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Hydrogen Storage in Wind Turbine Towers: Design Considerations

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Abstract

The paramount considerations associated with a hydrogen tower are corrosion (in the form of hydrogen embrittlement) and structural failure (through bursting or fatigue life degradation). Although hydrogen embrittlement (HE) requires more research and experimentation, it does not appear to prohibit the use of turbine towers for hydrogen storage. Furthermore, the structural modifications required to store hydrogen in a tower are technically feasible.

We discovered that hydrogen towers have a "crossover pressure" at which their critical mode of failure crosses over from fatigue to bursting. The crossover pressure for many turbine towers is between 10 and 15 atm. The cost of hydrogen storage per unit of storage capacity is lowest near the crossover pressure. Above the crossover pressure, however, storage costs rise quickly.

Introduction

Low-cost hydrogen storage is recognized as a cornerstone of a renewables-hydrogen economy. Modern utility-scale wind turbine towers are typically conical steel structures that, in addition to supporting the rotor, could be used to store hydrogen. During off-peak hours, electrolyzers could use energy from the wind turbines or the grid to generate hydrogen and store it in turbine towers. The stored hydrogen could later be used to generate power via a fuel cell during times of peak demand. This capacity for energy storage could significantly mitigate the drawbacks to wind's intermittent nature and provide a cost-effective means of meeting peak demand.

Hydrogen storage creates a number of additional considerations in turbine tower design. Under certain conditions hydrogen tends to react with steel, adversely affecting the mechanical properties such as ductility, yield strength, and fatigue life. Additionally, storing hydrogen at pressure significantly increases the stresses on the tower. These factors require a structural analysis to evaluate how internal pressure may affect the tower's design life.

Storing hydrogen in a turbine tower appears to have been first suggested by Lee Jay Fingersh at the National Renewable Energy Laboratory (NREL) (Fingersh 2003). As outlined above, this technology could play an important role in the hydrogen economy and is, therefore, worth exploring. The objective of this paper is to identify the paramount considerations associated with using a wind turbine tower for hydrogen storage. This paper summarizes work presented in an NREL technical report (Kottenstette and Cotrell 2003).

Benchmarks and Assumptions

We based our analysis on a 1.5-MW tubular steel tower designed to withstand peak and fatigue bending moments at the base and top. It has a linear taper of diameter and wall thickness, a constant tower diameter/wall thickness (d/t) ratio of 320, and the top diameter equal to ½ of the base diameter. We assume the construction material to be structural steel with a yield strength of 350 MPa. The cost of the tower is estimated by multiplying the tower mass by $1.50/kg (Malcolm 2002).

It should be mentioned that where the mass of pressurized hydrogen is computed, hydrogen is modeled as an ideal gas.

Corrosion

Both atmospheric corrosion and HE must be considered with regard to a hydrogen tower.

Conventional turbine towers are adequately protected from atmospheric corrosion by a layer of paint. When a tower is used to store a pressurized gas, however, it becomes subject to the guidelines set forth in the American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code. The ASME code requires that paint not be considered an adequate form of protection for the interior of pressure vessels. Enough material must therefore be added to anticipate corrosion (ASME 2001).

Fortunately, the interior of a hydrogen tower is a controlled environment. Hydrogen from a PEM electrolyzer does not contain contaminants that cause atmospheric corrosion (of primary concern are sulfur dioxide and chlorine). The product hydrogen (which would be fully saturated with water vapor) could be dried to below the critical humidity level (less than 80% relative humidity) at minimal cost. Under these conditions, corrosion would penetrate the steel's surface at the negligible rate of less than 0.1 μm per year (Roberge 1999).

Hydrogen Embrittlement

HE is the primary form of corrosion that threatens the viability of hydrogen towers. HE is a process in which atomic hydrogen (H as opposed to H_2) adsorbs to a metal surface and causes brittle failure far below the yield strength of an affected material. A component's susceptibility to HE is determined by environmental effects, including temperature, pressure, and hydrogen purity, as well as material properties, including grain size, hardness, and strength. This section explores HE's possible effect on a turbine tower.

