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Effects of Using Enamel as a Protection against Corrosion on External Surfaces of Thermosyphon Economizers for Waste Heat Recovery Systems

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ABSTRACT The effects of using enamel as a protection against corrosion on external surfaces of thermosyphon economizers were studied. The thermosyphons used in the experiment were made of standard and enamel coated steel, and standard and enamel coated copper. Three different thicknesses of enamel were employed on the evaporator section. Thermosyphons with an OD of 25.4 mm, with an evaporator and condenser section length of 0.7 and 0.3 m respectively, were installed in a modified economizer measuring 1.2 x 1.3 x 1.5 m. The test was conducted using flue gas burned at a temperature of 225 C. generated from a mixture of heavy grade A fuel and diesel oil at a ratio of 4:1 by volume. Data was collected while monitoring the corrosion levels of the thermosyphons. Fouling with its thermal resistance was also recorded at 250, 500, 750 and 1,000 hours respectively. It was found that, neither the direction of the flow of the flue gas nor the thickness of the enamel coating significantly affected the rate of corrosion, the fouling thickness, or the average rate of fouling. The average corrosion of 3 different thicknesses of enamel coated tubes for both the steel and copper tubes were 0.038 mm. At the completion of 1,000 hours the corrosion of the mild steel tube was 4.9 times higher than the enamel coated tube and the corrosion of the standard copper tube was 4.45 times higher than the enamel coated tube. The inorganic compound found in the fouling on the thermosyphon's surface was $CaSO_4$, which came from the combustion of the fuel. Thus, the fouling on the thermosyphon's surface did not originate from the material used in the tubes production, the enamel coating or depend on the operational time. In addition, it was found that the correlation between corrosion and time of the mild steel thermosyphon and the coated mild steel thermosyphon was $Cr = 0.008t^{0.4578}$ and $Cr = 0.0073t^{0.2431}$ respectively. The correlation between corrosion and time of the standard copper thermosyphon and the coated copper thermosyphon was $Cr = 0.0231t^{0.2938}$ and $Cr = 0.03474t^{0.0202}$ respectively. From the results, it was found that the correlation between the average rate of fouling and time of the mild steel thermosyphon and copper thermosyphon was $RW_{fouling} = 18.784t^{-0.9778}$ and $RW_{fouling} = 126.97t^{-1.2373}$ respectively.

KEYWORDS: thermosyphon, external corrosion, fouling, enamel protection.

INTRODUCTION

An economizer is used to recover heat from waste exhaust gas in a boiler stack and to transfer it to the feedwater of a boiler. This process allows heat energy from a boiler's stack to be reused. A thermosyphon economizer employs thermosyphons to transfer heat using the principle of phase change of a working fluid inside a tube as a heat transfer medium. However, the major problem of using a thermosyphon economizer is fouling, causing corrosion of the tube's external surface and a reduction of its heat transfer capability. Luan and Jin[1] found that, the rate of corrosion decreased and heat transfer performance also decreased when the operating time increased. It was found from their test (which lasted for 18 months) that, the corrosion depth was 0.13 mm and the heat transfer rate was reduced by 10.2%. And an asymptotic curve could be applied to the fouling deposition data. In order to predict the fouling deposition, Kern and Seaton[2] established the model in the form of:

$$R_{fouling} = \frac{\phi_d}{\beta}\left(1-e^{-\beta t}\right) \qquad (1)$$

Where, $R_{fouling}$ = the thickness of fouling
f_d = the rate of fouling accumulation
β = the coefficient fouling removal rate
t = the operating time

