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OPTIMIZATION OF FLOW DIRECTION TO MINIMIZE PARTICULATE FOULING OF HEAT EXCHANGERS

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ABSTRACT

The influence of flow direction with respect to gravity on particulate fouling of heat exchangers is investigated experimentally to determine the optimal flow direction to minimize fouling. Four orientations of flow have been investigated, horizontal flow, upward flow, downward flow and a flow under an angle of 45°. It is observed that fouling starts at the point of stagnation irrespective of the flow direction, and also at the top of the heat exchanger tubes. Particulate fouling grows from these two points till they meet and the fouling layer covers the whole surface of the heat exchanger tube. Fouling at the upper half of the tubes is much faster than the lower half of the tubes, and the fouling rate is faster at the bottom tubes of the heat exchanger section than at the upper tubes. The best orientation for lingering particulate fouling is the downward flow, where the flow stagnation point coincides with the top point of the heat exchanger tubes and the growth of the fouling layer only starts from one point.

INTRODUCTION

Particulate fouling is defined as the accumulation of particles on a heat transfer surface that form an insulating layer, which reduces the rate of heat transfer and can lead to operation failure as has been reported by many researchers, e.g. in waste incinerators by van Beek et al. (2001), in a coal-fired power plant by Bryers (1996) and in utility scale boilers by Gupta et al. (1999). Transport and capture of particles on heat transfer surfaces are functions of the size of particles, the chemical and physical properties of the transported particles, as well as the combustion system conditions, such as gas flow patterns, velocity, local temperature etc., Benson et al. (1993). A theoretical background about particulate fouling and especially gas side fouling can be found in literature of Epstein (1983, 1987) and Marner (1990). Many efforts have been made by numerous researchers to understand and control fouling in heat exchangers (Taborek et al., 1972; Müller-Steinhagen et al., 1988; Bohnet, 1987; Bott, 1995). Hupa (2005) has performed fouling experiments using mixtures of rice husk and eucalyptus bark as fuels. A mixture of the two fuels was burned in a 9 m tall entrained flow reactor and the fly ash produced was captured by an air-cooled probe at the bottom of the reactor. Hupa (2005) found that the rice husk ashes do not stick to the test probe surface because of their large size, i.e. several hundreds of microns, while the bark ash, which has a particle size in the order of microns, very readily sticks on the surface and forms a gradually growing deposit on the windward side of the probe, i.e. upstream of the flow. However, the results of Hupa (2005) differ from the work of Kaiser et al. (2002) and Abd-Elhady et al. (2004), who studied the deposition of particles on cylindrical tubes, and found that the formation of foulant is mostly at the rear part of the cylindrical probes, i.e. downstream side of the tubes. The direction of flow in case of Hupa's experiments (2005) was downwards while in case of Kaiser et al. (2002) and Abd-Elhady et al. (2004) was upwards, which suggests that the flow direction with respect to gravity might influence the position at which particulate fouling starts.

Kalisz and Pronobis (2005) found that particulate fouling in the economizer of a pulverized coal boiler occurred at the downstream side of the tubes, while at the end of the process a little wedge at the upstream was observed. In the measurements performed by Kalisz and Pronobis (2005) the upstream side of the tubes was the lower surface of the tubes, i.e. the flow was upwards. Nuntaphan and Kiatsiriroat (2007) investigated the effect of fly ash deposit on the thermal performance of a cross flow heat exchanger having a set of spiral finned-tubes as heat transfer surface (Nuntaphan, et al., 2005; Nuntaphan et al., 2005). The tubes of the heat exchanger were vertically mounted in a staggered array, and the flow was horizontal. Nuntaphan and Kiatsiriroat (2007) found that the deposition of fly-ash occurred at the frontal part of the tubes following the direction of flow, i.e. upstream of the flow. It can be concluded from the presented literature survey that the direction of flow influences the position at which particulate fouling starts as well as the fouling process. However**,** the relation between the flow direction and the position at which fouling starts is not well understood. In the presented research here the influence of the flow direction with respect to gravity on particulate

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fouling of heat exchangers is investigated experimentally to study this relation and to determine the best flow orientation to minimize fouling.

EXPERIMENTAL SETUP AND THE EXPERIMENTAL PROCEDURE

An experimental setup has been built to study the effect of flow direction with respect to gravity on particulate fouling of heat exchangers. A schematic of the experimental setup is shown in fig. 1. The experimental setup can be rotated 360° around its horizontal axis, i.e. axis of tube 5, to get different orientation of flows such as vertical flow, horizontal flow and a flow under an angle with the direction of gravity. The experimental setup consists of an air blower connected to a wooden duct of size 40 cm × 40 cm × 400 cm. The power of the air blower is 1.5 kW at 1450 rpm, and delivers 0.25 m^3/s of air at normal operating conditions. The wooden duct contains a heat exchanger with 9 tubes arranged in an inline matrix, i.e. 3×3 tubes, as shown in fig. 1. The tubes have an external diameter of 3.2 cm and are made of steel. The tubes are numbered from 1 to 9, so they can be easily distinguished during the fouling experiments, see fig. 1. There is no secondary fluid in the heat exchanger tubes, i.e. the surface of the heat exchanger tubes is isothermal. A screw particle feeder is used to dispatch calcium carbonate particles in the airflow. By varying the rotational speed of the screw of the particle feeder the injection rate can be varied. The deposition of particles on the heat exchanger tubes can be monitored through two glass windows mounted on the sides of the wooden duct as shown in fig. 1. Two inspection doors are installed at the sides of the wooden duct for maintenance and cleaning the setup from the fouling particles. The speed of the air is measured at the exit of the wooden duct by a hot wire anemometer with an accuracy of ± 0.01 m/s. Air exhaust from the setup is filtered through a bag filter before it goes into the atmosphere.

