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On-line Control of the Heat Exchanger Network under Industrial Constraints

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It is commonly known that the aim of the heat exchanger network (HEN) is maximization of heat recovery. Unfortunately, heat recovery is deteriorated by deposits mounting up on the heat transfer surface of the heat exchangers. Moreover, the process parameters (temperature, mass flow, etc.) are changing with time that also are influencing on heat recovery. Hence, to maximize heat recovery in real HEN, the authors proposed a mathematical model of on-line control of HEN. Unfortunately, the existing mathematical models of the heat exchanger are inaccurate because heat transfer coefficients are calculated with errors at values ranging from 10 to 40 %. To overcome this issue, the authors introduced a very accurate mathematical model of the heat exchanger. The model is based on industrial measurements of the process stream parameters. These parameters are used for on-line validation of the heat exchanger model. For the validated model, the results of calculation are very accurate, for the errors of calculations are less than 1 %. In this article, the proposed model is applied to HEN in Crude Distillation Unit (CDU), processing 800 t/h of crude oil. In proposed on-line model, the manipulated variables are mass flows of crude oil passing via several branches of the HEN. The results of the HEN simulation show that on-line control of the mass flow through several branches of the HEN gives an opportunity to 1.5 % increase of the total heat recovery.

1. Introduction

In industrial plants, most process media can form deposits on internal surfaces of process equipment units. The layer of a deposit which builds up on heat transfer surfaces deteriorates operation of the plant and leads to economic losses. In the chemical industry, this is the real operation problem which leads to reduction of plant output and heat recovery in HEN.
There are several methods that can be applied in industrial application aiming at reduction of detrimental effects of fouling in the HEN, for example:

- design methods aiming at selection of suitable network structure, heat exchanger type and parameters (Ravagnani and Caballero, 2007),
- on-line cleaning methods: chemical (application of antifoulants) (Müller-Steinhagen, 2000) or mechanical (application of tube inserts) (Krueger and Pouponnot, 2005),
- off-line cleaning methods: mechanical or chemical (Müller-Steinhagen, 2000),
- on-line diagnosis of HEN (Liporace and Oliveira, 2005),
- on-line cleaning methods of HEN using optimal cleaning schedule (Markowski and Urbaniec, 2005).

In industry, the common practice is mechanical cleaning of heat transfer surfaces in the framework of plant maintenance. In case of serious deterioration of thermal performance, a heat exchanger may also be temporarily taken out of operation and cleaned at a very short period of time. Most advanced and very profitable methods, that is, on-line HEN cleaning and control are applied rarely. When applying the advanced method of HEN control, it is necessary to monitor the state of HEN very precisely. Unfortunately, it is very difficult to predict a fouling resistance of deposits. Namely, the existing correlations describing heat transfer coefficients in the shell and tube heat exchangers are inaccurate because they are calculated with errors at values ranging from 10 to 40 % (Ullmann's Encyclopedia, 1988). A similar situation takes place with accurate prediction of the fouling resistance of deposits. Here, there are sophisticated models of fouling growth applied. Ishiyama et al. (2011) described

fouling as a phenomenon of deposition and ageing combination. Pogiatzis et al. (2012) introduced a two-layer model of fouling resistances. Yang and Crittenden (2012) used CFD method to predict heat transfer under fouling in bare tubes and tubes fitted with inserts.
To overcome these negative constraints, the author elaborated a mathematical model of the heat exchanger under fouling, based on industrial measurements of the process stream parameters. These measurements are used for upgrading the correlations describing the heat transfer coefficients by adjusting the values of constant, that is, power exponents for Reynolds and Prandtl number, etc.
For the proposed method the heat exchanger model is very accurate for the errors of calculations are less than 1 %. Thus, it is possible to apply this model for on-line control of HEN aiming at more efficient heat recovery.

2. Processing of the measurement data

In order to make validation of the heat exchanger model the required process data, obtained from measurements, include mass flow on shell side (m_{si}) and tube side (m_{ti}) of the heat exchanger, inlet/outlet temperature on shell side (T_{si}/T_{so}) and tube side (T_{ti}/T_{to}) of the heat exchanger (Figure 1).

