Grease Particle Deposition Measurements in a Kitchen Exhaust Duct for the Development of Low Cost Grease Sensors

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ABSTRACT

Grease deposition in kitchen exhaust ducts is an imminent fire hazard. There exists the need to quantize and measure the amount of grease deposition in a commercial kitchen exhaust duct in a cheap and efficient manner. Results from a real cooking emission study (ASHRAE 1375-RP) were used to model grease deposition onto a cylinder. Simulated cooking experiments were performed using a 200:1 ratio of non volatiles: uranine using a Polydisperse Aerosol Generator (PAG). The use of a cylinder in cross flow with a strain gage arrangement and a LED-photo resistor arrangement on two opposite walls of a 0.254 m by 0.203 m (10 inches by 8 inches) duct at two exhaust velocities namely 2.54 m/s (500 ft/min) and 7.62 m/s (1500 ft/min) were investigated. The size distributions obtained by the simulated cooking experiments were similar to that obtained in the ASHRAE 1375-RP study. The modeling results were within a factor of 1.5 of the simulated cooking results. This is reasonable considering the complexities of actual grease deposits. The photo resistor was very sensitive to minute changes of grease deposition layers. It would be beneficial to inspect the output signal of the photo resistor for greater thickness of grease deposits. The strain gage technique did not prove successful to measure grease deposition inside a duct due to the constant vibrations. Deposition results obtained flurometrically showed that deposition flux on to a cylinder placed in cross flow and all four walls of the duct increases with increasing exhaust velocity. Deposition flux on the windows for the LED and the photo resistor were in close proximity to the deposition flux on the two side walls. Correlations were developed for particle deposition on all four walls of the duct. Flow Reynolds number has a major impact on particle deposition in large exhaust ducts. A different approach is required in representing deposition results in terms of non dimensional parameters.
Acknowledgements

I would like to take this opportunity to thank my advisor Dr. T.H. Kuehn for accepting me into his research group. I am greatly indebted to his guidance, advise and support during the course of my graduate study. His words of encouragement have strived me to scale greater heights. I would also like to thank Dr. Bernard Oslo for his advice and support in lending me all the necessary equipment for my research project. My lab mates Nick Stanley, Zhili Zhou, Song Ge, friends Pradeep, Arvind, Abhijit, Vivek and many others made my stay at the University of Minnesota a memorable one. They were always ready to help me out and provide me with valuable suggestions. A special mention to Dan and John from the Particle Calibration Lab for helping me out with the flurometer and Bob Nelson from the machine shop for fabricating the duct work. Lastly I would like to thank my parents for their kindness and love.
Dedication

This thesis is dedicated to my parents
Dr.K.Ramesh and Mrs.Mohana Ramesh
and my sister Nandhini Ramesh
for their love and support all throughout my life.
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Chapter 1

Introduction

Studies on turbulent deposition of particles have been carried out for more than fifty years. Researchers have developed great insights in the field of electronics, combustion studies, lung deposition, indoor air quality, HVAC and various other fields by studying the pattern of particulate deposition in turbulent flows. Deposition studies dealing with grease laden airborne kitchen effluents have brought about a whole new research dimension to the commercial kitchen industry. At the turn of this century Grestler et al. (1998) performed a comprehensive study of cooking effluent emissions from various commercial kitchen appliances. It was found out that by reducing the minimum required velocity of commercial kitchen exhaust ducts to 500 fpm from the previous minimum velocity of 1500 fpm adapted from industrial ventilation standards, the amount of grease build up in commercial kitchen exhaust ducts was significantly reduced.

Grease deposition is a major concern in cooking exhaust ducts. Prolonged and continuous use of these exhausts ducts in commercial kitchens results in the accumulation of a uniform layer of grease and dirt. More important than the mere unpleasantness of the atmosphere and the surfaces, is safety. A coating of predominantly grease and fat is an imminent fire hazard. Taking into account the relatively hot temperatures in a kitchen and the fact that grease is combustible a small spark could cause substantial damage and even loss of life. Periodic cleaning would greatly minimize the damage that could otherwise be caused. Other benefits include increased efficiency and longevity of the exhaust system as a clogged system would require greater fan energy to
Cleaning of a kitchen exhaust system is a long and involved process. It would be greatly beneficial if cleaning companies know as to when cleaning is actually required in a duct. The intention of this study is the development of a low cost sensor which would address the issue of quantizing the thickness of grease deposits in kitchen exhaust ducts.

Outlined below is a brief overview of the different chapters in the thesis. Chapter 2 discusses the various experimental studies that have been carried out regarding particle deposition. Furthermore commercially available technologies and patents that can be incorporated in building a grease sensor are summarized. Chapter 3 deals with the modeling of a cylinder in cross flow which can act as a potential low cost sensor. Various particle deposition mechanisms such as impaction, diffusion and thermophoresis are modeled based on the findings of the ASHRAE 1375- RP report. Depositions onto a cylinder in cross flow are compared to that of the depositions onto a duct wall. Chapter 4 describes the validation of the model by experimentation using oleic acid particles impinged with uranine dye which acts as a surrogate for real cooking emissions effluents as demonstrated by Kuehn et al.(2004). Deposition studies are performed in a developing flow regime which is characteristic of exhaust ducts in the HVAC industry. Chapter 5 describes the use of the developed techniques in a real cooking environment. Finally conclusions and future work in the development of grease thickness measurement sensors are discussed.
Chapter 2

Literature Survey

2.1 Experimental Studies

Particle deposition from turbulent flow has been studied experimentally as well as theoretically because of its importance in numerous systems. Airborne particles deposit onto surfaces from turbulent flows by a variety of mechanisms. A number of parameters which influence particle deposition were looked into by various researchers over the years. The parameters are classified into the following broad categories.

- Characteristics of the conduit in which deposition takes place. These include shape, size, dimension, roughness and type of conduit material.

- Properties of the particle under investigation such as phase of the particle (solid or liquid), diameter, density, dimensionless relaxation time, etc.

- Fluid flow parameters such as flow Reynolds number.

This section provides a comprehensive review of the experimental work done by researchers over the past 50 years. Alexander et al. (1951) studied the deposition of water droplets of size 27 μm in horizontal steel tubing of 4.72 cm (1.86 inches) I.D. Friedlander et al. (1957) studied the rate of deposition of dust particles generated by a powder atomizer on cylindrical tubes. Two tube materials namely glass and brass were tested. The dimensions of the glass tubes ranged from 0.54 cm (0.21 inches) to 2.5 cm (0.98 inches) and the brass tubes from 1.38-2.5 cm (0.54-0.98 inches). Iron and aluminum
particles with size ranging from 0.8-2.63 \( \mu m \) were investigated. It was found that the net rate of particle deposition depended on both the rate of transport of particles to the wall and the rate of entrainment. They also showed that deposition from turbulent flow was predominantly due to particle inertia. Postma et al.(1960) studied the turbulent deposition of zinc sulphide particles of size range 2-4 \( \mu m \) in an aluminum tube of 2.54 cm (1 inch) I.D. for a flow Reynolds number ranging from 3000-20000. Wells, et al.(1967) looked at the deposition of polystyrene spheres produced by a La Mer generator from turbulent airstreams on vertical surfaces using radioactive particles. They found that Brownian motion played a significant role in the deposition of smaller particles and their experimental results were in accordance with the empirical law relating transport to the two-thirds power of the diffusivity of the particles. Montgomery et al.(1970) measured the deposition of mono disperse aerosols of Uranine-Methylene Blue in a 15 cm (5.9 inches) I.D. aluminum pipe. The aerosol particles were generated using a spinning disc aerosol generator. The study was confined to particle sizes ranging from 0.44-2.16 \( \mu m \) with the flow Reynolds number ranging from 5000-367,000. It was found that charged particles increase deposition by a factor of thirty. Their results also showed a strong relationship between particle dimensionless deposition velocity \((V^+)\) and flow Reynolds number but they could not obtain a strong relationship between the dimensionless relaxation time \((\tau^+)\) and dimensionless deposition velocity \((V^+)\).

Schmel(1971) studied the deposition of monodisperse uranine particles on to the floor and ceiling surfaces of a test section of dimensions 60 cm by 60 cm (1.97 ft by 1.97 ft). A spinning disc aerosol generator was used to generate particles of diameters ranging from 2-14 \( \mu m \). He obtained correlations to determine particle eddy diffusivities used to describe particle transport in the non-isotropic turbulence region adjacent to a smooth deposition surface. Liu et al.(1973) studied the deposition rate of monodisperse aerosol particles in a vertical cylindrical pipe 102 cm long (40.16 inches) and 1.27 cm (0.5 inches) I.D. for flow Reynolds numbers of 10,000 and 50,000. Monodisperse particles of size range 1.4-21 \( \mu m \) were generated using a Vibrating Orifice Aerosol Generator. They found that the dimensionless deposition velocity increased rapidly as a function of dimensionless relaxation time reaching a peak at \((\tau^+ =30)\) and then leveling
off. Papavergos and Hedley provided a comprehensive review of deposition work in turbulent flows up until 1984. Based on the large amount of experimental data available they came up with a model explaining the relationship between dimensionless relaxation time ($\tau^+$) and dimensionless deposition velocity ($V^+$). Lee et al. (1993) studied the deposition rates of Dioctyl phthalate (DOP) particles of various size ranges in both the inertial and diffusional deposition regimes. Their results showed that the theory of Wells et al. (1967) predicts deposition by diffusion in turbulent flows reasonably well while the theory of Friedlander et al. (1957) is suitable for correlating deposition by inertial impaction. They also showed that practice of estimating deposition rates in the transition regime through the use of arithmetic sum of deposition velocities derived from the two theories was inadequate.

Saldo et al. (1994) performed studies on aerosol deposition in large horizontal and vertical pipes of 6 m (19.68 ft) in length and internal diameter of 20 cm (7.87 inches) to better understand the deposition of CsI aerosol particle leaks in a nuclear facility. Four experiments with Aerodynamic Mass Mean Diameters of 1.4-3.2 $\mu$m were performed and the results obtained were in close agreement with the correlation of Liu and Agarwal. Muyshondt et al. (1996) performed experimental studies of particle deposition in turbulent flows very similar to the work performed by Liu et al. (1973), the only difference being large diameter pipes were investigated (up to 10.2 cm (4.02 inches)). Their correlation between dimensionless relaxation time ($\tau^+$) and dimensionless deposition velocity ($V^+$) paved the way for the design and evaluation of deposition in large sized transport tubes and ducts.

Most of the deposition experiments performed over the years deal with deposition onto conduits much smaller than dimensions of ducts in the HVAC industry. Chamberlain et al. (1984), Kvasnak et al. (1993) and Lai (1997) performed experiments in conduits with dimensions and air speeds similar to ducts in the HVAC industry but the studies were confined to deposition onto floors. Very few experiments take into account deposition onto floors, duct walls and ceiling all at the same time and also deal with the deposition and mechanics of liquid borne particles which is of primary concern regarding the kitchen industry. In the recent past Grestler et al. (1998) and Sippola et al. (2005)
have done extensive work dealing with deposition of liquid borne particles in exhaust and ventilating ducts. Grestler et al. (1998) found out that decreasing the exhaust velocity dramatically decreases the rate at which particles deposit on the wall. This is extremely helpful in reducing the amount of grease build up inside an exhaust duct. Sippola et al. (2005) looked at particle deposition from fully developed turbulent flows in ventilating ducts. They looked at deposition rates of particles with diameters ranging from 1-16 \( \mu \text{m} \) in galvanized steel and internally insulated ducts with hydraulic diameters of 15.2 cm (5.98 inches). It was found that deposition to duct walls and ceilings was greatly enhanced in insulated ducts compared to steel ducts. They concluded that deposition velocities increased with increasing particle size and air velocity. Furthermore particle deposition in ventilating ducts with connectors and bends in developing turbulent flow were investigated. It was found out that deposition at S connectors, in bends, and it straight ducts with developing turbulence were greater than deposition is straight ducts with fully developed turbulence.

