PNEUMATIC ENERGY STORAGE

The principle of energy storage in compressed air implies basically two distinct elements: the storage vesssels (the storage *volume*) and the compressor/expander (also called *transformer*. If there is an additional oil-to-air insert in the storage chain it is called *interface*) which constitutes the link between the stored air and the mechanical output, generally a rotating shaft. This shaft-to-shaft storage transforms into wire-to-wire storage by means of high efficiency electrical machinery (rotating DC or AC motor/generator).

So, the wire-to-air transformation requires at least two steps, which are air-to-shaft and shaft-to-wire; but sometimes it is useful to insert a „liquid step" between the air and the shaft (e.g. liquid piston systems called BOP/Batteries with Oilhydraulics and Pneumatics when using high pressure bottles or Aquifer Storages when realized in suitable caverns), where pressure is generated in the liquid and then transmitted to the air: this allows better transforming efficiencies as liquid dynamics imply better energy density for both volumetric (reciprocating) and centrifugal (turbine) machinery than working in the gaseous state.

All these transformation concepts are plagued by strong heat-up when compressing or strong cooling down when expanding according to well-known thermodynamical laws: the temperature deviation from isothermal conditions means lower transformation efficiency (a 50ºC variation corresponds roughly to a 10% efficiency drop in high pressure systems), so a good compressor/expander must limit strongly the temperature fluctuations during any pressure change occuring in the storage chain.

Having this in mind we can analyze all the systems which have been explored so far, which are:

1) **DIRECT ACTING MECHANICAL RECIPROCATING SYSTEMS** have very low efficiencies, as no reversible system could be designed so far: expansion (energy output) is realized by throttling down from high pressure to some 30 to 40 bar to avoid strong cooling down in the reciprocating motor, as no heat-exchange can be integrated (examples are Terry Millers pneumatic car in Joplin, Guy Negre's pneumatic motor and the old mining locomotives and tramways in use in the 2d half of the 19^{th} century), if hooked to a standard multistage compressor (η=50%) we will get full cycle efficiencies around 25 %.

2) **BULK LIQUID PISTON SYSTEMS (BOP type A)** have the storage vessels integrated in the compressor/expander, as the liquid is moved by standard oilhydraulic units to compress or expand trapped air, nitrogen or any other gas in the bottles (accumulator principle with or without flexible membrane or bladder): this allows to reach premium efficiencies up to 70% full cycle as standard steel bottle rated pressures reach 200 to 300 bar and heat fluctuations are minimized to negligible values given the slow pressure changes (distributed over the whole charging/discharging time) and the heat exchanger effect of the big bottle stack surface. These advantages are counter-balanced by the big size of the storage vessel pack and the need to have a liquid reservoir covering 60% of the vessel volume. This gives poor specific values (2 Wh/l and 3,2 Wh/kg with 250 bar steel vessel rated pressure): this system is suited for high power-to-capacity ratios and where high adaptability to input and output change is needed. Prototypes are running well in the kW-range, max. power can reach 200 kW with off-the-shelf hydraulic elements.

3) **RECIPROCATING INTERFACE SYSTEMS (BOP type B)** are now under development to act as full-fledged high efficiency compressor/expander close to isothermal conditions thanks to heat exchangers integrated in the piston workchambers. Although the R&D effort is still ongoing, main specifications can be accurately computed, as also standard steel bottles or CNG cylinders are used yielding 30 Wh/l and 30 Wh/kg for 250 bar max. pressure (55Wh/kg with CNG4 carbon filament wound cylinders). At the present development stage it seems possible to reach 65% full cycle efficiency with acceptable design effort, making this system a possible competitor of electro-chemical batteries for storages > 5kWh and high cycling rates, with the inherent advantages of pressurized systems like accurate state-of-charge monitoring, fast filling by docking of small auxiliary vessels, no aging through stratification and no damage if left discharged for years.

4) **<u>BIG COMPRESSED AIR ENERGY STORAGE SYSTEMS (CAES)</u>** based on centrifugal machinery in the fractional GW/GWh range are at the time present ***by no means an applicable renewable energy storage concept,*** as the bigger part of the expansion power has to be generated by a fuel burner to avoid excessive temperature decreases (an adiabatic expansion from 35 bar at 30ªC down to atmosphere would generate a 130ªC drop!) This fact limits the application of this kind of design to peak-shaving where the cost of input to output power exceeds a ratio of 4 to 5 (only two plants are working so far based on this principle, in northern Germany and in Alabama). Another shortcoming of turbine systems is the poor adaptability to fluctuating input and output power, an essential issue when direct coupling to windparks is scheduled, and present designs work more or less at half the pressure of BOP type B systems, which more than doubles storage volume needed.

As conclusion we note that a strong feeling is growing quite recently among storage specialists that the only way to store energy for grid quality enhancement is to use pneumatic storage, as the only known alternative (water storage with dams) cannot be expanded. This new awareness unleashed the discussion wether storage should be disseminated in the grid („sponge"-system, where the BOP type B could find its place for sizes up to 200 kW) or centralized in big plants where the burner part would be strongly curtailed or even completely eliminated from the Alabama-type CAES chain.

The latest news is a scramble towards R&D projects tackling this range of problems: the guess is that some kind of isothermal process similar to BOP type B will be found for turbine-based compressors/expanders.

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