

## Utilization of Phase Change for Sealing and Pressurization of Tubular Elements

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**ABSTRACT.** The process of freezing of water and blockage of pipes are summarized. Current research on freezing and its applications are briefly reviewed. Design concepts are introduced for doing work by utilizing pressures caused by ice blockage. Several conceptual designs are presented for experimental setups for the isostatic pressurization of thin walled tubes. Potential practical uses of pressures generated by freezing of water and blockage are mentioned. These include the burst testing of tubes made of composite materials, compaction of powders, as well as the plastic deformation of thin tubes.

**KEYWORDS:** blockage, bursting, freezing, ice, pressure, sealing, tube, water

### 1. Introduction

Akyurt and associates <sup>[1]</sup> conducted a survey on freezing, where they explained the process of freezing as summarized by Fig.1 Accordingly, the time-temperature relationship for freezing of pure water follows curve ABCDEF, starting from a temperature at A above freezing. The first thermal event that can be seen from the figure is undercooling, also called supercooling, below the freezing point of 0°C, from B to C, before the induction of crystallization. This is a non-equilibrium, metastable state which is analogous to an activation energy necessary for the nucleation process. Pure water can be undercooled by several degrees before the nucleation phenomenon begins.

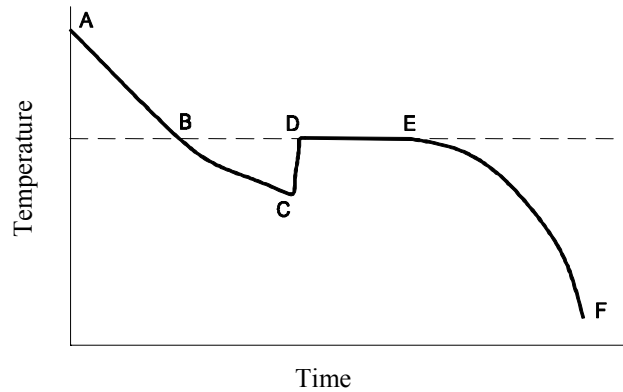


Fig. 1. Stages during freezing of water.

Once the critical mass of nuclei is reached, the system nucleates at point C in the figure and releases its latent heat faster than the heat that is being removed from the system. The temperature increases instantly to the initial freezing temperature at point D. The brief period from C to D is frequently called the stage of nucleation and dendritic ice formation.

The time line from D to E in the figure reflects the time during which crystal growth is occurring. Fast freezing rates promote the formation of many small ice crystals during this period. The partially frozen mixture will not cool until all of the "freezable" water has crystallized; hence, the line DE occurs at nearly constant temperature. The freezing time is defined as the time from the onset of nucleation at C to the complete removal of latent heat at E. After crystallization is completed, the temperature drops from E to F as sensible heat is released. For water freezing inside a pipe, the third stage (line DE) would be one of annular ice formation, and the fourth stage (EF) would be that of final cooling of the solid plug of ice to ambient temperature. In stage four the pipe no longer contains water; it is blocked completely by a solid plug of ice.

One of the interesting measurements made by Gordon <sup>[2]</sup> is depicted in Fig. 2. This figure shows the variation with time, of temperatures along a water-filled pipe that was exposed to cold ambient air. The same figure describes also the variation of pressure inside the pipe with time (right-hand ordinate). The usual initial stage of supercooling is observed at the beginning of the experiment (BC). Then the brief second stage, i.e., dendritic ice formation, commences at C. Annular ice formation (stage 3, DE) begins immediately afterwards. As the outdoor temperature continues to fall throughout the night and into the morning, annular ice formation continues throughout the night.

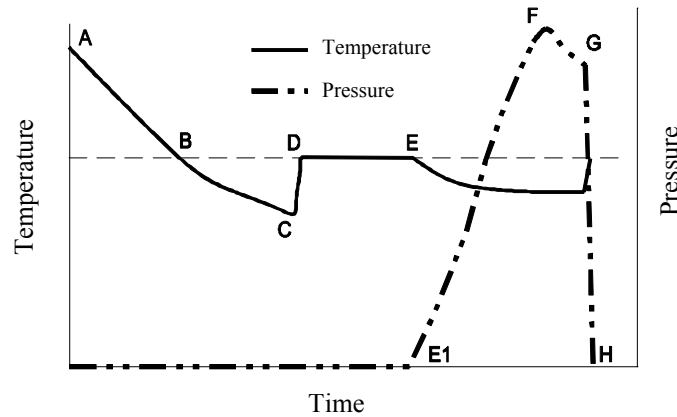


Fig. 2. Temperatures and pressures during pipe bursting [1].

