



## **SIMPLIFIED MODEL FOR THERMO- AND DIFFUSIOPHORETIC DEPOSITION IN A HEAT EXCHANGER**

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### **Abstract**

A model is presented to estimate the aerosol particle deposition in heat exchangers due to combustion processes. The model estimates deposition by thermophoresis and diffusiophoresis using parameters which are easily measurable during the power plant operation. These parameters are the flue gas temperature for thermophoresis and the humidity for diffusiophoresis. Aerosol particles are often found to have a log-normal distribution. The model for thermophoresis estimates the particle deposition using the mean diameter and the standard deviation of the log-normal size distribution. As thermophoresis is particle size dependent, the mean diameter and the

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Received: July 10, 2017; Accepted: October 14, 2017

Keywords and phrases: deposition, diffusiophoresis, heat exchanger, thermophoresis.

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standard deviation have influences on the deposition estimate and therefore on the deviation from the sum of the deposition calculated for different size bins. An easy-to-use graphic is introduced to correct this deviation.

## Introduction

Fouling is a process where scale is formed, initiated and sustained by sedimentating particles that deposited either shortly after their formation or through collision adhere on the wall in contact with the aqueous fluids [1]. Fouling problem occurs in heat exchangers has many causes such as the fluids being used crude oil and water. Crude oil fouling in preheat trains in refineries which is usually dominated by organic matter deposition in heat exchangers at high temperatures [2], in which it is found that changes in feedstock may lead to substantial deposition of inorganic salts or corrosion products, compromising heat exchange performance, pressure drop, and even safety.

Water that may include calcium and potassium ions that forms significant scaling on the internal walls of the heat exchangers, mainly when this water is exposed to different physical influences, such as heat transfer, friction and pressure change. They can revert back into natural solid stage against with one another and always lead to the formation of deposits on the surfaces and causing fouling problems [3, 4]. Worst conditions happen when sea water is used as it contains more dissolved solids and minerals.

In combustion processes of fossil fuels a particulate phase is present in the flue gas which can deposit onto surfaces and influence the performance of components in the energy production line. It has been found that the aerosol formation in combustion processes are often log-normally distributed [5]. The deposition of submicrometer soot aerosol particles in a miniature pipe bundle heat exchanger system has been investigated under conditions characteristic for combustion exhaust from diesel engines and oil or biomass burning processes [6], where it is found after the system has been characterized for a wide range of aerosol inlet temperatures (390-510 K) and flow velocities (1-4m/s), and particle deposition efficiencies up to 45%

have been achieved over an effective deposition length of 27 cm, that thermophoresis was the dominant deposition mechanism, and its decoupling from isothermal deposition was consistent with the assumption of independently acting processes.

Deposit formation is a major problem in heat exchangers operation as it increases both thermal resistance and pressure drop, thus affecting both the initial capital cost and the operating costs. Other than frequent cleaning, there are a number of active or passive techniques referred to in the published literature that may enhance a heat exchanger's efficiency and/or decrease fouling rates [7].

Spoiler design has been used to reduce particle deposition on the extended surface of heat exchanger on the gas side [8], where the effects on fouling resistance has been obtained experimentally. Deposition on heat exchanger tubes due to iron oxide has been investigated for Alloy-800 heat exchanger [9].

Reduction of the deposition rate in lignite fired utility boiler heat exchangers is theoretically investigated through comparison with an in-line arrangement with circular tubes [10]. The highest deposition reduction rate was found for elliptic-shaped tubes bundle arrangement [10]. Addition of cones to the front of cylinders in order to reduce particulate deposition and proceeded to find the optimum cone angles was proposed [11].

An experimental study has been carried out to investigate the performance of different types of exhaust gas circulation coolers in the presence of particulate fouling by soot particles under thermophoretic condition [12].

