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Detection of inner defects in industrial pipelines using transient IR thermography

Abstract

A long time operation of pipelines can lead to the reduction of their wall thickness. This process is accelerated by high temperature and variable pressure of the transported medium and can finally cause mechanical failures along with leaks and danger of explosion. The aim of this paper is to present a new method for the detection of abraded walls in industrial pipelines using the time-frequency analysis. The results of transient temperature measurements are used for the calculation of the thermal time constants corresponding - as demonstrated - to the pipeline wall thickness.

Keywords: infrared thermography, transient thermal testing, defect detection, polypropylene pipe.

1. Introduction

Industrial pipelines are used as a low-cost method of transport of various types of substances. In the last decades the number of transmission and distribution pipelines increased considerably [1], leading to an increased number of failures and rising the need for better and more accurate non-destructive methods of their detection and prevention. Even a short industrial process interruption can lead to considerable financial losses, and pose a risk to humans and the environment. A pipeline preventive maintenance or replacement program should be conducted based on detailed assessment of its technical condition. Thus, safe and non-destructive techniques are needed, which would allow for pipeline periodical inspection without, as much as possible, disturbing their operation [2].

The main cause of a pipeline walls thinning is its time of operation, with additional accelerating factors like high temperature and a varying pressure of the transported medium [1, 3].

The pipeline can be inspected internally using a CCD camera [4], but this approach requires a complete stoppage of the industrial process, which is seldom acceptable and provides qualitative, but not quantitative results.

Different methods can be used to quantify the abrasion process. Direct measurement approach may employ a pointed micrometer, a needle point depth gauge, a grid with ultrasonic spot measurements, an automated ultrasonic scanner or a laser range sensor used to measure the depth of the pits [5]. Indirect measurements are associated with the use of contactless non-destructive testing techniques, such as infrared thermography. Several studies have been devoted to the detection and evaluation of defects using active and passive thermal non-destructive testing [6, 7]. Active techniques have two main drawbacks. First, the emissivity of the tested object should be high. Second, if the measurements are to be performed on thin (1–2) mm metal objects, because of the material high thermal conductivity, short observation times are required, i.e. high-speed IR cameras are to be used. This problem is limited, if the tested object is made of plastic or polymers, i.e. materials having lower thermal conductivity. In the case of thicker objects, thermal stimulation should be powerful enough to ensure detectable temperature variations. The advantage of a passive approach is the fact, that no external thermal stimulation is needed.

In this paper the authors proposed a passive thermography method for the detection of defects in polypropylene pipeline's knees, based on the thermal transient impedance and transient thermal testing approach.

2. The test set up and measurement results

For the purposes of the tests, a measurement setup was build (Fig. 1) consisting of two polypropylene knees - one brand new without any defects and one with a wall abraded from inside, a controlled hot air source and a Cedip Titanium® 560M infrared camera with a cooled InSb FPA detector matrix (640 × 512 pixels resolution) providing a *NETD* value of 20 mK. After preparing the setup, the hot air source was switched on, and the temperature of the external surface of the factory new knee was measured with the IR camera for ca. 1700 s at 100 frames per second. Exemplary image from a sequence is presented in Fig. 2. Next, in the same ambient conditions, the measurement was repeated for the abraded knee, using the same camera settings.

