THERMAL PERFORMANCE OF RIGID CELLULAR FOAM INSULATION AT SUBFREEZING TEMPERATURES

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ABSTRACT

Rigid cellular foams exhibit pronounced variations in k-value as operating temperatures change. The almost universal practice of utilizing a fixed k-value to predict the performance of insulating systems regardless of operating temperature leads to serious errors, particularly in subfreezing applications such as refrigeration buildings and equipment.

This paper presents a straightforward method for designing insulation systems, taking into account variations in k-value as operating temperatures change. A computer model is created based on temperature variation through the insulation. This model generates data that may then be used to compute the expected heat flow under any given set of operating conditions. Experimental verification of this method is provided by testing, under simulated operating conditions, extruded polystyrene foam and polyurethane foam. The test method and test data are discussed in the paper.

INTRODUCTION

Rigid cellular foam insulation products that depend on fluorocarbons as blowing agents may have particularly sharp changes of conductivity at temperatures near 32F. Such foams are the mainstay of the design of cold storage warehouses and processing buildings, and of trucks and rail cars used to transport frozen products. Understanding the behavior of such materials in the subfreezing environment in which they are used will contribute to a more accurate design of the insulation envelope.

GENERAL COMMENTS

In cold storage applications, the cold side of the insulation is at a relatively unchanging temperature, regardless of the temperature of the warm side. The heat flux rises and falls as the temperature on the warm side changes, and this changes the temperature drop across the air film at the cold side. Practically speaking, however, these changes are negligible; the insulation next to the cold side operates at a relatively constant temperature and has the k-value characteristic of the insulation at the cold-side temperature. Conversely, the warm-side temperature varies enormously throughout the year. The insulation near the warm side may experience wide variations in k-value as consequence.

The operating temperature of the center of the insulation depends upon the type of insulation, its thickness, the heat flux density, and the temperatures of the cold and warm sides of the insulation.

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THE COMPUTER MODEL

A computer model developed by the authors computes a plot of temperature versus positions through the insulation beginning with the temperature at the cold side and ending with the temperature of the warm side. This temperature profile is developed for any insulating material whose k-value variation with temperatures is known. The user is cued to input the specific operating conditions, thickness, cold-side temperature and warm-side temperature. After computing the temperature profile, the computer model computes the overall R-value for these conditions using the conventional formula: R = (warm-side temperature - cold-side temperature) divided by heat flux density.

This model is based on a uniform infinite slab of insulation (i.e., no transverse heat flow) and steady-state conditions (i.e., no time variations of temperature). The insulation is assumed to be homogenous and of uniform thermal properties. Air films are not included here because they are not included in the experimental test method used to verify the model.

Fiqure 1 shows two temperature profiles developed by the computer utilizing k-value vs temperature data from ASHRAE, (ASHRAE, 1985) for one-inch-thick polyurethane and one-inch-thick extruded polystyrene. Temperature, on the vertical scale, ranges from a cold-side temperature of -30F to a warm-side temperature of +50F. Distance through the slab is on the horizontal scale. Note the heat flux density is not the same for the two cases because the overall R-values of the two materials are different.

Similar (ASHRAE data) temperature profile pairs have been generated for warm-side temperatures of 30F, 70F, and 90F. A plot of the overall R-values as a function of warm-side temperature is given in Figure 2. Note that at a warm-side temperature near 50F, both materials have the same R-value, while the effective R-values for extruded polystyrene exceed those of polyurethane at low warm-side temperatures.

THEORY

The formula for steady-state conduction in a homogenous medium is, q = k x a (dt/dx), where

q = heat flow rate, Btu/h
k = thermal conductivity, Btu/h x F x ft
a = cross section area ft2
dt/dx = thermal gradient F/in

Consider the elemental section cut from an indefinitely large insulation slab, shown in Figure 3. The section is dx thick along lines of uniform heat flow, and has a unit area normal to this direction. Assuming that the insulation is uniform within this element,

$$H = (k/dx)\ (T2-T1)$$

where H = heat flux density (Btu/h/ft2)
dx = thickness
k = thermal conductivity of the element
T1, T2 = temperatures at the unit element surfaces

In general, the value of k will be a function of location, and orientation of the element within the insulation slab as well as of the temperature of the element. If these k-values are known, an integration along the lines of heat flux will give the total temperature difference (degrees Fahrenheit across the slab and the R-value of the slab F/h x Btu).

