INTEGRATION OF AIRBORNE WIND ENERGY WITH THE OIL AND GAS INDUSTRY

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Abstract: The oil industry has regained a reputation of being a competitor to Renewable energy. With the ever-rising demand, towered energy and the momentum to shift into more sustainable solutions, a common ground between conventional and renewable energy production can be found by means of co-generation. This paper presents a method of integration between oil and renewable energy namely Airborne Wind Energy (AWE) focusing on Kite technology with brief introduction into the kinematics and force distribution on airborne kites. Deriving an analytical model of the so called pumping cycle kites which its principal of operation is to mechanically drive a ground based generator, an insight into crosswind motion is presented and a formula to find the mean mechanical power is obtained. Along with a wind distribution profile on various regions in Libya using a Weibull distribution model calculated by iterative techniques to specify its constants. Using the model to compute electrical power generation on board the platform, operate distant wells or pumping heads. Followed by a case study on using such technology in offshore platforms and the impact it can carry on energy consumption in such platforms, presenting results in terms of fraction of energy generated to the consumption of the platform as well as savings in CO2 emissions. Presenting the possibility of expansion and scalability of such technology and its impact on the oil and gas industry in Libya.

Keywords: Airborne energy, Wind Energy, Renewables.

INTRODUCTION

For many years, oil and gas sector was seen as a competitor for renewable energy with the prior offering practical satisfaction for energy demand while the latter focuses on sustainability, environment and planet habitation. The power generated using wind turbines increases with the cube of the wind speed, hence doubling the wind speed would increase the available power by a factor of eight times. It is this fact that motivated many researchers and engineers to propose various concepts for extracting electricity at high altitudes “1-10Km” (Bolonkin, 2004; Roberts *et al*, 2007). Such ideas manifested in attempting to locate wind turbines at high altitudes. However, in recent years several designs have been suggested to use tethered kite to collect energy at high altitude. In this paper the traction of pumping kite generator is considered. The operating principle of such a device revolves around driving a ground based electric generator using a tethered kite as an alternative to locating a wind turbine at high altitude. On the ground the lower portion of the tether is wound around a drum connected to a generator. Energy is harvested by allowing the kite to fly at high altitude in a lying eight orbit with high crosswind speed (Loyd, 1980). During the fast crosswind motion the kite develops high pulling forces unwinding the tether around the drum and thus rotates the drum generating electricity through the generator. The kite is controlled such as the pulling force is reduced during operation and the tether is wound back by operating the generator as motor. This cycle is repeated and hence the name pumping cycle. It is worth noting for generation with this system relies on kite dynamics control to obtain large and small pulling forces alternatively (Argatov *et al*, 2009).

More than two thirds of the power generated by a conventional turbine is extracted from the outer portion of its blade (Van der Vlugt *et al*, 2013). A kite represents the outer portion of the blade and hence, it generates electricity using the most active criteria

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of a wind turbine, disavowing complementary parts such hub, tower and others. These results in a sharp decrease in size required for the system.

Methods for using such a system with oil and gas production are presented and discussed. A numerical experimentation is carried out to calculate the power generated of such a system and compared with possible applications in the oil and gas industry.

KITE POWER

Kites have been seen to hold considerable application in pulling load and was refined by G. PoCock in around 1825 to as much as was technically possible at the time. However, with the rise of aerodynamics in early 1900 followed by energy crises have centred many efforts toward utilising wind energy, though kites where disregarded as mean of a viable source of energy (Schmehl *et al*, 2014).

A kite surface converts the wind energy to useful forms of energy either by housing a turbine on the kite or by driving a load on the ground e.g a generator. The latter is most interest in this paper. A motion of the kite tethered at a central point and moving downwind, will achieve a near transvers motion that will be termed as cross wind. This allows for the kite speed to increase beyond the wind speed due to the glide ratio of the kite profile CL/CD (Schmehl *et al*, 2014) thus, producing enough lift to sustain the kite airborne and generate energy.

Simple Model

As soon as kite is set to the atmosphere and allowed to move in cross direction to the wind vw with velocity va the tension in the cord noticbly increases due to increasing lift force experienced according to eq (1):

$$F_L = \frac{1}{2}pAC_L v_a^2 \qquad (1)$$

Thus if a kite with is flown with velocity va that is ten times faster the air speed than a force with a factor of 100 will be produced in comparison with a stationary kite in the sky.

