TECHNICAL SOLUTIONS

TS101

Temperature Errors Due to Transmission Losses

The series of articles examines the possible causes of temperature error when using an infrared brightness thermometer. The following article treats the optical transmission path as the only significant source of error. Another article focused on target emissivity as the source of error; additional articles will examine hot backgrounds and unavoidable error sources built into the instrument itself. It is important to note that all error components must be summed in order to find the total error of a system.

IMPORTANCE OF THE TRANSMISSION PATH

An infrared brightness thermometer determines an object's temperature by quantitatively measuring its radiance. In order to do this, it is very important that the instrument have a constant and predictable view of its target. Under ideal conditions, this would be insured by simply filling the field of view with the target; the amount of radiant energy received at the detector would be completely determined by the target's temperature. In reality, however, some radiation is lost in the "transmission path" between the emitting surface and the detector. If this loss is significant, the brightness thermometer detects less radiation than it should and indicates too low a temperature.

These transmission losses are caused by objects, particles, and even gas molecules which lie within the optical transmission path, as illustrated in Fig. 1. The intervening materials absorb, reflect, or "scatter" some of the emitted radiation before it reaches the detector within the sensing head. The losses increase with longer path lengths, yet the instrument cannot be placed too close to a hot target or it can overheat and be permanently damaged. It is possible, however, to minimize some transmission problems. For instance, instruments can be designed to avoid particular wavelength bands that are absorbed in the transmission path. Water vapor and CO_2, which are the primary atmospheric absorbers in the near infrared, have little effect on IRCON's infrared brightness thermometers.

AVOIDING TRANSMISSION ERRORS

Serious and unnecessary transmission losses can often be prevented with the proper care, installation, and use of a brightness thermometer. The lens within the instrument and any windows used must be kept clean of dirt, oil and other evaporated buildup. The unit must also be focused and/or aligned so that its transmission path is clear of all solid, opaque objects. It is equally important that any windows or sight holes are made large enough that no part of the "cone of vision" is cut off.

Procedures for cleaning the optical components are for sighting the instrument are included in the manual and can be supplemented by consulting The IRCON Technical Service Department. In some applications, transmission problems can be avoided simply: a target may be viewed from below if smoke rises up from its upper surface.

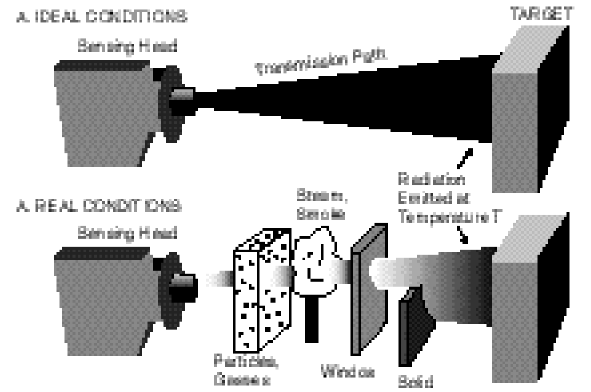

Fig. 1 – Materials in transmission path reduce radiation entering sensing head.

COMPENSATING FOR LOSS

In cases where the transmission losses are known, it is possible to compensate for them. Just as an emissivity (ε) value of 1.0 represents a perfect radiator, a transmission (τ) value of 1.0 represents a completely transparant material or path. When some radiation is lost, the transmission has a lower (fractional) value. When the radiation is completely blocked off, of course, the transmission is zero.

True temperature readings are possible only if the signal voltages are at the calibrated levels obtained when viewing an ideal (blackbody) radiator. Figure 2 shows that when ε_{TARGET} and τ_{PATH} are less than perfect, both factors contribute to losses in the detected radiant energy. These losses may simply be looked upon as an effective emissivity value (ε_{EFF}), since the source of the loss makes no difference to the instrument. Therefore the emissivity dial can be set to compensate for the total loss. The signal voltages produced by the detector are correctly amplified to blackbody levels when the dial is set to the value

$$\varepsilon_{EFF} = \varepsilon_{\substack{TARGET\\TRUE}} \times \tau_{\substack{PATH\\TRUE}} \qquad (1)$$