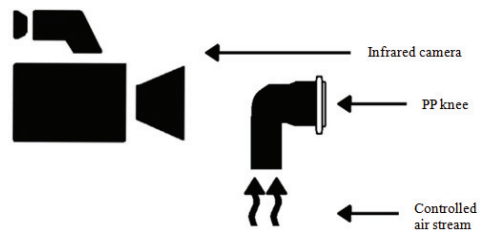

Fig. 1. Measurement setup

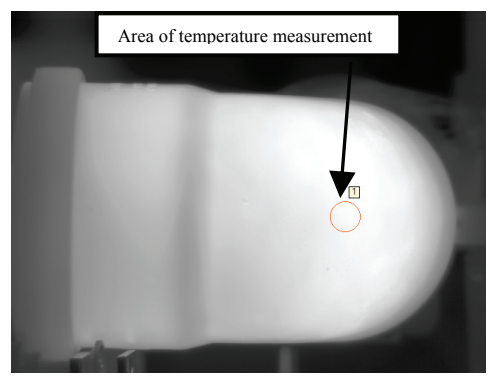

Fig. 2. Thermographic image of the polypropylene knee

The measured thermal responses of the knee without defects and the knee with defects are presented in Fig. 3. The temperature rise curve represents a mean temperature value for a selected area of the pipe surface. The heating curves have been transformed into the Nyquist plots (Fig. 4). The Nyquist diagram is the thermal impedance of the object as function of frequency using the Fourier transform – real and the imaginary parts of the impedance [8]. In this research one uses the commercially available software [9].

Using a mathematical approach presented in [10-11], based on the time dependent thermal response and assuming a quasi 1D heat flow through the bend walls, for the device under test one can calculate its time constants spectrum (Fig. 5). In Fig. 5 two time constants are visible for both pipes. The first one is representing the thermal behaviour of the pipe wall and the second one, an order of magnitude longer, is representing the convective cooling of the pipe. The latter will not be taken into account in the further analysis. The measured time constant of the abraded pipe wall heating process τ_{p1} is equal to 68.97 s and τ_{p2} = 77.60 s for the non-abraded case.

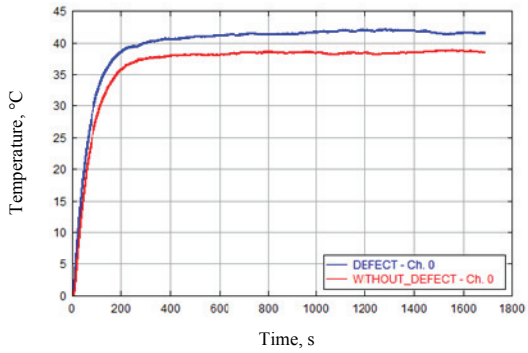

Fig. 3. Measured thermal response of the knee without defects (red curve) and of the knee with defects (blue curve)

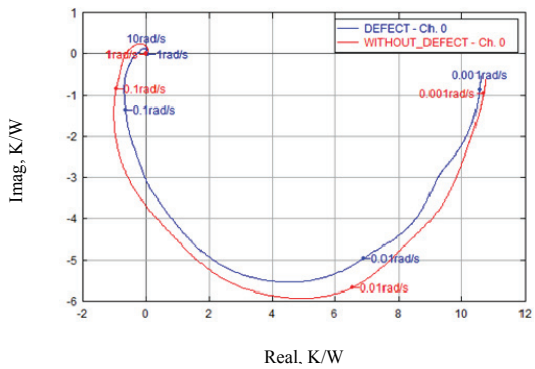

Fig. 4. The measured thermal response of the knee without defects (red curve) and of the knee with defects (blue curve)

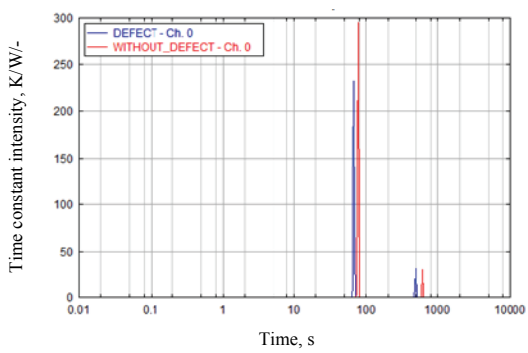

Fig. 5. The time constant spectrum measured for the knee without defects (red curve) and the knee with defects (blue curve)

3. Theoretical considerations

Assuming a constant power of the heat source and 1D heat flow perpendicular to the pipe wall surface from the hot transported medium (X) to ambient (A), the measured knee cross section can be presented as in Fig. 6, where T_a is the ambient temperature, T_o the temperature of the hot air stream, T_x the temperature of the internal pipe wall, T_m the measured temperature of the external pipe wall, and h_1 and h_2 are the heat transfer coefficients.