In the experiments, ambient air is fed by the air blower into the duct, and particles are added by a particle screw feeder. Calcium carbonate particles of average diameter of 40 μm with a standard deviation of ±16 μm are used in the experiments as a source of fouling. In the experiments the volume flow rate of air and the injection rate of particles are kept constant at 0.2 m^3/s and 20 g/m^3 of air, respectively. Fouling of the tubes of the heat exchanger occurs as the air-particle mixture passes the heat exchanger. Fouling of the heat exchanger tubes is monitored using a digital camera through the installed glass windows, as shown in Fig. 1. The digital camera is a Finepix S602 zoom, with a resolution of 2832 pixels × 2128 pixels, i.e. 6.03 million pixels, and optical zoom of 6×. The fouling layer thickness is measured optically. Images of the heat exchanger tubes are taken before and during fouling. The clean heat exchanger tube radius is taken as a reference. The tube radii in the camera images and hence the fouling layer thicknesses are determined with an accuracy of ± 1 pixel which corresponds to ± 0.04 mm.

Four experiments are performed with different flow orientations, i.e. horizontal flow, flow at 45°, upward flow and a downward flow, to investigate the influence of flow direction with respect to gravity on particulate fouling of heat exchangers. In each experiment, the whole experimental setup is rotated as shown in fig. 2 to give the required flow orientation.

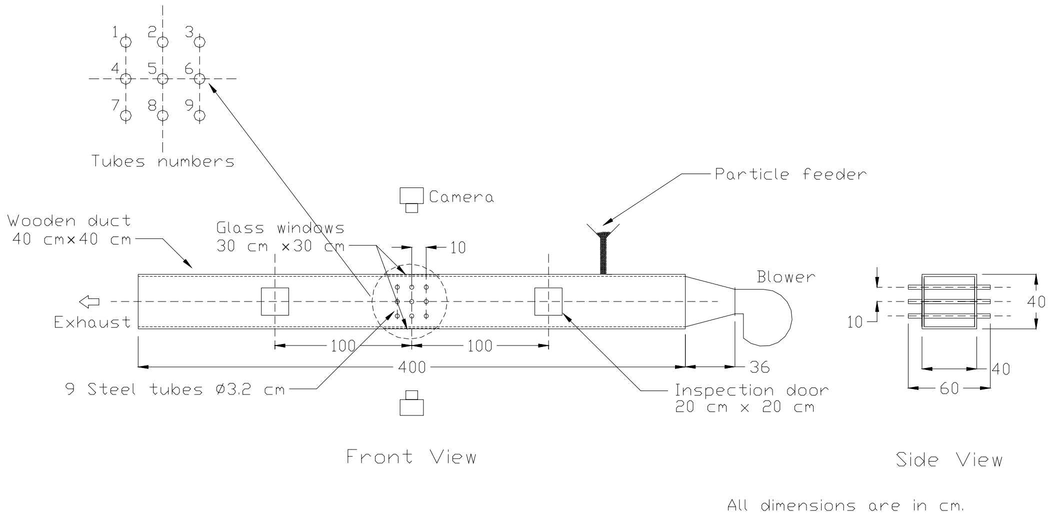


Fig. 1. The experimental setup used to study the effect of flow direction on particulate fouling of heat exchangers.

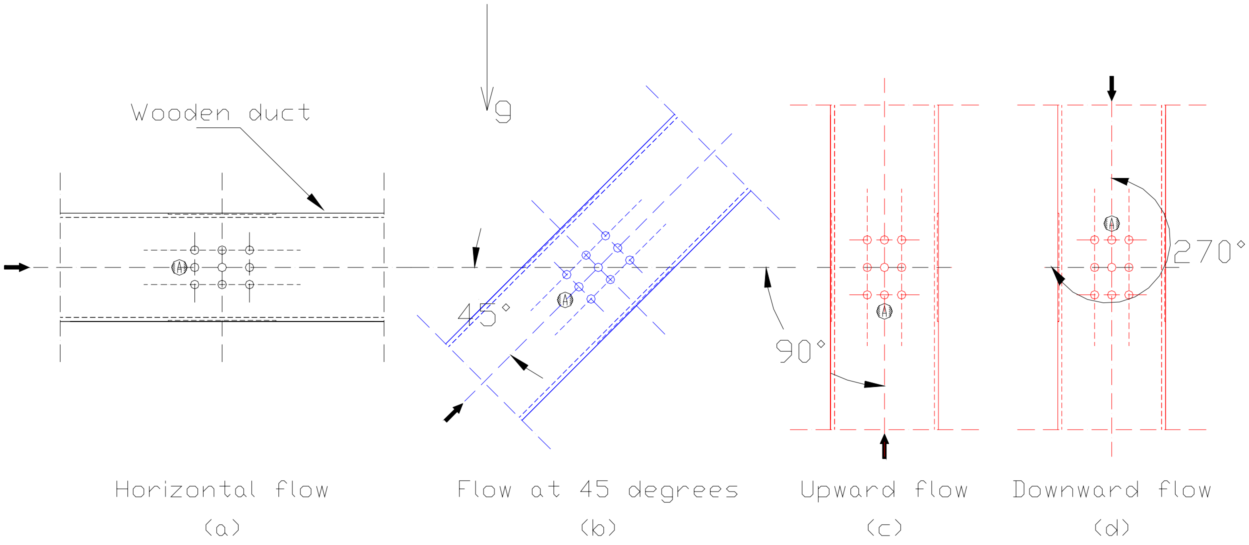


Fig. 2. The different orientations of the experimental setup to give (a) horizontal flow, (b) flow at 45°, (c) upward flow and (b) downward flow. g is the direction of gravity. Point A is at the upstream area of the heat exchanger, which is the same in all orientations.

