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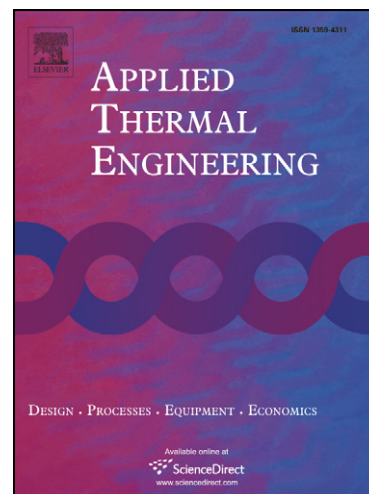
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Removal of gas-side particulate fouling layers by foreign particles as a function of flow direction

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ABSTRACT

Removal of particulate fouling layers by externally injected particles as a function of flow direction with respect to gravity is investigated experimentally. Three orientations of flow have been investigated, horizontal flow, upward flow and a downward flow. It is found that fouling starts at the point of stagnation irrespective of the flow direction, and also starts at the top point of the heat exchanger tubes. Particulate fouling grows from these two points except for 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 starts only from one point. It was not possible to remove the fouling layer in case of a horizontal and an upward flow by the externally injected particles, however in case of a downward flow most of the fouling layers were removed by the external particles. It can be concluded that the

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downward flow is the best flow orientation to linger particulate fouling and for removal of fouling layers by externally injected particles.

Key words: Particulate fouling, Heat exchangers, Deposition, Non-heating fouling

1. 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 [1-3]. 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 and conditions of combustion Benson et al. [4]. A theoretical background about particulate fouling and especially gas side fouling can be found in literature of Epstein [5,6] and Marner [7].

Many efforts have been made by numerous researchers to understand and control fouling in heat exchangers [8-11]. Hupa [12] has performed fouling experiments using mixtures of rice husk and eucalyptus bark as fuels, in which, 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 [13]. Hupa [12] found that the rice husk ash does not stick on 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. However, the results of Hupa [12] differ from the work of Kaiser et al. [14] and

Abd-Elhady et al. [15], 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 [12] was downwards while in case of Kaiser et al. [14] and Abd-Elhady et al. [15] was upwards, which indicates that the flow direction with respect to gravity influences the position at which particulate fouling starts. Kalisz and Pronobis [16] found that particulate fouling at the economizer of a pulverized coal boiler, in which the gas flow is upwards, occurred at the downstream side of the tubes, while at the end of the process a little wedge at the upstream was observed. Nuntaphan and Kiatsiriroat [17] 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 a heat transfer surface [18,19]. The tubes of the heat exchanger tubes were vertically mounted in a staggered array, and the flow was horizontal. Nuntaphan and Kiatsiriroat [17] 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.

Abd-Elhady et al. [20] proved that it is possible to remove fouling layers on the tubes of heat exchangers by introducing large particles in the gas flow, which has a mass larger than the already deposited particles. Klaren et al. [21,22] has shown the applicability of using externally injected particles to remove fouling layers in the water-side of heat exchangers. Klaren [23] used particles that are cut metal wire with a diameter of 2 to 3 mm and cut to a length equal to the wire diameter or spherical particles with a diameter of 2 to 3

mm. These particles impose a mild scouring action on the inner tube wall and remove any precipitated matter at an early stage of fouling. Klaren et al. [24] has applied that method in installations for more than 15 years and no erosion problems due to the injected particles have been reported. In the presented research, the removal of particulate fouling layers by externally injected particles as a function of the flow direction with respect to gravity is investigated experimentally. The purpose of this study is to determine the best flow direction at which particulate fouling layers can be removed by externally injected particles in the gas-side of heat exchangers.

2. EXPERIMENTAL SETUP AND THE EXPERIMENTAL PROCEDURE

A schematic of the experimental setup, which has been used, 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 a vertical flow, a horizontal flow and a flow with angle. The experimental setup consists of an air blower connected to a wooden duct of size $40\text{cm}\times 40\text{cm}\times 400\text{cm}$. The power of the air blower is 1.5 kW at 1450 rpm, and delivers $0.25\text{ m}^3/\text{s}$ of air at normal operation conditions. A screw particle feeder is used to dispatch either calcium carbonate or sand particles in the airflow, and varying the rotational speed of the screw of the particle feeder can vary the injection rate. Particles are injected at the inlet of the air blower, as shown in fig. 1, to insure that the particles are uniformly distributed in the cross sectional area of airflow. The wooden duct contains a heat exchanger that contains 9 tubes arranged in an inline matrix, i.e. 3×3 tubes, as shown in fig. 1. The tubes are of diameter 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. The transverse and the longitudinal pitches of the tubes are $10\text{ cm} \approx 3d$, which is larger than the normally used pitches, i.e. $1.5d$ to $2.5d$. This large pitch, $\approx 3d$, has been selected in order to have more or less a uniform distribution of the injected particles across the tubes of the heat exchanger. The inline arrangement is selected because the turbulence level is lower than in a staggered arrangement, so the fouling tendency is higher than in a staggered arrangement, and the removal of fouling layers by the injection of sand particles in case of an inline arrangement will be more difficult than in case of a staggered arrangement. The method of removal of fouling layer by the injection of sand particles is tested for an inline arrangement, and if the method is applicable for an inline arrangement it will probably work for the staggered

arrangements. There is no secondary fluid in the heat exchanger tubes, i.e. the surface of the heat exchanger tubes is isothermal. 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 hotwire anemometer with an accuracy of ± 0.01 m/s. Air exhaust from the setup is filtered before it goes into the atmosphere by a fiber glass filter with steel fine mesh at the sides of the fiber glass to prevent the fibers from collapsing.