HE may be most severe at ambient temperatures, and its effects increase with the square root of hydrogen gas pressure (Gray 1974; Mohitpour, Golshan, and Murray 2000). This suggests that designing turbine towers for relatively low-pressure storage may help prevent HE. It is fortunate, therefore, that the storage pressures under consideration are only about 10% of hydrogen pipeline operating pressures.

Hydrogen gas purity is another major environmental factor controlling HE. Experimental evidence has shown that crack propagation in a stressed specimen could be controlled by the introduction of oxygen into the hydrogen environment. Investigators demonstrated that a crack propagating in a pure hydrogen environment could be stopped with the introduction of as little as 200 ppm oxygen at atmospheric pressure (Gray 1974).

Because the method of H_2 production under consideration is via an electrolyzer, O_2 gas will be readily available. Although adding O_2 to H_2 can result in an explosive mixture, adding the necessary levels of O_2 is expected to have little effect on safety. This is because the required oxygen concentration (approximately 200 ppm) is far above the upper combustible limit of hydrogen in oxygen (93.9% by volume). Two hundred ppm oxygen in hydrogen represents only 0.02% (by volume) of the oxygen required to create an explosive environment.

Larger grains with precipitates heavily concentrated along grain boundaries can also expedite HE because they allow for easier diffusion of hydrogen through the metal's lattice structure (Gray 1974). The Sourcebook for Hydrogen Applications lists proper control of grain size as a successful measure of HE prevention (Bain et al., 1998). Grain size is controlled in the steel forming and treatment process. Fortunately, selection of steel plate with the appropriate grain size is not anticipated to be difficult.

Increased material hardness can also magnify the effects of hydrogen embrittlement. Typically, hardness is increased by causing residual tensile stresses in a material's surface through treatments like forging, cold rolling, or welding. Additionally, it is theorized that when hydrogen adsorbs to a material's surface, it decreases the energy required to form a surface crack (Mohitpour, Golshan, and Murray 2000). The combination of these two factors facilitates the formation of surface cracks.

Tower welds are therefore particularly susceptible to HE because rapid cooling of the welds can cause "hard spots" where carbon and other impurities coalesce. However, as a general guideline, trouble-free welds can be obtained in low-alloy steels containing up to about 0.28% carbon and to a carbon equivalent (C+1/4Mn) of about 0.55% (Cox and Williamson 1977).

Steels offering the strength assumed in this study (such as S355J0 as specified by British Standard EN 10025 and Grade 485 steel as specified by ASTM Specification A 516/A) have equivalent carbon contents of 0.65% and 0.60% respectively. These steels require preheating of the joint and the use of low-hydrogen electrodes to protect their welds from HE. Alternatively, the tower's structural requirements could be met with thicker walls made of steels having lower carbon and manganese contents. Tower welds that are protected from hydrogen embrittlement can therefore be devised without difficulty.

Material strength, a property related to both grain size and hardness, is perhaps the most predominant material property influencing hydrogen embrittlement. It has been generally observed that higher-strength steels exhibit greater loss of ductility, lower ultimate strengths, and greater propensity for delayed failure than their lower-strength counterparts when subjected to a hydrogen environment (Bain et al., 1998). It is for these reasons that many experts suggest use of lower-strength steels for hydrogen applications. Some experts have designated an ultimate strength of 700 MPa as a benchmark, below which steels are significantly less susceptible to HE (Mohitpour, Golshan, and Murray 2000; Cox and Williamson 1977). Steels commonly used for tower construction fall well short of this benchmark; towers are typically constructed of a low-strength, low-carbon structural steel with yield and ultimate properties at or below 350 and 630 MPa, respectively.

Based on the considerations outlined above, the risk of HE does not exclude the use of turbine towers for hydrogen storage. It is, however, difficult to compare the use of a wind turbine tower as a pressure vessel to more traditional hydrogen applications because, unlike conventional pressure vessels, they are subjected to significant dynamic loads. The dynamic structural loads applied to a turbine tower would serve to repeatedly open microfissures, one mechanism by which HE is theorized to propagate. Due to the potential for catastrophic failure, HE requires more research and experimentation.

