True R-Values of Round Residential Ductwork

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ABSTRACT

It is a common misconception that the actual R-value of flexible duct is similar to the rated R-value. This is approximately true for lower nominal R-values. For instance, under typical conditions, a six-inch diameter, nominal R-4.2 duct has an actual R-value of 3.41 not counting film resistances. In this case, including the film resistances more than compensates for this loss, with the total R-value being 4.34. The combination of both factors does not always result in an improved total R-value however, and the discrepancy between nominal and actual R-value gets larger with higher R-values and/or smaller diameters. For example, a six-inch diameter, nominal R-8 flex duct has an actual R-value of only 5.62 not counting surface films. With the film resistances the total R-value with films is only 7.81, 29% less than the nominal value. The primary cause for this discrepancy is that the rated R-value is measured with the insulation flat. When in use, it is wrapped in a cylinder around the duct, resulting in a reduced R-value.

This paper reviews the basic concepts and equations for correct calculation of heat loss in a cylindrical geometry including the effects of diameter and insulation thickness and density. The effects of duct air velocity, temperature and density on the internal film coefficient are given, as well as a discussion on the effect that air density changes due to elevation have on duct efficiency. Tables are given to simplify the estimation of actual R-values.

Standard Rating Method

Flexible, insulated duct has a rated R-value that is printed on the outer jacket. It is a common misunderstanding that this rating takes into account the effects of the cylindrical geometry on the heat transfer rate. However, it does not. This paper discusses the considerations appropriate for estimating actual R-value of flexible duct, which has in recent years become very common in both residential and small commercial applications. Very similar considerations apply for other round duct applications such as adding an insulating wrap or jacket to round metal duct.

The standard rating method published by the Air Diffusion Council (ADC) requires one to determine the installed thickness of insulation in the finished product by comparison of the radii or diameters of the inner and outer jackets (ADC 2003). The standard then requires the insulating material (usually fiberglass) to be tested *flat* at the installed thickness in a standard guarded hotbox test method. The resulting tested R-value must meet one of the allowed rating values of R-4.2, R-6, R-8, and R-11. The rated R-value does not include any effects of the cylindrical geometry or the surface film resistances on the inside and outside surfaces of the duct.

Notice that the manufacturer is free to use fiberglass of differing densities and fiber diameter, resulting in a different R-value per inch. Thus one brand of flexible duct rated R-4.2 may have an installed thickness of 1.5 inches while another may have an installed thickness of 1.25 inches. This would correspond closely to the difference existing between R-11 batts and R-13 batts for 2x4 wall insulation. This effect is illustrated in the tables below.

Another geometric factor arises from the fact that the ADC standard allows flexible duct to have an inner diameter that is oversized by as much as 3/8 inch from the nominal value to allow for easy installation over standard metal duct fittings. Many manufacturers of flexible duct do not state the actual inner diameters of their products.

Because the rated R-values do not include the effects of the geometry and the film coefficients, it is not possible to use them directly in calculating the heat loss from the duct. The most important effect is the cylindrical geometry causing the actual R-value of the insulation to be less than the rated (flat) value, especially for high R-values. This paper outlines the derivation of the standard heat loss calculation for cylinders, and also discusses the appropriate values for the film coefficients.

Thermal Loss Equations

The overall thermal resistance of a round duct can be expressed as the sum of three component resistances. These are 1.) a resistance due to the inside surface film of air; 2.) the actual resistance of the cylindrical insulation; and 3.) a resistance due to the outside film. We can express this in equation form as follows:

$$R_{total} = R_{in} + R_{actual} + R_{out}$$
 (Equation 1)

where

 $R_{total} = \text{total R-value of duct}$ $R_{in} = \text{R-value for inside surface convection heat transfer}$ $R_{actual} = \text{actual R-value of insulation in cylindrical installation}$ $R_{out} = \text{R-value for outer surface heat transfer}$

Appropriate calculation methods for each of these components are presented in any introductory heat transfer textbook (e.g., Incropera & DeWitt 2002) and in many engineering handbooks (e.g., ASHRAE 1993). These methods are reviewed below.

