TECHNICAL BULLETIN 0414

What You Should Know About Thermal Conductivity and Aging of Low-Temperature Mechanical Insulation

PURPOSE

This Technical Bulletin is another in Dyplast's series to provide objective information to decision-makers and end-users on important issues related to mechanical insulation (i.e. insulation for equipment). Although technically intense in some paragraphs, this Technical Bulletin objectively encapsulates more than can be gleaned from other documents generally available.

DEFINITION

Thermal aging is a term that refers to the tendency of some insulants to lose some thermal resistance over time - - predominantly due to the very slow diffusion of low-thermal-conductivity cellular gases out of the cells within the insulation, only to be replaced by "air" with higher thermal conductivity. Since thermal aging is so often used as an argument for or against a particular insulation, it is important to understand this somewhat complex phenomenon.

VARIABLES IN THERMAL AGING

Thermal aging occurs very gradually over many years, yet not linearly. At low temperatures, the vast majority of thermal aging occurs in the early years, though is likely not complete even after several decades. At very low temperatures (e.g. cryogenic), the rate of thermal aging is dramatically less.

The rate of thermal aging can depend on the following, sometimes interdependent, factors:

- The temperature: the lower the temperature, the slower the rate of thermal aging
- Cell size: The smaller the better
- Closed Cell Content (the blowing agent must be retained in the cell to be effective)
- Closed cell density and space between the cells (interstitial space): Can "short circuit" heat flow (such as with EPS)
- Thickness of the insulation (outer layers impede diffusion of blowing agents from inner layers)
- Voids or holes in the foam: Like the interstitial space between the cells, these can provide a pathway for the escape of the blowing agents contained within the cells
- The solubility of the blowing agent in the polymer (blowing agent must be retained in the cell to be effective)
- The diffusion rate of the blowing agent out of the foam, and rate of air diffusion into the foam
    - Can depend on the structure and thickness of the cell walls
- Physical enclosures over the insulation, such as vapor barriers, jackets, laminates, or "skins" dramatically retard the rate of gas diffusion.

"PREDICTING" THERMAL AGING

The practical problem has been how to accurately assess the thermal performance of the foam at a point in time. Two classical approaches have been developed to accelerate thermal aging so as to accurately predict thermal conductivity over the lifetime of the insulation, either: 1) aging at higher temperature or 2) aging a thin slice.

ASTM C591 requires that 12 x 12 x 1-inch samples be cut from the bun/block. After aging the material for 180 days in a controlled environment at 75°F, the foam's R-value is measured at mean temperatures ranging from -200°F to +200°F

It is important to note that the mechanical insulation service temperatures referenced in this document are normally well below 75F, and that thermal aging is reduced considerably at lower operating temperatures. Thicker insulation, vapor barriers, and metal constraints also limit gas diffusion.

PERSPECTIVE

To be effective, pipe and equipment below-ambient temperature conditions require insulation systems quite different from those in above-ambient conditions - - meaning that water condensation and freezing on pipe surfaces or the outer surfaces of the insulation system can have dramatic impact on the ultimate performance of the process. Admittedly, the insulant itself is the *last line of defense* against performance degradation, yet improper design or installation of vapor barriers, mastics, or jackets can doom the best of insulants. There have been dozens of scholarly papers and hundreds of marketing documents that provide sometimes credible and sometimes misleading or at least confusing information.

Since there is so much complexity and so much information, it is easy to *lose sight of the forest when trees block the view*. We do not trivialize the complexities of the related issues, yet we also understand that specifiers and end-users need informed and objective information upon which to base their decisions - - without the need to convene a panel of experts for each application.

As the basic perspective, there are many insulants with "*poor*" thermal efficiencies that exhibit no thermal aging, and there are some "*superior*" insulants that do so. It can be generalized that the Aged Thermal Conductivities of the "superior" insulants are still materially better than the "poor" insulants, and thus over a lifetime the energy savings can greatly outweigh any small premium in cost.

CLOSED CELL VS. OPEN CELL

Cellular foam insulants include polyisocyanurate, spray-foam polyurethane, extruded polystyrene (XPS), expanded polystyrene (EPS), phenolic foam (PF), cellular glass, polyicynene, and elastomeric rubbers. Cellular foams can be either open or closed, and closed cell foams may have a percentage of open cells where flaws in the manufacturing process result in the bursting or fracture of some cells. Thus Closed Cell Content is a key physical property when evaluating alternative foams. Cell size and the interstitial spaces between cells are also factors, with smaller cell size and less space between cells being advantageous.

