Detecting longitudinal damages in the internal coating of a tube

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A B S T R A C T

Longitudinal defects of the internal coated surface of a metal pipe can be evaluated in a fast, precise and cheap way from thermal measurements on the external surface. In this paper, we study two classes of real situations in which the thickness of the coating is much smaller than the thickness of the metal tube: the transportation of potable water and crude oil. A very precise and stable reconstruction of damages is obtained by means of perturbation methods. To do this, first we translate a composite (coating-plus-tube) boundary value problem in a virtual one on the metallic part only. The information about possible damages is now included in the deviations δh of the effective heat transfer coefficient from a known background value. Finally, we determine δh by means of Thin Plate Approximation.

1. Introduction

Internal coating of pipes is required by several applications involving the production and transportation of fluids. Such coatings protect the internal pipe surface from the effect of corrosion and erosion, and often are also used for reducing friction and turbulence in order to increase the flow efficiency. Another usage is in oil field drilling tools, were corrosion problems and paraffin deposit are very likely.

Let C be a cylindrical empty metallic tube. Suppose that the internal surface is coated with a layer made of an insulating or anyhow poorly conducting material. An orthogonal section of the tube consists of three concentric circles of radius $R - a_\epsilon, R, R + a$ such that $a_\epsilon \ll a \ll R$. The internal circle of radius $R - a_\epsilon$ bounds the empty part of the cylinder in which the fluid flows. The first layer (of thickness a_ϵ) is the section of the coating. The outer layer of larger thickness a is the section of the main metallic body of the tube.

Suppose that we are able to heat the specimen and take temperature maps of the external surface in order to check the integrity of the internal coating. This is a typical problem in Active Thermography applied to Nondestructive Evaluation (see for example [12]).

It is assumed that the fluid inside the cylinder exchanges heat with C through its inner surface following Newton's law of cooling.

A complete reference book about the classical theory of heat is [5].

A material often used for the internal coating of steel tubes is the Fusion Bonded Epoxy (FBE), whose thermal conductivity at ambient temperature is about $0.3 \, \text{W m}^{-1} \, \text{K}^{-1}$. Internal coatings having typical thickness between 250 and 1000 μm are employed in steel pipes used in the transportation of oil & gas, water and industrial and corrosive fluids. Numerical simulations of this kind of coating are described in Section 4.

Coatings are selected according to their function. A coating material can be needed to provide an inert surface, for example to maintain the water quality in a potable water transportation system. Or, it should provide adequate protection against corrosion of the metal composing the pipe, especially when chemicals are involved. In several cases, coating is necessary to provide a smooth surface in order to maintain the flow velocity. Incidentally, the internal surface of a pipe is "smooth" if its irregularities are fully submerged into the laminar film (assuming a turbulent regime), i.e. such to have no effect on the turbulent flow. The "smoothness" scale, therefore, is not an absolute number but depends on the Reynolds number. The importance of pipe smoothness is easily understood: an improvement of some percent in the flow efficiency, with respect to a bare pipe, on distances of kilometers means a sensible cost saving due to the pressure discharge.

When dealing with crude-oil pipelines, a thermally insulating coating could be useful when the fluid should be transported at a temperature significantly higher than the environmental one, for example for preventing the formation of gas hydrates, wax, asphaltenes and other unwanted products.

We know that the inner fluid could carry some solid impurities so that longitudinal damages may appear on the coating layer. This assumption suggests to study orthogonal sections of the pipe without loss of generality.

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Nomenclature

Parameters

C	cylindrical tube (pipeline)
C_a	metallic shell of the pipeline
C_ϵ	insulating shell (coating)
S	cross section of C
S_a	cross section of C_a
S_ϵ	cross section of C_ϵ
R	internal radius of S_a, m
a	thickness of S_a, m
a_ϵ	thickness of the coating S_ϵ, m
$\xi = \frac{a}{R}$	thickness-to-radius ratio
h_{int}	internal heat transfer coefficient, W m^{-2} K^{-1}
U_{int}	internal temperature, K
h_{ext}	external heat transfer coefficient, W m^{-2} K^{-1}
U_{ext}	external temperature, K
h_{eff}	effective heat transfer coefficient at $r = R$, W m^{-2} K^{-1}
δh	deviation of the effective heat transfer coefficient, W m^{-2} K^{-1}

T_{lim}	time required to reach stationary regime, s
q_a	power per unit volume dissipated in C_a, W m^{-3}
q_ϵ	power per unit volume dissipated in C_ϵ, W m^{-3}
κ_a	thermal conductivity of C_a, W m^{-1} K^{-1}
κ_ϵ	thermal conductivity of C_ϵ, W m^{-1} K^{-1}
$\tilde{\kappa} = \frac{\kappa}{R^2}$	normalized conductivity, W m^{-1} K^{-1} m^{-2}

Acronyms

BVP	Boundary Value Problem
IHCP	Inverse Heat Conduction Problem
HTC	Heat Transfer Coefficient
IP	Inverse Problem
TPA	Thin Plate Approximation
FEM	Finite Elements Method
FBE	Fusion Bonded Epoxy

Checking the integrity of the internal inaccessible layer means to detect the presence of such damages and to evaluate their size from one or more temperature maps taken on the external surface of the tube. More precisely, the cylinder is heated by means of a couple of electrodes and covered by an insulating dress. A small portion of the tube is lacking the insulating cover and exchanges heat with the external environment. In this place we observe the external temperature of the cylinder. This set up, typical of Active Thermography, is inspired by the experiment in [2].

