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TUBE-WALL TEMPERATURE MEASUREMENT IN FIRED PROCESS HEATERS

Materials Technology Institute of the Chemical Process Industries, Inc.

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TUBE-WALL TEMPERATURE MEASUREMENT

IN

FIRED PROCESS HEATERS

by

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SUMMARY

The central problem is that of measuring tube-wall surface temperature in direct fired process heaters under production conditions. Two methods are examined: thermocouples directly contacting the tube and radiation thermometers. The goal of the study is to assess current practices and to formulate recommendations for further development of the measurement technology.

Thermocouple installations are thought to be unreliable for extended operation because of the rapid drift in the calibration and deterioration of protective materials in the furnace gas atmosphere. Radiation thermometers are widely used in plants with beneficial results when attention is given to proper/frequent calibration procedures and to the effects of in-furnace conditions -- tube emissivity, reflected irradiance, and furnace gas emission/absorption -- on the indicated radiation thermometer readings. Through a radiation analysis and a series of field experiments, the effects of in-furnace conditions are demonstrated. To provide further background on the problem, an extensive literature search was performed and the information summarized.

The study leads to the conclusion that absolute measurement accuracies of $\pm 10^{o}C$ ($\pm 18^{o}F$) at $950^{o}C$ ($1750^{o}F$) are possible only if corrections for in-furnace conditions can be estimated. However, at present, only a few plants are capable of routinely obtaining reproducibilities (precision) of $\pm 10^{o}C$ ($\pm 18^{o}F$) which can be achieved by well-prescribed calibration procedures, good operator technique, and systematic data analysis including, in some instances, correlative models employing other furnace parameters.

Recommendations to develop the technology are offered. Educational activities at the engineering level need improvement in order to gain a better understanding of the principles of measurement methods, to train operating personnel and to define operating procedures. Investigative studies are called for to generate new information on radiation thermometry practices. Also, similar studies on improved thermocouple technology are warranted. The industry will greatly benefit by dissemination of data and measurement technology through participation in national technical society meetings.

PREFACE

This project was supported by the Materials Technology Institute of the Chemical Process Industries, Inc. under the direction of the Task Group headed by Mr. D.G. Damin, Engineering Department, ESD - Gulf Regional Office, DuPont Company, (previously with the Gulf Research and Development Company). The work was performed during the period January 1, 1983 to May 30, 1985. The authors wish to acknowledge with thanks the numerous persons who generously gave of their time and energy to provide information on activities relating to temperature measurement. Clearly the interest in the central problem is shared by a very large segment of the chemical process industries and is deserving of the national attention brought about by the conduct of this study. Drs. DeWitt and Albright are professors with the Schools of Mechanical and Chemical Engineering, respectively, Purdue University, West Lafayette, IN 47907.

NOMENCLATURE

c_1	First radiation constant
c_2	Second radiation constant, 14,388 μm.K
c_3	Third radiation constant, 2898 μm.K
F	View or configuration factor
L_λ	Spectral radiance, $W \cdot m^{-2} \mu m^{-1} \cdot sr^{-1}$
T	Temperature, K or ^{o}C
T_λ	Spectral radiance or apparent temperature, K or ^{o}C
ε	Emissivity

Subscripts

b	Blackbody conditions
f	Flame
ref	Reflected
s	Surface condition
sur	Surroundings
t	Tube, target
w	Wall
λ	Spectral concentration; spectral quantity

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1. INTRODUCTION AND BACKGROUND ON THE PROBLEM

The central problem is that of measuring tube-wall surface temperatures in direct-fired process heaters under production conditions. The goals of the study are two fold: (1) to provide an assessment of current practices and capabilities for temperature measurement and (2) to formulate recommendations for further development and improvement of the measurement technology.