There are several modes where a kite can be used to generate power. One way is by having a drum on the ground attached to the kite tether the drum is coupled with a generator that turns as the tether is reeled-out. Hence the power produced will be the tension on the tether TL multiplied by extension velocity of the tether vL:

$$P = T_L V_L \qquad (2)$$

As mentioned earlier the most efficient orientation would be to fly the kite in cross wind by roll controlling the kite to the desired condition to make use of the added velocity induced by lift. Such a velocity triangle is depicted in (Fig. 1).

It is noted that the velocity of wind, kite, and cross namely Vw, Va and Vc respectively form a right triangle. By using trigonometric relation, it can be shown that.

$$V_a = (V_w - V_L)\frac{L}{D_k} \qquad (3)$$

Hence, the lift can be defined as

$$F_L = \frac{1}{2}pAC_L(V_w - V_L)^2 \frac{L^2}{{D_k}^2} \qquad (4)$$

Now, by combining the former equation with definition of the power density in wind Pw

$$P_w = \frac{1}{2}p{V_w}^3 \qquad (5)$$

A function F can be defined which describes the operation of the kite. Since we are dealing with cross wind operation it will be termed as Fc

$$F_c = \left[\frac{L}{D_k}\right]^2 \left[\frac{V_L}{V_w}\right]^2 \left[1 - \frac{V_L}{V_w}\right]^2 \qquad (6)$$

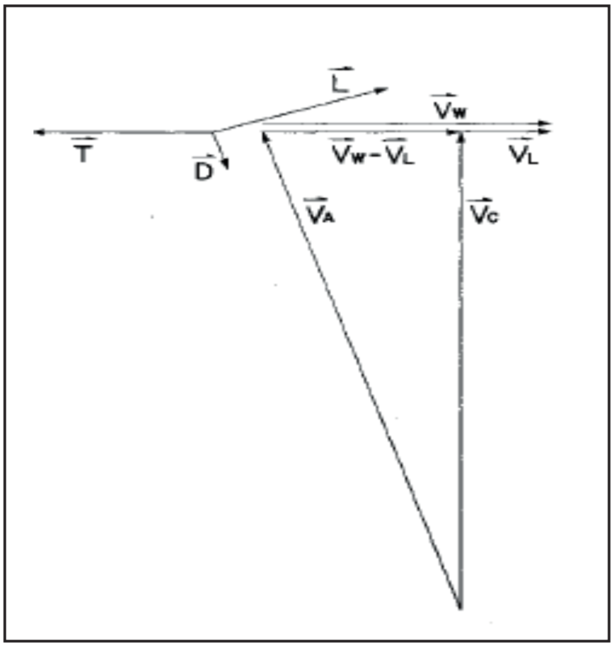

Fig. 1. A schematic of kite power systems with offshore rigs.

This allows to find the maximum point for Fc and hence power produced by the kite since power produced can be modelled as for any mode of kite operation:

$$P = P_w A C_L F \tag{7}$$

$$F_{max} \ when \ \frac{V_L}{V_w} = \frac{1}{3} \tag{8}$$

The maximum power produced is when the reeling velocity is one third of wind velocity. So, a kite with surface area of 576 m2 flying cross wind in 10 m/s wind speed would produce 22MW. Though this number presents the limit and cant actually be achieved at the moment due to tether drag, effects of gravity, cosine losses and the motion cannot be purely cross wind as assumed by the theory (Schmehl *et al*, 2014).

Advanced model

A more realistic model would account for effects of gravity and kite and tether inertia as well as centrifugal forces acting upon the kite (Argatov *et al*, 2009).