Recent study [13] conducted a set of fouling experiments to evaluate the mitigation of calcium carbonate scaling by applying diethylene triamine pentaacetic acid (DTPA) treated multi walled carbon nanotubes (MWCNT) based water nanofluids on heat exchanger surfaces. Investigation of additive DTPA-treated MWCNT-based water nanofluids on fouling rate of deposition was performed. Assessment of the deposition of calcium carbonate on the heat exchanger surface with respect to the inhibition of crystal growth was

conducted by Scanning Electron Microscope (SEM). The results showed that the formation of calcium carbonate crystals can be retarded significantly by adding MWCNT-DTPA additives as inhibition in the solution.

The objective of this work is to develop an easy-to-use model to estimate the aerosol particle deposition in heat exchangers by thermophoresis and diffusiophoresis using easily measurable parameters during power plant operation. These parameters are flue gas temperature as well as heat flux and humidity for thermophoresis and diffusiophoresis, respectively. Moreover the model estimates the particle deposition using the mean diameter and the standard deviation of the log-normal size distribution and presents a correction to the estimation.

### Theory

The focus here is on particle deposition by thermophresis and diffusiophoresis only. Deposition properties are presented here in terms of a deposition velocity  $U_{dep}$  [m/s], the actual velocity perpendicular to the wall with which the particles migrate into the wall. Consider  $C$  (g/m<sup>3</sup>) as the mass concentration of particles suspended in the gas, the product of  $U_{dep} \cdot C$  results in the mass of deposited particles per unit time and area.

Thermophoresis is caused by a temperature gradient in the gas phase between hot and cold surfaces. Gas molecules collide with the aerosol particles on the hot surface with higher energies than on the cold surface, causing a net momentum transfer in the direction of the decreasing temperature gradient. The following equation for the thermophoretic velocity was proposed by Talbot [14],

$$U_{TPH} = -Kv \frac{\nabla T}{T}, \quad (1)$$

where

$$K = 2C_s \frac{(\alpha + C_t Kn)(1 + Kn(A + Be)^{-\frac{C}{Kn}})}{(1 + 3C_m Kn)(1 + 2\alpha + 2C_t Kn)} \quad (2)$$

using the constants  $A = 1.20$ ,  $B = 0.41$ ,  $C = 0.88$ ,  $C_m = 1.146$ ,  $C_s = 1.147$ ,  $C_t = 2.20$ .  $\nu$  is the kinematic viscosity ( $\text{m}^2/\text{s}$ ),  $T$  the absolute temperature (K),  $\alpha = k_g/k_p$  the ratio of gas to particle thermal conductivities and  $Kn$  the Knudsen number (equal to the ratio of the gas mean free path to the particle diameter). The thermophoretic velocity can be written as

$$U_{TPH} = -K \frac{\nu}{kT} q'', \quad (3)$$

where  $k$  is the thermal conductivity ( $\text{W/mK}$ ) and  $q''$  is the heat flux ( $\text{W/m}^2$ ). Equation (3) shows that the thermophoretic velocity is directly proportional to the surface heat flux.

Typically, in the case of significant vapour condensation diffusiophoresis overshadows thermophoresis. If particles are present in a nonuniform mixture of gases, they experience a diffusiophoretic force due to concentration gradients of the gas components. This becomes especially important near condensing or evaporating surfaces. In case of water vapour condensation onto a surface, aerosol particles are drawn to the surface along with the water vapour. The diffusiophoretic deposition velocity can be expressed as [15],

$$U_{DPH} = \frac{x_{vap} \sqrt{M_{vap}}}{x_{vap} \sqrt{M_{vap}} + x_{nc} \sqrt{M_{nc}}} \cdot \frac{\dot{m}_{cond}''}{\rho_{vap}}, \quad (4)$$

where the density is  $\rho$  ( $\text{kg/m}^3$ ), the molecular weight  $M$  ( $\text{kg/mol}$ ) and the mole fraction  $x$  of vapour and non-condensable species. It is noteworthy that the diffusiophoretic deposition rate does not depend on particle size and is proportional to the vapour condensation rate  $\dot{m}_{cond}''$  ( $\text{kg/sm}^2$ ).

