ANALYSIS OF THE EFFECTS OF SELECTED QUANTITIES ON THE FOULING OF NATURAL GAS COOLER PIPES

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In this article, the effects of selected quantities on the thickness of a fouling layer that is formed on the internal surface of the pipes of natural gas (NG) coolers are discussed. Models created by applying an analytical method, a dimensional analysis, and a multiple linear regression were compared. The most complex model was the analytical model with a total of 16 relevant physical quantities. From the practicality point of view, that model was very complicated since it required applying the iterative process. The dimensional model comprised 6 similarity criteria. The difference between the fouling layer thicknesses identified analytically and those identified using a model based on a dimensional analysis did not exceed 3.06 %. Out of the total number of relevant quantities, only those that had the strongest effects on the fouling layer thickness were selected with the use of MinitabX software. Three regression models, containing 6, 5, and 4 variables, were thus created. The difference between the results obtained from the simplest regression model and the values obtained from the dimensional model amounted to a maximum of 3.20 %. The use of the presented regression models in technical practice may be recommended.

KEYWORDS

Natural gas cooler, dimensional analysis, fouling layer thickness, multiple regression analysis

1 INTRODUCTION

Long-term utilisation of cooling equipment results in the fouling on the heat-transfer surfaces of such equipment, while the fouling layers consist of various types of impurities. The process of formation of the fouling layer on the inner side of the cooler pipes and the rate at which its thickness increases depend on the type of the cooling medium (gas, water, emulsions, etc.) and the shape of the heat-transfer surface (smooth or rugged surfaces). If rejected materials accumulate on surfaces that are well-accessible for cleaning, the problems caused by the fouling are minimal. However, fouling layers formed on the inner heat-transfer surfaces are difficult to remove. The decision on whether the heat-transfer surface needs cleaning or not should be verified by applying an appropriate procedure. Natural gas cleaners (Fig. 1) consist of thousands of pipes through which natural gas flows at various operating conditions (gas temperature and pressure, gas mass flow rate, cooling air temperature and quantity, etc.). Cleaning of the inner heat-transfer surfaces of a cooler means that the cooler must be put out of service for a very long time, and that is not very beneficial for a gas transporter from the financial point of view. Dismantling of sealing elements of the cooler pipes on both ends of the collectors is followed by the cleaning of the inner surfaces of the pipes with the use of a special technique – by pushing the fouling materials through. The materials pushed out are then collected. Subsequently, the quantity of the fouling material pushed out and the number of the pipes in the cooler may be used to calculate an average thickness of the fouling layer formed on the inner sides of the pipes. Such a procedure, however, has its drawbacks. It is more beneficial to know the real thickness of the fouling layer, and only then decide on whether it is necessary to open the cooler and clean the pipes.

The purpose of this article was to identify the simplest possible method of identifying the thickness of the fouling layer inside the pipes of natural gas coolers.

Figure 1. Natural gas cooler – a detailed image of the fan section

2 ANALYSED COOLER DESCRIPTION

The cooler for which the fouling layer thickness was identified by applying both an analytical procedure and dimensional analysis consisted of 6 double-fan sections. In the cooler, gas was cooled by 12 fans installed under the cooler's body. The cooler was a heat-transfer unit of the "*double counter-current*" type, in which 3 rows of pipes in each cooler block conducted gas in one direction to the collector, in which the gas was turned 180 degrees and then flew in an opposite direction in 3 rows of pipes into the outlet collector (Fig. 2). The inlet and outlet of the cooled gas were located on the same side of the cooler. Each section consisted of 3 blocks, each with 378 pipes. The total number of pipes in the cooler was therefore 2,246.

Figure 2. One section of the cooler – 3 blocks

The cooler was designed to cool 242.3 $kg \cdot s^{-1}$ of natural gas with a pressure of 7.45 MPa from the temperature of 75 °C to 50 °C. The required quantity of the fan air with a temperature of 28 °C was 565.23 $kg \cdot s^{-1}$. The analysed cooler was operating at an ambient temperature that ranged from 28 to 0 °C. The pipes had ribs on their outer sides (Fig. 3). The pipes were made of steel, while the ribs were made of aluminium.