The tensions in the cable namely T:

$$T = T_1 + {w_c}^{II} + {F_C}^{II} \tag{9}$$

Where, w CII is the component of the cable weight in the direction of the tether. Where:

$$w_C^{II} = W_c cos\theta \tag{10}$$

A function FIIC is defined as

$$Fc = \frac{1}{2}\rho_a C_{II} sin^2\theta cos^2\emptyset \int_0^r V^2(xcos\theta)dx \tag{11}$$

Where, CII is the friction coefficient with kite and tether. Assuming the kite undergoes motion in equilibrium the tension T1 can be interpreted as:

$$T_1 = F^{aero} - F^{grav} + F^{Cf} \tag{12}$$

By using the crosswind motion model provided that VII is replaced with VII-VL, then:

$$F^{aero} = \frac{1}{2}\rho_a A C_L G_E \sqrt{1+G_E^2}(V_{ll} - V_L)^2 \tag{13}$$

Where GE is termed as the glide ratio, it represents the kite aerodynamic properties.

$$G_E = \frac{C_L}{C_D - \frac{C_{\perp rd}}{4A}} \tag{14}$$

The Aerodynamic force FAero is the largest active force on the kite larger than Fgrav and Fcf.

Mechanical Power generated by the kite

The mechanical power generated can be computed by substituting Eqs (13, 12 and 9 into 2) yielding

$$P_M = V_L \left(\frac{1}{2}\rho_a A C_L G_E \sqrt{1+G_E^2}(V_{ll} - V_L)^2 + F_{cf} - {F_r}^{Grav} - w_c^{ll} + {F_c}^{ll}\right) \tag{15}$$

Takin PM as a function of kite velocity VL a value for the maximum of the function can be found using asymptotic analysis. Giving:

$$P_m^{max} = \frac{1}{2}\rho_a A C_L {V_{ll}}^3 k \tag{16}$$

$k =$ Where,

$$\frac{4}{27} G_E \sqrt{1+G_E^2}\left(1 + \frac{9}{2}\frac{F_{cf} - {F_r}^{Grav} - w_c^{ll} - F_c^{ll}}{\rho_a A C_L G_E \sqrt{1+G_E^2}}\right) \tag{17}$$

Mean Mechanical Power

Averaging over one time period of open loop trajectory

$$\langle P_M^{max} \rangle \simeq \frac{1}{2}\rho_a A C_L V^3 \cos^3(\vartheta) k_0 k_* \tag{18}$$

Where,

$$k_0 = \frac{4}{27} G_E \sqrt{1+G_E^2} \tag{19}$$

$$k_* = 1 + \frac{2}{3}\frac{\langle F_{cf}\rangle - \langle {F_r}^{Grav}\rangle - \langle w_c^{ll}\rangle - \langle F_c^{ll}\rangle}{\rho_a A C_L k_0 V^2 \cos^2(\vartheta)} \tag{20}$$

Where the later equations can be solved numerically using an iterative software to yield a mean value for the power developed by the kite during a complete period of operation.

INTEGRATION OF KITE POWER IN THE OIL FIELD

Off shore Rigs

Decentralised power for Oil pump: One of the major losses for deep ocean oil pumps is the vast distance the electric wiring must cover which carries much initial cost and maintenance costs not to mention complexity of such a set up, furthermore, the carbon emissions generated at the rig site of generating using turbines with a large portion going to losses.

By using a float structure set up carrying a kite power generator operating the pumps and other auxiliary machinery will achieve a much better efficiency due to minimizing of transporting losses. The intermittent power supply would not be an issue, as the pumps do not need to be continuously active, instead operate when there is power available (Nilsson & Westin, 2014 and Fig. 2). However, these systems would require a storage device but since the power, demand is not significant it could use e.g. battery. Such structures can be made on shore and towed to specified test giving ease of movement to supply many sites and provide a better settings for oil pumps scattered in large area, these structures are discussed in more details in (Korpåsa *et al*, 2012).

The Set up of such system is considered applicable and its feasibility rely on factors such as water depth, reservoir characteristics and distance from platform to injection well. Analyses deem the concept technologically achievable under certain constraints and some essential parameters must be evaluated economically prior to investing in such set up:

- Distance between platform and injection head i.e. the cost implication of the cable
- CO_2 tax
- Fuel costs for running gas turbines
- Cost for floating wind turbine

When these important parameters are taken into account the solution is deemed highly interesting. A study made by DNV GL (2014) showed that a system with raw-water injection using a 5MW pump together with a 6MW turbine could be cheaper than traditional raw-water injection already at step out distance of 20-30Km. which a kite power system can provide power cheaper than the wind turbine making such integration highly motivating. Analyses by DNV GL have shown that there are no technical difficulties and that the commercial potential looks promising (Slätte, 2014).

