Strengthened Glass for Pipeline Systems

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New, Innovative Uses for a Stronger Glass

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1 Motivation

In today's resource driven economy, there is a growing interest on the part of utility companies to optimize their distribution systems for improved service. Utility companies are positioned to enhance their operations throughput if lower cost pipeline systems could be manufactured for use at higher pressures.

An innovative design concept is presented for a modern pipeline system manufactured from exceptionally strong glass. The primary benefit of using strengthened glass for utility pipes is the ability for the system to withstand substantially more contents under pressure. This means that utility companies could dramatically increase service throughput.

In addition to higher maximum pressure and flow rate derived from increased pipe strength, the strengthened glass pipeline system also capitalizes on not only a few but all of the favorable properties of glass: physical, thermal, optical, and chemical. The piping concept is designed to be manufacturable and feasible within both large and small scale industrial frameworks. Most importantly, the proposed pipeline system is a fundamentally unique concept because it can be made possible with exclusively one material: *strengthened glass.*

The following section will address the advantages and disadvantages of existing pipeline system materials. The design concept begins to take form in Section 3 where the strengthened glass pipeline system is introduced. The direct benefits of using high strength glass are presented first. Then, supplemental benefits of using strengthened glass for pipeline systems, which take advantage of properties besides strength, are explored.

2 Current Pipeline Systems

Steel pipe is widely used for conducting substances at extremely high pressures and temperatures. High strength alloy steel is used where a weldable, machinable, very high strength metal is required to save weight or meet ultimate strength requirements. The advantages of steel piping systems over plastic pipe include: both higher and lower operating temperatures, less thermal expansion, and inherent protection from ultraviolet rays. Disadvantages of such systems are that steel must be designed to prevent corrosion and steel pipes are expensive.

Another material that is common in many existing piping systems is high-density polyethylene (HDPE) plastic. Plastic piping systems are advantageous because they are relatively inexpensive and resist corrosion. The disadvantages of plastic piping systems are low maximum operating temperatures and pressures, and possible need for protection from ultraviolet rays.

3 Proposed Strengthened Glass Pipeline System

A strengthened glass piping system is proposed that will combine the advantages of steel pipes with the advantages of plastic pipes and that will have virtually no disadvantages relative to the existing systems.

3.1 Strength benefits of strengthened glass pipes

The ultimate tensile strengths of commonly used pipe materials are listed in Table 1. Assuming that strengthened glass with practical strength of 3.5 GPa is readily available, we have the freedom to design a piping system with material that is multiple times stronger than high strength alloy steel!

Table 1: Ultimate tensile strengths (failure stress) of common pipe materials.

Material	Ultimate Strength (MPa)	Density g/cm^3
High density polyethylene (HDPE)	37	0.95
Structural steel A36	400	7.8
Steel, High strength alloy A514	760	7.8
Glass in compression	50	2.53
Proposed strengthened glass	**3,500**	**2.53**

3.1.1 Increased maximum pressure

Intuitively, we expect that stronger materials can withstand higher pressures. Following this reasoning, we figure that it is possible to manufacture strengthened glass pipes that can withstand more pressure than steel pipe counterparts.

To establish a theoretical basis for our rationale of increased pressure rating, we use the following equation for stress in a thin-walled, cylindrical pressure vessel, and solve for pressure:

$$\sigma_\theta = \frac{pr}{t} \qquad \Longrightarrow \qquad p = \frac{\sigma_\theta t}{r}, \tag{1}$$

where σ_θ is the hoop stress, or stress in the pipe's radial direction, p is the internal pressure, r is the radius of the cylindrical pipe, and t is the thickness of the pipe wall. The derived equation for pressure in a cylindrical vessel shows that for a constant pipe radius and thickness, maximum pressure is directly proportional to failure stress (ultimate tensile strength). This means that given a strengthened glass pipe and a steel pipe of identical cross-sectional dimensions, the glass pipe could withstand an increase in pressure equal to the ratio of the glass ultimate strength to the steel ultimate strength — a pressure increase of approximately $\frac{3500MPa}{760MPa} = 4.6$ times.

