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Flow over submerged energy storage balloons in closely and widely spaced floral configurations

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A B S T R A C T

Water flow past the accumulator unit of an underwater compressed air energy storage plant was studied numerically. The accumulator unit consists of three underwater balloons arranged in a floral configuration. The numerical simulation was conducted at a Reynolds number of 2.3×10^5 using URANS k–ω and LES Dyna-SM turbulence models of the ANSYS-Fluent CFD software. The URANS mean values are compatible with those of LES; however, LES appeared to better predict the turbulent nature of the studied flow. The flow pattern was illustrated through iso-surfaces of the second invariant of the velocity gradient (*Q* criterion) and three-dimensional path lines. Several swirling tube flows were found to shed downstream of the balloons. The turbulence dynamic of the flow was illustrated through time-series snapshots of the vorticity contours on planes perpendicular to the flow direction; revealing the swinging movements of the observed swirling tube flows. The force coefficients of the hydrodynamic loading on these underwater structures were also investigated. The drag coefficient of the upstream balloon was found to be larger than the downstream one; the difference is more significant for the closely spaced configuration. It is noteworthy to mention that the total drag coefficient of the wide unit was larger than that of the closed one. A Fast Fourier transform of the time history of the force coefficients was used to find the Strouhal number. Strouhal numbers of approximately 0.52 and 0.18 were found for the widely spaced and closely spaced configurations respectively.

1. Introduction

The renewable energy industry in general, and the wind energy in particular, has made significant progress in recent years. Wind energy production in the USA experienced a 28 fold increase from 1998 to 2011 with production capacity reaching 46,919 MW (Statistics of Wind Energy in USA, 2011). In the same period, the wind energy production capacity in Canada increased to 5265 MW, i.e. more than 210 times what was produced at the beginning of the year 1998 (Statistics of wind energy in Canada, 2011). Despite this significant expansion, many notable challenges still remain. One of which includes the efficient management of supply and demand. That is, in contrast to fossil-fueled power plants, prevalent renewables like wind and solar are inherently intermittent and peak supply is often temporally out of phase with peak demand. Furthermore, grid congestion and stability issues can prevent the delivery of power to the grid (Safaei et al., 2013). Energy storage plants are viable options to overcome these issues and make intermittents dispatchable. One of the most efficient and environmentally friendly technologies is compressed air energy storage (CAES), which is driven by a modification of basic gas turbine technology (Rahman et al., 2012). CAES boasts a potentially long service life of approximately 40 years and high energy efficiency of 71% (Denholm and Kulcinski, 2004). However, the application of this underground storage system is limited to regulation of the onshore wind power stations (Ibrahim et al., 2008) while a significant portion of the wind-based power is generated by the offshore wind farms across the world, e.g. Denmark is generating up to 30% of its total electric power by offshore wind farms (Robb, 2010; MacKay, 2008). To add to this, North America is currently gearing up to make a significant entry into offshore wind. Subsequently, a new energy storage system based on CAES for application in the seas has been developed (Pimm and Garvey, 2009; Pimm et al., 2011; Cheung et al., 2012(a), 2012(b)). In this storage plant, namely under water CAES or UWCAES, the surplus electrical energy generated in the off-peak hours is utilized to compress air into submerged distensible accumulators. The accumulators are moored to the sea floor; hence, the stored air is under hydrostatic pressure, ready to be released back to the surface to drive turbines to supply the electrical grid when needed (see Fig. 1). A successful Pilot Experiment in Lake Ontario (Cheung et al. 2012(a)) has lead to design and construction of two planned demonstration facilities to be deployed at fresh and salt water sites.

To perform the role of distensible energy accumulator marine salvage balloons were chosen for their market availability and robust

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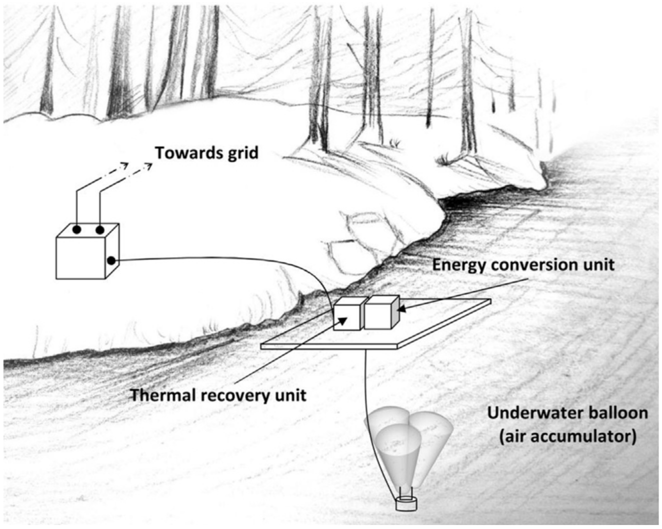

Fig. 1. Typical underwater compressed air energy storage; the accumulator unit consists of three distensible balloons arranged in floral configuration.

