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Effect of the Exhaust Gas Side Fouling on the Performance of a Plate and Shell Type Heat Exchanger

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Pakokaasupuolen likaantumisen vaikutus levylämmönsiirtimen toimintaan

Tiivistelmä

Tämän tutkimushankkeen tavoitteena oli selvittää, miten likaantuminen vaikuttaa levylämmönsiirtimen toimintaan. Likaantuminen huonontaa yleensä lämmönsiirtokykyä ja kasvattaa painehäviötä.
Tutkimus tehtiin Turun ammattikorkeakoulun Moottoritutkimuslaboratoriossa. Levylämmönsiirrin kytkettiin työkonedieselmoottorin pakoputkeen. Lämmönsiirtimen toisiopuoli jäähdytettiin suljetulla vesikierrolla. Tutkimuksen kokonaiskesto oli kolme viikkoa.
Tutkimus koostui kolmesta osiosta: referenssiajosta puhtaalla pakokaasulla, vaihtelevan kuormituksen ajosta sekä lopuksi likaavasta ajosta, jossa dieselmoottorin ruiskutusparametreja muutettiin savutuksen lisäämiseksi.
Referenssiajossa säädettiin virtaukset ja muut suunnitteluparametrit kohdalleen sekä mitattiin lämmönsiirtimen lämpöteho ja pakokaasupuolen painehäviö. Lämmönsiirtimen likaantuminen todettiin vähäiseksi, eikä merkittävää vaikutusta lämmönsiirtoon ja painehäviöön havaittu. Vaihtelevan kuormituksen ajossa tutkittiin lähinnä lämmönsiirtimen toiminnan stabiiliutta pakokaasun virtauksen ja lämpötilan muuttuessa nopeasti. Ongelmia lämmönsiirtimen käyttäytymisessä ei havaittu.
Likaavassa ajossa lämmönsiirtimen toiminnan todettiin muuttuvan nopeasti: lämmönsiirto huonontui ja painehäviö kasvoi selvästi ajon edetessä. Muutosnopeus kuitenkin hidastui ajan funktiona. Likaantumisen todettiin siten noudattavan asymptoottista käyrää. Tämän trendin varmistaminen olisi kuitenkin vaatinut selvästi pitempää ja lisäksi yhtäjaksoista ajoa.
Tutkimuksen lopuksi lämmönsiirrin avattiin. Levyjen pinta oli tasaisen noen peitossa. Selvimmin likaa kerääntyi kuitenkin poimutettujen levyjen kosketuspisteisiin, pakokaasuvirtauksen patopisteisiin.

Asiasanat
Lämmönsiirtimet, dieselmoottorit, lämmön siirtyminen, pakokaasut, likaantuminen

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Effect of the Exhaust Gas Side Fouling on the Performance of a Plate and Shell Type Heat Exchanger

Abstract

The aim of this research project was to investigate how fouling affects the performance of a plate type heat exchanger. In general, fouling usually deteriorates the heat transfer performance and increases the pressure losses.

The study was conducted in the Internal Combustion Engine Laboratory at Turku University of Ap-plied Sciences. The plate heat exchanger was installed into the exhaust pipe of an off-road diesel engine. A closed water circuit was adopted for cooling of the heat exchanger that was studied for a period of three weeks.

The study comprised three stages:

- Baseline measurements with clean exhaust gas
- Running procedure at varying engine loads
- Dirtying test cycle with higher exhaust smoke caused by the modified engine parameters

During the baseline measurements, the flows and other design parameters were adjusted correctly. The thermal capacity of the heat exchanger was also determined, as well as the pressure drop in the exhaust side. Fouling of the heat exchanger was observed to be low and no significant effect on the heat transfer or pressure drop was detected.

When running the engine at varying loads at the second stage of the study, the primary task was to study the stability of the heat exchanger operation during the fast changes of the exhaust flow and temperatures. No problems were detected in the operation of the heat exchanger.

At the third stage, dirtying test cycle, the heat exchanger operation was observed to change rap-idly. Heat transfer deteriorated and the pressure drop increased substantially during the test. The harmful changes, however, decelerated with increasing running hours. Fouling showed an asymp-totic curve shape. Confirming this trend would have, however, demanded for a considerably longer and continuous running period.

In the end of the study, the heat exchanger was opened. The plate surfaces were smoothly coated by soot. Most visibly, deposits were, however, found on the contact points of the corrugated plates, i.e., on the stagnation points of the exhaust flow.

Keywords

Heat exchangers, diesel engines, heat transfer, exhaust gases, contamination

Table of content

Figures

Tables

1 INTRODUCTION

To improve the energy efficiency of different prime movers, waste heat of working cycles is today increasingly recovered and utilized. In engine-driven power plants, exhaust heat forms the greatest waste thermal energy stream. Traditionally, this heat has been very thoroughly utilized in combined heat and power plants (CHP) but also in marine applications. Shell and tube type heat exchangers have been and are widely used as exhaust boilers since they can be rather easily cleaned: soot is easy to remove. However, new heat exchanger designs are being developed for exhaust thermal energy recovery to reduce the equipment size and cost.

The purpose of this study was to research the deposition of exhaust gas soot particles to the heat transfer surface and its effect on the performance of a plate and shell type exhaust gas heat exchanger, i.e. an exhaust gas economizer (EGE). Typically, soot deposition onto the heat transfer surface creates a resistant layer against heat transfer. This decreases the heat transfer rate. Soot deposition also increases the pressure drop of the gas flow, or it can even lead to total blockage of EGE. Furthermore, soot deposition increases the risk of soot fire inside the EGE.

A test installation was built in the Engine Research Laboratory at Turku University of Applied Sciences. The study was performed in close cooperation with the equipment manufacturer. The University of Vaasa also participated in the results analysis and publication.