Actual R-Value of Insulation

The nominal R-value of duct insulation is determined for flat installation; therefore we must first calculate the actual R-value of insulation installed on a round duct. The key assumption in the determination of the insulating value of cylindrically-installed insulation is that under steady-state conditions the same quantity of heat flows through any radius r, including the inner and outer surface radii. For a given small thickness of insulation, the heat flow is proportional to the thermal resistance per unit area (which is proportional to the thickness) and to the area of the annulus. Since the area increases as the radius becomes greater the effective resistance to heat flow decreases. Thus, the cylindrical geometry results in a reduced R-value relative to the same thickness laid flat. The basic geometry is illustrated in Figure 1.

Figure 1. Cylindrical Geometry for Heat Flow



Fourier's law of conduction in cylindrical coordinates, in any consistent set of units, states:

$$Q = A\left(-k\frac{dT}{dr}\right)$$
 (Equation 2)

where

Q	= outward heat flux
A	= surface area at radius r
k	= thermal conductivity of insulation
$\frac{dT}{dr}$	= rate of change of temperature with radius

It should be noted that the apparent thermal conductivity k is dependent on the bulk temperature of the insulation. Unlike the dependence on temperature of the conductivity of air itself, that of the insulation as a whole is very complex and depends on fiber density, fiber diameter, the gas conductivity, and the radiative properties of the fiber. In this paper, we ignore this dependence.

Expanding the area term in Equation 2 and rearranging yields the following differential equation:

$$Q\frac{dr}{r} = 2\pi L(-k\,dT)$$
 (Equation 3)

where

Integrating from the inner radius to the outer radius gives:

$$Q \ln\left(\frac{r_o}{r_i}\right) = 2\pi k L (T_i - T_o)$$
 (Equation 4)

where

 r_o = outer insulation radius

$$r_i$$
 = inner insulation radius

 T_{a} = temperature at outer surface of insulation

 T_i = temperature at inner surface of insulation

Rearranging and multiplying numerator and denominator by the inner radius gives the equation in terms of the inner surface area:

$$Q = \frac{A_i k(T_i - T_o)}{r_i \ln\left(\frac{r_o}{r_i}\right)}$$
(Equation 5)

where

 A_i = surface area at inner radius, r_i

Dividing through by the inner surface area and temperature difference and inverting gives:

$$\frac{A_i \left(T_i - T_o\right)}{Q} = \frac{1}{k} r_i \ln\left(\frac{r_o}{r_i}\right)$$
(Equation 6)

Note that the left side of the equation represents the actual R-value and the term 1/k, on the right side of the equation, is the insulation R-value per unit thickness. Also note that we are developing an actual R-value that is to be applied to the area of the inner surface of the duct. In (ASHRAE 1993) an R-value is developed that is to be used in conjunction with the area of the outer surface of the insulation layer. Equation 6 can be rewritten as:

$$R_{actual} = R_{insul} r_i \ln\left(\frac{r_o}{r_i}\right)$$
 (Equation 7)

where

 R_{insul} = nominal R-value of insulation per unit thickness (flat)

Converting to duct diameter specification, as is the more common practice, gives:

$$R_{actual} = R_{insul} \frac{d_i}{2} \ln \left(\frac{d_o}{d_i} \right)$$
 (Equation 8)

where

 d_i = inner duct diameter d_o = outer diameter of insulated duct

Noting that the outer diameter can be written in terms of the inner diameter and the difference between the insulated diameter and duct diameter (Δd) as:

$$d_o = d_i + \Delta d \tag{Equation 9}$$

where

 Δd = difference between insulated diameter and duct diameter

Note also that Δd is twice the installed thickness of the insulation. Rewriting Equation 8 using Equation 9 gives:

$$R_{actual} = R_{insul} \frac{d_i}{2} \ln \left(1 + \frac{\Delta d}{d_i} \right)$$
 (Equation 10)