For this paper we consider only the effect of different temperatures on k-value. We assume an arbitrarily chosen thickness of homogenous insulating slab extending indefinitely in directions perpendicular to the heat flow. A unit area through this slab will be made up of N = TK/dx elements, where TK is the thickness of the slab and dx is the thickness of the elements. If the temperatures of the two faces of the slab are different, heat will be conducted through the slab and the heat flux density, H, will be proportional to the temperature difference.

The computer model cues for the total thickness of the slab, and for the number of elements, N. The first element has as its outer side the outer side of the slab, the temperature of which is Tc. The other side of the first element has as its temperature,

$$T1 = Tc + H/k1 \times TK/N$$

where Tc = cold-side temperature
H = heat flux density
k1 = k-value at the temperature $\frac{(To + T1)}{2}$
TK = thickness of slab
N = number of elements

Note that the thickness of each element is TK/N.

The second element begins TK/N distance from the cold side of the slab and has a temperature of T1 on one side and a temperature T2 on the other:

$$T2 = T1 + H/k2 \times TK/N$$

The temperature at element M is,

$$Tm = Tc + \sum_{1}^{m} H/k1 \times TK/N + H/k2 \times TK/N + \_\_\_ H/km \times TK/N$$

where k1 is the k-value of the first element,
k2 is the k-value of the second element,

k is evaluated as before at the temperature of each element,

km is the k-value of the Mth element,
Tm is the temperature of the Mth element.

Extracting the common factors and rearranging,

$$Tm - Tc = TK/N \times H \times \sum_{1}^{m} 1/k1 + 1/k2 + \_\_\_ 1/km.$$

Note that, as in conventional practice, the temperature difference across the insulation depends on the thickness, the heat flux density, and the k-value of the material. Note, also that this equation is the conventional way of expressing the overall k-value of a series of pieces of insulation having different k-values. The boundary conditions require that TN = Tw (warm-side temperature) and To = Tc (cold-side temperature). The computer cues for these values and develops a first temperature profile using H = 0.115 (Tw-Tc) (an arbitrary starting value).

If TN does not equal the temperature (Tw) of the warm-side of the slab after the computer has developed its first temperature profile, what then? Since TK and N are fixed, the only way to make TN = Tw is to change the value of H. We do so by multiplying the first chosen value of H by the ratio of Tw-Tc/Tn-Tc and repeating the computation of N steps. Note that this process may change the value of each k. By imposing a requirement that TN lie between Tw +/- any desired accuracy limit, the computer must work until it gets the right TN. After TN is within prescribed limits the program prints the temperature profile, heat flux, and R-value.

In principle, this computer model will develop with precision the temperature profile through an insulating slab of any chosen thickness. However, this precision is limited by the accuracy with which the relationship between k-value and operating temperature is known. In practice, k-values are measured on relatively thick slabs (0.5 - 2 in) and the temperature across the slab is usually 50F. Published values for k versus temperature tend to smooth out any discontinuities in this relationship. Furthermore, most suppliers do not provide test data at temperatures other than 75F or 40F. The most comprehensive data is available in the ASHRAE Handbook - 1985 Fundamentals, volume 3, page 23.17. This gives k-values for various types of foam from -50F to 100F. The identical data appears in the 1981 edition, so we are persuaded that little reliable data exists for generating our model. We have, however, used the ASHRAE data in generating Figure 1 and Figure 2 curves. In Figure 2, data supplied by manufacturers was used to update the ASHRAE data in our computer formula, resulting in the higher R-values modeled for current materials.

The computer program used here employs a formula to relate k-value to operating temperature (a slight modification would enable use of a look-up table instead). Figures 1 and 2 were computed using curves fitted to data from the ASHRAE Handbook - 1985 Fundamentals, page 23.17. The formulas and data are given in Figure 4.