Figure 3. Cooler pipe with the ribs

As to the shape and size of the heat-transfer surface, the basic data on the cooler's pipe geometry are listed in Table 1.

Quantities	Value (mm)
Outer diameter of the pipe d_2 (mm)	25
Inner diameter of the pipe d_1 (mm)	33
Rib diameter d_r (mm)	57
Gap between the ribs b	2.6
Pipe spacing s_1	64
Pipe length L	9,000

Table 1. Basic parameters of the cooler

3 DESCRIPTION OF THE METHODS USED TO IDENTIFY THE FOULING LAYER THICKNESS

At present, various physical processes are examined with the use of numerical simulations. They may also be studied through analytical solutions, solutions based on dimensional analysis, as well as solutions based on regression analysis.

3.1 Analytical model

At present, some of the authors of this article deal with mathematic modelling of processes within a wide spectrum of technical problems. For example, paper [Karakash 2024] discusses the development of a mathematical model of the energy balance in a process of laser cladding process of metallic powders with a coaxial nozzle. Paper [Prusa 2023] describes the modelling of a manufacturing machine based on the outlet requirements etc.

Paper [Čarnogurská 2024] presents the application of an analytical procedure with the aim of creating an equation for calculating the thickness of a fouling layer (Equation (1)) – hereinafter referred to as **Model I**, as follows:

$$h_f = \frac{D \cdot \pi \cdot L \cdot d_1 \cdot \dfrac{S_e}{\alpha_1}}{\dfrac{S_e}{\lambda_f} + 2 \cdot D \cdot \pi \cdot L} \qquad (1)$$

wherein: S_e is the surface area of a single pipe (m²); λ_f is the thermal conductivity coefficient of the fouling layer (W·m⁻¹·K⁻¹); α_1 is the heat transfer coefficient on the inner side of the pipe (W·m⁻²·K⁻¹); while the remaining quantities are listed in Table 1.

Equation for the D parameter in Equation (1) is as follows:

$$D = \frac{S_\Sigma \cdot \overline{\Delta t}}{P} - \frac{s_p}{\lambda_p} \cdot \frac{S_e}{S_1} - \frac{1}{\alpha_2} \qquad (2)$$

wherein: S_Σ is the total heat-transfer surface area of the cooler (m²); $\overline{\Delta t}$ is the mean temperature gradient (K); P is the total heat transfer rate in the exchanger (W); s_p is the thickness of the pipe wall (m); λ_p is the thermal conductivity of the pipe material (W·m⁻¹·K⁻¹); α_2 is the heat transfer coefficient for the transfer of heat from a ribbed pipe into the cooling air (W·m⁻²·K⁻¹); and S_1 is the inner surface area of the pipe (m²).

The values of α_1 and α_2 variables were determined using the equations given in the literature [VDI 2010]. The process of identifying the thermal conductivity of the fouling layer is described in detail in the literature [Čarnogurská 2011].

3.2 Dimensional analysis

A special method for modelling various processes, not only in the power industry, is dimensional analysis. The basic information on that method is provided, for example, in papers [Barenblatt 1987], [Görtler 1975], [Huntley 1967], and [Koželník 1983]. Applications that use that method may be found in paper [Čarnogurská 2011]. Dimensional analysis was also used to describe, rather briefly and in a special manner, a solution for predicting the rate of fouling formed from soy milk in a plate heat exchanger [Sritham 2023]. Furthermore, dimensional analysis is also used in the modelling of vibrations propagated through the ground near a tunnel in which demolition works are performed [Gao 2023], in the process of describing the development of heat-distribution losses in distribution networks [Čarnogurská 2023], and in the identification of drops in the temperature of fluids transported in railway cisterns [Brestovič 2021].

Dimensional analysis was also used in the herein described examination of the thickness of the fouling layer formed on the walls of the natural gas cooler pipes. The reason why that method was applied is that the analytical procedure of expressing the fouling layer thickness is rather complicated and difficult to apply in real-world operations as it requires applying an iterative approach.

