Thermochimica Acta, 26 (1978) 199–207

ERRORS IN IN-SITU PIPE INSULATION PERFORMANCE DETERMINATION*

R. D. RINEHART AND A. D. LAMPERT
York Research Corporation, Stamford, Conn. 06906 (U.S.A.)

ABSTRACT

The in-situ performance of insulation covering heated pipes in an industrial environment has no data bank which brings together generic insulation types, service environments and age. A study to this end with ERDA support has been undertaken and is under way. The detailed thermal relationships are shown as well as the experimental errors which make up the project. The error analysis is presented with the techniques and instruments which are used to minimize the errors. The parameters are individually catalogued for their error contribution and a summary of the data reduction program is included.

INTRODUCTION

In determining the performance of in-situ pipe insulation systems, several determinations must be made. The resultant error in such determinations must be the sum of the individual errors in the determination process.

There are two usual types of errors in any determination; random or reading errors, and biased or equipment errors. Biased errors shift the experimental values to either side of the true value, but these biases can be removed by careful calibration and procedural approaches. Random errors can only be minimized by careful technique, instrument readings from quality instrumentation and by replicate data. It is the random errors that are being considered here.

The purpose of this paper is to discuss quantitatively the type, sources and magnitudes of the random errors encountered when determining an in-situ insulation system's thermal performance. What is in-situ thermal performance? We choose to define it as the ratio of the thermal conductance which would have been expected by the specifier of the insulation system to the thermal conductance determined from measured data taken in-situ at an insulation site, or C_d/C_m (design conductance/measured conductance).

* Presented at the 7th North American Thermal Analysis Society Conference, St. Louis, Missouri, September 25–28, 1977.

The experimental data taken in this study are to serve in providing the thermal conductance which is to be compared with the thermal conductance expected when the system was designed. To this end, the ultimate dependent variable is expressed as the ratio of design to in-situ measured thermal conductance or, simply, C_d/C_m.

The usual, albeit crude, C_d comes from

$$\frac{Q}{A} = C_d \, \Delta T \tag{1}$$

also, for pipes

$$\frac{Q}{A} \approx \frac{K_d \, \Delta T}{r_s \ln(r_s/r_p)} \tag{2}$$

Solving for $C_{d'} \approx C_d$

$$\Delta T \approx \frac{K_d \, \Delta T}{r_s \ln(r_s/r_p)}$$

or

$$C_d \approx \frac{K_d}{r_{sd} \ln(r_{sd}/r_{pd})} \tag{3}$$

where C_d = design thermal conductance (btu/ft.^{2} h °F), K_d = design insulation thermal conductivity (btu in./ft.^{2} h °F), r_{sd} = radius outer insulation surface (in.), and r_{pd} = radius outer pipe surface (in.). The approximations inherent in these relations include (a) scale on the inner surface of the pipe ignored; (b) thermal conductance of the pipe ignored; (c) scale on the pipe outer surface ignored; (d) a uniform contact between the surface of the pipe and inner insulation surface assumed; (e) accurate insulation thermal conductivity; and (f) uniform wall thickness of the insulation. That designers, in general, utilize these approximations does not mean that poor designs result but that the expected errors from such approximations are usually very small or that worst case conditions are being observed.

In the quantification of C_m, the following relations are applicable.

or

$$Q_m = C_m \, \Delta T_m \tag{4}$$

$$C_m = \frac{Q_m}{\Delta T_m} \tag{5}$$

Thus

$$\frac{C_d}{C_m} = \frac{K_d/[r_{sd} \ln(r_{sd}/r_{pd})]}{Q_m/\Delta T_m}$$

or, rearranging

$$\frac{C_d}{C_m} = \frac{K_d \Delta T_m}{Q_m r_{s_d} \ln (r_{s_d}/r_{p_d})} \tag{6}$$

If K_d is replaced with its equivalent in temperature terms and T_m is also, the working equation for the in-situ performance study is obtained.

$$\frac{C_d}{C_m} = \frac{\{[(t_{p_d} + t_{s_d})^2 a/4] + [(t_{p_d} + t_{s_d})b/2] + c\}\,(t_{p_m} - t_{s_m})}{Q_m r_{s_d} \ln (r_{s_d}/r_{p_d})} \tag{7}$$

where C_d = design thermal conductance (btu/ft^2. h°F); C_m = measured thermal conductance (btu/ft.^{2} h°F); t_{p_d} = design pipe temperature (°F); t_{s_d} = design surface temperature (°F); t_{p_m} = measured pipe temperature (°F); t_{s_m} = measured surface temperature (°F); Q_m = measured heat flow (btu/ft.^{2} h); r_{s_d} = design outer radius of insulation (in.); r_{p_d} = design outer radius of pipe (in.); a,b,c = coefficients of insulation thermal conductivity; and characteristic $K = at_m^2 + bt_m + c$ where t_m is the mean temperature, i.e. $(t_p + t_s)/2$.