2 FOULING OF HEAT TRANSFER SURFACE

Generally, the term ‘fouling’ is defined as accumulation and formation of unwanted materials on the certain surface. Fouling of heat transfer surfaces is one of the most important problems in the heat transfer equipment. Fouling on the heat exchanger surfaces is a major problem in waste heat recovery equipment which can lead to significant efficiency deterioration. Fouling of heat transfer surface affects both capital and operating costs of heat exchangers. The excess surface area is required to compensate for the reduced heat transfer coefficient due to fouling. The excess surface area means bigger and more expensive heat exchangers and increased installation costs. (Awad, 2011; Han et al. 2014)

Particulate fouling forms an insulating layer on the heat transfer surface which increases the heat transfer resistance by reducing the heat transfer coefficient. The fouling layer has a low thermal conductivity. The main determinant of the deposit thermal conductivity is density, which is just about 2% that of the density of the primary soot particles (98% porosity). The deposit thermal conductivity is in a magnitude of 0.040 W/Km, which is only approximately 1.5 times that of air (0.025 W/Km), since deposit is mostly composed of air. The deposit conductivity value is then comparable to the effective thermal insulator materials. (Abd-Elhady & Malayeri 2013; Awad, 2011; Lance et al. 2009)

As deposition occurs on heat transfer surface, the cross sectional area of the flow channel is reduced. The pressure drop is increased both due to the reduced flow area in the fouled condition and the rough character of the deposit. Rough surface promotes particulate deposition and sticking. (Abd-Elhady & Malayeri 2013; Awad, 2011)

Soot particles in the exhaust gases of diesel engines are within the nanometer range. They are mainly transported to the heat transfer surface due to the temperature gradient between the hot exhaust gases and the cold heat transfer surface. This is known as the thermophoresis mechanism. In a thermal gradient, gas molecules on the hot side of the particle collide with higher force than the molecules from the cooler side, and a net force is created toward the cooler region which is heat transfer surface. (Abarham et al. 2013; Abd-Elhady & Malayeri 2013)

The effect of the heat transfer surface temperature on fouling is not well defined. The rule of thumb is to expect more fouling as the temperature rises, due to the fact that the chemical activity rises with temperature. On the other hand, a low surface temperature promotes, for example, crystallization. As a result, depending on the fluid and surface material, an optimum surface temperature level could be found in many cases. (Awad, 2011)

The particulate fouling is of typical asymptotic fouling, which involves deposition of soot particles of incomplete combustion. The rate of fouling gradually falls with time and an asymptotic behavior is approached. During the asymptotic stage, the removal rate and the deposition rate remain constant and equal. The surface temperature of the fouling layer near the gas side increases as the fouling layer continues to grow. As a result, the temperature gradient between the gas and the fouling layer surface decreases, and, consequently, particle transport to the fouling layer decreases. The mechanisms leading to this stabilization are not clearly understood. The oscillating curve represents the practical asymptotic curve. The polynomial curve represents the ideal asymptotic curve. Asymptotic fouling is the most important and widely existed in the industrial applications. (Abd-Elhady & Malayeri 2013; Abarham et al. 2013); Awad, 2011; Incropera & De Witt, 1990)

3 EXPERIMENTAL SETUP

The test engine was a 4-cylinder, 4.4-liter, turbocharged, intercooled off-road diesel engine manufactured by AGCO Power in Nokia, Finland. The test engine was used to generate a predetermined exhaust gas flow to the inlet of the EGE. The used test fuel was summer quality fuel oil with a low sulphur content of below 10 mg/kg, provided by Neste Oil.

The plate and shell type EGE was installed into the diesel engine exhaust gas pipeline (Figure 1). The inlet and outlet cones were installed between the round exhaust pipe and the heat exchanger itself to get a smooth inlet and outlet flow for exhaust gas. The exhaust piping and EGE were thoroughly insulated to minimize the heat loss to surroundings.