In the experiments, ambient air is fed by the air blower into the duct, and particles are added by a particle feeder. Calcium carbonate particles of average diameter of $40 \mu\text{m}$ with a standard deviation of $\pm 16 \mu\text{m}$ are used in the experiments as a source of fouling, and sand particles of diameter $400 \pm 50 \mu\text{m}$ are used as the cleaning particles. Only calcium carbonate particles are injected at the beginning of experiments then after a certain period of time sand particles are injected to remove the calcium carbonate particles deposited on the heat exchanger tubes, i.e. the fouling layers. In the experiments the volume flow rate of air and the injection rate of particles are kept constant at $0.2 \text{ m}^3/\text{s}$ and $20 \text{ g}/\text{m}^3$ of air, respectively. The air temperature and relative humidity are $25 \text{ }^\circ\text{C}$ and 30% , respectively, and the free air velocity in the heat exchanger is 1.25 m/s , i.e. the main stream velocity in the air duct. 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, Finepix S602, through the installed glass windows, as shown in Fig. 1. The fouling

layer thickness is measured optically, and details about the procedure of measurements can be found in [15].

In the present research we are interested in the first phase of fouling, i.e. deposition of the particles on the tubes of the heat exchangers forming the first layers, and the removal of such layers as a function of flow direction. The deposition of particles at the beginning of fouling is highly dependent on the critical sticking velocity of the particles [25], which is defined as the maximum impact speed, at which a particle hitting a flat surface will stick and does not rebound [26]. The growth of the fouling layers is a function of the chemical properties as well as the physical properties of the particles [27]. Calcium carbonate particles has been selected as the fouling particles because it has a critical sticking velocity similar to most of the particles found in the fouling layers in waste incinerators [1] and coal fired power plants [2], e.g. calcium sulphate, sodium sulphate, potassium sulphate and potassium carbonate. It can be concluded that using calcium carbonate particles as the fouling particles can mimic the first phase of the fouling process in waste incinerator and coal fired power plants.

Three experiments are performed with three different flow orientations, i.e. horizontal flow, upward flow and a downward flow, to investigate the removal of fouling layers by externally injected particles as a function of the flow direction with respect to gravity. In each experiment, the whole experimental setup is rotated as shown in fig. 2 to give the required flow orientation.

3. EXPERIMENTAL RESULTS

3.1 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 [28,29] and the top of the heat exchanger tube no. 8, respectively, and the line of stagnation is indicated in fig. 3.b. A stagnation area occurs whenever a flow impinges on a solid object and the flow is blocked by that solid object. The flow speed at the area of stagnation is zero. 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 [17]. Fouling at the upper half of the tubes is 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.

Another fouling experiment has been performed for the horizontal flow case, in which sand particles are injected after 2 hours of operation for 5 minutes. The injection of the sand particles was only for 5 minutes then the fouling experiment continued. The growth of the fouling layers as a function of time before injecting the sand particles is shown in figs. 4.a, b and c, and after injecting the sand particles are shown in figs. 4.d and e. The shown pictures are for tube number 8. Fouling has started at the top of the heat exchanger tube and at the stagnation area of flow as can be seen in fig. 4.a., and as the previous experiment. It is found that the sand particles could not remove the fouling layers, and they deposited on the fouling layer as can be seen in fig. 4.d. and the fouling process continued, as shown in fig. 4.e.

3.2 Vertical Upward Flow

The growth of the fouling layer as a function of time in case of an upward flow is shown in figure 5 for tube 4. The top of the heat exchanger tubes is shown in figs. 5.a and 5.b, while the bottom is shown in fig. 5.c. It is found that fouling starts at two places, which are the top and the bottom of the tubes and this observation is valid for all of the tubes. This observation agrees with the work of Kalisz and Pronobis [16], Kaiser et al. [14] and Abd-Elhady et al. [15]. The bottom of the heat exchanger tubes in case of the upward flow is the area of stagnation. The fouling layer grows over the top as well as the bottom of the tubes until the whole surface of the tubes is fouled. The fouling layer growth over the top is faster

than the bottom, and the growth is more or less symmetrical around the vertical axis of the tubes. It can be concluded from comparing fig. 3 to fig. 5 that fouling starts at the highest point on the tube surface and near the stagnation area of flow irrespective of the flow orientation. Sand particles were injected after 1 hr of operation for 5 minutes. It is found that the fouling layers at the bottom of the heat exchanger tubes were removed by the sand particles, but the fouling layers at the top of the heat exchanger tubes were not removed, and the sand particles deposited on the fouling layers at the top of the tubes as can be seen in fig. 5.d.

3.3 Vertical Downward Flow

The growth of the fouling layer in case of a vertical downward flow is shown in fig. 6 for tube no 5. The pictures taken were 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. 6 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 has been observed for all of the tubes. This conclusion is in agreement with the observations of Hupa [12]. The top of the heat exchanger tube in case of a vertical downward flow coincides with the stagnation area of flow.

