A Practical Cost Model for Selecting Nonwoven Insulation Materials

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ABSTRACT

Elementary heat transfer in the range of density, thickness, and temperature normally used for house insulation, has been described experimentally for nonwoven structures. A model relating cost, density, and thermal efficiency of nonwoven insulating materials has been developed to aid in insulation materials selection and optimization of cost. Intrinsic to this system are material specific thermal conductivity slope coefficients readily derived from thermal conductivity versus specific volume plots.

INTRODUCTION

Thermal insulation materials are found in many structures from residential housing to space craft. In all applications, the purpose of a thermal insulator is to abate thermal transfer, precluding heat applied to one of its surfaces from escaping beyond other surface.

Regardless of its source, heat is transferred by conduction, convection, and radiation mechanisms. Of these mechanisms, only conductive heat transfer is easily formulated, and that, only for planar materials. The operating equation for conductive heat transfer is represented by Fourier's heat conduction equation;

$$\frac{Q}{t} = kA\left(\frac{\Delta T}{x}\right) \qquad (1)$$

where:
Q = Quantity of heat transferred (BTU)
t = Time (hr)
k = Heat transfer coefficient (BTU-in/hr-ft^2- °F)
A = Area (ft^2)
T = Temperature (°F)
x = Thickness (in)

There are number of unit systems that could be used for heat transfer coefficient, but BTU-in/hr-ft^2-°F gives the best sense of the actual engineering. Other formulations of the equation combine some of the units or divide the area units by thickness to cancel out one length dimension. W/m-°K is also a popular unit set for thermal transfer in metric units. In this study, the units for thermal conductivity were chosen as BTU-in/hr-ft^2-°F, and the further analysis was done in compatible units. This was chosen because the U. S. construction industry works in these units, and the thermal resistance, "R" (calculated in these units) is used to label all building products for walls, floors, and ceilings.

Frequently the measurement of thermal resistance, "R", is preferred to thermal conductivity. The thermal resistance is calculated by dividing the thickness of the insulation by thermal conductivity coefficient. The three heat transfer mechanisms are often lumped together in a concept called apparent heat conductivity and treated by the methods used in heat conduction above. The question of designing effective insulation is how to overcome all three aspects of thermal energy transfer.

For fibrous insulation, radiative energy may be diminished by increasing the density causing a decrease in the mean free path for photon movements. Mean free path is defined as distance traveled by a photon before it collides to another fiber surface [1]. Another approach would be increasing the surface area resulting in an increase in the scattering and absorption of radiative energy [2]. Convective energy transfer may be eliminated through absence of fluid movement (still air), created via tortuous or narrow paths for fluid movement [3]. It has been reported in an earlier study that convective energy (natural) is eliminated in the fibrous structure having bulk density greater than 1.25 lb/ft^3, since the air molecules are subdivided into adequately small pores by the fibers [4]. Heat transfer through conduction takes places by two mechanisms: conduction through solid and conduction through gas.

In an atmosphere of air, the lower thermal conductivity limit of insulation is usually considered to be the conductivity of still (quiescent) air. This value is 0.17 BTU-in/ hr- ft^2-°F at room temperature [5]. There is evidence that this limit might be lower if the pore size in the insulation is less than the mean free path of air molecules [6]. This lower limit can also be reduced by creation of a vacuum or by replacing the air with a low conductive gas such as carbon dioxide, hydro chlorofluorocarbons, etc. [7, 8]. Conduction through the solid is directly proportional to material specific thermal conductivity constant. The selection of the best material for a fibrous insulating need then becomes the primary question.