U-VALUES

The computer model was extended to include the effects of air films on the warm and cold sides. The same language was used, assuming a windless inside surface (R=0.61) and a windy outside surface (R=0.167) per ASHRAE Handbook - 1985 Fundamentals, page 32.14. This extended program (not shown) can be used to provide U-values for an insulated wall under expected operating conditions.

The authors believe that this model is equivalent to that described in ASTM 680-82. A further refinement, to include the wind and emissivity relationships of ASTM 680 can be accomplished.

EXPERIMENTAL VERIFICATION

Tests were run on samples of extruded polystyrene and modified polyisocyanurate material. The test samples were cut from two-inch-thick slabs to the one-inch test thickness. The samples were then tested using a guarded hot plate. The configuration of the extruded polystyrene sample is:

Dimensions	12 in x 12 in
Thickness	1.03 in
Density	1.35 lb/ft3
Blowing Agent	F12

Aged over 90 days at room temperature.

The configuration of the polyisocyanurate sample is:

Dimensions	12 in x 12 in
Thickness	1.0 in
Density	1.74 lb/ft3
Blowing Agent	F11

Aged over 90 days at room temperature.

Each sample was tested at four operating conditions. The cold side was maintained at approximately -30F for all tests. Warm-side temperatures were approximately +25F, +65F, +75F and +100F. Thus, the operating temperature differences were 55F, 95F, 105F and 130F, fairly typical of seasonal variations throughout the year across the USA. The results are summarized in Table 2.

CONCLUSION

The extruded polystyrene material test results agreed remarkably well with the computer model which used manufacturers-supplied data. The R-values were about 12% higher than the model using ASHRAE data predicted. This is no doubt due to the small cell size of newer extruded foam.

The computer model used to generate the R-value per inch curves of Figure 2 for ISO, employed a formula for k-value temperature dependence similar to the formula used to develop the ASHRAE curve, but modified to match the 75F data supplied by the manufacturer. It is clear that test data points do not agree with the model at low temperatures. More up to date data on low temperature performance of polyisocyanurate foam is clearly needed to explain these differences.

REFERENCES

ASHRAE, 1985, ASHRAE Handbook-1985 Fundamentals, p. 23.17 Atlanta: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, Inc.

BIBLIOGRAPHY

ASTM, 1984, Annual book of ASTM Standards, section 4, volume 04, 06, page 384. ASTM C680-82 Standard practice for DETERMINATION OF HEAT GAIN OR LOSS AND THE SURFACE TEMPERATURES OF INSULATED PIPE AND EQUIPMENT BY THE USE OF A COMPUTER PROGRAM. ASTM 1916 Race Street, Philadelphia, PA 19103.

APPENDIX 1

Computer program to generate temperature profile through an insulating slab where k-value is temperature dependent.

