Experimental results are presented on silica deposition in a typical domestic heat exchanger during combustion of siloxane-containing gas as a model system of biogas that is produced naturally during the anaerobic degradation of organic material in landfills and waste water treatment plants. Substantial silica layers are formed in the heat exchanger during combustion of biogas leading to a decrease in performance and eventual failure of the appliance. A model description of silica deposition is developed in order to demonstrate that the mass flux of silica to heat exchanger surfaces is not sensitive to particle coagulation process and particle size distribution. It is shown that the deposition flux of silica depends linearly on siloxane concentration in input air/gas mixture.

7.1 Introduction

In Chapter 6 the formation of silica fractal-like nanoparticles during combustion of a stoichiometric methane/air mixture with the hexamethyldisiloxane (L2) admixture was studied. In Chapter 7 we consider macroscopic effects which can be caused by silica nanoparticles formed in a flame. When using siloxane-containing biomethane as an energy source, the silica particles are deposited onto internal parts of the equipment [5,8,9]. As an example, domestic boilers have compact heat exchangers (HE) with narrow channels (see Fig 7.1), which can be relatively easily blocked. These appliances are particularly susceptible to clogging by silica deposition. With the expected wide-spread injection of biogases directly into the gas grid the performance and safety of domestic boilers will be at risk. It may seem that the siloxane related problem can be solved by reducing the siloxane content or the dilution of biogas with the natural gas. We have observed in our experiments that the mean size of silica particles decreases with decreasing siloxane
concentration in the gas/air mixture. A question arises: is it possible to avoid fouling of a gas burning appliance by reducing silica particle size so that the silica particles will not deposit inside the appliance, but can be collected outside the appliance in a filter? It seems that the answer is negative.

In the next section we present experimental results on silica deposition in the form of a white powdery-looking substance during combustion of siloxane-containing methane in a domestic heat exchanger. In section 7.3 we describe the model for silica particle transport in the hot combustion products and find the silica flux to HE. It is shown that the mass flux of silica to HE surfaces is not sensitive to details of particle coagulation and particle size distribution. Thermophoretic transport of silica nanoparticles is considered in the approximation of a laminar boundary-layer flow along a flat isothermal surface. We show that the deposition flux depends linearly on total silica concentration close to the burner (or, equivalently, on siloxane concentration in input air/gas mixture). This means that the fouling effect is linear in siloxane concentration, and even trace amounts of siloxanes during prolonged operation of equipment can result in a decrease of thermal performance and premature equipment failure due to clogging by silica particles.

7.2 Experimental

A boiler used in this work was Intergas Kombi Kompakt HR 28/24 widely used in the Netherlands (Fig. 7.1). It is a tankless, modulating and condensing boiler designed for both central heating and production of domestic hot water. This lamella-type heat exchanger is considered to be particularly susceptible to clogging by silica, due to its narrow channels.

Figure 7.1. Intergas Kombi Kompakt HR 28/24 boiler. General view without the cover (left) and detailed view of the lamella heat exchanger (right).
The gas handling system for feeding the domestic boiler is schematically shown in Fig. 7.2. Natural gas from the local grid (Groningen Gas) was used as a fuel during experiments. The natural gas flows were measured using mass flow meters with an accuracy of 0.5% + 0.1% of full scale. During experiments the gas flows were at least of 2% of flow meter full scale that provided accuracy of the measured mass flow rates better than 5% (typically 1 to 2%).

Hexamethyldisiloxane L2 was added to the natural gas flow using custom made pressure resistant gas bubblers. The temperature and pressure in the gas bubblers were measured using a digital thermometer and an analogue pressure gauge. The first two gas bubblers are filled with the liquid L2, while the last bubbler is empty to capture and prevent the liquid L2 entering the gas line to the domestic boiler (Fig. 7.2). The L2 concentration in the methane gas flow was determined by gravimetric method using a Mettler Toledo balance with a reproducibility of 0.1 g.