Example: If a window is the only object in the transmission path that causes a significant loss, $\tau_{PATH} = \tau_{WINDOW}$. If $\varepsilon_{TARGET} =$ 0.80 and $\tau_{WINDOW} = 0.85$, the emissivity dial should be set to 0.80 x 0.85 = 0.68

ERROR CALCULATION

If there is an error in the transmission value used to determine the dial setting, there is also an error in the indicated temperature. (It is assumed in this article that the target's true emissivity value is always known and correctly taken into account.) The magnitude of this temperature error varies with both the target's temperature and the instrument's spectral region. Tables 1 and 2 show representative temperature error values that result from a 1% transmission error. The effect of larger errors may be calculated by multiplying the percentage of transmission error* times the effect of a 1% error as follows:

$$\Delta T = 100 \times \left[\frac{\varepsilon_{EFF} - \varepsilon_{DIAL}}{\varepsilon_{EFF}}\right] \times \Delta T_{TABLE} \qquad (2)$$

where ε_{EFF} is given by equation (1). This formula may be used with reasonable accuracy for transmission errors up to 40%.

See figure 3 for summary of symbols.

TRANSMISSION THROUGH WINDOWS

Whereas most transmission losses vary with changing environmental conditions, the transmission loss caused by a window remains constant (as long as it is kept clean, stationary, etc.). Because of this, windows afford the most straightforward example for calculating the effects of transmission errors. The errors can arise from uncertainty in the transmission value or from the very common mistake of neglecting the effect of the window entirely. It is also important to realize that the transmission of a window material is not the same for all wavelengths.

Example 1

IGNORING THE EFFECT OF A WINDOW

Some silicon wafers are enclosed in the quartz bell jar of an epitaxial reactor. For successful processing, the wafers must be heated to a temperature of 1800°F. A Modline 3, 3W series thermometer is used to monitor the temperature of the wafers, which have an emissivity of .66. In order to do this, however, the instrument must view through the bell jar, which has a transmission 0f .94 at 0.9µ. How is the indicated temperature affected if the operator forgets to compensate for transmission losses and corrects for target emissivity only?

Answer: From equation (2),

$$\Delta T = 100 \times \left[\frac{\varepsilon_{EFF} - \varepsilon_{DIAL}}{\varepsilon_{EFF}}\right] \times \Delta T_{TABLE}$$

In this case, $\varepsilon_{EFF} = \varepsilon_{TARGET} \times \tau_{WINDOW} = .66 \times .94 = .62$

$\varepsilon_{DIAL} = \varepsilon_{TARGET} = .66$

$\Delta T_{TABLE} = 1.8$

so

$$\Delta T = 100 \times \left[\frac{.62 - .66}{.62}\right] \times 1.8 = -12°F$$

The indicated temperature is 12°F lower than the true temperature.

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*The percentage of transmission errors is the same as the percentage of dial setting error when the target's true emissivity value is know.

Fig. 3. Summary of Symbols used in this article.

SYMBOL	DEFINITION
T_{IND}	Target Temperature Indicated by Instrument
T_{TRUE}	True Target Temperature
ΔT	Indicated Temperature Error: $T_{IND} - T_{TRUE}$
ΔT_{TABLE}	Error Value in °F from Tables 1F and 1C
ε_{DIAL}	Actual Emissivity Setting on Instrument
$\varepsilon_{TARGET,\,TRUE}$	True Target Emissivity
$\tau_{PATH,\,TRUE}$	True Path Transmission

