Applied Energy 102 (2013) 755–764

Contents lists available at SciVerse ScienceDirect

Applied Energy

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

Identification of the influence of fouling on the heat recovery in a network of shell and tube heat exchangers

Mariusz Markowski, Marian Trafczynski *, Krzysztof Urbaniec

Department of Process Equipment, Plock Campus of Warsaw University of Technology, 2/4 Jachowicza, 09-402 Plock, Poland

HIGHLIGHTS

- ▶ Heat recovery in a heat exchanger network (HEN).
- ▶ Method of identification of the influence of fouling on the heat recovery.
- ▶ Details are developed for shell and tube heat exchangers.
- ▶ Developed approach allows long-term monitoring of changes in the HEN efficiency.

ARTICLE INFO

Article history:
Received 29 May 2012
Received in revised form 6 August 2012
Accepted 19 August 2012
Available online 17 September 2012

Keywords:
Energy saving
Fouling identification
Heat exchanger fouling
Heat exchanger network
Heat recovery
Shell and tube heat exchanger

ABSTRACT

The aim of this work is to elaborate a method of identification of the influence of fouling on the heat recovery in a heat exchanger network (HEN). The method is based on mathematical models enabling the interpretation of industrial measurements of operating parameters of the HEN. Details of the models are developed for shell and tube heat exchangers. The crucial assumption is that measurements of the mass flowrate and inlet and outlet temperature, and chemical composition are available for each process stream, this making it possible to evaluate fouling-induced reduction in the recovered energy flow. Using the proposed identification method and an industrial data base acquired in a typical crude distillation unit, the mathematical models are thoroughly tested. The developed approach allows long-term monitoring of changes in the condition of the HEN and assisting plant operator decisions aimed at maximizing heat recovery over the period of plant operation. A case study and an example of optimal scheduling of cleaning interventions on the individual exchangers are presented.

1. Introduction

In order to minimize the energy consumption in a process plant equipped with a heat exchanger network (HEN), the plant operator needs to know how to avoid the reduction of heat recovery over the period of plant operation. In various branches of the chemical industry, fouling which builds up on heat transfer surfaces is a chronic operation problem which necessitates installing oversized heat transfer equipment, burning extra fuel to compensate for reduced heat recovery, accepting the reduction of plant output due to periodic equipment cleaning and covering the costs of cleaning interventions. In the oil refining industry alone, the resulting economic losses are estimated at 0.25% of the combined GNP of countries involved, and the associated consumption of extra fuel significantly contributes to the over-all emission of carbon dioxide and other greenhouse gases.

The detrimental effects of fouling in the industrial HENs can be partly prevented by goal-oriented choice of heat exchanger type and parameters, and network structure and parameters [1–3] but from the practical point of view, most important are fouling mitigation measures, like mechanical or chemical cleaning for use during HEN operation [4]. In case of degraded thermal performance, specific heat exchangers may be temporarily taken out of operation and cleaned on an ad hoc basis but a common approach assumes cleaning of heat transfer surfaces in the framework of periodic plant overhauls only.

Various approaches to the mitigation of fouling effects in industrial HENs were reported in recent years. Markowski and Urbaniec [5] proposed a procedure for cost-optimal scheduling of cleaning operations based on the predictions of fouling build-up in the individual exchangers. Krueger and Pouponnot [6] reported various applications of tube inserts for both fouling mitigation and heat transfer enhancement. Rodriguez and Smith [7] proposed an approach based on the recognition that operating variables, such as wall temperature and flow velocity, may have a significant effect on fouling deposition rate in a heat exchanger; the optimization

* Corresponding author. Tel.: +48 24 262 26 10; fax: +48 24 262 65 42.
E-mail address: mariant@poczta.fm (M. Trafczynski).

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http://dx.doi.org/10.1016/j.apenergy.2012.08.038

Nomenclature

a, b, o, C	constants in the empirical equation for Nusselt number
A	average area of the heat transfer surface (m^2)
c_p	specific heat (J/(kg K))
$C1$, $C2$	constants in the equations for surface film conductances (W/(m^2 K))
dA	differential of the area of heat transfer surface (m^2)
D_1	internal tube diameter (m)
D_2	external tube diameter (m)
f_t	coefficient of correction of the mean temperature difference
h	surface film conductance (W/(m^2 K))
l	distance between baffles (cell width) (m)
$\dot{M}$	mass flowrate (kg/s)
n_b	number of tubes in one exchanger pass
Pr	Prandtl number
Pr_w	Prandtl number calculated at wall temperature
$\dot{Q}$	thermal power (W)
Re	Reynolds number
R_f	total thermal resistance of deposits (fouling) (m^2 K/W)
R_w	thermal resistance of the tube wall (m^2 K/W)
T	temperature (K)
U	coefficient of heat transfer (W/(m^2 K))
U_c	coefficient of heat transfer in the clean exchanger (W/(m^2 K))
U_f	coefficient of heat transfer in the exchanger with fouling (W/(m^2 K))
δT	temperature increment (K)
ΔT	local temperature difference (K)
ΔT_M	effective mean temperature difference in the heat exchanger (K)
ΔT_{LM}	logarithmic mean temperature difference in the heat exchanger (K)