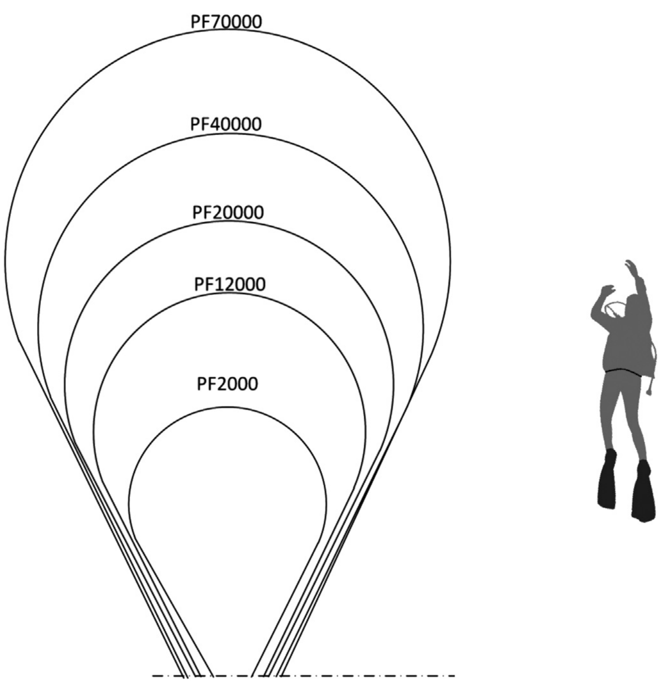

Fig. 2. An approximate comparison between dimensions of different underwater balloons of the professional (PF) series manufactured by SUBSALVE USA CORPORATION. The PF20000 model was applied in the present application.

nature. The PF20000 model of Professional (PF) lift bags manufactured by SUBSALVE USA CORPORATION were chosen as the base accumulator unit of the UWCAES system owing to their optimal size and flexible rigging points. The general droplet shape of PF lift balloons with various sizes are compared with an average human body in Fig. 2. To develop more innovative and cost-effective designs for the foundations and support structures of the accumulator units, it is necessary to provide a credible estimate of hydrodynamic loading (Graff, 1981; Haritos, 2007). There has been a significant progress in understanding of fluid-structure interactions over the last couple of decades. The focus, however, has been limited to flow over circular cylinders (Mureithi et al., 1994a and 1994b); Sumner et al., 1999; Akosile and Sumner, 2003; Zhang et al., 2007; Yang and Zheng, 2010; Sarkar and Sarkar, 2010; Griffith et al., 2011; Bao et al., 2012a, 2012b), square cylinders (Shyam Kumar and Vengadesan, 2009; Huang et al., 2010; Mahbub Alami et al., 2011; Bao et al., 2012a, 2012b), rectangular cylinders (Lin and Huang, 2010; Lam et al., 2012; Maiti, 2012; Tian et al., 2013) and elliptical cylinders (Peng et al., 2012); these are all primarily two-dimensional studies. There are also several three-dimensional studies but they are mostly concerned with the flow over regular shapes such as spheres (Taneda, 1978; Constantinescu and Squires, 2000; Yoon and Yang, 2009; El Khoury et al., 2010; Dixona et al., 2011), circular cylinders (Sumner and Heseltine, 2008; Li and Sumner, 2009; Adaramola et al., 2010; Zhou et al., 2010; Kanaris et al., 2011; Uzun and Yousuff Hussaini, 2012) and square cylinders (Sheard et al., 2009). Our review on flow over bluff bodies appeared to indicate a dearth of published research exploring the cross-flow over droplet-shaped bluff bodies. Hence, at the first step, the fundamental case of flow over a single isolated balloon was studied (Vasel-Be-Hagh et al., 2013) and then the current numerical study was carried out to examine the practical case of flow over floral units of balloons. Developing a good understanding of the force characteristics and the structure of this flow is an essential part of this project. Due to the absence of any experimental evidence, simulations were carried out using both URANS and LES turbulence models to validate the results. To assert the verification of the numerical methodology, the turbulence model features were discussed as well as the numerical code qualifications. Grid independence was assessed for both URANS and LES simulations separately. Furthermore, for the LES simulation the grid size was compared with LES filter width, and y^+ in close proximity to the balloons surfaces was set to be in accordance with what is recommended for an LES simulation in the literature.

2. Computational details

In order to decrease computational expenses, dimensions of the PF20000 balloon are scaled down by a factor of 100. As the force coefficients are functions of Reynolds number, the free stream velocity is scaled up 100 times to retain the same Reynolds number. Dimensions of the scaled balloon are presented in Fig. 3. Original dimensions of the PF20000 balloon are reported in inches in the Subsalve U.S.A. Corporation Manual (2012); therefore, in Fig. 3 the scaled dimensions are presented in both meters and inches (inch values in brackets) to ensure the decimal accuracy.

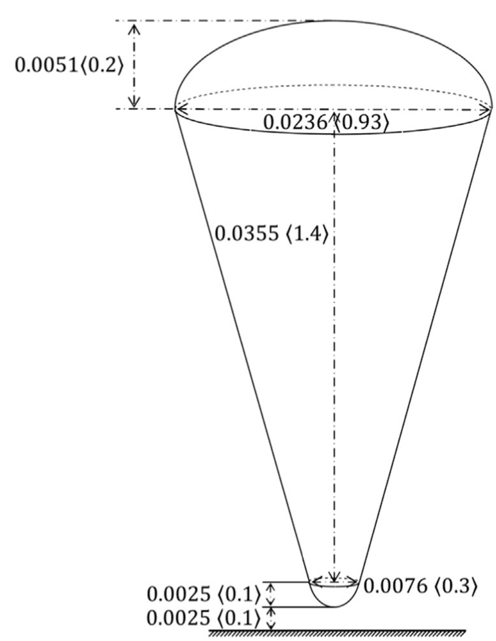

Fig. 3. Scaled down PF20000 balloon. Values are in meters, the bracketed values ⟨−⟩ are in inches.