Another fouling experiment has been performed in which sand particles are injected in the air flow after one hour of operation for 5 minutes, and the results are shown in fig. 7.

Tube no. 2 is shown in fig. 7.a, 7.b and 7.c after 15 min, 45 min and 1 hr of operation, respectively, and it can be seen that most of the fouling occurs at the top of the tube and non at the bottom of the tube as was seen in the previous experiment. Figure 7.d is a picture of the tube at the end of the sand injection period and it can be clearly seen that most of the fouling layer was removed by the injected sand particles.

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4. DISCUSSION OF RESULTS

4.1 Deposition of Particles

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, where points A and B are the stagnation point [28,29] and the top of the heat exchanger tube in case of a horizontal flow, respectively. The stagnation point A became the bottom of the heat exchanger tube in case of an upward flow and the top of the heat exchanger tube in case of a downward flow. 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.

Large particles ($d_p > 5 \mu\text{m}$) are transported 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. The Stokes number, Stk , can be used to characterize the transport regime of particles from the carrier gas stream to the heat exchanger tubes, and it is equal to [30],

$$Stk = \frac{\rho_p d_p^2 U_\infty}{9\mu_g D_{\text{tube}}}, \quad (1)$$

with ρ_p is particle density, d_p is the particle diameter, D_{tube} is the diameter of the heat exchanger tubes, U_∞ and μ_g are the main stream velocity and viscosity, respectively. The Stokes number for the $40 \mu\text{m}$ CaCO_3 particles and the $400 \mu\text{m}$ sand particles are 19.7 and

1715, respectively, which are larger than 0.125, i.e. the critical Stokes number [30] for inertia-controlled transport. It can be concluded that the transport regime for the calcium carbonate particles and the sand particles is by inertial impaction, i.e. the particles are not capable to follow the fluid fluctuations and the particle paths deviate from the mean flow. Inertial impaction accounts for the bulk of deposit growth in the presented research. Particles stick to the heat exchanger tube if their speed is lower than or equal to the critical sticking velocity [26]. 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 [25,31]. The material properties of the calcium carbonate and the steel used to calculate the critical sticking velocity are given 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 and become entrained in the flue gas stream as observed by Raask [32], Baxter [35] and Benson et al. [4].

Separation of flow from the heat exchanger tubes occurs when the flow does not follow the contour of the tubes. The shear stress acting on the flow is zero at the point of separation. Separation of flow occurs towards the top of the heat exchanger tube [36,37] in case of a horizontal flow and an upward flow, 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 °C, 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 80° from the stagnation point according to Sons and Hanratty [36]. Due to separation of the flow at the top of the heat exchanger tube, both the removal of particles by shear flow decreases [38,39] and the speed of the particles decreases. Both effects increase the deposition rate of particles at the top of the heat exchanger tube.

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 [40] from the numerical simulations he has performed for a particle-laden flow through a tube bundle.

4.2 Removal of Fouling layers by Externally Injected Particles

The injected sand particles ceased to remove the fouling layers at the top of the heat exchanger tubes in case of a horizontal flow and an upward flow due to separation of flow. Separation of flow at the top of the tubes resulted in a low impact speed of the sand particle, consequently the sand particle deposited on the fouling layers instead of removing it. The injected sand particles had a high impact speed at the top of the heat exchanger tube in case of a downward flow, due to gravity and flow direction, such that the sand particles were capable of removing the fouling layers at the top of the tubes. The injected sand

particles hit the heat exchanger tubes at the stagnation area with a large impact speed, such that they were capable of removing the fouling layers deposited on the tubes at the stagnation area.

Injection of large solid particles in a downward flow can be extensively used to remove fouling layers in the gas-side of heat exchangers, especially at the low temperature sections, e.g. evaporators and economizers. Removal of fouling layers by externally injected particles can be applicable where particulate fouling only occurs and no slagging [41] happens, i.e. melting of fouling layers due to the high operating temperature, and then solidification of such layers to form very condensed structures. The surface temperature of particulate fouling layers increases as the fouling layer develops. As a result, the fouling layer sinters. The degree of sintering depends upon the gas side temperature and sintering time [42]. Sintering leads to the reduction of the void volume and reinforcement of the contact bridges between particles [43], such that the layer structure changes from powdery and fragile into a robust and a very strong structure attached to the tubes, that can hardly be removed from the tube by knocking [27]. Therefore, it is recommended to inject the sand particles before sintering starts. The exact timing is a function of the operating temperature, material of the fouling layer and the fouling rate. The optimum frequency of injection and the physical properties of the injected particles still have to be investigated. The applicability of such method in heat exchangers where slagging occurs is the point of future research.

5. CONCLUSIONS

An experimental setup has been built to investigate removal of particulate fouling layers by externally injected particles as a function of flow direction with respect to gravity. Three orientations of flow have been studied, horizontal flow, upward flow and a downward flow. 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, and promotes the downward flow as the best orientation for lingering particulate fouling. It was not possible to remove the fouling layers at the top of the tubes by the externally injected particles in case of a horizontal and an upward flow, however in case of a downward flow most of the fouling layers were removed by the external particles. It can be concluded that the downward flow is the best flow orientation to linger particulate fouling and for removal of fouling layers by externally injected particles.