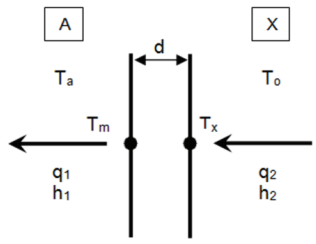

Fig. 6. The cross-section view of the pipe wall

The amount of energy (heat flux) q transported through the pipe wall depends on the pipe's material thermal conductivity λ_p of the material it is made of (polypropylene), the temperature difference $\Delta T = T_x - T_m$ and the thickness d of the wall. It can be expressed using the Fourier's law (1).

$$q = -\lambda \frac{\Delta T}{d} \tag{1}$$

According to the polypropylene pipes manufacturer specifications, the values of thermal conductivity and other thermal parameters are summarized as presented in Table 1.

Tab. 1. Polypropylene parameters [12, 13]

ρ_{PP}, kg/m^3	910
c_p, J/kgK	2100
λ, W/(m·K)	0.12

Assuming 1D heat transfer trough the wall, after reaching the steady state condition, the inlet and outlet heat fluxes are equal (2).

$$h_1(T_m - T_a) = h_2(T_o - T_x) \tag{2}$$

Then, the inner wall temperature T_x can be estimated by (3).

$$T_x = T_o - \frac{h_1(T_m - T_a)}{h_2} \tag{3}$$

Further analysis of the transient heating response of the pipe can reveal additional information for its thermal characterization. Such a thermal characterization parameter is thermal time constant – the product of thermal resistance R_{th} and heat capacity C_{th} of the pipe (4).

$$\tau = R_{th} \cdot C_{th} \tag{4}$$

As one can see in Fig. 5, the transient state of the object can be represented by 2 thermal time constants. One time constant corresponds to the heat transfer through the polypropylene wall. Taking into account the wall thickness d, thermal conductivity λ_p, surface of the wall S, one can estimate the thermal resistance of the polypropylene wall R_{thp} (5). The heat capacity is the product of volume V, density ρ and specific heat c_p (6).

$$R_{thp} = \frac{d}{\lambda S} \tag{5}$$

$$C_{th} = V \cdot \varrho \cdot c_p \tag{6}$$

$$\tau_p^* = \frac{d^2 \cdot \varrho \cdot c_p}{\lambda} \tag{7}$$

Using the values listed in Tab. 1 and the thickness d = 2.25 mm, one can get a value τ_p^* = 80.6 s, which agrees well with the left peaks shown in Fig. 5.

There is also the second time constant τ_c^* involved in the analysis, given by the product of the thermal capacity of the material and the thermal resistance of the convective cooling.

$$\tau_c^* = \frac{d \cdot \varrho \cdot c_p}{h_1} \tag{8}$$

Inserting the values mentioned above one can obtain the second time constant equal to τ_c^* = 429 s. This value is close to the second peaks observed in Fig. 5. Due to the more unstable cooling condition on the ambient side of the pipe, the convective time constant τ_c^* is not used in the analysis.

Using the polypropylene data given in Tab. 1 and a thickness d_2 = 2.25 mm for a factory-new pipe, one gets a time constant value of τ_{p2}^* = 80.62 s which is close to the measured one (τ_{p2} = 77.60 s) and confirms the correctness of estimation the values of parameters used in the analysis. Next, based on the measurement

results presented in Fig. 5, one can estimate the level of degradation of the abraded pipe, i.e. its wall thickness d_1 using the simple relations (9,10).

$$\frac{\tau_{p1}}{\tau_{p2}} = \frac{d_1^2}{d_2^2} \tag{9}$$

$$d_1 = d_2\sqrt{\frac{\tau_{p1}}{\tau_{p2}}} \tag{10}$$

where τ_{p1}, τ_{p2} denote the shorter time constants for the wall with and without defect, d_2 is the thickness of the new wall without any defect.

Based on (10) one gets a value of d_1 = 2.12 mm. The full set of the quantitative results obtained from the analysis is presented in Tab. 2.