Paper [Čarnogurská 2024] presents an equation for calculating the thickness of a fouling layer in the pipes of a natural gas cleaner which is based on dimensional analysis. The equation was derived from 16 relevant quantities, while the final form of the equation includes only 12 quantities. The quantities that do not change throughout the gas cooling process (they are constant) are included in the C constant. Equation (3), hereinafter referred to as **Model II**, is as follows:

$$\frac{d_1^2}{(d_1 - 2 \cdot h_f)^2} = C \cdot \left(\frac{K_{NG}}{K_a}\right)^{z_1} \cdot \left(\frac{T_{1,NG}}{\Delta T_{NG}}\right)^{z_2} \cdot \left(\frac{T_{2,NG}}{T_{1,a}}\right)^{z_3} \left(\frac{\rho_{NG}}{\rho_a}\right)^{z_4} \cdot \left(\frac{\lambda_f}{\lambda_{NG}}\right)^{z_5} \qquad (3)$$

wherein: K_{NG} is the heat capacity rate of gas (W·K⁻¹); K_a is the heat capacity rate of air (W·K⁻¹); $T_{1,NG}$ is the gas temperature at the inlet into the cooler (K); ΔT_{NG} is the mean temperature of gas (K); $T_{2,NG}$ is the gas temperature at the outlet from the cooler (K); $T_{1,a}$ is the air temperature at the inlet into the cooler (K); ρ_{NG} is the gas density (kg·m⁻³); ρ_a is the air density (kg·m⁻³); λ_{NG} is the thermal conductivity of gas (W·m⁻¹·K⁻¹) and λ_f is the thermal conductivity coefficient of the fouling layer (W·m⁻¹·K⁻¹).

C constant and the individual exponents for relevant criteria were identified by applying multiple linear regression, and their values are listed in Table 2. Specific values of the individual quantities used in the regression solution of Equation (3) are given in the literature [Čarnogurská 2024]. The calculated thickness of the fouling layer inside the pipes ranged from 0 to 6.7 mm.

Quantities	Value
C	$1.3848 \cdot 10^{-72}$
z_1	0.017396
z_2	1.4880
z_3	-78.565
z_4	-83.971
z_5	173.23

Table 2. C constant and the individual exponents to be used in Equation (3)

On the left side of Equation (3), the criterion includes the searched fouling layer thickness h_f. That quantity is linked with the inner diameter of the cooler pipe d_1. The expression of h_f based on that Equation was made by adjusting the criterion on the left side of the Equation and identifying the roots of the quadratic equation. Both roots were positive. However, only one of them, the lower one, was of physical importance.

3.3 Regression models

Due to the fact that Equation (3) is rather difficult to solve in common technical practice, MinitabX software and R page programme, version 4.3.3., were used to find the way how to describe the thickness of the fouling layer inside the natural gas cooler by applying multiple linear regression while directly using the variable quantities. The purpose of regression analysis is to identify the correlation between a dependent variable and k-independent variables. The correlation between the explained (dependent) variable Y and k-explaining (independent) variables may be expressed through a regression model. The following typical linear regression model was used:

$$Y = \beta_0 + \sum_{j=1}^{k} \beta_j \cdot X_j + \varepsilon \qquad (4)$$

wherein: β_0 and β_j for $j = 1,2,...,k$ are the model parameters; Y is the input (dependent) variable; variables X_j, $j = 1,2,...,k$, represent k-independent input variables; and ε is the random error. The model parameters were identified by applying the least squares method [Keith 2019]. Statistical significance of the regression model was verified using the F-test of statistical significance. Similarly, tests of statistical significance were also used to verify statistical significance of all parameters of the regression model. As a rule, in the testing of statistical hypotheses, the decision on rejecting or accepting the null hypothesis is made on the basis of the p-value. If the p-value is lower than the level of significance α, then the null hypothesis is rejected in favour of the alternative hypothesis. If the p-value equals or is higher than the selected level of significance α, then the null hypothesis is not rejected. Strength of the correlation between the Y variable and the impact of k independent variables is expressed through the coefficient of multiple determination R^2 [Montgomery 2018].