The L2 concentration in the fuel was varied by diluting the fuel leaving the bubblers with pure natural gas. A fan in the boiler extracts air from the surroundings which is premixed with the natural gas near the burner surface. The gas flow can be changed between 30% (stabilized flame) and 100% (free flame) of full load 2.5 m$^3$/h. It should be noted that variation of the thermal power of the boiler (by changing the total air/gas flow) influences the flame temperature due to changes of heat losses to the burner head. During the experiments the air/gas flow was fixed at 84% of full load.
load. The equivalence ratio $\phi$ of the unburned natural gas/air mixture was typically around 0.8.

Temperature in the heat exchanger is measured at various positions using thermocouples. They are also used to determine the temperature of the flue gases, the cold water supply and the hot water leaving the appliance. Based on the measured temperature difference between the hot and cold water the performance of the boiler can be evaluated.

Since no previous experimental data were available, a test with L2 concentration of 400 ppm was performed to evaluate the rate of silica deposition in HE. Unexpectedly, the experiment stopped after just 1 hour due to the failure of ionization probe. This probe is used for both ignition of the gas/air mixture during boiler startup and controlling the flame presence by measuring ionization current through the flame. Examination of the probe showed that it was completely covered with silica layer having insulating effect and preventing correct measurement of the ionization current. Inspection of the HE revealed enormous for this short period contamination with silica (Fig. 7.3). Although biogases typically contain lower concentrations of siloxanes [8], this example clearly shows potential risks associated with combustion of siloxane containing biogas.

Figure 7.3. Photo of the heat exchanger completely clogged with silica particles. The appliance failed after 1 h experiment at siloxane concentration of 400 ppm.
Silica deposits were collected from HE and studied using SEM and EDS. Examination revealed a columnar structure of the layer (Fig. 7.4). High magnification images (Figs. 7.4b and 7.4c) confirm that the layer is formed by small globular particles, similar to those found in flame (see Chapter 6). Chemical composition was determined using EDS. The typical EDS spectrum is shown in Fig. 7.5. Quantitative analysis of the spectrum confirmed that composition of the deposits corresponds to $\text{SiO}_2$.

![Silica deposition layer collected from HE. Image reveals the formation of a columnar structure (a). Details of top (b) and bottom (c) of the layer show that these structures are composed of smaller particles.](image)

![Typical EDS spectrum of the deposited layer. Quantitative analysis confirms the composition of $\text{SiO}_2$. Carbon peak is due to an adhesive tape used to fix the sample on SEM holder.](image)
Taking into account results of the experiment with 400 ppm, further investigations of silica deposition were performed using the air/gas mixture containing 22 ppm of L2, the concentration which is close to naturally present in biogas [8]. The boiler was running for 400 hours in order to get a layer of deposited silica large enough for characterization. The boiler used in this research is equipped with HE made of aluminum alloy. To collect silica deposits the aluminum cuboids were selected as a substrate because they have similar thermal expansion and heat conductivity coefficients. These cuboids were inserted in region 1 between HE lamellas at different distances from the burner starting at 20 mm. The heat exchanger is shown schematically in Fig. 7.6.

![Figure 7.6. Configuration of a heat exchanger. $U_0$ and $T_0$ are the initial velocity and the temperature of combustion products.](image1)

![Figure 7.7. Heat exchanger and cuboids at different distances covered with silica after the experiment.](image2)
Two aluminum cuboids were placed at each distance to check if the deposited layer is homogeneous (Fig. 7.7). The deposited layer appeared to have weak adhesion to the substrate. As a result, some of the layers were partly broken off during removal of cuboids from HE. A typical deposited layer is shown in Fig. 7.8. The cuboids were weighted before and after the experiment, resulting in a mass difference of about several milligrams. This was enough to measure accurately the weight of the deposited material.

Figure 7.8. Top view of the layer deposited onto the substrate installed in the HE.