To utilize this relation properly, one additional expression must be considered. The value of t_{s_d} does not come from any source except by computation. To find t_{s_d}, the expression developed by Heilman[1] is utilized for the convection of heat with the radiation portion as given by Stefan-Boltzman[2]. To find t_s, it is required to know the emissivity ε in addition to the above terms of eqn. (7).

The t_s can be found iteratively by equating the heat flow through the insulation with the radiation plus convection from the cylinder's surface.

$$\frac{(t_p - t_s)\,\{[(t_p + t_s)^2 a/2] + [(t_p + t_s)b/2] + c\}}{r_s \ln (r_s/r_p)}$$

$$= 0.174\varepsilon \left[\frac{(t_s + 459.6)^4}{100^4} - \frac{(t_a + 459.6)^4}{100^4}\right]$$

$$+ C \times \left(\frac{1}{2r_s}\right)^{0.2} \times \left(\frac{2}{t_s + t_a}\right)^{0.181} \times (t_s - t_a)^{1.266} \tag{8}$$

where ε is surface emissivity, C is a constant (= 1.016 for horizontal cylinders) and t_a is ambient air temperature (°F). All other symbols are as before.

PARAMETRIC ERRORS

Design pipe temperature (t_{p_d})

This parameter is usually not subject to error. If the temperature is an estimate, it is still treated as an absolute number in calculations and is not subject to measurement errors. Judgement errors may abound, but these do not alter the use of this temperature.

Design surface temperature (t_{s_d})

This is a calculated value as described in eqn. (8). The principle variable in the calculation which is unknown or not a direct design value is the guess made for emissivity, ε. This is a guess that must be made by the experimenter unless the design data reveals the original concept. If the surface temperature had entered into the original calculations because, for instance, a maximum t_s was to be limiting, there is reason for using ε at the design stage. This is not too usual in most applications. As described earlier, t_s can be calculated from other design data by guessing at ε, changing ε slightly and recalculating t_s to get $\Delta t_s/\Delta\varepsilon$, and multiplying this by the probable range to give a probable change in t_{s_d} to be used. For example, a value of t_s was found with $\varepsilon = 0.3$; $\Delta t_s/\Delta\varepsilon$ was found to be 25 and thus ε ± 0.2 would give $\Delta t_s = 0.2 \times 25 = \pm 5$°F.

Measured heat flows (Q_m)

Depending upon the jacketing and upon the surface temperature, the heat flow meter used is good to $\pm 5\%$. Calibrations over many weeks have verified that this figure is a reasonable one and it includes the errors in the digital voltmeter used to read the meter's output.

Design outer radius of insulation (r_{s_d})

Based upon the standard practices of manufacturers and contractors, this value is known to about $\pm 1/4$ in. Given better data, a closer tolerance may be used, but a fair amount of variation is anticipated.

Design pipe outer radius (r_{p_d})

Industry standard tolerances are available from handbooks and may be used.

K value coefficients (a, b, c)

The design K is used as given in the applicable literature with no attempt made to second guess a tolerance. Moisture, installation faults, etc. will modify the real world; but the designer is presumed to have utilized the published data. Some generic data may be used and those data are subject to an error, but the design K must still be considered a true number. (Whatever number is or was used by the designer in a given situation will be questioned by practitioners in the art.)

Measured pipe temperature (t_{p_m})

Temperature probe values are about $\pm 4\%$ with good calibrations.

Measured surface temperature (t_{s_m})

The thermocouple readings are $\pm 5\%$ of the real values.