Heat transfer through nonwoven fibrous structure has been studied extensively in order to optimize product design and development. Bhattacharyya developed a model to calculate thermal conductivity of fibrous materials and showed that effective thermal conductivity increases by increasing material thickness and mean temperature [4]. Stark and Fricke improved Bhattacharyya's model by introducing variable fiber orientation concept. By considering the coupling between the solid and gaseous conduction, they found a good agreement between the developed model and the experimental results as a function of temperature, density, and air pressure [9]. Lee and Cunnington developed a theoretical model for radiation heat transfer for high porous fiber insulation and validated their model experimentally by using silica fibers [10]. Mohammadi *et al.* measured effective thermal conductivity of multilayered ceramic and fiberglass needled nonwovens. Their statistical analysis revealed that fabric weight, thickness, and porosity along with the applied temperature are enough for an accurate prediction of effective thermal conductivity [11]. They also calculated the conduction component of total heat transfer analytically and estimated the radiative thermal conductivity of the tested samples. It is concluded that addition of fiberglass into the structure increases radiative conductivity, since fiberglass has lower packing density than ceramic causing a higher mean free path for the photons [1]. Wang *et al.* numerically modeled the effective thermal conductivity of fibrous materials by using lattice Boltzmann algorithm. Their model revealed that thermal conductivity increases with increasing fiber length and becomes almost constant when the fibers get sufficiently long enough [12].

Even though numerical and analytical modeling studies provide more insight into the understanding the mechanism of heat transfer in fibrous insulation, most of them cannot be used for practical applications, as they are too complex and difficult to use. This paper takes advantage of the experimentally observed linear relationship between apparent thermal conductivity and batt specific volume. This allows some useful calculations and a new approach for selecting cost effective fibrous insulation materials for product design and development.

EXPERIMENTAL

Testing Method and Apparatus

All thermal conductivity testing was performed using a Holometrix, Inc., k-Matic thermal conductivity measurement system. The k-Matic measurement system is a guarded-plate system allowing for the assumption that edge-flow loss or interference is insignificant. ASTM C518 was followed for the tests [13]. The k-Matic calculates apparent thermal conductivity by measuring the heat flow through a material from a fixed temperature hot surface to a fixed temperature cold surface (75 and 32 ^{o}F respectively). The sampling chamber will accommodate a 12x12 inch sample, of up to a three and one-half inch thickness. Heat flow is measured by a transducer with a four by four inch sampling area in the center of the cold plate. Thermal conductivity is calculated by the instrument as

$$k = \phi\left(\frac{\Delta t}{\Delta T}\right) \tag{2}$$

where ϕ is heat flux [BTU / (hr-ft^2)], and Δt and ΔT are the distance and temperature differences between the surfaces, respectively [14].

The instrument was calibrated to a known standard before each test series and checked for calibration drift after each. Testing time depended on the thickness and density of the samples. Thicker and denser samples required longer testing time periods to establish the equilibrium values.

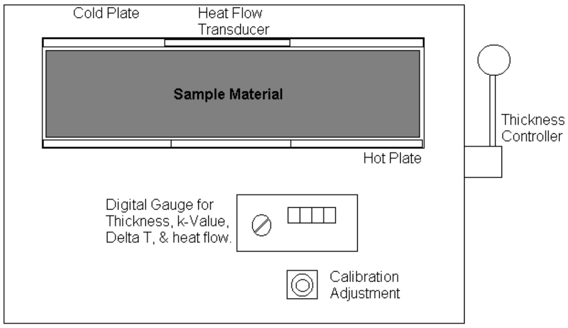

FIGURE 1: Heat Flow Meter Instrument; Holometrix k-Matic[14].

Materials

All samples measured were air-laid, thermally-bonded, nonwoven materials produced at Auburn University. The thermal binder for all samples was 3 denier, 2 inch bicomponent, CelBond™ fibers, used in an amount of 20% by weight. The major fiber component was chosen to provide a broad range of materials and was blended in amounts of 80% by weight with the binder. Samples were produced using a crimped fiberglass Miraflex™ (4 Denier, 2 inch), polyester (3 denier, 2 inch), down, chicken feathers, and an oxidized poly(acrylonitrile) Panox™ (3 denier, 2.5 inch). Density variations were achieved by layering and altering material thickness during bonding or in the instrument without going below the anticipated minimum thickness. Aluminum foil, polyethylene films were purchased from local stores.