Kuehn et al. (2009) characterized emissions from various commercial kitchen appliances in the plume region and the exhaust duct. The tests were performed without the use of filters. It was found that particles larger than 10 \( \mu \text{m} \) accounted for majority of the mass associated with cooking emissions. Larger particles present in the plume were not captured in the exhaust duct indicating a loss mechanism largely dominated by impaction. An earlier study by Kuehn et al. (2004) developed a standard reliable method to determine the performance of devices intended to capture grease particles in commercial cooking effluents. Oleic acid was demonstrated to act as a reliable surrogate for hamburger particulate grease effluents.

Very little work has been performed in measuring the thickness of grease build up in kitchen exhaust ducts. The present work aims to increase the knowledge pool with regard to deposition of liquid borne particles by developing a method to quantize grease laden cooking effluents and provide a low cost method of measuring the grease build up in a commercial kitchen exhaust duct. The first step in the process was to look at the available technology in the market which could be used in the development of a low cost grease sensor. The following section describes the available technologies in detail.
2.2 Commercial Technologies

Film thickness measurements can be carried out in a number of ways. Broadly speaking they can be categorized into two main classes, intrusive and non-intrusive. The main objective of this sub section is to look into the technologies available in the market and the possibility to use them to measure the amount of grease that accumulates in a kitchen exhaust duct. The following is a brief summary of sensors manufactured by various companies and patents available that could be used for grease deposition measurement.

- LION PRECISION

Lion precision based in St Paul Minnesota, specializes in manufacturing capacitive sensors. They commercialize two capacitive sensor methodologies, single channel and dual channel methods. The single channel method uses one sensor probe which has to be placed in the interior of the duct. Here the wall of the duct is taken as the reference surface. Once the reference distance is calibrated, the amount of grease deposited onto it can be measured by the sensor probe. A major limitation of this method is that it assumes the material to be measured is perfectly flat against the reference surface. Any deformity of the reference surface will result in an error in thickness measurements.

Figure 2.1: Single Channel, Source: www.lionprecision.com

This is overcome by using the dual channel method which uses two sensors, one which can be placed on the exterior of the duct and other in the interior. The sum of the measurements from the two sensors can be used to determine the thickness of grease deposit on the inside of the duct as seen in Fig 2.2. ADE TECHNOLOGIES use a similar principle to measure thickness using their capacitive sensors.
MTI INSTRUMENTS

Capacitive measurements of electrically grounded targets are affected by changes in the electrical conductivity of the material to be measured. To eliminate the affect of target conductivity, MTI instruments use a push pull capacitive sensor.

The individual probes are calibrated to produce an AC voltage. However there exists a 180 degree phase shift between the signals that allows the current path to travel across the target rather than through the target to the ground. This technology has several applications in the semiconductor industry and can be applied to measure grease deposits after incorporating suitable changes.

OMRON

Omron makes use of laser technology to carry out thickness measurements. Their technology consists of compact sensors heads which can be placed on either side of the duct to carry out measurements. Their controller is one of the smallest in its category. Using a collimator lens an ideal parallel beam is created. The CCD
(Charge Couple Device) detects the shadow made from the material to be measured and by performing sub-pixel calculation is able to calculate the thickness.

Figure 2.4: Laser sensor, Source: www.omron.com

- **MICRO-EPSILON**

  A confocal measurement principle is used to carry out thickness measurements. Polychromatic white light is focused on to the target surface by a multi-lens optical system. The lenses are arranged so that white light is dispersed into monochromatic light by controlled chromatic aberration. A specific distance to the target is assigned to each wavelength. The light deflected from the top and bottom of the deposit is passed through a confocal aperture onto a spectrometer which detects and processes it for spectral changes thus measuring thickness.

- **MICROPHOTONICS**

  A confocal measurement technique similar to Micro-epsilon is used to measure the thickness of materials.

- **PIEZOCRYST**

  A quartz crystal is used to measure the amount of grease deposited. The resonant frequency of oscillation of the quartz crystal is used to measure the amount of grease deposited. One limitation though is that quartz crystals have a limited
operating temperature of 100 degrees Celsius or less. With the invention of gal- 
lium phosphate, this temperature has been raised up to 800 degrees Celsius thus 
abling accurate measurements for a variety of applications. This application is 
very similar to TEOM (Tapered Element Oscillating Microbalance).

- **THERMOSCIENTIFIC**

TEOM (Tapered Element Oscillating Microbalance) manufactured by Thermo 
Scientific utilizes an inertial mass weighing principle. A TEOM detector consists 
of a filter placed at the end of a hollow tapered tube. The tube with the filter 
on the free end is oscillated in a clamped-free mode at its resonant frequency. A 
particle laden air stream is drawn through the filter where the particles deposit. 
As particles deposit, the mass of the filter increases and the frequency of the 
system decreases. By measuring the change in frequency, the mass deposited is 
measured.

- **UNITED STATES PATENT**

Patent Number: US 6,701,787 B2 Date of Patent: March 9, 2004 

**Acoustic Sensor for Pipeline Deposition Characterization and Monitoring of Pipeline** 

**Deposits.**

This Patent described an apparatus for analyzing a deposited layer on the inner 
surface of a fluid container wall having inner and outer surfaces. The method 
comprised of transmitting an acoustic signal from a transmitter, receiving a first 
signal A, comprising a reflection from the wall outer surface, receiving a second 
signal B, comprising a reflection from the wall inner surface and a third signal C 
from the deposited layer. By calculating the acoustic impedance of the deposited 
layer the thickness of the deposited layer is calculated.

- **EUROPEAN PATENT**

Application Number: 95306965.5 Date of Publication: 10.04.1996 Bulletin 1996/15 

**Device for monitoring deposits in a pipe or vessel.**

This patent described a non-intrusive device for attachment to a pipe or vessel 
through which a fluid flows for monitoring the accumulation of deposits on the
interior surface of the pipe or vessel. The device consisted of a tubular member having an internal cross-sectional configuration similar to the pipe, the tubular member being made from an electrically insulating material and having associated therewith three spaced electrodes for monitoring the change of dielectric constant within the pipe or vessel thus measuring the thickness of the deposited layer.

- Asphalt and Paraffin Scale Deposit Measurement by Neutron Back Diffusion Using 252Cf and 241Am-Be Sources.

Hydrocarbon deposits often found in oil or polymer industries are detected by this method. Neutrons from 252Cf and 241Am-Be sources are allowed to interact with carbon steel pipes containing either asphalt or paraffin scale. Fast moving neutrons penetrate the pipe wall without significant interaction and are scattered elastically with H or C atoms in the scale and hereby slow down. Some of the slowed down neutrons diffuse backward and are measured by a BF3 slow neutron detector thus measuring the deposited asphalt or paraffin deposits.

Table 2-1 is a brief listing of the various commercial products and their important specifications that could be used to measure cooking grease deposits. Looking at the table we can notice that the available technologies in the market are too expensive to be implemented in the development of a low cost sensor. Hence there exists the need to look into simple techniques like a cylinder in cross flow or a simple LED photo resistor arrangement.
<table>
<thead>
<tr>
<th>S.No</th>
<th>Company</th>
<th>Sensor Technology</th>
<th>Film Thickness Range (μm)</th>
<th>Probe Diameter (mm)</th>
<th>Driver Details</th>
<th>Temp Range (°C)</th>
<th>Price (Dollars)</th>
<th>Address and Contact info</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Lion Precision</td>
<td>Capacitive</td>
<td>10-1000</td>
<td>5,8</td>
<td>Elite Series CPL190 Bandwidth 15kHz Resolution 0.004 Output Voltage 10V</td>
<td>4-50</td>
<td>3810-4160</td>
<td>563 Shoreview Park Road, Saint Paul MN-55126 Ph-(651)-484-6544 Fax-(651)-484-6824</td>
</tr>
<tr>
<td>2</td>
<td>ADE technologies</td>
<td>Capacitive</td>
<td>10-1000</td>
<td>5,2,1</td>
<td>5000 Series Bandwidth 100kHz Output Voltage 10V</td>
<td>5-50</td>
<td>80 Wilson Way Westwood MA-02090 Ph-(781)-467-3500 Fax-(751)-467-0500</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>MTI instruments</td>
<td>Capacitive</td>
<td>25-1250</td>
<td>6.8,15.8</td>
<td>Accumeasure 9000 Series Frequency Response 5kHz Resolution 0.005</td>
<td>0-100</td>
<td>3586</td>
<td>325, Washington Avenue Extension, Albany NY-12205-5505 Ph-(518)-218-2550 Fax-(518)-218-2506</td>
</tr>
<tr>
<td>4</td>
<td>PI (Piezo Nano Positioning)</td>
<td>Capacitive</td>
<td>10-500</td>
<td>6</td>
<td>E 500 Series Bandwidth 10kHz Resolution 0.002</td>
<td>0-100</td>
<td>4792</td>
<td>16 Albert St Auburn MA-01501 Ph-(508)-832-3456 Fax-(508)-832-0506</td>
</tr>
</tbody>
</table>
Table 2.2: Table 2.1 continued

<table>
<thead>
<tr>
<th>S.No</th>
<th>Company</th>
<th>Sensor Technology</th>
<th>Film Thickness Range (µm)</th>
<th>Probe Diameter (mm)</th>
<th>Driver Details</th>
<th>Temp Range (°C)</th>
<th>Price (Dollars)</th>
<th>Address and Contact info</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>Omron</td>
<td>Laser through Beam</td>
<td>20-1000</td>
<td>NA</td>
<td>ZX series</td>
<td>NA</td>
<td>NA</td>
<td>55 Commerce Drive Schaumburg, IL 60173 Ph-(847) 882-2288</td>
</tr>
<tr>
<td>6</td>
<td>Micro Photonics Inc</td>
<td>Optical</td>
<td>20-27000</td>
<td>NA</td>
<td>Confocal Chromatic Set up Light Source LED</td>
<td>10-50</td>
<td>11000</td>
<td>492 Medical Centre Allentown PA-18106 Ph - (610)-366-7103 Fax- (610)-366-7105</td>
</tr>
<tr>
<td>7</td>
<td>Micro Epsilon</td>
<td>Capacitive Confocal displacement</td>
<td>50-100000 125</td>
<td>6,7</td>
<td>capaNCDT Series Frequency Response 6kHz Measuring Rate 100-2000kHz Light Source LED</td>
<td>0-100 10-50</td>
<td>4465 15000</td>
<td>8120 Brown Leigh Drive Raleigh NC-27617 Ph-(919)-787-9707 Fax-(919)-787-9706</td>
</tr>
<tr>
<td>8</td>
<td>Piezocryst</td>
<td>Quartz crystal</td>
<td>NA</td>
<td>13.97</td>
<td>R20 crystals</td>
<td>0-450</td>
<td>4005</td>
<td>Tangidyne/Beach sensors Ph - 315-673-2024 Fax - 315-673-2082</td>
</tr>
</tbody>
</table>
Chapter 3

Modeling of the Low Cost Sensors

3.1 Introduction

The grease deposition modeling was divided into two important parts. Grease deposition onto a cylinder placed in cross flow was modeled. Secondly grease deposition in a circular duct was modeled. The following paragraphs explain the modeling in detail.

3.2 Cylinder in cross flow

It was proposed to introduce a cylinder perpendicular to the air stream in the duct as the basic grease deposition sensor element. This configuration is inexpensive and easy to fabricate, rotation is not important when replaced, and a simple sensor such as a strain gage, thermocouple or capacitance monitor can be used to determine the amount of grease deposited on it. There exists well known correlations for flow resistance and heat/mass transfer for a cylinder in cross flow thus making it easier to predict the amount of grease deposition on it. Also this geometry is easy and inexpensive to fabricate.

Grease deposition onto this cylinder can take place by four important mechanisms.

- Particle Impaction
- Particle Convection/Diffusion
- Particle Thermophoresis
- Vapor Transport
3.2.1 Particle Impaction

Particle impaction onto a cylinder depends on the collection efficiency. Based on this concept and the schematic diagram of body impactors and corresponding particle collection efficiency obtained by Willeke et al. the particle efficiency curve vs Stokes number for a cylinder with body diameter of 0.02 m (0.78 inches) was determined and is shown in Fig 3.1. One would expect an increase in particle deposition with an increase in cylinder body diameter. The mass deposition rate per unit length per unit mass concentration was calculated using the equation

\[ M_{impac} = \eta U_{avg} \pi d_b \]  

where \( \eta \) is the efficiency of capture of particles by the cylinder placed in cross flow, \( U_{avg} \) is the flow velocity and \( d_b \) is the cylinder body diameter. The mass deposition rate per unit length per unit mass concentration is shown by Fig 3.2. We notice an increase in deposition rate with an increase in cylinder body diameter.