The thickness and the area of the deposited layer were measured with an Olympus VANOX-T optical microscope (OM). A Philips XL30 scanning electron microscope (SEM) was used to examine the microstructure of silica layers. The thickness of the deposited layers, measured by OM, ranged from 100 to 200 µm. Using this data in combination with mass and area of deposited layer, the surface density of the layer were calculated for each substrate.

SEM micrographs revealed a complex microstructure of deposits, but no significant changes in microstructure have been noticed between different samples, except for their thickness. With increasing distance from the burner, the thickness of deposited layer decreases. SEM images illustrating the microstructure and the dependence of the thickness on distance from the burner are shown in Fig. 7.9.
Figure 7.9. SEM micrographs of deposition layer cross-sections. Distance from the burner: (a) 20 mm, (b) 55 mm, (c) 85 mm, (d) 105 mm and thickness respectively 200, 145, 105 and 100 µm.

7.3 Model

A gas burner is situated above the left edge of the HE shown in Fig. 7.6. Flow of hot combustion products is indicated with arrows. From above HE is covered with the cover plate (not shown) that touches lamellas of region 2 (Fig. 7.6). We do not consider in detail the combustion process of methane-air mixture with L2 impurity. The methane-air mixture is assumed to be stoichiometric. The oxidation of fuel and impurities is very fast close to the burner surface [13,14]. The combustion can be presented by the following overall chemical reactions

\[
CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad (7.1)
\]

\[
C_{6}H_{18}Si_{2}O + 12O_2 \rightarrow 6CO_2 + 9H_2O + 2SiO_2 \quad (7.2)
\]

Because of low mole fraction of L2 \((Y_{L2} \ll 1)\) the total number of moles does not change significantly during combustion, and therefore the mole fraction of SiO\(_{2}\)
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$m$ molecules $Y_0$ in combustion products near the burner is estimated as $Y_0 = 2Y_{\ell_2}$. In the present calculations the uniform concentration $Y_0$ at the inlet is assumed. Small clusters and nanoparticles of silica form and grow due to collisions between $\text{SiO}_2$ molecules and silica nanoparticles

$$\left(\text{SiO}_2\right)_i + \left(\text{SiO}_2\right)_j \rightarrow \left(\text{SiO}_2\right)_{i+j}, \ i, j = 1, 2, 3, \ldots \quad (7.3)$$

We assume that no fragmentation of colliding clusters occurs. $\text{SiO}_2$ molecules, clusters and nanoparticles drift along HE with the flow velocity of combustion products. At the same time in a temperature gradient silica particles are driven from the high to low temperature regions [15], i.e. they are transported by thermophoresis to surfaces of HE. We assume that all arriving particles are permanently captured by the cold wall.

In the framework of mean-field approach, the evolution of the discrete size distribution of silica particles is described by a set of equations [15] (see also Chapter 4)

$$\frac{\partial C_k}{\partial t} + \text{div}\left(-D_k \nabla C_k + \mathbf{V} C_k\right) = \left\{\frac{\partial C_k}{\partial t}\right\}_{\text{Coag}}, \ k \geq 2. \quad (7.4)$$

The equation for the density of $\text{SiO}_2$ molecules $C_1$ is given by

$$\frac{\partial C_1}{\partial t} + \text{div}\left(-D_1 \nabla C_1 + \mathbf{V} C_1\right) = -C_1 \sum_{k=1}^{\infty} w_{1k} C_k \quad (7.5)$$

