Originally appeared in:
June 2016, pgs 65-68.
Used with permission.
HYDROCARBON PROCESSING®

M. DAHER and **O. J. SMITH IV**,
Air Products, Allentown, Pennsylvania

Pyrometer temperature measurement corrections ensure reliable reformer operation

Steam methane reforming (SMR) is the leading industrial process for the production of hydrogen (H_2). The heart of this process is the reformer, where steam and natural gas react in catalyst-filled reformer tubes located inside a furnace. An important operating parameter that must be monitored during this process is the tube wall temperatures (TWTs) of the reformer tubes.

In general, as the furnace operating temperature increases and the TWTs increase, the process operates more efficiently. However, because tube life is inversely proportional to TWT, optimal operation requires a balance between the efficiency benefits of high-temperature operation and the potential negative aspects on tube life and mechanical integrity.

Central to achieving this balance is accurate measurement of TWTs. The industry-standard method for determining tube temperatures is radiation thermometry. However, this method suffers from inherent errors due to geometric view factors and reflected radiation.

Here, errors in measuring TWTs are analyzed, and examples are presented to illustrate the importance of correcting for these errors to obtain accurate TWT measurements. Ultimately, this helps ensure the safety, efficiency and reliability of the SMR process.

TWT measurement. Methods for measuring TWTs generally fall into two categories: contact methods and non-contact methods. In contact methods, such as gold cup and surface thermocouples, the measuring device contacts the tube surface. These contact methods[1] are characterized by a number of practical issues that have prevented their widespread adoption in operating plants.

With non-contact methods, such as radiation thermometry, the measuring device does not contact the tube surface. Due to its ease of use and practicality, radiation thermometry with optical pyrometers has been the industry-standard technique for many years. However, because it is a non-contact method, radiation thermometry has a number of inherent errors due to its reliance on measuring temperature through radiance signals.

Optical pyrometer inaccuracies. Optical pyrometers function by sensing incoming infrared radiation and converting it to a temperature. Optical pyrometers, although practical, have many sources of error that must be considered to establish a high level of confidence in their measurement.

A comprehensive overview of these errors is given by Saunders,[2] who categorizes the errors into two groups: those associated with the instrument itself and those related to the target and its surroundings. It was determined that the most important errors for industrial applications are related to the target and its surroundings. In particular, the largest errors come from the emissivity of the target surface and the reflected radiation originating from its surroundings.

The infrared signal received by the pyrometer from the tube wall is a summation of the radiation emitted by the tube and the radiation reflected off the tube that originated from other surrounding objects. Since the pyrometer cannot differentiate between these sources, the resulting temperature measurement has errors that depend on the ratio of emitted radiation to reflected radiation.

Reflected radiation can be characterized by an object's emissivity and incident angle, which is the angle formed between the line of sight and the measured body. For example, a black body object has no reflection and, therefore, has an emissivity of 1, whereas reformer tubes have been found to have an average emissivity of approximately 0.85 when measured with an incident angle of 90°. The emissivity of the body generally becomes smaller as the incident angle is reduced.

For an average reformer tube measured at a 90° incident angle, 85% of the radiant signal received by the pyrometer is emitted by the tube, and the other 15% has been reflected by the tube and originated from surrounding objects. If the surrounding objects are at the same temperature as the tube, then the pyrometer does not need to differentiate between the sources, and there would be no error in the measurement.

However, in a reformer, the tubes are usually the coldest objects, with the walls, floor and ceiling measuring as much as 400°F to 500°F higher. Therefore, errors due to reflected radiation would make the pyrometer report a higher temperature than the actual value.

The effects of the reflected radiation can be accurately accounted for if the surrounding bodies' temperatures are known, as given by Saunders in Eq. 1:

$$S(T_m) = \varepsilon S(T_S) + (1 - \varepsilon) S(T_w) \qquad (1)$$

In Eq. 1, $S(T_m)$, $S(Ts)$ and $S(T_w)$ are the radiant signals corresponding to the measured temperature, true tube temperature and effective background temperatures, respectively, and ε is the tube emissivity.