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NOMENCLATURE

d_p	diameter of the particle, m
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, kg/m^3
ν	Poisson's ratio, dimensionless

FIGURES CAPTIONS

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) upward flow and (c) 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.

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.

Fig. 4. Horizontal flow with sand particles injected after 2 hrs of operation for 5 minutes. The pictures shown are for tube number 8. Points A and B indicated in fig. 4.a correspond to the stagnation point and the top of the heat exchanger tube no. 8.

Fig. 5. Growth of the fouling layer over the heat exchanger tubes in case of an *upward flow* as a function of time. g is the direction of gravity. Figures a, b and d show the top of the heat exchanger tubes, while fig. c shows the bottom of the tubes. The white surface is the fouling layer, the black part is the tube surface and the yellow color is the sand particles.

Fig. 6. Growth of the fouling layer over the heat exchanger tube no. 5 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.

Fig. 7. Tube no. 2 after 15 min (a), 45 min (b) and 1 hr (c) of operation. Tube no. 2 is shown in (d) after injecting sand particles for 5 minutes at the end of one hour of operation. The flow is downwards and g is the direction of gravity.

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

ACCEPTED MANUSCRIPT

Table 1. Physical properties of calcium carbonate and steel [33,34].

	Calcium Carbonate	Steel	Sand
Young's modulus, E (N/m ²)	0.35×10 ¹¹	2.15×10 ¹¹	0.5×10 ¹¹
Density, ρ (kg/m ³)	2830	7800	2470
Poisson's ratio ν	0.27	0.28	0.27
Surface energy Γ (J/m ²), Calcium carbonate – steel	0.29		-
Surface energy Γ (J/m ²), Sand – steel	-	0.16	

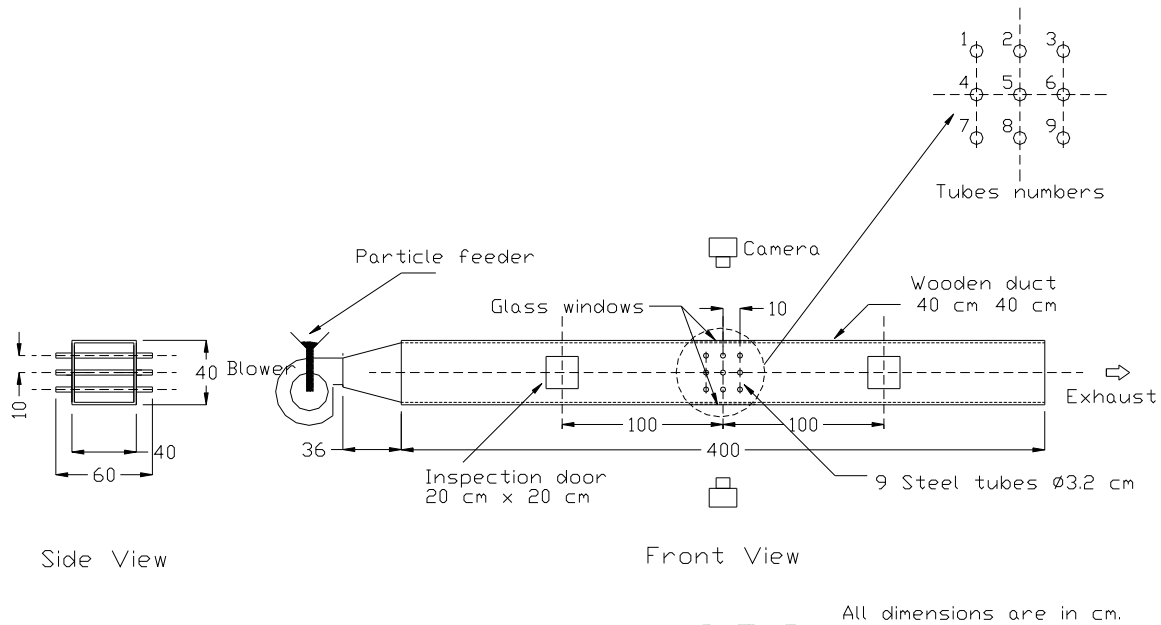


Fig. 1. The experimental setup used to study the effect of flow direction on particulate fouling of heat exchangers.