RESULTS AND DISCUSSION

Fibrous Insulation

Since our instrument cannot distinguish the different heat transfer mechanisms, a few experiments were done and reported previously [15, 16] in order to separate and understand the heat transfer mechanisms operating in fibrous structure. This was accomplished using multiple layers of various films and fabric separated by narrow (~ ¼ inch) spaces held in a frame. The materials included transparent and black polyethylene film, spun-bond polyester, and aluminum foil. The measured apparent conductivity coefficients are shown in *Table I*.

TABLE I: Apparent thermal conductivity of different layers.

Set-up	k (BTU-in/hr-ft^2-°F)
No Film or Fabric	1.196
Aluminum Foil	0.194
Clear Polyethylene Film	0.916
Spun-bond PET	0.708
Black Polyethylene Film	0.465

When there was no film, the apparent thermal conductivity was 1.196 BTU-in/hr-ft^2-°F, and convection, conduction through air and radiation all played role on this result. If the film was aluminum foil, the measured thermal conductivity was almost the same as the conductivity of still air, meaning that both radiation and convection were eliminated in this set- up. Further, the high thermal conductivity of the aluminum foil had little or no effect on the overall thermal conductivity of the sample. If the aluminum was replaced by thin household olefin food wrap, the apparent thermal conductivity increased to 0.916 BTU-in/hr-ft^2-°F. Since the aluminum foil layers prevented convection, the household wrap should do likewise, and the increase in apparent thermal conductivity must be due entirely to radiation through the transparent film (which is not entirely IR transparent). As the apparent thermal conductivity for spun-bond PET had a value between aluminum and clear film, its transparency to radiation was less than that of the transparent film. Convection was still minimal because of the small pore size in the spun-bond sheet. In the case of black polyethylene film, radiation was absorbed by each layers and then reemitted, so it had lower apparent conductivity than either the clear film or the spun-bond sheet. It was still higher than the aluminum foil because the emissivity of the black polyethylene film was higher than aluminum. Since we cannot change the thermal conductivity of still air, the major function of fibrous insulation is to prevent heat transfer by convective currents and to minimize electromagnetic radiation.

Development of the Theoretical Equations

Selection criteria for insulation will likely always balance efficiency versus cost. Insulation efficiency is typically expressed as an R-Value. The R-value is the dividend of the thickness of the insulating material, and its inherent thermal conductivity value. Although not obviously stated in this relationship, the density of the insulating material is of critical importance. Density is the relationship of the material's weight per unit of volume, and volume is proportional to thickness.

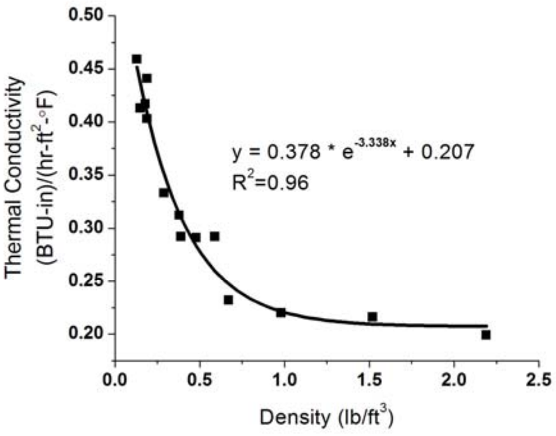

FIGURE 2: Oxidized PAN Fiber Insulation: k vs. density.