### Model

Due to its high content of  $N_2$ , the flue gas can be approximated by pure nitrogen. Power fit functions of temperature ( $K$ ) are used for the kinematic viscosity ( $\text{m}^2/\text{s}$ ), thermal conductivity ( $\text{W/mK}$ ) and mean free path ( $\mu\text{m}$ ) of

nitrogen,

$$\nu(T) = 8.37 \cdot 10^{-10} \cdot T^{1.7275}, \quad (5)$$

$$k(T) = 10^{-3} \cdot (0.803 \cdot T^{0.65} - 6.831), \quad (6)$$

$$\lambda(T) = 6.088 \cdot 10^{-5} \cdot T^{1.2275}. \quad (7)$$

The power fit functions for kinematic viscosity and thermal conductivity are generated from tabular data [16] and are valid from 200 K to 700 K. The power fit functions are used extensively in literature [17, 18] to fit experimental data for physical properties evaluation of fluids.

The factor  $K$  in equation (2) and in equation (3) can be interpreted as a dimensionless thermophoretic deposition velocity at given temperature and heat flux. Its dependency of  $\alpha$ , the ratio of thermal conductivities, is often expressed as a function of the inverse Knudsen number. This expression can be modified by using equation (7) to obtain a simple relation of particle

radius  $R_p$  and temperature as  $\xi = \frac{R_p}{T^{1.2275}}$ . By knowing the particle size and

the gas temperature, the value for  $K$  can be easily obtained from Figure 1 and the thermophoretic deposition velocity calculated from equation (3). The actual deposition is the product of the deposition velocity and the particle concentration.

Thermophoresis is dependent on particle size. Approximating the thermophoretic deposition by  $U_{TPH}(DPG)$ , the mean diameter of the log-normal distribution, times the mass concentration generates an error which depends on the mean diameter, DPG, and the standard deviation,  $\sigma$ . Figure 2 shows the relative deposition to be added (AD) when it is calculated using DPG and  $\sigma$  instead of calculating the sum of deposition for different size bins.

The diffusiophoretic deposition can be rewritten as the vapour condensation flux times a factor containing all other variables. Therefore, equation (4) becomes

$$U_{DPH} = \Psi_{DPH} \cdot \dot{m}_{cond}'' , \quad (8)$$

where

$$\Psi_{DPH} = \frac{1}{x_{vap} + x_{nc} \sqrt{M_{nc}/M_{vap}}} \cdot \frac{R \cdot T}{p \cdot M_{vap}} . \quad (9)$$

For the total pressure,  $p$  (Pa), we use 100 kPa a quite realistic value for heat exchangers. The factor  $\Psi_{DPH}$  as a function of vapour mole fraction ( $X$ ) is shown in Figure 3. If the pressure significantly differs from  $p = 100$  kPa it can be easily corrected in equation (8) as  $U_{DPH}$  is inversely proportional to pressure.

### Example

The aerosol measurements were done in a large size diesel engine as used in power plants [19]. The measurement shows a bimodal mass-size distribution ( $\varphi = dm/d\log(Dp)$ ). The distribution can be approximated by a superposition of two separate distributions (Figure 4). The absolute values of the original data were classified but the total mass concentration was announced to be  $100 - 150 \text{ mg/Nm}^3$ . We rescaled the distribution to obtain the upper end of the concentration,  $150 \text{ mg/m}^3$ . The temperature was  $350^\circ\text{C}$ .

Now, we can generate log-normal distributions, fct 1 and fct 2, with the mean diameters, mean 1 and mean 2, for the separated distributions, distr. 1 and distr. 2, respectively as shown in Figure 5.

The mass concentration has to be separated into two different ones according to the area of the distributions. The corresponding values are shown in Table 1. Figure 1 is used to obtain the values for  $K$  and calculate the thermophoretic deposition velocities for both distributions. The surface heat flux we assumed to be  $2000 \text{ W/m}^2$ . Then, the thermophoretic deposition is simply the product of the concentration, the thermophoretic deposition velocity and the factor  $(1 + \text{additional deposition})$ .