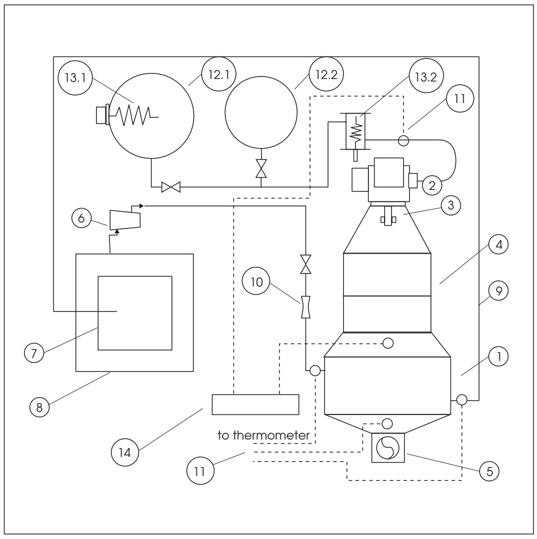
The value of β can be adjusted according to the unit of the parameter used in the correlation. In addition, Bubenicek *et al*[3] found that many factors affected the formation of fouling such as, temperature, fuel compounds, flow characteristics, speed of the flow, flue gas constituents, the tube's material, surface temperature and heat flux.

Protection from corrosion can be done in several ways, one example being material selection. Novotna *et al*[4] did an experiment with aluminum and steel pipes. After testing the pipes for 10,000 hours, it was found that no corrosion occurred with the aluminum pipes, whereas after just 6,000 hours corrosion occurred with in? the steel pipes. Another way to protect from corrosion is to coat the external surface of the tube. Polasek and Stule[5] found that an enamel coated steel heat pipe with low carbon could be more resistant to corrosion than a stainless steel one. On the other hand, Terdtoon[6] protected the tubes by coating them with Red lead, Red oxide and Hi-temperature resistant paint. They found that, after 1,000 hours, corrosion of the standard tubes was at twice the rate of the coated tubes. It could be seen that, enamel provided a good protection against corrosion. However, there is still a problem in using enamel to coat pipes. Due to the problem of bonding between enamel and a base material, it is necessary to use a compatible enamel for each base material. As a result, the expense is relatively high. However, if a mass produced enamel could be selected, then production costs could, therefore, be reduced. It was, therefore, decided to use a commercially produced enamel in this research. The objectives of the experiments were to solve the above stated problems and to investigate:

1. The external surface corrosion of standard thermosyphons and enamel coated thermosyphons at different levels of thickness.
2. The fouling accumulation on thermosyphons

Experimental Setup and Procedure

The economizer measured 1.2 x 1.5 x 1.5 m and consisted of 64 thermosyphons. The total length of each thermosyphon measured 900 mm. The evaporation section was 695 mm, the adiabatic section was 10 mm and the condenser section was 195 mm long. Water was selected as the working fluid. The thermosyphons were made of mild steel, which were 26.7 mm in diameter and 2.87 mm thick, and copper, which were 28.5 mm in diameter and 1.27 mm thick. These sizes were chosen as they correspond to the size of tubes which are widely available and in general use. Only the evaporation section of the tubes were coated with enamel and three different thicknesses were used. The economizer was set in a test rig as shown in Fig 1. The experiment was started by burning grade A heavy fuel oil and



1. Thermosyphon economizer
2. Burner
3. Blower
4. Combustion zone and flow channel
5. Stack
6. Water pump
7. Cooling tower
8. Storage tank
9. Inlet and outlet water channel
10. Rotameter
11. Thermocouple sensor

12.1 Heavy fuel oil tank
12.2 Diesel tank
13.1 Main heater
13.2 Supplementary heater
14. Control box

Fig 1. Experimental setup.

diesel at a ratio of 4:1 at 225°C in a burner and passing the exhaust gas through an economizer and allowing the exhaust gases to pass out of a stack. According to the final analysis, sulfur content of the used fuel was about 1.435%. O_2, CO_2 and CO content of the flue gas were 17.9, 2.3 and 0.68% respectively. Next, water was pumped into the economizer and then into the cooling tower in order to reduce the temperature. Finally, the water was returned to the water tank for reuse. The experiment ran for 16 hours a day for a total of 1,000 hours. The thermosyphons were grouped into sets of four consisting of a standard tube, a tube coated with enamel to a thickness of 190 µm, a tube coated with enamel to a thickness of 286 µm, and a tube coated with enamel to a thickness of 482 µm. Two samples were analyzed for each set. A metal disk was attached to the face side and the lee side of each tube and was analyzed to find the "average" fouling thickness. The enamel included a composition of BaO_2 and SiO_2. Data was collected every 250 hours from a representative group of samples from the test rig. Fouling deposition was monitored first, and data was recorded before removing all the samples in the representative groups. After that, the corrosion depth of the outside surface of the samples were recorded with a 25x optical microscope and an average value of the corrosion depth was determined for each group.

