Freeze Protection of Pipes: A Characterization of the Time Required to Freeze Stagnant Water

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ABSTRACT

A recent focal point of solar domestic hot water research has been on cost reduction. The market share of SDHW systems can only increase if they are less expensive and simpler to install. Because the heat exchanger commonly included in SDHW systems represents both a significant cost and a significant thermal performance penalty, it is a good candidate for replacement or removal. However, the decision to remove the heat exchanger from the system requires that some other method be used to protect the system from freezing temperatures. While many technologies have been proposed as solutions to the freeze protection problem, less research has been focused on characterizing the locations in which freeze protection needs to be a concern.

This paper proposes that the piping to and from the collector is the critical feature of an SDHW system with regards to freeze protection. The collector itself is a fairly well insulated box. The piping, however, is more difficult to protect. Insulation is difficult to form around elbows and T-pieces while long sections are well exposed to wind.

Both steady state and transient models are developed and verified against experimental and theoretical results. The models are then used to predict the amount of time required to form an ice blockage in a section of pipe exposed to extreme ambient conditions. Various pipe diameters and insulation levels are studied. The range of pipes studied is from 3/8" pipe with 3/8" insulation to 1" pipe with 2" insulation.

1. BACKGROUND

Characterization of the time required to freeze stagnant water in a pipe is a far more difficult task than it initially sounds. There are problems involved with simply defining the problem; what will be counted as freezing the water? Should the values be reported for horizontal or vertical pipes? Why do pipes break in the first place?

According to researchers at the University of Illinois at Urbana-Champaign [1] a pipe breaks because a volume of water becomes isolated and no longer has room to expand as it freezes. Thus it is the pressure increase in a section of pipe that is blocked off at both ends (one or both ends by ice) that breaks the pipe and not the actual volume increase of the ice water mixture.

Two models were developed during the course of this investigation. A constant ambient temperature (CAT) model was developed in order to gain a better understanding of the various methods used in industry to calculate time to freeze. However, the CAT model is of limited practical use because constant ambient temperatures rarely occur in the real world. Thus a variable ambient temperature (VAT) model was developed using the same equations as in the CAT model.

2. CONSTANT AMBIENT TEMPERATURE MODEL

2.1 Development

The equations used to compute the time required for water at an initial temperature T_o to reach a final temperature T

given constant ambient temperature are well known. Equation 1 is an energy balance on the water of density *r*, specific heat *c* and volume *V* contained within a pipe insulated with and overall heat transfer coefficient *UA*[1]. The thermal mass of the pipe and the insulation are neglected.

$$rcV\frac{dT}{dt} = -UA\left(T - T_{\infty}\right)$$

Equation 1 assumes that the water contained in the pipe is at a uniform temperature. The justification for this assumption is two fold. First, the thermal resistance of the insulation surrounding the pipe is so much higher than the internal thermal resistance of the water that the water will tend towards a uniform temperature. Second, the analytical results are borne out by experimentation as will be discussed in section 3.2.

Solving Equation 1 for the time t required to reach any temperature T yields Equation 2:

$$t = \frac{rcV}{UA}\ln\left[\frac{T - T_{\infty}}{T_o - T_{\infty}}\right]$$

After the water reaches $T_{freezing}$, (0°C) it's temperature ceases to change while the latent heat of fusion is removed[2]. Again assuming constant ambient conditions, it is possible to analytically calculate the time required to remove all the latent heat of fusion using Equation 3.

$$t = \frac{h_{fi}\rho V}{UA(T_{freezing} - T_{\infty})}$$

Once the latent heat of fusion has been removed from the fluid, a blockage is assumed to have formed. If the water is trapped by a second blockage (either an ice blockage or mechanical blockage such as a valve), the pressure buildup due to the still cooling water will burst the pipe. Calculating the time for this event to occur involves knowing the volume between the blockages. A worst-case assumption is that the volume is very small (zero). The procedure involves calculating the radial expansion of the pipe necessary to reach critical hoop stress. Equation 4 is used to compute the radial expansion.

$$\Delta r = \frac{r}{E}\left(s_{hoop} - n s_{radial}\right)$$

where E is the modulus of elasticity of the material, σ_{hoop} and σ_{radial} are the hoop and radial stresses and ν is Poisson's ratio. If the stresses used in this equation are the critical stresses necessary for yield, then the radial displacement calculated can be used to determine the specific volume of ice water mixture necessary to reach yield stress.

