Applied Thermal Engineering 125 (2017) 702–713

Contents lists available at ScienceDirect

Applied Thermal Engineering

journal homepage: www.elsevier.com/locate/apthermeng

Research Paper

Standards for fired heater design: Analysis of two dominant heat flux variation factors

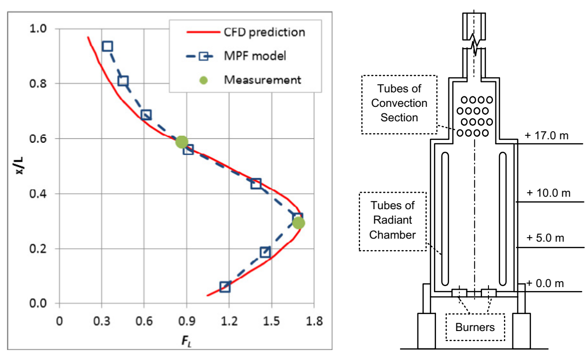
Jiří Hájek *, Zdeněk Jegla

Brno University of Technology, Faculty of Mechanical Engineering, Institute of Process and Environmental Engineering, Technická 2, 616 69 Brno, Czech Republic

HIGHLIGHTS

- Evidence is provided that fired heater design standards need correction.
- Longitudinal heat flux variability is analysed experimentally and computationally.
- Tube circumferential heat flux variability is systematically analysed.
- Impact of tube deformations on heat flux variability is evaluated.
- Impact of tube alignment in coils with changing diameter is evaluated.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 22 December 2016
Revised 5 May 2017
Accepted 8 July 2017
Available online 10 July 2017

Keywords:
Fired heater
Radiant zone
Heat flux
Surface-to-surface radiation model

ABSTRACT

Many fired heaters in all parts of the globe are designed according to long-standing standards of the American Petroleum Institute. The relevant API standard 560 is to a large degree based on heat flux non-uniformity factors that have been first graphed early in the 20th century using idealised 2D calculations of radiative heat transfer. The basic set of assumptions and values for these factors has recently been challenged, as they neglect or underestimate several significant aspects of nonuniformity including longitudinal heat flux variation due to up-to-date low-NO_x burners, interaction of flames from multiple burners, Coandă effect and non-ideal geometry.

This paper brings new data and quantified corrections of two dominant heat flux variation factors (tube circumferential factor and longitudinal factor) that are based on numerical modelling, large-scale laboratory measurements and real-life data from operating fired heater. The new information provides evidence that standardised design calculations of fired heaters for refinery service need urgent update and revision, mainly concerning the longitudinal factor. The results show that real-life heat flux distribution can be significantly less uniform than estimated by traditional design techniques (such as API Design Standards).

1. Introduction

Tubular furnaces (also called fired heaters) are key units mainly in refineries. They are typically the last element in the process of heating up crude before it enters the distillation column (following process heat exchangers). They provide heat by combustion of various fuels. The processed stream is heated to a level required by a key processing unit of the production technology, which is mostly a distillation column or reactor.

Most contemporary installations of fired heaters belong to one of two prevalent basic types, cabin (also called shaft or box type) and cylindrical (always vertical). Cabin type furnaces are used for high thermal duties, whereas cylindrical furnaces are preferred

* Corresponding author.
E-mail address: hajek@fme.vutbr.cz (J. Hájek).

http://dx.doi.org/10.1016/j.applthermaleng.2017.07.062
1359-4311/

Nomenclature

Symbol	Description (Unit)
d	tube diameter (m)
D	diameter of a cylindrical furnace (radiant section in fired heater) (m)
F_C	tube circumferential heat flux variability global factor, Eq. (3) (–)
$F_{C,local}$	tube circumferential heat flux variability local factor, Eq. (2) (–)
F_L	furnace longitudinal heat flux variability factor (–)
F_T	tube metal temperature heat flux variability factor (–)
F_{jk}	fraction of energy leaving surface j incident on surface k (view factor) (–)
L	length of furnace (along the flame) (m)
q	local (point) radiant heat flux (W/m^2)
q_m	local-maximum radiant heat flux (W/m^2)
q_r	average radiant heat flux (to the tube coil) in a furnace (W/m^2)
q_{rc}	average convection heat flux (to the tube coil) in a furnace (W/m^2)
q_{tube}	average heat flux on a single tube (W/m^2)
$q_{scenario}$	average heat flux on all tubes in a single scenario (W/m^2)
Q_r	radiant heat duty of a furnace (W)
Q_{tube}	radiant heat duty of a single tube (W)
$Q_{scenario}$	radiant heat duty of all tubes in a model representing furnace (W)
W	width of a cabin type furnace (distance of main walls) (m)
x	length-wise coordinate in a furnace (along the flame) (m)

for lower thermal duties. In spite of apparent similarity, each unit is custom-made and tailored for maximum compatibility with the specific process.