Here $C_k$ are densities of particles ($k$ refers to the number of $\text{SiO}_2$ molecules in the particle), $D_k$ is the diffusion coefficient of particles of size class $k$, $\mathbf{V}$ is the particle velocity that is the sum of the gas flow velocity $U$ and the thermophoretic velocity $V_{th}(k)$ of particles of size class $k$

$$\mathbf{V} = U + V_{th}(k) \quad (7.6)$$

The term in the RHS of Eq. (7.4) describes the Smoluchowski coagulation that is driven by Brownian diffusion and particle collisions

$$\left\{\frac{\partial C_k}{\partial t}\right\}_{\text{Coag}} = \frac{1}{2} \sum_{i=1}^{k-1} w_{i,k-i} C_i C_{k-i} - C_k \sum_{i=1}^{\infty} w_{ik} C_i, \quad (7.7)$$
where $w_{ik}$ is the coagulation kernel that depends on particle sizes and morphology [15]. The first term in the RHS of Eq. (7.7) is the rate at which clusters of size $k$ are formed by coagulation and the second term is the rate at which clusters are lost by growth to larger sizes.

In Eqs. (7.4) and (7.5) we will neglect the diffusion of silica particles over macroscopic distances. There are two reasons. First, the relative importance of thermophoresis to diffusion is measured by the Schmidt number $Sc_k = \mu / \rho D_k$. Silica nanoparticles form a dilute gas mixture in combustion products. Hence, diffusion of each nanoparticles size class can be considered independently, as it was done in Chapter 4 for copper nanoparticles in inert buffer gas. The main component in combustion products is nitrogen. This means that nanoparticles collide more frequently with nitrogen molecules. Therefore diffusivity of silica nanoparticles can be estimated as diffusion in a binary mixture, using a formula for rigid spheres of unequal masses [16]

$$D_k = \frac{1}{3} \sqrt{\frac{2}{\pi}} \left( \frac{1}{m_N} + \frac{1}{k m_S} \right) \frac{(k_B T)^{3/2}}{P \pi \left( r_N + r_S k^{1/3} \right)^2}$$

(7.8)

where $m_{N,S}$ are the mass of nitrogen and silica molecules, $r_{N,S}$ are the radii of nitrogen and silica molecules. The ideal gas law is assumed in Eq. (7.8). Near the wall of HE, at temperatures $T > 363$ K, for particles with sizes $k > 10$ the Schmidt number is estimated as $Sc_k \geq 10$. This means that diffusion is only important in a thin layer next to the cold walls of HE. The second reason to neglect diffusion is as follows. According to estimations, for silica nanoparticles the Peclet numbers are large $Pe_k = Uh / D_k \gg 1$ (where $h$ is the typical length scale, see Fig. 7.6 and Table 7.1), i.e. the convective transport dominates the diffusional one.

Further simplification of the model is associated with the size dependence of thermophoretic velocity. Silica particles formed in combustion processes are frequently aggregates of smaller particles which formed earlier. The transition to aggregate formation and the aggregate size distribution depends on initial concentration of siloxane in the gas/air mixture (Chapter 6). Aggregates possess a dendritic fractal-like structure that is characterized by a fractal dimension $D_f < 3$. 
Table 7.1. Material parameters used in model calculations.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gas temperature, $T_0$, K</td>
<td>1950</td>
</tr>
<tr>
<td>Temperature of HE wall, $T_w$, K</td>
<td>400</td>
</tr>
<tr>
<td>Pressure, $P$, Pa</td>
<td>$10^5$</td>
</tr>
<tr>
<td>Gas flow velocity, $U_0$, m/s</td>
<td>4</td>
</tr>
<tr>
<td>Concentration of L2, ppm</td>
<td>22</td>
</tr>
<tr>
<td>Prandtl number</td>
<td>0.7</td>
</tr>
<tr>
<td>Size of the simulation domain $h \times L$ in region 1, mm$^2$</td>
<td>25x200</td>
</tr>
<tr>
<td>Size of the simulation domain $h \times L$ in region 2, mm$^2$</td>
<td>4x50</td>
</tr>
</tbody>
</table>