The yield stress analysis is valid for rigid materials such as copper and PVC. However, the material properties of polymers change dramatically at cold temperatures so care must be taken to use temperature-dependent yield-strength data. Elastomers do not behave in the same manner as rigid materials and so the yield strength analysis is not valid.

An Engineering Equation Solver (EES) [2] program was developed to calculate all the times involved with cooling water to freezing. A diagram window allows the user to select the pipe size, insulation thickness, initial conditions and ambient conditions. The program then computes the time required for a blockage to form and then the amount of time from that point until the pipe material's yield strength has been reached by internal pressure.

2.2 Verification

In order to verify the EES steady state model, its results were compared to two other sources of time to freeze information; the ASHRAE Fundamentals handbook [3] and SRCC tabulated data [4].

The 1993 ASHRAE Handbook [3] presents a semi empirical equation for computing the time required to freeze a pipe. In the 1997 handbook [5], however, ASHRAE has switched to using the analytical method employed by the EES constant ambient temperature model. Correlation between EES's computation of the time to reach 0°C and the ASHRAE's equations is perfect. It should be noted that the ASHRAE Handbook reports the time to freezing as the time required to reach 0°C from initial conditions and does not take the latent heat of fusion into account. This is a more conservative method for computing the time required to freeze.

The Solar Ratings and Certification Commission (SRCC) provides tabulated data in the OG-300 Standard for various pipes and various insulation thicknesses commonly found

[1] UA is calculated as a combination of pipe and insulation thermal resistances and an outside heat transfer coefficient.

[2] Actually, subcooling can occur but is neglected in this analysis. Subcooling occurs if no nucleation sites are present for freezing to begin. Once an ice crystal is formed, the energy of subcooling is quickly used to freeze additional liquid. If the ambient temperature is low, the effect of neglecting subcooling on the time to blockage is small since the only impact is a somewhat lower temperature difference for heat loss.

in solar domestic hot water (SDHW) systems. Figure 2.2.1 shows the correlation between the EES model and the SRCC data.

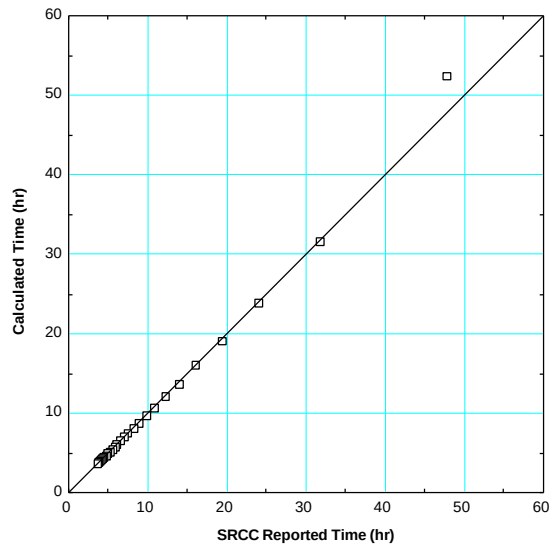

Figure 2.2.1: Constant Ambient Temperature Model and SRCC Tabulated Data Comparison

It is apparent from the above figure that there is extremely good correlation between the constant ambient temperature model and the SRCC data for short freeze times (small diameter pipes or extremely cold conditions). There is one data point at a freeze time of about 48 minutes corresponding to large diameter pipes or small temperature differences in which the agreement is not perfect. The SRCC reports a longer time to freeze under these conditions than are predicted by the EES model.