Outside Film Coefficient

The heat transfer coefficient for the outside of the duct is calculated as:

$$h_{out} = h_r + h_c \tag{Equation 11}$$

where

 $\begin{array}{ll} h_{out} &= \text{ overall outer surface heat transfer coefficient} \\ h_r &= \text{ radiant heat transfer coefficient} \\ h_c &= \text{ convection heat transfer coefficient} \end{array}$

For the range of diameters, outer air and surface temperatures found in residential construction, the outer convection coefficient can be estimated using the simplified equation for laminar natural convection in air given by (ASHRAE 1993).

$$h_c = 0.27 \left(\frac{\Delta T}{d_o}\right)^{0.25}$$
 (Equation 12)

where

 h_c = the convection heat transfer coefficient (Btu/h-ft²-F)

- ΔT = the temperature difference between the outer surface and the surrounding air (F)
- d_o = the outside diameter of the duct (ft)

With a ΔT of 10 F and an outer diameter of 1.0 ft., we get 0.48 Btu/h-ft²-F for the convection heat transfer coefficient. For laminar flow there is a weak dependence on the outer diameter of the duct and the temperature difference. For instance, if we double the diameter the convection coefficient will increase by a factor of 2^{0.25} or about 1.2. Thus the convection coefficient might increase from, say, 0.5 to 0.6. Using a typical value of 1.0 Btu/h-ft²-F for the radiant transfer coefficient, this will increase the overall outer surface film coefficient from 1.5 to 1.6 or about 6.6%. For a six-inch duct with R-4.2 rated insulation, as shown in Table 1, this will change the overall R-value by 0.02 from 4.34 to 4.32 or about 0.6%. For better-insulated ducts, the change in overall R-value will be even smaller.

Since the outer radiant and convection coefficients are both dependent upon unspecified temperatures, we have for purposes of this paper assumed constant values for these coefficients. In English units, typical values for the radiant and convective heat transfer coefficients are 1.0

Btu/h-ft²-F and 0.5 Btu/h-ft²-F respectively, which gives an outer film resistance of R-0.667 h-ft²-F/Btu. For a duct with a shiny foil or galvanized exterior, h_r should be reduced to values in the range of 0.2 to 0.6 Btu/h-ft²-F. See (Kratz, Konzo & Engdahl 1944) for measured emissivities of new and aged galvanized metal.

Inside Film Coefficient

The heat transfer coefficient for the inside of the duct is calculated as (ASHRAE 1993):

$$h_{in} = kNu / d_i$$
 (Equation 13)

where

h_{in} = inside convection heat transfer coefficient
 k = thermal conductivity of duct air
 Nu = Nusselt number (dimensionless heat transfer coefficient)

In this paper, we use the following correlation for the Nusselt number (ASHRAE 1993; Incropera & DeWitt 2002):

$$Nu = 0.023Re^{4/5}Pr^{X}$$
 (Equation 14)

where

Re= Reynolds number (dimensionless)Pr= Prandtl number (dimensionless)X= 0.30 for fluid being cooled, 0.40 for fluid being heated

For this paper we assumed a constant Prandtl number of 0.711 for dry air at 20 C and used an exponent of 0.35 as an average between the values for heating and cooling. The correlation given above is valid for fully developed flow in a round duct with perfectly smooth walls. Lack of fully developed flow and roughness of the duct walls each result in a larger heat transfer coefficient and a smaller film resistance.

Using any consistent set of units, the Reynolds number is defined as:

$$Re = \rho V d_i / \mu$$
 (Equation 15)

where

 $\rho = duct air density$ V = duct air velocity $d_i = inner duct diameter$ $\mu = duct air viscosity$

The dependence of the internal heat transfer coefficient on $Re^{0.8}$ shows that it will be strongly affected by velocity for a fixed diameter and fluid properties. If we double the velocity, the internal film resistance will be almost halved.