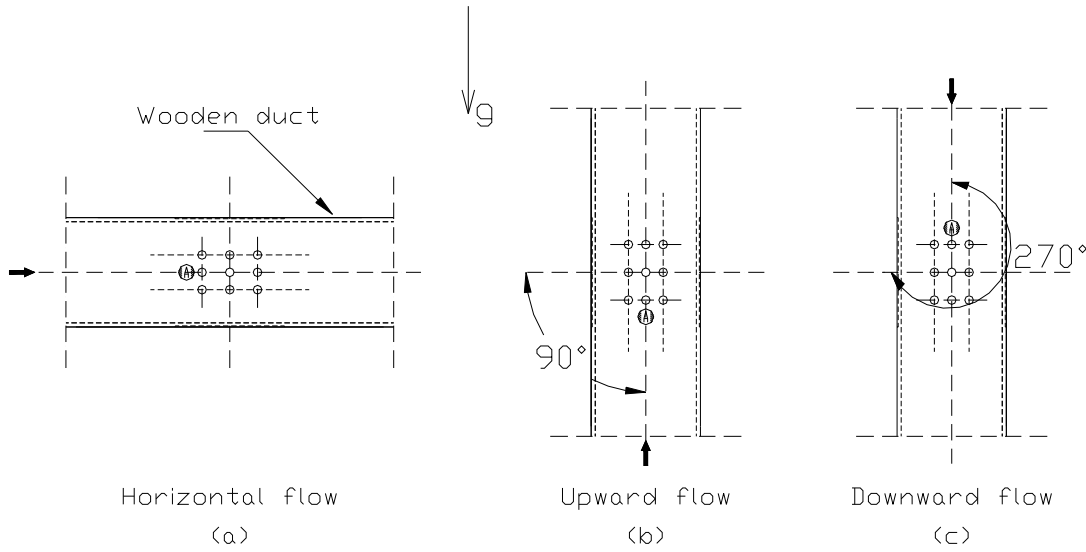


Fig. 2. The different orientations of the experimental setup to give (a) horizontal flow, (b) upward flow and (c) downward flow. g is the direction of gravity. Point A is at the upstream area of the heat exchanger, which is the same in all orientations.

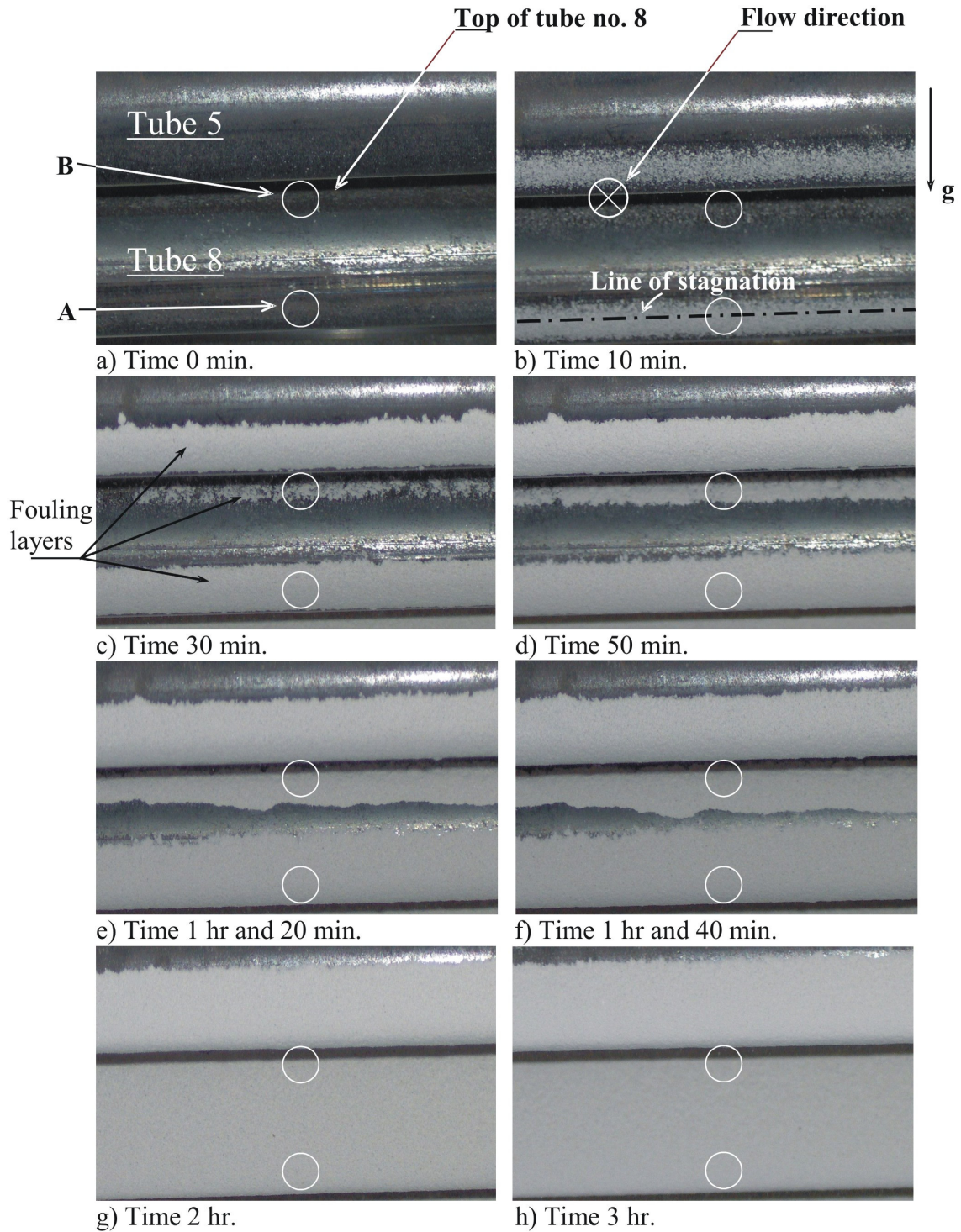


Fig. 3. Fouling of the heat exchanger tubes 5 and 8 as a function of time. The position of tubes 5 and 8 in the heat exchanger section is indicated in fig. 1. The airflow is *horizontal*, and only the upper quarter of the tubes in the upstream is shown. Points A and B indicated in fig. 3.a correspond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

