Journal of Energy Storage 8 (2016) 27–34

Contents lists available at ScienceDirect

Journal of Energy Storage

journal homepage: www.elsevier.com/locate/est

Tubular design for underwater compressed air energy storage

Javier Mas *, Jokin Mendia Rezola

Faculty of Physics, Universidade de Santiago de Compostela, 15782 Santiago de Compostela, Spain

ARTICLE INFO

Article history:
Received 23 May 2016
Received in revised form 11 July 2016
Accepted 9 August 2016
Available online 29 September 2016

Keywords:
CAES
UWCAES
Energy storage

ABSTRACT

Underwater compressed air energy storage (UWCAES) in deep seas is a promising scenario for energy storage. When considered at large scales, specific difficulties arise beyond the ones present when dealing with individual energy bags. After reviewing the set of requirements that a realistic large size project should meet, we propose what we think is the optimal design, the tubular bag. A particular case study is computed numerically aiming at a 1 GWh storage at 1000 m depth. Depending on the material used, lengths lie in the range of 1–15 km. Whereas scaling up is very natural, ballasting poses a challenge and some alternative is proposed.

1. Introduction

Renewable energy has in large scale energy storage its Achilles heel. Hydraulic pumping and compressed energy storage (CAES) stand out as the only strategies capable of dealing with massive capacities in the range of GWh and power loads in the range of MW. Only two examples of commercial CAES are operative at present, and both use large underground salt caverns [1]. These are cases of so called *isochoric* type, were the volume of the storage vessel is constant. A more efficient strategy is to resort to *isobaric* storage, where volume occupied by the gas is reduced while air is being taken out, so as to keep the pressure constant. Isobaric storage is much preferred over isochoric when possible. Exhaust turbines work always at constant design pressure, and energy density of the storage is increased given the fact that no remnant cushion gas needs to be left behind.

A number of works have examined the feasibility of using underwater compressed air energy storage (UWCAES) where hydrostatic outer pressure would counteract the pressure of air inside. The context of advantageous applicability of this scenario demands deep enough seabeds at reasonably close distances to the shore. Otherwise, the intense input and output flow of air through the access hoses would be hindered by strong pressure drop due to friction. This fact restricts severely the amount of suitable coastal locations where depth increases sufficiently fast close to the shore. Most interestingly, apart from some continental locations, plenty of oceanic islands enjoy such bathymetric profiles.

To place our work in perspective, we shall be dealing with UWCAES designs that involve the use of flexible fabric. This idea has been around for more than thirty years, probably starting with [2]. The state of the art, so far, involves balloon shaped vertical axisymmetric energy bags [3]. This is a smart design that seems ripe by now, having reached the level of real off shore tests [4,5]. It succeeds in not being exceedingly expensive, and rather simple in installation and manipulation. However, as we shall show, reaching massive energy storage asks for a delicate compromise between large size and moderately deep waters. In this work values in the range 500–1500 m will be assumed. When dealing with off shore operations that involve manipulating large fragile objects at considerable depths, simplicity is a demand whose importance is hard to over emphasize. Spherical bags are not that simple. Their inflating shape is obtained by means of a precise design, whereby lobules are sewn together along meridional seams with tendons added to achieve the required structural resistance. An additional equatorial release fold is needed. All these features affect the unit cost of each bag and bring in additional leakage risks. As a matter of fact, a number of leaks was found in the test runs, some of them along the seams. Failures can be acceptable whenever they can be fixed on the spot. This is the case of the tests exposed in [4] which were handled by standard scuba immersions. At depths beyond 100 m, leaks should be essentially absent, since repairing one should involve the use of expensive submarine robots or bringing the whole setup to the surface.

Installation and anchoring is another demanding challenge. Working at large depths, any realistic design should make sure that the setup operation is made of a succession of simple steps that can

* Corresponding author.
E-mail addresses: javier.mas@usc.es (J. Mas), jm.rezola@hotmail.com (J.M. Rezola).

http://dx.doi.org/10.1016/j.est.2016.08.006
2352-152X/

Nomenclature

C	material cost of the flexible fabric [€]
d	equivalent diameter of transverse section [m]
g	acceleration of gravity [9.8 m/s^2]
h	depth of pressure bag [m]
l	perimeter of transverse section or short side length of the rectangular strip [m]
L	long side length of tubular bag [m]
l_p	length of input/output conexion pipe [m]
p_i	inside air pressure at the turbine inlet [bar]
p_s	inside air pressure at the surface level [bar]
p_h	air pressure inside the bag [bar]
p_{at}	outside atmospheric air pressure [bar]
V_s	volume of air stored inside the bag [m^3]
V_m	material volume of flexible fabric [m^3]
T	mean temperature of water [°K]
Δp	dynamical pressure loss [bar]
ϵ	flexible material width [m]
κ	round trip efficiency
γ	polytropic exponent
ρ_a	air density inside storage bag
ρ_w	water density [kg/m^3]
σ_{rup}	rupture tension [N/m^2]
τ	linear (meridional) tension [N/m]
τ_0	linear tension of zero pressure bag [N/m]

be accomplished, as much as possible, from the surface. We find this, a limitation to the interesting large scale design put forward and analyzed in [6].