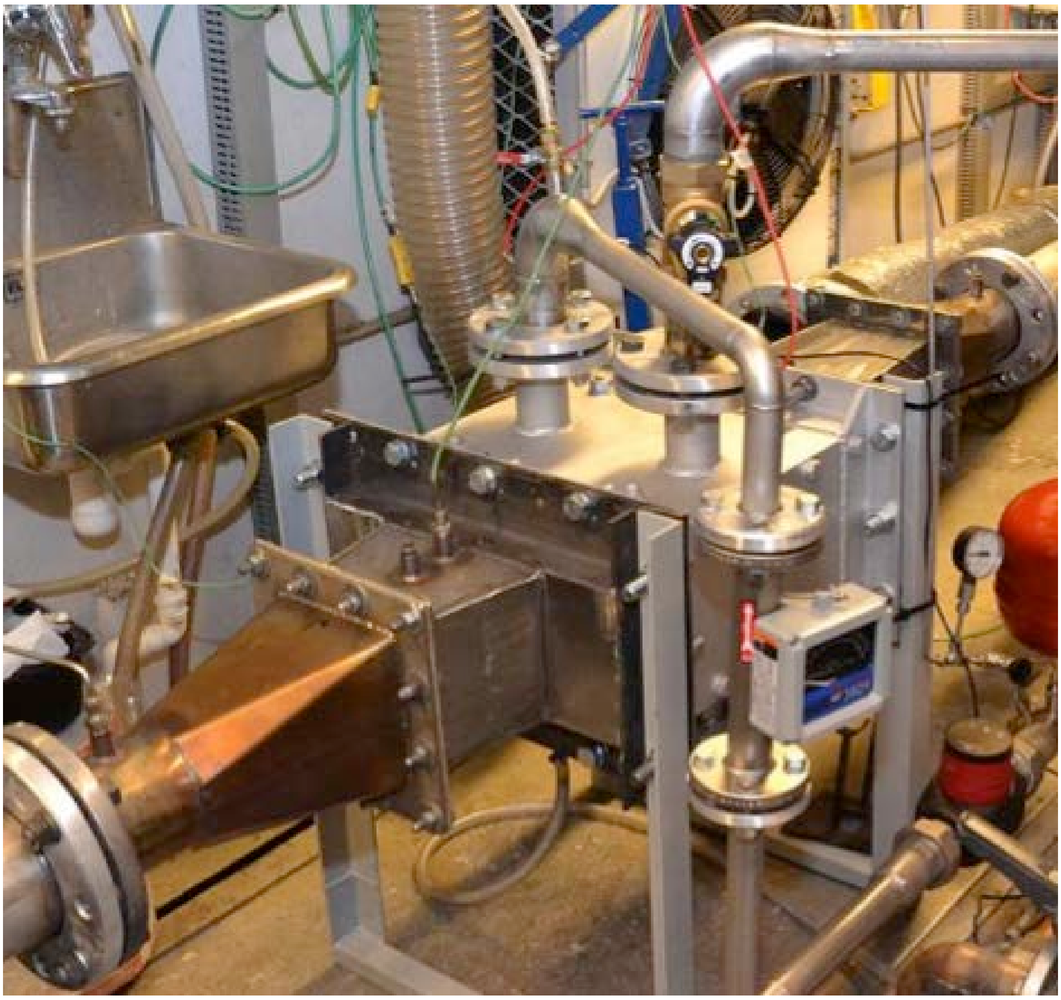

Figure 1. EGE in the diesel engine exhaust gas pipeline, still without insulation.

The heat from the exhaust gas was transferred to a closed-loop circulating water system. The exhaust gas and circulating water flows were cross-connected. Circulating water was further cooled by raw water in a separate cooling heat exchanger. The main purpose of the closed-loop circulating water system was to maintain a constant water mass flow (0.35 kg/s) through EGE and a constant water temperature (60°C) at the EGE inlet. The constant water flow was adjusted by a flow control valve and monitored by a variable area flow meter. The constant water temperature was controlled by a three-way motor valve, which had its own temperature sensor at the inlet water pipeline before/upstream the EGE.

The flow and instrumentation diagram of the test plant is presented in Figure 2.

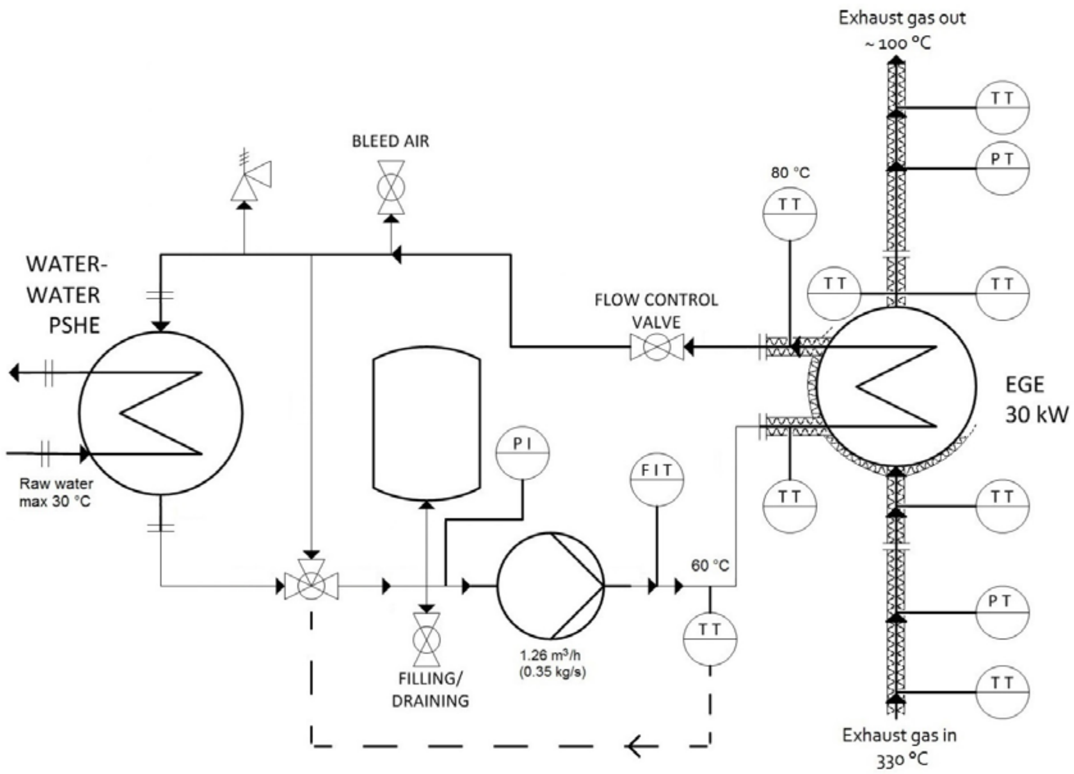

Figure 2. Flow and instrumentation diagram of test plant.

4 MEASUREMENTS

The measuring instruments are listed in Table 1.

Table 1. Measuring instruments.

Measured variable	Instrument specification
Temperature	Thermocouple type K (gas side), PT-100 sensor (water side)
Pressure	Keller Piezo-resistive pressure sensor
Water volume flow	Brooks MT 3809 flow meter
Charge air flow	ABB Sensyflow P Thermal Mass Flow meter
Fuel flow	Micro Motion CMF025M Coriolis Flow meter
Exhaust smoke	AVL 415 S Smoke meter

The exhaust pressure was measured before and after the EGE to determine the pressure drop. The exhaust gas temperature was measured at the inlet cone by one temperature sensor and after the EGE at the outlet cone by three temperature sensors. Because the EGE was cross-connected, the exhaust gas temperature profile after the EGE can be quite heterogeneous. Thus, using only a single temperature sensor could possibly lead to an error of several degrees. This phenomenon was taken into consideration by using three separate temperature sensors. An average value was used in calculations. Additionally, a temperature sensor was installed in the exhaust gas pipe at both inlet and outlet sides for checking.