Structural Analysis

Pressurizing the interior of a wind turbine tower creates unique structural demands. A pressurized tower must not only withstand loads caused by normal operation of the wind turbine, but it must also fulfill the requirements of a pressure vessel. Tubular towers for modern utility-scale wind turbines are typically limited by the fatigue strength of the horizontal welds. One primary concern, therefore, is the effect of pressurizing the tower on the fatigue strength of these welds. In addition, the hydrogen pressure loads must not exceed allowable margins for pressure vessels.

Loads and Stresses

Wind turbines are subjected to widely varying aerodynamic loads. These loads induce large bending moments that, in turn, cause tensile and compressive stresses parallel to the axis of the tower (axial stresses). At the base of the tower, these stresses significantly exceed the compressive stresses caused by the weight of the turbine. Frequent, fluctuating aerodynamic loads seen during normal operation make fatigue the critical mode of failure for modern turbine towers.

Subjecting a tower to internal pressure creates a different loading scenario. Because the pressure is uniform, it causes loads in the axial direction and in the plane normal to the tower's axis. The axial stresses induced in cylindrical pressure vessels are half the magnitude of the stresses induced in the plane normal to the axis (hoop stresses). The loads to which pressure vessels are subjected make ultimate strength the limiting design constraint for most pressure vessels.

Fatigue Failure

One popular theory describes fatigue failure as crack propagation resulting from repetitive plastic deformation. In turbine towers, cracks primarily propagate when a tensile stress is applied perpendicular to the crack's length. This suggests that, in turbine towers, the stress state in the hoop direction has little effect on fatigue in the axial direction.

When a tower is pressurized, however, the large surface area over which this pressure acts results in significant axial tensile stresses even at low pressures. For the tower geometry considered in this study, the tensile stress induced by one atmosphere above gauge pressure is nearly four times the magnitude of the compressive stress caused by the entire weight of the turbine. As a result, internal pressures work together with the aerodynamic loads on the tower to degrade its fatigue life.

The Goodman equation accounts for the effect of mean stress on fatigue strength. One way to ensure an adequate tower life is to increase the tower wall thickness, thereby distributing the load and reducing the stresses. During this study, the Goodman equation was used to derive an expression for the increase in wall thickness required to maintain the tower's designed fatigue life:

$$t_2 - t_1 = \Delta t = \frac{pr}{2(S_{ut})} \qquad (1)$$

where

t_2	=	the thickness required of a pressurized tower
t_1	=	the thickness required of an equivalent tower without internal pressure
p	=	the gauge pressure
r	=	the radius of the cross section being considered
S_{ut}	=	the ultimate tensile strength.

This equation dictates the amount of wall reinforcement required to maintain the tower's fatigue life. It is valid for all towers and tower sections that are critically limited by fatigue rather than peak loads or buckling constraints. See the appendix for a derivation of this equation.

Crossover Pressure

As the pressure rating of a hydrogen tower is increased, the primary mode of failure for the tower walls crosses over from fatigue to bursting. Once this "crossover" pressure is reached, the required wall thickness is determined by the maximum allowable hoop stress, rather than axial fatigue. From the ASME Pressure Vessel Code (ASME 2001), the maximum allowable stress in a pressure vessel equation is given as:

$$\sigma_{max} \leq \frac{S_{ut}}{3.5} \qquad (2)$$

where

σ_{max}	=	the maximum allowable stress
S_{ut}	=	the ultimate tensile strength.

Fig. 1 shows required thickness as a function of pressure for both the fatigue and burst conditions.