2.3 Results

The EES steady state model was run for a number of pipe sizes and insulation thicknesses to demonstrate the effect of these parameters on the time required to freeze.

Plots were generated for 1/4,1/2, and 5/8-inch nominal diameter schedule K copper pipes with various insulation thicknesses. All the plots have the same shape, differing only in scale. One interesting feature to note is the relationship between the time required to form an ice blockage (the end of the latent heat of fusion) and the time required to break the pipe once the blockage has formed. Figure 2.3.1a shows the time required to form an ice blockage and Figure 2.3.1b shows the additional time to reach the yield stress.

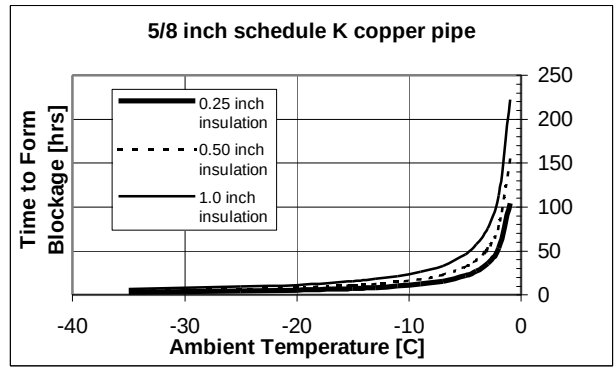

Figure 2.3.1a: Time Required to Form Ice Blockage

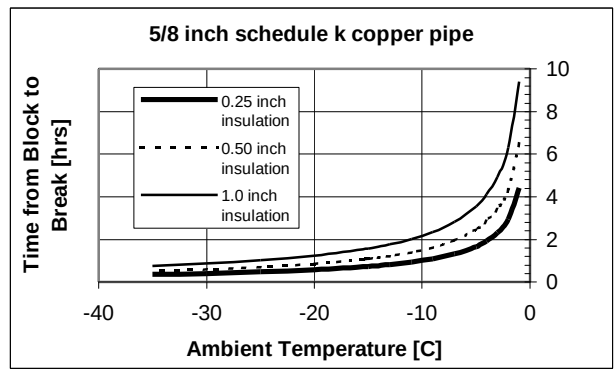

Figure 2.3.1b: Time Required to Reach Yield Stress Once Blockage Has Formed

It is evident from the figures that the time of interest is the time required to form an ice blockage and not the total time. The time it takes for the pipe to burst once a blockage has formed (trapping a small volume) is an order of magnitude smaller than the time for the blockage to form and is therefore insignificant.

2.4 Conclusions Drawn from the CAT Analysis

There are two major problems with the constant ambient temperature analysis. First, it is of limited use as ambient temperature is never constant. It is arguable that this constant ambient temperature can be thought of as an average ambient temperature. In this, as long as the ambient temperature is significantly below freezing (such as in the Upper Midwest in winter) then the results of the CAT model are quite valid. However, if the ambient temperature is near freezing, then the using a constant temperature corresponding to the average ambient temperature will likely give inaccurate results.
Second, the calculated time to reach yield stress in the pipe is questionable, as the trapped water volume is quite important. Our calculation assumes that when a blockage occurs, the trapped water volume is zero; a worst-case assumption. The problem is that the volume of the water

trapped in the pipe is an important factor in the result; if a large quantity of water has been trapped then it will take longer for the pipe to burst than if a very small volume were trapped. Perhaps the most useful conclusion to be drawn is that it takes only a 0.1% change in fluid volume to reach a copper pipe's yield stress. Thus we can neglect these calculations and concentrate on the time it takes for the blockage to form assuming that once that event occurs, bursting is soon to follow.