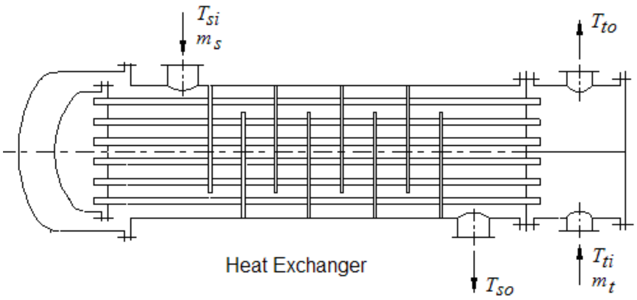

Figure 1: Required set of process data aiming at on-line control of the HEN (Markowski et al., 2013)

However, measured process data (raw data) contains errors caused by inaccurate instruments, disturbances in data transmission, transient state of the operated HEN. Therefore, raw data cannot be directly used for upgrading the correlations describing the heat transfer coefficients and finally for determination of fouling resistances. To overcome this problem at the beginning, all the data should be pre-processed by filtering aiming at the elimination of gross errors. After that measured data should be averaged over the properly selected time intervals to make the application of steady-state model of the heat exchanger possible. Finally, data reconciliation should be carried out to minimize the uncertainty caused by the limited accuracy of measurements and the bias due to application of steady-state modeling.

3. Modeling of the heat exchanger basing on measurements

As it is commonly known, heat transfer in a heat exchanger can be calculated from the following equation:

$$Q = \int U_f \cdot \Delta T \cdot dA \quad (1)$$

where: Q – heat flow, U_f – overall heat transfer coefficient, ΔT – temperature difference, dA – differential of the area of heat transfer surface.
The overall heat transfer coefficient can be expressed as:

$$U_f = \frac{1}{\frac{1}{h_t} + \frac{1}{h_s} + R_f} \quad (2)$$

where: ht and hs - heat transfer coefficient on the tube and shell side, respectively, Rf – fouling resistance of deposits.
Commonly, the heat transfer coefficient is a function of Reynolds number Re and Prandtl number Pr.
For example, this coefficient can be determined using an empirical equation of the form:

$$h=A \cdot Re^{b} \cdot Pr^{e} \cdot (Pr/Pr_w)^{n} \quad (3)$$

Commonly, the constants *A, b, n,* and *e* are determined on the base of literature, but the obtained value of heat transfer coefficient is inaccurate. The correlation expressed by Eq(3) can be corrected by adjusting new values of constant *A, b, n, e* using the measurement data for heat exchanger in clean condition (R_f=0). Assuming that the heat exchanger was cleaned from fouling during the maintenance time, these measurement data (for clean condition) can be collected at the beginning of run time operation of exchanger.
The algorithm of adjusting new values of constant *A, b, n, e* is as follows. The inlet temperature (T_{ti} and T_{si}), mass flow (m_t and m_s) and outlet temperature (T_{to} and T_{so}) are known from measurements. Consequently, using Eqs(1-3), it is possible to calculate the outlet temperature from the model (T_{tm} and T_{sm}). The numerical values of constants *A, b, n and e* are determined by minimization of the objective function defined as the sum, over the entire data pool (j=1..N), of squares of errors in the outlet temperature:

$$FC = \sum_{j=1}^{N} \left[(T_{tm(j)} - T_{to(j)})^2 + (T_{sm(j)} - T_{so(j)})^2 \right] \rightarrow \min \qquad (4)$$

After upgrading heat transfer correlations, the numerical calculation of fouling resistance R_f takes place, for the assumed interval of time (for example every week). For this purpose, Eqs(1-4) are used.
The above approach makes it possible to upgrade the empirical correlation (Eq(3)) and after that calculate the fouling resistances R_f and the results of modeling of the heat exchanger are more accurate. For example, using Eq(1) and Eq(2) and upgraded correlation (Eq(3)), the theoretically assumed curve 1 comparing with the numerically reproduced curve 2 is in good agreement in variation of the thermal resistance of fouling (Figure 2).

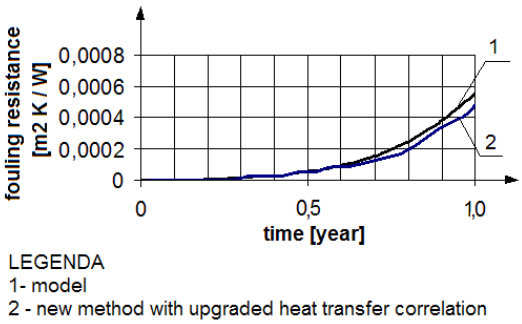

Figure 2: Theoretically assumed (curve 1) and numerically reproduced (curve 2) variation of the thermal resistance of fouling in time for heat exchanger No. 11 from Figure 5 (Markowski et al., 2013)

4. The mathematical model of HEN control

The heat interactions between 1...*n* hot process streams and *n*+1..*m* cold process streams can be described by the following formulae (Figure 3):
Heat balance between *i*-th hot stream and *k*-th cold stream in the *jl*-th heat exchanger:
- the decrement of enthalpy flow for *i*-th hot process stream

$$\Delta H_{Hij} = - \int_{T_{ij}}^{T_{ij+1}} m_i \cdot c_{Hi} \cdot dT \qquad (5)$$

- the increment of enthalpy flow for *k*-th cold process stream

$$\Delta H_{Ckl} = \int_{T_{kl}}^{T_{kl+1}} m_k \cdot c_{Ck} \cdot dT \qquad (6)$$