Out of the total number of 16 relevant quantities, MinitabX was used to select 6 quantities as those with the strongest effects on the formation of the fouling layer. They included the cooling air mass flow rate $Q_{m,a}$ ($kg \cdot s^{-1}$); gas temperature at the inlet into the cooler $T_{2,NG}$ (K); temperature of the cooling air $T_{1,a}$ (K); gas density ρ_{NG} ($kg \cdot m^{-3}$); cooling air density ρ_a ($kg \cdot m^{-3}$) and specific heat capacity of gas $c_{p,NG}$ ($J \cdot kg^{-1} \cdot K^{-1}$). In the solution that included 6 quantities, the fouling layer thickness was calculated using Equation (5), hereinafter referred to as **Model III**:

$$\begin{aligned} h_f &= -5784.25 - 0.00491 \cdot Q_{m,a} + 1.32825 \cdot T_{2,NG} + \\ &+ 0.45745 \cdot T_{1,a} + 6.90863 \cdot \rho_{NG} + +113.457 \cdot \rho_a + \\ &+ 1.70938 \cdot c_{p,NG} \end{aligned} \qquad (5)$$

In Equation (5), it was necessary to respect the changes in the gas density ρ_{NG} which occur as the gas temperature changes during the cooling process. The Equation was solved by substituting the value of density at a mean temperature $t_{mean,NG} = (T_{1,NG} + T_{2,NG})/2 - 273.15$ and it was calculated using Equation (6):

$$\rho_{NG} = 1.4563 \cdot 10^{-3} \cdot t_{mean,NG}^2 - 3.6377 \cdot 10^{-1} \cdot t_{mean,NG} + 63.00 \qquad (6)$$

It was also necessary to respect the changes in the air density ρ_a, which was calculated using Equation (7):

$$\rho_a = 1.313 \cdot 10^{-5} \cdot t_{mean,a}^2 + 4.628 \cdot 10^{-3} \cdot t_{meaan,a} - 1.276 \qquad (7)$$

wherein $t_{mean,a} = t_{1,a} + \Delta T_{NG}$.

Specific heat capacity of gas depends on $t_{mean,NG}$ and was calculated using Equation (8):

$$\begin{aligned} c_{p,NG} &= 1.1696 \cdot 10^{-9} \cdot t_{mean,NG}^4 - 6.3457 \cdot 10^{-7} \cdot t_{mean,NG}^3 + \\ &+ 1.3139 \cdot 10^{-4} \cdot t_{mean,NG}^2 - 1.0701 \cdot 10^{-2} \cdot t_{mean,NG} + \\ &+ 2.9979 \end{aligned} \qquad (8)$$

In another solution, out of 6 relevant quantities included in Equation (5), only 5 quantities were tested; in particular, the mass flow rate of cooling air $Q_{m,a}$; the temperature of gas at the inlet into the cooler $T_{2,NG}$; temperature of the cooling air $T_{1,a}$; gas density ρ_{NG}; and density of cooling air ρ_a. In that solution, specific heat capacity of gas $c_{p,NG}$ was not taken into consideration (**Model IV**). The thickness of the fouling layer was calculated as follows:

$$\begin{aligned} h_f &= -1936.2 - 5.04 \cdot 10^{-3} \cdot Q_{m,a} + 1.842342 \cdot T_{2,NG} + \\ &+ 0.470826 \cdot T_{1,a} + 3.44455 \cdot \rho_{NG} + 116.5479 \cdot \rho_a \end{aligned} \qquad (9)$$

The last regression model only contained 4 relevant quantities. In that solution, specific heat capacity of gas $c_{p,NG}$ and the mass flow rate of cooling air $Q_{m,a}$ were not taken into consideration (**Model V**). The thickness of the fouling layer was calculated using the following equation:

$$\begin{aligned} h_f &= -1966.98 + 2.171793 \cdot T_{2,NG} + 0.201271 \cdot T_{1,a} + \\ &+ 24.7926 \cdot \rho_{NG} + 60.8488 \cdot \rho_a \end{aligned} \qquad (10)$$

4 RESULTS AND DISCUSSION

The analysed models, presented below, are described in Table 3 (Model I through Model V).

Table 4 presents the correlations between the individual quantities in the given model.