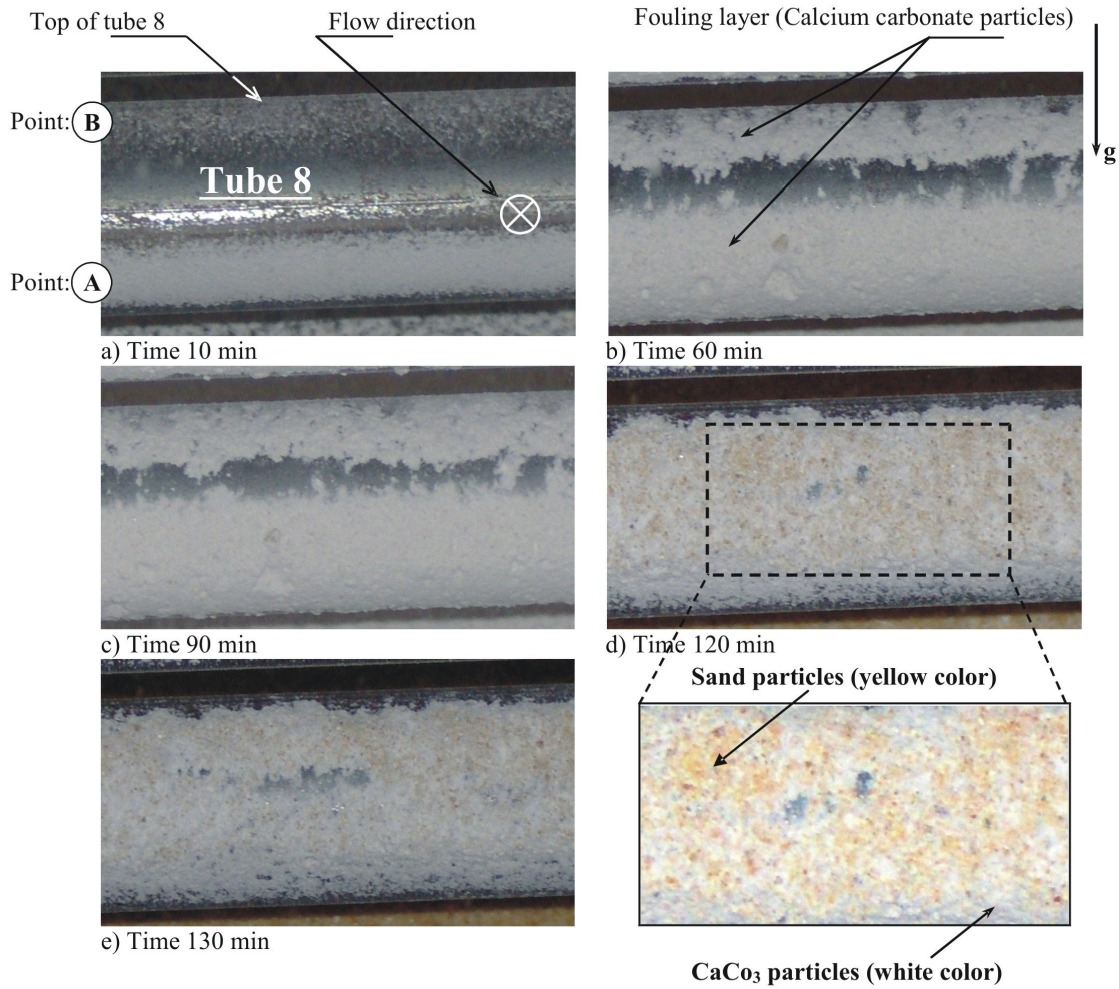


Fig. 4. Horizontal flow with sand particles injected after 2 hrs of operation for 5 minutes. The pictures shown are for tube number 8. Points A and B indicated in fig. 4.a correspond to the stagnation point and the top of the heat exchanger tube no. 8.