In *Figure 2*, the relationship between thermal conductivity and density of oxidized PAN fiber insulation is shown. The shape of the curve displayed in this graph is typical for apparent thermal conductivity versus density of fibrous insulation. In the lower density regions (0.0 to 0.2 lb/ft^3), the thermal conductivity values were characteristically high. This implies that there was very poor insulation in this region. The reason for that is all three components of the thermal energy transfer were available. The density was low so that the air cells formed within the web were large enough for natural convection [17]. Moreover, at the low density region fiber volume fraction was not sufficient to block radiation through the structure causing a low chance of a photon getting intercepted by the fibers [18, 19]. In this extreme low density area, conduction within the solid fibers was not significant because there was diminishing solid state contact from surface to surface [6, 7]. As the density increased, the apparent thermal conductivity of the insulation leveled off to a constant value very close to the conductivity of still air.

It has been shown both experimentally and theoretically that on the other extreme of the spectrum, when the curve is extended into much greater density regions, it upwards exponentially [20, 21]. This occurs because as the density increases, the material more closely approximates a solid. Increasing density results lower mean free path and higher tortuosity which diminishes the radiation component of heat transfer [1, 2]. On the other hand, increasing solidity increases conduction through the solid [17, 22]. When the density comes to a critical point, the increase in conduction component outweighs the decrease in radiation component resulting in a raise in the apparent thermal conductivity [23, 24].

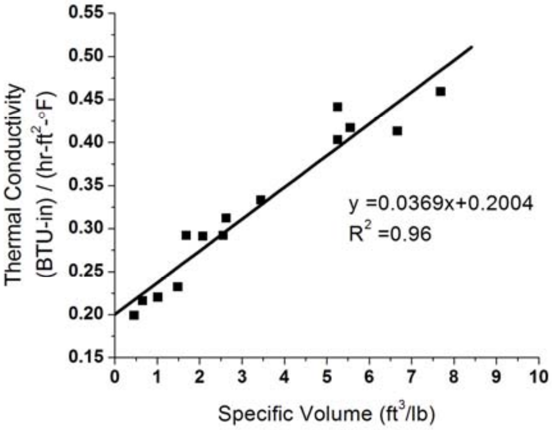

FIGURE 3: Oxidized PAN Fiber– Specific Volume vs. k.

The reciprocal of density (ρ) is called specific volume (V_{sp}) and relates to the volume occupied by a given weight of material. *Figure 3* uses the same data shown in *Figure 2*. When apparent thermal conductivity was plotted against specific volume, a straight line plot was observed. A straight-line equation was valid only in the particular region between the extremes of specific volume for the specific material. When the density is very low (high specific volume) convection and radiation will be significant; and when the density is very high the apparent thermal conductivity will approach the conductivity of the solid fiber. Fortunately, this linear region is in the density range of construction insulation, and by the reasoning above, the insulating effect in this linear region is mostly the reduction of radiative heat transfer. Neither convection nor conduction through the solid material is significant in this region.

The equation of the line shown in *Figure 3* indicates its y-axis intercept as k = 0.2. This value is significant in that the intercept closely approximates the thermal conductivity of still air alone.

The significance of the thermal conductivity versus specific volume comparison is that it is linear and allows thermal conductivity to be expressed as a straight-line equation ($y = mx + c$).

$$k = mxVsp + 0.2 \qquad (3)$$

Because insulation efficiency R is defined in terms of k, then R can be defined in terms of the above equation.

$$R = \Delta t /(mxVsp + 0.2) \qquad (4)$$

The cost of insulating material, probably including the cost of manufacture, is proportional to the weight used. Weight is the product of the material's density and volume. Total material cost is the product of weight and cost per unit weight.