Model	Model description
Model I	Analytical solution, Equation (1)
Model II	Dimensional analysis, Equation (3)

Model III	Multiple linear regression, Equation (5)
Model IV	Multiple linear regression, Equation (9)
Model V	Multiple linear regression, Equation (10)

Table 3. Models analysed in the article

Model	Correlations between the individual quantities in the given model
Model I	$h_{f,(Model\ I)} = f$ (all quantities included in Equation (1))
Model II	$h_{f,(Mode\ II)} = f$ (all quantities included in Equation (3))
Model III	$h_{f,(Model\ III)} = f\,(Q_{m,a},\ T_{2,NG},\ T_{1,a},\ \rho_{NG},\ c_{p,NG},\ \rho_a)$
Model IV	$h_{f,(Model\ IV)} = f\,(Q_{m,a},\ T_{2,NG},\ T_{1,a},\ \rho_{NG},\ \rho_a)$
Model V	$h_{f,(Model\ V)} = f\,(T_{2,NG},\ T_{1,a},\ \rho_{NG},\ \rho_a)$

Table 4. Correlations between the individual quantities in the given model

Fig. 4 shows the correlation between the thickness of the fouling layer, calculated using Equation (3), hereinafter referred to as Model II. It was compared with the analytical solution based on Equation (1), hereinafter referred to as Model I.

The value of coefficient of determination R^2 was calculated as follows:

$$R^2 = 1 - \frac{\sum_{i=1}^{n} \left(h_{i,\,M} - h_i\right)^2}{\sum_{i=1}^{n} \left(h_{i,\,M} - \bar{h}_M\right)^2} \tag{11}$$

wherein n is the number of compared values; $h_{i,M}$ is the i^{th} value of the fouling layer thickness calculated from the model that was chosen as a reference; and h_i is the i^{th} value of the fouling layer thickness calculated from the evaluated model.

The average value $\bar{h}_M$ was calculated using the following equation:

$$\bar{h}_M = \frac{1}{n} \sum_{i=1}^{n} h_{i,\,M} \tag{12}$$

The range of the coefficient values was ⟨0 ;1⟩. Generally, the closer the value is to 1, the stronger the correlation is.

Fig. 6 indicates excellent agreement between the expressions ($R^2 = 0.9997$). At the gas temperature of, for example, 75 °C at the inlet into the cooler, and at a temperature of cooling air of 20 °C, the difference in the expression describing the thickness of the fouling layer with the use of Equations (1) and (3) was as little as 3.06 %.

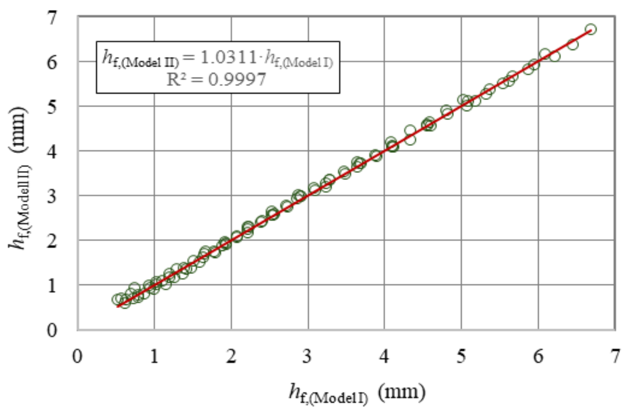

Figure 4. Correlation between the thicknesses of the fouling layer identified with the use of Model I and Model II

The first criterion for the comparison was Model I. Since the results from Model II were practically identical to those obtained from Model I, Model II was chosen as the reference for regression models (III, IV, and V).

Fig. 5 shows the correlation between the thicknesses of the fouling layer identified with the use of Model II and those identified using Model III, obtained through multiple regression analysis – by calculating Equation (5). The figure also indicates excellent agreement between the expressions of the thickness of the fouling layer ($R^2 = 0.9985$). At the gas temperature of 75 °C at the inlet into the cooler and the colling air temperature of 20 °C, the difference of the fouling layer thicknesses calculated using Equations (5) and (3) was as low as 1.53 %.