3. VARIABLE AMBIENT TEMPERATURE MODEL

3.1 Development

The major drawback of the CAT model is that it assumes the ambient temperature to be constant, a situation that rarely occurs in the real world. It is not possible to vary the ambient temperature in the CAT model because the analysis only performs three calculations: the time needed for the water to go from its initial temperature to freezing; the time needed once the water reaches 0°C for the latent heat of fusion to be removed, and the time necessary for copper's yield stress to be reached once the latent heat of fusion has been removed. For each set of conditions, two times are reported; the time to form a blockage and the time required for the pipe to burst once a blockage has formed.

For the variable ambient temperature analysis, time was divided into increments (timesteps) and the amount of energy transferred between the pipe and ambient was computed. In this manner, the temperature response of the water in the pipe to changing ambient conditions is obtained.

As in the CAT situation, there are two distinct regimes defined in the VAT analysis. In the first regime, the pipe water temperature is above freezing and so responds to ambient temperature changes according to Equation 1.1. Once the temperature of the water has reached 0°C, then it behaves according to Equation 5 but modified to account for the variable ambient temperature. For a time increment *Dt*, over which the ambient temperature remains nearly constant, the relationship is:

$$UA\left(T_{freezing} - T_{ambient}\right)\Delta t = r\, h_{ig} V \Delta f$$

where during the time increment *Dt* the fraction *Df* of the total latent heat is removed. Thus, Equation 5 relates the amount of energy that is removed (or added) to the fluid during each timestep. Consequently, the amount of energy removed from the fluid at each timestep must be summed to determine when the total latent heat of fusion has been removed. Once the total latent heat of fusion is removed from the fluid, then an ice blockage is assumed to have formed and little additional time is required for the pipe to burst.

A TRNSYS [6] Type was written in order solve Equations 1 and 5. TRNSYS Type100 takes pipe parameters (pipe size and overall insulation UA), various fluid properties (density, specific heat, and latent heat of fusion) as well as the ambient temperature and calculates the fluid temperature or state of freezing as a function of time. If ever the fluid reaches 0°C, then the Type performs all the bookkeeping required to determine when all of the latent heat of fusion has been removed.

Because the TRNSYS model requires the user to enter an overall UA value for the pipe, some of the copper pipe configurations can be seen as having equivalents in insulated PVC pipe. The comparison is further valid because the TYPE computes the time required for an ice blockage to occur (as opposed to the time required for the pipe to break) in which case the yield strength of the material does not come into play.

In order for the VAT model to work, it needs ambient temperature conditions. There are a number of sources of weather data including generated data and typical meteorological year (TMY) data. Both types of data are commonly used in simulations. However, for our purposes, we are not interested in average conditions. We are interested in how long pipes can exist without breaking under poor conditions.

Extreme weather conditions were generated using an ASHRAE program called Extremes [7]. The program allows the user to generate a sequence of hot, cold or average conditions for any length of time up to 7 days during any month. Conditions for a cold week during the month of January were generated for 176 locations across the United States. The locations were selected in such a way that they represent weather regions, under which transitions from one type of the climate to the other would be most noticeable.

Simulations were run for 3/8, 5/8 and 1 inch diameter schedule K copper pipes having four different insulation thicknesses 3/8," 3/4," 1," and 2," respectively.

3.2 Verification

The TRNSYS simulation was verified in two ways. First, it was compared to the CAT calculation method used previously. Second, it was compared to experimental data.

The TRNSYS VAT model, using a constant ambient air temperature, was tested against the EES CAT model and, as expected, the two models give identical results.

TRNSYS results were compared with the results of an experiment carried out by the Building Research Council at the University of Illinois at Urbana-Champaign [1]. In this experiment, various water filled pipes were placed in a constant temperature environment and were allowed to burst. The TRNSYS produced cooling curve was compared to the experimental cooling curve and a few important observations can be made. The time required to cool water contained in a 3/4 inch schedule K copper pipe covered by R3 insulation from an initial temperature of 20°C to 0°C in a –6.67°C environment was 1.8 hours, almost exactly equal to the experimental results.