Direct Generation on Deck of the Rig: Floating and stationary kite power systems can be connected to the oil platform directly thus enabling direct supply of renewable energy instantly to the platform. As oil platforms are customarily located in deep waters where vast wind resources can be harnessed, providing the potential for high production and capacity factors. Though the intermittent power supply by the kite systems can cause concern, where renewable energy alone

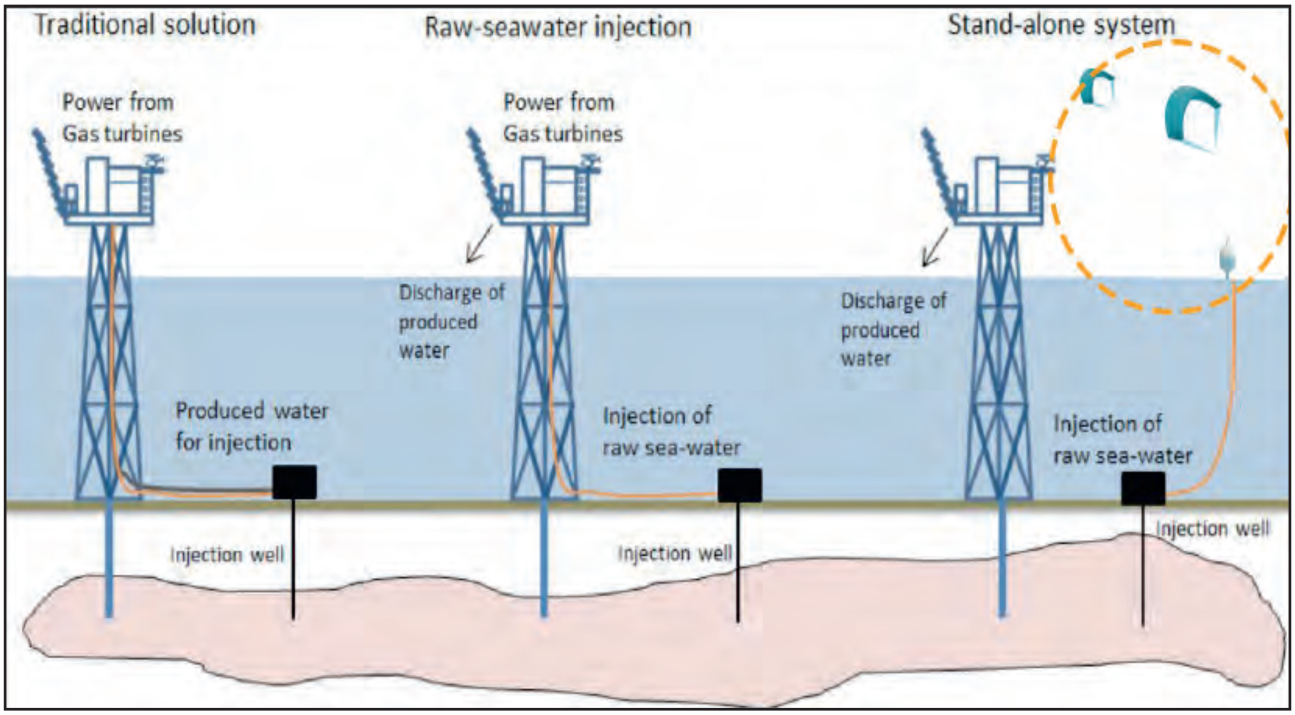

Fig. 2. Crosswind motion velocity triangle.

will not be able to supply the platform all the time (48021HI Energy, 2014). For platforms that already employ gas turbines or connected through cables to national grids these systems can work in parallel. Helping to drive fuel prices as turbines usually require high grade fuels not to mention the carbon emission reduction. One example is the Beatrice Wind farm in Norway, where two turbine systems with 5MW were connected build at a depth of 40 m and connected to a nearby oil rig providing 30% of its total energy demand. It is worth reminding that such a capacity using kite power would require less size and fewer complications as using kites have economical advantage over blades (Marvik *et al*, 2012).