3.2.2 Particle Convection/Diffusion

Particle diffusion onto a cylinder in cross flow is calculated based on a heat mass transfer analogy using \( Nu=0.26Re^{0.6}Pr^{0.37} \). The mass transfer coefficient for deposition of particles onto a cylinder of various body diameters is calculated and shown by Fig 3.3. Mass deposition rate per unit length of cylinder per unit mass concentration for various body diameters is given by

\[ M_{diffusion} = h_m \pi d_b \]  

where \( h_m \) is the mass transfer coefficient. Mass deposition rate per unit length of cylinder per unit mass concentration for various body diameters has also been plotted. Convection/diffusion transport is more pronounced for smaller particles as is evident from Fig 3.4 because of their higher diffusivity.
Figure 3.1: Particle collection efficiency curve for cylinder body diameter of 0.02 m.
Figure 3.2: Mass deposition rate by impaction onto a cylinder vs particle diameter
Figure 3.3: Mass transfer coefficient vs particle diameter
Figure 3.4: Mass deposition rate onto a cylinder by convection vs particle diameter.
3.2.3 Particle Thermophoresis

Deposition due to particle thermophoresis occurs when there is a temperature gradient between the cylinder and the free stream. A temperature difference of 10 degrees Celsius and 50 degree Celsius was assumed between the free stream temperature and the surface of the cylinder. Fig 3.5 shows the thermophoretic velocity for various particle diameters. The dotted lines represent the 50 degree Celsius temperature difference. Thermophoretic velocity decreases with an increase in particle diameter. The mass deposited per unit time per unit length of cylinder per unit mass concentration is given by the equation shown below. The graphical representation is shown in Fig 3.6.

\[ M_{thermo} = V_{thermo} \pi d_b \]  
(3.3)

3.2.4 Vapor Transport

To account for grease vapor transport, 4 cooking effluent components with a relatively high degree of occurrence were selected based on results from the ASHRAE 1375-RP final report (Kuehn et al., 2008) and a recent paper by McDonald et al., (2003). These four components are Acenaphthylene, Naphthalene, Pyrene and Phenantrene. Table 3.1 shows various properties of these four compounds.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Naphthalene</td>
<td>128.16</td>
<td>218</td>
<td>80.2</td>
<td>8.36</td>
<td>7.18</td>
</tr>
<tr>
<td>Acenaphthylene</td>
<td>152.19</td>
<td>280</td>
<td>91</td>
<td>6.07</td>
<td>10.19</td>
</tr>
<tr>
<td>Pyrene</td>
<td>202.25</td>
<td>404</td>
<td>147</td>
<td>6.68</td>
<td>7.42</td>
</tr>
<tr>
<td>Phenantrene</td>
<td>178.22</td>
<td>340</td>
<td>100</td>
<td>6.54</td>
<td>7.5</td>
</tr>
</tbody>
</table>

Note that all four of these have melting points higher than 80 degrees Celsius so they will be in solid form on the inner surface of an exhaust duct or on the sensor. The Antoine equation is a simple parametric fit to experimental vapor pressure data over a restricted temperature range that was used to obtain the saturated vapor pressure of the 4 compounds. The equation is given by
\[ \log P = A - \frac{B}{T + C} \]  

where \( P \) is the pressure in kPa, \( T \) is the temperature in degree Celcius and \( A \), \( B \) and \( C \) are constants. Fig 3.7 shows the vapor mass transfer coefficient of these four compounds obtained by heat mass transfer analogy for a cylinder in cross flow. Fig 3.8 shows the mass deposited per unit length per unit time per unit mass concentration. ASHRAE-1375 RP reports the mass concentration in the effluent stream of these four components for various appliances. The mass thus transferred by vapor convection/diffusion can be calculated.

Figure 3.5: Thermophoretic velocity vs particle diameter
Figure 3.6: Mass deposition rate by thermophoresis vs particle diameter
Figure 3.7: Vapor mass transfer coefficient vs cylinder body diameter
Figure 3.8: Mass deposition rate by vapor transport vs cylinder body diameter.
3.3 Grease deposition rate per unit length of the cylinder

In order to design an optimum sensor we need to have an approximate idea of the rate of grease deposition that takes place per unit length onto the cylinder surface. The next step is to calculate the amount of grease deposited per unit length of the cylinder during typical cooking conditions. This should be closely related to the rate of grease that accumulates on the inner wall of the exhaust duct. We chose to use the results obtained from the conveyor broiler cooking hamburger (ASHRAE 1375-RP) as the results are well characterized. Based on the particle concentration versus particle size results obtained in the exhaust duct from the PCI (Personal Cascade Impactor) and SMPS (Scanning Mobility Particle Sizer), the grease deposited per unit length of the cylinder can be computed.

Deposition rate per unit length is governed by four important mechanisms namely particle impaction, particle convection/diffusion, particle thermophoresis and vapor transport. All four of these mechanisms have been calculated and the results combined to yield the total grease deposition rate per unit length of the cylinder. Results from the conveyor broiler experiment in the ASHRAE 1375 RP final report were used to estimate the effluent within an exhaust duct. SMPS (Scanning Mobility Particle Sizer) and the PCI (Personal Cascade Impactor) instruments obtained concentrations for different particle sizes in the duct. Concentration results from the ASHRAE 1375 RP final report used for the present analysis can be found in Appendix C. The SMPS instrument was used to characterize the smaller particles and the PCI instrument the larger particles. The concentration data of the particles captured by these instruments were used for the present calculations. Grease vapor calculation in the exhaust duct was determined using an EPA Method 5 sampling train.

3.3.1 Particle Impaction

A Marple PCI Model-290 (Particle Cascade Impactor) was used to obtain particle concentration data for the various impactor stages. Table 3.2 shows the cut sizes of the various stages and the respective mean particle size for each stage. It is assumed that for the first stage plus inlet sampling tube, the mean particle diameter is 20 μm. For the final filter the size corresponding to the maximum concentration as measured
by the SMPS instrument was used which is 0.2 μm. With the mean particle sizes and the data from the ASHRAE 1375 RP final report, the particle mass deposition rate per unit length cylinder with different diameters was calculated and is shown by Fig 3.9.

<table>
<thead>
<tr>
<th>Stages</th>
<th>Cut size (μm)</th>
<th>Mean particle size (μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined 1 and 2</td>
<td>14.8 and above</td>
<td>20.00</td>
</tr>
<tr>
<td>3</td>
<td>9.8-14.8</td>
<td>12.30</td>
</tr>
<tr>
<td>4</td>
<td>6.0-9.8</td>
<td>7.90</td>
</tr>
<tr>
<td>5</td>
<td>3.5-6.0</td>
<td>4.75</td>
</tr>
<tr>
<td>6</td>
<td>1.55-3.5</td>
<td>2.53</td>
</tr>
<tr>
<td>7</td>
<td>0.93-1.55</td>
<td>1.24</td>
</tr>
<tr>
<td>8</td>
<td>0.52-0.93</td>
<td>0.73</td>
</tr>
<tr>
<td>Filter</td>
<td>Below 0.52</td>
<td>0.20</td>
</tr>
</tbody>
</table>

### 3.3.2 Particle Convection/Diffusion

Using a heat mass transfer analogy and the convective heat transfer correlation for a cylinder in cross flow which is given by $Nu = 0.26Re^{0.6}Pr^{0.37}$ the mass transfer coefficient for particle deposition was calculated. As convection/diffusion is more pronounced in smaller diameter particles only the SMPS concentration data was used for these calculations. Multiplying the data shown by Fig 3.4 with the concentration values obtained by the SMPS in the ASHRAE 1375-RP report the mass deposition rate per unit length of the cylinder was obtained. Fig 3.10 shows the mass deposition rate per unit length due to convection/diffusion.

### 3.3.3 Particle Thermophoresis

Thermophoretic velocity of the particle sizes collected by both the SMPS and PCI instruments is multiplied with the concentration data from the conveyor broiler experiment in the ASHRAE 1375 RP final report to obtain the mass deposition rate per unit length due to thermophoresis.
Figure 3.9: Mass deposition rate per unit length by particle impaction
Figure 3.10: Mass deposition rate per unit length by particle convection/diffusion
Figure 3.11: Mass dep. rate per unit length by thermophoresis, 10 deg. C diff.
Figure 3.12: Mass dep. rate per unit length by thermophoresis, 50 deg. C diff.
Fig 3.11 and Fig 3.12 show the deposition rate by particle thermophoresis when the cylinder surface temperature is maintained at 25 and −15 degree C respectively with the bulk temperature maintained at 35 degree C. A greater temperature difference between the free stream and the cylinder surface results in greater mass deposition by particle thermophoresis and is quite evident from the graphs. Smaller particles have a higher deposition than larger particles because of higher thermophoretic deposition velocity. Table 3.3 shows the particle mass deposition rate per unit length of the cylinder for different cylinder diameters for an isothermal duct with the bulk mean temperature at 35 degree C. No thermophoresis occurs as there is no temperature difference in this case. It can be noticed that most of the deposition takes place due to particle impaction. Also there is a decrease in deposition rate with an increase in cylinder diameter. This is because the mass contribution by smaller particles reduces as they are not captured efficiently by the cylinder placed in cross flow. A similar trend is seen in the cases where the cylinder surface temperature is maintained at 25 and −15 degree C providing a 10 and 50 temperature difference respectively and is shown by Table 3.4 and Table 3.5 respectively. An important assumption made is that all the deposition processes are independent.

Table 3.3: Dep. rate per unit length of cyl.: Isothermal Duct- Bulk Temp 35 deg. C

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body Diameter (m)</th>
<th>Impaction (mg/ms)</th>
<th>Diffusion (mg/ms)</th>
<th>Thermophoresis (mg/ms)</th>
<th>Total (mg/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>1.866</td>
<td>0.007</td>
<td>0</td>
<td>1.873</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>3.022</td>
<td>0.014</td>
<td>0</td>
<td>3.036</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>3.794</td>
<td>0.016</td>
<td>0</td>
<td>3.810</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
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<td>0.017</td>
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<td>4.358</td>
</tr>
<tr>
<td>5</td>
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<td>4.763</td>
<td>0.019</td>
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<tr>
<td>6</td>
<td>0.02</td>
<td>5.829</td>
<td>0.028</td>
<td>0</td>
<td>5.857</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>6.132</td>
<td>0.036</td>
<td>0</td>
<td>6.168</td>
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<tr>
<td>8</td>
<td>0.04</td>
<td>6.087</td>
<td>0.042</td>
<td>0</td>
<td>6.129</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>5.812</td>
<td>0.049</td>
<td>0</td>
<td>5.861</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>5.432</td>
<td>0.055</td>
<td>0</td>
<td>5.487</td>
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</tbody>
</table>
### Table 3.4: Mass dep. rate per unit length of cyl., 10 deg. C temp. diff.