SENSITIVITY ANALYSIS

Random errors, as opposed to bias errors associated with the measurement of

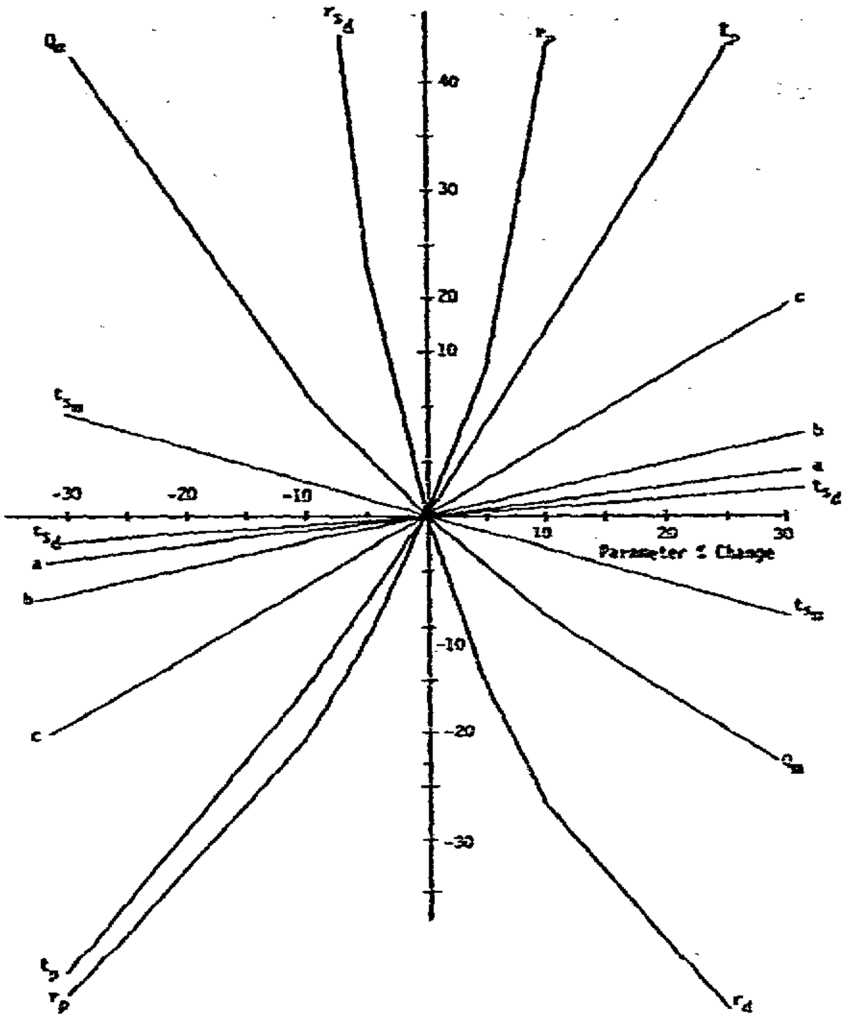


Fig. 1. Sensitivity of C_d/C_m to change in the input parameters.

the parameters necessary to determine thermal performance, are not correctable. The question remains as to the degree of accuracy by which the parameters must be measured in order to produce meaningful results. The sensitivity of the calculated thermal performance, C_d/C_m, to an error in each of the parameters must be determined. Such a sensitivity analysis involves the independent altering of each of the parameters for a variety of example cases and observing the change in the value of C_d/C_m that results. To investigate the sensitivity of C_d/C_m to variations in measured heat flow, Q_m, measured pipe surface temperature, t_{p_m}, measured insulation surface temperature, t_{s_m}, design pipe radius, r_{p_d}, design insulation surface radius, r_{s_d}, design surface temperature, t_{s_d} and design thermal conductivity, K, each parameter has been altered by -30%, -10%, $+10\%$ and $+30\%$ of a given value. The percent change of C_d/C_m has been calculated for each alteration; the accompanying plot, Fig. 1, has been made of the mean results of a number of reasonable cases. From this plot we can make certain observations concerning the relative importance of accurately determining each of the parameters.

The most significant item in terms of instrumentation is that t_{s_m}, the insulation system surface temperature, is not a critical temperature in terms of accuracy. That is, if the t_{s_m} value is $\pm 10\%$, then the error in C_d/C_m is only $+3\%$ to -4% of the nominal value for the case at hand. This means that the measurement of surface temperature is not as critical as was at first anticipated. Further, it is noted that the measurement of the pipe temperature, t_{p_m}, must be made with good precision because a $\pm 10\%$ error in t_{p_m} means a -18% or $+15\%$ error in C_d/C_m for this case. This is four times the influence of the insulation surface temperature.

The most sensitive design parameters are the pipe and insulation radii or the thickness of the insulation. This single most sensitive dimension makes one immediately aware that in-situ situations where the insulation is no longer round or the strength of the insulation has permitted a sagging inside the jacketing are no longer performing in the manner which was originally envisioned by the designer. Moisture and other deterioration of the material shows up as an increase in the a, b + c values which will contribute to a loss of performance.