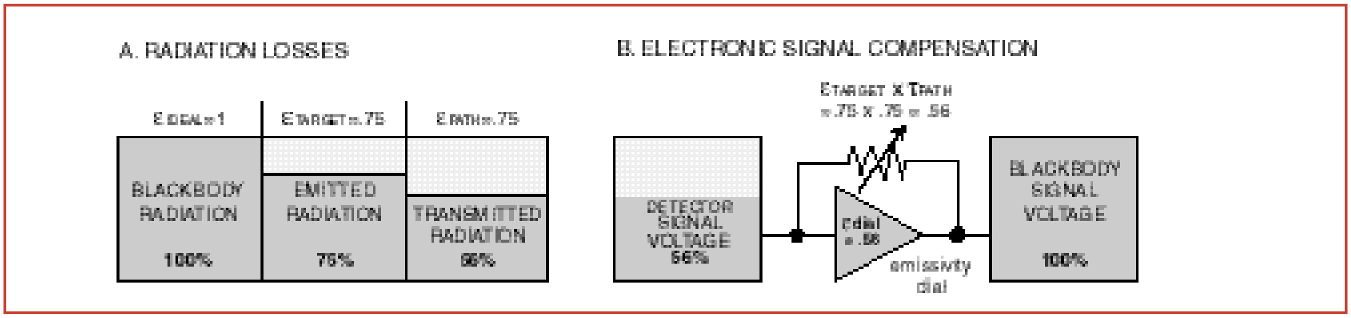

Fig. 2 – An infrared brightness thermometer can compensate for radiation losses (A) if the emissivity dial is set to the proper value (B).

Notice from Tables 1 and 2 that the ΔT_{TABLE} values become larger with increasing temperature. Thus the temperature error in the above example would be worse if the process temperature were increased.

VARIABLE TRANSMISSION ERRORS

Example II

STEAM INTERFERENCE

A steel strip in a rolling mill has a temperature of 1680°F as it exits the final finishing stand. A Modline 3, 200 series thermometer with an emissivity dial setting of .82, the emissivity of the steel, indicates the correct temperature when the process begins. Gradually, water from nearby cooling sprays starts to evaporate off the hot steel and generate steam. A recorder connected to the Modline 3, 200 series unit begins charting a series of jagged spikes showing temperature variations of 80°F and more as the process continues. Can the emissivity dial be set to compensate for the serious steam interference. What is the temperature error?

Answer: There is, of course, no dial setting that always produces a correct temperature indication. Continually varying amounts of steam flow through the optical path; the transmission of the path varies unpredictably and causes the instrument's chart recorder to produce a jagged tracing. Equation (2) can be solved for τ_{PATH} to find, for instance, that the transmission was 0.67 when the indicated temperature had dropped 80°F (assuming the true temperature stayed the same). Although the exact amount of error continually varies, the steam clearly has a significant effect on the indicated temperature.

MINIMIZING TRANSMISSION ERRORS

Transmission errors generally are minimized by using the shortest wavelength unit capable of measuring the temperature range of interest. Tables 1 and 2 show that the ΔT_{TABLE} error values become larger for longer wavelength units. Thus transmission losses comparable to those in the above example would result in even worse temperature errors if a longer wavelength unit were used.

TABLE 1F – ERROR TABLE °F

Brightness thermometer temperature errors caused by 1% transmission errors

IRCON SERIES	**DISAPPEARING FILAMENT***	**200, 3V, 3W M2 20 SA10 LS2X 1100**	**3G MG 30 SA16**	**600 M6 60 46 LS65**	**340 M3 43 LS3X**	**45**	**700 M7 47 LS7X**	**800 M8 48**	**M4 44 22**
EFFECTIVE WAVELENGTH	0.65µ	0.9µ	1.6µ	2.3µ	3.4µ	3.9µ	5.0µ	8.0µ	10.6µ
TARGET TEMPERATURE [°F]									
0	0.05	0.07	0.13	0.18	0.27	0.31	0.41	0.64	0.86
200	.10	.14	.27	.38	.57	.64	.85	1.3	1.7
400	.18	.25	.46	.66	.97	1.1	1.4	2.2	2.8
600	.28	.38	.70	1.0	1.5	1.7	2.2	3.3	4.1
800	.40	.55	1.0	1.4	2.1	2.3	3.1	4.5	5.6
1000	.53	.73	1.3	1.9	2.8	3.1	4.1	5.8	7.1
1200	.69	.95	1.7	2.5	3.6	4.0	5.2	7.2	8.7
1400	.87	1.2	2.2	3.1	4.5	5.0	6.4	8.8	10
1600	1.1	1.5	2.7	3.8	5.5	6.1	7.6	10	12
1800	1.3	1.8	3.2	4.5	6.5	7.2	9.0	12	14
2000	1.5	2.1	3.8	5.4	7.6	8.4	10	14	16
2200	1.8	2.5	4.5	6.2	8.8	9.7	12	15	17
2400	2.1	2.8	5.2	7.2	10	11	13	17	19
2600	2.4	3.3	5.9	8.2	11	12	15	19	21
2800	2.7	3.7	6.7	9.2	13	14	17	21	23
3000	3.0	4.2	7.5	10	14	15	18	22	25
3500	4.0	5.4	9.8	13	18	19	22	27	30
4000	5.1	6.9	12	16	21	23	27	32	34
4500	6.3	8.5	15	20	25	27	31	36	39
5000	7.6	10	18	23	30	31	36	41	44