Therefore, Eq. 1 can be used to determine the true tube temperature from the measured temperature and the effective background temperature. The effective background temperature is equal to the weighted average of the temperatures of all of the surrounding objects that can be seen by the tube at that location. For a given reformer geometry, the contributions from each of the i objects to the effective background temperature can be found from Eq. 2:

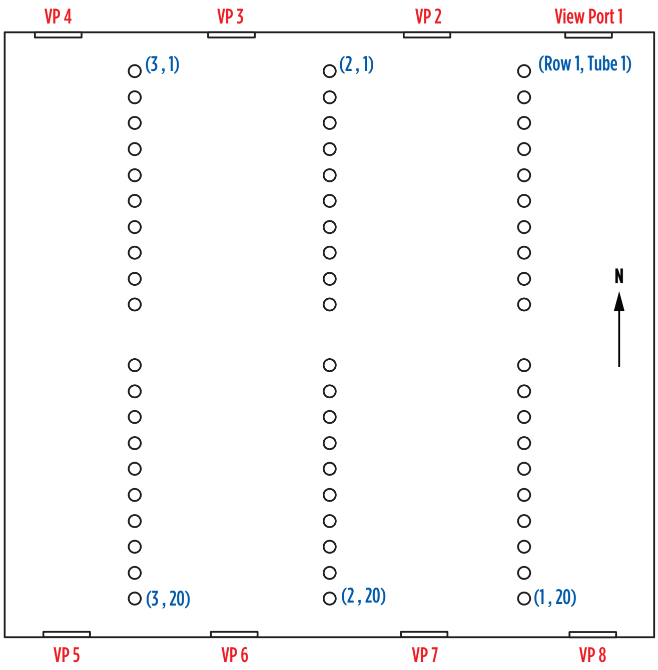

FIG. 1. Generic box reformer configuration.

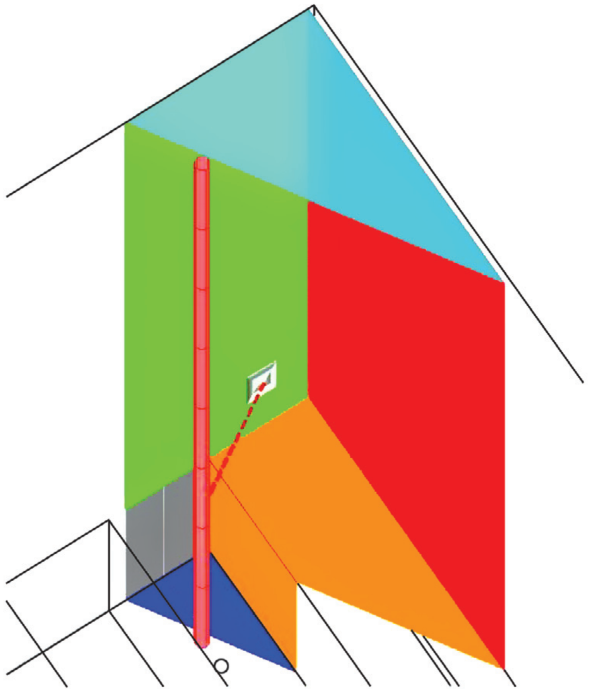

FIG. 2. Surfaces seen by R1T1 from a point viewed through VP1.

$$S(T_w) = \sum_{i=1}^{N} g_i S(T_i) \tag{2}$$

In Eq. 2, T_i is the temperature of the ith object, and g_i is the geometric view factor to the measured spot on the tube.

The geometric view factor represents the portion of the radiation that leaves object i and strikes the tube. View factors can be calculated by performing a surface integral over all of the surfaces surrounding the tube, and can be written as shown in Eq. 3:[3]

$$g_i = \frac{1}{\pi} \int\int_{A_i} Cos\ \theta_{in} \frac{dA}{r^2} \tag{3}$$

In Eq. 3, A_i is the area of surface i, θ_{in} is the angle between the surface and the normal distance to the tube, and r is the distance between the measured tube and the surface. If the geometry of the reformer is known, then this surface integral can be calculated via numerical integration across each individual surface.

These equations are well known and can be applied in a straightforward manner; however, application to reformer furnaces is challenging due to the large number of surfaces that arise from the reformer's complicated geometry.

These complications are illustrated here through a series of solved example cases, which also serve to illustrate the magnitude of the correction factors and how they vary significantly within a typical reformer furnace.

Temperature correction examples. The examples that follow were performed for a reformer with box geometry. A generic configuration is given in **FIG. 1.** This design consists of a rectangular layout with alternating rows of tubes and burners. View ports that can be opened and used for pyrometer measurements are located between each row of tubes and on the ends. For these examples, it was assumed that the pyrometer measurements were taken on the tubes at the same height as the view ports.