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body diameter (m)</th>
<th>Impaction mg/ms</th>
<th>Diffusion mg/ms</th>
<th>Thermophoresis mg/ms</th>
<th>Total mg/ms</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>1.866</td>
<td>0.007</td>
<td>0.094</td>
<td>1.967</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>3.022</td>
<td>0.014</td>
<td>0.142</td>
<td>3.178</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>3.794</td>
<td>0.016</td>
<td>0.181</td>
<td>3.991</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>4.341</td>
<td>0.017</td>
<td>0.216</td>
<td>4.574</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>4.763</td>
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<td>0.246</td>
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<tr>
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<td>5.829</td>
<td>0.028</td>
<td>0.374</td>
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<tr>
<td>7</td>
<td>0.03</td>
<td>6.132</td>
<td>0.036</td>
<td>0.476</td>
<td>6.635</td>
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<tr>
<td>8</td>
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<td>6.087</td>
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<td>6.695</td>
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<tr>
<td>9</td>
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<td>5.812</td>
<td>0.049</td>
<td>0.648</td>
<td>6.509</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>5.432</td>
<td>0.055</td>
<td>0.723</td>
<td>6.210</td>
</tr>
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</table>

### Table 3.5: Mass dep. rate per unit length of cyl., 50 deg. C temp. diff.

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body diameter (m)</th>
<th>Impaction mg/ms</th>
<th>Diffusion mg/ms</th>
<th>Thermophoresis mg/ms</th>
<th>Total mg/ms</th>
</tr>
</thead>
<tbody>
<tr>
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<td>0.002</td>
<td>1.866</td>
<td>0.007</td>
<td>0.469</td>
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<tr>
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<td>3.022</td>
<td>0.014</td>
<td>0.711</td>
<td>3.747</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>3.794</td>
<td>0.016</td>
<td>0.907</td>
<td>4.717</td>
</tr>
<tr>
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<td>0.008</td>
<td>4.341</td>
<td>0.017</td>
<td>1.077</td>
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</tr>
<tr>
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<td>0.01</td>
<td>4.763</td>
<td>0.019</td>
<td>1.232</td>
<td>6.014</td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>5.829</td>
<td>0.028</td>
<td>1.568</td>
<td>7.425</td>
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<tr>
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<td>0.03</td>
<td>6.132</td>
<td>0.036</td>
<td>2.382</td>
<td>8.550</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>6.087</td>
<td>0.042</td>
<td>2.830</td>
<td>8.959</td>
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<tr>
<td>9</td>
<td>0.05</td>
<td>5.812</td>
<td>0.049</td>
<td>3.237</td>
<td>9.098</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>5.432</td>
<td>0.055</td>
<td>3.609</td>
<td>9.096</td>
</tr>
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</table>
3.3.4 Vapor Transport

To account for grease vapor transport, 4 cooking effluent components with a relatively high degree of occurrence were selected based on results from the ASHRAE 1375-RP final report (Kuehn et al., 2008) and a recent paper by McDonald et al., (2003). These four components are Acenaphthylene, Naphthalene, Pyrene and Phenanthrene. It is assumed that these four components occur in equal proportions in the effluent stream. Using the ASHARE 1375-RP final report, the concentrations of these four components in the effluent were obtained. These values can be found in Appendix C. The saturated vapor pressure of all four components at the cylinder surface was determined based on the surface temperature assuming that each component provides a saturated vapor pressure boundary condition to the air stream. It was also determined that the saturation vapor pressure of each component on the cylinder surface was higher than the partial pressure in the effluent stream. Therefore vapor transport would take place from the cylinder surface to the free stream, i.e. it would oppose the particle deposition. Table 3.1 shows the diffusion coefficient of the four components. Based on a heat and mass transfer analogy the mass transfer coefficient of each component was determined. Knowing their free stream concentration the mass deposition rate per unit length for the 4 components was found out. Table 3.6 shows the vapor mass deposition rate per unit length for different cylinder diameters.

### Table 3.6: Vapor Mass transport from the cylinder to air

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body diameter(m)</th>
<th>Naphthalene mg/ms *10^{-6}</th>
<th>Acenaphthylene mg/ms * 10^{-6}</th>
<th>Pyrene mg/ms *10^{-6}</th>
<th>Phenanthrene mg/ms *10^{-6}</th>
<th>Total mg/ms *10^{-6}</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>0.268</td>
<td>0.0877</td>
<td>2.24</td>
<td>1.65</td>
<td>1.062</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>0.406</td>
<td>0.133</td>
<td>3.39</td>
<td>2.51</td>
<td>1.609</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>0.519</td>
<td>0.170</td>
<td>4.32</td>
<td>3.20</td>
<td>2.052</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>0.616</td>
<td>0.202</td>
<td>5.14</td>
<td>3.80</td>
<td>2.439</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>0.705</td>
<td>0.230</td>
<td>5.87</td>
<td>4.35</td>
<td>2.788</td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>1.068</td>
<td>0.349</td>
<td>8.90</td>
<td>6.59</td>
<td>4.227</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>1.362</td>
<td>0.445</td>
<td>11.40</td>
<td>8.40</td>
<td>5.391</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>1.619</td>
<td>0.529</td>
<td>13.50</td>
<td>9.99</td>
<td>6.407</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>1.850</td>
<td>0.605</td>
<td>15.4</td>
<td>11.4</td>
<td>7.325</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>2.04</td>
<td>0.675</td>
<td>17.2</td>
<td>12.7</td>
<td>7.655</td>
</tr>
</tbody>
</table>
3.3.5 Net Effective Grease Deposition per unit length of the cylinder

Table 3.7 shows the net effective grease deposition that takes place on the cylinder surface in an isothermal duct. We see that the deposition rate increases for small diameters and decreases for larger cylinder diameter. Tables 3.8 and 3.9 represent conditions when the cylinder surface temperature is maintained at 25 and −15 degrees celsius respectively. Nevertheless an overall broad picture is obtained as to how much deposition can be expected on a cylindrical sensor for different diameters.

Table 3.7: Grease dep. per unit length of cyl., Bulk Mean Temperature: 35 deg. C

<table>
<thead>
<tr>
<th>Option diameter (m)</th>
<th>Cylinder Body mg/ms</th>
<th>Particle mg/ms</th>
<th>Vapor mg/ms</th>
<th>Total mg/ms * 10^-6</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>1.873</td>
<td>-1.062</td>
<td>1.872</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>3.036</td>
<td>-1.609</td>
<td>3.035</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>3.810</td>
<td>-2.052</td>
<td>3.809</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>4.358</td>
<td>-2.439</td>
<td>4.357</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>4.782</td>
<td>-2.788</td>
<td>4.779</td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>5.857</td>
<td>-4.227</td>
<td>5.856</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>6.168</td>
<td>-5.391</td>
<td>6.167</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>6.129</td>
<td>-6.407</td>
<td>6.128</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>5.861</td>
<td>-7.325</td>
<td>5.860</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>5.487</td>
<td>-7.655</td>
<td>5.486</td>
</tr>
</tbody>
</table>
Table 3.8: Grease dep. per unit length of cyl., 10 deg. C temp. difference

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body diameter(m)</th>
<th>Particle $mg/ms$</th>
<th>Vapor $mg/ms$</th>
<th>Total $mg/ms$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>1.967</td>
<td>-1.062</td>
<td>1.966</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>3.178</td>
<td>-1.609</td>
<td>3.177</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>3.991</td>
<td>-2.052</td>
<td>3.990</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>4.574</td>
<td>-2.439</td>
<td>4.573</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>5.028</td>
<td>-2.788</td>
<td>5.027</td>
</tr>
<tr>
<td>6</td>
<td>0.02</td>
<td>6.231</td>
<td>-4.227</td>
<td>6.230</td>
</tr>
<tr>
<td>7</td>
<td>0.03</td>
<td>6.635</td>
<td>-5.391</td>
<td>6.634</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>6.695</td>
<td>-6.407</td>
<td>6.694</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>6.509</td>
<td>-7.325</td>
<td>6.508</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>6.210</td>
<td>-7.655</td>
<td>6.209</td>
</tr>
</tbody>
</table>

Table 3.9: Grease dep. per unit length of cyl., 50 deg. C temp. difference

<table>
<thead>
<tr>
<th>Option</th>
<th>Cylinder Body diameter(m)</th>
<th>Particle $mg/ms$</th>
<th>Vapor $mg/ms$</th>
<th>Total $mg/ms$ * $10^{-6}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.002</td>
<td>2.342</td>
<td>-1.062</td>
<td>2.341</td>
</tr>
<tr>
<td>2</td>
<td>0.004</td>
<td>3.747</td>
<td>-1.609</td>
<td>3.746</td>
</tr>
<tr>
<td>3</td>
<td>0.006</td>
<td>4.717</td>
<td>-2.052</td>
<td>4.716</td>
</tr>
<tr>
<td>4</td>
<td>0.008</td>
<td>5.435</td>
<td>-2.439</td>
<td>5.434</td>
</tr>
<tr>
<td>5</td>
<td>0.01</td>
<td>6.014</td>
<td>-2.788</td>
<td>6.013</td>
</tr>
<tr>
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<td>7.425</td>
<td>-4.227</td>
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</tr>
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<td>0.03</td>
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<td>8.549</td>
</tr>
<tr>
<td>8</td>
<td>0.04</td>
<td>8.959</td>
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<td>8.958</td>
</tr>
<tr>
<td>9</td>
<td>0.05</td>
<td>9.098</td>
<td>-7.325</td>
<td>9.097</td>
</tr>
<tr>
<td>10</td>
<td>0.06</td>
<td>9.096</td>
<td>-7.655</td>
<td>9.096</td>
</tr>
</tbody>
</table>
3.4 Circular Duct

Grease deposition in a circular duct takes place by the same four mechanisms as in the case of a cylinder in cross flow. However impaction and convection/diffusion are usually combined into a single turbulent flow deposition velocity. Thermophoresis can be added to this or combined into a single deposition velocity. The vapor transport is always handled separately. Fig 3.13 shows the mass deposition rate per unit concentration of particles along the length of the duct. We note that for particles larger than 20 microns, the mass deposition rate decreases significantly along the length of the duct primarily because the concentration is being reduced significantly. For smaller particles the deposition rate is much smaller and nearly constant along the length of the duct. It is necessary to calculate the deposition rate per unit length of the duct wall and correlate it with the amount of deposition that takes place on the sensor. The technique followed is similar to the one followed for a cylinder in cross flow except for a few changes.

3.4.1 Duct Particle Impaction and Convection/Diffusion

An empirical relation for non dimensional depositional velocity in turbulent flows as suggested by Woods is

$$u_d^+ = 0.057Sc^{-2/3} + 0.00045\tau^+$$

where

$$u_d^+ = \frac{V_{dep}}{u^*}, u^* = Uf^{0.5}, f = \frac{0.316}{4Re^{0.25}}, \tau^+ = \frac{\nu_d^2a^*^2}{18\mu}$$

The first term is particle deposition due to diffusion and the second term is particle deposition induced by eddy diffusion-impaction. Fig 3.14 is the graph of deposition velocity vs. particle diameter using the correlation stated by Woods. Once the deposition velocity is calculated and knowing the concentration data obtained from the ASHRAE 1375-RP final report the particle mass deposition rate per unit length of the circular duct is calculated as follows.

$$M_{circduct} = V_{dep}C\pi d_b$$

(3.5)
Figure 3.13: Particle mass deposition rate vs length of the duct.

Particle Diameter: 0.5 μm
Particle Diameter: 20 μm
Particle Diameter: 25 μm
Particle Diameter: 30 μm
Particle Diameter: 40 μm
Figure 3.14: Deposition velocity vs particle diameter in a round duct
3.4.2 Duct Particle Thermophoresis

Thermophoretic velocity is calculated similarly as done for the case of the cylinder in cross flow, the only difference being that the correlation for flow in a turbulent duct was used which is \( Nu = 0.024 Re^{0.786} Pr^{0.45} \) instead of the correlation for a cylinder in cross flow.

Table 3.10 shows the results of grease deposition inside a circular duct of diameter 15.24 cm (6 inches).

<table>
<thead>
<tr>
<th>Duct diameter</th>
<th>Impaction and Diffusion</th>
<th>Thermophoresis 10 deg. C difference</th>
<th>Thermophoresis 50 deg. C difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>m</td>
<td>mg/ms</td>
<td>mg/ms</td>
<td>mg/ms</td>
</tr>
<tr>
<td>0.1524</td>
<td>0.0483</td>
<td>0.915</td>
<td>4.575</td>
</tr>
</tbody>
</table>

3.4.3 Duct Particle Vapor Transport

The driving force for grease vapor transport to the duct surface is similar to the case for a cylinder in cross flow. As in the case of thermophoresis the only difference is the use of a correlation for turbulent flow in a duct instead of a cylinder in cross flow. As in the case of the cylinder vapor transport, the duct vapor transport also opposes the particle deposition. Table 3.11 shows the vapor mass deposition rate per unit length of the circular duct.