However, the time between arriving at a water temperature of 0°C and the time for a blockage to form is approximately 9.7 hours in the experiment and 13.2 hours according to the simulation. If the insulation value is taken to be R 2.4 instead of R3[3], then the simulation and experimental results match well. Slight changes in R-value can translate into significant time difference for water to freeze. Figure 3.2.1a shows the experimental results reported in [1]. Figure 3.2.1b shows the TRNSYS results using an insulation value of R2.4. It should be noted that in the TRNSYS simulation the ambient temperature changes at t=10 in order to ensure that all initial conditions are steady state.

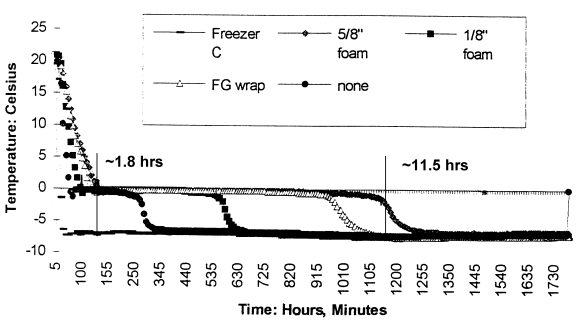

Figure 3.2.1a: Experimental Results with Reported R3 Insulation

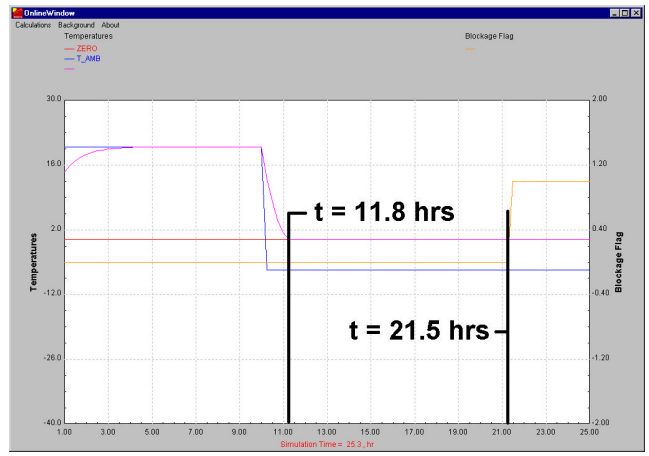

Figure 3.2.1b: TRNSYS Simulation Results with R2.4

3.3 Results

Various pipe and insulation configurations were simulated, making an effort to both cover the range of possible combinations and to use readily available materials. Both copper pipe and insulation properties were taken from the 1998 McMaster Supply Company catalog. The thermal conductivity of the insulation material was taken as 0.24 Btu-in/hr-ft^2-°F (0.035 W/m°C), typical of polyethylene foam pipe insulation. The insulation available in the catalog ranges in thermal conductivity between 0.14 Btu-in/hr-ft^2-°F (urethane foam) to 0.42 Btu-in/hr-ft^2-°F (calcium silicate) with the majority at 0.24 to 0.25 Btu-in/hr-ft^2-°F. Simulations were run for four insulation thicknesses (3/8”,34”,1” and 2”) on each of three nominal pipe diameters (3/8”,5/8”,1”).

The results for the twelve simulations of extreme cold conditions in January are shown below as plotted on a US map. The color of the dot at a given location indicates the time required for the water to freeze. Red dots indicate long times, black dots shorter times. The legend shown in Table 3.3.2 is the same for all maps.

Color	Hours
Black	0 – 6
Purple	6.1 – 12
Dark Green	12.1 – 18
Dark Blue	18.1 – 24
Light Blue	24 – 48
Grey	48.1 – 72
Light Green	72.1 – 96
Light Yellow	96.1 – 120
Dark Yellow	120.1 – 144
Red	> 144

[3] No source was given for the quoted R-value of 3. It is not unreasonable that the actual value varies somewhat from the quoted value, a fact that would explain the difference between calculated and experimental results.