Fouling was collected and analyzed for organic compound with an X-ray diffractometer (XRD), and inorganic compounds with an infra-red spectroscope (IR) by a laboratory available at the author's academic institute. Each sample disk and tube was weighed at specific times to obtain weight differences.

Results and Discussion

Results of the different aspects of the experiments will be presented and discussed in the following order: the corrosion of the external surfaces, the fouling deposition, and the accumulation rate of fouling. Although the experimental data was collected for up to a total of 1,000 hours, predicted results have been given for operating time of 2,000 - 4,000 hours, based on data extrapolated from the experiment. This has been made possible by employing the widely accepted mathematical model of fouling established by Kern and Seaton.[2]

Corrosion of external surfaces

From the results of the experiment it can be concluded that, there was no significant difference between the corrosion of the thermosphon's external surfaces facing the flue gas and those of the lee side since fouling accumulation was rapid causing very low erosional corrosion. There was no significant difference in corrosion on the thermosyphon between the 3 different thicknesses of enamel used. In other words, all data taken from each set of coated metal can be classified as one group. The optimum coating thickness was found to be 190 µm. The average amount of corrosion of 3 different thicknesses enamel coated tubes for both steel and copper tubes at 1,000 hours of operating time was 0.038 mm. In case of mild steel tubes, corrosion of the enamel coated tubes was 0.15 mm lower than that of standard tubes. And in case of copper tubes, corrosion of the enamel coated tube was 0.136 mm lower than that of standard copper tubes. This result corresponds to the experiment of Polasek and Stule[5] although their testing dealt with the enamel coating of low carbon steel thermosyphons and widely available copper tubing.

In the case of operating time, it was found that corrosion of a standard tube increase with operating time. Fig 2 shows the correlation between the corrosion and operating time of standard and enamel coated tubes with different thicknesses according to the following correlation:

$$Cr = 0.008t^{0.4578} \tag{2}$$

where Cr is the corrosion measured in millimeters
t is the operating time in hours

and the corrosion of steel thermosyphons with 3 different enamel thicknesses can be predicted with respect to time by the following correlation:

$$Cr = 0.0073t^{0.2431} \tag{3}$$

After comparing the corrosion of the coated and standard steel tubes, it can be observed that, at the completion of the experiment of 1,000 hours the corrosion of the standard tubes was 4.9 times higher than that of the enamel coated tubes. In the case of copper standard tubes, corrosion occurred in in the form of:

$$Cr = 0.0231t^{0.2938} \tag{4}$$

Corrosion of the coated copper thermosyphon can be correlated as follows:

$$Cr = 0.0347t^{0.0202} \tag{5}$$

At the conclusion of the experiment of 1,000 hours the corrosion of the standard copper tube was 4.45 times higher than that of enamel coated tubes.

Fouling accumulation on external surfaces of the thermosyphons

Fouling deposition

From the monitoring of fouling deposition, it can be concluded that, there was no significant difference between the fouling deposited on the external surface of thermosyphons facing the flue gas and those of the lee side. In addition, the graph in Fig 4 shows the correlation between fouling deposition and the operating time of standard steel tubes and enamel coated steel tubes. It was also found that, the fouling deposition increased with the operating time. By using the model of Kern and Seaton, the correlation between the deposition and operating time of steel thermosyphons was as follows:

$$R_{fouling} = 28.6275(1-e^{-0.0018t}) \tag{6}$$

where $R_{fouling}$ is the thickness of deposited fouling in millimeters
t is the operating time in hours