<table>
<thead>
<tr>
<th>Option</th>
<th>Circular duct diameter(m)</th>
<th>Naphthalene ( mg/ms ) ( *10^{-6} )</th>
<th>Acenaphthalene ( mg/ms ) ( *10^{-6} )</th>
<th>Pyrene ( mg/ms ) ( *10^{-6} )</th>
<th>Phenantrene ( mg/ms ) ( *10^{-6} )</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.1524</td>
<td>2.83</td>
<td>0.95</td>
<td>24</td>
<td>17.8</td>
<td>11.38</td>
</tr>
</tbody>
</table>

3.5 Decision Table

A decision table was generated and is shown below as Table 3.12. Each sensor methodology conceived or found in the literature was assessed and given a score. It was
found out that the direct weighing method was an easy and simple method to proceed with and received a high score. But this method is not commercially beneficial as it requires manual access and is not suited for long duct runs. The techniques with low scores are ruled out the single most important reason being the cost. Thus we are left with the strain gage technique and the optical LED technique. The LED technique looks promising as it is a non-intrusive method and would not cause any hindrance to the flow in the duct. Both of these options can easily be mounted. The next decision to be made is which of these options should be fabricated and tested in the laboratory. It was decided to proceed with the following two options.

- Optical sensor with light source and photo resistor mounted in opposite sides of the duct in either vertical or horizontal ducts.
- Cylindrical sensor with one or two strain gauges mounted near the base mounted in a horizontal position in either a vertical or horizontal duct.
<table>
<thead>
<tr>
<th>Method</th>
<th>Cost</th>
<th>Reliability</th>
<th>Simplicity</th>
<th>Calibration</th>
<th>Maintenance</th>
<th>Install. Ease</th>
<th>Sig. Cond.</th>
<th>Power Req.</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strain gauge</td>
<td>3</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>19</td>
</tr>
<tr>
<td>Cantilever Beam type</td>
<td>2</td>
<td>1</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>16</td>
</tr>
<tr>
<td>Direct Weighing method</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>21</td>
</tr>
<tr>
<td>Vibrating Element</td>
<td>1</td>
<td>2</td>
<td>2</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>2</td>
<td>12</td>
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<td>Acoustic Capacitive Sensors</td>
<td>1</td>
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<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
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<td>LED Technique</td>
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<td>2</td>
<td>3</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>2</td>
<td>17</td>
</tr>
</tbody>
</table>

3=Excellent, 2=Good, 1=Fair
Chapter 4

Particle deposition in a horizontal duct- An Experimental Study

4.1 Introduction

In order to validate the developed model and investigate the use of sensors in a cooking process, experiments were performed in a horizontal duct section at two different exhaust velocities. This chapter describes in detail the experimental duct setup, aerosol generation and sampling, deposition measurements and conclusions of the investigation.

4.2 Experimental Setup

The experimental set up is shown in Fig 4.1. A Blower/Centrifugal Fan was used to provide the necessary flow rate for the deposition studies. Room air was sucked into the fan and the motor caused the impeller to rotate blowing air at right angles to the direction of intake. A transition section connected the blower to a 0.1524 m (6 inch) diameter circular duct section. This section housed a butterfly damper and a honeycomb arrangement. The butterfly damper which was placed 0.3048 m (12 inches) downstream of the transition section was used to vary the flow rate. The honey comb structure placed 2.12 m (83.5 inches) downstream of the butterfly damper acted like a flow straightner to ensure a smooth uniform flow. A hole was drilled 0.0508 m (2 inches) downstream of the honey comb structure to inject particles into the duct stream. A 90 degree bend injection
probe of internal diameter 0.01 m (0.39 inches) was used for this purpose. The circular duct transitioned into a rectangular section wherein the deposition measurements were carried out. The other end of the rectangular duct section transitioned back to a 0.1524 m (6 inch) diameter circular duct section followed by a flexible duct which exhausted particles out of the window. A pitot tube was located 0.762 m (30 inches) downstream of the rectangular section to obtain centreline velocity pressure measurements inside the duct.

ASHRAE standards were followed to ensure flow separation did not occur during transition from a circular to a rectangular section. An angle of 7.5 degrees ensured no separation occurred during the transition. The rectangular section of dimensions 0.254 m by 0.2032 m (10 inches by 8 inches) and 0.4953 m (19.5 inches) long was located 1.46 m (57.5 inches) downstream from the point of injection of the aerosol particles. The rectangular section was bolted to transitions on either side and the interior was easily accessible. Only the downstream end of the rectangular section was used to access the interior. This was done so as to ensure that the flow pattern entering the rectangular duct section was not disturbed every time the duct was accessed.

Five holes were drilled in the rectangular duct section. These were done to accommodate a cylinder in cross flow, two windows on two opposite walls, a hole on the top wall to determine velocity profiles inside the duct and the last hole for particle concentration and size distribution measurements. The holes for the two windows were located 0.1524 m (6 inches) from the beginning of the rectangular section. The hole for the cylinder was located 0.0635 m (2.5 inches) downstream of the holes for the two windows. It was also offset by 0.0508 m (2 inches) vertically from the axis of the holes for the windows to ensure that there was very little disturbance in the path of the particles striking the cylinder. This was because the windows when placed in the duct projected into the duct section resulting in a step. This step would have affected the flow pattern across the cylinder if it was placed downstream and in line with the windows. A hole was drilled 0.2032 m (8 inches) downstream of the windows to accommodate a sampling tube of internal diameter 0.01 m (0.39 inches). This was done to obtain the size distribution of particles inside the rectangular duct section. The final hole was drilled in the top exactly at a location corresponding to the centre of the cylinder to obtain velocity profiles at different vertical locations inside the rectangular duct.
Figure 4.1: Experimental Set up
4.2.1 Cylinder Construction

Fig 4.3 shows a schematic of the cylinder assembly. 304 stainless steel was used to fabricate the flat plate, plugs and the cylinder. As seen from the figure the cylinder assembly consists of two parts. One part consists of a flat plate welded onto a 0.0191 m (0.75 inch) NTP pipe thread on one end and a plug for mounting the cylinder on the other end. The flat plate could be used to mount a strain gage which could act as a deflection sensor. The length of the flat plate was based on the distance the NPT thread would go into the feed through before it got jammed. The concept was to have the length of the plate sufficient enough to ensure that one end of the cylinder is flush with the end of the feed through inside the duct. Thus the length of the flat plate used was 0.0191 m (0.75 inches). The width of the flat plate was 0.01 m (0.39 inches). The thickness of the flat plate used was 0.0055 m (0.22 inches). Two holes were drilled in the NPT pipe thread for the circuitry of the strain gage. No strain gage was installed during simulated cooking experiments. The plug provided a tight fit with the hollow cylinder which constitutes the other part. On the other end of the cylinder a second plug was press fitted.

The cylinder was made hollow as the weight of grease is not going to be substantial as compared to the assembly and we would like the cylinder to be as light as possible. The length of the cylinder was chosen to be 0.189 m (7.48 inches). The outer diameter of the cylinder was 0.0191 m (0.75 inches) and the internal diameter 0.0157 m (0.62 inches). Detailed diagrams can be found out in Appendix D.

4.2.2 Window Construction

Two Evergreen quik seal feed throughs (Part No :172, www.evergreentool.com) which produce weld-tight seals were modified to act as window fixtures on opposite sides of the duct wall. The two feed through’s were counter bored and fitted with a glass window of thickness 0.003 m (0.118 inches) and diameter 0.03 m (1.18 inches). The glass windows were sealed in place using RTV glue. Fig 4.4 provides a photo of the window assembly. Detailed diagrams are provided in Appendix D.
Figure 4.2: Details of the rectangular duct section, window and cylinder assemblies.
4.2.3 Substrates

Six stainless steel substrates, two on each wall of dimensions 0.0762 m by 0.0762 m (3 by 3 inches) similar to the ones used by Gerstler (2000) were placed inside the rectangular duct to determine the particle deposition on the four walls. Double sided Scotch tape was used to attach the substrates onto the walls. Care was taken to ensure the substrates were flush with the four walls. The substrates on the ceiling and at the bottom of the duct were placed in line with the locations of the windows on the two walls. The substrates on the two walls were placed 0.0508 m (2 inches) downstream of the windows. To determine the deposition on the cylinder, the circumference of the cylinder was divided into ten equal parts. Substrates in the form of tape strips of equal width were placed along the circumference of the cylinder. The substrates placed along the circumference of the cylinder were labeled 1 to 10 in a clockwise direction. Care was taken to ensure that substrate labeled 1 was located at a position corresponding to the leading edge of the cylinder when the cylinder was placed inside the duct.
4.3 Particle Characterisation

Previous investigators have used oleic acid as a successful surrogate to simulate real cooking processes. A similar simulated cooking process was carried out to test the sensors. A solution mix consisting of a known proportion of oleic acid, iso-propyl alcohol, deionized water and uranine dye was prepared. The percentage composition of each component was chosen to ensure oleic acid aerosol particles with a mass mean average diameter of around 2 \(\mu\text{m}\) was generated. This would replicate a size distribution very similar to that found in an actual kitchen exhaust duct as found out by Kuehn et al.\footnote{2009} wherein the sensors would be placed.

4.3.1 Aerosol Solution Composition

Uranine is a fluorescent dye that has been used for many years to track and trace various flows. Uranine dye dissolves in deionised water and the resulting mixture dissolves in isopropyl alcohol. Since oleic acid also dissolves in isopropyl alcohol a clear solution mix consisting of all the components can be prepared. Varying the percentage of oleic acid in the solution changes the size distribution of the generated oleic acid particles. During the aerosolization process of the mixture, water and isopropyl alcohol vaporize resulting in oleic acid particles tagged with uranine. The amount of uranine deposited on the walls of the duct and on the cylinder can be measured using fluorometric analysis. Knowing the percentage composition of oleic acid to uranine in the original mixture the amount of oleic acid deposited inside the duct can be calculated. Table 4.1 shows the percentage composition of components used to make the solution. This solution produced a mass mean average diameter of 2.3 \(\mu\text{m}\).

<table>
<thead>
<tr>
<th>Solution Component</th>
<th>Mass(%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uranine</td>
<td>0.3</td>
</tr>
<tr>
<td>DI water</td>
<td>13.4</td>
</tr>
<tr>
<td>Oleic Acid</td>
<td>59.97</td>
</tr>
<tr>
<td>Iso propyl Alcohol</td>
<td>26.33</td>
</tr>
<tr>
<td>Nonvolatiles</td>
<td>60.27</td>
</tr>
<tr>
<td>Nonvolatiles: Uranine</td>
<td>200:1</td>
</tr>
</tbody>
</table>

Table 4.1: Percentage Composition by mass of the components in the solution
4.3.2 Aerosol Generation

Poly dispersed particles were generated using a Modified Vibrating Aerosol Generator set up as shown in Fig 4.5. The solution to be aerosolized was placed in a chamber which was pressurized to 137.89 kPa (20 psi). The pressurized liquid was then introduced through a nozzle into the long vertical cylindrical chamber of the modified VOAG. Dispersion air with a flow rate of 1.5 lpm aided in the aerosolization process. Dilution air with a flow rate of 50 lpm aided in the transport the generated particles from the cylindrical chamber.

Figure 4.5: Aerosol Generation Process

In order to neutralize the particles and bring the aerosol charge to Boltzmann equilibrium a proven technique of using a charge neutralizer which holds six Po 210 units
was used. It consisted of a 0.0508 m (2 inch) PVC pipe with 3 Po neutralizer strips on one side with 3 others offset and placed on the opposite side. This assembly was placed on top of the cylindrical chamber. Since the mass contributed by large particles would outweigh that contributed by small sized particles, the large particles need to be filtered out and kept to a minimum to obtain a size distribution very close to that seen in a real kitchen exhaust duct. Thus the aerosol particles exiting the neutralizer were made to pass through a first stage impactor having a cut size of 18 \( \mu \text{m} \) in order to filter out larger particles and prevent them from entering the duct. A flexible tygon tubing connected the neutralizer to the first stage impactor. This is analogous to a real cooking process wherein large particles are captured by the grease filters. The first stage impactor was then connected to the injection probe which injected particles into the duct. Leaks in the system were tested by using an NSAM (Nanoparticle Surface Area Monitor) to sample air at various possible leak locations. An increase in the NSAM reading would indicate the presence of a leak. These locations were sealed using RTV glue and tested again using the NSAM for leaks. Care was taken to ensure there were no leaks in the system.

