Evaluation of Longitudinal and Hoop Stresses and a Critical Study of Factor of Safety (FoS) in Design of a Glass-Fiber Pressure Vessel

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Abstract**—**The design, manufacture, and operation of thin-walled pressure vessels must be based on maximum safe operating pressure and an adequate factor of safety (FoS). This research paper first reports experimental evaluation of longitudinal and hoops stresses based on working pressure as well as maximum pressure; and then includes a critical study of factor of safety (FoS) in the design of a glass fiber pressure vessel. Experimental work involved the use of measuring instruments and the readings from pressure gauges. Design calculations involved the computations of design stress and FoS; the latter was based on breaking strength of 55 MPa for the glass fiber (pressure-vessel material). The experimentally determined FoS value has been critically compared with the general FoS allowed in the design of glass fiber pressure vessels.

Keywords**—**Thin-walled pressure vessel, hoop stress, longitudinal stress, factor of safety (FoS), fiberglass.

I. Introduction

MODERN pressure vessels are made of composite materials, such as glass-fiber composite (glass fiber held in place with a polymer). Due to high tensile strength of glass-fiber, these vessels can be very light, but are much more difficult to manufacture. The composite material may be wound around a metal liner, forming a composite overwrapped pressure vessel. Important parameters in the design of composite pressure vessels include: internal pressure, axial force, body force due to rotation, temperature and moisture variation [1], [2].

Pressure vessels can theoretically be almost any shape, but shapes made of sections of spheres, cylinders, and cones are usually employed. A common design is a cylinder with end caps called heads. Head shapes are frequently either hemispherical or dished (tori spherical). More complicated shapes have historically been much harder to analyze for safe operation and are usually far more difficult to construct.

Pressure vessels are used in a variety of applications in both industry and the private sector. They appear in these sectors as industrial compressed air receivers and domestic hot water storage tanks.

Other examples of pressure vessels are diving cylinders, recompression chambers, distillation towers, pressure reactors, autoclaves, and many other vessels in mining operations, oil refineries and petrochemical plants, nuclear reactor vessels, submarine and space ship habitats, pneumatic reservoirs, hydraulic reservoirs under pressure, rail vehicle airbrake reservoirs, road vehicle airbrake reservoirs, and storage vessels for liquefied gases such as ammonia, chlorine, propane, butane, and LPG.

A pressure vessel is considered to be "thin-walled" if its radius r is larger than 5 times its wall thickness t ($r > 5t$). An accurate prediction of the burst pressure is very important in the engineering design of cylindrical pressure vessels [3]. A pressure vessel is acted upon by the principal stresses: (1) hoop stress, σ_H and (2) longitudinal stress, σ_L (see Fig. 1). Hoop or circumferential stress is the stress which is set up in resisting the bursting effect of the applied pressure and can be most conveniently treated by considering the equilibrium of the cylinder.

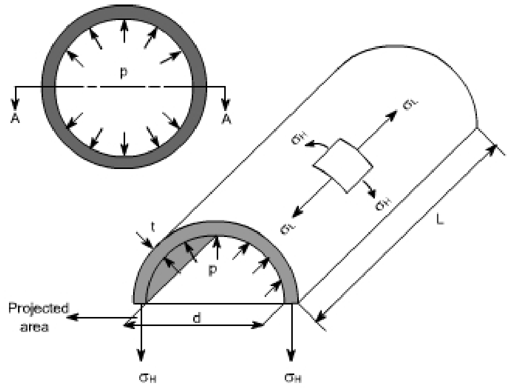

Fig. 1 Principal stresses and the design parameters in a pressure vessel

Hoop stress or circumferential stress can be expressed as follow:

$$\text{Hoop Stress} = \sigma_H = (p\,.d) / 2t \quad (1)$$

where p is internal fluid pressure, d is internal diameter, and t is the wall thickness of the pressure vessel.

Longitudinal Stress can be expressed by the relationship:

$$\text{Longitudinal Stress} = \sigma_L = (p\,.d) / 4\,t \quad (2)$$

where the symbols have their usual meanings.

Equations (1) and (2) hold good for thin-walled pressure vessels [4]. It must be noted that the hoop stress is twice as

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much as the longitudinal stress for the cylindrical pressure vessel.

The above formulas are good for thin-walled pressure vessels. Generally, a pressure vessel is considered to be "thin-walled" if its radius r is larger than 5 times its wall thickness t ($r > 5\ t$). When a pressure vessel is subjected to external pressure, the above formulas are still valid. However, the stresses are now negative since the wall is now in compression instead of tension.