There is no noticeable pressure variation during the early phases of ice formation. The pressure inside the pipe stays exactly where it began, at the typical water pressure of the water system (around 42 psi = 2.9 bars at the test site). Only when ice formation is complete at point E, does the pressure within the pipe start to increase. In fact it grows dramatically, ultimately leading to a burst event. The pressure in the pipe peaks at about 4000 psi (270 bars) at F, and then it eases down to about 3500 psi (240 bars) at G while the pipe undergoes plastic deformation under the influence of the imposed internal pressure. The actual rupture in the wall of the pipe occurs at G, when liquid water is ejected through the crack, bringing the gauge pressure down to essentially zero at H.

It must be stressed here that bursting of pipes and containers occurs after a complete blockage of ice totally isolates a body of water. A typical example is a pipe section that is trapped between a non-leaking faucet at one end, and a solid plug of ice at the other end. Since water is essentially incompressible, any further ice growth from the end with ice blockage will result in spectacular increases in water pressure. Thus if ice continues to form in the confined pipe section, the volumetric expansion from freezing results in rapidly increasing water pressure between the blockage and the closed outlet, and causes bursting and other failures. Because the entire pipe section downstream of the ice blockage experiences the same elevated pressures, the failure can occur at any point in the system, and the weakest link will be found. Besides pipes themselves, failures involving solder joints, elbows, and fixtures themselves can also occur. Ironically, because burst events arise from water pressure and not from the ice itself, failures often occur in a part of the pipe section where almost no ice has formed, even within the heated space of a building.

In the case of the burst event in Fig. 2, it is a copper pipe that burst. Upon blockage, the pressure builds rapidly and consistently. Through this initial pressure rise to the apex of the pressure curve, the pipe is still *elastic*. Whatever deformation resulting from the increased pressure, the pipe retains the capability of returning to its initial shape. A major change occurs at point F when the pressure reaches its maximum 4000 psi. At this point, the pipe is said to go *plastic*. Deformation is permanent once the pipe material reaches its elastic limit and goes plastic. Examination of a burst pipe shows that a sizable "bulge" in the pipe wall appears at the point of the rupture. The pressure drop following the maximum pressure represents the creation of this deformation in the pipe: the pipe is stretching in response to the pressure, resulting in a thinner pipe wall at the location of the deformation. Once the bulge is created (point G), the pipe is subject to rupture at the location of the thinner pipe wall. Upon rupture, the pressure drop is immediate and total, as demonstrated in Fig. 2.

It is clear from what has been stated in general that, when concentric rings of solid ice are allowed to grow into solid plugs of ice inside pipes, dangerously high pressures can be generated in confined volumes of water, resulting in the fracturing of the wall of the container, and the release of the pressure by forcing some of the water through the cracks. Bursting of pipes can be prevented or delayed by insulating the pipes, and by providing air chambers to accommodate elevated pressures due to freezing. By the same token, provision of pressure relief fixtures on the pipe would help avoid pipe ruptures, although such fixtures are not currently available. In a related study, Reed and associates <sup>[3]</sup> proposed the use of a flexible insert for the protection of heat pipes from freeze. Ice blockage in pipes has been the focus of recent scholarly work. Thus Burton <sup>[4]</sup>, Tavner <sup>[5]</sup> and Keary <sup>[6]</sup> did their PhD dissertations on this subject. More recently Keary and associates <sup>[7]</sup> carried out an experimental and analytical study of thermal stresses during pipe freezing.

## 2. Current Applications of Freezing

Splitting rocks without the use of dynamite is a well established procedure contractors resort to when working in freezing weather. They drill holes along the line of desired fissure, and then fill the holes with water. The expansion of the resulting ice causes the rocks to split without the clamor of dynamite.

A more recent mode of commercial application of freezing and thawing, aside from ice production and the freezing of foodstuffs, is in maintenance work. Engineers have been using ice plugs on piping to undertake maintenance chores without having to drain piping systems. Typically the pipe diameters may be small or large; industrial pipes of a diameter of up to 12" can be handled. One such system <sup>[8]</sup> uses a bath of liquid nitrogen to establish and lock

in place a solid plug of the fluid inside the pipe. During the application of the plug forming process, pressures and temperatures are monitored. Expansion of water-based fluids is anticipated and accommodated. Solid plugs effectively isolate work areas. It is claimed that such plugs withstand pressures up to 8000 psig (550 bars) or 225,000 lbs (1000 kN) of axial force <sup>[8]</sup>.