Other research support the idea of integrating renewable sources with oil and gas rigs such SINTF energy research (48021HI Energy, 2014). This clearly shows that development of kite system would make a great solution to the energy demand for of shore platforms. Sue to its inherit advantages over conventional wind turbines and lower risks for equipment failure, such that if the kite is detached during rough weather it will not be such a disaster like blades of turbine failing, or a tower bending, clearly pointing to a very intriguing and potentially applicable solution.

NUMERICAL EXPERIMENTATION

As a closing remark, a value of the generated power is calculated using numerical solver octave. Using the kite parameters from (Argatov *et al*, 2009); area of the kite is 500m2, mass of the kite m is 850kg, coefficient of lift CL is 1.5, coefficient of drag CD is 0.04. average length of tether assumed to be r =1260m with a diameter of 6.7cm, normal reaction force (drag) coefficient C⊥ is 1.0 and friction coefficient Cll is 0.02. The density of the tether material pt is 1450Kg/m3 and thus the linear mass of the tether is μ=ptπ(d/2)2 the wind speed for this calculation was taken based on Ref (Argatov, I.; Rautakorpi, P. and Silvennoinen, R. (2009)) with an average value of 10m/s, and acceleration due to gravity g=9.81m/s2 and air density pa=1.23Kg/m3. The mean angle the kiteline forms with the vertical θ* is about 1.25 radians (71.61o degrees)

To calculate the mean mechanical power using eq. (18) the effective glide ration and average values of <Fcf>, <FrGrav>,<wcII> and <Fcll>. Effective glide ratios is taken from eq. (14) to be 12.2.

$$F_{cf} = mr\omega^2 \quad F_C^{ll} = \frac{1}{2} p_a C_{ll} r d V^2 cos\vartheta_*{}^2$$

$$w_c^{ll} = \mu r g sin\vartheta_* \quad F_r^{Grav} = mg sin\vartheta_*$$

Here ϑ_* is the mean angle of inclination of the kiteline with the horizon. Before calculating an estimation of the average centrifugal force a lying eight orbit must first be defined using equations

$$\theta = \theta_* + \frac{\pi}{18}\sin(2\tau) \quad \emptyset = \frac{\pi}{12}\sin(\tau)$$

Where τ is a parameter that goes from 0 to 2 during one period of operation.

If we define the period as:

$$T = \frac{L}{G_e V cos\vartheta_*}$$

Where; L is the length of the orbit. Next the centrifugal force is

$$F_{cf} = mr\omega^2 = \frac{mr}{T}\int_0^T ((\theta`)^2 + (\emptyset`)^2 sin^2\theta)dt$$

The mean power generated by such a setting is about 5.7MW. comparing with Diehls result of 4.9MW a note must be understood, that in Diehl's model the unwinding of the tether is pulled back while in our model it is assumed that the kite is constantly pulling the tether out of the drum.

A VIEW OF THE APPLICATION

Offshore platforms come at various sizes considering the troll A platform in the Norwegian shelf close to Kollsnes where the processing plant is located. Such a platform that uses a nominal value of 100MW (ABB, 2003). A system of kite generation can be used to supply its half power with a maximum number of 11 kites which will take less size since the kites will be operating at high altitude of about 300 m and by this reduce the costs of fuel and carbon production significantly.

Using such systems to power water injection pumps on floating structures is technically feasible. Utilizing a smaller size kite systems to power the pumps and auxiliaries such as 45m kite area would be more than sufficient to supply a pump such as HP200 by Framo which is capable of providing a pressure of 2500psi at flow rate of 3960 m3/h consuming 8500KW rated (FOGPS, 2018).

CONCLUSION

Means for integrating the renewable energy sector with oil and gas production is presented with a focus on kite power. Investigating the working principle of: “traction kite power system” with a brief discussion of the crosswind motion law. Different possible application for using such a setup is explored and the following is found:

- A kite power system would provide considerable energy while using considerably less space compared with wind turbines.
- Kite power may have the possibility of in platforms to generate part of the electricity demand
- Kite power systems can work to operate distant pumps and other machinery and thus decrease the cost of transporting the energy from the platform using cables.

FUTURE WORK

More research and development is required upon this technology as it still rather new. A more detail into practical experiments are needed, comparison with numerical and analytical models for further development of the model are required. A more economical approach into the subject comparing the costs of gas turbines, grid reliance and wind turbines with kite power system is required, drawing upon the advantages of each and applicability.

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