The viscosity depends on absolute temperature. An accurate method of calculating the viscosity of air is the Sutherland equation. In the form used in (USSA 1962) the viscosity in SI units is given by:

$$\mu = \beta \frac{T^{\frac{3}{2}}}{T+S}$$
 (Equation 16)

where

where

$$\mu = \text{duct air viscosity (N-s/m^2)}$$

$$\beta = 1.458 \times 10^{-6} \text{ N-s/m}^2 \text{-K}^{1/2} \text{ (exact)}$$

$$T = \text{duct air temperature (K)}$$

$$S = \text{Sutherland constant for air (110.4 K) (exact)}$$

In order to calculate h_{in} , we need to know the thermal conductivity of air, which depends on temperature. A convenient and accurate formula for the thermal conductivity of dry air (USSA 1962] in SI units of W/m-K is:

> $k = \frac{2.648 \times 10^{-3} T^{3/2}}{T + 245.4 \times 10^{-12/T}}$ (Equation 17) T = absolute duct air temperature (K)

As was the case for the external convection coefficient, the dependence of the internal convection coefficient on the duct diameter is weak. It varies inversely with $d_i^{-0.2}$.

For uninsulated metal ducts the entire thermal resistance is due to the internal and external film coefficients. An excellent reference for measured temperature drops in uninsulated ducts that show good agreement with temperature drops using calculated internal and external film coefficients is (Kratz, Konzo & Engdahl 1944). Another more recent report containing graphs of measured values for insulated flex duct is (Levinson et al. 2000).

In general, one of the advantages of insulating ducts, is that the effect of variations in these convection and radiation coefficients due to differing emissivity, bulk air properties, surface temperature, and temperature difference between the surface and ambient air have only a minor effect on the total R-value.

The Total R-Value

Finally we can insert the results above into Eq. 1. The total R-value of the duct, in any consistent set of units, is

$$R_{total} = \frac{1}{h_{in}} + R_{actual} + \frac{1}{h_{out}} \left(\frac{d_i}{d_o}\right)$$
(Equation 18)

Notice the outside film resistance has to be multiplied by the diameter ratio to properly account for the larger outside surface area. Expanding and translating to American Society of Heating, Refrigeration, and Air-conditioning Engineers (ASHRAE) IP units, the total R-value of the duct including surface films can be written as:

$$R_{total} = \frac{1}{h_{in}} + R_{insul} \frac{d_i}{2} \ln\left(1 + \frac{\Delta d}{d_i}\right) + \frac{1}{h_{out}} \left(\frac{d_i}{d_o}\right) \quad \text{(Equation 19)}$$

where

R_{total}	= total R-value of duct (h-ft ² -F/Btu)
R_{insul}^{ional}	= R-value of flat insulation per inch thickness (h-ft ² -F/Btu-in)
h_{in}	= inside convection heat transfer coefficient (Btu/h-ft ² -F)
h_{out}	= overall outer surface heat transfer coefficient ($Btu/h-ft^2-F$)
d_i^{m}	= inner duct diameter (in)
d_{o}	= outer diameter of insulated duct (in)

Results

The authors have implemented the calculations outlined above in a spreadsheet. The remainder of this paper is devoted to selected results from the spreadsheet. Unless specifically stated otherwise, all of the results below are for standard sea level pressure (101325 Pa) and a duct air temperature of 69°F. This results in air properties very close to ASHRAE standard air, defined as air with a density of 0.075 lbm/ft³. Unless stated otherwise the velocity is 500 FPM which corresponds to about 98 CFM in a six inch diameter duct.

Tables 1 through 4 all have the same form. The first column lists the available nominal inner diameters of flexible round ducts in inches. The second column gives the duct surface area in square feet per foot of length. The third column gives the internal film resistance, which depends on diameter and velocity but is independent of the duct insulation. Four pairs of columns follow this, one for each of the standard R-value ratings of R-4.2, R-6, R-8, and R-11. Also shown in the headings is the installed thickness required to produce the nominal R-value. In each pair of columns are shown the actual R-value of the insulation in its cylindrical form and the total R-value after adding the internal and external film resistances calculated as explained in the preceding section. The overall conductance (UA) of the duct insulation can be calculated as LA/R_{total} where L is the length in feet and A is the internal surface area per foot of length.

Table 1 shows sea level R-values for an air velocity of 500 FPM. The insulation is assumed to be R-2.8 per inch, which gives an installed thickness of exactly 1.5 inches for nominal R-4.2 insulated flexible duct.