The results for the twelve simulations of extreme cold conditions in January are shown below as plotted on a US map. The color of the dot at a given location indicates the time required for the water to freeze. Red dots indicate long times, black dots shorter times. The legend shown in Table 3.3.2 is the same for all maps.

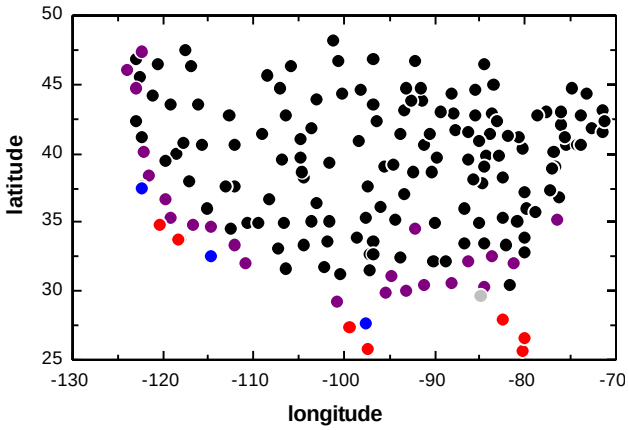

Figure 3.3.1: Time to Form Ice Blockage for US Locations (3/8" pipe with 3/8" foam insulation)

The results for the other extreme situation, a 1" copper pipe covered in 2" of insulation are shown in Figure 3.3.3.

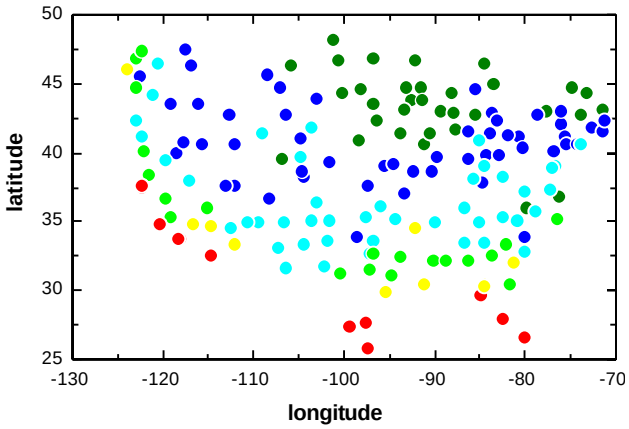

Figure 3.3.2: Time to Form Ice Blockage for US Locations (1" pipe with 2" foam insulation)

In this case, the fastest freezing location takes between 18 and 24 hours to freeze.

A number of generalizations can be made from looking at the plots. First, there is a thin area along the Pacific stretching from southern Alaska, down the coastline of Washington, Oregon, and California characterized by longer freeze times under extreme weather conditions. This feature is evident at both extremes (small pipe with little insulation and a large pipe with heavy insulation). Second, another coastal zone exists along the Gulf of Mexico and along the southeastern US. The difference between this zone and the Pacific coastal zone is that the southeastern zone is much wider as you would expect from a warmer more southerly climate. In the first case the ocean provides a moderating effect, in the second case, the ocean combines with more southern latitudes to increase freeze times.

The areas in which the time required for water in pipe to freeze is short also follow the geographical pattern. The Rocky Mountain and Upper Midwest regions are also characterized by fast freeze times. It should be kept in mind here that no credit has been taken for solar energy incident on the pipes. The pipes were assumed not to have any gains in their favor. Thus a pipe in a cold sunny climate such as Denver's has the same disadvantages as one in a cold cloudy climate. Fargo, ND, and Duluth, MN, were both found to be the locations with shortest freezing times (with the exception of Alaska), with the freezing times of 1.75 hours.

Most of the other areas that do not belong into fast or slow freezing regions but form a kind of transition zone. These regions typically have a freeze time between 2.5 and 4.5 hours. This intermediate region covers most of the continental United States.

5. REFERENCES

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