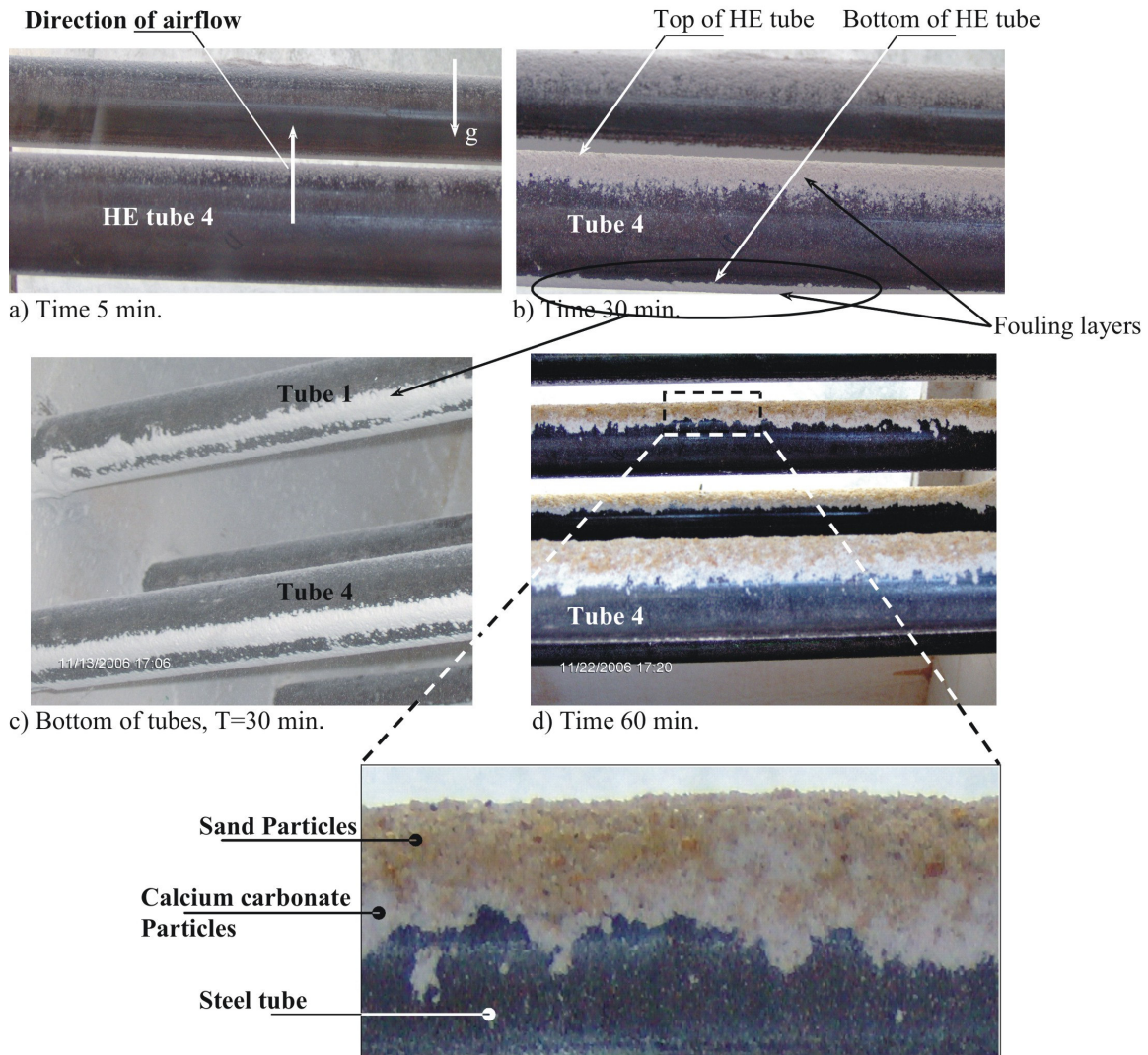


Fig. 5. Growth of the fouling layer over the heat exchanger tubes in case of an *upward flow* as a function of time. g is the direction of gravity. Figures a, b and d show the top of the heat exchanger tubes, while fig. c shows the bottom of the tubes. The white surface is the fouling layer, the black part is the tube surface and the yellow color is the sand particles.

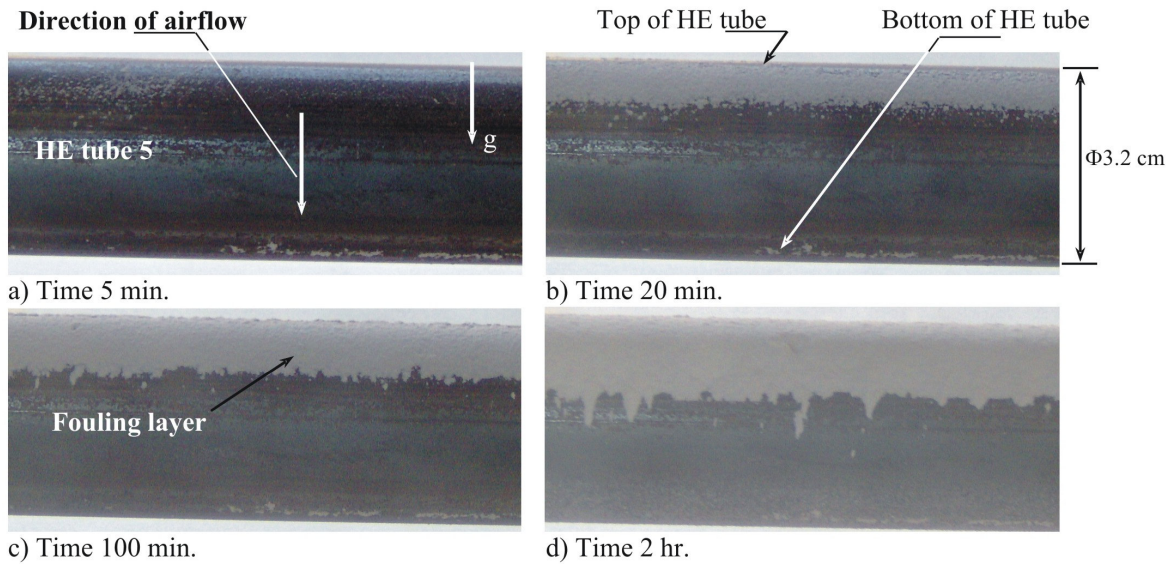


Fig. 6. Growth of the fouling layer over the heat exchanger tube no. 5 in case of a downward flow as a function of time. *g* is the direction of gravity. The white surface is the fouling layer while the black part is the tube surface.