There is some lack of agreement on a concise definition of "open" cells, but for the purpose of this TB we identify polyicynene, some types of low density spray-foam polyurethanes, and EPS as open cell foams since they do not depend on their cellular structure to restrain gases within the cells. Closed cell rigid foam insulants generally have better R-values, moisture absorption, water vapor transmission (WVT), and compressive strength.

THERMAL AGING: BLOWING AGENTS

The manufacture of polyiso, spray polyurethane, XPS, EPS, PF, cell glass, and polyicynene insulants each depends on the expansion of a liquid or mixture of liquids into "foam" using blowing agents consisting of either a fluorocarbon, hydrocarbon, carbon dioxide, air, or steam (each of which has successively poorer thermal conductivity). Over the past few decades, the Montreal Protocol has mandated incrementally staged phase-outs of CFCs and HCFCs from insulation foams because of their high ozone depletion potential (ODP). Since CFCs and HCFCs had excellent (low) thermal conductivities this has inevitably led to a slight decrease in the R-values for closed cell rigid foam insulants that used such blowing agents. Hydrocarbons such as pentane (cyclo, n-, or iso-pentane or a combination) or HFC have generally taken their place within the cells.

The portion of such cells that are exposed to "air" have a *partial-pressure* across their cell boundaries which creates a "drive" for the blowing agents to diffuse through cell walls - - being replaced by atmospheric air (acknowledging air is 78% nitrogen and 21% oxygen) - - and eventually achieving an equilibrium across the cell wall. There are, however, situations where the diffusion of the gases across cell boundaries is impeded: for example, if the cells are in the interior of the foam and not exposed to air, covered with vapor barriers, and so forth.

INSULANTS THAT DO NOT THERMALLY AGE

EPS and cellular glass are the most common insulants that do not thermally age, yet the R-values of EPS and cell glass are nominally well below that of, for example, aged polyisocyanurate. EPS is very rarely used in low temperature applications due to concerns over high water absorption and/or WVT. Cellular glass is very commonly used yet conventional wisdom concludes its very high cost combined with poor thermal conductivity make it a poor choice for most low temperature applications.

THERMAL CONDUCTIVITY

It is important to communicate concisely: *Thermal Conductivity* is defined in ASTM C168[1] as the time rate of steady state heat flow through a unit area of a homogeneous material induced by a unit temperature gradient in a direction perpendicular to that unit area - - typically expressed as the symbol "*k*", in units of Btu·in/hr·ft²·°F. In other words *k*-factor is the number of BTUs per hour that pass through a one inch thick by one foot square section of insulation with a 1°F temperature difference between the two surfaces. It is very important to also note that the thermal conductivity of insulation materials varies with temperature. Typically, *k*-factors improve (get lower) at lower temperatures, and the insulation's thermal performance improves. Most ASTM material specifications subscribe to thermal conductivity measurements at a mean temperature of 75°F. Yet often, such as in the case of ASTM

1 http://www.wbdg.org

C591, *k*-factors are required to be tested over a wide range of mean temperatures.

The term *apparent thermal conductivity* is used for many insulation materials to indicate that additional non-conductive modes of heat transfer (i.e. radiation or free convection) may be present.

Thermal conductivity (*k*) and thermal resistance (R) of an insulant are essentially the inverse of each other to the extent that:

- As the numerical measure of thermal conductivity ("*k*") decreases, thermal energy finds greater resistance to flow across the insulation - - thus the thermal insulation performs better;
- Conversely, the higher the thermal resistance ("R"), the greater the resistance to heat flow, and similarly the better the thermal performance of the insulation.

The *k*-factor is inherently defined *per inch*, whereas the R-value ($hr \cdot ft^2 \cdot °F/BTU$) can be ascribed to multi-inch materials.

A number of other terms related to thermal conductivity are sometimes used[2]. These are not material properties, yet are sometimes used to describe the thermal performance of specific products or systems.

Product datasheets typically list the relevant *k*-factor, along with its inverse - - R-factor at one inch. For insulation products more than one inch thick, the R-factor is typically multiplied by the number of inches, and the result referred to as the total R-value. Yet this is only appropriate for flat surfaces, and even then may be inappropriate for certain insulations (the *Thickness Effect* is discussed later). For non-flat surfaces such as pipe, the actual R-value calculation is more complex (also discussed later).