FIG. 2 shows an example where the temperature of the first tube in Row 1 (R1T1) is measured from View Port 1 (VP1). For this example, the spot measured on the tube is only exposed to hot wall, floor and ceiling surfaces; it is not exposed to other tubes. In **FIG. 2,** the six surfaces that are seen by the tube at the spot where it is being measured from VP1 have each been colored as shown in **TABLE 1.**

TABLE 1. Color schemes for six surfaces seen from the tube spot measuring position

Color	Location
Green	North wall
Red	East wall
Turquoise	Ceiling
Dark blue	Floor
Orange	Tunnel ceiling and wall
Grey	Tunnel end wall

To obtain an accurate tube temperature:

1. The geometric view factors to the measured spot on the tube are computed by integrating Eq. 3 across each surface individually. As long as each tube is always measured at the same spot and from the same view port, this analysis will be based on furnace geometry alone and can be completed before any temperature measurements are taken.
2. The temperatures of each of these surfaces and that of the tube are measured with the pyrometer.
3. Eqs. 1 and 2 are used to determine the true tube temperature.

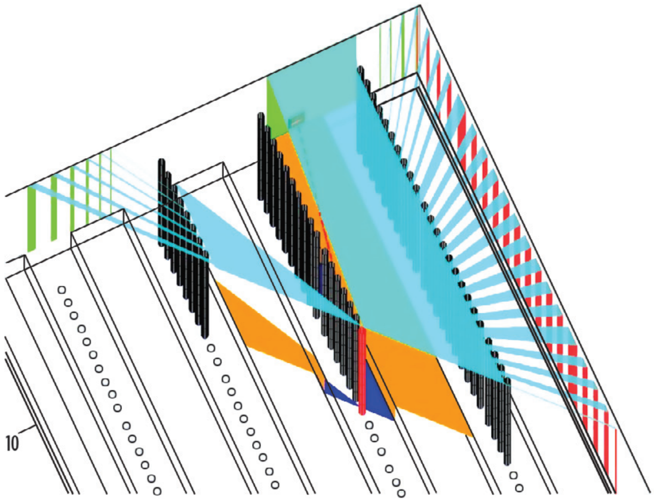

FIG. 3. Surfaces seen by R2T17 from a point viewed through VP2.

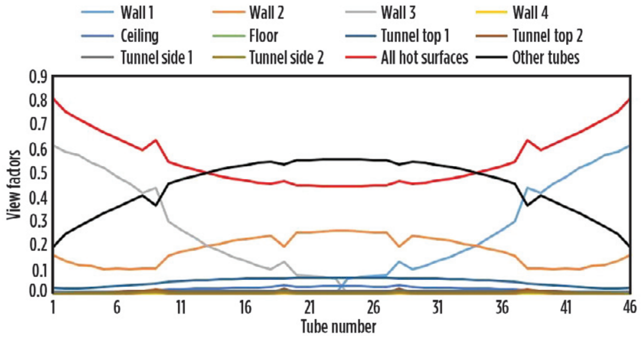

FIG. 4. View factors across a row of tubes.

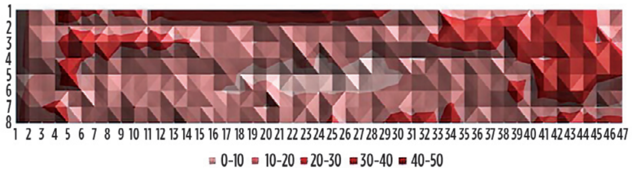

FIG. 5. Temperature correction for full reformer.

Software has been developed to automatically perform this temperature correction procedure for more than 25 world-scale SMR plants. At each facility, a standardized sequence is developed for all of the pyrometer measurements, including the tube and surrounding objects. These measurements automatically populate a spreadsheet for which all the geometric view factors have been predetermined. The temperature correction calculations are then performed. The resulting corrected temperatures are used to both monitor and further optimize the reformer operation.

The number of individual surfaces that a reformer tube can see increases very quickly as tubes on the inner rows are analyzed. Tubes on the inner rows now also see other tubes, and those other tubes serve to block the view of the tube to each of the previously considered surfaces, thereby dividing each surface into many sub-surfaces. **FIG. 3** represents such an example, where R2T17 is viewed from VP2. The different surfaces are colored the same as in **FIG. 2,** but now over 62 sub-surfaces are defined that must be individually integrated using Eq. 3. The true tube temperatures can then be calculated from the surface temperatures and from Eqs. 1 and 2.

When comparing the examples in **FIGS. 2** and **3,** it becomes clear that the view factors can vary significantly depending on where a tube is located in the reformer, as well as from which view port the pyrometer measurements are taken. In **FIG. 2,** the tube does not see any other tubes, but rather only hot surfaces. In **FIG. 3,** the tube sees more tubes and fewer hot surfaces. This has a direct impact on the size of the correction for each tube. Those tubes that see more hot surfaces will have a larger correction than a tube that sees fewer hot surfaces.

