Models of temperature fields and their influence on polymeric coating adhesion

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Abstract. The article provides the results of the research into the high-frequency electromagnetic radiation influence on polyvinyl chloride based polymeric piping coatings as well as forecasting how radiation can affect adhesion. It also exhibits the improvement of materials efficiency leading to longer service and higher reliability of piping systems. A calculation method for temperature changes and distribution across the coated material under the influence of microwave radiation has been developed which is required to establish the most appropriate polymer treatment techniques.

1. Introduction

Metal piping service corrosion protection and their service life extension is an acute problem [1, 2]. One of the solutions is creating new coating materials and improving the existing ones. A large number of works dedicated to microwave radiation influence on polymeric materials namely polyvinyl chloride film have been published lately [3, 4]. This work reviews adhesion changes which is one of the critical parameters contributing to reliable pipe coating operation [5].

2. Research carrying out method and its results

Coating adhesion was tested per the A method [6]. The A method is used to test polymeric coating tapes adhesion. The adhesion is checked in three locations where 2 nearest locations are at least 0.5 m from each other.

Hardware. The adhesion tester AP-2 consists of a casing equipped with a holder for coating strips and a steel knife consisting of two parallel blades, the distance between which can vary from 10 to 40 mm. To ensure pipe support and a constant pull off angle $\theta$ the casing is seated on the rollers, a pair of which can be moved and fixed in the seats depending on the pipe diameter. A force gauge is secured on the casing with two tandem springs.

The casing knives cut out a coating strip 10 to 40 mm wide depending on the expected adhesion volume:

- for the adhesion within 30 to 40 N/cm (3 to 4 kgf/cm) the strip shall be 10-15 mm wide;
- for the adhesion within 1 to 5 N/cm (0.1 to 0.5 kgf/cm) the strip shall be 30-40 mm wide.

The end of the cut strip is notched with the steel knife, raised and secured by the unit holder.

The unit shall be installed on a coated pipe making sure all the rollers are in contact with the pipe.
Moving the unit along the pipe, we pull off the cut strip to the length 100 mm and measure the prevailing pull-off force and visually assess the nature of the failure (adhesion, cohesion or mixed).

Adhesion failure is represented by bare metal.

Cohesion failure is represented by pull-off along the primer.

Mixed failure combines adhesion and cohesion failure indications.

The coating adhesion \( A \), N/cm (kgf/cm) is determined by the equation:

\[
A = \frac{F}{b}
\]

where \( F \) is the pull off force, N (kgf);
\( b \) is the width of the pulled off strip, cm.

The final bond strength is the average of three measurements with the accuracy to 0.1 N/cm (0.1 kgf/cm).

The testing was carried out to determine the adhesion of a coating exposed to microwaves before or after the application on different steel grades (Steel 3, 09Mn2Si, 12Cr18Ni10Ti).

**Figure 1.** Dependence of adhesion of PVC film exposed before application to Steel 3 on the microwave radiation strength.

**Figure 2.** Dependence of adhesion of PVC film exposed after application to Steel 3 on the microwave radiation strength.

**Figure 3.** Dependence of adhesion of PVC film exposed before application to 09Mn2Si steel on the microwave radiation strength.

**Figure 4.** Dependence of adhesion of PVC film exposed after application to 09Mn2Si steel on the microwave radiation strength.
Figure 5. Dependence of adhesion of PVC film exposed before application to 12Cr18Ni10Ti steel on the microwave radiation strength.

Figure 6. Dependence of adhesion of PVC film exposed after application to 12Cr18Ni10Ti steel on the microwave radiation strength.

The above curves indicate that the most appropriate microwave exposure for better PVC film adhesion is 100-250 kJ/kg where the adhesion nearly doubles. This can be explained by both increased coating surface activity due to pre-application material structure conformity and minor degradation-free material softening contributing to tighter coating sitting when treated after application.

The treatment of piping surface by SHF electromagnetic field increases the material temperature. To determine the temperature changes during the polymer electromagnetic exposure the following heat equation is used:

$$C_m \rho \frac{\partial T}{\partial \tau} = \text{div}(\lambda \text{grad} T) + I_q$$

(2)

where $C_m$ is service specific heat;
$\rho$ is density;
$\lambda$ is heat transfer coefficient;
$I_q$ is bulk density of heat sources caused by electromagnetic radiation absorption;
div, grad are differential operators.

The bulk density of heat sources is the following function:

$$I_q = \frac{P}{V}$$

(3)

where $P$ is SHF radiation strength;
$V$ is the treated piping area.