The water temperature was measured before and after the EGE with a temperature sensor at each side.

The smoke generated by the test engine was measured by a paper blackening method. It determines Filter Smoke Number (FSN) in the range of 0 to 10 as defined in Standard ISO 10054. The sampling point of the smoke meter was downstream of the EGE.

5 CALCULATIONS

The pressure drop (Δp) at exhaust gas side was simply calculated as a difference of static pressures measured at inlet (p_{inlet}) and exit (p_{exit}) of the EGE:

$$\Delta p = p_{inlet} - p_{exit}$$

The exhaust gas mass flow rate ($\dot{m}_{exh}$) was calculated as a sum of charge air mass flow rate ($\dot{m}_{air}$) and fuel mass flow rate ($\dot{m}_{fuel}$):

$$\dot{m}_{exh} = \dot{m}_{air} + \dot{m}_{fuel}$$

The heat transfer rate was calculated at both exhaust gas (ϕ_{exh}) and water sides (ϕ_{water}), using thermodynamic properties and measured mass flow rates and temperature data:

$$\phi_{exh} = \dot{m}_{exh} \Delta h_{exh}$$

$$\phi_{water} = \dot{m}_{water} c_p \Delta T$$

The specific heat capacity (c_p) for water was determined as an average value within the measured temperature range, being approximately 4,186 kJ/ (kgK). The exhaust gas specific enthalpies (h_{exh}) were determined according to *Mollenhauer & Tschoeke, 2010* (Enclosure 2) as a function of the exhaust gas temperature and air/fuel ratio. The air/fuel ratio was calculated by means of the charge air mass flow rate, fuel mass flow rate and stoichiometric air/fuel ratio for diesel fuel oil (14,55 kg_{air}/kg_{fuel}):

$$\lambda = \frac{\dot{m}_{air} / \dot{m}_{fuel}}{14,55}$$

The service value for the heat transfer coefficient (U) was calculated by means of the heat transfer rate (ϕ), heat transfer surface area (A) and logarithmic mean temperature difference LMTD (θ_{ln}), calculated from the temperature data:

$$\phi = FUA\theta_{\mathrm{ln}}$$

A value of 0.94 was used for the LMTD correction factor F of the cross flow heat exchanger.

6 EXPERIMENTAL MATRIX

The EGE was investigated in three different test runs:

- reference test with a clean EGE
- cycle test
- smoke test.

Every test lasted one week, including five test days with a total of approximately 36 running hours per one test run.

The first test was a reference test with a clean EGE. The test engine was driven using factory settings in the engine parameters. This resulted in a smoke level of 0.03 FSN, which is typical of modern off-road diesel engines. Only one engine loading point (torque 300 Nm, 2200 rpm) was used in the reference test to generate the predetermined exhaust gas flow of 0.16 kg/s with an inlet gas temperature of 330°C.

The second test was the cycle test run. The engine control system was programmed to follow the predetermined engine loading points (Table 2).

Table 2. Cycle test run loading points.

Point	Torque (Nm)	RPM (1/min)
LP1	360	2200
LP2	300	2200
LP3	300	1600
LP4	150	1600

The loading point 2 was the same as the constant loading point in the reference test. The duration of the run at one loading point was 30 minutes and during that time three 60-second-average measurements were recorded.

After the cycle test the EGE was detached from the system for inspection. It was observed that the gas side heat transfer surface was completely covered by soot. The EGE was cleaned using a pressure washer in order to obtain a level of heat transfer rate as close as possible to the reference test.

The third and last test was the smoke test run. The engine fuel injection parameters were adjusted so that the smoke level was increased to 1.0 FSN. This value is typical of diesel engines made in or before the early 2000's. The selected value proved to be highly suitable to highlight the effect of soot deposition on the heat transfer rate and pressure drop at the selected test run period.

7 RESULTS AND CONCLUSIONS

7.1 Reference Test

The heat transfer rate, recorded during the reference test, is presented as a function of the time in Figure 3.

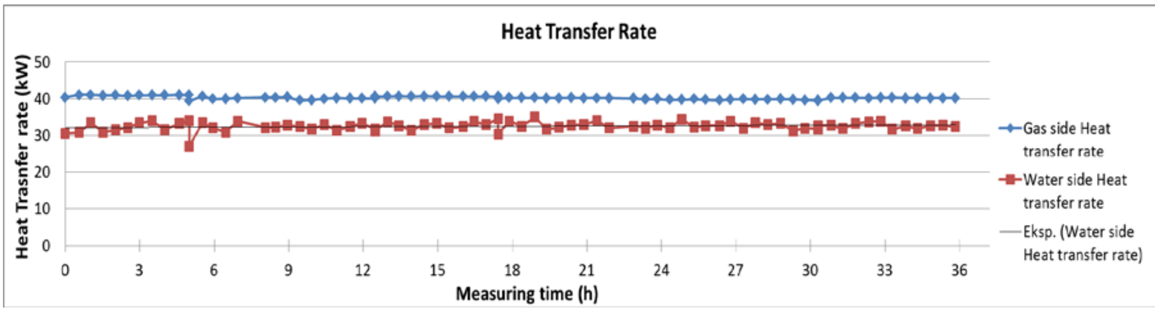

Figure 3. Heat transfer rate as a function of the measuring time

No clear reduction in the heat transfer rate could be observed during this test run. The heat transfer rate trend lines are practically horizontal.

A too large difference between the gas and water side heat transfer rates was detected which indicates an unrealistically high heat loss. This EGE was thoroughly insulated, so there could not be such a heat flow to the surroundings.

At first, the problem was investigated in gas side measurements. For example, comparison test measurements were conducted for temperature sensors, and the accuracy of the air flow meter was checked by measuring the oxygen content in exhaust gas. No explanation for the difference in the heat transfer rates were detected in these measurements.