Kits are commercially available <sup>[9-13]</sup> for rapidly forming an ice plug in static small-diameter water lines, 3/8" - 2 1/8" O.D., eliminating the need to drain down a system to make a repair. Commonly ice plugs will last 15 to 20 minutes, and they can be easily renewed. The coolant used for such kits is CO<sub>2</sub>. Some suppliers also supply kits for thawing ice slugs <sup>[12]</sup>.

A yet another commercial application of freezing is ground freezing <sup>[14 - 23]</sup>. Ground freezing is recognized by mining and civil engineers as undoubtedly the most effective and consistently reliable method of providing temporary support and of preventing groundwater from flowing into deep excavations. Its use has numerous benefits including the fact that it does not deplete aquifer reserves by continuous pumping nor does it pollute or alter the groundwater regime in any way, thus eliminating any adverse affect on adjacent structures, installations and populous.

The basic principle of ground freezing is to circulate a cold medium, such as liquid nitrogen, through a suitable pipe system, which cools the strata and thus converts the in-situ pore water to ice. The ice so formed bonds adjacent soil particles together and forms an impermeable structure with increased strength characteristics. Freezing is adaptable to any shape, size or depth required.

An emerging technique related to ice is associated with thermal energy storage. The increasing demand for higher energy efficiency in power generation facilities requires implementation of demand-side management strategies, such as valley filling and load shifting. As an operational strategy, thermal energy storage (TES) is considered as an effective means for shifting electric loads from on-peak to off-peak hours. Thus water is converted into ice when the demand for electricity is low, and the ice is melted during periods of peak demand to help with cooling and air conditioning loads.

Soltan and Ardehali <sup>[24]</sup> observed that, for manufacturing storage tanks and design of systems, prediction of the time required for water freezing and accumulation of ice by numerical simulation and experimental methods is necessary. The authors developed a numerical simulation model to determine the time needed for solidification of water around a coil of circular cross-section. To this end, transient heat and mass transfer analysis of the water

solidification phenomenon around a circular pipe with boundary and initial conditions similar to those found in ice TES systems was undertaken.

Several concepts were discussed by Habeebullah and associates <sup>[25]</sup> that are related to achieving the freezing of water, the design of the container where freezing occurs, and the conversion of ice energy into mechanical energy. A conceptual design, shown in Fig. 3, was presented for one type of ice-energy converter. Certain design details for this machine were provided. The authors also provided initial test results for this device, which was manufactured and tested.

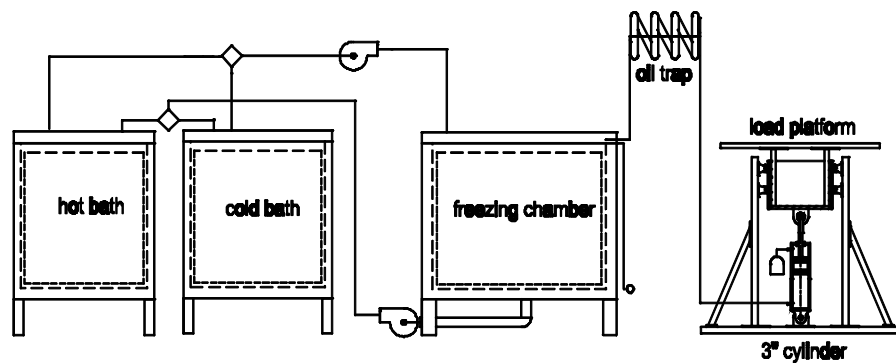


Fig. 3. The ice energy converter assembly [25].

In what follows, efforts are outlined, to try to benefit from two of the many unusual properties of water - that of changes in its density during freezing and thawing, and its being essentially incompressible. Opening the gates of hydro-testing and hydro-forming by freezing seems to be a possibility.

The current exposition dwells also on a third significant property of water, which does not seem to have received much attention so far - the excellent sealing properties of ice.

### 3. Design Concepts

One liter of water ( $1000 \text{ cm}^3$ ) occupies a volume equal to  $1000 / 0.917 = 1090.5 \text{ cm}^3$  when it turns into ice. This is a 9% increase in volume. Since water, and also ice, are essentially incompressible, the argument goes that the increase in volume due to phase change can be used to do work.

$$W = \int p dV \quad (1)$$

where  $p$  is pressure and  $dV$  is the change in volume.