Each of these furnace types consists of two main parts – combustion chamber (radiant zone) and convective part (convective zone). Process medium flows inside of a tubular system, which forms the heat exchanger. By changing the shape and configuration of tubes in radiant and convective zone, multiple heater design types are formed that satisfy specific demands and conditions of concrete process.

The design practice of fired heaters is based on long-standing standards, among which prominent are the standards of the American Petroleum Institute (API), namely standard 530 [1] and 560 [2]. It is important to note that the design calculation methodology described by these standards is almost a century old [3] and is based on a few correlations that are deeply rooted in the engineering practice [4]. At the core of the design calculation methodology are correlations drawn historically using simplified 2D radiation models (see e.g. [1]).

Our previous analysis [5] led to the conclusion that the prevailing classical fired heater design methodology significantly underestimates the heat flux variability occurring in fired heaters which has significant consequences for fouling, safety and the lifespan of heaters. A correction to the standard methodology was recommended accounting for the types of variability observed in detailed 3D model predictions. It was however also concluded that more detailed analysis of the individual variability factors is necessary to quantify with more confidence each of the factors.

Advanced modelling results have been reported in recent years with broad range of modelling capabilities, e.g. in [6] detailed combustion chemistry, in [7] NO_x emission prediction, in [8] coupled simulation of flue gas and process side, in [9] coking rates in tubes, in [10] another coupled simulation in a naphtha cracking furnace, etc. These achievements demonstrated the current capabilities of detailed, coupled, 3D modelling that can provide much insight into the operation of fired heaters. However, none of these results have been translated into the terms and conditions applied in fired heater design.

The API standards indicate that tube circumferential heat flux variability factor is responsible for most of the heat flux nonuniformity on tube surface. In contrast to that, our previous results indicate [5] that longitudinal factor and a newly identified "furnace circumference" factor are of comparable importance and that the real heat flux variability may significantly exceed the estimate provided by standard design calculations. In this work we add a systematic analysis of the tube circumferential factor in configurations that are not covered by the standards, but are often encountered in practice. The previous results [5] indicated a certain correlation of tube coil deformations with changes in heat loading, but in combination with other phenomena. Thus here we provide an independent analysis of tube coil imperfections.

The API standards also indicate that longitudinal heat flux variability (along the flame) is moderate, compared to the tube circumferential variability. In this work we provide multiple measured evidences that the longitudinal heat flux variability may easily reach comparable level to the tube circumference and contribute to overall heat flux variability in a fired heater much more significantly than previously expected.

All results in this work are interpreted in terms of the standard design calculation methodology to facilitate meaningful interpretation by furnace designers. Consequently, it is necessary to provide in the beginning a brief introduction of the standard design practices. In the results chapter, evidence is provided on how flame shape, tube coil deformations and tube coil arrangement with changing tube diameter influence heat flux uniformity. The findings indicate that continuation of the strict adherence to standard design practices in this specific industry [11] may lead to unnecessary operating problems including significant fouling propensity and wear of the tube coil.

2. Fired heater design and operational issues

The design calculation of fired heaters is based on a single equation, which we have to briefly introduce in order to define terminology that will enable us to translate our results into the language of the furnace designers. After that, configurations investigated in this work are described and related to the issues faced in design and operation of fired heaters.

2.1. Design calculation according to API standards

Fired heaters for refinery applications are generally designed for an average radiant heat flux (q_r), which is one of the most important design parameters. The typical way to obtain the average radiant heat flux is to first calculate the radiant heat duty (Q_r) of the new fired heater (from the required total heat duty). A method of obtaining Q_r is not part of API standards, but there are several well-established 1D quasi-theoretical calculation techniques, e.g. [12]. These are based on global design parameters of the fired heater and its tube coil, like tube spacing and outer tube diameter d.