Due to the nature of SHF heating it allows homogeneous heat spreading:

$$\text{div}(\lambda \text{grad} T) \ll I_q$$

(4)

The equation (2) can be presented as:

$$C_m \rho \frac{\partial T}{\partial \tau} = I_q - \alpha ST$$

(5)

where $\alpha$ is piping to environment heat exchange coefficient divided by a volume unit, W/m$^3$*(m$^2$*K); $S$ is the contact area between the coated piping and the environment, m$^2$. Thus the equation (5) can be presented as follows:
\[ T(\tau) = \frac{I_d}{\alpha S} \left( 1 - e^{-\frac{\alpha S}{C \rho}} \right) \]
\[ T(\tau) = T_v - T_c \]

where \( T_v \) is the temperature of treated substance
\( T_c \) is the ambient temperature

A typical heating time can be obtained by the equation

\[ \tau_H \approx \frac{5 C \rho}{\alpha S} \]  

When this time is over, the temperature is settled as per the electromagnetic radiation strength

\[ T_y = T_c + \frac{P}{\alpha SV} \]

The S and V parameters in equations (7) and (8) are:

\[ S = 2\pi R_4 L \]
\[ V = \left[ \pi (R_2^2 - R_1^2) + \pi (R_3^2 - R_2^2) + \pi (R_4^2 - R_3^2) \right] L = \pi L \left( R_1^2 - R_2^2 \right) \]

where \( L \) – where \( L \) is the length of piping exposed to electromagnetic field;
\( R_1 \) – radius from the pipeline axis to its wall;
\( R_2 \) – radius from the pipeline axis to the primer;
\( R_3 \) – radius from the pipeline axis to the insulation material;
\( R_4 \) – radius from the pipeline axis to the environment.

The average density \( \rho_m \) is obtained by the equation

\[ \rho_m = \frac{m}{V} = \frac{\rho_1 V_1 + \rho_2 V_2 + \rho_3 V_3}{V} \]
\[ V_1 = \pi L \left( R_{i+1}^2 - R_i^2 \right) \]

where \( \rho_{1,2,3} \) are the density of piping material, primer and polymer film correspondingly.

The average specific coated pipe heat is

\[ C_m = \frac{C_1 m_1 + C_2 m_2 + C_3 m_3}{\rho_1 V_1 + \rho_2 V_2 + \rho_3 V_3} \]

where \( C_{1,2,3} \) are heat capacities of pipe material, primer and polymer film correspondingly.

To establish the piping treatment parameters, the heat distribution for the metal - primer - polymer layers is obtained per the equation:

\[ \frac{1}{r} \frac{\partial}{\partial r} \left( \lambda_r \frac{\partial T(r)}{\partial r} \right) T(r) = I_q \]

The solution to the equation (12) for each layer is:
where $\lambda_3$ is coating heat coefficient, W/(m*K);
$\lambda_2$ is primer heat coefficient, W/(m*K);
$\lambda_1$ is metal heat coefficient, W/(m*K);

The equations (13) have the following limitations

$$T(r = R_4) = T_c$$
$$T(r = R_1) = T_y$$

With that said, the equality of temperatures at layer borders and heat flow equality are observed. The following is based on the limitations and the heat flow equality:

$$\begin{align*}
\frac{B_1}{\lambda_3} \ln R_4 + B_2 &= T_c \\
\frac{B_3}{\lambda_2} \ln R_3 + B_4 &= \frac{B_1}{\lambda_3} \ln R_3 + B_2 \\
\frac{B_5}{\lambda_1} \ln R_5 + B_6 &= \frac{B_3}{\lambda_2} \ln R_2 + B_4 = T_y
\end{align*}$$

(15)

The following is based on the heat flow equality at layer borders:

$$B_1 = B_3 = B_5$$

(16)

Thus, temperature changes in a polymer coating are represented by the following ratio:

$$T(r) = T_c + \frac{B_1}{\lambda_3} \ln \frac{r}{R_3}; \quad R_3 < r \leq R_4$$

(17)

Temperature distribution in the primer layer can be obtained by the equation:

$$T(r) = T_y + \frac{B_1}{\lambda_2} \ln \frac{r}{R_2}; \quad R_2 < r \leq R_3$$

(18)

The pipe wall temperature will follow the law:

$$T(r) = T_y + \frac{B_1}{\lambda_1} \ln \frac{r}{R_2}; \quad R_1 < r \leq R_2$$

(19)

With the metal heat coefficient $\lambda_1 \gg \lambda_{2,3}$ the following inequation is true:

$$\frac{B_1}{\lambda_1} \ln \frac{r}{R_2} = \frac{(T_y - T_c) \lambda_3 \lambda_2}{\lambda_3 \ln \frac{R_2}{R_3} + \lambda_2 \ln \frac{R_3}{R_4}} \ln \frac{r}{R_2} << T_4$$

(20)

With the latter accounted, the pipe wall temperature will be obtained by the following ratio:
The temperature distribution profile is pictured as follows (figure 7)

\[
T(r) \approx T_y = T_c + \frac{P}{\alpha SV}
\]

The temperature distribution profile is pictured as follows (figure 7)

The below table shows the settled temperatures for a 0.6 mm thick polyvinyl chloride film, a 0.1 mm thick primer and 4 mm thick metal (with the sheet length 110 mm, and the width 100 mm), at the ambient temperature 22°C. These temperature values do not differ much from the earlier experimental data for material temperature changes under the influence of microwave radiation.

**Table 1.** Design temperature and experimental temperature of polyvinyl chloride film after microwave radiation exposure.

| The amount of radiation, kJ/kg | Design temperature | Experimental temperature |
|---------------------------------|--------------------|-------------------------|
| Reference standard | 22 | 22 |
| 102 | 30.5 | 34.7 |
| 205 | 39 | 39.4 |
| 258 | 43.1 | 40.1 |
| 309 | 47.6 | 50.7 |

3. Conclusions
The research into the influence of electromagnetic radiation on polymeric coatings has shown that certain amounts of energy significantly improve coating service properties and hence piping systems reliability [7].

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