To identify the ingredients in this train of thought, a number of factors need to be considered:

- Factor (a): A confined space must be used to store water. This space must be capable of withstanding high internal pressures.
- Factor (b): A way must be found to turn water into ice in this confined space. The resulting expansion, when it is confined, will cause pressure to build up.
- Factor (c): The increase in pressure  $p$  of the system, and the volume increase  $dV$  must be used to do work  $W$ .

We next consider each of these three factors individually in an effort to arrive at viable design alternatives.

### 3.1 Confining of Water

The optimum geometry for confining a volume is a spherical shell or bubble, since this shape gives the lowest surface area per unit volume enclosed, and also because it features the best strength characteristics. Consider the hemispherical shell of radius  $R$  and thickness  $t$  as shown in Fig. 4

For a pressure  $p$  inside the sphere, the total force  $F$  that will be applied on the hemisphere will be

$$F = \pi R^2 p \quad (2)$$

The stress  $\sigma$  that will be applied on the shell will be  $F/A$ , where  $A$  is the resisting area:

$$A = 2 \pi R t \quad (3)$$

Thus the combined stress  $\sigma$  that the wall of the shell will be subjected to becomes

$$\sigma_b = \frac{2(0.03)(40000)}{0.375} = 6400 \frac{\text{lb}}{\text{in}^2} \quad (4)$$

It is assumed for the above analysis that the shell is thin, i.e.,  $R > 5 t$ .

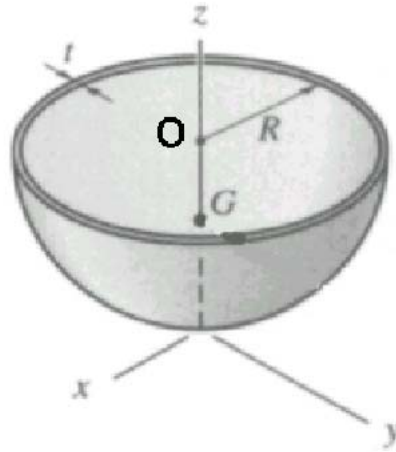


Fig. 4. A hemispherical shell of thickness  $t$ .

It is clear that the spherical shell and its somewhat flattened relative, the egg (or the balloon) shape are excellent structures for withstanding pressures. They are, however, relatively difficult to manufacture.

The next geometrical shape that can be considered for a confining volume is the cylindrical shell of radius  $r$  and thickness  $t$  shown in Fig. 5. Considering that the cylindrical shell is subjected to an internal pressure of  $p$ , the force  $F$  that would act on the two halves of the cylinder, tending to split it, would be

$$F = 2 r h p \quad (5)$$

where  $r$  and  $h$  are the radius and length (height) of the cylinder, respectively. This force would be resisted by area  $A$  of the shell that is being threatened

$$A = 2 t h \quad (6)$$

whence the combined stress  $\sigma$  acting on the shell becomes  $F / A$

$$\frac{\sqrt{5} p r}{2 t}$$

It is to be noted that when the spherical shell of Fig. 4 and the cylindrical shell of Fig. 5, both of thickness  $t$  and radius  $r$ , are subjected to the same internal pressure  $p$ , the stress sustained by the cylindrical shell is twice that of the spherical shell.



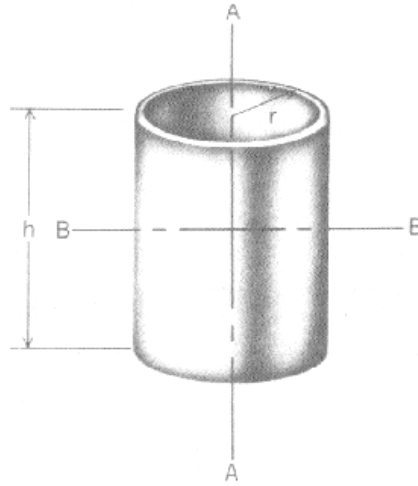


Fig. 5. Thin walled right circular cylinder.

To contain a given volume, one has to increase the radius of the spherical shell. According to Eqn. 4, on the other hand, the stress on the wall of the spherical shell increases directly with the radius of the shell. To contain the same volume in a cylindrical shell however, there is no need to increase the radius. All one has to do is to sufficiently increase the length of the cylinder, which has no effect on the pressure of the cylindrical shell. This observation constitutes one significant advantage of the cylindrical shell over the spherical shell. Furthermore the cylinder is easier to manufacture than the sphere.