It was also predicted that at 2,000 hours the

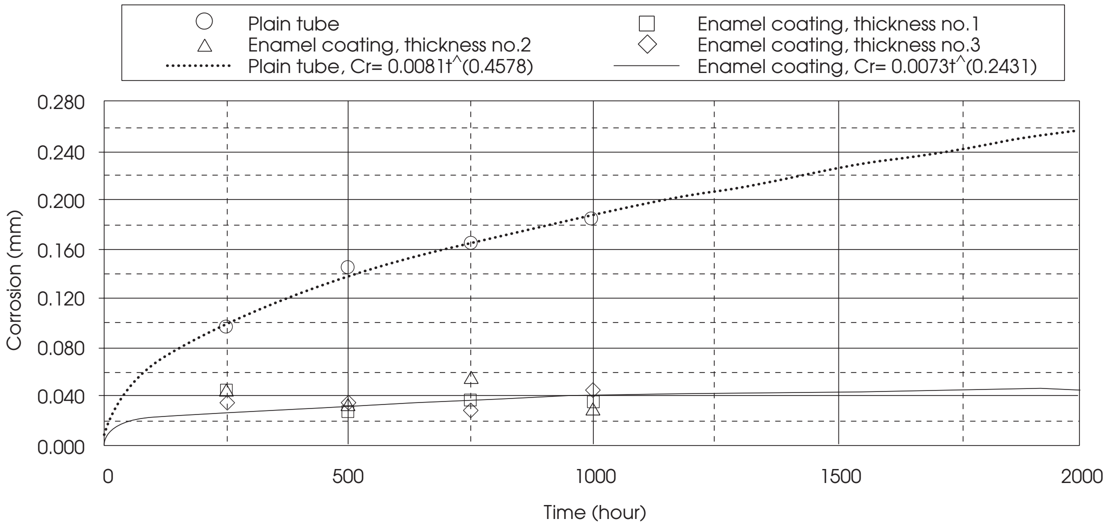


Fig 2. Corrosion with respect to operating time of standard and enamel coated steel tubes.

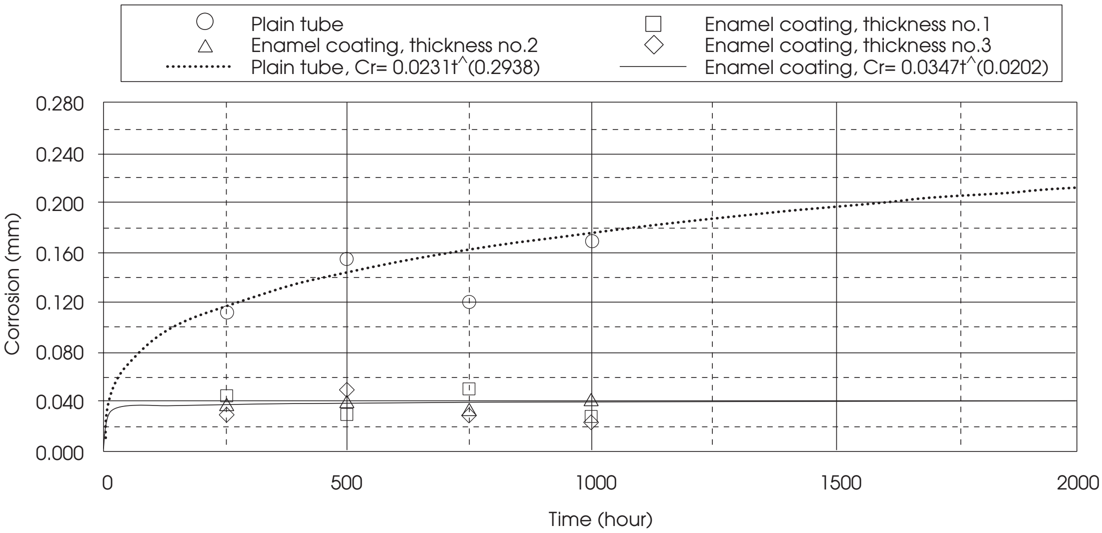


Fig 3. Corrosion with respect to operating time of standard and enamel coated copper.

maximum deposition would be 28.63 mm and fouling deposition is likely to be 28.30 mm thick. As cleaning should be conducted at the asymptotic operating time (because the deposition rate would be at the minimum value and the total thermal resistance of the tube would be at the maximum value also), the highest fouling accumulation point at 2,000 hours would, therefore, be the optimum time.

