THE ROCKY ROAD TO THE UPPER ATMOSPHERE

NASA’s quest to create long-term platforms in the stratosphere

A recent program by NASA aims to develop balloons capable of carrying payloads of several tonnes to above 99% of the Earth’s atmosphere for up to a hundred days. However, the road to the stratosphere turned out to be much harder and longer than expected.

Although the scientific basis of ballooning was laid by Archimedes (287-212 BC) it took another two millennia until the dawn of the aerospace age in 1783 when the Montgolfier brothers made the first public launch of a large scale hot-air balloon. This was the signal for a breathtaking development of aircraft that finally brought men into space in less than two hundred years. Even though balloons were soon eclipsed by airplanes and rockets they are still of importance since they can stay aloft without using energy.

The first hydrogen filled balloon, made by Jacques Charles, flew only twelve weeks after the impressive demonstration of the Montgolfier brothers. It quickly turned out that the hydrogen balloon was generally superior to the hot-air balloon. The reason for this was not its higher lifting capacity but the fact that hot-air balloons at that time were made out of paper and were usually ruined after one flight. Charles’ first two hydrogen balloons were based on different designs. The first balloon was a superpressure design with a closed envelope. This led to increasing differential pressures during the ascent so that the envelope finally burst. To avoid another structural failure he designed his second, manned balloon with an opening at the bottom so that the stresses in the envelope were relatively small and nearly independent of the altitude. These types of balloons are known as zero-superpressure designs.

A new generation of balloons was developed after the Second World War when polyethylene became widely available. The German expatriate Otto Winzen was the first to construct natural shaped zero-superpressure balloons from a number of identical flat polyethylene gores, by welding neighbouring lobes together and incorporating a stiff tendon along the common boundary. This resulted in a highly efficient design since the curvature of the film between the load tapes is, in case of parachutes, considerably increased. Hence the differential pressure is carried towards the load tapes with much smaller membrane stresses so that it became possible to design balloons with a larger payload to self-weight ratio.

Material technology, especially the ability to manufacture thinner polyethylene films, improved steadily in the second half of the twentieth century. Therefore it became possible to construct balloons that were capable of carrying increasing payloads to higher altitudes. By 1972, the largest balloons had a volume of 1,500,000m$^3$ and lifted more than six tonnes to low altitudes. One of these further developed Winzen balloons reached a record altitude of 52km in 1972. This record was held until 2002 when Japan launched a 60,000m$^3$ balloon, made out of an ultra thin LLDPE (Linear Low Density Polyethylene) film with a thickness of 3.4 μm, to an altitude of 53km. Current zero-superpressure balloons are capable of carrying payloads of several tonnes to constant altitudes for periods of about 1-2 days. Launching these balloons during the Antarctic summer increases the flight durations to 10-20 days since not much ballasting is necessary due to the lack of daylight cycles.

NASA started to develop Ultra Long Duration Balloons (ULDBs) in the mid 1990s that take advantage of further improvements in material technology such as high strength fibers and LLDPE. The goal of this program is to develop a general purpose platform that is capable of carrying payloads of several tonnes for up to
a hundred days above 99% of the Earth’s atmosphere. The initial ULDB concept was a classical sphere design. Nevertheless it turned out that scaling this proven design to the dimensions needed for the ULDB program is, mainly due to the attachment of the payload, not trivial. Furthermore, the necessary membrane thickness increases linearly and the surface area quadratically with the radius of the balloon so that the self-weight is proportional to its volume. The current concept under consideration that avoids these problems is a pumpkin shaped design. These balloons are in principal similar to zero-superpressure balloons that were introduced by Winzen except that they are closed at the bottom, see figure 1. However, the resulting shape at flight altitude differs considerably from zero-superpressure balloons since the differential pressure is nearly constant throughout the balloon. It is interesting to note that the pressurized shape of pumpkin balloons and parachutes is described by the same equations, G.I. Taylor (1963).

Although the realization of this concept seemed to be straightforward it turned out that NASA suffered from the same instabilities that were previously observed by Nott (Nott, 2004) in the 1980s during his attempt to circumnavigate the globe in a pumpkin balloon, see figure 2. It was found that balloons buckle if the energy released by increasing their volume is larger than the energy needed to deform the balloon film. Although the underlying physics is quite simple, these instabilities are a rather serious problem that slowed down the development of large superpressure balloons for more than a decade. After years of failed small- and large-scale experiments by NASA we were able to optimize the geometry of the used cutting-patterns such that the balloon stability is maximized without exceeding the allowed membrane stresses (Pagitz & Pellegrino, 2010). Figure 3 shows original and optimized cutting-patterns for balloons with 16, 80 and 145 lobes. It can be seen that optimized cutting-patterns are fully stressed. This increased the buckling pressure by up to 300% and finally resulted in a record breaking flight above Antarctica in 2009. The optimized balloon floated at an altitude of 34km for 54 days and carried a payload of 82kg.

Despite contributing significantly to a new world record we aim to further improve the technology of superpressure balloons here at the Aerospace Structures and Computational Mechanics (ASCM) group. The fundamental problem of pumpkin shaped pressure vessels is the uniaxial alignment of the tendons and the thereby resulting high surface area to volume ratio. In contrast, an optimal design distinguishes itself by providing an easy way to attach the payload, a surface with a minimum curvature and finally an optimal surface to volume ratio. By using topology optimization we found that optimal superpressure balloons are similar to radiolarians. It is interesting to note that the growth of the skeleton of radiolarians is driven by the need to keep a certain altitude in the ocean (Mann & Ozin, 1996). A corresponding pressure vessel as shown in figure 4 is currently under development at ASCM.

Students that are interested in doing their Master or PhD research on optimal pressure vessels that can be used from fuel tanks for rockets to high altitude balloons are encouraged to contact Markus Pagitz (M.E.Pagitz@tudelft.nl).

References


Figure 1a. Concept of pumpkin balloons

Figure 1b. Size comparison of current experimental ULDBs with Tower Bridge and Swiss Re Tower (final ULDBs will be scaled up)

Figure 2a. Experimental pumpkin balloon with a diameter of 10 m: (a) Fully inflated

Figure 2b. Balloon buckled in a split second after reaching critical pressure

Figure 3: Comparison between original cutting-patterns that were used by NASA and optimized cutting-patterns

Figure 4a. Optimal superpressure balloon for constant differential pressure

Figure 4b. Optimal superpressure balloon for linearly varying differential pressure is composed of a pumpkin and radiolarian design