The average water film temperature will be estimated as 36 F (mixed mean fluid temperature of 34 F). Then case 3, Table 5 yields:

$$h = 0.00486\ (1 + 0.36)\ \frac{(11.2 \times 10^5)^{0.8}}{(0.1725)^{0.2}} = 650 \text{ Btu per hour per square foot per degree Fahrenheit.}$$

The transfer area on which this conductance is based is the inside tube area. Associated with 1 ft length of pipe there are:

$$\pi \times \frac{2.067}{12} \times 1 = 0.542 \text{ sq ft.}$$

Thus the resistance for 1 ft of tube length is:

$$R_1 = \frac{1}{h\pi D \times 1} = \frac{1}{650 \times 0.542} = 2.8 \times 10^{-3} \text{ hr degree Fahrenheit per Btu.}$$

Case 9, Table 5 is applicable for calculating the free thermal convection resistance, R_c, existing between the surrounding air and the insulation. The air temperature is given as 120 F. As an approximation a 20 F temperature difference between the air and the pipe surface will be assumed. Then case 9 yields:

$$D = \frac{4.375}{12} = 0.364 \text{ ft.}$$

$$h = 0.23 \left(\frac{20}{0.364}\right)^{0.25} = 0.63 \text{ Btu per hour per square foot per degree Fahrenheit.} \quad (13)$$

This result may not be deemed conservative inasmuch as the expression is for *still* air. If, however, the air is not still, but flows at approximately 5 mph or 7 fps the mass velocity corresponds to:

$$G = 7 \times 0.07 \times 3600 = 1770 \text{ lb air per hour per square foot.}$$

A magnitude of $k = 0.014$ Btu per hour per square foot per degree Fahrenheit for one foot thickness applied to case 4 yields:

$$h = 0.45 \left(\frac{0.014}{0.364}\right) + 0.178\ (1770)^{0.56} \left(\frac{0.014}{0.364}\right)^{0.44}$$

$$= 0.017 + 2.8 = 2.8 \text{ Btu per hour per square foot per degree Fahrenheit.}$$

This conductance is based on 1 sq ft of outside lagging area. Thus, since there are $\pi \times \frac{4.375}{12} = 1.14$ sq ft of outside lagging area associated with 1 ft length of pipe:

$$R_c = \frac{1}{2.8 \times 1.14} = 0.312 \text{ hr degree Fahrenheit per Btu.}$$

The radiation resistance, R_r, which acts in parallel with the convection resistance, R_c, for the transfer of heat to the surface of the insulation, may be calculated. For the purposes of this illustrative problem it will be assumed that the insulated pipe is exposed to (*sees*) surroundings, which exist at 120 F. Then the angle factor, F_A, is unity and for an estimated surface emissivity of 0.9 (see Table 6), $F_e = 0.9$. As a first approximation the insulation surface temperature will be estimated as 20 F lower than the surroundings at 120 F. Then the radiation per degree of temperature

difference, by Equation 3 (or more conveniently by Table 8) divided by the temperature difference will be:

$$h_r = \frac{(196 - 170)\ 0.95}{20} = 1.17 \text{ Btu per hour per square foot per degree Fahrenheit.}$$

The outside surface area of the insulation associated with 1 ft of pipe length was previously calculated as 1.14 sq ft. Thus:

$$R_r = \frac{1}{1.17 \times 1.14} = 0.75 \text{ hr degree Fahrenheit per Btu.}$$

The resultant resistance of R_c and R_r acting in parallel (see Fig. 4) can now be evaluated as:

$$\frac{1}{R_4} = \frac{1}{R_c} + \frac{1}{R_r} = \frac{1}{0.312} + \frac{1}{0.75} = 4.54 \text{ Btu per hour per degree Fahrenheit.}$$

$$R_4 = 0.22 \text{ hr degree Fahrenheit per Btu.}$$

The individual resistances for a 1 ft length of pipe applying to the illustrative problem depicted in Fig. 4 have now been calculated and are summarized as follows:

R_1 convection from the pipe wall to the cold water $= 2.8 \times 10^{-3}$ hr degree Fahrenheit per Btu.
R_2 conduction through the pipe wall $= 8.5 \times 10^{-4}$ hr degree Fahrenheit per Btu.
R_3 conduction through the cork insulation $= 3.9$ hr degree Fahrenheit per Btu.
R_4 parallel convection and radiation from the surroundings $= 0.22$ hr per degree Fahrenheit per Btu.

Then:

R_T = the over-all resistance surroundings to cold water $= R_1 + R_2 + R_3 + R_4 = 4.1$ hr degree Fahrenheit per Btu.

Note that the controlling resistances are R_3 and R_4. That is, the neglect of R_1 and R_2 would not significantly influence the total resistance, R_T.

On the basis of this resistance calculation the heat transfer from the surroundings to the cold water may be evaluated as:

$$\frac{q_{rc}}{N} = \frac{t_o - t_f}{R_T} = \frac{120 - 34}{4.1} = 21 \text{ Btu per hour per foot}$$

or about 0.175 tons of refrigeration per 100 ft of pipe.

Since the calculation is based on a 1 ft pipe length:

$$q_{rc} = 21 \text{ Btu per hour.}$$

The temperature drops through the various resistances are now readily evaluated by Equation 12 as:

$t_o - t_{s3}$ air to insulation surface $= R_4\, q_{rc} = 0.22 \times 21 = 4.6$ F.
$t_{s3} - t_{s2}$ through the insulation $= R_3\, q_{rc} = 3.9 \times 21 = 82$ F.
$t_{s2} - t_{s1}$ through the pipe wall $= R_2\, q_{rc} = 8.5 \times 10^{-4} \times 21 = 0.02$ F.
$t_{s1} - t_f$ pipe wall to cold water $= R_1\, q_{rc} = 2.8 \times 10^{-3} \times 21 = 0.06$ F.

The solution was obtained on the assumption that the air temperature and the outside temperature differed by 20 F. In order to obtain a slightly better estimate of the rate of heat transfer the numerical solution should be repeated using the temperatures calculated from the previous listed temperature differences.

The foregoing problem serves to illustrate a general method of solving