SYSTEM ERRORS

Using the relationship that probable errors are the square root of the sum of squares of the individual contributions, a typical system may be as shown in Table 1 using the sensitivities of Fig. 1.

DISCUSSION

If r_s is taken as a design value with no error, the most probable error is immedi-

TABLE 1

Parameter	*Value*	*Error*		*% Error*	*(% Error)²*
t_{p_d}	450°F	0	× 0.44	0	0
t_{s_d}	105°F	5	× 0.103	0.515	0.265
Q	75	5	× 1	5	25
r_s	4.5	5.5	× 1.9	10.6	112.36
r_p	1.5	0.33	× 0.91	0.30	0.09
a	0.0000006433	0	× 0.15	0	0
b	0.00028936	0	× 0.25	0	0
c	0.19978	0	× 0.61	0	0
t_{p_m}	440	4	× 1.29	5.15	26.52
t_{s_m}	100	5	× 0.294	1.47	2.16
					$\Sigma = 166.4$
					$\sqrt{\ } = \pm 12.9\%$

TABLE 2

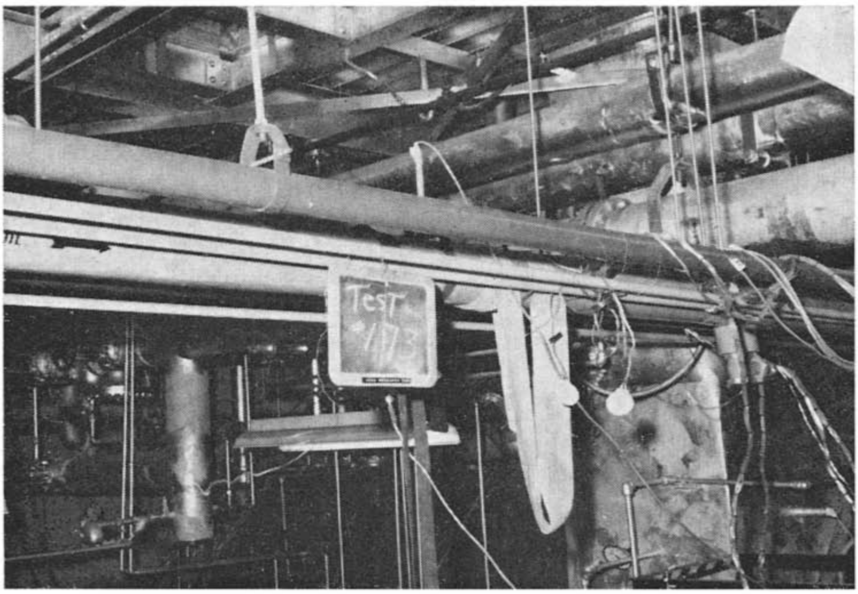
Parameter	*Value*	*Error* — *With design data (%)*	*Error* — *Without design data (%)*
t_{p_d}	450°F	0 × 0.44 = 0	10 × 0.44 = 4.4
t_{s_d}	105°F	0 × 0.103 = 0	5 × 0.103 = 0.515
Q	75 btu/ft.² h	5 × 1 = 5	5 × 1 = 5
r_s	4.5 in.	0 × 1.9 = 0	5.5 × 1.9 = 10.6
r_p	1.5 in.	0.33 × 0.91 = 0.3	0.33 × 0.91 = 0.3
a	0.0000006433	0 × 0.15 = 0	10 × 0.15 = 1.5
b	0.00028936	0 × 0.25 = 0	10 × 0.25 = 2.5
c	0.19978	0 × 0.61 = 0	10 × 0.61 = 6.1
t_{p_m}	440	4 × 1.29 = 5.15	4 × 1.29 = 5.15
t_{s_m}	100	5 × 0.294 = 1.47	5 × 0.294 = 1.47
		E^2 = 54.6	232.3
		= ±7.4%	±15.24%