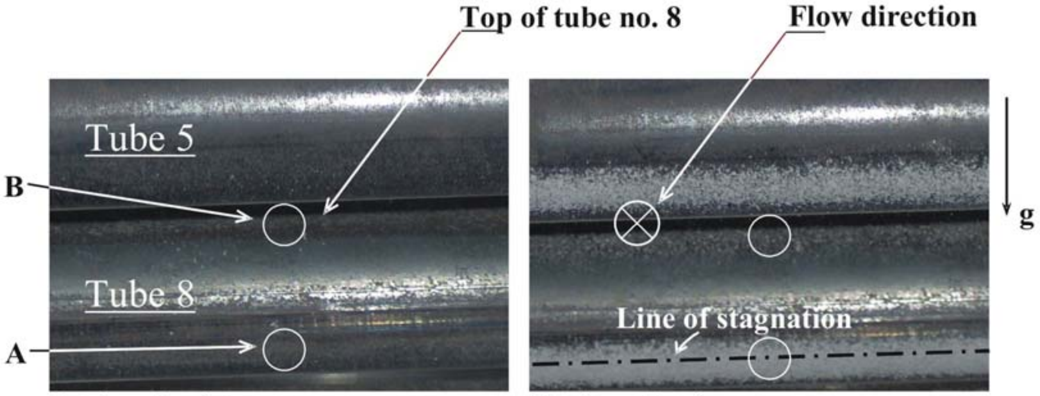
EXPERIMENTAL RESULTS

Horizontal Flow

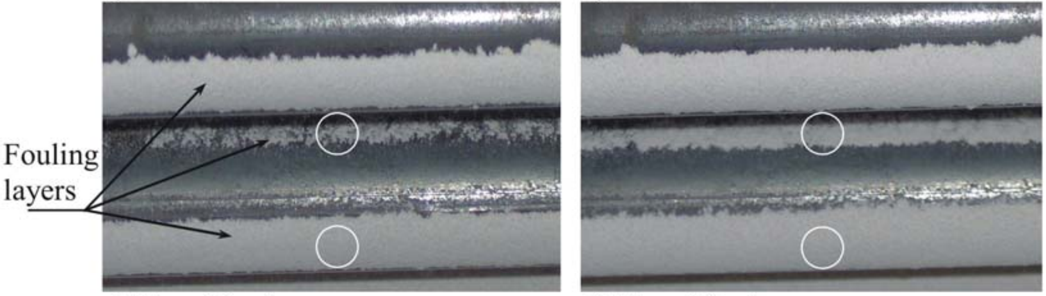
The growth of the fouling layer as a function of time for the horizontal flow case is shown in fig. 3. The pictures are for tubes number 5 and 8 in the second column of tubes of the heat exchanger section shown in fig. 1. The flow is horizontal and passing into the plane of the paper as indicated in fig. 3.b. The tubes at the beginning of the fouling experiment, i.e. time = 0, is shown in fig. 3.a. The grey color corresponds to the clean steel surface of the tubes. Points A and B indicated in fig. 3.a. correspond to the stagnation point (Achenbach, 1968; Lam et al., 2003) and the top of the heat exchanger tube no. 8, and the line of stagnation is indicated in fig. 3.b. The tubes after 10 and 30 minutes of operation are shown in fig. 3.b and 3.c, the white color corresponds to the fouling layer deposited on the tubes. The fouled part of the tubes shown in fig. 3 is the frontal part of the tubes in the upstream. It can be concluded from figs. 3.b and 3.c that fouling starts at two points, the point of stagnation, i.e. point A, and the top of the heat exchanger tube, i.e. point B, and the growth of the fouling layer continues from these two points as can be seen from the preceding pictures. This observation is in agreement with the findings of Nuntaphan and Kiatsiriroat (2006). Fouling at the upper half of the tubes is much faster than the lower half of the tubes, because particles that stick at the upper half of the tubes can not fall off by gravity due to the obstruction of the tube surface; however particles that stick to the lower half can fall off due to gravity. It is also found that the fouling rate is faster at the bottom tubes of the heat exchanger section, i.e. tubes 7, 8 and 9, than the upper tubes, i.e. tubes 1, 2 and 3. This is attributed to the increased concentration of particles in the lower portion of the heat exchanger caused by the falling off particles from the upper tubes.

Flow at 45º

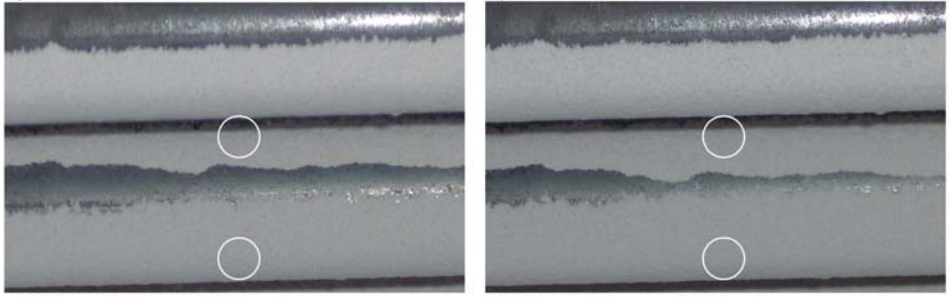
The growth of the fouling layer as a function of time in case of a 45º flow is shown in fig. 4. The tube shown is tube number 5. The flow is coming out of the plane of the paper as indicated in fig. 4.b. It can be seen that fouling starts at the top of the tube, which is the area bounded by points B and C. The growth of the fouling layer over the heat exchanger tube with respect to flow and gravity is illustrated in fig. 5. Points B and C in fig. 4.a correspond to points B and C in fig. 5. It is also found that fouling starts at the stagnation area of flow, i.e. point A presented in fig. 5. The growth of the fouling layer over the upper half of the tubes, i.e. area bounded by the curve A-B-C as indicated in fig. 5, is much faster than the fouling rate at the lower surface area of the tubes, i.e. area bounded by the curve A-D-C. The average thickness of the fouling layer at the upper half of the tubes after 3 hours of operation was 1 mm, however the thickness of the fouling layer at the lower surface of the tubes was very small, i.e. less than 0.05 mm.