An important consideration in design of pressure vessels is factor of safety (FoS). The FoS is used to provide a design margin over the theoretical design capacity to allow for uncertainty in the design and manufacturing process. FoS is the ratio of the minimum load that would cause failure to the actual peak load. Numerically,

$$\text{FoS} = \frac{\text{failure load}}{\text{design load}} = \frac{\text{breaking strength}}{\text{design strength}} \tag{3}$$

The objectives of the research reported in the paper are as follows: (a) to determine whether or not the water filter tank is a thin-walled or a thick-walled cylinder; (b) to compute longitudinal stresses for the working pressure and the maximum working pressure; (c) to compute hoop stresses for the working pressure and the maximum working pressure; and (d) to critically study the factor of safety (FoS) in design of the filter tank.

Fig. 2 The Water-Filter Tank installed outside the Canteen of Nilai University (inside the campus)

Fig. 3 Working pressure reading on the pressure gage

II. Experimental Work

The water filter tank installed in Nilai University Canteen was found to be made from fiberglass material (see Fig. 2). The thickness of the water filter was found out to be 40 mm.

The maximum allowable working pressure was noted to be 700 kPa. The working fluid pressure as recorded on the pressure gage to be 4.8 kgf/cm^2 (see Fig. 3).

A rope was tied around the circumference of the cylinder; and then a measuring tape was used to determine the length of the rope. The circumference of the cylinder was measured to be 159 cm.

The outer diameter, D, of the cylinder was calculated by using:

$$\text{Circumference} = \pi D \tag{4}$$

The internal radius was found out by subtracting the thickness of the wall from the external radius of the water tank calculated before. The vessel was determined to be a thin walled pressure vessel as the radius is larger than 5 times the thickness ($r > 5\ t$) of the wall. The longitudinal stress and the hoop stress for the working pressure (4.8kgf/cm^2) and for the maximum working pressure (700 kPa) were calculated using the hoop stress and longitudinal stress formulae (1) and (2).

The factor of safety (FoS) for structural materials for fiberglass was found out to be 4 from reliable sources from the internet. Hence, the strength of the water filter tank was determined using the formula for Factor of Safety (3)

III. Choosing the Right Fiberglass Pressure Vessel

Pressure vessels are often the overlooked component of water softening and water treatment systems [6]. Because they do not require any adjustments over time and are not sold with extensive user manuals, there is little reason to give them much thought after they're installed.

Water treatment dealers can avoid tank failures and customer complaints by learning about the differences between tanks and specifying the right tank for the application.

Tanks are generally made from either fiberglass or steel. Although most commercial tanks are made of steel, fiberglass is the material of choice for residential applications.

Steel tanks were replaced by fiberglass in most residential applications because fiberglass weighs less, resists corrosion and tends to be more durable.

There are two basic types of fiberglass tanks: (1) composite, and (2) fiber reinforced plastics.

Composite tanks have replaced fiber reinforced plastic (FRP) tanks in all but a limited number of applications because composite tanks are made with a more efficient manufacturing process, allowing for lower prices.

Fiber reinforced plastic (FRP) tanks provide certain advantages critical to some applications, which continue to make them more appropriate for these applications despite of their higher prices.

A. Selecting the Best Tank for Application

Composite Tanks

To ensure selection of the most appropriate composite fiberglass pressure vessel for a residential or commercial application you must match your application requirements with the feature sets of the many tanks available. Some important considerations include:

Capacity

Capacity can vary from 1 to 1,600 gallons and range in size from 5” to 16” in diameter for residential applications and 18” to 63” in diameter for commercial and industrial applications.

Pressure Rating

Although most tanks have maximum operating pressure ratings of 150 psi, some manufacturers offer tanks with lower pressure ratings at reduced prices.

Temperature Rating

Composite tanks applied in residential applications are usually rated to operate to a maximum temperature of 120 deg f. Larger composite tanks with flanged connections and frp tanks can operate in temperatures up to 150 degrees Fahrenheit. Steel tanks can be subjected to even higher maximum temperatures.

Cycle Life

In order to pass NSF certification pressure vessels must provide a minimum service life of 100,000 cycles. However, some manufacturers exceed this standard and offer tanks that provide performance as long as 250,000 cycles.

Inlets

Threaded openings are offered in diameters up to 4” in diameter and flanged openings up to 6” in diameter. Because ASME will not certify non-metallic openings, ASME tanks are only equipped with flanges or stainless steel inlets.