	K 2.6 per men, o udet diameter over 5.20									
Nom.	Actual		R _{nomina}	al: 4.2	R _{nomina}	R _{nominal} : 6		R _{nominal} : 8		: 11
Duct	Duct Area		Thickne	ess: 1.50 in	Thickness: 2.14 in		Thickness: 2.86 in		Thickness: 3.93 in	
Dia.	(ft ² per ft	R _{in}	Ractual	R _{total}	Ractual	R _{total}	Ractual	R _{total}	R _{actual}	R _{total}
(in)	length)									
4	1.05	0.45	3.13	3.97	4.08	4.85	4.97	5.69	6.09	6.76
5	1.31	0.47	3.29	4.18	4.33	5.16	5.33	6.12	6.61	7.34
6	1.57	0.49	3.41	4.34	4.53	5.40	5.62	6.45	7.03	7.81
7	1.83	0.50	3.50	4.47	4.68	5.60	5.85	6.72	7.38	8.19
8	2.09	0.52	3.57	4.57	4.80	5.76	6.04	6.94	7.66	8.52
9	2.36	0.53	3.62	4.65	4.91	5.89	6.19	7.13	7.91	8.79
10	2.62	0.54	3.67	4.73	4.99	6.00	6.33	7.29	8.12	9.03
12	3.14	0.56	3.75	4.84	5.13	6.18	6.54	7.56	8.46	9.43
14	3.67	0.58	3.81	4.93	5.23	6.32	6.71	7.76	8.73	9.74
16	4.19	0.59	3.85	5.01	5.32	6.44	6.84	7.93	8.95	9.99
18	4.71	0.61	3.88	5.06	5.38	6.53	6.95	8.06	9.13	10.20
20	5.24	0.62	3.91	5.11	5.44	6.61	7.04	8.18	9.28	10.38
24	6.28	0.64	3.96	5.19	5.52	6.73	7.18	8.36	9.52	10.66
28	7.33	0.66	3.99	5.26	5.58	6.83	7.28	8.50	9.70	10.88

Table 1. R-Values and Internal Film Resistance for 4 Nominal Insulation LevelsR-2.8 per inch, 0" duct diameter oversize

Note: All R-values are in h-ft²-F/Btu. R_{in} is the internal film resistance, R_{actual} is the actual R-value of the insulation layer only and R_{total} is the overall R-value including the internal film and R-0.667 for the external film

N-3.30 per men, o under unameter over size										
Nom.	Actual		R _{nomina}	R _{nominal} : 4.2		R _{nominal} : 6		R _{nominal} : 8		: 11
Duct	Duct Area		Thickne	ess: 1.25 in	Thickness: 1.79 in		Thickness: 2.38 in		Thickness: 3.27 in	
Dia.	(ft ² per ft	R _{in}	Ractual	R _{total}	R _{actual}	R _{total}	R _{actual}	R _{total}	Ractual	R _{total}
(in)	length)									
4	1.05	0.45	3.26	4.12	4.29	5.09	5.27	6.02	6.52	7.22
5	1.31	0.47	3.41	4.32	4.53	5.39	5.62	6.43	7.03	7.79
6	1.57	0.49	3.51	4.47	4.71	5.61	5.89	6.75	7.44	8.24
7	1.83	0.50	3.59	4.59	4.85	5.79	6.10	7.00	7.77	8.61
8	2.09	0.52	3.65	4.68	4.96	5.94	6.28	7.21	8.04	8.92
9	2.36	0.53	3.71	4.76	5.05	6.06	6.42	7.39	8.27	9.18
10	2.62	0.54	3.75	4.82	5.13	6.16	6.54	7.54	8.46	9.41
12	3.14	0.56	3.82	4.93	5.25	6.33	6.74	7.78	8.78	9.77
14	3.67	0.58	3.86	5.01	5.34	6.45	6.89	7.96	9.02	10.06
16	4.19	0.59	3.90	5.07	5.42	6.56	7.00	8.11	9.22	10.29
18	4.71	0.61	3.93	5.13	5.47	6.64	7.10	8.23	9.38	10.48
20	5.24	0.62	3.96	5.17	5.52	6.71	7.18	8.34	9.52	10.64
24	6.28	0.64	4.00	5.24	5.59	6.82	7.30	8.50	9.73	10.89
28	7.33	0.66	4.02	5.30	5.65	6.90	7.39	8.62	9.88	11.09