In principle, thermophoretic mobility of a fractal-like aggregate may depend on its size and properties. In our experiments with the laboratory burner the air/gas mixture contained 270 ppm of L2 (see Chapter 6). We have observed that at this rather high L2 concentration the mean linear size of silica agglomerates was less than 100 nm at a distance of 75 mm from the burner. It is reasonable to assume that the silica particles formed in the boiler have similar size. The mean free path of gas molecules is estimated as (parameters are listed in Table 7.1)

$$\lambda = \sum_i \lambda_i Y_i \sim 400 \text{ nm}$$

(7.9)

where $Y_i$ is the mole fraction of gas component $i$ ($i = \text{N}_2, \text{H}_2\text{O} \text{ and CO}_2$) and $\lambda_i$ is the mean free path of a molecule of species $i$ [17]

$$\lambda_i = \frac{k_B T}{P} \left[ \sum_i \sigma_{ik} Y_k \left( 1 + \frac{m_i}{m_k} \right) \right]^{-1},$$

(7.10)

where $P$ is the gas pressure and $\sigma_{ik}$ is the collision cross section. Therefore in our case the Knudsen number is greater than one, i.e. suspended silica particles are smaller than the mean free path of carrier gas molecules $Kn = \lambda / L_k > 1$ (free molecular regime). Here $L_k$ is the linear size of particles of size class $k$.

According to Waldmann and Schmitt [18], in the free molecular regime the thermophoretic velocity of spherical particles does not depend on particle size and composition [18].
\[ V_{th} \approx 0.55 \frac{\mu}{\rho T} \nabla T , \]  \hspace{1cm} (7.11)

where \( \mu \) is the dynamic viscosity, \( \rho \) is the gas density and \( T \) is the temperature.

Experimental studies and model calculations [19-22] have revealed a remarkable property of aerosol particles, including fractal-like agglomerates – the thermophoretic velocity is not sensitive to particle size and morphology in the free molecular (\( Kn \gg 1 \)) and transition (\( Kn \approx 1 \)) regimes. In Ref. [20] the deposition of agglomerate soot aerosol particles has been studied experimentally under flow and temperature conditions relevant for diesel engine exhaust gas systems. Throughout the investigated particle size range of 34–300 nm (electrical mobility diameter), the observed deposition efficiencies were nearly independent of particle size and Knudsen number \( Kn \) in free molecular regime and in the transition regime. Later this observation was confirmed by Monte Carlo simulations [21] performed on aggregates with a range of fractal dimensions and by analytical calculations [22] for particles of arbitrary shape in the free molecular regime. We will assume the same behavior of silica particles in HE and will use Eq. (7.11) for the description of thermophoretic motion of silica nanoparticles. In what follows, we neglect the thermophoretic velocity along the x-axis (gas flow direction).

We are interested in the total mass deposition flux. Below we show how to find it in terms of the total silica density \( C = \sum_{k=1}^{\infty} k C_k \). Multiplying Eq. (7.4) by \( k \), summing over \( k \) and assuming independence of the thermophoretic velocity on \( k \), we find the equation for the total silica concentration

\[ \frac{\partial C}{\partial t} + \text{div}\left[(U + V_{th})C\right] = \sum_{k=1}^{\infty} k \left( \frac{\partial C_k}{\partial t} \right)_{coag} \]  \hspace{1cm} (7.12)

On a local scale the Smoluchowski coagulation conserves the total number of \( \text{SiO}_2 \) molecules; by direct summation it can be checked that

\[ \sum_{k=1}^{\infty} k \left( \frac{\partial C_k}{\partial t} \right)_{coag} = 0 . \]  \hspace{1cm} (7.13)

At steady state \( \frac{\partial C_k}{\partial t} = 0 \), \( k \geq 1 \). Therefore the total silica concentration obeys the equation
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\[
div\left([U + V_{th}]C\right) = 0. \tag{7.14}
\]

This equation contains no information about the size distribution of silica nanoparticles, provided that particles are smaller than the mean free path of the gas molecules. If the initial density \(C_0\) of SiO\(_2\) in the gas, the velocity and temperature fields are known, then the total silica concentration, hence, the silica flux to surfaces of HE can be found as a solution to Eq. (7.14). The important conclusion from the analysis presented above is formulated as follows: the flux of silica to HE does not depend on details of nanoparticle size distribution. The Smoluchowski coagulation operates on a local scale, while on a larger scale a group of silica nanoparticles moves as a single “macro particle” (Fig. 7.10a), undergoing internal rearrangements. Basically, Eq. (7.14) treats the population of silica particles as monodisperse.