$$W = \rho x V \qquad (5)$$

Setting $b = \cos t / unit - weight$;

$$Total - Cost(C) = \rho x V x b \qquad (6)$$

Substituting specific volume for density $(\rho = 1/Vsp)$

$$C = Vxb \ / Vsp \qquad (7)$$

Where volume V is area (A) times thickness (Δt)

$$C = Ax \Delta txb \ / Vsp \qquad (8)$$

Normalizing for unit area

$$C / A = \Delta txb / Vsp \qquad (9)$$

Establishing a relationship between R and cost

$$(C / A)/ R = [\Delta txb / Vsp]/[\Delta t /(mxVsp + 0.2)] \qquad (10)$$

$$C /(AxR) = (b / Vsp) x (mxVsp \ + 0.2) \qquad (11)$$

$$C /(AxR) = (mxb) x (0.2 xb / Vsp) \qquad (12)$$

$$C /(AxR) = (mxb) + (0.2 xbx \rho) \qquad (13)$$

$$C / A = bxRx(m + 0.2 x \rho) \qquad (14)$$

This equation allows for the establishing of a basis of comparison of cost and efficiency. The slope value, m, is the lone material intrinsic property included. Cost per unit weight is of course a consideration, but is an external variable.

The thermal conductivities of different nonwovens were individually measured and plotted against the respective specific volumes (*Figure 3* and *Figure 4*). This allowed for regression analysis to determine the slope (m) for each material. It is proposed that the value of the slope is material specific and is a useful representation of the material's conductive behavior. The slope values for each material was incorporated into the equations developed earlier to evaluate insulation efficiency and cost.

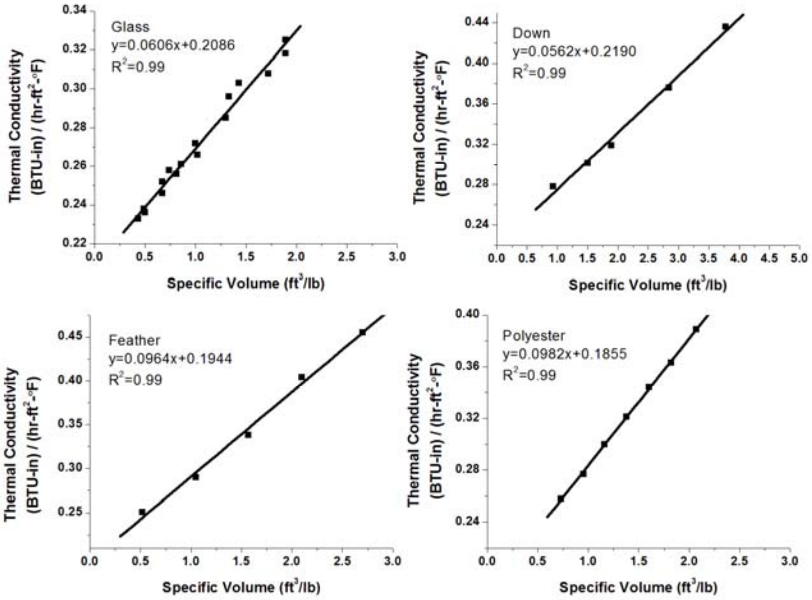

FIGURE 4: k-Values for some the Studied Materials.

Most obvious was the significant difference between the k-value of the oxidized PAN fiber material and all others. This difference was expected based on previous evaluations. Also notable were the similarities between entirely different material types (i.e. polyester and feathers; crimped fiberglass and down). A disparity between polyester and the fiberglass was not unexpected, in that their molecular structures are so different. The separation between materials of identical molecular structure, but different physical structure, as shown by the plots of down and feather batts, is reasoned by fiber diameter. For a given weight or density, a greater number of smaller diameter fibers will occupy the same amount of space, but their increased specific surface area decreases the radiative transmission by lowering the mean free path for a photon [18, 23, 25].

The effect of fiber denier was further evaluated by examining different diameters of oxidized PAN fiber in identical fabric structures. These results are shown in *Figure 5*. Sp6 and Sp8 represent 6 and 8 micron diameter fiber structures, respectively. Although it appeared that the relationship between the 6 and 8 were reversed from what would be expected, it was more aptly reasoned that there was no appreciable difference, particularly in the lower specific volume regions.