LIST

```
10   DIM T (200)
20   PRINT"PROGRAM NAME EXPHEAT"
30   PRINT"PANEL THICKNESS INCHES";
40   INPUT TK
45   REM:  number of steps is limited by DIM statement to 200
46   REM:  little change in results occur for N greater than 10
50   PRINT"NUMBER OF STEPS";
60   INPUT N
70   PRINT"COLD SIDE TEMPERATURE, DEGREES FAHR.";
80   INPUT TC
90   PRINT"WARM SIDE TEMPERATURE";
100  INPUT TW
105  REM:  H=k times temperature difference
106  REM:  .115 is arbitrary choice of k to begin program
110  H=.155•(TW-TC)
120  FOR A = 1 TO N
125  REM:  start at cold face of slab
130  T(0) = TC
135  REM:  compute k-value using formula k=(.15 + .0004(50-T))
136  REM:  compute temperature at Ath step
140  T(A) = T(A-1) + H•(TK/N)•1/(.15 + 4.000001E-04•(50 + (T(A-1) + T(A))/2))
150  NEXT A
155  REM:  revise value of H if TN differs from Tw
160  H = H•(TW-TC)/(T(N)-TC)
165  REM:  repeat loop if TN is out of chosen limits
166  REM:  use + .001 as limits
170  IF T(N)<.999•TW or T(N)>1.001•TW THEN 120 ELSE 180
180  PRINT"DISTANCE","TEMP"
190  FOR Y = 0 TO N
200  PRINT USING"###.##"; Y•TK/N;
205  PRINT TAB(13) USING "###.##"; T(Y)
210  NEXT Y
220  PRINT"PANEL R VALUE"; (TW-TC)/H
230  PRINT"HEAT FLUX DENSITY, BTU/Hr/SqFt";H
     REM:  run a sample program using 10 steps
```

```
RUN
PROGRAM NAME EXPHEAT
PANEL THICKNESS INCHES? 2
NUMBER OF STEP? 10
COLD SIDE TEMPERATURE, DEGREES FAHR.? 30
WARM SIDE TEMPERATURE? 50

DISTANCE        TEMP

  0.00        -30.00
  0.20        -21.29
  0.40        -12.76
  0.60        - 4.40
  0.80          3.79
  1.00         11.84
  1.20         19.73
  1.40         27.49
  1.60         35.11
  1.80         42.61
  2.00         50.00

  PANEL R VALUE 11.49329
  HEAT FLUX DENSITY, BTU/Hr/SqFt 6.960581
```

TABLE 1

Data for Figure 1

Panel thickness inches? 1
Number of Steps? 20
Cold side temperature, degrees Fahr.? -30
Warm side temperature? 50

Temperature profiles, ASHRAE data

Distance inches	Temp F ISO	Temp F extruded
0.00	-30.00	-30.00
0.05	-26.11	-25.62
0.10	-22.23	-21.29
0.15	-18.36	-17.00
0.20	-14.49	-12.76
0.25	-10.63	- 8.56
0.30	- 6.77	- 4.40
0.35	- 2.92	- 0.28
0.40	0.92	3.79
0.45	5.23	7.83
0.50	9.50	11.83
0.55	13.73	15.80
0.60	17.91	19.73
0.65	22.05	23.62
0.70	26.15	27.48
0.75	30.21	31.31
0.80	34.23	35.11
0.85	38.21	38.88
0.90	42.16	42.61
0.95	46.08	46.32
1.00	49.96	50.00

ASHRAE data		
Core	ISO	EXTRUDED
R-value	5.78	5.74
HT flux	13.83	13.92

TABLE 2

THE APPARENT THERMAL CONDUCTIVITY AND THERMAL RESISTANCE

OF THREE SPECIMENS OF PLASTIC FOAM INSULATION MATERIALS

Specimen	Test Thickness		Test Density		Temperature, F		Apparent Thermal Conduct.		Thermal Resist.
	mm	inches	kg m^{-3}	lbs ft^{-3}	H	C	Wm^{-1} K^{-1}	Btu in hr^{-1} ft^{-2} F^{-1}	Btu^{-1} hr ft^2 F
STM-150	26.1	1.03	21.7	1.35	25.0	-31.6	0.0214	0.148	6.95
					57.2	-32.7	0.0229	0.159	6.5
					77.0	-32.6	0.0232	0.161	6.4
					102.5	-31.6	0.0247	0.171	6.0
STM-400	27.5	1.08	34.9	2.17	24.8	-31.6	0.0189	0.131	8.25
					50.0	-31.1	0.0199	0.138	7.85
					74.6	-31.3	0.0208	0.144	7.5
					101.9	-32.2	0.0224	0.155	6.95
STM-ISO	25.3	0.995	27.9	1.74	23.5	-30.3	0.0188	0.130	7.65
					51.1	-30.8	0.0189	0.131	7.6
					75.2	-34.4	0.0189	0.131	7.6
					101.7	-30.0	0.0196	0.136	7.3