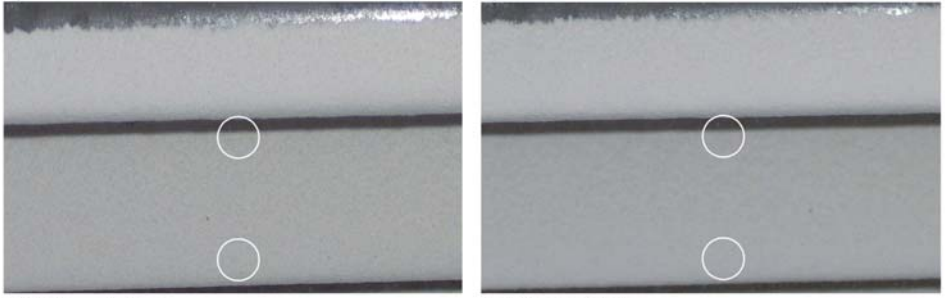
a) Time 0 min. b) Time 10 min.



c) Time 30 min. d) Time 50 min.

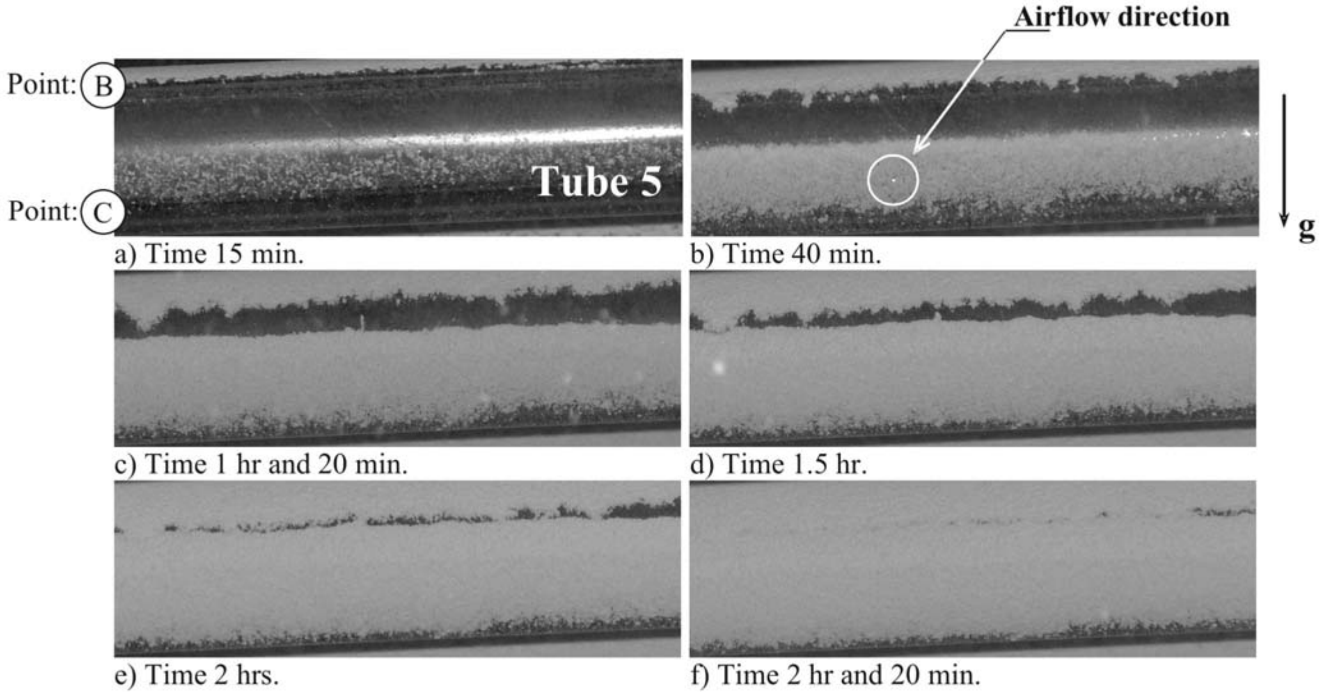


e) Time 1 hr and 20 min. f) Time 1 hr and 40 min.



g) Time 2 hr. h) Time 3 hr.

Fig. 3. Fouling of the heat exchanger tubes 5 and 8 as a function of time. The position of tubes 5 and 8 in the heat exchanger section is indicated in fig. 1. The airflow is *horizontal*, and only the upper quarter of the tubes in the upstream is shown. Points A and B indicated in fig. 3.a correspond to the stagnation point and the top of the heat exchanger tube no. 8.



a) Time 15 min. b) Time 40 min.

c) Time 1 hr and 20 min. d) Time 1.5 hr.

e) Time 2 hrs. f) Time 2 hr and 20 min.

Fig. 4. The growth of the fouling layer as a function of time in case of a 45º flow. The presented area is the rear end of tube number 5, and points B and C in fig. 4.a correspond to points B and C in fig. 5.