Tab. 2. Summary table of the results, for h_1 = 10 W/m^{2}K, h_2 = 100 W/m^{2}K

	Knee with defect	Knee without defect
τ_p, s (measurement)	68.97	77.62
T_m, °C	39.77	38.52
T_a, °C	20.00	
T_o, °C	93.00	
T_x, °C	85.44	85.30
P, W (for S = 25 cm^2)	3.91	3.57
$R_{th\text{-}pipe}$, °C/W	7.07	7.50
$C_{th\text{-}pipe}$, J/K	10.13	10.75
τ_p, s (model)	71.57	80.62
d, mm	2.12	2.25

In Table 3, the results obtained by the thermographic measurement and predicted by model using the values of physical thermal parameters of polypropylene, were compared.

Tab. 3. The comparative results obtained from the measurement and theoretical considerations

	Material with defect	Material without defect	$\frac{\Delta d_x(\Delta\tau)}{d_x(\tau)_{without\ defect}}$ %
d, mm	2.12	2.25	5.7
τ_p, s (measurement)	68.97	77.62	11
τ_p, s (model)	71.57	80.62	11

In order to verify that results, using a destructive approach, the pipe was cut and the abraded wall thickness was measured using a calliper as shown in Fig. 7. The measured thickness of the pipeline wall was d = 2.25 mm and 2.15 mm for new and abraded wall, respectively.

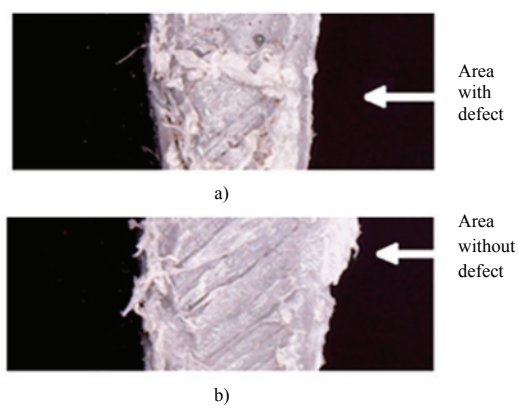

Fig. 7. a) Microphotograph of the cutted pipe cross section: abraded knee, b) non-abraded knee

4. Accuracy analysis

The measurement were performed in the laboratory. One used the *NID* methodology to calculate thermal constants [8, 10]. This procedure is based on deconvolution, and it is quite complex mathematically, especially if one wants to perform the uncertainty analysis in the analytical way.

The indirect measurement of the wall thickness uses (10). The original thickness d_2 is measured using a classical calliper. The maximum error of the thickness measurement by a calliper is Δd_2 = ±0.1 mm. It corresponds to the relative error $\Delta d_2/d_2$ = 4.5%. The A-type uncertainty was estimated for n = 10 consecutive measurements [14].

$$u_A(\bar{d}) = \sqrt{s_{\bar{d}}^2} = \sqrt{\frac{1}{n(n-1)}\sum_{i=1}^{n}(d_i - \bar{d})^2} = 0.02 \text{ mm} \tag{11}$$

B-type uncertainty is equal to [14]:

$$u_B(d) = \frac{\Delta d_2}{\sqrt{3}} = 0.06 \text{ mm} \tag{12}$$

The coverage factor was equal to k = 2.26 for n–1 = 9 degrees of freedom and confidence level p = 0.95. In consequence, the combined uncertainty of the thickness measurement using calliper was estimated as:

$$U = k\sqrt{u_A^2 + u_B^2} = 0.14 \text{ mm} \tag{13}$$

The estimation of uncertainty of the thermal time constants was carried out by adding the Gaussian noise to the temperature rise simulated by a simple program in Matlab. The temperature curve contained 2 thermal time constants τ_1 = 80 s and τ_{1l} = 500 s as it was during the measurements. It was assumed that temperature can deviate by ΔT = ±20 mK during the registration of thermal sequence. The value of 20 mK was chosen due to the cooled photon camera used in the experiment. Noise of such cameras does not exceed *NETD* ≈ 20 mK. After a hypothetical temperature vs. time curve $T(t)$ generation, the Gaussian noise with the variance 400 (mK)^2 was added to each point of the curve.