Indices

(j, k)	j-th heat exchanger pass, k-th channel between baffles
i	i-th time interval or data set, or inlet
o	outlet
s	shell side
t	tube side
w	relating to tube wall

of operating conditions can be combined with the optimal management of cleaning actions in a comprehensive mitigation strategy for the entire HEN. Ishiyama et al. [8] developed a simulation tool incorporating the impact of fouling on the heat transfer in, and throughput of preheat trains. The tool can be used for techno-economic analysis of the performance and optimization of cleaning operations for the preheat trains subject to fouling. Ishiyama et al. [9] and Pogiatzis et al. [10] considered fouling build-up as the combination of deposition and ageing phenomena. They introduced a two-layer (aged "coke" and fresh "gel") model of fouling resistance and used a simplified heat exchanger model to identify optimal cleaning cycles, possibly using both chemical and mechanical cleaning, for a single exchanger. Aiming at the development of strategies to mitigate fouling, Yang and Crittenden [11] considered a single heat exchanger and used CFD simulation package COMSOL to predict flow conditions for fouling initiation both in bare tubes and tubes fitted with inserts.

Both industrial practice [12] and results of recent research [13] prove that the applications of simulation models and optimization procedures to HEN operation are truly successful only if sufficient and accurate information on the build-up of fouling in, and its influence on the performance of, the HEN is continuously available. It is a prerequisite for fully exploring the cost-saving potential of optimal scheduling of cleaning interventions in the individual exchangers, as well as for reliably evaluating the effectiveness of other fouling mitigation measures if applied.

An early attempt to establish continuous monitoring of fouling build-up was presented by Jerónimo et al. [14]. Owing to the use of simplified mathematical models, HEN performance could only be analysed qualitatively. Rodera et al. [15] considered a methodological framework for the improvement in HEN operation including automatic analysis of output variables when the operating conditions change and the analysis of the trends follow by these variables during a given time period. Liporace and Oliveira [16] presented the results of application of a software tool to evaluate, on a real-time basis, the performance of a preheat train including fouling factors in the individual exchangers. Negrao et al. [17] proposed a procedure in which the values of heat exchanger effectiveness are predicted using classical literature relations as a function of NTU and capacity ratio R (continuously adjusted according to mass flowrate changes), and compared with values calculated from temperature measurements. An index of fouling is defined for the whole network, and the series of index values derived from consecutive temperature measurements shows the performance degradation of the network with time. Waters et al. [18] reported their experience with a fouling monitoring program which calculates the fouling factors for each exchanger on a preheat train from daily plant data. The fouling trend so determined shows the fouling behavior of individual exchangers and makes it possible to simulate network performance and find out which exchangers will offer the largest benefit if cleaned.

A weak point of most mathematical models and procedures presented in the above cited publications is that heat transfer coefficients are calculated using empirical equations of the form:

$$Nu = C \cdot Re^a \cdot Pr^b \cdot (Pr_t/Pr_{tw})^o \quad (1)$$

where Nu, Re and Pr are Nusselt, Reynolds and Prandtl numbers; C, a, b and o are constants, and Pr_w is Prandtl number calculated at wall temperature.

As the uncertainty margins in the calculated coefficient values may be as large as ±20%, their use in modelling or simulation of heat exchanger operation negatively affects the reliability of results. While this does not preclude qualitative evaluation of trends in fouling deposition rate or exchanger performance degradation, quantitative estimates like those of economically optimal cleaning cycles may be brought into question.

The objectives of the present work are following:

- to develop a robust procedure for continuous and reliable monitoring of the build-up of fouling in a HEN comprising shell and tube exchangers,
- to minimize the uncertainty margin in the determination of heat transfer coefficients and fouling factors in the individual exchangers thus determining the total recovered heat flow with the uncertainty margin sufficiently narrow to enable cost-optimization of cleaning cycles for exchangers in the HEN.

The main novelty in the developed procedure is that the constants in empirical equations for the calculation of heat transfer coefficients are adjusted according to the measurements of operation parameters. It has been observed that for a given set of measured operation parameters, the proposed method yields time