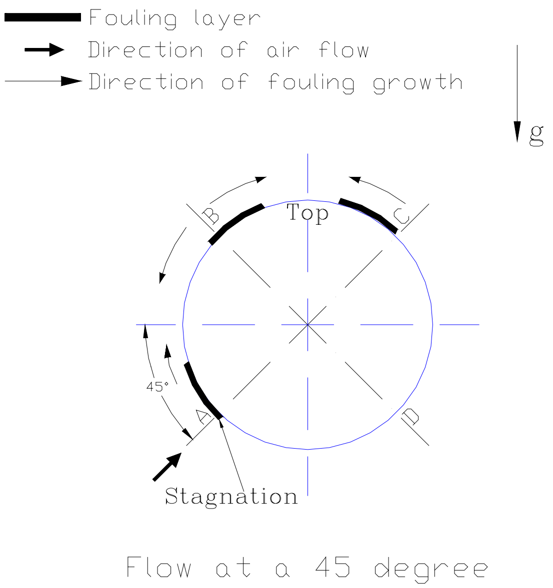
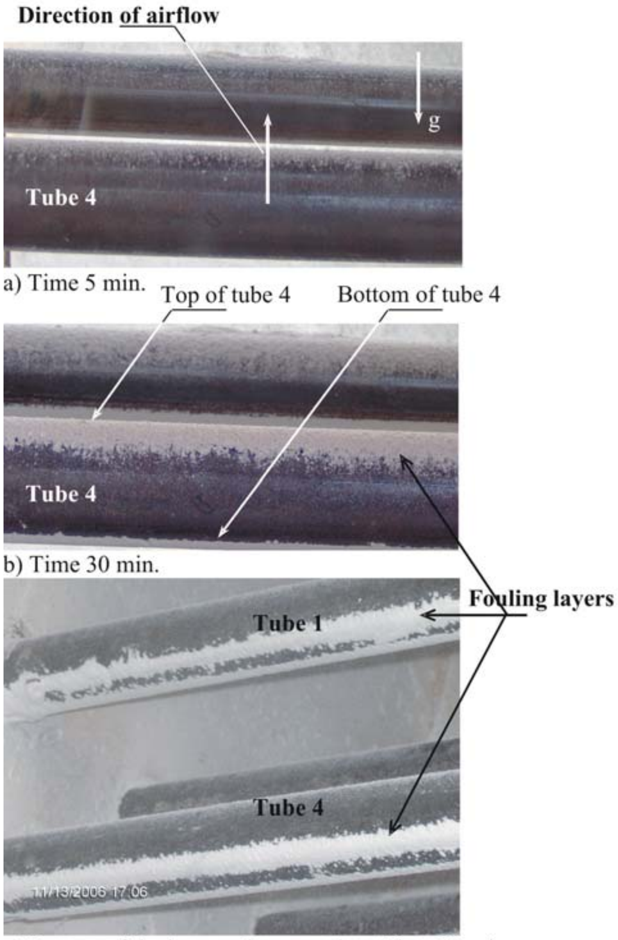


Fig. 5. Areas at the tube at which fouling starts in case of a flow at 45 degrees with the direction of gravity.

Vertical Upward Flow

The growth of the fouling layer as a function of time in case of an upward flow is shown in figure 6. The top of the heat exchanger tubes is shown in figs. 6.a and 6.b, while the bottom is shown in fig. 6.c. The top and the bottom of tube no. 4 after 30 minutes of operation are shown in figs. 6.b and 6.c, respectively. It is found that fouling starts at two places, which are the top and the bottom of the tubes. This observation agrees with the work of Kalisz and Pronobis (2005), Kaiser et al. (2002) and Abd-Elhady et al. (2004). The bottom of the heat exchanger tubes in case of upward flow is the area of stagnation. The fouling layer grows from the top as well as from the bottom of the tubes until the whole surface of the tubes is fouled. The fouling layer growth at the top is faster than at the bottom, and the growth is more or less symmetrical around the vertical axis of the tubes. The fouling layer in case of a horizontal flow covers a quarter of the heat exchanger tube after 3 hrs of operation, in case of a 45 degree flow covers the upper half of the tube, and in case of an upward flow covers the whole tube. It can be concluded that the flow direction with respect to gravity affects strongly the growth of particulate fouling layers over the tubes of heat exchangers.



a) Time 5 min.

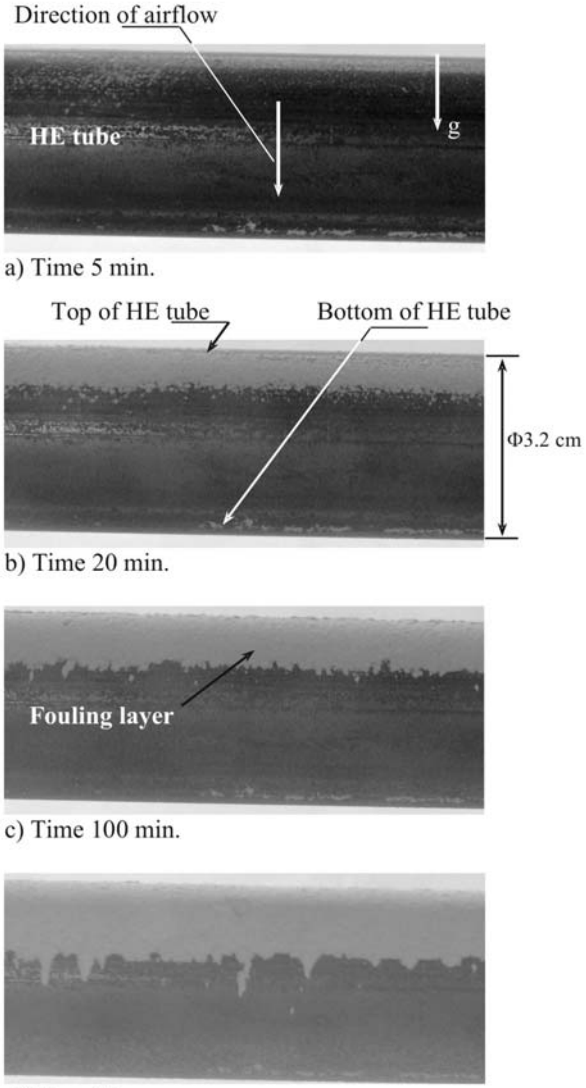
b) Time 30 min.

c) Bottom of the heat exchanger tubes, Time 30 min.