Reference: UCI-17

October, 1985

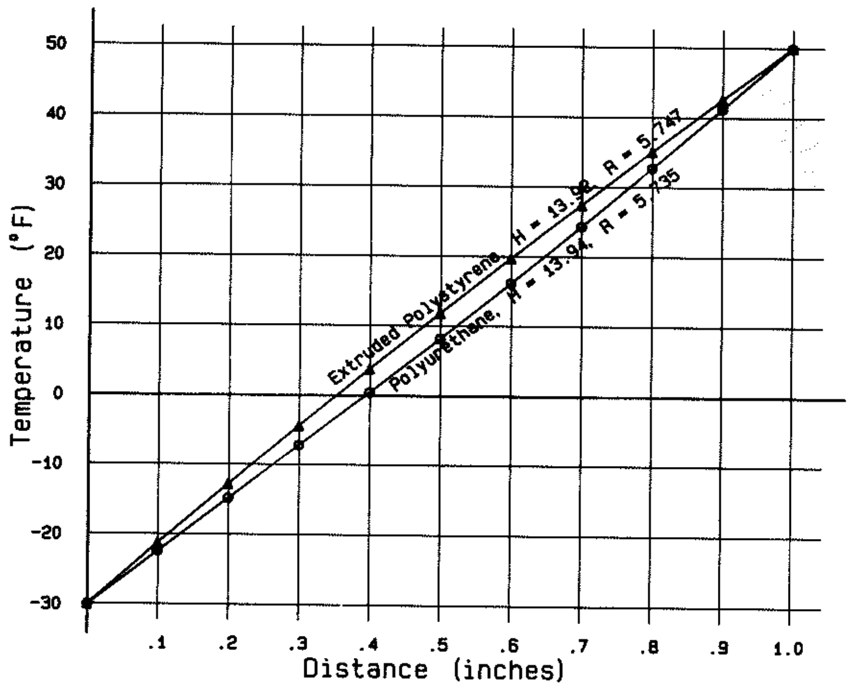

Figure 1. Temperature profiles: computed temperature vs. position for polystyrene and polyurethane foams

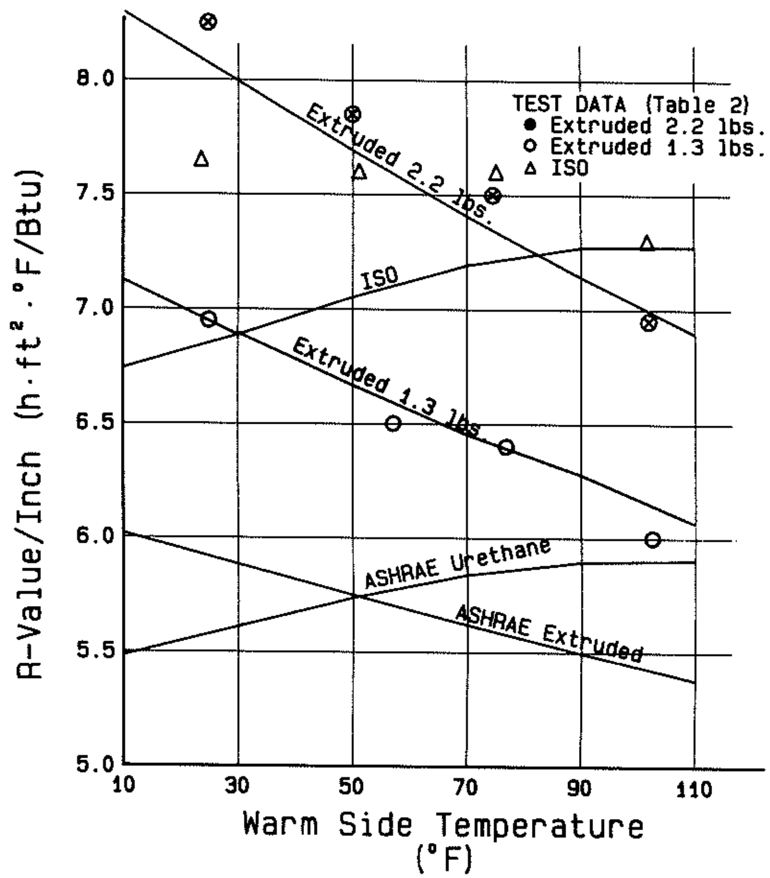

Figure 2. R-value vs. warm-side temperature, computed for cold-side temperature = -30 F

q = ka (dt/dx)
H = q/a
dt = (H/k) dx
= (H/k) (Tk/N)
T (a) = T (a-1) + (H/k) (Tk/N)