Attention was then directed to the water side. The temperature sensors and flow meter were checked for accuracy. The flow meter was discovered to show low readings by 5…7 %. This explains the difference partially.

The difference in the calculated heat transfer rates looked to be clearly based on a systematic error in the measurements and does not affect the conclusions about the correlation between the heat transfer rate and soot deposition. This same difference in the calculated heat transfer rates was observed throughout all the test runs. Therefore, only gas side results are presented later in this report.

In the reference test, only a slight reduction in the service value for the heat transfer coefficient could be observed (Figure 4).

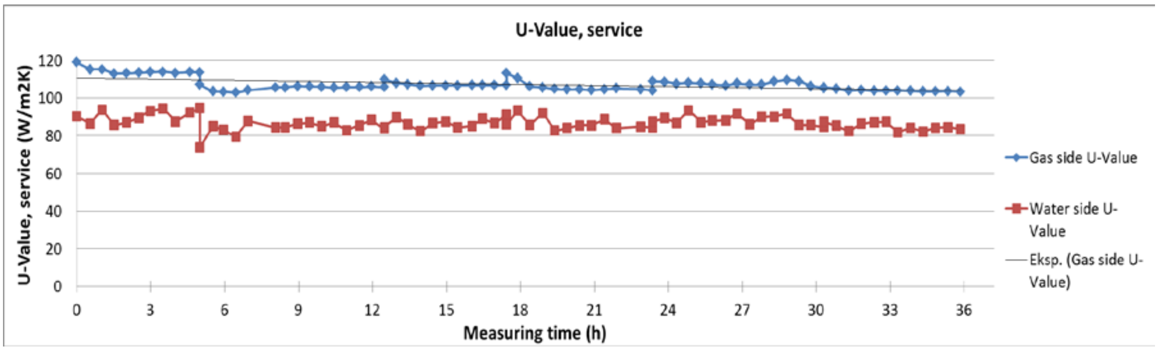

Figure 4. Service value for heat transfer coefficient as a function of the measuring time

A slight increase in the pressure drop over the EGE could be observed (Figure 5), but it flattened out when the test advanced. The pressure drop was approximately 12 mbar or 1.2 kPa.

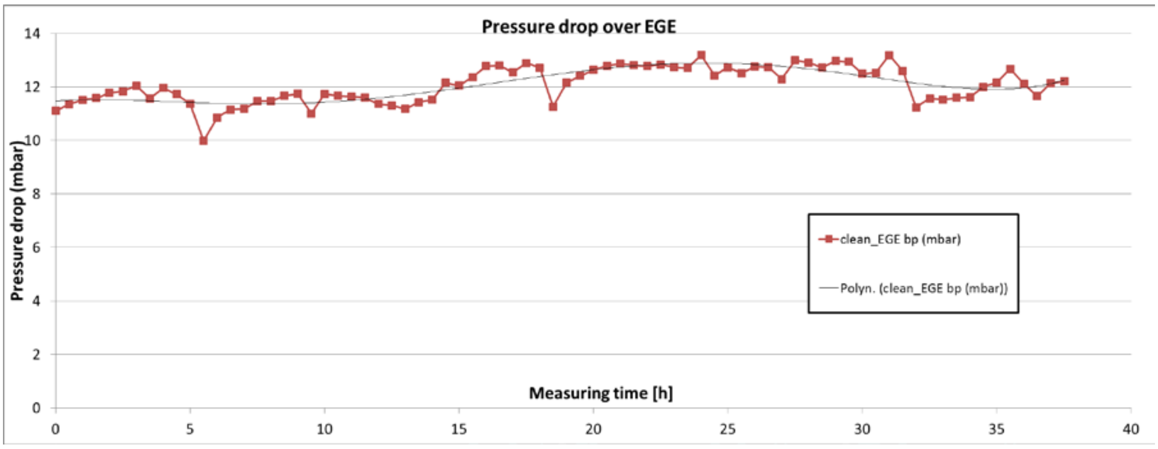

Figure 5. Exhaust gas pressure drop as a function of the measuring time.

As a conclusion, the one week test run with a very low smoke level led to a minuscule soot deposition onto the heat transfer surface and had a very small effect on the heat transfer rate.

7.2 Cycle Test

The heat transfer rate, determined during the cycle test run, is given as a function of the measuring time in Figure 6. In this test, the engine was operated in four different loading points to find out how the EGE works when the exhaust mass flow rate and temperature vary within a large range. When the first test (steady state reference test) simulated a constant load generator set, this second test simulated transient loading, typical of vehicle applications, for example.

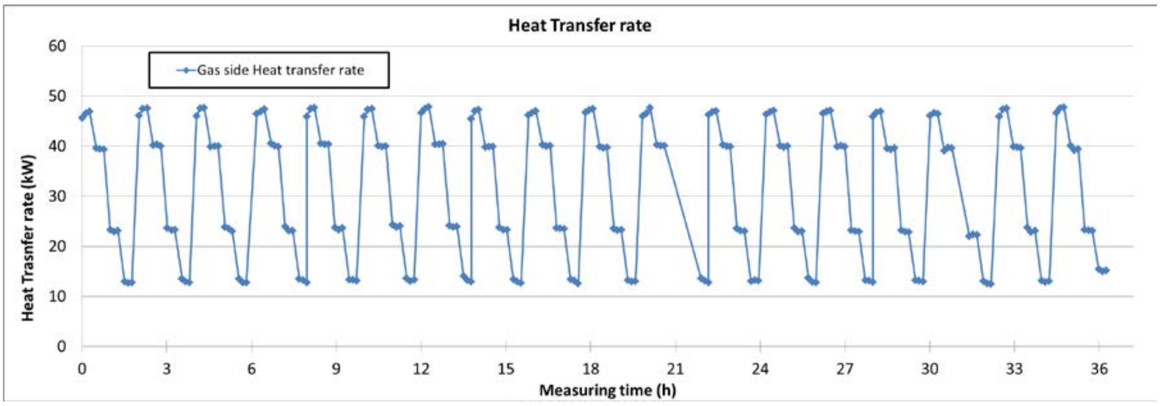

Figure 6. Heat transfer rate as a function of the measuring time.

