pull. Synchronization between winch and drum pay-off is often troublesome. Three “WATUCAB” techniques, using water under pressure, have been developed to install energy cables into ducts, see Fig. 1. The typical drawbacks for winch pulling are taken away, and also the forces on the cable (and wear) are reduced.

Fig. 2: Cable installed by using water

Floating

In the first technique, called Floating, water under pressure is injected into the duct with cable, creating a high speed (higher than the cable speed) water flow, while at the same time the cable is pushed into the duct (and pulled from the drum), see Fig. 2. The high-speed water flow creates a distributed drag force propelling the cable. This distributed force locally compensates the friction between cable and duct, avoiding axial force build up in the cable, hence eliminating the capstan effect. The same trick as with cable blowing [2], a technique used worldwide today to install optical cables into ducts. Extra beneficial effect with Floating is the buoyancy of the water, reducing the friction between cable and duct. With this technique extremely long installation lengths can be reached (with Low Voltage cables already 10 km has been reached), also in trajectories with many bends. Moreover, there is the benefit of single point entry (installation equipment, cable drums and labour), reducing costs considerably. The technique is user and cable friendly (low forces, no cable wear) with compact equipment and does not suffer from synchronization problems with the cable drum. With the present equipment a comfortable cable speed of 15 m/min can be used.

WaterPushPulling

The second technique, called WaterPushPulling is mainly the same as Floating, except that a pig is mounted at the foremost end of the cable. Now all forces exerted by the water under pressure are concentrated at the cable front head and the water flows with the same speed as the cable. The latter makes it possible to still use relatively small pumps for larger diameter ducts (e.g. larger than 100 mm internal diameter). The relatively high pulling force at the cable front head also enhances passing sharp bends. But, the capstan effect is back again. Fortunately, duct trajectories for energy cables are rather straight and buoyancy has not vanished. With balanced pushing and pulling forces (still lower than with winch pulling) installation lengths can also be very long (3.3 km reached with cables with aluminium core), usually much longer than with winch pulling. When using a “sonic head” (pig with valve that opens at adjustable pressure) the advantages of Floating and WaterPushPulling can be combined and optimized to the duct trajectory, even when the latter is extremely curved and with small bend radii (a 82 mm 3x36 kV cable could be installed over 646 m into a HDPE duct with internal diameter of 102 mm which was wound in 46 coils with a continuous bend radius of 2 m [5]).

FreeFloating

The third technique, called FreeFloating, is maybe the most appealing one. It starts after a cable has been entirely installed by WaterPushPulling, with a special pig used. Then the duct is extended at the entry side such that the cable is entirely inside, and with some space to insert a rear pig. The rear pig can either be attached to the cable, like in Fig. 3, or placed loosely as a “bumper pig”. Next the duct is closed and water under pressure admitted. The rear pig is “communicating” with the front pig such that they share the water pressure. In this way the cable is effectively PushPulled by the sole action of water, and travels further like “tube post”. The cable can be placed at any desired location. There is in fact no limit how far the cable can be transported, as the water pressure difference is mainly effective at the pigs. There might be some viscous pressure loss over the feed length of duct, but this can be reduced at wish by reducing the cable (and water) speed. In fact, higher cable speeds are reached with FreeFloating (in the Copenhagen and Nissum Bredning projects, see further, 25 m/min and 28 m/min were reached, respectively) than with WaterPushPulling, for ducts not too narrow and long.

Fig. 3: Rear end of cable prepared for FreeFloating

FIRST FREEFLOATING TRIAL

FreeFloating was demonstrated to work in a trial at the EHTP / Plumettaz facilities in St. Etienne du Grès (France), in a test circuit of a 976 m PVC duct of 160/152 mm, buried in the ground [3]. This circuit has been built in 4 loops and contains 14 bends of 90° and 3 siphons. This circuit was used earlier to demonstrate WaterPushPulling of a 82 mm 90 kV cable, with 1000 mm² aluminium core and weight of 68 N/m. To demonstrate FreeFloating, where the cable has to “travel” some length “loose from the machine”, a shorter (700 m) and slightly larger (89 mm, 84 N/m) cable was used. After installing this cable by WaterPushPulling (see Fig. 4) the cable could be FreeFloated further to the end, with a pressure of only 2 bar (maximum pushing and pulling force on the cable < 200 daN).