*Discontinued, for Reference Only

SOURCE: IRCON, INC.

There are several accessories for IRCON's brightness thermometers which may be used to further minimize transmission problems. Interferences like steam and smoke are carried on turbulent air currents which occasionally allow a clear glimpse of the target. The "peak picking" option essentially latches on to these highest, "clear" readings and can greatly improve the accuracy of the indicated temperature. The "sight tube" option is useful for shielding the optical path from transmission interferences. Finally, the "air purge" option helps to prevent particles from settling on an instrument's lens.

TABLE 1C – ERROR TABLE IN °C

BRIGHTNESS THERMOMETER TEMPERATURE ERRORS CAUSED BY A 1% SHIFT IN EMISSIVITY

IRCON SERIES	DISAPPEARING FILAMENT*	200, 3V, 3W M2 20 SA10 LS2X 1100	3G MG 30 SA16	600 M6 60 46 LS65	340 M3 43 LS3X	45	700 M7 47 LS7X	800 M8 48	M4 44 22
EFFECTIVE WAVELENGTH	0.65µ	0.9µ	1.6µ	2.3µ	3.4µ	3.9µ	5.0µ	8.0µ	10.6µ
TARGET TEMPERATURE [°C]									
0	0.03	0.04	0.08	0.12	0.17	0.26	.26	0.41	0.54
100	.06	.08	.15	.22	.33	.37	.49	.76	1.0
200	.10	.14	.25	.36	.53	.60	.79	1.2	1.6
300	.15	.20	.37	.53	.78	.87	1.2	1.7	2.2
400	.20	.28	.51	.73	1.1	1.2	1.6	2.3	2.9
500	.27	.37	.68	.96	1.4	1.6	2.1	3.0	3.6
600	.35	.47	.87	1.2	1.8	2.0	2.6	3.7	4.4
700	.43	.59	1.1	1.5	2.2	2.5	3.2	4.4	5.2
800	.52	.72	1.3	1.8	2.7	3.0	3.8	5.2	6.1
900	.63	.86	1.6	2.2	3.2	3.5	4.4	6.0	7.0
1000	.74	1.0	1.8	2.6	3.7	4.1	5.1	6.8	7.8
1100	.86	1.2	2.2	3.0	4.3	4.7	5.8	7.6	8.7
1200	.99	1.4	2.5	3.4	4.9	5.4	6.6	8.5	9.6
1300	1.1	1.6	2.8	3.9	5.5	6.0	7.3	9.3	11
1400	1.3	1.8	3.2	4.4	6.1	6.7	8.1	10	11
1500	1.4	2.0	3.6	4.9	6.8	7.4	8.9	11	12
1600	1.6	2.2	4.0	5.5	7.5	8.1	9.6	12	13
1800	2.0	2.7	4.8	6.5	8.9	9.6	11	14	15
2000	2.4	3.2	5.8	7.7	10	11	13	16	17
2200	2.8	3.8	6.8	9.0	12	13	15	18	19
2400	3.3	4.5	7.8	10	13	14	16	19	21
2600	3.8	5.1	9.0	12	15	16	18	21	23
2800	4.3	5.9	10	13	17	18	20	23	25
3000	4.9	6.6	11	15	18	20	22	25	27

* Discontinued for reference only

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