The Importance of R!

K-factor (or its inverse, R-value) is typically the most importance physical property used to select an insulant. The installed cost is also generally considered an important factor, yet in the majority of situations the long term energy cost savings that accrue from an incrementally better R-value make even a higher installed cost immaterial. R-values in the U.S. are measured in accordance with the appropriate ASTM Specification: for instance ASTM C591 for polyisocyanurate, ASTM C578 for polystyrene, ASTM C1029 for spray-applied polyurethane, and C177 for elastomeric foam and cellular glass - - just to name a few.

These ASTM specifications are designed to yield k-factors that can be used to compare one insulant against another. Although there can be some debate over whether ASTM specifications actually provide for "apples-apples" comparisons, it is not the intent of this TB to discuss minor deficiencies within ASTM methodologies. Rather, we wish to focus on educating interested parties on the factors that influence R-values and make them better able to make informed decisions in the selection of the "best" for their particular mechanical insulation application.

[2] Thermal Conductance, or C-value, is the time rate of steady state heat flow through a unit area of a material or construction induced by a unit temperature difference between the body surfaces. Or a flat board or blanket insulation, C is calculated as the thermal conductivity divided by the thickness (C=k/t). The thermal transmittance, or U-factor is the heat transmission rate through unit area of a material and the boundary air films, induced by a unit temperature difference between environments on each side. Units of U are typically $Btu/hr \cdot ft^2 \cdot °F$.

Simple or Complex??

When wandering through the aisles of a home improvement store, one may note that insulation products are labeled with a single R-value. A batt of fiberglass insulation may be labeled as R-19; a two-inch thick "blue-board" may be labeled as R-10, and so forth. The labeling of such products for residential use is regulated by the Federal Trade Commission. Since these products are used in similar applications (e.g. roof or insulation in homes), the stated R-value is likely a sufficient amount of information for a homeowner to make a selection.

Yet when selecting an insulation for an industrial or commercial piping application, making a selection based on only on R-value may be folly, since the actual thermal performance within the installed insulation system depends on:

1. Its operating temperature, which varies from the inner surface to the outer surface (for instance, some insulants have improved R-values at lower temperatures);
2. The differential in temperature across the insulation (i.e. the greater the differential, the greater the thermal *drive*);
3. The moisture content, if any;
4. Possibly the age of the insulant (e.g. *thermal aging*);
5. Possibly the material thickness (e.g. EPS The Thickness Effect
6. Possibly other environmental conditions such as wind, humidity, intensity of sunshine, etc.

To further complicate the issues, the quality of the design and installation can either mitigate minor disadvantages of a given insulation, or exacerbate the risks. For instance:

- A properly installed vapor barrier can improve the performance of an insulant by preventing water vapor from coming in contact with an insulant that may have poor WVT properties;
- The use of a vapor *retarder* rather than a *barrier*, a poorly installed vapor barrier, or one which may be subjected to mechanical abuse (e.g. foot traffic) must be compensated for by an insulant with excellent WVT properties;
- A properly designed insulation *system* using the optimal insulant, with expansion joints, vapor stops, proper use of joint sealants, pipe coatings as necessary to mitigate corrosion under insulation (CUI), and so forth results in a system that can expand, contract, vibrate, survive exposure to rain, wash-downs, humidity, wind, and intense sunlight. In such an ideal system, the risk of failure of any one component can be mitigated by the other components.
- Higher compressive strength insulation (e.g. higher density) should be used in pipe hangars, and where mechanical abuse is likely.

In summary, the advertised R-value is irrelevant if the insulant is inappropriate for the application or if part of a poorly-designed or installed system.

The Thickness Effect

Low-density thermal insulants (nominally defined for this discussion as less than 1.7 lb/ft^3) have been demonstrated to lose some of their insulating capability otherwise predicted as thickness of the insulation increases. For example, assume that the thermal resistivity (R-value) is measured on two specimens: one 4 inches thick, and the other 1 inch thick. The R-value of the thicker specimen is less than the R-value as predicted from the 1 inch thick specimen multiplied by the inches. Thus a glass fiber or low-density EPS insulant 6 inches thick may have an actual thermal conductivity worse than one would expect given the measured *k*-factor at 1 inch. Yet since there is no ASTM standard to measure this, suppliers of lower density insulation do not report their R-values at thicknesses greater than one inch.