4.3.3 Aerosol Sampling

A nine stage MOUDI impactor was used to obtain the particle size distribution measurements. A sampling probe of internal diameter 0.01 m (0.39 inches) was used to isokinetically sample particles from the rectangular duct section. Since most of the particles greater than 18 \( \mu \text{m} \) were filtered out before they entered the duct, the fractional penetration efficiency expression given by Pui et al. (1987) in turbulent flow was not used. It is a reasonable approximation to assume all particles passing through the sampling tube reach the MOUDI. A vacuum pump was used to maintain a flow rate of 30 lpm through the impactor. A TSI mass flow meter was placed in line with the vacuum pump. The pressure drops through stages 1 – 6 and 6 – 9 were measured using differential pressure gages. The pressure gages and the TSI mass flow meter were calibrated by drawing air through the MOUDI using a vacuum source and connecting a dry gas flow meter at the inlet of the MOUDI.
4.4 Experimental Procedure

The window assemblies were installed in the duct side walls. The 6 substrates were then placed inside the rectangular duct section and the accessible section was bolted shut. The cylinder with its circumference covered with tape substrates was placed inside the duct too. The blower was turned on and allowed to run for 5 minutes. The chamber containing the solution to be aerosolized was pressurized to 137.89 kPa (20 psi) and the dispersion and dilution flow rates were set to 1.5 and 50 lpm respectively. The MOUDI was set to sample at 30 lpm. The entire experimental process was carried out for 25 minutes after which the blower, the aerosol generator and the MOUDI were turned off. Three sets of experiments were performed for two exhaust velocities namely 500 ft/min and 1500 ft/min.

4.4.1 Deposition Measurements

The system was left idle for 4 to 5 hours for the aerosol particles to settle down. The downstream end of the rectangular section was unbolted and substrates on the four walls and the cylinder were carefully removed using gloves and tweezers. All the substrates were placed in a dessicator and allowed to dry overnight. A cotton tip swab was dipped in a laboratory grade glass beaker containing 25 ml solution of DI water and NaOH with a molarity of 0.0013 N. This cotton swab was then stroked back and forth on the substrate. Two cotton swabs were used for each substrate and both were stroked at least twice to ensure all the uranine deposited on the substrate was removed. The cotton tip swabs were then placed into the beaker and allowed to settle down for a couple of hours. This procedure was followed for each of the substrates placed on the four walls and the cylinder, the two glass windows and the various aluminum substrates placed in the MOUDI. The sampling tube and the tygon tubing connecting the sampling tube to the MOUDI were also swabbed and the deposition onto them were accounted for along with the first stage of the impactor. The beakers were then sonicated and the solution containing uranine was analysed using a fluorometer. The fluorometer was calibrated everytime an analysis was performed. A sample calibration curve of the fluorometer is shown in Appendix D.
4.5 Results

To begin with it was assumed that there was no temperature gradient between the exhaust air and duct wall for the experiments performed. Thus the effect of thermophoresis on deposition was insignificant. The following sections investigate the deposition onto the cylinder placed in cross flow and the deposition to the four walls and two windows of the horizontally placed rectangular duct.

4.5.1 Particle Size distribution inside the duct

Figures 4.6 and 4.7 show the size distribution of particles obtained for the two exhaust velocities tested namely 500 ft/min and 1000 ft/min. Log normal fits of the data were performed using excel and the mass mean average diameter of the size distributions were obtained. Since the aerosol source of input was similar for both the exhaust velocities we notice a reduction in the concentration of particles at the higher exhaust velocity.

4.5.2 Flow analysis

A calibrated hot film anemometer was used to determine the velocity profiles inside the rectangular duct section. The orientation of the butterfly damper was adjusted to obtain a flow velocity of 500 and 1500 ft/min. This corresponded to an average flow Reynolds number of 38000 and 115000 respectively. Fig 4.8 shows the velocity profiles obtained inside the rectangular duct section. Comparing the velocity profiles to that obtained by Schlichting (1968) for a smooth duct at Re-137000 it was found out that the flow was not fully developed inside the duct. This was quite expected as the rectangular duct section was placed very close to the transition. Considering the fact that the sensors might be placed inside kitchen exhaust ducts where flow need not be fully developed, the present situation is quite acceptable.
Figure 4.6: Particle size distribution obtained at exhaust velocity: 500 fpm
Figure 4.7: Particle size distribution obtained at exhaust velocity: 1500 fpm
Figure 4.8: Normalized velocity profiles measured in the rectangular duct section
4.5.3 Deposition results onto the cylinder

Figures 4.9 and 4.10 show the deposition results obtained on the cylinder for two exhaust velocities namely 500 ft/min and 1500 ft/min. The flow Reynolds number across the cylinder was 3000 and 9000 respectively. Three sets of data were collected for each exhaust velocity and the results were very repeatable. The abscissa shows the cylinder angle beginning from the leading edge and divided into 10 equal parts. These 10 parts correspond to the 10 substrates placed along the circumference of the cylinder. The ordinate represents the normalized deposition flux. It was normalized by dividing the mass of oleic acid deposited per unit area of the substrates per unit time by the total concentration of oleic acid in the free stream and the free stream velocity. Normalization of the deposition results help us to compare the deposition at the two different exhaust velocities.

The data were collected for a particle mass mean average diameter of approximately 2 microns. It would be a reasonable approximation to assume that majority of the mass deposited would be contributed by particles lying outside the diffusional regime. Thus impaction would be the primary mode of deposition of particles onto the cylinder surface. Deposition onto the cylinder predominately occurred on the front face exposed to the flow as expected. Some amount of deposition was also recorded on the back side of the cylinder. This is probably due to mass diffusion. Taking a look at the photos of a cylinder in cross flow we notice that flow separation for both cases occurs approximately 90 degrees from the leading edge. Eddies and recirculation regions follow the flow separation point. These recirculation regions could be another plausible reason for mass deposition on the back side of the cylinder. We clearly see a greater amount of deposition onto the cylinder at a higher exhaust velocity. Comparing the deposition at 1500 ft/min to that of 500 ft/min we notice that deposition on the leading edge of the cylinder has increased by a factor of almost 10. Deposition on the back side though was almost the same for both the exhaust velocities. Thus the effect of change in exhaust velocity did not affect the deposition onto the cylinder due to diffusion by a great amount. Lowering the exhaust velocity lowered the deposition velocity of particles on the cylinder. This is in agreement with the results obtained by Gerstler et al. (2000).
Figure 4.9: Particle deposition on to a cylinder with Re-3000
Figure 4.10: Particle deposition on to a cylinder with Re-9000
4.5.4 Deposition results in a horizontal duct

Deposition of particles in a horizontal duct can be represented in a number of ways. These include deposition flux, deposition velocity and deposition in the form of dimensionless parameters.

4.5.4.1 Deposition Flux

Deposition flux onto a horizontal duct is given by the formula

\[ N = \frac{m_s}{A_s t} \]  

(4.1)

where \( N \) is the deposition flux, \( m_s \) is the mass of oleic acid deposited on the substrates, \( A_s \) is the area of the substrates and \( t \) is the time taken for the particles to deposit. Fig 4.11 shows the deposition flux on the ceiling, bottom, two side walls, two windows and the average deposition inside the horizontal rectangular duct. We notice that the deposition flux increases with increasing exhaust velocity. The level of turbulence increases with increasing exhaust velocity thus increasing the deposition flux. We notice that the deposition flux is maximum at the bottom wall of the duct for both exhaust velocities. This is because of gravitational settling aiding other mechanisms of particle deposition. Depositional flux due to gravitational settling depends on the settling velocity of particles \((V_{ts})\), and their concentration \((C)\) and is given by

\[ N_{settling} = V_{ts}C \]  

(4.2)

With an increase in exhaust velocity the settling velocity of particles as given by Eqn 4.2 remains the same though the concentration of particles will decrease if a constant source of input is considered. Thus the deposition flux due to settling decreases with increasing exhaust velocity. However at higher exhaust velocities the concentration of particles in the boundary layer close to the four walls might be higher because of turbulence. Thus the overall deposition increases with increasing exhaust velocity inspite of the reduction in settling deposition flux.
Figure 4.11: Deposition flux in a horizontal duct for particle MMAD 2-2.3 μm
It can also be argued that gravitational settling reduces the concentration of particles close to the boundary layer of the top wall thus reducing the deposition flux. This phenomenon is also noticed for the two side walls but is lesser compared to the top wall. What is interesting to note is that the deposition flux on the window surface is almost identical to the deposition flux on the side walls. Thus the step in the feed through did not affect the deposition of particles onto the window surface. Deposition on the window is a very good representation of deposition on the side walls of the duct.

### 4.5.4.2 Deposition Velocity

A more practical method of comparing deposition of particles is using the depositional velocity method. This method subdued the effect of concentration of particles during different test runs. In other words it normalizes the depositional flux by dividing it with the total concentration of particles inside the duct and is given by the formula

$$V_{dep} = \frac{N}{C}$$

Fig 4.12 shows the deposition velocity at the exhaust velocities tested. We notice that inspite of the higher concentration at lower exhaust velocity, the deposition velocity of particles increases with increasing exhaust velocity. The deposition velocity on the two walls is similar to that of the two windows and increases with increasing exhaust velocity. The deposition velocity on the bottom wall is highest and is lowest for the ceiling.

### 4.5.4.3 Non-Dimensionalization

Non dimensionalization helps in comparing data with previous investigations. The data are represented in the form of dimensionless velocity and dimensionless relaxation time. The following were the steps followed to non dimensionalize the recorded data.

Dimensionless deposition velocity is defined by

$$V^+ = \frac{V_{dep}}{u^*}$$

where $u^*$ is the friction velocity. The friction velocity is given by
Figure 4.12: Deposition velocity at the two exhaust velocities
Here $f$ is the Moody friction factor and $U_{avg}$ is the average flow velocity inside the duct. The friction factor is determined using the Colebrook’s natural roughness function (ASHRAE, 1997) and is given by

$$\frac{1}{\sqrt{f}} = 1.14 + 2\log\left(\frac{D_h}{k_s}\right) - 2\log\left(1 + \frac{9.3}{Re\left(\frac{k_s}{D_h}\right)^1.5}\right)$$

where $Re$ is the flow Reynolds number. Galvanized steel was used as the material for the duct work. It has a roughness of 0.000153 m (0.0005 ft). Using a hydraulic diameter of 0.23 m (0.74 ft) for the rectangular duct section the Moody friction factor was 0.0243 for an average flow velocity of 1500 ft/min.

The relaxation time is a measure of the characteristic time for the velocity of the particle to respond to a change in local air velocity. The dimensionless relaxation time is given by

$$\tau^+ = \frac{\tau u^2}{\nu} = \frac{\rho_p d_p^2 u^2}{18\mu \nu}$$

where $\rho_p$ is the particle density, $d_p$ is the particle diameter, $\mu$ is the dynamic viscosity of air and $\nu$ is the kinematic viscosity of air.

The non dimensional form of representation is by plotting the non dimensional relaxation time ($\tau^+$) on the absicca and the non dimensional velocity ($V^+$) on the ordinate. Experiments were performed at two different flow velocities resulting in 2 data points in the non dimensional representation. The average value obtained by the three sets of experiments for each case is plotted and shown by Fig 4.13. The average deposition velocities are used in the non dimensional representation shown by Fig 4.13. The aerosol generator produced a constant output for both the test cases. The next section compares the results obtained from the present investigation with previous documented non dimensional experimental results.
Figure 4.13: Non dimensional representation of present investigation
4.5.5 Comparison with available non dimensional deposition results

Non dimensional representation of turbulent deposition has been carried out for many years. Papavergos and Hedley summed up the work done in turbulent deposition over the years in their review paper and came up with correlations based on the available experimental results. It should however be noted that their correlations were mostly based on experimental data available in vertical flow systems wherein deposition occurred in small enclosures rather than in dimensions equivalent to that of exhaust ducts.