Fig. 6. Growth of the fouling layer over the heat exchanger tubes in case of *upward flow* as a function of time. g is the direction of gravity. Figures a and b show the top of the heat exchanger tube, while fig. c shows the bottom of the heat exchanger tube. The white surface is the fouling layer while the black part is the tube surface.

Vertical Downward Flow

The growth of the fouling layer in case of a vertical downward flow is shown in fig. 7. The pictures were taken during two hours of operation. It was seen that the growth of the fouling layer was symmetrical around the vertical axes of the tubes. It can be seen from fig. 7 that the bottom of the tube is clean and did not foul during the experiment, however the top of the tube has fouled from the beginning of the experiment and continued fouling till the end. It can be concluded that fouling starts only at one point, which is the top of the heat exchanger tube, and at which the fouling layer continues its circumferential growth. This conclusion is in agreement with the observations of Hupa (2005). The top of the heat exchanger tube in case of a vertical downward flow coincides with the stagnation area of flow.



a) Time 5 min.

b) Time 20 min.

c) Time 100 min.

d) Time 2 hr.

Fig. 7. Growth of the fouling layer over the heat exchanger tubes in case of a *downward* flow as a function of time. g is the direction of gravity. The white surface is the fouling layer while the black part is the tube surface.

DISCUSION OF RESULTS

The growth of the fouling layer as a function of the flow direction with respect to gravity is summarized in fig. 8. Points A and B indicated in fig. 3.a correspond to points A and B in fig. 8.a, and points B and C indicated in fig. 4.a corresponds to points B and C in fig. 8.b. It is found that in all orientations of the flow, fouling starts at the stagnation area of flow around the heat exchanger tube and at the top of the tube. The top of the heat exchanger tube in case of a vertical downward flow coincides with the stagnation area of flow, which is the main reason for having only one position at which fouling starts. The reasons for fouling to start at the top of the heat exchanger tubes and at the stagnation area of flow are discussed in the next paragraphs.

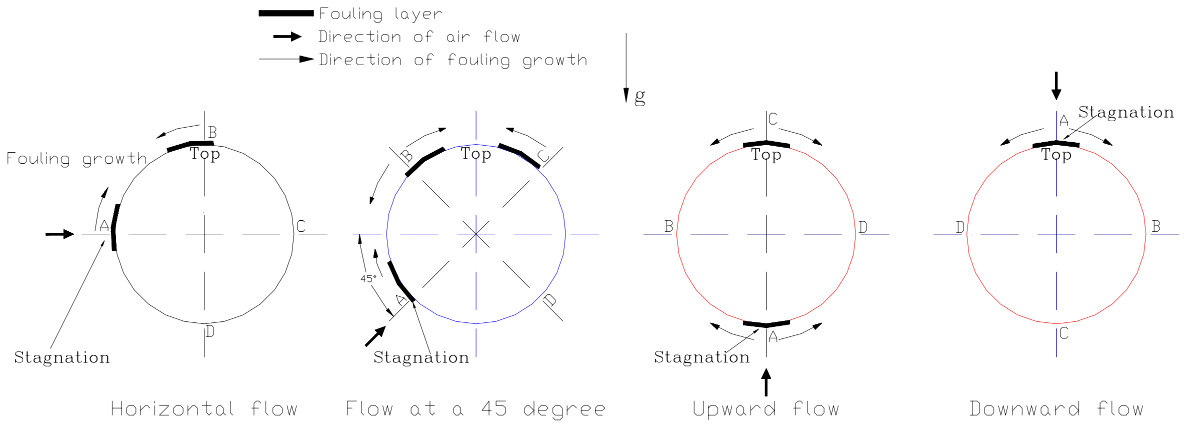
Submicron particles are transported by large particles, usually $d_p > 5$ µm, or vapor diffusion, whereas the intermediate sized particles, i.e. $d_p < 5$ µm, can be transported by a thermophoretic or an electrophoretic force (Raask, 1985), and the large particles mainly by inertial impaction. Inertial impaction takes place when large particles have too large an inertial momentum to follow the gas stream lines around the heat transfer surface, and instead impact on the surface. Inertial impaction accounts for the bulk of deposit growth in the presented research. The temperature difference between the gas-side and the surface of the heat exchanger tubes affect the transport of submicron and intermediate sized particles but hardly influences the transport of large particles (De Best, 2007). Despite the fact that there is no secondary fluid in the heat exchanger tubes and the temperature difference between the gas-side and the tube surface is zero, still the performed experiments can explain the onset of large particulates on the tubes of heat exchangers and the position at which fouling starts. Particles stick to the heat exchanger tube if their speed is lower than or equal to the critical sticking velocity (Abd-Elhady et al., 2005), which is defined as the maximum impact speed at which a particle hitting a surface will stick and does not rebound. The critical sticking speed V_s for the used calcium carbonate particles hitting a steel tube is equal to 0.02 m/s and it is calculated from (Thornton and Ning, 1998),

$$V_s = 1.84\left[\frac{(\Gamma/R)^5}{\rho^3 E^{*2}}\right]^{\frac{1}{6}}, \qquad (1)$$

where Γ is the surface energy between the interacting bodies, R the radius of the particle, ρ the density of the particle, E* the reduced Young's modulus which is calculated from (Abd-Elhady et al., 2006),

$$E^* = \left(\frac{1-\nu_1^2}{E_1} + \frac{1-\nu_2^2}{E_2}\right)^{-1}, \qquad (2)$$

with the subscripts 1 and 2 representing the interacting particle and the tube surface. E is the Young's modulus of elasticity and ν the Poisson's ratio (Fenner, 1989). The material properties of the calcium carbonate and the steel used to calculate the critical sticking velocity are shown