Fig. 4: FreeFloating trial in St. Etienne du Gres

COPENHAGEN (LAND) PROJECT

The first real project where FreeFloating was used was in Ballerup, a suburb of Copenhagen. Here 6 cables were installed for Energinet in 2 sections of the connection Veljeå-Ejbygård, see Fig. 5. Cable lengths were 1695 m and 1574 m in Section 1 and 2, respectively. The cables were 132 kV cables with 1400 mm^2 solid Aluminium conductor, with outer diameter 94 mm and mass 9.2 kg/m. Their semi-conductive PE jackets contain graphite, resulting in a relatively high coefficient of friction. The cables were installed into 160/140 mm PE ducts. Cable installation was carried out by NCC.

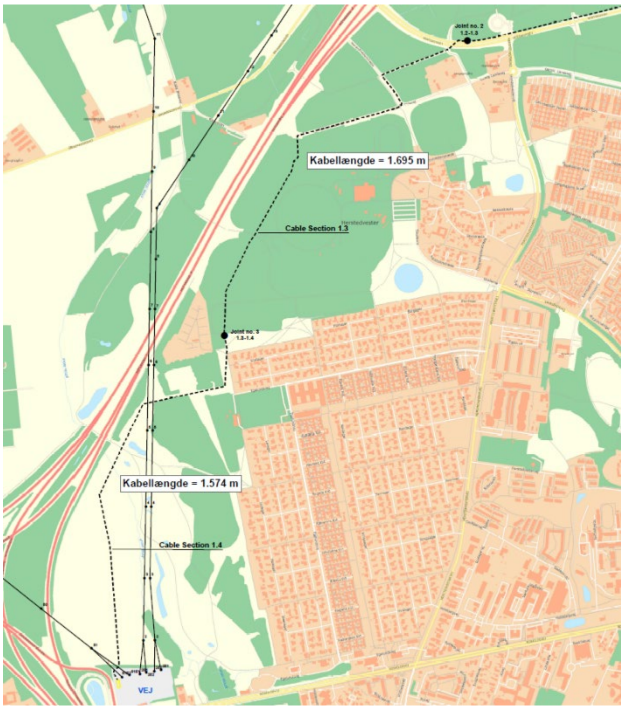


Fig. 5: Trajectory Copenhagen FreeFloating project

The cables for the 2nd section were installed by FreeFloating, after initial inserting the cables into the duct (1st section) by WaterPushPulling (see Fig. 6). After recoupling of the ducts the cables for the 1st section could be installed behind the installed cables by WaterPushPulling again. Advantage is that all the work can be done from one launch location, enabling deployment in city centres from surrounding entry points. After the initial learning curve of the first time FreeFloating in a real project it was possible to install 2 cables in one day (1st cable installed by WaterPushPulling, further installed by FreeFloating and 2nd cable installed behind the 1st by WaterPushPulling). In the project the water was recycled and the remaining water brought to a waste water station.

Fig. 6: Installation of the cable in Copenhagen

NISSUM BREDNING OFFSHORE WINDFARM

Siemens Gamesa Renewable Energy A/S has designed and installed an offshore wind farm with 4 wind turbines of 7 MW in the Nissum Bredning (Limfjord) at Thyborøn, Denmark, see Fig. 7. In this project they implemented 8 of their innovations, one of them the Cable In Pipe solution. Here the cables were not directly laid into the seabed, but installed into HDPE pipes, jetted previously into the seabed as a bundle of 4. Cable and pipe installation was subcontracted to JD Contractor A/S. All three techniques where water under pressure is used to install the cables in the ducts were used in this project, Floating, WaterPushPulling and FreeFloating, the latter allowing to install from shore (see Fig. 8), also at Beaufort wind force 8, showing how much the working window can be enlarged for offshore in the “bad season” (and bad it was!).

All connections were made with three 72 kV (1x630 mm^2 Alu stranded core) cables with outer diameter of 68.1 mm and with a mass of 4.6 kg/m, installed into 110/90 mm HDPE ducts in a bundle of 4 configuration (one spare duct) and a 40/29 mm duct in the centre for an optical cable. Cable lengths were between 950 m and 1250 m.