To further illustrate this point, **FIG. 4** gives the individual view factors for a number of surfaces for all of the tubes in one reformer row. The sum of the individual view factors for all of the hot surfaces, such as walls, floors, tunnel walls and ceilings, is shown in red and varies by 50% to 80% across the row. This variation can cause a significant difference in the correction calculated for each tube, with the corrections for the tubes on the end of the row being larger than for those in the center.

Magnitude of corrections.

To better quantify the magnitude of these corrections, a map showing the corrections calculated for an entire reformer comprised of eight rows with 47 tubes per row is given in **FIG. 5.** The corrections were found to vary significantly throughout the reformer, with the largest corrections being between 40°F and 50°F. This surprisingly wide variation must be considered to obtain accurate tube temperature measurements so that efficient and reliable reformer operation can be achieved.

All of the preceding examples considered the case when the pyrometer temperatures were measured at the same horizontal height as the view ports. To assess how the view factors change along the length of the tube, pyrometer measurements were taken in the field by angling the pyrometer up and down from the view ports. The angles and locations were noted, and these were used in the calculation procedure.

This analysis also found that the corrections varied widely along the length of a tube. In general, the biggest correction is calculated at the top of the tube where the tube is the coldest and exposed to more of the very hot ceiling. The smallest

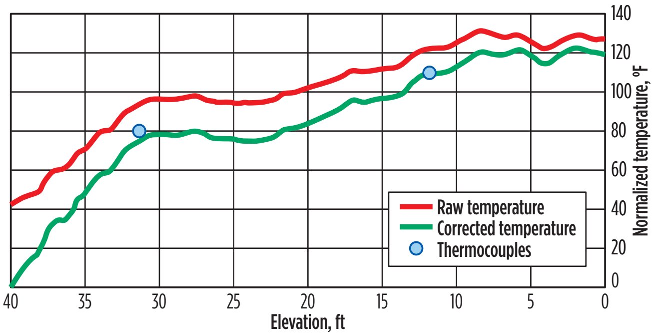

FIG. 6. Full tube raw and corrected temperature profiles.

correction is found to be very close to the bottom, just above the top of the flue gas exit tunnel.

FIG. 6 plots the normalized raw and corrected tube temperature every few inches for the entire length of a tube. The temperatures were normalized by subtracting the lowest corrected tube temperature from all of the measurements. The difference in the two curves gives the magnitude of the corrections. The corrections range from about 10°F at the bottom of the tube to over 40°F at the top of the tube.

Also included in this plot are two surface thermocouples that were mounted on this tube. It can be seen that the thermocouples are more in agreement with the corrected temperatures vs. the raw data. Therefore, these corrections are of a magnitude that must be considered when accurate temperatures are needed.

Recommendations. Accurate measurement of the TWTs in reformers is important to ensure safety and increase reliability and efficiency of the SMR operation. The industry standard technique of optical pyrometry suffers from inherent errors, the largest of which is the reflected radiation from surrounding surfaces. This error was shown to be as large as 50°F and highly dependent on a number of factors, including where the tube is located, which view port it is measured from, and its elevation in the reformer.

These corrections must be considered when accurate tube temperatures are needed, as well as to enable a better reformer balance and determination of remaining tube life. Procedures have been developed to more easily make corrections to optical pyrometer measurements and to use the corrected temperatures to both monitor current operation and improve the operational efficiency and reliability of reformer furnaces. HP

LITERATURE CITED

[1] Smith O. J. and B. Cotton, "Reformer monitoring via in-tube temperature measurement," *Petroleum Technology Quarterly,* Q2 2014.

[2] Saunders P., *Radiation Thermometry: Fundamentals and Applications in the Petrochemical Industry,* SPIE Press, Bellingham, Washington, 2007.

[3] Saunders P. and D. R. White, "A model for reflection errors in radiation thermometry: Application to tube misalignment in reformer furnaces," Proc. TEMPMEKO 1996, Torino, Italy, 1997.

MAJD DAHER is an advanced process controls engineer in the hydrogen and syngas business at Air Products. He has developed tools and processes to capture and correct reformer temperatures across the Air Products global fleet. Most recently, he has developed and implemented model predictive control applications for the optimization of hydrogen plants. Mr. Daher holds a BS degree in chemical engineering from the Pennsylvania State University.

OLIVER J. SMITH IV is the global operations excellence lead for the hydrogen and syngas business at Air Products, where he has 25 years of experience in the industrial gas business. He has authored more than six patents and numerous journal articles in the areas of process optimization and asset utilization. Dr. Smith holds a BChe degree from the University of Delaware and a PhD in chemical engineering from Carnegie Mellon University.

For more information please contact Air Products at 1-610-481-4861