(a) (b) (c) (d)

Fig. 8. Areas at the tubes at which fouling starts as a function of flow direction, i.e. (a) horizontal flow, (b) flow at a 45 degrees, (c) upward flow and (d) a downward flow. g is the direction of gravity.

in table 1. The critical sticking velocity for the calcium carbonate particles is very low compared to the main stream velocity, i.e. 1.25 m/s, and therefore deposition of particles on the tubes surface occurs at areas where the speed of particles is low, such as at the area of separation of flow and at the stagnation area of flow. If the particle has too much kinetic energy in excess, it can also bounce off the heat transfer surface and become entrained in the flue gas stream as observed by Benson et al. (1993), Raask (1985) and Baxter (1993).

Separation of flow occurs towards the top of the heat exchanger tube (Sons and Hanratty, 1969; Wu et al., 2004) in case of a horizontal flow, upward flow and a flow at 45 degrees, and the separation angle is a function of the Reynolds number of the flow around the tube. Based on the flow conditions, i.e. main stream velocity of 1.25 m/s and air temperature 25 ºC, the Reynolds number of the flow for the tubes of the heat exchanger is equal to 3.2×10^4, which corresponds to a separation angle of 80º from the stagnation point according to Sons and Hanratty (1969). Due to separation of the flow at the top of the heat exchanger tube, both the removal of particles by shear flow decreases (Cabrejos and Klinzing, 1992; Halow, 1973) and the speed of the particles decreases. Both effects increase the deposition rate of particles at the top of the heat exchanger tube.

Table 1. Physical properties of calcium carbonate and steel (Gilman, 1960; Rogers and Reed, 1984).

	Calcium Carbonate	Steel
Young's modulus, E (N/m^2)	0.35×10^{11}	2.15×10^{11}
Density, ρ (kg/m^3)	2830	7800
Poisson's ratio ν	0.27	0.28
Surface energy Γ (J/m^2), Calcium carbonate – steel	0.29	

At the area of stagnation, where the flow velocity is zero, removal of particles by shear flow ceases, and consequently the particles that stick to the surface of the tube at the area of stagnation are not removed by the flow. The impact speed of the particles is so high at the area of stagnation due to the blockage of the flow by the tubes, such that the incident particles bounce off the tubes. However, when the incident particles bounce off at the area of stagnation they are decelerated by the flow such that when they hit the tube again, they impact at a very low speed and they stick to the tube surface. This explanation has been observed by Kuerten (2007) from the numerical simulations he has performed for a particle-laden flow through a tube bundle.

CONCLUSIONS

An experimental setup has been built to investigate the influence of flow direction with respect to gravity on particulate fouling of heat exchangers. Four orientations of flow have been studied, horizontal flow, upward flow, downward flow and a flow at 45 degrees. It was found that in all orientations fouling starts at the stagnation area of flow around the heat exchanger tube and at the top of the tube. The area of stagnation coincides with the top of the heat exchanger tube in case of a downward flow which is the main reason for having only one position at which fouling starts. Fouling at the upper half of the tubes is much faster than the lower half of the tubes, and the fouling rate is faster at the bottom tubes of the heat exchanger section than the upper tubes. Fouling starts at two positions on the heat exchanger tubes in case of a horizontal flow, upwards flow and a flow at 45 degrees, while in case of a downward flow it starts only at one position, which promotes the downward flow as the best orientation for lingering particulate fouling.

NOMENCLATURE

d_p	diameter of the particle, m
E*	reduced Young's modulus, N/m^2
E	Young's modulus, N/m^2
g	gravity
R	radius of the particle, m
t	time
V_s	critical sticking speed, m/s
Γ	surface energy, J/m^2
ρ	density of the particle, kg/m^3
σ_y	yield strength, N/m^2
ν	Poisson's ratio, dimensionless

REFERENCES

Abd-Elhady, M.S., Rindt, C.C.M., Wijers, J.G., van Steenhoven, A.A., Bramer, E.A., and van der Meer, T.H., 2004, Minimum gas speed in heat exchangers to avoid particulate fouling, *International Journal of Heat and Mass Transfer*, Vol. 47(17-18), pp. 3943-3955.

Abd-Elhady, M.S., Rindt, C.C.M., Wijers, J.G., and van Steenhoven, A.A., 2005, Particulate fouling in waste incinerators as influenced by the critical sticking velocity and layer porosity, *Energy*, Vol. 30, pp. 1469-1479.

Abd-Elhady, M.S., Rindt, C.C.M., Wijers, J.G., and van Steenhoven, A.A., 2006, Modelling the impaction of a micron particle with a powdery layer, *Powder Technology*, Vol. 168(3), pp. 111-124.

Achenbach, E., 1968, Distribution of local pressure and skin friction around a circular cylinder in cross-flow up to Re = 5×10^6, *Journal of Fluid Mechanics*, Vol. 34 (4), 625-639.

Baxter, L.L., 1993, Ash deposition during biomass and coal combustion: A mechanistic approach, *Biomass and Bioenergy*, Vol. 4(2), pp. 85-102.

Benson, S.A., Jones, M.L., and Harb, J.N., 1993, Ash formation and deposition, in *Fundamental of Coal Combustion – for Clean and Efficient Use, Coal Science and Technology, ed. L.D. Smoot*, Elsevier Science Publishers, Amsterdam, ISBN 0-444-89643-0, chapter 4, pp. 299-373.

Bohnet, M., 1987, Fouling of heat-transfer surfaces, *Chemical Engineering Technology*, Vol. 10, pp. 113-125.