To find the mass flux of silica it is convenient to use a particle trajectory method\,[23-25]\,i.e. the Lagrangian methodology. In the Lagrangian description particles released at the inlet are tracked during their motion in the gas until they either leave the simulation domain or deposit on HE walls (Fig. 7.10b). Trajectories of particles obey equations

\[
\frac{dx}{dt} = U_x, \quad \frac{dy}{dt} = V_{th} \tag{7.15}
\]

with the initial condition \(y_i\big|_{x=0} = y_{i0}\), where \(i\) numbers trajectories.

Particle trajectories do not cross, hence, the number of particles conserves in a flow tube that is formed by adjacent trajectories. Therefore the deposition flux \(F\) to the wall at a point \(x_{i+1/2}\) situated between points \(x_i\) and \(x_{i+1}\) is given by (see Fig. 7.10a)

\[
F^{(i)} \equiv F(x_{i+1/2}) = C_0 U_x^0 \frac{\Delta y_i}{\Delta x_i} = 2Y_{L2} \frac{U_0 P}{k_B T_0} \frac{\Delta y_i}{\Delta x_i} \tag{7.16}
\]

where \(\Delta y_i = y_{i+1}^0 - y_{i}^0\) is the spacing between trajectories at the inlet \(x = 0\), \(\Delta x_i = x_i^w - x_{i+1}^w\) is the spacing between trajectories near the HE wall and \(C_0 = Y_0 P / k_B T_0\) is the volume density of silica molecules at \(x = 0\). In Eq. (7.16) the silica flux to HE is defined as a number of SiO\(_2\) molecules arriving to unit area of HE per one second. The mass flux is \(F_m^{(i)} = m_S F^{(i)}\).
Figure 7.10. (a) The Smoluchowski coagulation inside the “flow tube”. The residence time and the final size of particles depends on landing position \( x_i \). 
\[ C_0 = \frac{y_0}{k_B T_0} \] is the volume density of silica molecules at \( x = 0 \) and \( C_w \) is the volume density of silica molecules at the wall. Yellow arrows show the conserving flux of silica molecules. (b) Particle trajectories in two-dimensional gas flow.

The most difficult part of the problem is to find the velocity and temperature fields of gas flow inside the HE even in a simple geometry. The point is that the convective heat transfer involves large temperature differences. Therefore one has to take into consideration the effect of variable temperature-dependent properties such as viscosity, thermal conductivity and density. In a real HE the flue gases flow both above and between lamellas in region 1. However, for simplicity, in order evaluate the velocity and temperature fields we replace the undulate surface above lamellas (region 1 in Fig. 7.6) with an isothermal flat plate. Then we use the approximation of
a laminar boundary-layer flow along this plate. Governing equations of a laminar forced convection are written as [26]

\[
\frac{\partial \rho U_x}{\partial x} + \frac{\partial \rho U_y}{\partial y} = 0 ,
\]

\[
\rho U_x \frac{\partial U_x}{\partial x} + \rho U_y \frac{\partial U_x}{\partial y} = \frac{\partial}{\partial y} \left( \mu \frac{\partial U_x}{\partial y} \right),
\]

\[
\rho U_x \frac{\partial c_p T}{\partial x} + \rho U_y \frac{\partial c_p T}{\partial y} = \frac{\partial}{\partial y} \left( \kappa \frac{\partial T}{\partial y} \right),
\]

where \( \kappa \) is the thermal conductivity. Boundary conditions are given by

\( y = 0 : \quad U_x = 0 , \quad U_y = 0 , \quad T = T_w , \)

