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A new transient thermal fouling probe for cross flow tubular heat exchangers

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ABSTRACT

The present probe is developed in order to accurately estimate in situ not only the convective exchange coefficient but also the fouling thickness of heat exchangers from a reliable transient state estimation method.The originality of the estimation method consists in considering a global response time of the system in fouling conditions to be compared to clean conditions. The sensitivity function is then built from the experimental signal without precise knowledge about the model or the absolute thermophysical properties. The reliability of the method is demonstrated in theoretical cases and with calibrated experiments.

1. Introduction

Heat exchangers are used in numerous industrial processes. They can also be found as part of many systems in transportation and residential and tertiary applications. Most heat transfer operations involve the deposition of unwanted residues on exchange surfaces. In gaseous systems, the deposition of particulate matter constitutes the fouling. The effectiveness of heat exchangers can decrease because of this foulant deposition onto the heat transfer surface. Attempts have been made to model heat exchangers fouling. Pioneer work [6,16], essentially an asymptotic curve-fitting exercise, tends to dominate the concepts and leaves much to empirism. Marner [9] reviewed several analytical and experimental studies relating developments in gas side fouling. Other models [1–4,13,18,19] are based on deposition and removal mechanisms, but they still involve a strong empirical content.

Ever since the end of the 1970s, some gas-side fouling measuring devices have been envisaged [5,7,10–12,14,17]. All of them provide physical information on fouling. Nevertheless, they are still far from giving thermal information and taking into account the deposit phenomena involved.

Thus, although considerable work has been carried out through the years, it is clear that progresses remain to be made, more particularly to provide the basis for improved predictive methods. Currently, the various solutions, even if they are numerous and varied, are not completely satisfactory. However, they allowed to work out the main quality that a fouling probe has to present. In particular, it has to be cheap, easy to implement and it has to take into account the heat transfer and the deposit phenomena involved [20].

So, the here developed probe replaces directly a part (or the totality) of the tubular heat exchanger. This device can be described by a multilayered system where the transient temperature measurement is achieved simultaneously and at the same location as a thermal excitation. The associated data processing is developed in order to estimate the heat transfer coefficient and the particulate fouling thickness of tubular heat exchanger. Indeed, such parameters enable to determine heat exchangers fouling level.

The 3D transient heat transfer problem is modelled by an extension of the thermal quadrupole formalism. The study of the transfer function linking excitation to system temperature response allows the probe sizing and the theoretical sensitivity study establishment.

Since the probe must be used in harsh conditions, since the nominal values of the problem are not precisely known, the estimation method is directly realised from the experimental temperature responses. This method is sturdy and is based on an experimental sensitivity study. It does not require sophisticated physical considerations or complete forward model. So, two simplified transient forward models have been developed.

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Nomenclature

Latin letters

A, B, C, D	quadrupole coefficients
C_p	constant pressure specific heat (J kg^{-1} K^{-1})
L	heater half length (m)
M	quadrupole matrix
M_{-1}	-1 order moment (K)
N	acquisition points
Q	flowrate (m^3 s^{-1})
R	resistance (W^{-1} K)
S	area (m^2)
T	temperature (K)
X	sensitivity coefficient
a	thermal diffusivity (m^2 s^{-1})
b	heater width (m)
e	thickness (m)
h	convective heat transfer coefficient (W m^{-2} K^{-1})
k	Fourier coefficient
p	Laplace variable (s^{-1})
r	radial coordinate (m)
t	time (s)
x	angular coordinate (rad)
z	axial coordinate (m)

Greek letters

α_n	Fourier variable
β	parameters vector
ϕ	radial heat flux (W)
φ	heat flux produced by the heater (W)
λ	thermal conductivity (W m^{-1} K^{-1})
ρ	density (kg m^{-3})
σ^2	standard deviation
θ	Laplace transform of T
τ	characteristic time constant (s^{-1})

Symbols

–	normalized
∼	Fourier transform
*	reduced

Subscripts

c	clean
d	deposit

A testing bench has been realised in which the probe is laid to obtain experimental results in clean or in fouling conditions.

At first, the probe description is realised. Then, the different transient forward models are developed and the theoretical sensitivity analysis from the 3D forward model is presented. Lastly, experimental data in clean and in fouling conditions are detailed and the estimation method is presented and validated.

2. Probe description

The studied probe, 50 mm length, 5 mm inside radius and 13 mm outside radius, can be described by a cylindrical multilayered system (Fig. 1). Each layer is 2 mm thick. The internal and the external layers are in stainless steel to be able to come under the same thermohydraulic and fouling influences as exchangers. A copper slab (10 mm length, 2/10 mm thick) heated by Joule effect produced by a heat step, encircling the centre section of the cylinder and is inserted between two other layers. These layers are in polytetrafluoroethylene polymer (PTFE) to be able to limit heat transfer from the heater and to make insignificant the contact resistances. The power supply to the heating element is controlled through a constant-voltage transformer. The final constituted pipe is inserted between two stainless steel tubes which act as heat exchangers parts. The temperature variation along the heater is measured by several T type thermocouples implanted parallel to the cylinder axis.

3. Experimental device

The probe is inserted into a testing bench named GAZPAR (GAZ PARticles) to be both tested in clean conditions and in fouling conditions. It is a three parts system (Fig. 2). The probe is mounted in a rectangular wind tunnel with 80 × 80 mm^2 a cross section. The fluid used is air at 323 K. A flow of cool water is sent through the central stainless steel pipe to simulate real tubular heat exchangers conditions and to maintain the probe inlet surface temperature at a constant value.

The probe then acts as a foulant deposition site by simulating a heat exchanger tube in the gas stream. The primary constituents in exhaust gases causing fouling include SiO_2, Na_2SO_4, and $CaSO_4$ [16]. So, fouling tests were carried out using sodium sulfate of 4 μm medium diameter in the gas stream as foulant. The foulant particles are generated by ultrasound pulverization. Such generator achieves a particle size distribution close to monodispersion.

4. Forward models

The thermal quadrupole formalism using integral transforms methods [8] is used to model the three-dimensional transient heat transfer in the studied multilayered system. The interest of this approach lies in the fact that a linear relationship is given between the input and the output temperature and the heat flux after a double Laplace Fourier transform. The main advantage of this temperature-flux vector representation is to make the analytical modelling of multimaterials possible by multiplying the corresponding quadrupole matrices.

4.1. 3D forward model

The following case (Fig. 3) where the transient temperature measurement is achieved simultaneously and at the same location as a thermal excitation carried out by the heater is considered.

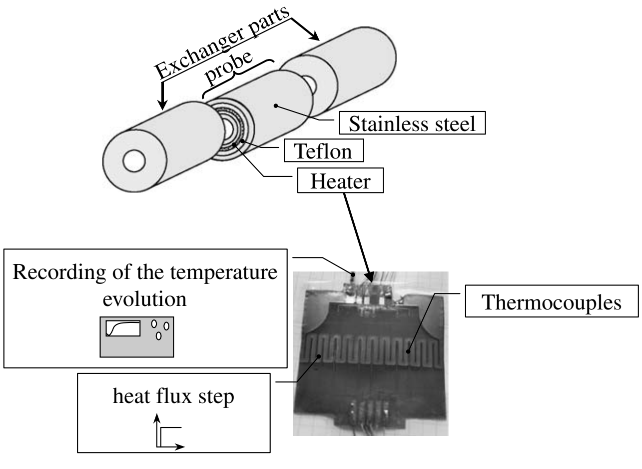

Fig. 1. Schematic diagram of heat transfer probe.