Finally, scalability is a natural demand. In principle, larger storage volume can be also handled within the spherical bag paradigm by unit replication [7]. This is a rather crude way of sizing up the system. A quick evaluation of the needs to deal with some days lull at London sets the need in the range of hundreds of bags [4]. When operating a large number of compressed air bags, they will have to be interconnected to one another and to the main access pipeline coming from ashore. Most important: all bags will need to be placed at the same depth. Being interconnected, the pressure of the air inside will always be that of the deepest point in the system, submitting the uppermost parts to overpressure. Whereas finding profound waters close to the coast is feasible in many islands and some continental coasts, adding the requisite of being flat and even removes almost all examples.

The plan of the paper is as follows. In Section 2 we will motivate and introduce the design of the tubular storage for and UWCAES system. In Section 3 we will compute the volume of air needed for a 1GWh storage at depths in the range 500–1500 m. Although this is standard material, we want to stress our point of view on the different possible scenarios for compression and decompression which control the round trip efficiency. Section 4 is devoted to a particular case study. We consider two materials, Nylon and Kevlar, in order to model two extreme situations which yield the longest and shortest lengths for the tubular bag respectively. We describe and obtain numerically the cross sectional profiles and the associated tensions. This is, ultimately, the factor that constraints the geometry and size of the tubular bag. In Section 5 we look at the retention system. Ballasting is calculated and seen to be problematic; some speculative alternative is briefly sketched. The advantages of the linear design with regard to scaling up is commented in Section 6. Finally, in Section 7 we pay attention to

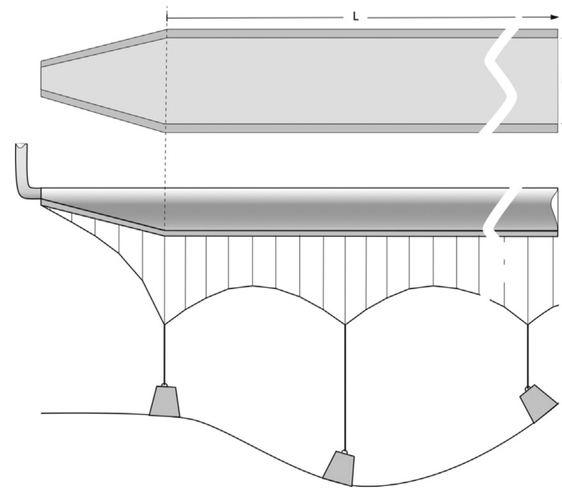

Fig. 1. A flat rectangle is curved and the two long sides are sewn together. The ends are capped of by reducing the section progressively. The length of the ropes compensate for small scale unevenness of the ground.

collateral aspects of the proposal, namely installation, just to make sure there are no severe obstacles and we put forward a possible protocol.

2. The tubular bag

From the considerations in the introduction, we summarise a list of requisites that a realistic design should try to cope with. These include

1. Structural simplicity. This equates to low cost, and also to reduction of failure risk.
2. Scalability. This means extending the system without actually needing to replicate all its components.
3. Robustness. The system should exhibit dynamical stability in a wide range of operation and environment conditions. No need of subsea electronics nor controllers.
4. Very low or zero maintenance. Hence no need to go down to check, clean, or change anything during long times of operation.
5. Feasibility of installation operation.

Not all of them can be met at the same time at the same level, therefore one needs to prioritize. In our opinion, requisite 1 is really compelling. On the other hand, as we will now explain, scalability cannot be other than linear scalability.

As mentioned before, extending the system must be done while keeping accurate levelling of all its components. Otherwise, top parts of the system will be over pressurized. However, in the vast majority of cases, depths in the range of 500–1500 m close to the coast are everything but flat. On the contrary, they are typically very steep and probably abrupt. For example, in the Canary Islands, the sea bottom drops down to depths of 3000–4000 m within 10 km from the shore, with slopes of 30–40%. This will force any storage arrangement to extend itself along equal depth level curves (isobathymetric lines). This is how the linear scaling comes into play as a geometrical constraint imposed from the environment.

Our proposal, the tubular bag is, we think, the simplest solution to these two constraints (see Fig. 1). It is as easy to manufacture as it takes to cut a long rectangular sheet of flexible material, and curve the short side. Sew the long edges together, and cap the ends off. The short side of the rectangle, l, will become the perimeter of the cross section, and the long side, L, the length of the linear bag, with $L \gg l$. In order to counteract buoyancy, a set of cables will attach the tubular bag to a regularly spaced array of ballasts