1.1. Details of the direct model

Like in [2,8], we consider the 2D model of the section of the specimen (see Fig. 1). Heat equation (transient and stationary),
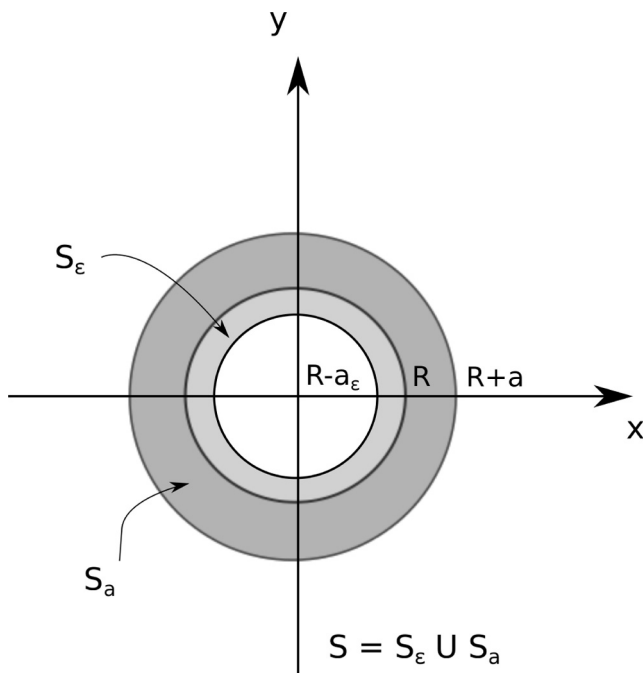

y

S_ϵ

$R-a_\epsilon$ R $R+a$

x

S_a

$S = S_\epsilon \cup S_a$

Fig. 1. Geometry of the problem.

equipped with classical boundary conditions, accounts for the physics of our ideal experiment.

Let $S = \{(r\cos(\phi), r\sin(\phi)); r \in (R - a_\epsilon(\phi), R + a); \phi \in [0, 2\pi)\}$ be the cross section of the cylindrical tube C of radii $R + a$ (external radius) and $R - a_\epsilon$ (internal one) with $a_\epsilon \ll a \ll 2\pi R$. The shell C_a of radii $R + a$ (external radius) and R (internal one) is a good thermal and electrical conductor (example: stainless steel type AISI 304 considered in [2,9]). The cylindrical coating C_ϵ of radii R (external radius) and $R - a_\epsilon$ (internal one) is usually characterized by low thermal and electrical conductivity. Thermal conductivities are κ_ϵ in C_ϵ and κ_a in C_a. The geometry and the physical characteristics of the coating depend on a quantity ϵ used to parametrize a family of thin-coated tubes (the actual meaning of ϵ will be clear in the section devoted to the limit properties of the model).

The geometry is shown in Fig. 1.

Assume that C is subjected to a constant heat generation Q_ϵ and Q_a, respectively in C_ϵ and C_a, obtained by connecting a couple of electrodes (see [2]) along the tube, separated by a distance L and having a potential difference V between them. The heating terms are readily computed by considering the resistive divider formed by the electrical resistances of the section of tube between the voltage electrodes. The resistances per unit length are inversely proportional to the surface cross sections of the metallic tube ($S_a = \pi a(2R + a)$) and of the coating ($S_\epsilon = \pi a_\epsilon(2R - a_\epsilon)$) and to their electrical conductivities (σ_a and σ_ϵ). The power dissipated by Joule effect in the metallic tube and in the coating are:

$$Q_a = \frac{V^2}{L}\sigma_a S_a$$

$$Q_\epsilon = \frac{V^2}{L}\sigma_\epsilon S_\epsilon$$

hence, the relationship between the powers q_ϵ and q_a dissipated per unit volume in the coating and in the metal is:

$$q_\epsilon = \frac{\sigma_\epsilon}{\sigma_a}q_a \qquad (1)$$

Furthermore, it is known that the temperature of the specimen reaches a reasonably stationary regime for $t \geqslant T_{lim}$ whose value is related to the diffusivity of the tube C and to the boundary conditions at its surfaces. In the Appendix we show that T_{lim} is of the order of some hundreds of seconds in the cases of interest here.

Let $\alpha_\epsilon : (0, 2\pi) \to (0, a_\epsilon)$ a function describing the internal surface of the coating.