Bott, T.R., 1995, *The Fouling of Heat Exchangers*, Elsevier Science, New York.

Bryers, R.W., 1996, Fireside slagging, fouling and high temperature corrosion of heat-transfer surface due to impurities in steam-raising fuels, *Progress in Energy and Combustion Science*, Vol. 22, pp. 29-120.

Cabrejos, F.J., and Klinzing, G.F., 1992, Incipient motion of solid particles in horizontal pneumatic conveying, *Powder Technology*, Vol. 72, pp. 51-61.

De Best, C., 2007, Novel Aerosol Condensing Heat Exchanger for Small-Scale Biomass Combustion Applications, *PhD thesis*, Eindhoven University of Technology, The Netherlands.

Epstein, N., 1983, Thinking about heat transfer fouling: a 5 × 5 matrix, *Heat Transfer Engineering*, Vol. 4(1), pp. 43-56.

Epstein, N., 1987, Fouling in heat exchangers in: *Proceedings of the 6th International Heat Transfer Conference*, pp. 235-253.

Fenner, T.R., 1989, *Mechanics of Solids*, Blackwell Scientific Publications, Oxford, UK.

Gilman, J.J., 1960, Direct measurement of the surface energies of crystals, *Journal of Applied Physics*, Vol. 31(12), pp. 2208-2218.

Gupta, R.P., Wall, T.F., Baxter, L.L., 1999, The thermal conductivity of coal ash deposits: relationships for particulate and slag structures, in: R.P. Gupta, T.F. Wall, L.L. Baxter (Eds.), *The Impact of Mineral Impurities in Solid Fuel Combustion*, Kluwer Academic Press, New York, pp. 65-84.

Halow, J.S., 1973, Incipient rolling, sliding and suspension of particles in horizontal and inclined turbulent flow, *Chemical Engineering Science*, Vol. 28, pp. 1-12.

Hupa, M., 2005, Interaction of fuels in co-firing in FBC, *Fuel*, Vol. 84, pp. 1312-1319.

Kaiser, S., Antonijevic, D., and Tsotsas, E., 2002, Formation of fouling layers on a heat exchanger element exposed to warm, humid and solid loaded air streams, *Experimental Thermal and Fluid Science*, Vol. 26, pp. 291-297.

Kalisz, S., and Pronobis, M., 2005, Investigations on fouling rate in convective bundles of coal-fired boilers in relation to optimization of sootblower operation, *Fuel*, Vol. 84, pp. 927-937.

Kuerten, J.G.M., 2007, Numerical simulation of particle-laden flow through tube bundles, Report for EU Project SES6-CT-2003-502679, BIOASH.

Marner, W.J., 1990, Progress in gas-side fouling of heat-transfer surfaces, *Applied Mechanics Review*, Vol. 43(1), pp. 35-66,.

Müller-Steinhagen, H., Reif, F., Epstein, N., and Watkinson, P., 1988, Influence of operating conditions on particulate fouling, *The Canadian Journal of Chemical Engineering*, Vol. 66, pp. 42-50.

Nuntaphan, A. and Kiatsiriroat, T., 2007, Thermal behavior of spiral fin-and-tube heat exchanger having fly ash deposit, *Experimental Thermal and Fluid Science*, Vol. 3(8), pp. 1103-1109.

Nuntaphan, A., Kiatsiriroat, T., and Wang, C.C., 2005, Air side performance at low Reynolds number of cross-flow heat exchanger using crimped spiral fins, *International Communication in Heat and Mass Transfer*, Vol. 32, pp. 151-165.

Nuntaphan, A., Kiatsiriroat, T., and Wang, C.C., 2005, Heat transfer and friction characteristics of crimped spiral finned heat exchangers with dehumidification, *Applied Thermal Engineering*, Vol. 25(2-3), pp. 327-340.

Lam, K., Li, J.Y., Chan, K.T., So, R.M.C., 2003, Flow pattern and velocity field distribution of cross-flow around four cylinders in a square configuration at a low Reynolds number**,** *Journal of Fluids and Structures*, Vol. 17(5), pp. 665-679.

Raask, E., 1985, *Mineral Impurities in Coal Combustion*, Hemisphere Publishing Corporation, ISBN 0-89116-362-X.

Rogers, D.E., and Reed, J., 1984, The adhesion of particles undergoing an elastic-plastic impact with a surface, *Journal of Physics D: Applied Physics*, Vol. 17, pp. 677-689.

Sons, J.S., and Hanratty, T.J., 1969, Velocity gradient at the wall for flow around a cylinder at

Reynolds numbers from 5×10^3 to 10^5, *Journal of Fluid Mechanics*, Vol. 35(2), pp. 353-368.

Taborek, J., Aoki, T., Ritter, R., and Palen, J.W., 1972, Fouling: the major unresolved problem in heat transfer, *Chemical Engineering Progress*, Vol. 68, pp. 59-67.

Theis, M., Skrifvars, B.J., Hupa M., and Tran, H., 2006, Fouling tendency of ash resulting from burning mixtures of biofuels, Part 1: Deposition rates, *Fuel*, Vol. 85(7-8), pp. 1125-1130.

Thornton, C., and Ning, Z., 1998, A theoretical model for the stick behaviour of adhesive, elastic-plastic spheres, *Powder Technology*, Vol. 99, pp. 154-162.

Van Beek, M.C., Rindt, C.C.M., Wijers, J.G., and van Steenhoven, A.A., 2001, Analysis of fouling in refuse waste incinerators, *Heat Transfer Engineering*, Vol. 22(1), pp. 22-31.

Wu, M., Wen, C., Yen, R., Weng, M., and Wang, A., 2004, Experimental and numerical study of the separation angle for flow around a circular cylinder at low Reynolds number, *Journal of Fluid Mechanics*, Vol. 515, pp. 233–260.