 Table 2. R-Values and Internal Film Resistance for 4 Nominal Insulation Levels

 R-3.36 per inch, 0" duct diameter oversize

Note: All R-values are in h-ft²-F/Btu. R_{in} is the internal film resistance, R_{actual} is the actual R-value of the insulation layer only and R_{total} is the overall R-value including the internal film and R-0.667 for the external film

The difference between the nominal and actual R-values for the insulation layer itself are striking, especially for small diameters and large installed thickness. For instance, 4-inch flexible duct rated at R-11 has an actual R-value of only 6.09 or 55% of the nominal value. Even with the film resistances added the total R-value is only 6.76, which is still only 61% of the nominal value. The discrepancy grows smaller as the inner duct diameter increases. Consider 20-inch diameter duct, which is about the largest diameter seen in residential construction. In this case, R-11 rated flexible duct has an actual R-value of 9.28, which is 84% of the rated value and a total R-value of 10.38 or 94% of the rated value. Notice for 5- and 6-inch ducts rated at R-4.2, the total R-value is close to the rated value, that is, the added film resistances approximately cancel the loss due to the cylindrical geometry.

Fiberglass insulation is manufactured with varying R-values per inch, ranging from about R-2.5 up to almost R-4 (ASHRAE 1993). Table 2 shows the same variables as Table 1, but assumes a higher density fiberglass of R-3.36 per inch. This results in an installed thickness of 1.25 inches for an R-4.2 rated duct. Because the installed thickness is less for a given inner diameter and nominal R-value, the penalty due to the cylindrical geometry will be smaller. Thus in general lower conductivity insulation will yield better overall R-values for a fixed nominal rating. For instance, R-11 rated 4-inch duct has an actual R-value of 6.52 versus 6.09 in Table 1, about a 7% improvement. The total R-value of 7.22 versus 6.76 in Table 1 shows a 6.8% improvement. At larger diameters the benefit of using insulation with a greater R-value per inch decreases.

Tables 3 and 4 show the same information as Tables 1 and 2 respectively, however the internal diameter is increased by 3/8-inch. It was mentioned earlier that most flexible duct is manufactured with a slightly oversized inner core to allow easy connection to standard metal fittings. The ADC standard allows for a maximum of 3/8-inch oversize in the inner diameter. Therefore a given installed thickness of insulation is applied to a slightly larger inner diameter, which will cause a slight improvement in the actual R-value and also in the internal film resistance.

However, the internal surface area is increased by a larger amount than the R-value so the overall conductance or UA of the duct is larger than before thus increasing the heat loss. For instance in Table 3 we see that nominal R-11 duct with a 4 inch diameter has a total R-value of R-6.99 compared with R-6.76 in Table 1, a 3.4% increase in R-value. The internal surface area per unit length increases from 1.05 square feet to 1.15 square feet, an increase of about 9.5%. The overall heat loss per unit length therefore increases from 0.155 to 0.164 Btu/h-F, or about 5.8%. Thus most flexible duct has a larger heat loss than expected otherwise because of the increased inner diameter.

A factor that affects total R-value is the velocity of air in the duct, which can have a large impact on the internal film resistance. Residential duct systems typically have velocities ranging from about 500 FPM (feet per minute) to about 1000 FPM. The value recommended by ASHRAE for residences is 600 FPM. Small diameter runouts to individual registers tend to be in the 500 FPM range while trunk ducts near the air handler may have higher velocities. Small commercial ductwork frequently has somewhat higher design velocities. The velocity only affects the internal film coefficient, so is of less importance for well-insulated ducts.