Fig 5 shows the correlation of fouling deposition and the operating time of standard and enamel coated copper thermosyphons at 3 different thicknesses as:

$$R_{fouling} = 31.3438(1-e^{-0.009t}) \qquad (7)$$

This correlation is similar to correlation (6), the maximum deposition would be 31.34 mm and fouling deposition is likely to be 30.09 mm thick at 5,000 hours. As cleaning should be undertaken at the highest fouling accumulation point, 5,000 hours would therefore be the optimum time.

Comparing the fouling deposition of the steel and copper thermosyphons, it was noticed that, steel thermosyphons were quicker to reach a constant fouling deposition. By using the mathematical model of Kern and Seaton,[2] it was predicted that, the deposition was likely to be the same amount.

Average fouling deposition rate

From the results it can be concluded that, there

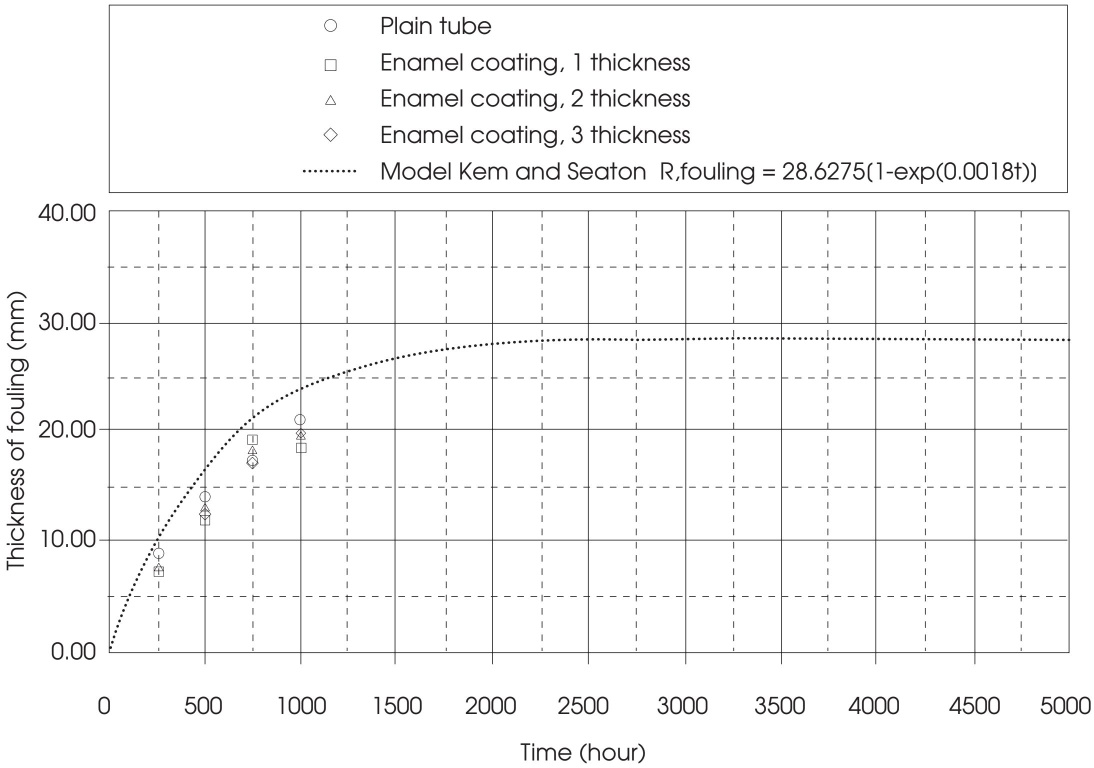


Fig 4. Fouling deposition with respect to operating time of standard and enamel coated steel thermosyphons.