The vapour content of the exhaust gas can be roughly estimated to be 10-

15%. This means that for an operating pressure around 1 bar condensation occurs for surface temperatures below 330 K. For  $\text{mol}(\text{vap})/\text{mol}(\text{total}) = 0.1$  and  $T = 625 \text{ K}$  the diffusiophoresis factor equation (8) becomes  $\Psi_{DPH} = 2.3$ . For a condensation flux, e.g.  $\dot{m}'' = 5 \cdot 10^{-4} \text{ kg}_{\text{vap}}/\text{m}^2\text{s}$ , the diffusiophoretic deposition velocity becomes  $U_{DPH} = 1.15 \cdot 10^{-3} \text{ m/s}$  and the deposited mass  $M_{DEP} = U_{DPH} * C = 0.1725 \text{ mg}/\text{m}^2\text{s}$ .

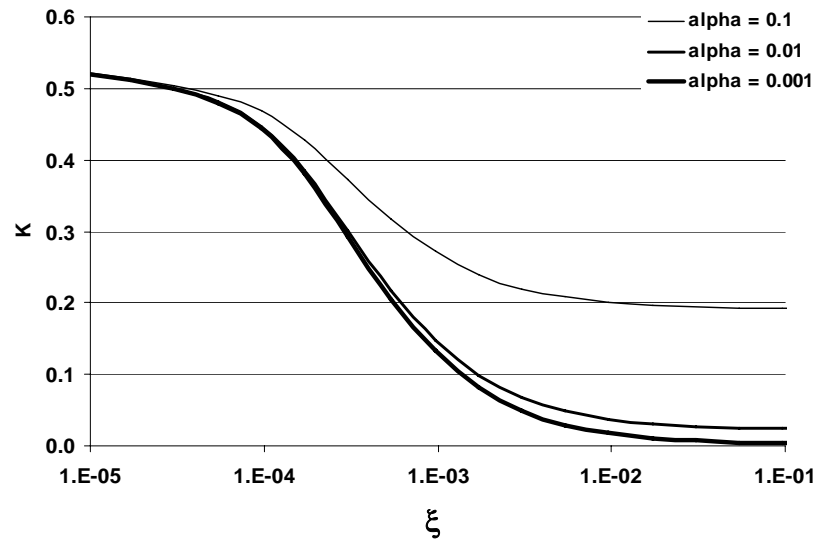
### Conclusions

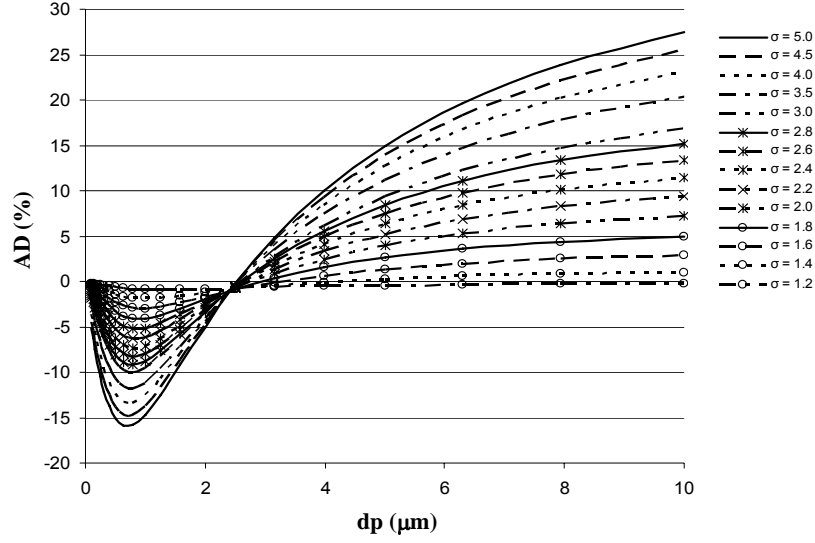
A model is developed to estimate aerosol particle deposition by thermophoresis and diffusiophoresis in heat exchangers. The model uses parameters easily achievable during the power plant operation. These parameters are the flue gas temperature as well as the heat flux and the humidity for thermophoresis and diffusiophoresis, respectively. Aerosol particle are often found to have a log-normal distribution. The model for thermophoresis estimates the particle deposition using the mean diameter and the standard deviation of the log-normal size distribution. As thermophoresis is particle size dependent the mean diameter and the standard deviation have an influence on the deposition estimate and therefore on the deviation from the sum of the deposition calculated for different size bins. An easy-to-use graph is introduced to correct this deviation. The diffusiophoretic deposition velocity can be easily estimated by only knowing the gas temperature, the humidity as well as the condensation flux. This model offers a fast way to estimate deposition changes if plant operating parameters like gas temperature, heat or condensation flux are changed.