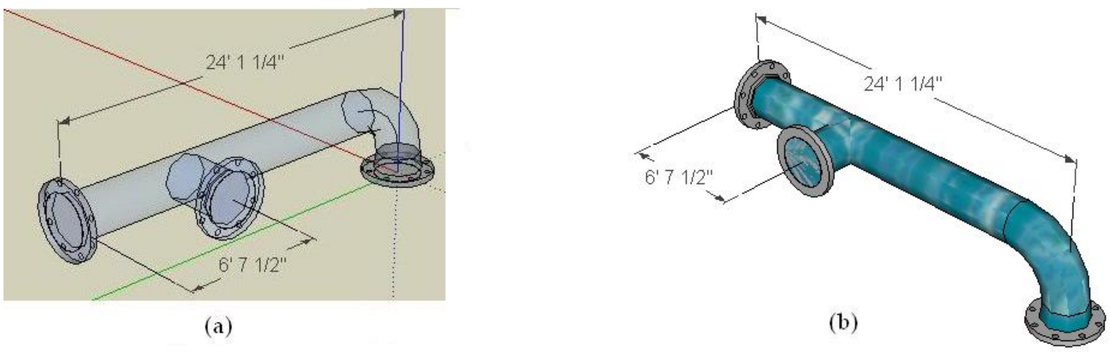

Figure 1: (a) Computer-aided rendering of strengthened glass pipe; (b) simulated turbulent flow in pipe.

3.1.2 Reduced pipe size

In Section 3.1.1, we found that a strengthened glass pipe of equal dimensions to a steel pipe could withstand higher pressure before material failure. Alternatively, instead of increasing the maximum pressure in a given size pipe, we could reduce the size of the glass pipe.

To validate that size reduction is indeed viable, we begin with the formula for the minimum mass of a pressure vessel, and then deduce a relation between mass and the pipe material's ultimate strength, σ:

$$M = \frac{3}{2} pV \frac{\rho}{\sigma} \qquad \Longrightarrow \qquad M \propto \frac{1}{\sigma}, \tag{2}$$

where M is mass, p is pressure, V is volume, ρ is the density of the pressure vessel material, and σ is the failure stress of the material. From the above relation, we can see that minimum mass decreases as strength increases. This means that glass pipes can be a fraction of the size of steel pipes that share the same pressure specification. For example, from substituting approximate values into the mass equation, we can see that the overall mass of a strengthened glass pipe can be 10% of the mass of a steel pipe and still handle equal pressure flow. Such a design possibility may be considered when installing a piping system inside a building where interior space is valuable.

3.2 Supplemental benefits of glass pipes

The following design benefits are established on glass's inherent physical, thermal, optical, and chemical properties which make it favorable for piping systems.

3.2.1 Improved energy efficiency

Within this section, we prove that flow through glass pipe is more energy efficient than flow through steel and plastic pipes. We first consider a simplified approach for understanding the efficiency of flow in glass, and then we examine a more technical hydrodynamic explanation.

Generally speaking, the inner surface of glass pipe is less rough than that of a steel pipe. Glass thereby has a lower coefficient of friction. Knowing that frictional force is proportional to the coefficient of friction, we argue that flow through a steel pipe experiences more resistive frictional force, f_F, than does flow through glass pipe. By using our general understanding that $Work = Force * Distance$, $Power = Work/time$, and $Energy = \int(Power)dt$, we see that a finite amount of energy is dissipated due the roughness inside the steel pipe.

For a more technical analysis, we consider principles of turbulent flow. Hydraulic flow losses in pipes depend in part upon the roughness of the pipe material. When considering flow in a pipe, friction against the inner walls of the pipe causes flow to transition from laminar to turbulent. When energy is dissipated due to turbulent flow, one says that head is lost. The Darcy-Weisbach equation is used to calculate the head loss due to friction, as follows:

$$h_f = f \frac{L}{D} \frac{V^2}{2g}, \tag{3}$$

where f is the fiction factor, L is the length of the pipe, and g is acceleration due to gravity. The key to the Darcy-Weisbach equation is solving for the friction factor. The roughness height for glass is listed as approximately 0.0015 mm and for HDPE plastics as 0.002 mm. While the roughness height for steel ranges from 0.01 to 0.1 mm — anywhere from ten to one hundred times as rough as glass.

Equipped with values for the roughness heights of the different materials, we look up the friction factor graphically from a Moody diagram, which relates the friction factor for fully developed pipe flow to the Reynolds number and relative roughness of a circular pipe. For Reynolds numbers in the turbulent region, the friction factor of glass is