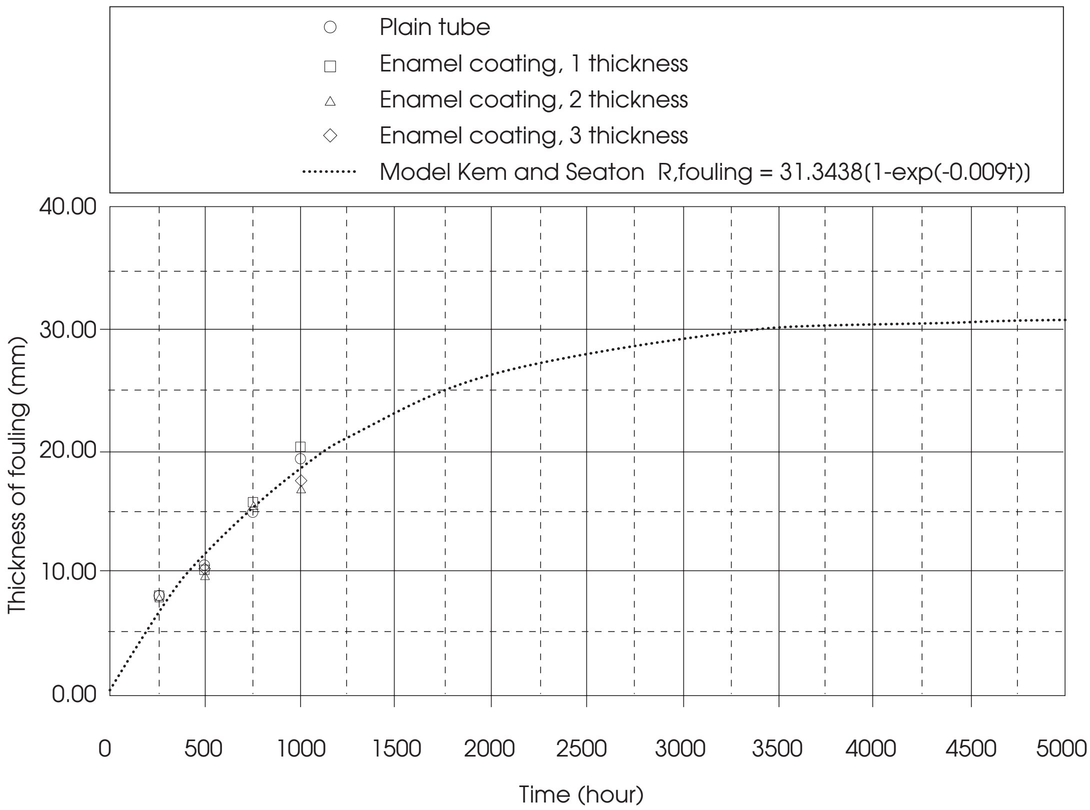


Fig 5. Fouling deposition with respect to operating time of standard and enamel coated copper thermosyphons.