\( y \to \infty : \quad U_x = U_0 = \text{const} , \quad T = T_0 , \)

where \( T_0 \) is the temperature

To solve the set of Eqs. (7.17)-(7.19) we use the similarity transformation [26]

\[
\eta = \frac{y}{x} \left( \frac{1}{2} \text{Re}_x \right)^{1/2} , \quad \text{Re} = \frac{x U_x}{v_0}
\]

\[
U_x = U_0 W_x(\eta)
\]

\[
U_y = U_0 \left( \frac{1}{2} \text{Re}_x \right)^{-1/2} W_y(\eta)
\]

\[
\theta(\eta) = \frac{T - T_0}{T_w - T_0}
\]

where \( \eta \) is the dimensionless coordinate variable, \( \text{Re}_x \) is the local Reynolds number, \( W_{x,y}(\eta) \) are the dimensionless velocity components and \( \theta(\eta) \) denotes the dimensionless temperature. Partial differential Eqs. (7.17)-(7.19) are transformed to the set of ordinary differential equations
\[ 2 \frac{dW_y}{d\eta} - \eta \frac{dW_x}{d\eta} + \frac{1}{\rho} \frac{d\rho}{d\eta} \left( 2W_y - \eta W_x \right) = 0 \] (7.26)

\[ \frac{d^2W_x}{d\eta^2} = \left[ \frac{\nu}{\nu} \left( 2W_y - \eta W_x \right) - \frac{1}{\mu} \frac{d\mu}{d\eta} \right] \frac{dW_x}{d\eta} \] (7.27)

\[ \frac{d^2\theta}{d\eta^2} = \left[ \text{Pr} \frac{\nu}{\nu} \left( 2W_y - \eta W_x \right) - \frac{1}{\kappa} \frac{d\kappa}{d\eta} \right] \frac{d\theta}{d\eta} \] (7.28)

with the boundary conditions

\( \eta = 0 : \ W_x = 0, \ W_y = 0, \ \theta = 1, \)

\( \eta \to \infty : \ W_x = 0, \ \theta = 0, \)

Here \( \nu = \mu / \rho \) and \( \nu_0 = \nu(T_0) \) is the kinematic viscosity. It is known that for most gases the Prandtl number \( \text{Pr} = c_p \mu / \kappa \approx const \) is nearly constant over a wide range of temperature. The specific heat \( c_p \) is also assumed to be constant.

The gas pressure does not change appreciably inside HE. Therefore, using the ideal gas law we obtain relation between gas density and temperature

\[ \rho k_B T = P \sum_i m_i Y_i = const \] (7.29)

The temperature dependence of the dynamic viscosity is approximated by the Sutherland formula using nitrogen parameters

\[ \mu = 1.41 \times 10^{-6} \frac{T^{3/2}}{T + 111} \text{ Pa} \cdot \text{s} \] (7.30)

It is known that the approximation of laminar boundary-layer overestimate the transverse velocity [27-29] therefore we will not take into account the y-component of gas flow velocity in Eq. (7.15).

## 7.4 Results and comparison with experimental data

The boundary layer Eqs. (7.26)-(7.28) were solved in region 1 by the shooting method using parameters listed in Table 7.1. Figure 7.11 shows the velocity and temperature profiles. The calculated thermophoretic velocity (Fig. 7.12) is in the range 5-20 mm/s. A set of particle trajectories are plotted in Fig. 7.13.
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![Graphs of velocity and temperature profiles at several locations x along the gas flow direction.](image)

Figure 7.11. Velocity (a) and temperature (b) profiles at several locations $x$ along the gas flow direction.

![Graph of thermophoretic velocity as a function of distance along the gas flow direction.](image)

Figure 7.12. Thermophoretic velocity as a function of distance along the gas flow direction.