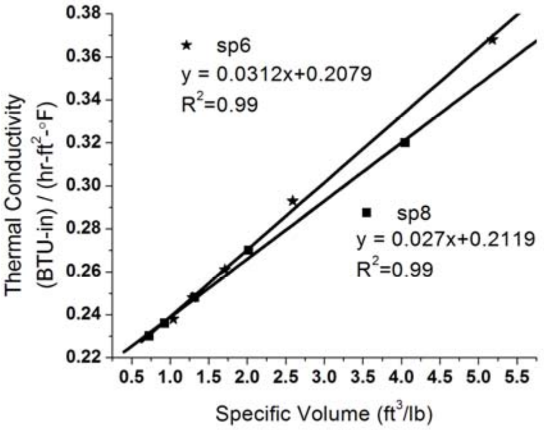

FIGURE 5: Effect of Oxidized PAN Fiber Diameter on Apparent Conductivity.

Manipulation of Data

The purpose of the sampling done was not to determine which material was the most cost effective to use, but rather to provide a reasonably broad spectrum of material types for modeling purposes. Initially, each material was assigned a cost per pound that would be considered reasonable in the current market.

In order to calculate how an insulation fibrous structure is effective, one has to consider four variables; R value, thickness, volumetric density, and slope of the k vs specific volume curve. *Figure 6* shows the relationship between slope, density, and R value at 3.5 in thickness (common wall thickness). As it can be seen, at the low density region selection of insulation material (slope values) made a big difference on R value. For instance, oxidized PAN fiber (slope value 0.037) provided 10 hr-ft^2-°F/ BTU insulation at 0.25 lb/ft^3 density level; whereas polyester fiber (slope value 0.098) provided almost half of oxidized PAN fiber with 5.9 hr-ft^2-°F/ BTU insulation for the same density point. On the other hand, this difference became less significant with increasing bulk density. As can be seen, when the density was 6 lb/ft^3, oxidized PAN fiber provided 17 hr-ft^2-°F/BTU insulation, and polyester fiber provided almost the same insulation value with 16.2 hr-ft^2-°F/ BTU. The reason is that the increase on R value with increasing density (from 0 to 6 lb/ft^3) was mostly due to nonwoven packing structure rather than its constituents. All of the fibers functioned mainly as interrupting convection and reducing radiation transmittance by creating small enough air pockets and lowering mean free path for a photon, respectively [1, 4]. Also, density was low enough so conduction through the solid was not significant for the specified density regions which resulted in very little difference on R value when the material type was changed.

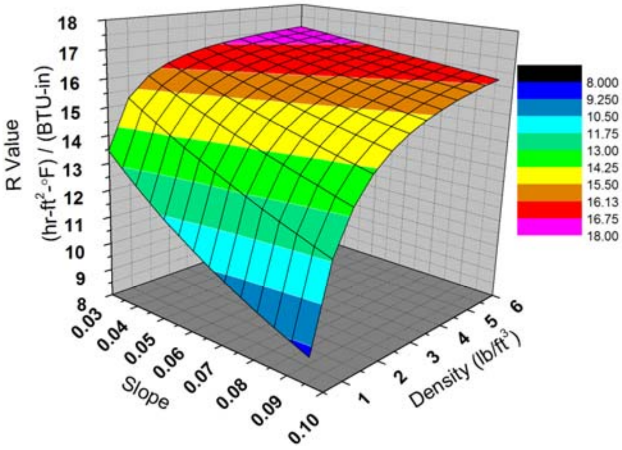

FIGURE 6: Thickness, Slope, Density Relationship at t=3.5 inch.