Even during this test run, no clear reduction in the heat transfer rate could be observed but the heat transfer rates were at a very constant level in every four loading points. The EGE behavior was quite stable, as seen in Figures 7 and 8, where the loading points 1 and 4 are separately presented.

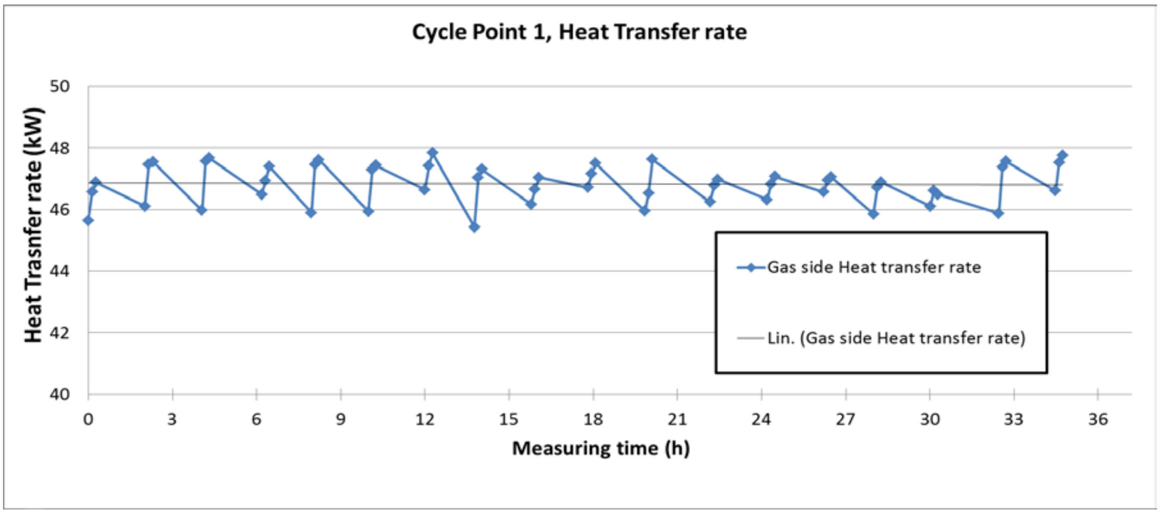

Figure 7. Heat transfer rate at loading point 1 as a function of the measuring time

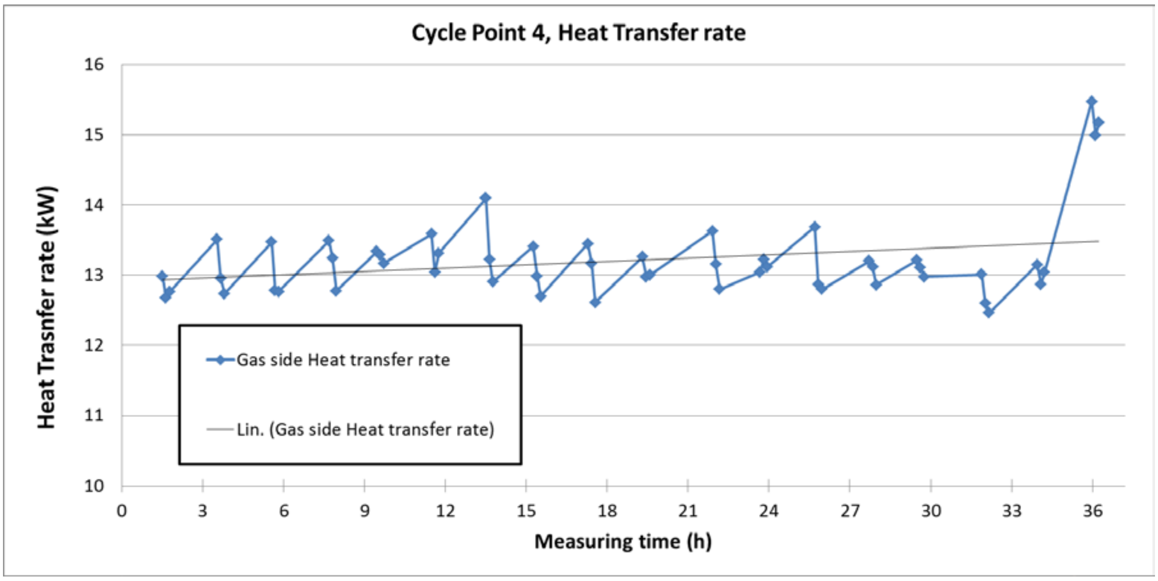

Figure 8. Heat transfer rate at loading point 4 as a function of the measuring time.

7.3 Smoke Test

The heat transfer rate, measured during the smoke test run, is illustrated as a function of time in Figure 9.