Only 3 experimenters provided deposition data in horizontal ducts comparable to the present investigation. These include Sehmel (60 cm by 60 cm), Gerstler (25.4 cm by 25.4 cm) and Nazarof (15.2 cm by 15.2 cm). The results of these three experimenters along with the correlations obtained by Papavergos and Hedley have been compared with the present investigation. Deposition on the duct ceiling, floor and walls have been plotted separately and are shown by Fig 4.14 through Fig 4.19. The following conclusions can be made from the plots.

The results obtained by the present investigation are in close agreement with the results obtained by Gerstler though deviating from the results obtained by Nazarof and Sehmel. Only one data point was obtained in the present investigation as effect of changing particle size was not investigated. One would expect the data obtained by different investigators to collapse to a single line when represented in a non dimensional form. This is clearly not the case as seen from the plots. This would mean that parameters other than $V^+$ and $\tau^+$ may have a direct or indirect effect on particle deposition. One of the possible parameters would be the flow Reynolds number. We notice a shift to the right in the plots obtained by Gerstler with an increase in flow Reynolds number. This clearly indicates the influence of flow Reynolds number on $V^+$. Another possible factor to be considered might be the influence of $\rho_p/\rho_f$ on particle deposition. It can thus be concluded that further research is required to fully understand the parameters that influence particle deposition.

A good thing to note though is that all the plots compared seem to have roughly the same slope. It can also be concluded that the effect of $\tau^+$ on $V^+$ is insignificant for small and large values. It is assumed that particles are deposited in a turbulent flow by the circulating eddies. At high values of $\tau^+$ the particle inertia is large and thus the particles do not attain the eddy velocity required for deposition. Thus $V^+$ levels out at
higher values of $\tau^+$. Correlations have been developed between $V^+$ and $\tau^+$ for ceiling, floor and wall deposition in a 0.254m by 0.203 m (10 inches by 8 inches) duct. Table 4.2 shows the range of values of $\tau^+$ these correlations are valid.

### Table 4.2: Correlations developed for particle deposition

<table>
<thead>
<tr>
<th>Flow Reynolds Number</th>
<th>Location</th>
<th>Equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>115000</td>
<td>Ceiling</td>
<td>$V^+ = (0.00001) + (0.015\tau^{+2})$ for $0 &lt; \tau^+ &lt; 2.75$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V^+ = 0.11$, for $\tau^+ &gt; 2.75$</td>
</tr>
<tr>
<td>115000</td>
<td>Floor</td>
<td>$V^+ = (0.00001) + (0.13\tau^{+2})$ for $0 &lt; \tau^+ &lt; 1$</td>
</tr>
<tr>
<td>115000</td>
<td>Wall</td>
<td>$V^+ = (0.00001) + (0.03\tau^{+2})$ for $0 &lt; \tau^+ &lt; 2$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V^+ = 0.11$, for $\tau^+ &gt; 2$</td>
</tr>
<tr>
<td>38000</td>
<td>Ceiling</td>
<td>$V^+ = (0.00001) + (0.1\tau^{+2})$ for $0 &lt; \tau^+ &lt; 1$</td>
</tr>
<tr>
<td>38000</td>
<td>Floor</td>
<td>$V^+ = (0.00001) + (1.7\tau^{+2})$ for $0 &lt; \tau^+ &lt; 0.25$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V^+ = 0.11$, for $\tau^+ &gt; 0.25$</td>
</tr>
<tr>
<td>38000</td>
<td>Wall</td>
<td>$V^+ = (0.00001) + (0.65\tau^{+2})$ for $0 &lt; \tau^+ &lt; 0.4$</td>
</tr>
<tr>
<td></td>
<td></td>
<td>$V^+ = 0.11$, for $\tau^+ &gt; 0.4$</td>
</tr>
</tbody>
</table>

Fig 4.20 shows the variation of deposition velocity with respect to the average flow velocity inside the duct. We notice that deposition velocity is maximum at the floor of the duct. This is expected because of gravity aiding the deposition. Deposition velocity to both the side walls is in close agreement and the deposition velocity to the ceiling is lesser compared to the other sections of the duct. Also deposition velocity increases with increase in flow Reynolds number as seen in the plots. This further corroborates the strong influence on flow Reynolds number on particle deposition.
Figure 4.14: Ceiling non dimensional representation- Avg. Flow velocity 1500 ft/min
Figure 4.15: Floor non dimensional representation- Avg. Flow velocity 1500 ft/min
Figure 4.16: Side wall non dimensional representation- Avg. Flow velocity 1500 ft/min
Figure 4.17: Ceiling non dimensional representation - Avg. Flow velocity 500 ft/min
Figure 4.18: Floor non dimensional representation- Avg. Flow velocity 500 ft/min
Figure 4.19: Side wall non dimensional representation- Avg. Flow velocity 500 ft/min
Figure 4.20: Variation of deposition velocity with avg. flow velocity
4.5.6 Comparison with Model

This section compares the experimental deposition results on the cylinder with that of the modeling results. The experimental results were based on the amount of uranine deposited onto the cylinder and back calculating the amount of oleic acid based on the percentage of uranine to oleic acid in the original mixture. Table 4.3 shows the comparison between the experimental and the modeling results.

<table>
<thead>
<tr>
<th>Avg. Flow velocity (ft/min)</th>
<th>Experiment (µg/ms)</th>
<th>Modeling (µg/ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>500</td>
<td>0.72</td>
<td>1.14</td>
</tr>
<tr>
<td>1500</td>
<td>16.80</td>
<td>12.01</td>
</tr>
</tbody>
</table>

We notice that the modeling results differ from the experimental results by a factor of 1.5 for an average flow velocity of 500 ft/min and under predict the results by a factor of 0.7 for an average flow velocity of 1500 ft/min. A possible explanation could be that the modeling considered all mechanisms responsible for deposition to be independent of each other. Also the modeling considered flow to be fully developed but the experiments were performed in a region where flow was not fully developed. Nevertheless the modeling results provide a good estimate of the actual deposition onto a cylinder placed in cross flow inside a kitchen exhaust duct.

4.5.7 Conclusions

The experimental results brought to light the need for more work in understanding the physics of particle deposition in large horizontal ducts. A different approach might be required in representing deposition results in terms of non dimensional parameters. The modeling results though not in close comparison with the experimental results provide an estimate in the amount of deposition that would occur on a cylinder when placed in cross flow in an actual cooking process.
Chapter 5

Real Cooking Experiments and Sensor Testing

5.1 Introduction

The previous chapter looked at simulated cooking processes in order to determine the viability of the sensors in a real environment. In this chapter a real cooking procedure is carried out in accordance with ASTM and ASHRAE standards and the compatibility of the sensors in a real cooking environment is investigated.

5.2 LED and Photo resistor selection

It was found out that the deposition rate on the windows was very similar to that on the duct wall. The presence of a step before the window section did not alter the deposition rate of particles settling onto the windows. The next step involved the suitable selection of an LED and a photo resistor. It was decided to test the performance of a 5 mm red LED which is the most common type of LED available in the market. The intensity of this red LED was 1000 MCD.
5.2.1 LED Bench Experiments

In order to test the performance of an LED and photo resistor, an environment resembling a duct enclosure was constructed. It consisted of a rectangular enclosure with one open accessible end. Fixtures were built to hold both the LED and the photo resistor. The LED mounting was fixed at one end and the photo resistor mounting was placed at various distances from the LED. A transparent substrate paper fixture acting as an interference between the LED and the photo resistor similar to that of a glass window in the actual duct was also manufactured and placed between the LED and photo resistor using a ring stand during the experimentation process. Lard layers of various thicknesses were manually applied onto the transparent substrate paper to test the performance of the photo resistor for various grease thickness deposits. A simple experiment was performed to calculate the density of lard used for the experiments. A known mass of lard was introduced in a measuring flask containing water. Applying Bernoulli’s principle and measuring the quantity of water displaced, the density of lard was calculated. Three tests were conducted and the average density was found to be $1105 \text{ kg/m}^3$.

Calculating the density was critical in obtaining the average thickness of the various samples of grease deposits. A transparent substrate paper was used to obtain grease deposits of various thicknesses. The substrate paper was weighed before and after the introduction of lard using a micro-balance. The lard was initially heated on a hot plate to its liquid state and a syringe was used to introduce it on to the substrate paper. Care was taken to obtain a fairly uniform layer of grease thickness on the substrate paper. Four samples of lard were tested for the LED experiment and are shown in Table 5.1.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Weight (mg)</th>
<th>Average Thickness ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>378.1</td>
<td>550</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>669.6</td>
<td>950</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>783.4</td>
<td>1100</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>1506.4</td>
<td>2200</td>
</tr>
</tbody>
</table>
The photo resistor was connected to a multi meter and the resistance of the photo resistor was recorded for various distances between the LED and the photo resistor. Fig 5.1 shows the variation of the resistance of the photo resistor with distance from the LED for different grease thickness deposits.

We notice that the photo resistor is quite sensitive for low grease thickness layer values as compared to higher values. This plot can be extrapolated to find the variation of the photo resistor in duct size dimensions and is shown by Fig 5.2. Though a rough estimate of the signal that can be expected in an actual duct, the bench experiments provided an insight into the validity of the LED photo resistor technique. It can thus be concluded that the LED photo resistor technique is quite beneficial for measuring low grease deposit thickness layers. Since the properties of actual grease are quite different from that of lard, a red LED with an higher intensity of 5000 MCD was used for the actual cooking experiments. The next step was the development of permanent fixtures to hold the LED and the photo resistor in an actual duct. Fig 5.3 shows the fixtures for the LED and the photo resistor. Both the LED and the photo resistor were glued to these fixtures using RTV glue. Detailed diagrams can be found in Appendix D.

This made sure that the LED and photo resistor were rigidly attached and not subjected to a change in orientation due to vibration or any other external disturbance. The fixtures with the LED and the photo resistor attached to them were then placed in the modified Evergreen quick seal which act as windows on either side of the duct wall.
Figure 5.1: Variation of photo resistance with distance from Red LED
Figure 5.2: Extrapolated variation of photo resistance with distance from Red LED
5.2.2 LED and Photoresistor Instrumentation

The LED instrumentation consisted of a simple bread board, an AC to DC converter, a voltage regulator, and a Keithley multimeter. The LED circuit diagram is shown by Fig 5.4. It consisted of a 15 volt AC to DC converter. A 4805 voltage regulator was used in the circuit. This voltage regulator supplied a constant voltage of 5 V to the LED. A 330 ohm resistance was connected in series with the LED to ensure excess current does not pass through and damage the LED. A CdS photoresistor (Model 276-1656) purchased from Radioshack was used as the light detector. Wires were soldered to the photoresistor leads and connected to a Keithley 2700 series multimeter.
5.3 Cylinder/ Strain Gage Technique

It was decided to attach a strain gage onto the flat plate of the cylinder assembly and check the response of the strain gage signal with the deposition of grease particles onto the cylinder. A Vishay- Ellis strain gauge indicator was used to measure the strain values. An omega strain gauge of resistance 350 ohms (serial number SGD 5/350—LY11) was used for the experiments. The concept behind the application would be that the deposition of grease particles would cause an increase in weight of the cylinder assembly. This would in turn increase the deflection by the cylinder as it is supported in the duct work at only one end. The strain gage would sense this deflection and produce a corresponding signal.

5.3.1 Strain Gage Installation and Instrumentation

Once the cylinder assembly was manufactured the next step was to install the strain gage. This first required the surface of the flat plate to be chemically clean. Proper surface preparation ensures a strong and stable bonding of the strain gauge to the surface. The following were the five steps performed to ensure a clean surface.

- Degreasing
- Abrading
- Burnishing
- Conditioning
- Neutralizing

Degreasing involved using a chlorinated degreasing agent to clean the surface of the flat plate. A gauze sponge was used for this purpose and the process was carried out until the gauze sponge came out clean. The surface of the flat plate was then flooded with M prep conditioner A and 320 silicon carbide paper was used to clean the surface of the flat plate. A dozen strokes of silicon carbide paper was good enough. Layout lines were required to correctly orient the strain gauge onto the bonding surface. Using a clean pencil and straight edge a clear line was burnished over the flat plate. M prep conditioner A was used to clear off the stain left by the pencil. The stain was cleared off using a cotton tip applicator. It was necessary to replace the applicator once it got
soiled with graphite. The process was repeated until a clean clear surface was obtained. The final step was use of the neutralizer. The neutralizer was used to provide a proper pH value necessary for bonding the strain gage. These five steps ensured the surface was chemically clean for strain gauge installation.