The values in Tables 1 through 4 can be easily adjusted for other velocities. For instance suppose we are interested in a 6-inch nominal duct, 3/8-inch oversized, using R-3.36 per inch flexible duct, with a nominal rating of R-4.2, and airflow with a velocity of 1000 FPM. We start with Table 4. The internal film resistance given in the table is R-0.49 for a velocity of 500 FPM. From Equations 13 and 14, we know that internal film coefficient is proportional to the velocity raised to the 0.8 power. The velocity ratio in our case is 2, so the internal heat transfer coefficient will increase by a factor $2^{0.8} = 1.74$, therefore the film decreased by the same factor from R-0.49 to R-0.28. The total R-value changes from 4.52 to 4.31 (4.52-0.49+0.28).

Table 3. R-Values and Interr	ial Film Resistance f	for 4 Nominal Insul	ation Levels
R-2.8 per 1	inch, 3/8" duct diam	ieter oversize	

Nom. Duct	Actual Duct Area		R _{nomin} Thickne	ominal:4.2Rnominal:6Rnominal:8ckness:1.50 inThickness:2.14 inThickness:2.86 in			ı: 8 s: 2.86 in	R _{nominal} : 11 Thickness: 3.93 in		
Dia. (in)	(ft ² per ft length)	R _{in}	R _{actual}	R _{total}	R _{actual}	R _{total}	R _{actual}	R _{total}	R _{actual}	R _{total}
4	1.15	0.46	3.20	4.05	4.18	4.98	5.12	5.87	6.30	6.99
5	1.41	0.48	3.34	4.24	4.41	5.26	5.45	6.25	6.78	7.53
6	1.67	0.49	3.44	4.39	4.59	5.48	5.71	6.56	7.17	7.96
7	1.93	0.51	3.52	4.51	4.73	5.66	5.92	6.81	7.49	8.32
8	2.19	0.52	3.59	4.60	4.85	5.81	6.10	7.02	7.76	8.63
9	2.45	0.53	3.64	4.68	4.94	5.93	6.25	7.19	7.99	8.89
10	2.72	0.55	3.69	4.75	5.02	6.04	6.37	7.35	8.19	9.11
12	3.24	0.56	3.76	4.86	5.15	6.21	6.58	7.60	8.52	9.49
14	3.76	0.58	3.81	4.95	5.25	6.35	6.74	7.79	8.78	9.79
16	4.29	0.60	3.86	5.02	5.33	6.46	6.86	7.95	8.98	10.03
18	4.81	0.61	3.89	5.07	5.39	6.54	6.97	8.09	9.16	10.24
20	5.33	0.62	3.92	5.12	5.45	6.62	7.05	8.20	9.30	10.41
24	6.38	0.65	3.96	5.20	5.53	6.74	7.19	8.37	9.53	10.69
28	7 43	0.67	3 99	5 26	5 59	6.83	7 29	8 51	9 71	10.90

Note: All R-values are in h-ft²-F/Btu. R_{in} is the internal film resistance, R_{actual} is the actual R-value of the insulation layer only and R_{total} is the overall R-value including the internal film and R-0.667 for the external film

K-5.50 per men, 5/6 duct diameter over size										
Nom.	Actual		R _{nomina}	R _{nominal} : 4.2		R _{nominal} : 6		R _{nominal} : 8		: 11
Duct	Duct Area		Thickne	ess: 1.25 in	Thickness: 1.79 in		Thickness: 2.38 in		Thickness: 3.27 in	
Dia.	(ft ² per ft	R _{in}	Ractual	R _{total}	R _{actual}	R _{total}	R _{actual}	R _{total}	R _{actual}	R _{total}
(in)	length)									
4	1.15	0.46	3.32	4.20	4.39	5.21	5.41	6.19	6.72	7.45
5	1.41	0.48	3.45	4.38	4.60	5.48	5.73	6.56	7.19	7.97
6	1.67	0.49	3.54	4.52	4.76	5.69	5.97	6.85	7.57	8.39
7	1.93	0.51	3.62	4.62	4.89	5.85	6.17	7.09	7.87	8.74
8	2.19	0.52	3.68	4.71	5.00	5.99	6.33	7.28	8.13	9.02
9	2.45	0.53	3.72	4.78	5.08	6.10	6.47	7.45	8.34	9.27
10	2.72	0.55	3.76	4.85	5.16	6.20	6.58	7.59	8.53	9.48
12	3.24	0.56	3.83	4.94	5.27	6.35	6.77	7.81	8.83	9.83
14	3.76	0.58	3.87	5.02	5.36	6.47	6.91	7.99	9.06	10.10
16	4.29	0.60	3.91	5.08	5.43	6.57	7.02	8.14	9.25	10.33
18	4.81	0.61	3.94	5.14	5.48	6.65	7.11	8.25	9.41	10.51
20	5.33	0.62	3.96	5.18	5.53	6.72	7.19	8.35	9.54	10.67
24	6.38	0.65	4.00	5.25	5.60	6.83	7.31	8.51	9.74	10.92
28	7.43	0.67	4.03	5.30	5.65	6.91	7.40	8.63	9.90	11.11