- the heat flow for *jl*-th heat exchanger

$$Q_{jl} = \Delta H_{Hij} = \Delta H_{Ckl} \qquad (7)$$

- the matrix of matching between process streams
δ_{ijkl} = 1 for heat interaction between *i*-th hot stream and *k*-th cold stream in the *jl*-th heat exchanger
δ_{ijkl} = 0 for the case that interaction does not exist
The aim of HEN control is maximization of heat recovery. Thus, the objective function is defined as the sum of heat recovered Q_w in each w-th heat exchanger:

$$\mathrm{OF} = \sum_{w=1}^{z} Q_w \tag{8}$$

The decision variables are mass flows through the branches of the splited stream (m_p, m_{p+1},…. m_{p+g} in Figure 4). The process control system of HEN is shown in Figure 4. The process control procedure is as follows. For the assumed interval of time, there is prepared data base of measurements. It is used for validation of the HEN model (upgrading heat transfer correlations after starting up (clean conditions, $Rf = 0$); calculation of fouling resistances for the assumed interval of time). In the next step a numerical simulation takes place aiming at maximization of the objective function OF. Obtained in this way the decisive variables (m_p, m_{p+1},…. m_{p+g}) are adjusted by the process control system. After that the procedure is repeated.

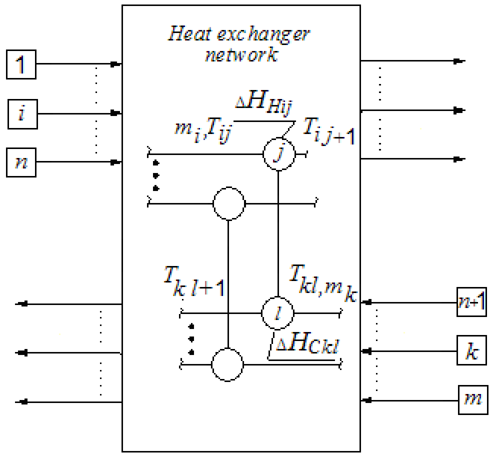

Figure 3: Scheme of interaction between process streams in HEN

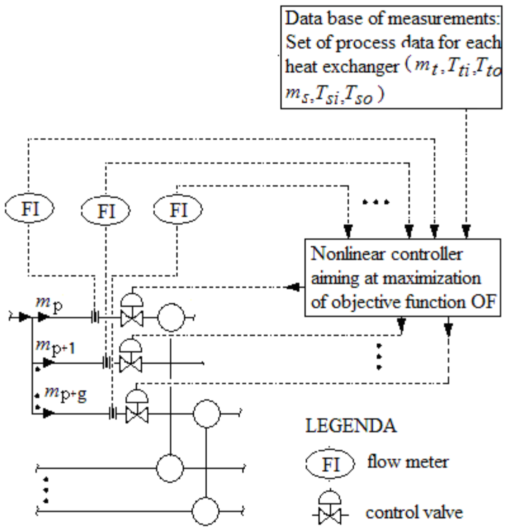

Figure 4: Scheme of the nonlinear process control system for HEN

5. Example of HEN control on the case of Crude Distillation Unit

The process control procedure is applied to HEN shown in Figure 5. This HEN belongs to Crude Distillation Unit, processing 780 t/h of crude oil. HEN is composed of 20 hot and 6 cold process streams (pairs of streams (23, 24) and (25, 26) have its origin from splitting crude oil) which are connected by shell and tube heat exchangers. In Figure 5 there are shown only heat exchangers which serve for heat recovery. The average values of process parameters (temperature, heat flows) are shown in Figure 5.

For HEN shown in Figure 5, the proposed procedure for on-line control was used. The selected results of numerical simulation are shown in Figures 6 and 7.