It is widely recognized that operation of furnace tubes above their creep-rupture design temperatures results in diminished lifetimes and increases the prospects for tube failures. Tube life decreases rapidly with increased temperature at higher temperatures. Jaske, Simonen, and Roach [1]* give an example for typical steam reformer tubes operating at about 500 psi and 871 ^{o}C (1600 ^{o}F) mean tube wall temperature. A 28 ^{o}C (50 ^{o}F) rise in tube temperature resulted in about a 40% reduction in tube life for modified HP alloys and about 55% reduction for HK-40 alloys. Even more pronounced reductions in tube life can occur with greater temperatuie increases.

In addition, productivity or yield of desired product is often adversely affected by temperatures only slightly greater or less than design temperatures. Heiman [2] reports that for a 1.0 billion pound/year ethylene plant using naphtha feedstock, the annual loss would be about $1.5 million/year with a 10 ^{o}C deviation of the desired temperature at the coil outlet. Such a loss is caused by less than desired conversion of the feedstock at temperatures that are 10 ^{o}C too low and by overcracking and increased coke formation at

* The number in brackets designates a literature citation listed in Section 11 of the report.

temperatures 10 °C too high. Large uncertainties in the tube surface temperature measurement are unacceptable if the process is to be operated under nearly optimized conditions with any degree of confidence.

Two measurement technologies are commonly employed: the contact method using thermocouples and the non-contact method employing radiation thermometers (optical and infrared pyrometers). The concerns of this study are the industrial practices of these methods and whether their technologies can be refined or extended to achieve improved measurement accuracies from typical values of 14 to 28 °C (25 to 50 °F) to 3 to 6 °C (5 to 10 °F).

This temperature measurement problem is not a new one. Under the sponsorship of several chemical process firms, Battelle performed a study [3] in the early 1970's with objectives very similar to the present study. In a sense, the present study will determine the level of progress in this area within the last twelve or so years.

As background to the current problem, it is appropriate to review the specific objectives and conclusions of the Battelle study [3]. That study was undertaken because most catalyst tube failures in steam reformers were thought to be caused by creep rupture resulting from overheating and that overheating occurred because of inadequate surface temperature measurement methods. Information on temperature-measurement equipment, practices and procedures were obtained by Battelle using questionnaires and plant visits. The major conclusions of their study were:

- Temperature-measurement accuracy of ±14 °C (25 °F) can be obtained using current (1972) instrumentation and proper operator practices.

- Improvements in accuracy to ±8 °C (15 °F) are possible if the conditions within furnaces (such as tube emissivity, reflected flux and combustion product effects) could be better understood.

- Inadequate training of personnel in the plants and poor understanding of techniques was a major factor in regard to inaccurate temperature measurements. The lack of adequate training was attributed by Battelle to questionable technical and management decisions. Technical personnel had failed to obtain the information that indicated the need for better measurements. Management personnel had frequently failed to provide the leadership or support required to improve the situation.

- In addition to numerous suggestions toward improved techniques using radiation thermometers (such as the need for blackbody references, periodic calibration checks, etc.), the major suggestions of the Battelle study for future technical development included the following:

  - use of an in-furnace target probe with a calibrated thermocouple to assess how furnace conditions affect indicated readings obtained by radiation thermometry.

  - installation of surface thermocouples on tubes selected to be representative of furnace conditions and then use of the surfaces adjacent to the thermocouples as targets for the radiation thermometer,

  - use of infrared photography to provide a means of observing spatial variations along the length of furnace tubes,

- inference of tube surface temperatures from models, using as input, process variables such as feedstock inlet/outlet temperatures, flow rates, combustion firing rate and product composition, etc.

- the measurement of the spectral variation (rather than just at a single wavelength) of radiant flux and correlation of such information with other furnace conditions, especially firing conditions.

Further detail on some of these conclusions and recommendations are presented in subsequent sections of the present report.