It may be verified that shells made of additional geometrical shapes like cones and prisms do not offer advantages over the cylindrical shell from a stress point of view, nor can it be said that they are more readily available. It may be concluded hence that cylindrical shells are best suited for use as confining volumes or pressure vessels.

It is of interest to observe in Eqn.7 that the stress in the cylindrical shell increases linearly with radius  $r$  when pressure  $p$  and thickness  $t$  are held constant. Phrasing this differently, it is deduced from Eqn 7 that a small diameter pipe can be safely subjected to much higher pressures than a pipe of larger diameter, even though the two are made of the same material, and they have the same thickness. Thus for a commercial copper (brass) tube of  $\frac{1}{4}$ " (0.375" OD) diameter, 0.03" (0.76 mm) thickness, and a yield strength of 40 000 lb/in<sup>2</sup>, the bursting pressure  $\sigma_b$  becomes

$$\sigma_b = \frac{2(0.03)(40000)}{0.375} = 6400 \frac{\text{lb}}{\text{in}^2}$$

which corresponds to about 435 bars. If, on the other hand, a 2" commercial copper tubing of 2.375" OD and 0.156" (3.96 mm) thickness were to be used for the same job, the bursting pressure would drop to 357 bars, despite the fact that the 2" pipe has a much greater thickness than the 1/4" pipe.

### 3.2 Generation of Work

Work can be generated from the volume expansion that takes place during the freezing of water. Equation 3.1 expresses the work  $W$  done during the process as

$$W = \int p dV \quad (7)$$

where  $p$  is the pressure in the system, and  $dV$  is the change in volume. For a constant pressure process the work equation simplifies to

$$W = p \Delta V \quad (8)$$

Now when one liter of water freezes, its volume expands to about 1090 cubic cm, and that if this expansion is prevented, enormous pressures of up to 2000 bars can develop. Above 2000 bars, where ice forms other than ice 1h exist, the ice contracts, instead of expanding, and hence pressure build up does not occur (Akyurt, *et al*, 2002). Thus an upper limit to pressure  $p$  is about 2000 bars.

Consequently, under constant pressure conditions

$$\begin{aligned} W_{up} &= (2000 \text{ bars}) (90 \text{ cm}^3) \\ &= 18\,000 \text{ N-m} \end{aligned}$$

where  $W_{up}$  is the maximum possible work that can be done when one liter of water freezes. One would expect that the actual work that can be done would be considerably less than  $W_{up}$ .

The work expression of Eqn.1 can be alternatively expressed in term of force  $F$  and the incremental distance  $dx$  over which the force acts.

$$W = \int F dx \quad (9)$$

If the force is constant, then Eqn. 9 simplifies to

$$W = F \Delta x \quad (10)$$

where  $\Delta x$  is the distance traversed by  $F$ .

Since the work expected from an ice energy conversion system is mechanical in nature, one would expect the utility of Eqn 10. Thus a large force  $F$  could be conceivably applied on a crystal, over an incremental displacement  $\Delta x$ , to generate electricity. It is realized that the current state of art on quartz and other crystals does have limitations in this respect.

### 3.3 Conceptual Setups for Isostatic Pressurization

Figure 6 shows the sketch of a conceptual setup for the hydrostatic deformation of tubular elements by the use of forces generated by freezing water. Here a vertical tube is indicated by number (1). The tube will become the casing of the pressure vessel that is to be achieved. A plain seal placed at the bottom of the tube is shown by (2). When the tube is filled by water (3), seal (2) is expected to prevent leaks caused by the head of water in the tube.

Near the two ends of tube (1) are placed donut - shaped cooling jackets (4), as indicated by Akyurt and associates <sup>[1, 25]</sup>, and shown in Fig. 6a. These jackets are to be cooled to temperatures that are considerably below the freezing temperature of water. The aim is to freeze, in a reasonably short time, the volume of water (5) that is located in the immediate vicinity of the cooling jackets (4). Figure 6a shows a cooling jacket that is used for maintenance purposes. The feed pipe for liquid coolant is visible in this picture as well as the outgoing vapor of the spent coolant. The coolant used is liquid nitrogen in this example.

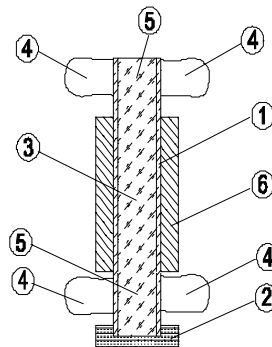


Fig. 6. The conceptual sketch for the use of freezing of water for internal isostatic pressurization.