Where k is evaluated at:
(T (a) + T (a-1)) /2

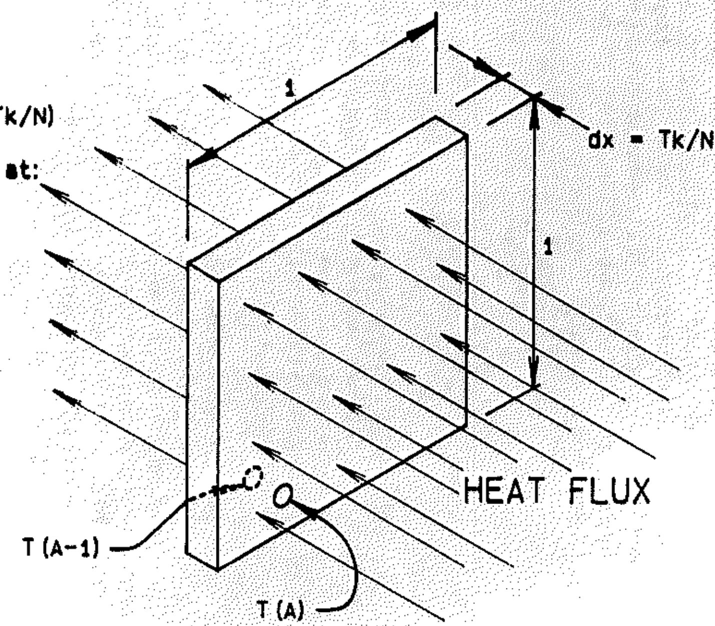

Figure 3. Elemental cell

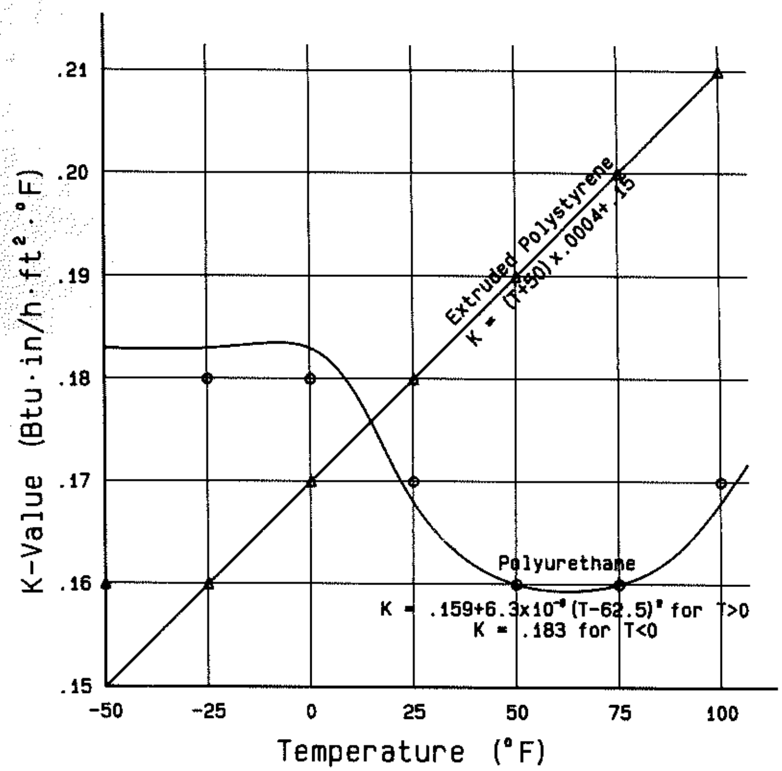

Figure 4. K-value vs. temperature. ASHRAE data points: Δ extruded polystyrene, o polyurethane