 Table 4. R-Values and Internal Film Resistance for 4 Nominal Insulation Levels

 R-3.36 per inch, 3/8" duct diameter oversize

Note: All R-values are in h-ft²-F/Btu. R_{in} is the internal film resistance, R_{actual} is the actual R-value of the insulation layer only and R_{total} is the overall R-value including the internal film and R-0.667 for the external film

Another factor which changes the internal film coefficient at a given duct air temperature is the atmospheric pressure, reflected in the density of the air. For instance in Denver, CO at 5000 feet elevation the air pressure and the density of the air in a duct at a given temperature is 83.2% of that at sea level. A forced air distribution system is, to a reasonable approximation, a constant volume device, meaning that the same system with the same fan turning at the same speed will move the same actual volume of air. The velocities everywhere in the duct system will remain the same as at sea level. The internal film resistance needs to be adjusted for the new density. Using the same duct as the velocity example, we would calculate the internal heat transfer coefficient to change by a factor of $0.83^{0.8} = 0.86$, so the internal film resistance will increase from R-0.49 to R-0.57. The total R-value would then be adjusted in the same fashion as above from R-4.52 to R-4.60.

Conclusions

Failing to reduce the rated R-value of round duct insulation to account for the cylindrical geometry can lead to significant errors. For instance, increasing the nominal R-value of six-inch duct from R-4.2 to R-11 only increases the total R-value by a factor of 1.80 instead of a factor of 2.62 based on the nominal values, thus giving an error of about 31% in the improvement.

Use of insulation with a greater R-value per inch will result in greater actual and total R-values for the same nominal rated R-value, because the geometric penalty is reduced.

The variation in film coefficients on the interior and exterior surfaces of the duct becomes relatively minor with nominal R-values greater than R-4.2. They are, of course, very important in the case of uninsulated ducts.

References

- [ADC] Air Diffusion Council. 2003. *Flexible Duct Performance and Installation Standards*. 4th edition. Schaumberg, Ill.: Air Diffusion Council.
- [ASHRAE] American Society of Heating, Refrigerating, and Air-Conditioning Engineers. 1993. *ASHRAE Handbook: Fundamentals.* Atlanta, Ga.: American Society of Heating, Refrigerating, and Air-Conditioning Engineers.
- Incropera, Frank P., and David P. DeWitt. 2002. *Introduction to Heat Transfer*. 4th edition. New York, N.Y.: John Wiley & Sons.
- Kratz, Alonzo P., S. Konzo, and R.B. Engdahl. 1944. "Temperature Drop in Ducts for Forced-Air Heating Systems." *University of Illinois Bulletin*. Bulletin Series No. 351. May 2.
- Levinson, Ronnen M., Wm. Woody Delp, Darryl J. Dickerhoff, and Mark P. Modera. 2000. Effects of Air Infiltration on Internal Fiberglas Insulation and on the Delivery of Thermal Capacity Via Ducts. LBNL-42499. Berkeley, Calif.: Lawrence Berkeley National Laboratory.
- [USSA] United States Standard Atmosphere. 1962. U.S. Government Printing Office.