Seamless Construction

Seams provide additional opportunities for leakage. Although tanks designed without seams cost more to manufacture, they provide additional protection against leakage.

NSF and ISO Certification

Buy tanks that have been tested and certified by independent laboratories to ensure they meet the performance claims made by the manufacturer. While most tanks are certified to meet minimal performance requirements, some manufacturers provide added protection against tank failure by building tanks that exceed these standards.

Buying tanks with NSF certification is only the first step to ensuring that the tanks you install perform as expected. Certification is based on the test results of just the few tanks submitted for testing. The degree to which your tanks perform to the tested standards depends to a great extent on the manufacturer’s quality control procedures for its manufacturing process.

ISO certification is a rigorous independent auditing process that evaluates the quality of the manufacturing process. Buying tanks from manufacturers that have earned ISO certification improves the chance that your tanks meet the standards of those tested to NSF standards.

B. FRP Applications:

Because FRP tanks are made using an older, less efficient manufacturing process, they are more expensive than other comparable composite pressure vessels. However, FRP tanks offer options not found in composite tanks that can make them a better choice for some applications:

Side Openings

FRP tanks allow for reinforced openings to be post-drilled in the sides. There is less flexibility in the positioning of openings in wound composite tanks.

Higher temperatures — FRP tanks can be used in applications with temperatures of up to 150 deg. F.

Dimensional Consistency

The FRP closed mold manufacturing process produces tanks of consistent height. The winding-over-liner process of composite tanks results in a higher level of variation. This could be an important consideration for those applications with extremely tight size requirements.

IV. Results and Discussion

The technical specifications of the fiberglass water filter (pressure vessel) are presented in Table I; which includes the data resulting from experimental work (Section II).

TABLE I
TECHNICAL SPECIFICATIONS OF FIBERGLASS TANK

Wall thickness	4 cm
Circumference	159 cm
Outer diameter	50.6 cm
Outer radius	25.3 cm
Internal radius	21.3 cm
Working pressure	4.8 kgf/cm^2 ~ 470 kPa
Max. working pressure	700 kPa

In order to evaluate hoop stress and longitudinal stress, we applied (1) and (2). However, prior to applying the Equations, it is important to convert kgf/cm^2 to kPa, as follows:

$$\frac{4.8\ \text{kgf}}{\text{cm}^2} = \frac{(4.8)(9.81)}{(1*10^{-2})^2\text{m}^2} = 470.880\ \text{N/m}^2 \approx \mathbf{471\ kPa}$$

The results obtained by the application of (1) and (2) are presented in Table II.

TABLE II
LONGITUDINAL AND HOOP STRESSES DATA

	Working fluid pressure of 470 kPa	Maximum working fluid pressure of 700 kPa
Longitudinal stress	1.25 MPa	1.86 MPa
Hoop stress	2.50 MPa	3.73 MPa

The stress data in Table II enables us to assess the design stress in water-filter tank. It is evident that a maximum (hoop) stress of 3.73 MPa (= 3,730 kPa) acts on the tank material. Hence, the design stress can be taken as 3730 kPa.

Now, we consider the composite material used in the fabrication of the pressure vessel: Water-Filter Tank. High

Strength, low cost, resistance to corrosion and light-weight of fiberglass makes it acceptable as a material to be used as a pressure vessel. In particular, fiberglass yarn has a high strength-to-weight ratio. It is twice as strong as steel wire.

In order to compute the factor of safety (FoS), we need to refer to the design stress and the breaking strength. According to the mechanical properties data of fiberglass, it is found that the breaking strength or flexural strength of fiberglass can be taken as 30,000 psi (= 206843 kPa) [5]. Now, we apply (3) to compute FoS of the water-filter tank under investigation.

$$FoS = (\text{breaking or flexural strength}) / \text{design stress}$$

$$FoS = 206843 / 3730 = 55 \qquad (5)$$

As per engineering practices in the design of water-filter tanks, a factor of safety (FoS) of 4:1 is recommended [6-7]. The very high FoS value of 55 indicates that the filter tank is extra-ordinary safe to use. This is because the FoS value is much higher than required value of FoS=4.

V. Conclusion

The control devices and measuring tools were used to observe working fluid pressure and the geometric design parameters of the water-filter tank. The longitudinal stress and hoop stress in the tank were evaluated to be in the range of 1.25 – 3.73 MPa. The FoS was computed to be 55; which was found to be more than safe to operate the machine.

Acknowledgment

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