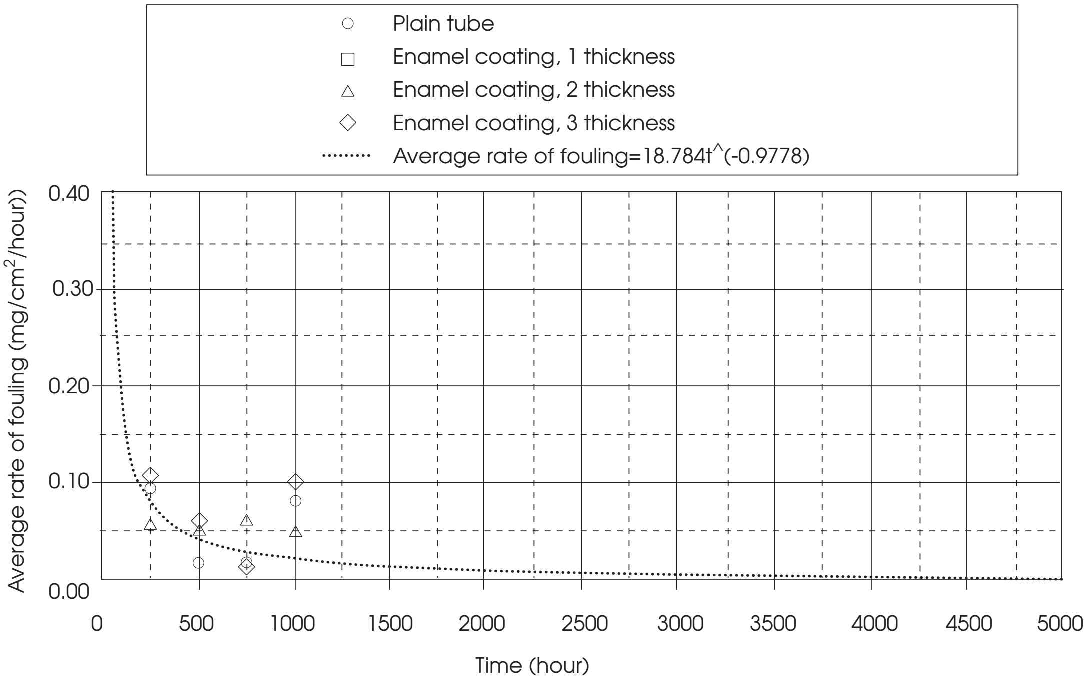


Fig 6. Average fouling deposition with respect to operating time of standard and enamel coated steel tubes.

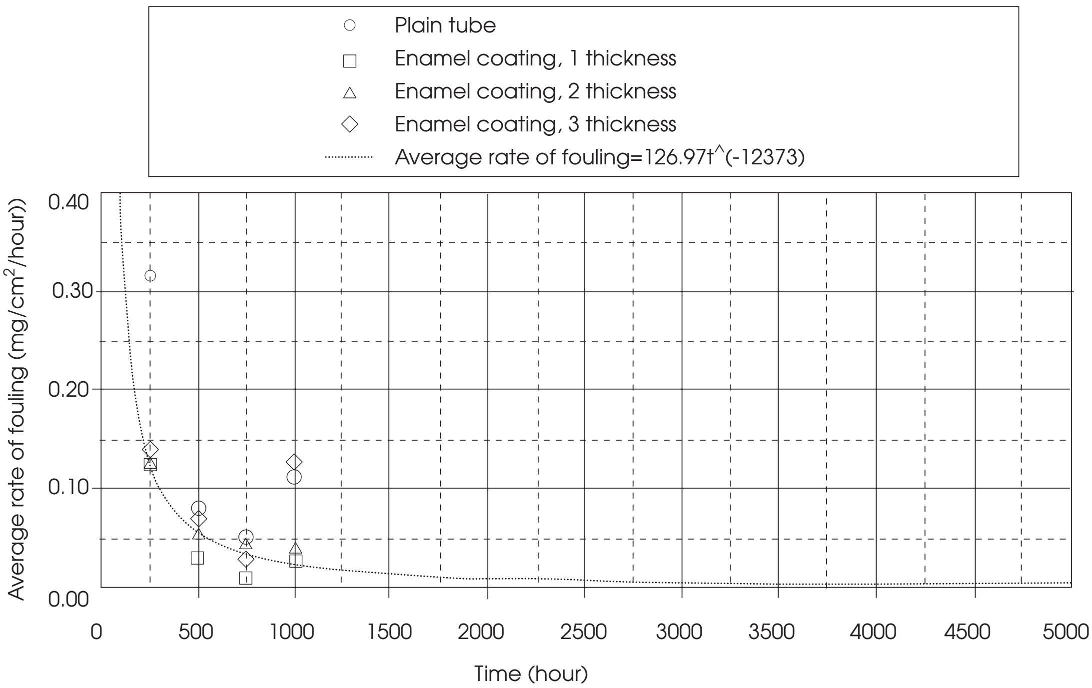


Fig 7. Average fouling deposition with respect to time of standard and enamel coated copper samples.