In Fig. 7 two details are enlarged, showing the duct return loops at the foot “bunkers” of the turbines. To FreeFloat a cable to be placed between the two turbines in the front (with the enlarged views) this cable is first installed by WaterPushPulling from land (see Fig. 8) until it is entirely in the duct. Then it is FreeFloated further, passing the slack duct loops at the foot of the turbine in the front at right, the J-tube up, through the bunker to the other side of it, through the duct return loop at right, back through the bunker, J-tube and duct loops, and then further to the turbine in the front at left, again through the duct loops and the J-tubes. The duct return loop in the turbine at right has a bend diameter of 5.25 m and is reinforced with a steel cross to keep its shape. Also double loop FreeFloating was done, now the cable also passing through the return loop in the turbine in the front at left, the cable finally reaching the turbine in the back at left. The second duct return loop has a diameter of only 3.25 m (radius 1.625 m!), without the need for reinforcement, and also here the cable could pass.

Fig. 7: Nissum Bredning Offshore Wind Farm, with details of FreeFloating return loops

Although all cables could be installed from shore, 2 cables were installed from the vessel at a calmer day, to show that this is also possible (solution for wind farms far away from shore, but in the next section also FreeFloating from shore to remote offshore wind farms is discussed). In total 12 Medium Voltage cables were installed. For monitoring and communication optical cables were installed into HDPE pipes (central in the bundle) using the Floating technique, this time all the way from the substation. A MiniJet with sonic head was used, longest distance reached of 3.8 km. The first kWh power was produced on February 18th 2018.

Fig. 8: Installation of the cable at Nissum Bredning

LIMITS OF FREEFLOATING

In this paper the limits of the FreeFloating technique are discussed. What is the maximum length over which the cables can be FreeFloated, and at which speed (high enough for the installation to still be economical)? And what about hydrostatic pressure differences at large elevation differences over long length? In this paper it is argued that FreeFloating is still possible over long distances (40 km!) while at the same time a high speed (40 m/min!) can be reached. This means that in 24 hours a cable can be installed, including preparation. And with a second or third feeder duct the daily production can be enlarged (still with one launch unit, with simple water feeding units for the cables underway with FreeFloating), making installation economical also for such long distances. Finally it will be treated how to optimize pressures and how to handle ducts with differing diameters.

Elevation differences

When a cable is FreeFloated over a very long length (many cable lengths), there might be a large difference in elevation between the launch point and the end point (or a point halfway). As every 10 m elevation difference is equivalent to a hydrostatic pressure difference of 1 bar, this might be a limiting factor for the distance over which FreeFloating can be used. For downhill installations the maximum duct pressure can be limited using a pig with safety valve [5]. Uphill there is no problem with water pressure getting too high, but there will be reduced pressure available for the pig, reducing the installation performance. In some cases intermediate water pumps can be used to boost the pressure. This is all for land projects. For offshore (submarine) projects the duct ends at destination are usually not much higher (or lower) in elevation than at the launching point, so here there is no hydrostatic problem. And when there are deep dips in the duct route, the water pressure outside the duct increases with the inside, so the duct will not see too high pressure.

How far and fast can cables be FreeFloated?

FreeFloating is normally done at very low pressure losses (pig pressure close to applied pressure). However, when FreeFloating (and water) speed are high and the total duct length is long, a viscous pressure drop limits the available pressure difference to move the cable. Fortunately, it is still possible to reach long distances (e.g. 40 km at a speed of 40 m/min!). And higher speeds are possible at shorter lengths. As long as the cable speed remains smaller than 60 m/min, sudden stops are still okay for cable and duct (water hammer, cable inertia), as will be explained.

Water speed

As for FreeFloating the water speed must be at least as high as the cable speed (and for Floating even higher), it is relevant to consider water hammer effects in this paper. Moreover, the theory which is developed in this paper for a sudden cable stop finds a lot of common ground with the existing theory of water hammer, which is therefore treated first. Water hammer (or, more generally, fluid hammer, also called hydraulic shock) is a pressure surge or wave caused by a fluid (usually a liquid but sometimes also a gas) in motion when it is forced to stop or change direction suddenly (momentum change). A water hammer e.g. occurs when a valve suddenly closes (also other causes of sudden blocking possible, e.g. when a cable or pig passes or hits a duct narrowing) somewhere downstream in a duct system, and an upstream pressure wave propagates through the duct. This pressure wave can cause major problems, like duct bursting. When a valve in a duct is suddenly closed, the moving column of water will stop. But, this is not occurring instantaneously for the entire column of water (which would result in infinite pressure when the valve is closed instantaneously). First the water at the valve stops and a pressure wave travels backwards, the amount of water which has stopped growing with the speed of sound c (about 1500 m/s in water). From this the Joukowsky formula follows for the water hammer pressure p when a fluid with speed v is suddenly blocked [6]:

$$p = \rho c v \qquad [1]$$

Here ρ is the density of the fluid (1000 kg/m^3 for water). Example: For a water speed of 1 m/s (60 m/min) this would result in a pressure of 15 bar. In pipes the speed of sound in water is lower because of expansion of the duct. For even relatively thick-walled HDPE ducts with SDR 11 (duct OD divided by wall thickness) the speed of sound would already decrease to 23% of the speed in bulk water, and the water hammer pressure decreases proportionally. As such pipes are rated 16 bar for their lifetime, the short term water hammer will by far not be a problem for water speeds of 60 m/min. Moreover, when no valve is suddenly closed and the water hammer is caused by a sudden stop of cable and pig, the safety valve in the pig [5] will limit the pressure to a safe value (of course the opening in the safety valve shall be large enough to release the full water flow, which is also dependent on the duct and cable diameter).

Cable speed

When the cable end hits an obstacle and comes to a sudden stop, it will experience a compressive axial force under which it will buckle in the duct (note that with buckling is meant that the cable shows undulations, it does not mean that the cable is out of specification). As the buckling "absorbs" effective cable length, not the whole cable is stopped at once. The portion of stopped and buckled cable will increase, like a wave traveling backwards (same as for water hammer). First it is calculated how much relative length ε_s of cable can be stored as a function of axial compressive force F_c. The worst case situation is considered that the duct is fixed in its position, not moving sideward or elongating. The total "absorbed" relative length ε_s of the stopped cable length L_s is given by [7]:

$$\varepsilon_s = \left[\frac{1}{k_c} + \frac{c_b \left(D_d - D_c \right)^2}{4\pi^2 B} \right] F_c \qquad [2]$$

Here k_c is the effective spring constant of the cable, B the stiffness of the cable, D_c the diameter of the cable, D_d the internal diameter of the duct and c_b a geometric factor which is equal to 2.23 for 2-dimensional (sinusoidal) buckling and equal to 4.93 (= ½π^2) for 3-dimensional (helical) buckling. The left term is the relative axial compression of the "straight cable" and the right term the "buckling relative storage length". When the cable with initial speed v_c suddenly stops, not the whole cable stops instantaneously. First the front end stops and then the amount of cable coming to a standstill grows backwards, like a sound wave, with a speed v_s given by:

$$v_s = \frac{v_c}{\varepsilon_s} \qquad [3]$$

The mass M_s stopped in a time Δt is given by:

$$M_s = m_c v_s \Delta t \qquad [4]$$

Here m_c is the mass of the cable per unit of length. The change of momentum $M_s v_c$ of the stopped cable is equal to $F_c \Delta t$, so it follows:

$$F_c = m_c v_s v_c \qquad [5]$$

This equation looks similar to the Joukowsky formula for water hammer (dividing by a surface in m^2 changes force into pressure and mass per unit of length into density). Writing out further, with equations [2] and [3], it is found:

$$F_c = \sqrt{\frac{m_c}{\dfrac{1}{k_c} + \dfrac{c_b \left(D_d - D_c \right)^2}{4\pi^2 B}}} \cdot v_c \qquad [6]$$

From equations [5] and [6] also the speed v_s of the "buckled cable wave" follows:

$$v_s = \sqrt{\frac{1}{m_c \left(\dfrac{1}{k_c} + \dfrac{c_b \left(D_d - D_c \right)^2}{4\pi^2 B} \right)}} \qquad [7]$$