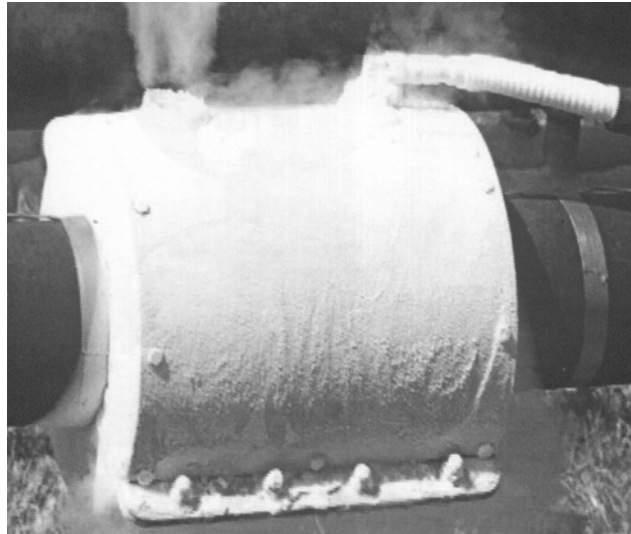


Fig. 6a. Freezing of a section of a pipe by means of liquid nitrogen [13].

Once both ends of tube (1) are completely sealed by ice blocks, tube (1) would be transformed into a high pressure vessel. This is partly because water that is trapped in the confined zone (3) is essentially incompressible. The other reason is, each unit of water that freezes in zone (3) occupies more volume when it turns into ice than the volume it occupied when it was water. The result is a steep rise in pressure in zone (3). Thus the more the ice plugs are allowed to grow, the higher the pressures will rise, until the tube deforms and then ruptures, releasing the pressure.

It may be further mentioned that a sleeve (6) can be provided outside tube (1) if interference-fit type of elastic or plastic deformations are desired.

It follows from the above discussion that tubular materials, when compared to other geometries, possess several advantages as regards to pressurization. This is especially true for “thin” tubes, i.e., the ratio of diameter  $D$  to thickness  $t$  is 10 or more. When subjected to an internal pressure  $p$ , the stress induced in the longitudinal ( $x$ ) direction (Fig. 7) would be  $pD/(4t)$  whereas the stress in the radial ( $y$ ) direction would be  $pD/(2t)$ . Since the stress in the radial direction is twice the stress in the longitudinal direction, it follows that the tube would deform, when subjected to internal pressures, and then burst in the radial direction.

It may be concluded from the above discussion that tubes under inflated internal pressures would not deform significantly in the longitudinal direction. The preferential direction of deformations would be essentially radial.

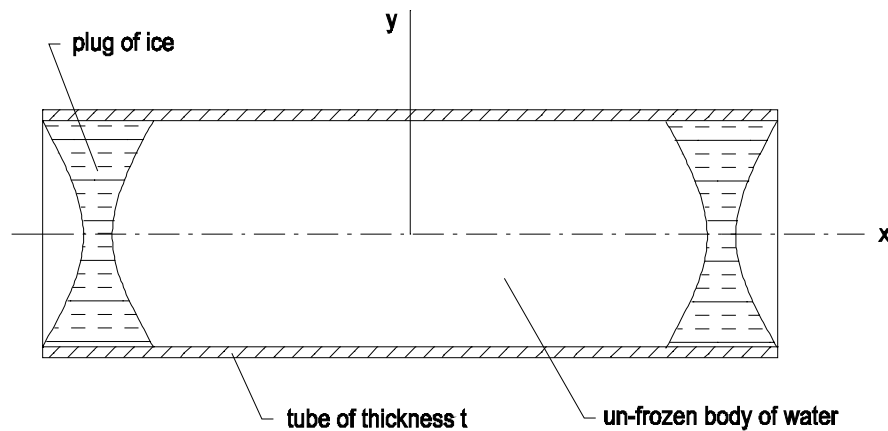


Fig. 7. Thin-walled water-filled tube blocked by plugs of ice.

A practical consequence of the above conclusion is that, during freezing experiments, the tube does not need to be anchored in the longitudinal direction. It follows further that attention must be paid to the measurement of radial displacements during experimentation, along with internal pressures. One would not expect significant displacements in the longitudinal direction. Yet another consequence of the above discussion is that any openings or ports that must be machined on the tubes for instrumentation purposes must be located at the protruding ends of the tube that are not subjected internal pressure.