A new program for calculating thermal time constant was applied. This program written in MATLAB uses classical network theory based on the transfer functions in Laplace domain. Such solution is an alternate to the existing *NID* protocol [8] and estimates the complex thermal impedance as a ratio of polynomials in frequency domain. The thermal impedance is then converted to the sum of fractions using the residual method. The obtained solution corresponds to the Foster *RC* network and directly leads to the thermal time constant estimation.

In order to estimate the distribution and variance of thermal time constants, the overall procedure were repeated 1000 times. The results are presented in Table 4. The errors are relatively small. It is not a surprise, if one notices that the proposed methodology uses integral Laplace transform. Such approach has a natural tendency to reduce the noise influence.

Tab. 4. RMS errors of time constants calculated using thermal impedance and Foster RC network approach (τ_{1l} denotes the 2'nd long time constant)

time constant	τ_1 = 80 s	τ_{1l} = 500 s
$error_{RMS}$ (%)	0.1818	0.1770

RMS errors in Table 4 allow to estimate B-type uncertainty for measurement of thermal time constants using thermal camera. It can be estimated as [14]:

$$u_B(\tau_1) = \frac{\tau_1 * error_{RMS}}{100\sqrt{3}} \approx 0.08 \text{ s} \quad \text{and} \quad u_B(\tau_{1l}) \approx 0.5 \text{ s} \tag{14}$$

One can notice that B-type is very small. It has to be underlined, that time constant measurement does not depend on the thermal

accuracy of an IR camera. It confirms the advantage of using IR technique and thermal impedance method in such industrial measurements.

In this research, due to the practical reasons, A-type uncertainty was calculated for 5 measurements only. Each calculation of time constant last a long time. In order to calculate $u_A(\tau)$, an area of 5 pixels from each thermal images were selected. Hence $u_A(\tau)$ was estimated as [14]:

$$u_A(\overline{\tau_{p1}}) \approx 2.5 \text{ s} \quad \text{and} \quad u_A(\overline{\tau_{p2}}) \approx 0.02 \text{ s} \tag{15}$$

It can be concluded that the uncertainty for new pipeline, without defect $u_A(\overline{\tau_{p2}})$ is very small in comparison to the tinned wall. Probably, it is because the thinning is not uniform over a certain area of polypropylene tube. In this case, for $n-1 = 4$ degree of freedom, the coverage factor $k = 2.78$.

Finally, using (10) the combined uncertainty of the measurement of thickness of the wall takes a form [14]:

$$U(d_1) = k\sqrt{\left[\frac{\partial d_1}{\partial d_2}u_c(d_2)\right]^2 + \left[\frac{\partial d_1}{\partial \tau_{p1}}u_c(\tau_{p1})\right]^2 + \left[\frac{\partial d_1}{\partial \tau_{p2}}u_c(\tau_{p2})\right]^2} \tag{16}$$

The uncertainty value takes the acceptable, and finally the thickness of the pipe is estimated as

$$d_1 = 2.12 \pm 0.11\ mm \tag{17}$$

5. Conclusions

In the article two polypropylene knees - one factory-new without any defects and one with a wall abraded from inside were tested using a heat step and an IR camera temperature measurement. The results of the thermographic transient measurements were analysed next. Applying a thermal time constant approach, it was possible to estimate the thickness of the wall of the abraded pipe. The calculated value of 2.12 mm (compared to 2.25 mm for the factory-new pipe) was next verified by direct destructive measurement, which gave a result of 2.02 mm, closed to the calculated one. Whereas the presented solution was based on a heating step, the same approach could be used for a cooling step. One has to underline, that the uncertainty of the thickness measurement takes the low value due to 2 facts. Firstly, because one uses the time constants, neither the temperature nor thermal resistance, and secondly because the calculus is based on the integral transform naturally reducing the noise of the measurement.

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