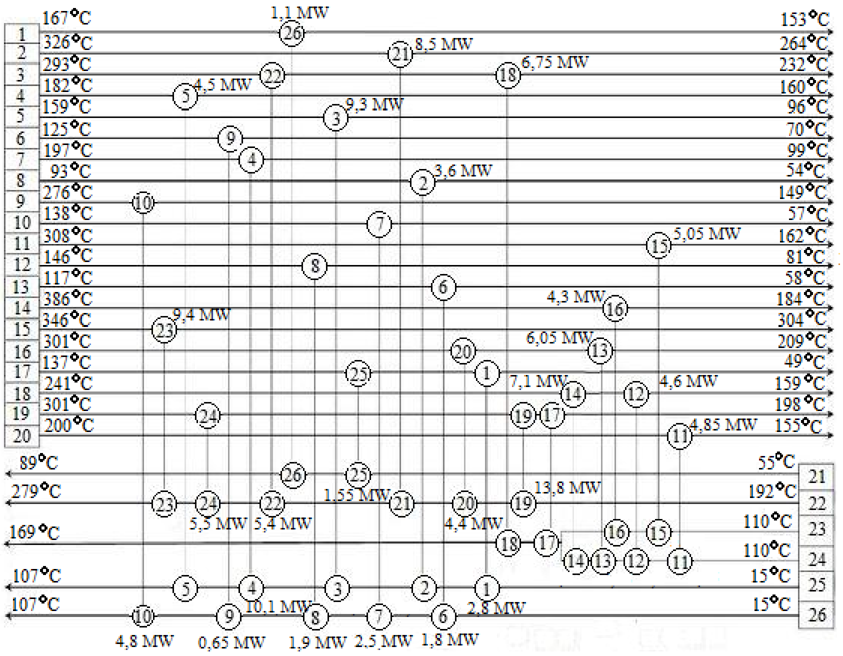

Figure 5: Scheme of HEN for Crude Distillation Unit

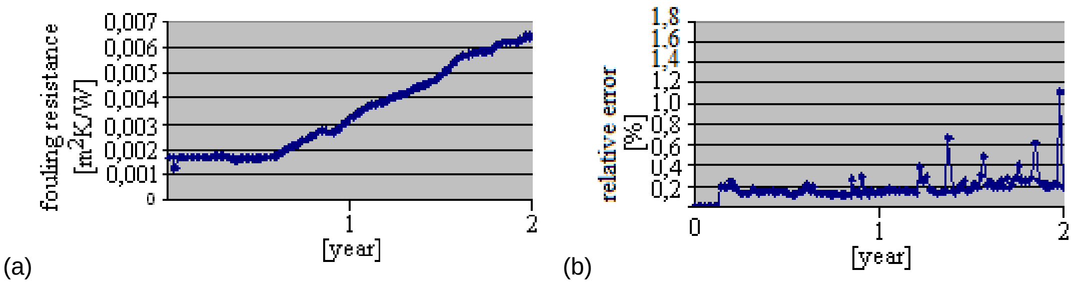

Figure 6: Characteristics of the heat exchanger No. 3 from Figure 5; a) the fouling resistance, b) the relative errors in outlet temperature

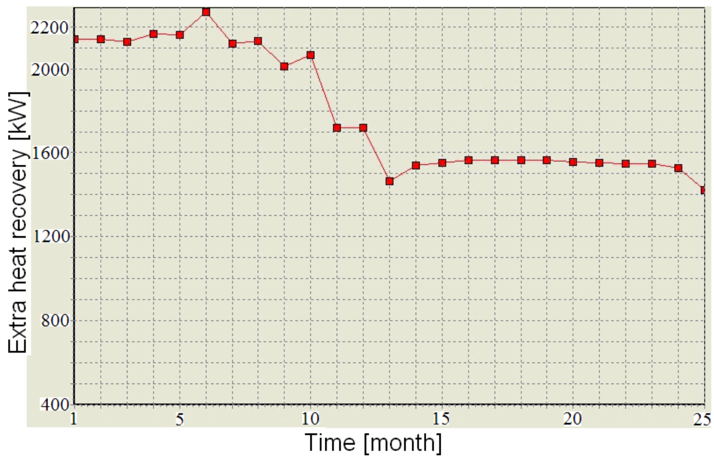

Figure 7: Influence of the process control system on variation of the heat recovery gain

6. Conclusions

As it can be seen in Figure 7, an application of the proposed process control system brings measurable savings in total heat recovery (increase of heat recovery by 1.4 – 2.3 MW). The results of numerical simulation show that on-line control of HEN gives opportunity to 1.5 % increase of total heat recovery. Because the margin of savings is low (1 - 2 %) the mathematical model of HEN must be very accurate. It imposes an employment of sophisticated models which must be validated on the base of on-line industrial measurements.

Symbols

A, b, n, e – coefficients in the empirical equation for heat transfer coefficient
A – area of the heat transfer surface [m^2]
c_H, c_C – specific heat for hot and cold process stream, respectively [J/(kg·K)]
dA – differential of the area of heat transfer surface [m^2]
dT – differential of the temperature [K]
h_t, h_s – heat transfer coefficient on the tube and shell side, respectively [W/(m^2·K)]
m_t, m_s − mass flow on the tube and shell side, respectively[kg/s]
Pr – Prandtl number
Pr_w − Prandtl number calculated at wall temperature
Q – heat flow in the heat exchanger [W]
Re – Reynolds number
R_f – thermal fouling resistance of deposits [m^2·K/W]
T – temperature [°C]
U_f – overal heat transfer coefficient in the exchanger with fouling [W/(m^2·K)]
ΔH_H, ΔH_C – the increment of enthalpy flow for hot and cold process stream, respectively [W]
ΔT – temperature difference [K]

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