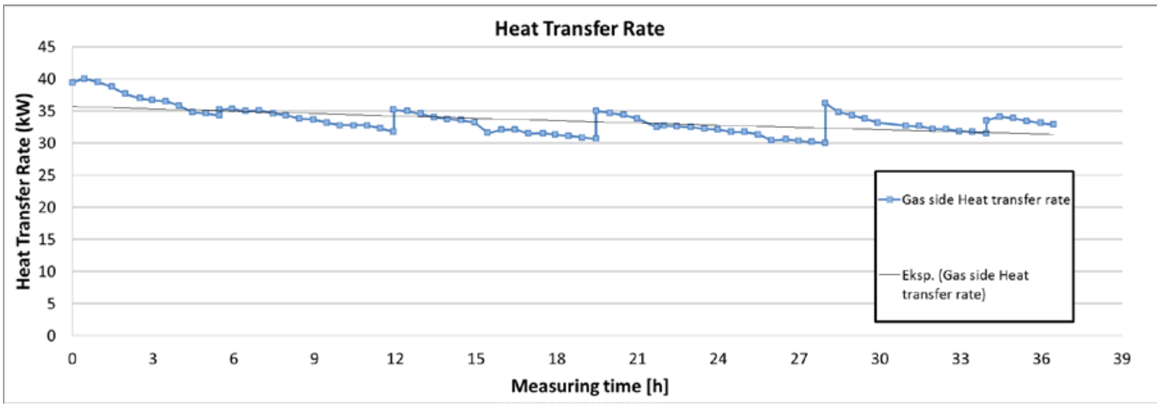

Figure 9. Heat transfer rate as a function of the measuring time

In this third test run, a clear reduction in the heat transfer rate was observed due to soot deposition onto the heat transfer surface. According to the trend line, the reduction was approximately 13%.

It should however be noted that a recovery of the heat transfer rate was detected between the test days (after 6, 12, 19, 28 and 34 running hours, approximately, in Figure 9). One reason for this might be EGE's cooling and warm up between the test days. The thermal expansion coefficients of the steel plates and soot are different, so temperature fluctuation may crack the soot layer which is then blown away during the engine warm-up period.

As concluded by Abarham et al. (2013), water condensation may be important for deposit removal. The small particles that form the bulk of the deposit layer are held on the surface by Van der Waals forces. The hypothesis is that the condensed water creates an environment where those forces are weakened, so that the deposit layer can be cracked and blow away. Water condensation occurs during the start-up phase when the heat transfer surfaces are cold. The phenomenon was also observed visually when looking at the dismantled heat exchanger. The deposit layer near the cooling water inlet region was moist.

In the beginning of the test, a similar decreasing trend could be seen in the U value as in the heat transfer rate but the U value flattened/levelled out after approximately 12 hours of testing (Figure 10). One reason for this might be the growth of the soot layer which reached the balance between the build up and removal of soot particles on the heat transfer surface. After that point, the U value became steady/almost constant (asymptotic fouling).

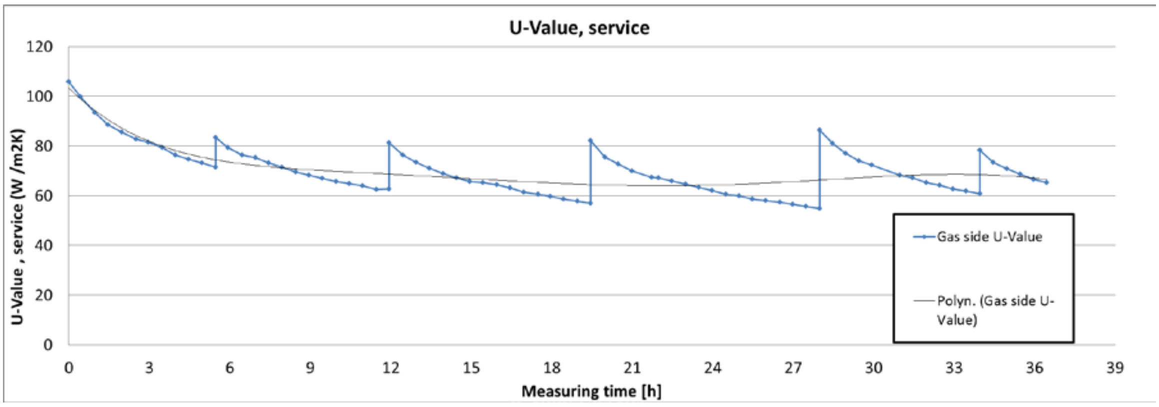

Figure 10. Service value for heat transfer coefficient as a function of the measuring time

Abd-Elhady & Malayeri (2013) also observed that fouling had a significant impact on the performance of the heat exchanger during only the first 12 hours of operation. The thermal resistance of the cooler increased continually throughout the test period, but the rate of increase of the thermal resistance decreased with time until it reached an asymptote.

The measured pressure drop trend seemed to confirm this phenomenon since the pressure drop reached the asymptote after 40 hours of operation, approximately (Figure 11). The long term progression remained still uncertain. For comparison, the pressure drop increased from its initial state to the asymptote within 42 hours of operation in the studies of Abd-Elhady & Malayeri (2013).

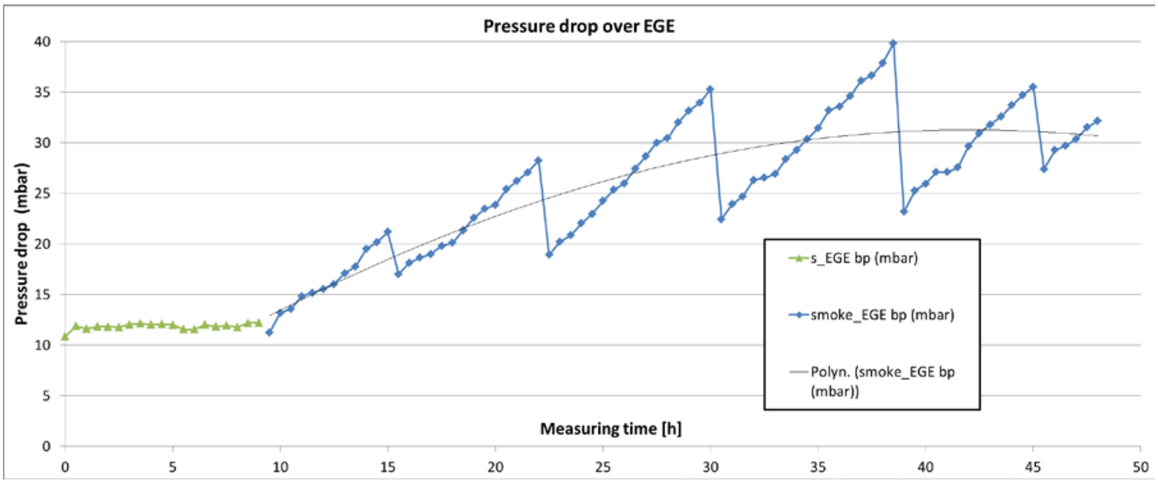

Figure 11. Exhaust gas pressure drop as a function of the measuring time.