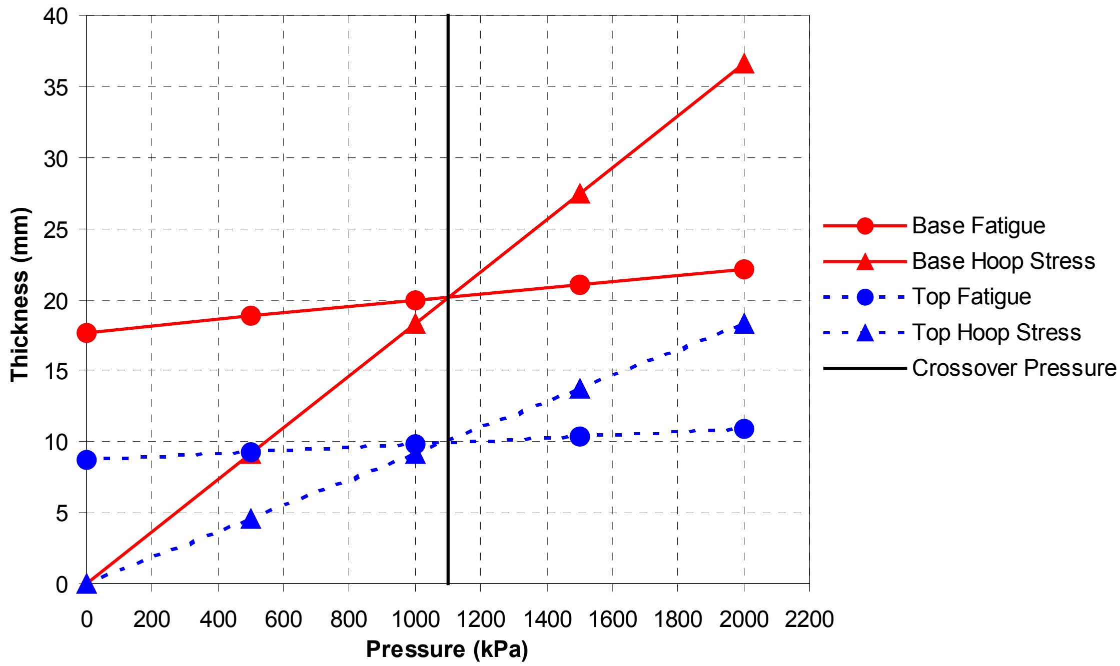

Figure 1: Wall thickness as a function of pressure for different failure modes.

The solid set of lines describes thickness required at the base of the tower, and the dashed set of lines describes thickness required at the top of the tower. The crossover pressure for a given tower cross section is defined as the point where the line describing maximum stress requirements (the line with the steeper slope) overtakes the line describing fatigue requirements (the line which is almost horizontal). Below the crossover pressure, the required tower wall thickness is determined by the more gradual fatigue line. Above the crossover pressure, the required thickness is determined by the steeper line for the burst strength.

Solving for the crossover pressure (the intersection of the two lines) at an arbitrary tower cross section results in the following equation:

$$p_{crossover} = \frac{4(E)S_{ut}}{7\left(\frac{d}{t_1}\right)\left(1-\frac{E}{7}\right)} \qquad (3)$$

where

E = the welded joint efficiency
S_{ut} = the Ultimate Tensile Strength
$\left(\frac{d}{t_1}\right)$ = the diameter/thickness (d/t) ratio.

This study assumes that the tower is fatigue constrained at every section and has a constant d/t ratio. For these assumptions, the crossover pressure is the same at all points in the tower. This can be seen in Fig. 1 by noticing that the solid lines and dashed lines cross at the same pressure. Furthermore, this equation demonstrates that crossover pressure is dependent only on ultimate tensile strength, welded joint efficiency, and d/t ratio. For the assumptions in this study (S_{ut} = 636 MPa and d/t = 320), the crossover pressure is 1.1 MPa (11 atm). Crossover pressures for most utility-scale turbines are expected to be between 1.0 and 1.5 MPa (10 and 15 atm).