Even though relationship between the factors effecting insulation value and unit cost can be shown graphically, a look-up table would be a better choice for actual use, since it is hard to see the details in graphs. By the help of the Eq. (4) and Eq. (14), the look up table including cost/area and areal density can be developed and used as a reference for selecting and optimizing the cost of insulation materials (*Table II*). Computer spreadsheets were set up to make calculations of cost for a variety of R-values, densities, thicknesses and unit costs. The per unit weight costs were assigned as $0.75 for polyester, $0.25 for crimped fiberglass, and $3.00 for oxidized PAN fiber, and cost/area as well as a real cost for unit insulation (cost/area*R) were calculated for different configurations at t=3.5 inch. It can be broadened and a comprehensive look-up table can be created in order to select the cost effective insulation fibrous insulation.

An obvious conclusion drawn from *Table II* is that in any composition fiberglass provided the cheapest unit insulation among the others. However, oxidized PAN gave the highest R value for a given density. The difference between the unit insulation cost of materials was increasing linearly with increasing density. Therefore, for applications where weight is critical, selection of oxidized PAN fiber would be more reasonable, even though it had higher unit insulation cost. On the other hand, as shown in *Figure 6*, at high density region material type became less significant on insulation; whereas cost of unit insulation differed noteworthy to one another. Thus, applications where there is no volume or weight restriction, selection of low unit insulation cost material such as crimped fiberglass would be more reasonable.

TABLE II: The look-up table for t=3.5 inch.

	Oxidized PAN			**Crimped Fiberglass**			**Polyester**		
Density(lb/ft3)	R	C/A	C/(AxR)	R	C/A	C/(AxR)	R	C/A	C/(AxR)
0.5	12.8	5.25	0.41	10.9	0.44	0.04	8.8	1.31	0.15
1.0	14.8	10.50	0.71	13.4	0.88	0.07	11.7	2.63	0.22
1.5	15.6	15.75	1.01	14.5	1.31	0.09	13.2	3.94	0.30
2.0	16.0	21.00	1.31	15.2	1.75	0.12	14.1	5.25	0.37
2.5	16.3	26.25	1.61	15.6	2.19	0.14	14.6	6.56	0.45
3.0	16.5	31.50	1.91	15.9	2.63	0.17	15.0	7.88	0.52
3.5	16.6	36.75	2.21	16.1	3.06	0.19	15.4	9.19	0.60
4.0	16.7	42.00	2.51	16.3	3.50	0.22	15.6	10.50	0.67
4.5	16.8	47.25	2.81	16.4	3.94	0.24	15.8	11.81	0.75
5.0	16.9	52.50	3.11	16.5	4.38	0.27	15.9	13.13	0.82
5.5	16.9	57.75	3.41	16.6	4.81	0.29	16.1	14.44	0.90
6.0	17.0	63.00	3.71	16.7	5.25	0.32	16.2	15.75	0.97

R= Thermal Resistance (hr-ft^2-°F/ BTU), C=Cost (U.S. $), A=Area (ft^2).

CONCLUSIONS

The slope of k versus specific volume curve seems to be a characteristic of the fabric/fiber composition and it can be used to calculate the k and cost/area of the insulation at different densities. In other words, the fiber and batt variables (excluding density) are adequately represented by the slope of the k versus specific volume curve. While this is not particularly satisfying to the theoretician, it is very helpful for practical calculations. If the density and thickness of the material is known, R for the insulation, as well as for the areal density can be calculated. Since insulation is either sold on weight or area basis, cost can be calculated as well. These calculated results can be represented graphically, but actual use requires a look-up table.

The assumption that a material specific slope coefficient may be measured and appropriately used in determinations of optimal cost considerations seems to be valid. In all material considerations, the lowest useable density, 1.25 lb/ft^3 (where convective energies become negligible), is the start of most efficient density point for obtaining the greatest value of R for a desired cost per unit area. The model appears valid for a variety of fiber types, andprovides much more usable approach than does examination of k-value versus density evaluation.

The testing method used in this study is for construction insulation and is based around the interior temperature for human comfort and typical exterior temperatures. This model is valid at low density region (0-6 lb/ft^3), and it has not been demonstrated whether this analysis applies at high density and environmental temperature applications.

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