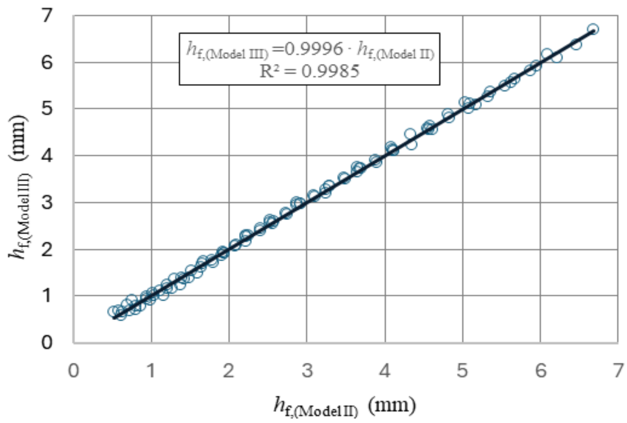

Figure 5. Correlation between the thicknesses of the fouling layer identified with the use of Model II and Model III

In Fig. 6, the fouling layer thicknesses calculated using Equation (9) – Model IV, was compared with the results obtained using Equation (3) – Model II. The solution indicated that Model IV also provides a relevant result (Fig. 6). Coefficient of determination R^2 was 0.9968. At the inlet gas temperature identical to that used in the previous solution, i.e. at the gas temperature of 75 °C and the temperature of cooling air of 20 °C, the difference in the expression of the thickness of the fouling layer using Equation (9) was as low as 2.38 % compared to that pertaining to Equation (3).

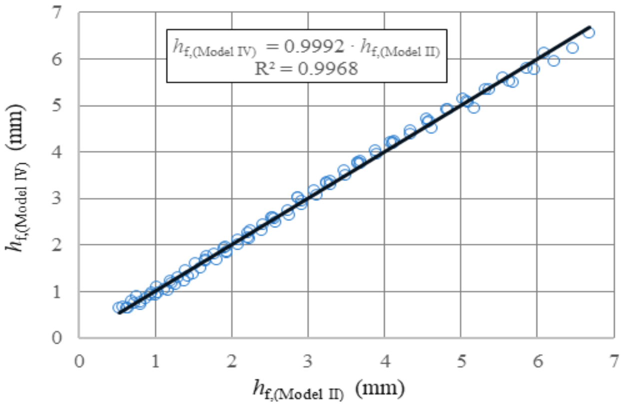

Figure 6. Correlation between the thicknesses of the fouling layer identified with the use of Model II and Model IV

Fig. 7 shows the correlation between the thicknesses of the fouling layer identified using Model V – Equation (10) and Model II – Equation (3). The solution indicated that Model V also provides a very good result. Coefficient of determination R^2 was 0.9937. At the identical inlet gas temperature of 75 °C and the temperature of cooling air of 20 °C, the difference in the expression of the thickness of the fouling layer using Equations (3) and (10) was 3.20 %.

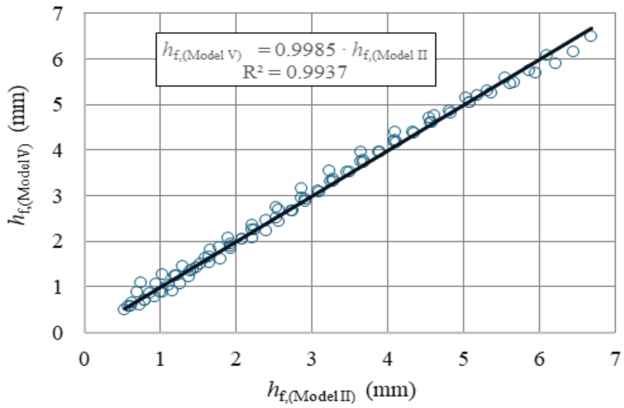

Figure 7. Correlation between the thicknesses of the fouling layer identified with the use of Model II and Model V

Statistical significance of all regression models, as well as all parameters of the regression models, was verified using the tests of statistical significance at the level of significance $\alpha = 0.05$. Results of the testing showed that all models – Model II (Eq. (3)), Model III (Eq. (5)), Model IV (Eq. (9)) and Model V (Eq. (10)), were statistically significant, and that all of the considered parameters were statistically significant.