Tower Radius and Taper

Below the crossover pressure, where fatigue is the limiting constraint, tower thickness requirements are sensitive to tower radius and subject to Eq. 1 given above (the thickness equation). This relationship is demonstrated by the following figure:

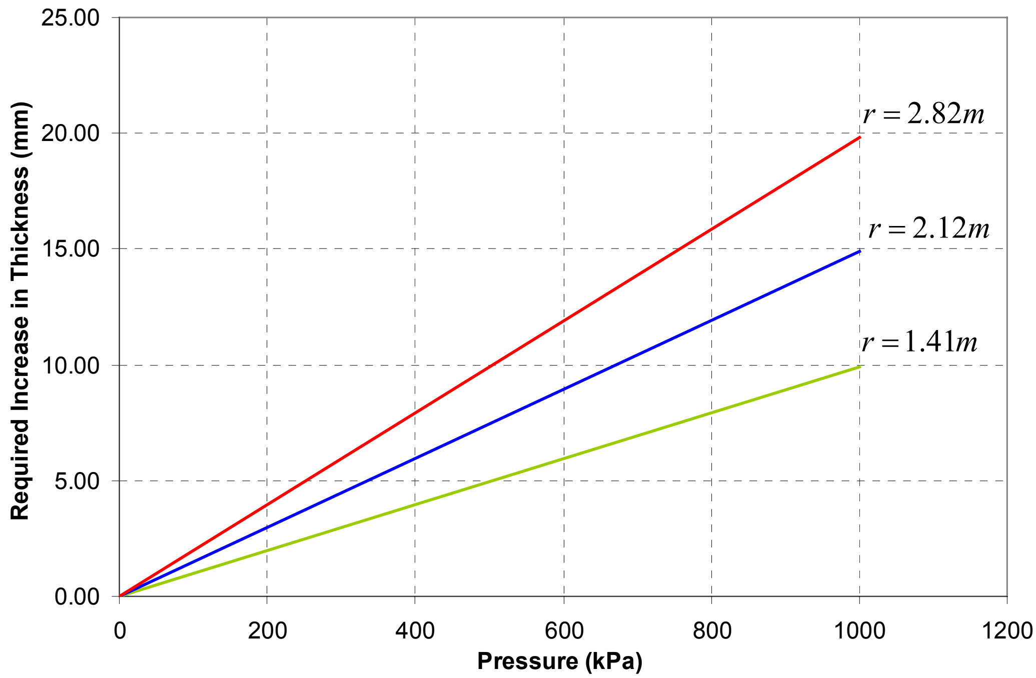

Figure 2: Plot of the thickness equation for three tower radii.

This figure suggests that towers with smaller radii are able to tolerate higher pressure with a smaller increase in thickness than their larger-radii counterparts. Larger radius towers, on the other hand, enclose a greater volume. These two factors must be weighed to determine the radius size that is most economical for hydrogen storage.

The relative cost of a tower section is reflected by the ratio of the mass of wall reinforcement to the mass of H_2 stored. For a fatigue-limited tower, this ratio is independent of both pressure and tower radius. This ratio is given by the following equation:

$$\left(\frac{m_{H_2 stored}}{m_{steel}}\right) = \left(\frac{S_{ut}}{\rho(RT)}\right) \quad (4)$$

where

ρ	=	the density of steel
S_{ut}	=	the ultimate tensile strength of the steel
R	=	the gas constant for molecular hydrogen
T	=	the absolute temperature of the gas.

This equation, together with the fact that end caps are more costly per kilogram than wall reinforcement, suggests that the ideal pressure vessel geometry is long and slender. It also implies that the methods described for determining costs associated with wall reinforcement apply to towers of any taper angle.

Conclusions

As a result of this study, we developed two significant conclusions regarding hydrogen towers. First, HE does not appear to be a major obstacle, but more research is needed in the area of long-term, low-pressure storage. Second, fatigue-driven towers have a crossover pressure at which they offer the most cost-effective storage capacity. For most utility-scale towers, this crossover pressure is expected to be between 1.0 and 1.5 MPa (10–15 atm). Finally, turbine towers may offer economical hydrogen storage because they approach the ideal pressure vessel geometry.

Future Work

A literature review reveals a need for further study of the effects of HE as it pertains to hydrogen storage. Additionally, when considering the construction of a hydrogen tower, it must be considered whether or not the value of hydrogen stored at the turbine tower justifies the storage cost. NREL is currently evaluating the value of storing hydrogen in turbine towers as part of its WindSTORM study.

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