Example (cable and duct used in the Nissum Bredning project): Cable 72 kV (1x630 mm^2 Alu stranded core), diameter D_c of 68.1 mm, mass m_c of 4.6 kg/m, effective spring constant k_c of 60 MN (educated guess, 0.1% strain at 60 kN) and stiffness B of 2500 Nm^2 (rule of thumb estimation) in SDR 11 duct 110/90 mm. For 2-dimensional buckling (worst case) a force of 12.9 kN is found for a cable speed of 1 m/s. For this force the cable is compressed axially by about 0.022% and buckling takes about 0.014%, a total of 0.036%. The backwards “wave” travels with more than 2800 m/s (faster than the water wave). Max pulling force on the cable is 18.9 kN, so with 1 m/s cable speed the maximum force at crash is still well below this maximum. The force on the cable at sudden stop will probably be less, because the duct will also expand during cable buckling. The maximum sidewall forces and the minimum bending radius of the buckled cable can also be calculated. Their values are far away from the critical values.

The above equations were derived for a sudden cable stop due to blocking at the front end. It is also possible that blocking occurs at the cable inlet, e.g. when a lump is present in the cable jacket. Now the cable stops from the cable inlet, and the elongation is tensile. In this case a forward “wave of cable under strain” is travelling, not under compressive but under tensile stress. Buckling storage will not occur, so equations [6] and [7] will be with a c_b value of zero. For a cable speed of 1 m/s the forces on the cable at sudden stop will be 16.6 kN (still okay) and the forward “wave” travels with speed of more than 3600 m/min.

Viscous pressure drop along duct

The fluid speed v for a pressure drop p over a length of duct L is given by Blasius’ equation [6]:

$$v = 2.9\frac{D_d^{5/7}}{\mu^{1/7}\rho^{3/7}}\left(\frac{p}{L}\right)^{4/7} \qquad [8]$$

Here μ is the dynamic viscosity (10^{-3} Pas for 20 °C water) of the fluid (note that the majority of the duct is without cable, so D_d can be taken as the hydraulic diameter). In order to reach a speed of 40 m/min over a 160/130 mm duct with length of 40 km a water pressure of 12.4 bar is sufficient, leaving some pressure to FreeFloat the cable.

Different duct diameters

Finally it will be treated how to optimize pressures and how to handle ducts with differing diameters, e.g. from export to array (at platform) or at outer edges of a wind farm. The cable then has to pass places with changes in inner duct diameter, usually to a smaller one, see Fig. 9. In this case the pig is replaced by a smaller one when the cable arrives, and reinserted into the smaller duct, closing again the duct system. FreeFloating can then be restarted until also the rear pig comes out and is replaced, after which the cable is FreeFloated further into the smaller duct. No need to store heavy cable drums at platforms in offshore wind farms!

During the time that the cable is partly in the larger and in the smaller duct, pressure regulation is needed at the connection point. FreeFloating goes best when the force F_2 on the front pig is about the same as the force F_1 on the rear pig. For this a pressure p_m follows in between the pigs:

$$p_m = \frac{D_1^2 p_1 + D_2^2 p_2}{D_1^2 + D_2^2} \qquad [8]$$

The optimal pressure p_m might differ a bit from the one of equation [8]. Usually it is better to have a slightly higher F_2 than F_1. Also corrections have to be made for the viscous pressure drops in duct 1 and duct 2 (using Blasius). But, the best results are obtained when optimizing the pressure in a feedback loop, maximizing the flow that comes out at the duct connection.

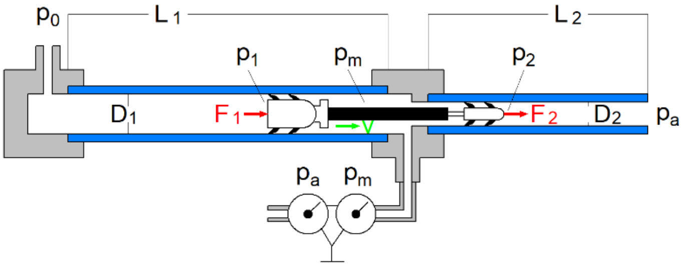


Fig. 9: Schematic view of connection to smaller duct

CONCLUSIONS

The remarkable technique of installing a cable into a duct by FreeFloating (from any suitable location to any desired location, avoiding difficult to access places) has proved to work in a test trial and in two pilot projects, one on land and one from land to offshore. Advantages are huge, like the possibility to install offshore cables in extreme weather conditions. It is argued that this can even be done over long distances, e.g. 40 km away from shore, with economical speed of 40 m/min.

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