Fig. 8 and Fig. 9 show the correlation between the thicknesses of the fouling layer identified using Model III and Model IV, and those identified using Model III and Model V. Coefficients of determination R^2 were 0.9985 and 0.9952, respectively.

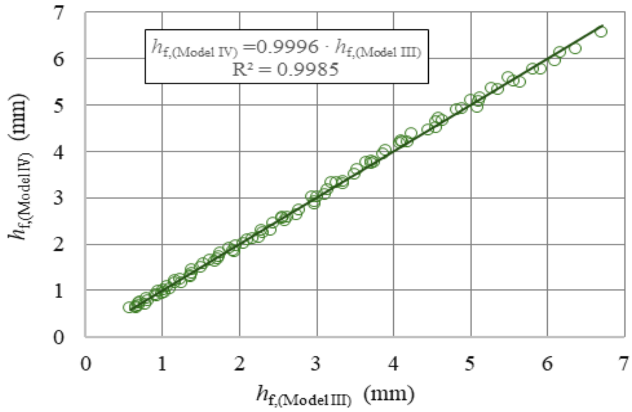

Figure 8. Correlation between the thicknesses of the fouling layer identified with the use of Model III and Model IV

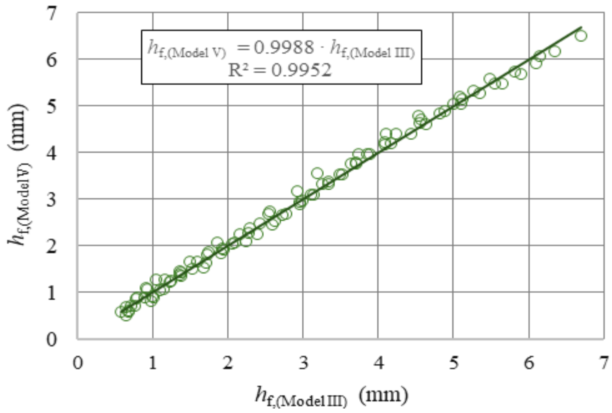

Figure 9. Correlation between the thicknesses of the fouling layer identified with the use of Model III and Model V

Based on the comparison of results obtained using Model II, Model III, Model IV, and Model V, it may be stated that they were comparable, and such a statement may be demonstrated by comparing those results using the Friedman test. The Friedman test is a non-parametric test comparing several dependent sets and represents an extension of the Wilcoxon pairwise test. It is also regarded as a non-parametric version of the analysis of the distribution of two-factor authentication [Garcia 2010]. The tested null hypothesis was H_0: $m_{Model\ II} = m_{Model\ III} = m_{Model\ IV} = m_{Model\ V}$ and it was compared against the alternative hypothesis H_1: non H_0. The value of the testing statistics was 3.6211 and *p*-value was 0.1636. Since the *p*- value > α ($\alpha = 0.05$), the null hypothesis was not rejected. As a result, it may be stated that the resulting values obtained using the above specified models were comparable.

5 CONCLUSION

In this article, a number of potential methods how to express a thickness of a fouling layer formed on the heat-transfer surfaces of the pipes in a natural gas cleaner are presented. Out of those methods, the most complicated one is the analytical method, presented through Equation (1), since some of the quantities are mutually dependent and, therefore, the iteration process is required. That method cannot be recommended for common application in practice because the staff operating such coolers does not possess the knowledge of iteration calculation procedures.

The second method, which is based on dimensional analysis (Equation (3)), was assessed as being more appropriate for the intended purpose; however, some quantities included therein must be identified analytically for each of the analysed operational states, in particular the heat capacity rate of gas and of air. The difference between the fouling layer thicknesses calculated using the dimensional equation and those calculated using the analytical equation did not exceed 3.06 %.

The third method for the identification of the thickness of the fouling layer consists in the use of regression Models III, IV or V (Equations (5), (9) or (10)). The difference between the fouling layer thicknesses identified using the regression models and those calculated using the dimensional equation did not exceed 3.20 %.

All of the simplified regression models described herein may be used in practice for the purpose of approximate identification of the thickness of the fouling layer formed on the heat-transfer surfaces. Their results are acceptable for technical operations. All of the quantities that must be known to be used in the regression equations presented above are monitored online during the use of the coolers.

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