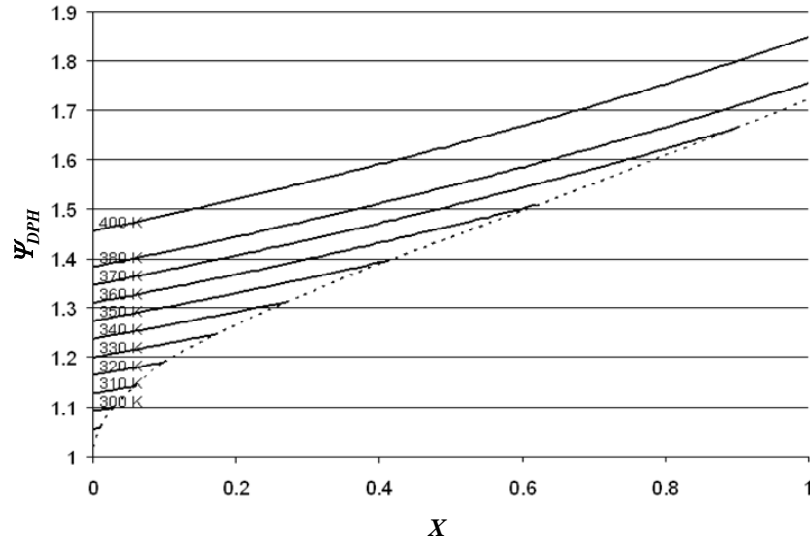
**Table 1.** Parameters according to distributions 1 and 2

	Distribution 1	Distribution 2
Mean diameter, $\mu$ [ $\mu\text{m}$ ]	0.062	0.75
Standard deviation, $\sigma$	1.41	5.25
Mass concentration, $C = 150 [\text{mg}/\text{m}^3]$	$\sim 43\%$	$\sim 57\%$
$R_p/T^{1.2275}$	$1.15\text{E-}05$	$1.39\text{E-}04$
$K$	0.52	0.42
UTHP (m/s)	$-2.05\text{E-}03$	$-1.66\text{E-}03$
Additional deposition (%)	-1	-16
Deposition, ( $\text{mg}/\text{m}^2\text{s}$ ), $C*UTPH*(1 + \text{add depos.})$	0.131	0.119

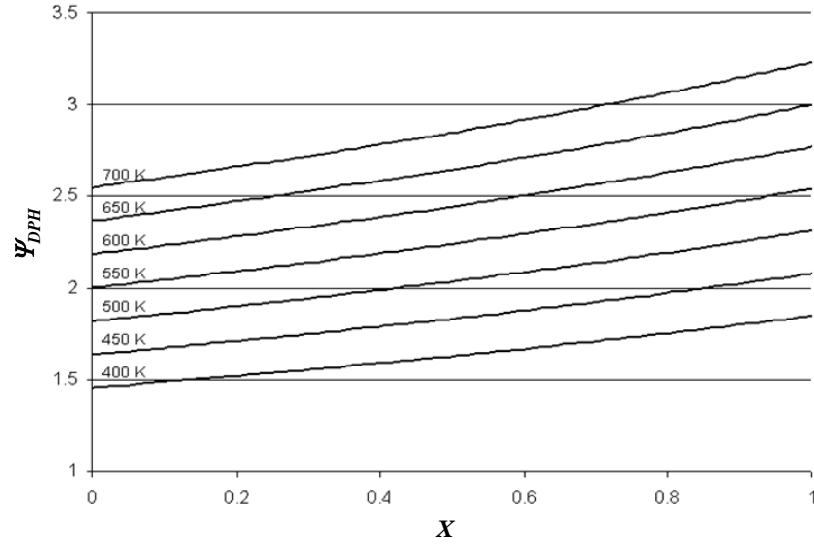
**Figure 1.** Variation of  $K$  with the modified inverse Knudsen number for different particle thermal conductivity ratios.