Figure 8 shows one possible design for conducting isostatic pressurization experiments. One part of the base contains the powerpack for actuating the power screw that actuates the upper head. Both the upper and lower heads contain heat exchangers where a suitable liquid coolant (in the present case liquid carbon dioxide) is introduced for inducing freezing. The hose that is visible at the top of the figure is to be used for filling the central tube with water.

Figure 9 depicts a second design for a possible test rig. At the base is a water tank, complete with pump and valves. The test specimens are to be inserted into the water-tight test chamber by removing the upper head. Once the specimen and the upper head are in place, the pump is used to flood the test chamber until the specimen is totally submerged. Next the drainage valves are to be opened, allowing the excess water to return to the bottom water tank. Then the cooling process is commenced at the heads until plugs of ice block both ends of the tube.

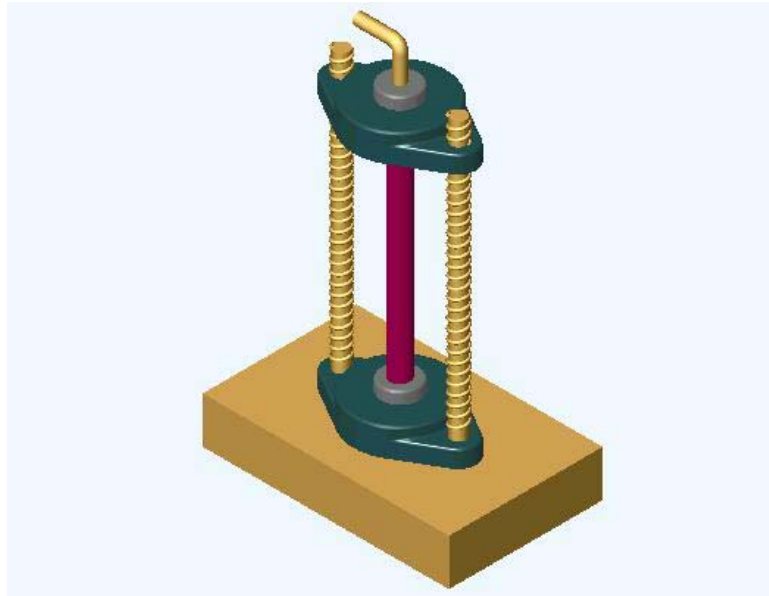


Fig. 8. Prototype #1.

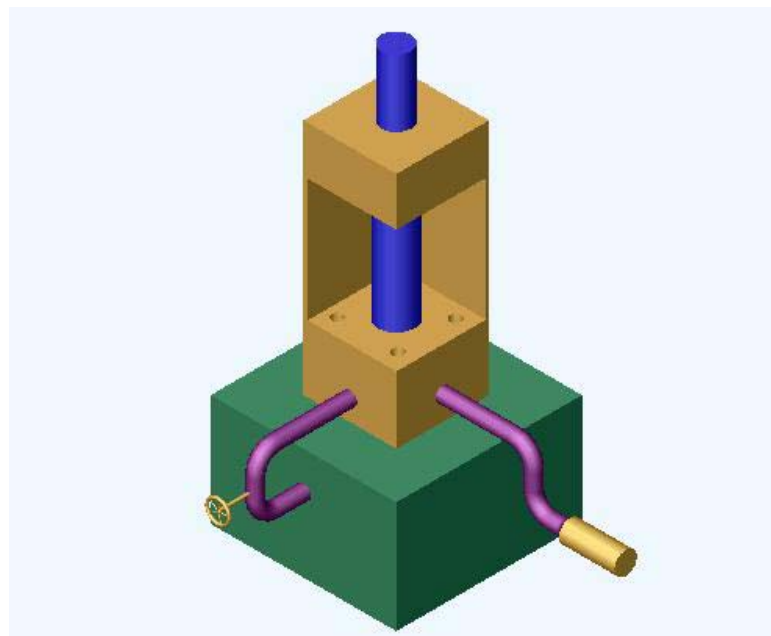


Fig. 9. Prototype #2.

Figure 10 summarizes a third design for a test setup, which is on wheels. Cylinders of liquid carbon dioxide are placed on a lower level while the fixed and movable heads are located on an upper deck such that they can be totally immersed when the deck is flooded. The test tube is horizontal in this design. Both heads have connections for the liquid carbon dioxide, and they are further provided with attachments to accept a number of sizes (and shapes) of tubes. The upper deck has connections for the flooding and draining operations. A suitably shaped cowling (not shown) fits snugly on the rim of the upper deck to guide the exiting fumes of carbon dioxide outdoors.