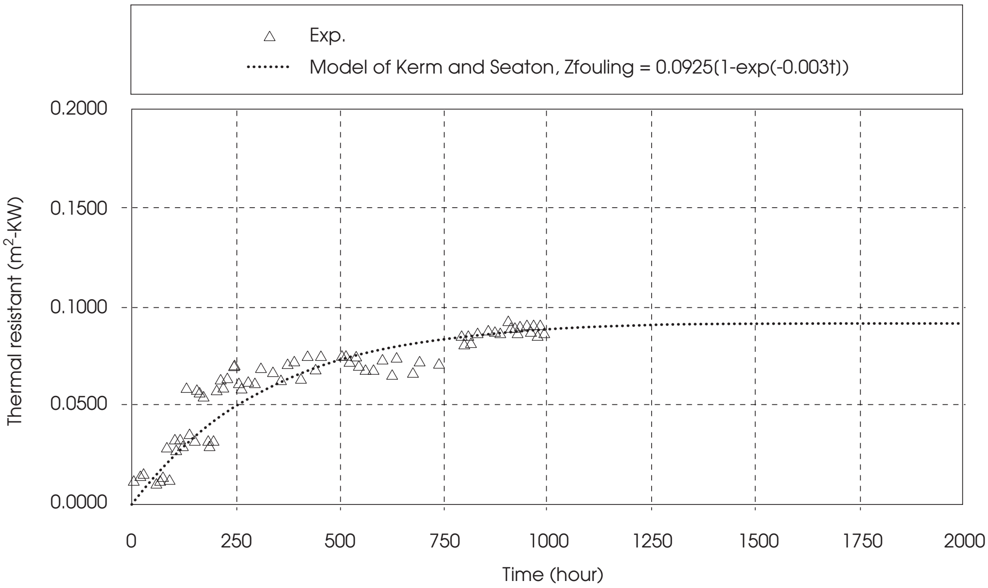


Fig 8. Fouling's total thermal resistance of thermosyphon economizer with respect to time.

was no significant difference between the fouling deposited on the external surface of thermosyphons facing the flue gas and that of the lee side. In addition, the graph in Fig 6 shows the correlation between the average fouling deposition rate and operating time of standard steel tubes and enamel coated steel tubes. It was also found that, the average fouling deposition rate increased with the operating time. By using the model of Kern and Seaton, the correlation between the deposition rate and operating time of the steel thermosyphon is as follows:

$$RW_{fouling} = 18.784t^{-0.9778} \quad (8)$$

where $RW_{fouling}$ is the deposition rate in mg/cm^2/hour
t is the operating time in hours

Basing the prediction on the mathematical model of Kern and Seaton (1959), the study also revealed that, the average rate of fouling accumulation is likely to be 0.011 mg/cm^2/hour at 2,000 hours. The rate also appeared very low compared to the fouling deposition rate.

Fig 7 presents the correlation of the average fouling deposition rate and operating time of both the standard and enamel coated sample disk with different thicknesses. The graphs plotting the data taken from the sample steel and copper coated disks were found to be similar. The correlation is as follows:

$$RW_{fouling} = 126.97t^{-1.2373} \quad (9)$$

By using the mathematical model of Kern and Seaton (1959), the study revealed that, the average rate of fouling accumulation is likely to be 0.01 mg/cm^2/hour at 2,000 hours. The rate seems to be very low compared to the fouling deposition rate.

Fouling composition

It can be observed from the analysis by the XRD and IR that, the inorganic compound found in the fouling on the tubes was $CaSO_4$, which was the same as found by Novotna *et al.*[4] The compound indicated that the fouling found on the thermosyphons was the product of combustion in the burner. No organic compounds were found from results obtained from the IR

Conclusion

Protection against corrosion on the external surface of thermosyphon economizers by enamel coating was experimentally investigated. Results showed that:

- At an operating time of 1,000 hours, the average corrosion of 3 different thicknesses enamel coated tubes for both steel and copper tubing was 0.038 mm. Corrosion of standard mild steel tubing was 4.9 times higher than that of the enamel coated tubing and corrosion of standard copper tubing was 4.45 times higher than that of the enamel coated ones.

- Fouling composition was $CaSO_4$.
- Correlation between corrosion and time of the standard mild steel thermosyphon and the coated mild steel thermosyphon was $Cr = 0.008t^{0.4578}$ and $Cr = 0.0073t^{0.2431}$ respectively. The correlation between corrosion and time of the standard copper thermosyphon and the coated copper thermosyphon was $Cr = 0.0231t^{0.2938}$ and $Cr = 0.03474t^{0.0202}$ respectively.
- Correlation between the average rate of fouling and time of the mild steel thermosyphon and copper thermosyphon was $RW_{fouling} = 18.784t^{-0.9778}$ and $RW_{fouling} = 126.97t^{-1.2373}$ respectively.

SYMBOLS

Cr	corrosion	mm
$R_{fouling}$	fouling thickness	mm
$RW_{fouling}$	average rate of fouling deposition	$mg/cm^2/hour$
t	operating time	hour
b	fouling deposition coefficient	
f_d	fouling deposition rate	

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