In both the heat transfer coefficient and pressure drop curves, an asymptotic fouling behavior could be observed. The measured oscillating curve shapes represent the actual behavior, still also showing an asymptotic trend. The shapes of the curves are combined results of, on one hand, partial removal of some deposit to be followed by, on the other hand, a rapid build-up of a new deposit layer. The polynomial curves represent the ideal asymptotic-like curves. Asymptotic phenomenon was also reported by Garrett-Price et al. (1985), Abd-Elhady et al. (2011) and Warey et al. (2012).

8 THICKNESS OF DEPOSITION LAYER

After the test runs, the EGE was dismantled for inspection. The thickness of the deposit layer was measured by using the triangular instrument shown in Figure 12.

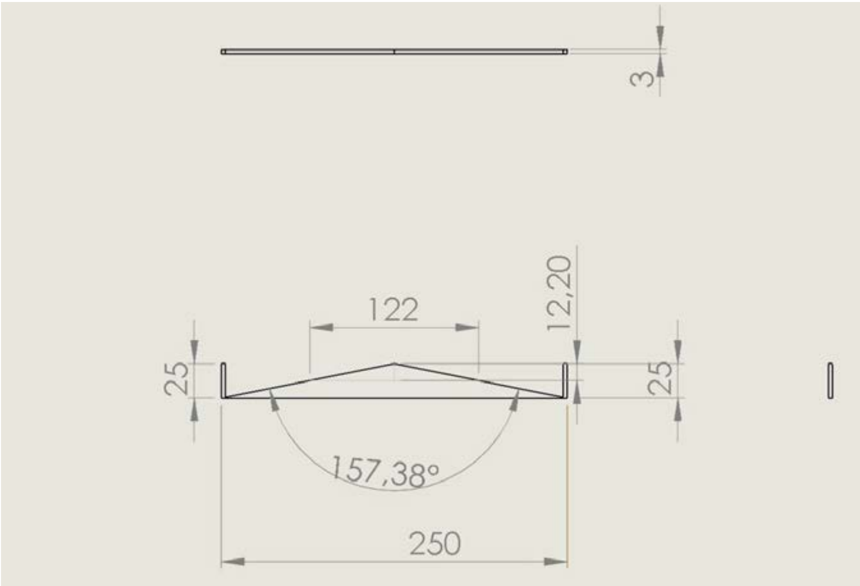

Figure 12. The triangular instrument for measuring the thickness of the deposit layer

The surface of the heat transfer plate was scratched by the obtuse angle of the instrument. Then the width of the scratch was measured by an electron microscope (Figure 13). The thickness of the layer is one tenth of the width of the scratch. A thickness within the range of 20 – 30 µm was observed. As stated by Awad (2011), in many cases the thickness of the deposit layer is relatively small, less than 50 µm, so direct measurement is not easy to perform.

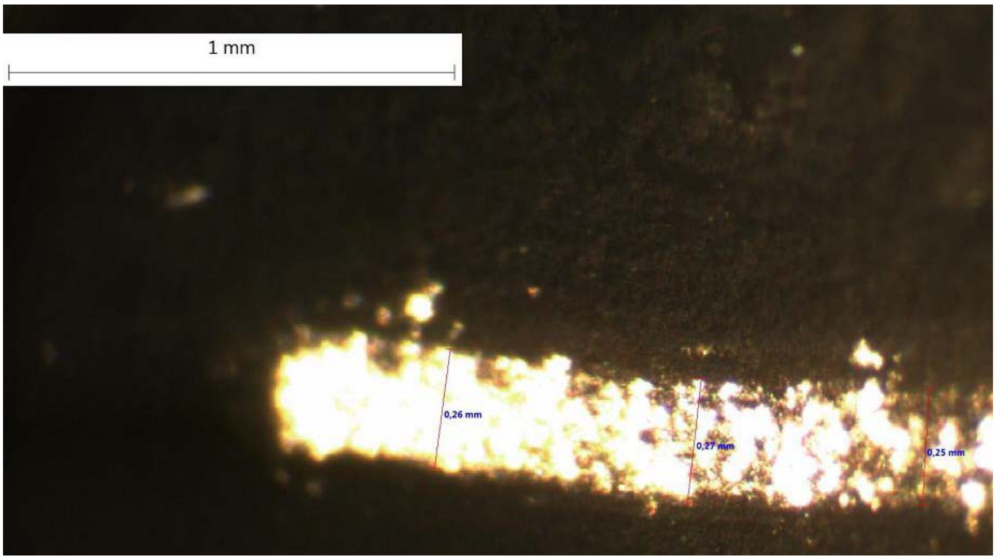

Figure 13. The width of the scratch measured by the electron microscope

Most of the deposits were agglomerated onto the points, where corrugated plates contact each other. As stated by Han et al. (2014), particle deposition mainly occurs in the flow stagnation region, where the flow velocity is relatively low.

9 ACKNOWLEDGMENTS

Several people have contributed to the success of this study. The authors wish to thank the Finnish company Vahterus Inc. for the interesting project topic and their confidence in Turku University of Applied Sciences (TUAS) as a partner.

The test runs were carried out at the Engine Research Laboratory at TUAS. Mechanic Aarni Andersson was a key person both to build up and maintain the experimental setup. Project assistants Aku Hietaranta and Arttu Niemi were closely coupled both to the test runs and the design and construction of the experimental setup. They also made their B.Sc Theses in this project.

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