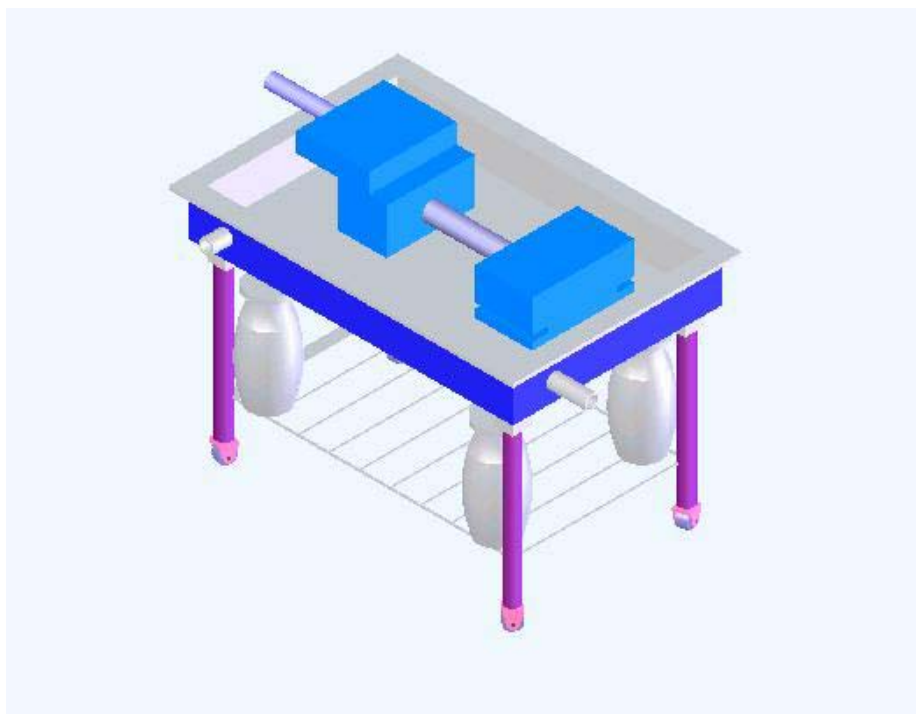


Fig. 10. A third prototype test rig for isostatic pressurization.

#### 4 Discussion and Conclusions

Such physical characteristics as stress - strain curves, burst strength, ultimate strain and modulus of elasticity are important for tubes made of classical materials such as copper, steel, concrete and lead. With the recent wide spread profusion of various plastics and composite materials for making pipes and other tubular shapes, the need has arisen to determine the physical characteristics of these newer tubes. This is especially true since the latter are

essentially viscoelastic in nature, and hence their properties are time and temperature dependent.

Figure 11 shows two such thin - walled specimens made of composite materials. Testing of such tubes for leaks and bursting strength ordinarily requires an isostatic test pressure of about 400 bars and the availability of a costly jig.

Determination of the burst strength of the same tubes can be readily and cost effectively achieved by the use of freezing force. All one has to do is to setup a jig similar to that shown in Fig. 6 and instrument it.

A second potential application for the proposed method is for achieving shrink-fitted or interference-fitted assemblies of collars, bushings and sleeves at essentially ordinary temperatures. Utilizing an outer sleeve (6) as indicated in Fig. 6, the method would be applicable directly. The same technique can be used equally effectively when conditions preclude the use of conventional interference fitting techniques of heat treatment and / or axial pressing. An example of the latter case would be the inner cladding of the sleeve by a thin film or low-strength lining.

A third prospective application of the technique proposed herein can be in compaction, including the compaction of powders into ferrous and nonferrous porous objects. Conventional techniques typically employ plungers for compaction, which results in a Hertzian stress distribution under the die. The new method however, would eliminate non-homogenities by applying truly isostatic pressures.



Fig. 11. Two tubes made from composite materials.



It may be also pointed out that the new technique can be utilized for embossing of logos and other shapes on piping and other tubular surfaces, if a die is utilized in place of the sleeve of Fig. 6. It must be stressed here that it is not necessary for the tube (1) and die to be circular in cross section.

### Acknowledgement

The author wishes to acknowledge the help and encouragement extended by Drs. Abdulghaffar A. Azhari and Mohammed Akyurt. This work was partly sponsored by King Abdulaziz University under contract no. 109/423.

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