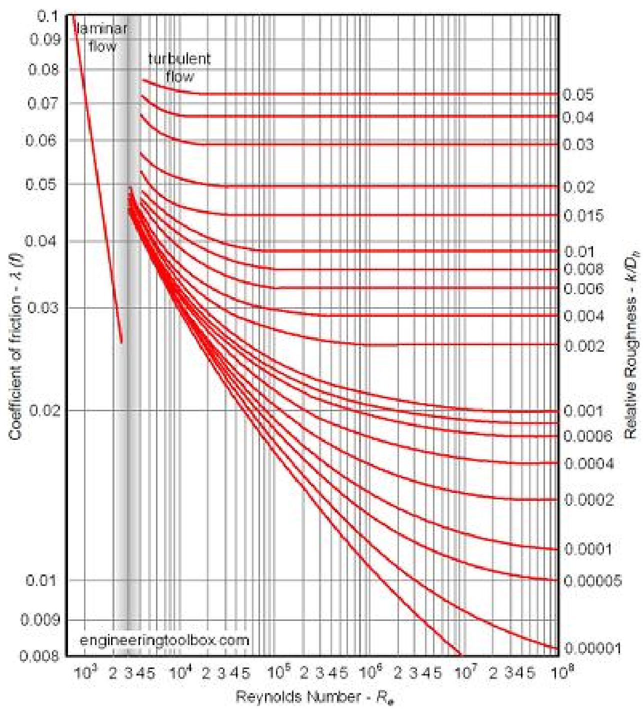

Figure 2: Moody diagram for friction in laminar and turbulent flow.

anywhere from 25–50% less than that of steel. By using strengthened glass pipes instead of steel, friction would be reduced, head loss would decrease, and energy dissipation would be minimized.

3.2.2 Reduced heat conduction

Thermal conductivity is the intensive property of a material that indicates its ability to conduct heat. Glass pipes have an inherently lower thermal conductivity coefficient than steel pipes. The thermal conductivity of HDPE plastic is approximately 0.52 W/mK and the thermal conductivity of steel is 15 W/mK. The thermal conductivity of glass is approximately 0.8 W/mK, on the same order of magnitude as plastic.

To put these conductivity figures into perspective, we consider the formula for thermal resistance in the radial direction for heat conduction in a cylinder,

$$r_{th} = \frac{\ln\left(\frac{r_o}{r_i}\right)}{2\pi k l}, \tag{4}$$

where r_o is the radius from the center to the exterior surface of the pipe, r_i is the radius to the interior surface, k is thermal conductivity of the pipe material, and l is the length. The r_{th} relation represents the thermal resistance or insulance of the pipe. By substituting values into this equation, the thermal resistance equation reveals that steel pipe conducts fifteen times more heat than glass pipe! In other words, glass is an order of magnitude better than steel for thermal insulation.

What are the implications of glass pipes with a lower heat conductivity? The high thermal insulance of glass would mean that an industrial plant with a glass piping system could save roughly 15 times its spending on coolant and possibly reduce HVAC usage by an order of magnitude!

3.2.3 Transparent flow diagnostics

Since glass piping systems can be transparent, maintenance and diagnostic technicians would easily be able to observe the flow within the system. For example, instead of using an array of expensive sensors to identify increased resistance areas, technicians would visually be able to identify the exact location where the flow changes from laminar to turbulent.

3.2.4 Chemical resistance

The corrosion of steel piping is a continuous and virtually unstoppable process. Even with the application of available countermeasures, pipe corrosion is one of the most potentially damaging threats to any private, industrial, or commercial property — second only to fire. The cost of corrosion protection and maintenance for steel pipe mains can be as high as $700 per mile per year.

For many properties, the net result is an added maintenance problem, greater energy costs, unnecessary threat and liability, property damage, high remedial expense, and in the most extreme examples, the need for partial or total pipeline replacement.

The high corrosion resistance of glass is one of its most important properties. Glass is much more resistant to corrosion than most other materials, so much so that it is often considered corrosion-proof. The chemical property of glass make it a versatile material choice for distributing various substances. Further, whether indoor or outdoor, a strengthened glass pipeline system would be unburdened by the concern of harmful substances leaching into the distribution system.

3.2.5 Self-cleaning pipe coating for water supply lines

A final ancillary benefit of glass pipes involves a glass coating that can be applied to create a self-cleaning surface for water supply pipelines. The inner surface of the pipes would be coated with an active layer of nanocrystalline titanium dioxide (TiO_2). When ultraviolet radiation from the sun penetrates the glass and interacts with the TiO_2 pipe coating, the energy of the ultraviolet light is absorbed. If moisture is present within the pipe, strongly oxidizing free radicals are formed, which clean the glass surface. Glass cleaned in this way becomes super hydrophilic. This forces water to spread across the surface, rather than beading, thereby washing away debris on the surface of the glass.

4 Conclusion

The strengthened glass pipeline system proposed and analyzed in this concept paper demonstrates a versatile combination of advantages over existing pipeline systems. The unique physical, thermal, optical and chemical properties of glass make it an exceptional material for use in a strengthened glass pipeline system. Since utility companies strive to optimize their distribution systems, they could substantially increase service throughput and lower costs by using a pipeline system manufactured with strengthened glass.

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