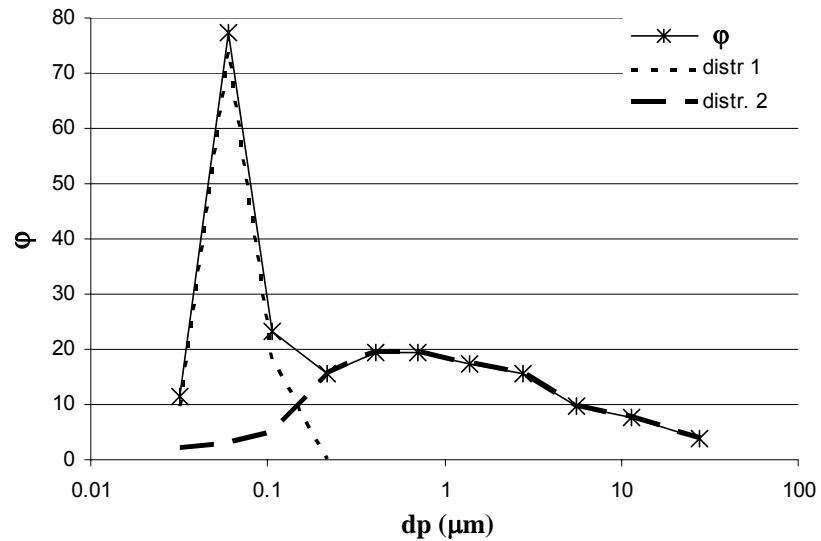
**Figure 2.** Distribution of additional deposition. Relative deposition to be added when thermophoresis is calculated by the mean diameter, DPG, and the standard deviation,  $\sigma$  instead of calculating the sum of deposition for different size bins.



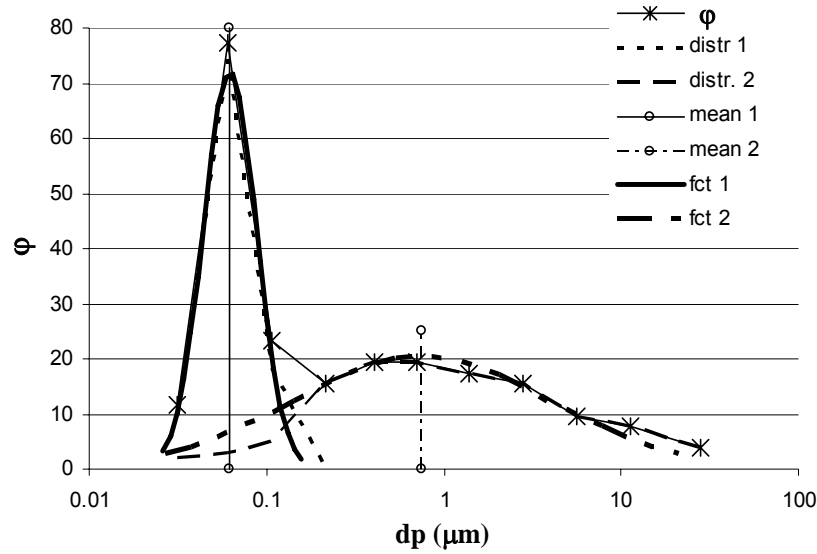
**Figure 3(a).** Variation of diffusiophoresis using the gas temperature as a parameter. This factor times the condensation mass per unit area and time results in the deposition velocity. Gas temperature is up to 400 K.



**Figure 3(b).** Variation of diffusiophoresis using the gas temperature as a parameter. This factor times the condensation mass per unit area and time gives the deposition velocity. Gas temperature: 400 K-700 K.



**Figure 4.** Exhaust ash aerosol mass size distribution for a large diesel engine.



**Figure 5.** Log-normal distributions with their mean diameters.

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