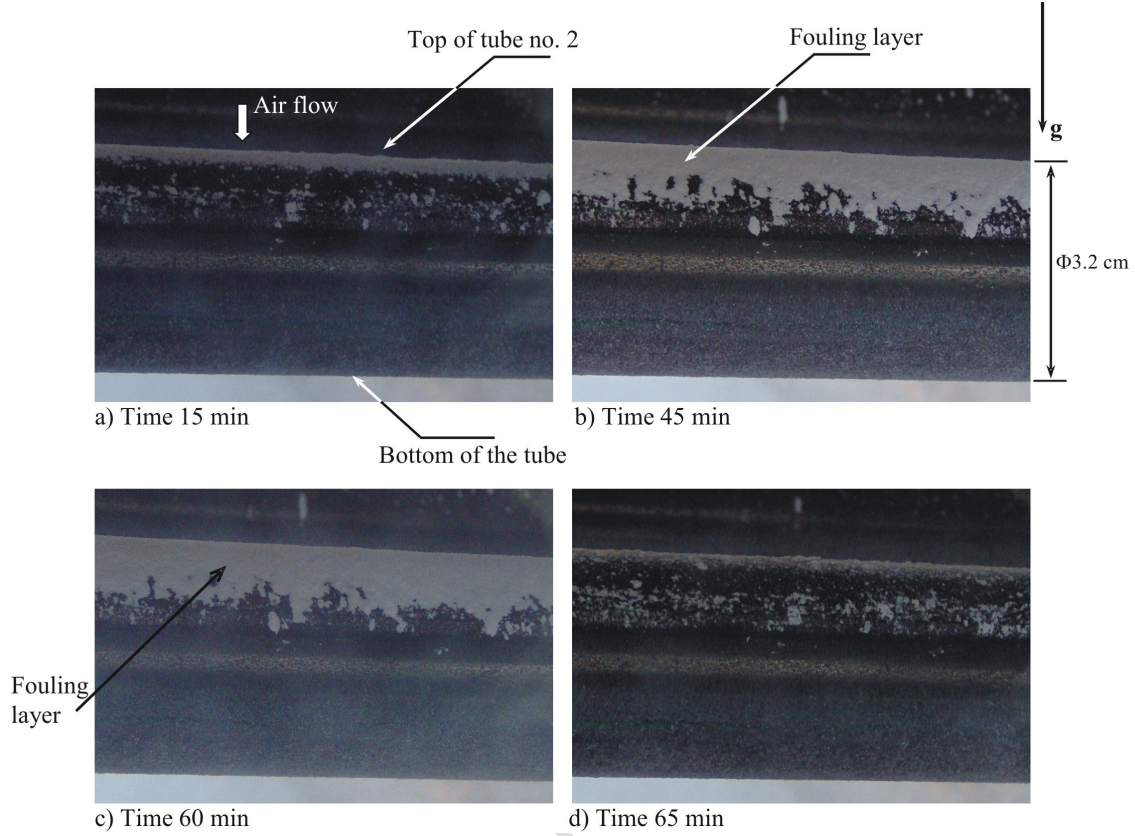


Fig. 7. Tube no. 2 after 15 min (a), 45 min (b) and 1 hr (c) of operation. Tube no. 2 is shown in (d) after injecting sand particles for 5 minutes at the end of one hour of operation. The flow is downwards and g is the direction of gravity.

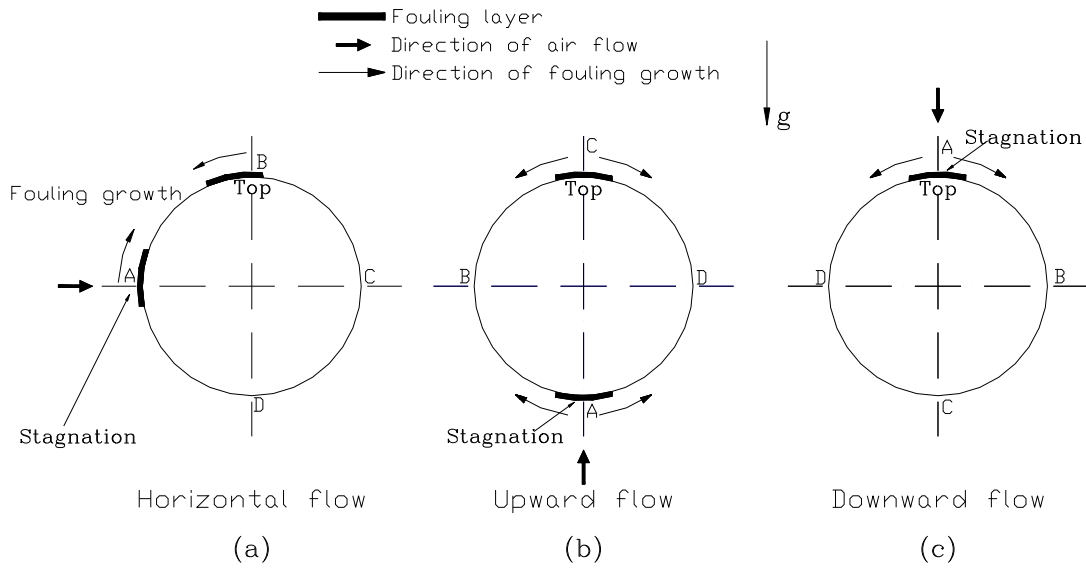


Fig. 8. Areas at the tubes at which fouling starts as a function of flow direction, i.e. (a) horizontal flow, (b) upward flow and (d) a downward flow. g is the direction of gravity.