It is seen that a fraction of trajectories escape the simulation volume. For the uniform initial distribution of silica at the inlet $x=0$ the deposition efficiency can be calculated as a fraction of trajectories ending at the cold wall ($y=0$). The deposition efficiency corresponding to parameters of Table 7.1 is about 10% (the deposition efficiency is defined as a mass fraction of silica deposited to the walls of HE.) The rest of silica is transported by gas flow into region 2 (Fig. 7.6) where the flue gases flow between lamellas.

Using the average values of velocity and temperature at the outlet of simulation region 1 as the input parameters we have simulated the gas flow between lamellas and silica deposition in region 2. Figure 7.14 shows the deposition efficiency versus the distance along the flow direction. It was seen that the deposition efficiency in the
end of region 2 is about 57%. The combined efficiency of regions 1 and 2 is about 60%. However in an experiment using filters in the exhaust pipe we have seen that about 90% of silica remains in the heat exchanger. The difference between model and experimental results is explained by the fact that a big portion of the flue gases are between the lamella even in region 1. Between the lamella the particles have to travel only 1-2 mm to hit the walls. Therefore the actual percentage of silica deposition in HE is higher.

\[ \text{Figure 7.13. Particle trajectories. The cold wall is situated at } y = 0. \]

In our experiment the air/gas mixture containing 22 ppm of L2 were burned in the boiler for 400 hours. Fig. 7.15 shows the measured surface density of deposited silica. It turned out that the calculated surface densities of silica is about 4 times higher than the experimental ones. Possible reasons for discrepancy are:

- the real surface of HE is undulated as in Fig. 7.6, therefore the silica flux is distributed to a larger area as compared with the flat surface;
- the approximation of the boundary-layer overestimate the thermophoretic velocity, especially near the entrance of HE;
- From an experimental viewpoint probably not all silica nanoparticles stick to the walls of HE.

The deposition efficiency can change with time because of the effect of the insulating silica layer. This question needs a separate experimental study. We believe that the main reason of discrepancy is the replacement of real complicated configuration of HE with the flat surface.

In order to reduce the calculated surface density, in Fig. 7.15 we have introduced into the mass flux a coefficient of 0.25, i.e.
\[ F^{(i)} = 0.25 m_s \frac{U_0 P}{k_B T_0} \frac{\Delta y_i}{\Delta x_i} 2Y_{L2}. \] (7.31)

It is seen that both experimental and calculated surface densities of silica decreased along the flow direction in the same fashion.

**Figure 7.14.** Deposition efficiency of silica particles in region 2 (between lamellas).

**Figure 7.15.** Surface density of silica deposited in HE in region 1 during combustion of the gas/air mixture containing 22 ppm of L2 for 400 hours. Symbols correspond to experimental data. The solid curve is given by Eq. (7.31) multiplied by 400 hours.
7.5 Conclusions

1. Experimental results are presented on silica deposition in a typical domestic heat exchanger during combustion of siloxane-containing gas.

2. Thermophoretic transport of silica nanoparticles in the hot combustion products is considered within the approximation of a laminar boundary-layer flow taking into account the temperature dependence of gas properties.

3. It is shown that the flux of silica to HE walls is not sensitive to details of particle size distribution, i.e. the Smoluchowski coagulation does not influence the total amount of silica deposited to HE walls.

4. The mass flux of silica depends linearly on siloxane concentration in the input air/gas mixture. The model predicts that clogging of HE by silica deposition during combustion of siloxane-containing gas (e.g. biogas) is a linear function of time and siloxane concentration, i.e. the surface density of silica layer is proportional to $Y_0 t$. The practical conclusion is that the maximum allowable silicon content in biogases can be determined by extrapolating results from short-term tests. This avoids the need to perform time consuming long-term tests at very low siloxane concentrations.

5. The developed model provides a physical picture of silica deposition during combustion of siloxane-containing biogas and may serve as a framework for a more detailed and complicated description.

7.6 References


Deposition of SiO$_2$ nanoparticles in heat exchanger