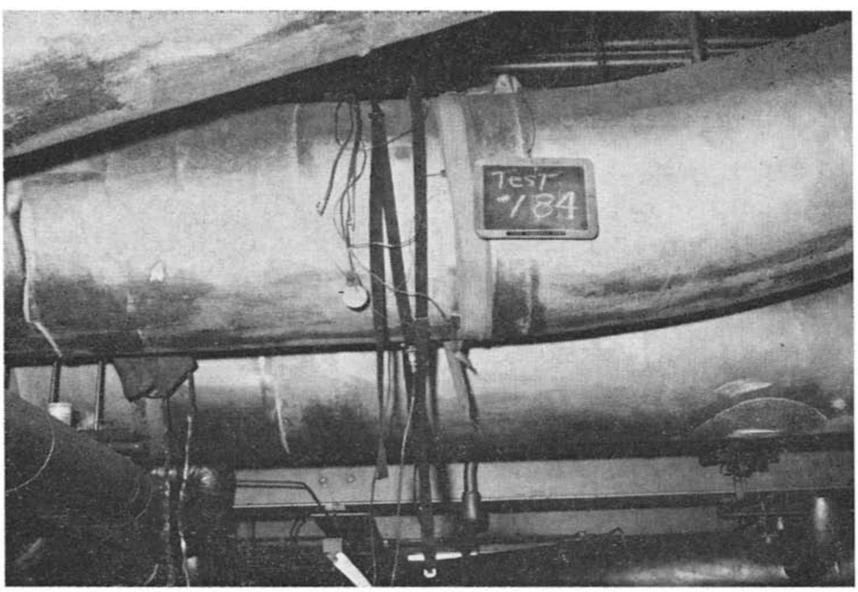
ately reduced to ±7.5%. The validity of this step is immediately questioned. Whatever value the designer chose is the one which was used to predict the performance of the system, that is the rationale for assigning no error to the number. Given, then, the design data, a zero error can be assigned, but not given the design data, the experimenter must assign rational design values. This latter value assignment is the one which leads to the greatest confusion. Using the problem again, the comparison shown in Table 2 can be made. Thus the most probable error for this case will be between ±7.4% and ±15.2% depending upon the degree of certainty that is held about the design data.

DATA ANALYSIS

The data being collected in the current program will consist of several hundred data points taken at many sites. At each point, the in-situ insulation will perform in some fashion relative to the design of the system. This data bank, properly analysed, should contribute to more effective designs. Because of its ability to generate predictive equations from observed data, regression analysis will be used to quantify the relationships between the environmental and system parameters previously identified and thermal performance.

Physical equations derived to describe complex events are frequently found to fail in the satisfactory prediction those very events when applied to real operational conditions. Their failure in dynamic situations can generally be attributed to the restrictions that must be made to make the operational world conform to the theoretical world. The use of statistical regression techniques to generate prediction equations is under no such handicap. While there is no guarantee that the coefficients derived will be stable, the technique has proved to be extremely useful in forecasting numerical variables by empirical methods which are not severely dependent on dynamic or physical laws. The regression technique derives its prediction equation by selecting significant variables from simultaneously collected sets of observations obtained under operational conditions. In the use of multiple regression techniques, theory is not ignored; it must be kept in mind to select logical variables and to limit their number. The equation with most predictions will not necessarily yield the best fit to independent data. The long equation may actually "overfit" by ascribing variation due to small scale fluctuations to one of the predictions by accident.





Figs. 2 and 3. In-situ measurements of heat flow, pipe temperature and surface temperature.

Statistical multiple regression analysis is used to obtain the best fit of a set of observations of dependent and independent variables to an equation of the form

$$y = b_0 + b_1x_1 + b_2x_2 + \ldots + b_nx_n$$

Where y is the dependent variable, x_1, x_2 . . . are the independent variables and b_0, b_1 . . . are coefficients to be determined. Multiple regression is not restricted to a linear solution. As long as the coefficients to be determined are linear, the predictive equation itself can be of many forms. A multiple regression solution gives the least squares estimates for the coefficients for a particular sample of observations. The solution also gives a measure of reliability for each of the coefficients so that inferences can be made regarding the parameters of the population from which the sample of observations was drawn.

Figures 2 and 3 illustrate the measurement of heat flow, pipe temperature and surface temperature.

CONCLUSIONS

The establishment of the parametric sensitivity of the C_d/C_m model has identified the parameters which contribute the most toward errors, i.e. insulation thickness, rate of heat flow, measured pipe temperature and insulation conductivity.

The calibration of instrumentation reduces bias errors.

The knowledge of design parameters improves the data accuracy significantly as opposed to being forced to estimate what was in the designer's original work.

ACKNOWLEDGEMENT

The authors wish to express their thanks to ERDA under whose sponsorship most of this work was done, to the Oak Ridge National Laboratories who analysed the pipe test equipment and to the U.S. Bureau of Standards who guided us to the heat flow meters.

REFERENCES

1 R. H. Heilman, quoted in J. F. Malloy, Thermal Insulation, van Nostrand Reinhold, New York, 1969, p. 42.

2 Stefan-Boltzmann, Quoted in J. F. Malloy, Thermal Insulation, van Nostrand Reinhold, New York, 1969, p. 43.