In order to put the Battelle report in proper perspective, it is useful to have some understanding of the state of radiation thermometry instrumentation as of that time. Nutter [4,5] provides a survey of radiation thermometry technology as of 1970. Since that time, the major advances in the field, relevant to the scope of the study, are as follows:

- the development of very stable silicon photodiode-based radiation thermometers for operation in the visible and near infrared (0.6 to 0.9 μm)

- improved opto-electronic components (detectors and amplifiers) permitting the construction of reliable radiation thermometers operating at almost any spectral or band condition desired from 0.6 to 14 μm; thermometers can now be operated under narrow spectral band conditions as opposed to the broad (or total) band conditions of the past,

- digital circuitry is now available permitting reliable and convenient direct readout of indicated temperatures,

- electronic means for adjustment of target emissivity have become more commonplace, (unfortunately, there are no simple ways to measure directly the emissivity values to be used),

- smart radiation thermometers with microprocessors permit more accurate indication of temperatures (improved algorithms relating detector signal and temperature) and greater consideration of other variables (such as dual wavelength operation, temperature of a furnace wall, etc.) in providing the indicated temperature.

It is important to recognize that these are instrumental-type developments. Later in the review of the technical literature, a summary will be provided of developments that relate to the specific application of in-furnace tube measurements.

Having provided some background on the problem in terms of a previous study and instrumentation developments, the scope and organization of this report follows. In Section 2 of this report, the objectives and organization of the present study are outlined. A technical discussion on the central problem follows in Section 3 as related to radiation thermometers, with detailed treatment of the three major in-furnace effects: tube emissivity, reflected flux and combustion products. To gain further insight into temperature measurement technologies relevant to the central problem, a literature search was performed and is summarized in Section 4. Following this, sections dealing with industrial practices using thermocouples, radiation thermometers and infrared scanners are included (Sections 5, 6 and 7).

The results of a field experiment on an oil-fired process heater conducted using four radiation thermometers with different spectral band-passes are summarized in Section 8 and presented in greater detail in Appendix B. Section 9 presents a summary and assessment of the technology followed by the final section offering specific recommendations for improvement of the temperature-measurement technology.

2. OBJECTIVES AND ORGANIZATION OF THE STUDY

The present study considers three major objectives.

- State-of-the-Art Assessment. The objective was to provide an analytical and critical review of the current measurement technology with commercially available equipment. Four tasks were addressed: collection of information on methods and instrumentation by means of plant visits and discussions with manufacturers; thorough review of the relevant scientific and technical literature; analysis and synthesis of collected information; and preparation of a critical review. Appendix A identifies the contacts made during the course of the study.

- Guide for Recommended Practice. The objective was to provide a guide for the field practitioner that will describe procedures for selecting and using commercial instrumentation for various applications. The procedures for estimating the accuracy of temperature measurements for various plant conditions is discussed. The Guide included in this report as Appendix C is written to be used independently of the report.

- Recommendations for Development of the Technology. Drawing from the critical review summarizing the state-of-the art assessment, the critical problems central to improvement of the measurement technology are identified. Two approaches were taken. First, consideration was given to improved experimental or operational procedures (better use of instruments, improved calibrations, etc.) that will provide improved accuracy. Second, consideration was given to those areas where studies of some depth are required to generate better understanding of the basic thermal and chemical phenomena at or near the tube wall.

3. THE MEASUREMENT PROBLEM

The general conclusion of the present study is that radiation thermometers are very promising for most temperature measurements of surfaces in high-temperature systems. Key advantages of radiation thermometers relative to thermocouples attached to the solid surfaces are as follows:

- The conditions at or near the surfaces are unaffected by the radiation thermometers, whereas thermocouples attached to the surface always have some effect, especially for very high-heat flux surfaces, that change the temperature at the point of contact between the thermocouple and the surface.

- A radiation thermometer can be used to make measurements at a large number of locations on the tube or in the furnace, whereas a thermocouple can make measurements at only one location.

As is discussed in detail later, when a better understanding is