The strain gage installation took place within thirty minutes of cleaning the surface. The strain gage was transferred over to the workplace. The strain gage was transferred to a cellophane tape and was aligned over the flat plate. After lifting the tape, catalyst and a cyano acrylate adhesive were applied onto the flat plate. The tape was then pressed over the flat plate and a uniform pressure was applied onto the strain gage. This was done to ensure that the strain gage firmly attaches itself to the flat plate. After a couple of minutes the tape was removed. This completed the process of strain gage installation.

Once the strain gage was installed the next step was to solder wires to connect the strain gage to the strain gage indicator. This was an extremely difficult job as the dimensions of the flat plate were comparable to that of the strain gage. Solder tabs were used to connect the leads of the strain gage to the wires that would be plugged into the strain gauge indicator. The wires were successfully installed through the two holes on the pipe thread and were sealed using RTV.

5.3.2 Strain Gage Bench Experiments

To have an idea of the strain output by the cylinder technique bench experiments were performed before the strain gage was installed in the duct. Calibrated weights were hung from the centre of the cylinder using a thread and the strain values recorded. Fig 5.5 shows the strain readings as a function of weights added. There exists a linear relationship between the strain output and the weights added as seen from Fig 5.5.
Figure 5.5: Variation of strain gage output with the addition of weight.
5.4 Experimental Set up

Fig 5.6 shows the experimental set up that was used in a real cooking environment to test the sensors developed. A D029734 NSF electric broiler was used for cooking hamburgers. The broiler hood assembly had a 0.254 m by 0.254 m (10 by 10 inches) opening on one side. Since duct sections readily available in the market do not have a dimension of 0.254 m by 0.254 m (10 by 10 inches), this opening was reduced to 0.254 m by 0.203 m (10 by 8 inches). This dimension was chosen to ensure that the instrumented cylinder fits inside the duct work. Connected to the exhaust opening of the broiler was a 0.609 m (24 inches) long horizontal duct section. This section housed the LED and the photo resistor in addition to the cylinder. The horizontal section was followed by a 90 degree elbow and a 0.3048 m (12 inches) vertical section. This directed the cooking effluent into a canopy exhaust hood connected to an exhaust fan. Two holes at a distance of 0.254 m (10 inches) from the beginning of the horizontal duct section and centered from top to bottom were drilled on either side of the duct for the LED and photo resistor connections. The hole for the cylinder was offset by 0.0508 m (2 inches) from the hole for the photo resistor so that the cylinder did not lie in the wake region of the fittings for the photo resistor. The hole for the cylinder was drilled 0.0508 m (2 inches) from the top of the duct as compared to 0.1016 m (4 inches) from the top of the duct for the LED and the photo resistor. An Evergreen quik seal feed through was used to provide perfect sealing for the 3 holes drilled in the duct. Thin aluminum and steel substrates were placed inside the duct to determine the amount of grease deposition onto the walls. This is useful to correlate the signal output from the led technique and the cylinder technique to the actual amount of grease deposition inside the duct. The stainless steel substrates were of dimensions 0.0762 m by 0.0762 m (3 by 3 inches) and had a thickness of 0.004 inches. Eight of these substrates were placed inside the duct with two on each wall orientation. The other substrate used was a thin aluminum sheet of diameter 0.047 m (1.85 inches). Six of these were used with three placed on each of the side walls (front and rear walls) of the duct. Double sided tapes were used to place the substrates inside the duct. These were used as a secondary means of collecting grease deposits on the walls of the duct and comparing it with the deposition obtained by the stainless steel substrates. All the substrates were placed downstream of the LED.
Figure 5.6: Front view of the experimental Set up with specifications
and cylinder attachments and positioned in a manner to ensure the substrates did not lie in the wake region.

5.5 Cooking Experiments

The exhaust fan was run at 30 Hz for the cooking experiments. Three sets of experiments were conducted. Each experiment consisted of cooking 64 quarter pound beef patties with a fat content of 25 percent in batches of four. In the beginning it was not sure as to how much time the patties were to be cooked to result in a reduction of mass by at least 35 percent to meet the ASTM standards of cooking hamburger patties. To determine this, four patties were weighed initially before the cooking process. These patties were cooked for four minutes and were then flipped over. After another four minutes of cooking, the temperature at the centre of the patties was determined using a T type thermocouple. The patties were then weighed on a balance to determine the loss in weight.

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Initial Weight (g)</th>
<th>Weight after 8 minutes of cooking (g)</th>
<th>Weight Reduction (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>106.71</td>
<td>64.32</td>
<td>39.72</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>109.53</td>
<td>64.38</td>
<td>41.22</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>108.35</td>
<td>68.96</td>
<td>36.35</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>109.21</td>
<td>68.00</td>
<td>37.73</td>
</tr>
</tbody>
</table>

Table 5.2 shows that eight minutes of cooking time is sufficient to cause a weight reduction of 35 percent or more. The substrates were also weighed before the experiments. The stainless steel substrates were not taken out from the duct until the end of all three cooking experiments. Four aluminum substrates (two from each wall) were weighed after each experiment set to estimate the amount of grease deposition over time. The remaining two aluminum substrates were weighed at the end of all the three experiments.
5.5.1 LED Technique

The initial output of the photo resistor was recorded using a multimeter. The cooking experiments were conducted on three consecutive days. The final output of the photo resistor at the end of each experiment was noted down after the entire system was left to settle down overnight. The output signal of the photo resistor was also noted down after each batch of cooking. Fig 5.7 shows the average reading of the photo resistor at the end of each day.

As seen from Fig 5.7 there is a consistent increase in the output of the photo resistor versus cooking duration. This is attributed to the deposition of grease particles on the windows thus reducing the amount of red light detected by the photo resistor. It was also noticed that during the cooking process the resistance value of the photo resistor increased but once cooking was completed, there was a gradual decrease in the output of the resistor. This decrease in value leveled out after a few hours. A possible explanation for this is that smoke produced during cooking process restricted the photo resistor to detect red light. Once cooking was completed and smoke and fumes escaped from the duct, a relatively clearer environment inside the duct caused a more intense light to strike the photo resistor thus reducing the output signal. Moisture could also have been involved that evaporated over time.

5.5.2 Cylinder/Strain Gage Technique

The strain gage indicator was calibrated before the start of the experiments. It was noticed that when the exhaust fan was switched on the strain gage output readings began to fluctuate significantly and was never constant. It was expected that this would level off at the end of the experiments and a strain value greater than the initial value would be recorded because of the addition of the mass onto the cylinder. However unfortunately this was not the case and output of the strain gage was not meaningful. Table 5.3 show the results of the strain gage experiments.
Figure 5.7: Photo resistor output variation with time
Table 5.3: Strain Gage Experimental results

<table>
<thead>
<tr>
<th>S.No</th>
<th>End of Experiment</th>
<th>Strain Gage Reading ((\mu)strain)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>412</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
<td>408</td>
</tr>
<tr>
<td>3</td>
<td>2</td>
<td>423</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>416</td>
</tr>
</tbody>
</table>

One of the reasons could a slight change in orientation of the strain gage because of the vibrations. Another possible reason could be the connections of the strain gage might have been affected inside the duct due to grease deposition. Grease deposition on to the strain gage might be hindering the output signal from the strain gage. This problem has to be further looked into and meaningful results have not been yet achieved.

5.6 Correlation of Signal output to Grease deposition

The signal output from the photo resistor had to be correlated to the amount of grease deposition taking place inside the duct. We know the area of the substrates over which grease deposition takes place. Assuming a uniform density of grease, the thickness of grease deposit can be calculated. This can be then correlated to the output signal of the photo resistor. Two important assumptions were made here. Firstly the pattern of grease deposition on the aluminum or stainless steel substrates is similar to that taking place on the windows of the feed through. Secondly a constant uniform density of the grease particles has to be assumed. In our case we have assumed a density of 895 \(kg/m^3\) similar to the modeling section.

5.6.1 Aluminum Substrates

Since double sided Scotch tape was used to stick the aluminum substrates to the duct wall, the effect of Scotch tape to the weight of the substrate was investigated before carrying out the experiments. Table 5.4 shows the tare weight of the aluminum substrates and their weight after attaching removable Scotch tape and removing it. A microbalance was used to measure the weight of the aluminum substrates.

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Table 5.4: Effect of Scotch tape on weight of aluminum substrates

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Tare Weight (mg)</th>
<th>Weight after Tape removal (mg)</th>
<th>Weight Addition (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A</td>
<td>77.442</td>
<td>77.477</td>
<td>0.035</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>77.812</td>
<td>77.852</td>
<td>0.040</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>77.539</td>
<td>77.568</td>
<td>0.029</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>77.568</td>
<td>77.600</td>
<td>0.032</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>77.424</td>
<td>77.452</td>
<td>0.028</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>77.228</td>
<td>77.259</td>
<td>0.031</td>
</tr>
</tbody>
</table>

As seen from Table 5.4 there seems to be an average addition of 0.033 mg by the Scotch tape. This value is subtracted from the mass of the substrates after the cooking experiments to determine the mass contribution by grease particles. Four aluminum substrates were weighed after every cooking process and the other two were weighed at the beginning and the end of the experiments. Since the same quantity of patties were cooked for the same time interval during the three experiments conducted it is a reasonable approximation to assume that each cooking process contributed equal amounts of grease particles onto the aluminum substrate. This approximation was applied to two aluminum substrates namely A and D which were weighed before the start and end of the three experiments. Table 5.5 shows the amount of grease added onto each aluminum substrate during the three experiments.

Table 5.5: Mass of grease added onto aluminum substrates during each experiment

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Mass of Grease particles deposited (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Exp1</td>
</tr>
<tr>
<td>1</td>
<td>A</td>
<td>7.478</td>
</tr>
<tr>
<td>2</td>
<td>B</td>
<td>6.556</td>
</tr>
<tr>
<td>3</td>
<td>C</td>
<td>4.978</td>
</tr>
<tr>
<td>4</td>
<td>D</td>
<td>8.575</td>
</tr>
<tr>
<td>5</td>
<td>E</td>
<td>6.337</td>
</tr>
<tr>
<td>6</td>
<td>F</td>
<td>3.588</td>
</tr>
</tbody>
</table>

The samples A, B and C were placed on the rear side duct wall and samples D E F on the front side duct wall. The rear duct wall housed the photo resistor and the
front duct wall housed the LED. Fig 5.8 shows the average deposition per unit area on the rear and the front duct wall.

![Bar chart showing deposition per unit area at different locations on the rear and front wall.](chart.png)

**Figure 5.8:** Deposition per unit area at different locations on the rear and front wall

We notice that there is a decrease in deposition when we move along the front and rear side walls from the bottom to the top of the duct. There are no error bars for the bottom most substrates as they were untouched during the course of all the three experiments and it was assumed that accumulated mass equally partitioned among the three tests. The trend observed could be attributed to the effect of gravitational settling inside the duct. Fig 5.9 shows the response of the photo resistor as a function of grease layer thickness.

The windows were not cleaned for the entire duration of the three experiments but the mass of grease collected was recorded at the end of each experiment. The average mass deposited during each experiment can be converted to a corresponding grease thickness layer assuming a uniform density. Detailed calculations are provided in Appendix B. It was very interesting to note that the LED technique is quite sensitive to
minute changes in grease deposition thickness. As seen from Fig 5.9 there exists a linear correlation between the grease deposition thickness and the photo resistor output from 0 to approximately 25 microns. Thus the LED technique proved successful to measure low thickness grease deposits in exhaust ducts.

5.6.2 Stainless Steel Substrates

A similar analysis was conducted for the stainless steel substrates. Since they are thicker as compared to the aluminum substrates there was hardly any contribution to the mass by the Scotch tape. This is illustrated by Table 5.6.

The weights of the substrates were measured initially and after the three experiments. A Sartorius balance with a least count of 0.1 mg was used to weigh the stainless steel substrates. Table 5.7 shows the amount of grease deposited onto the stainless steel substrates.

As seen from Table 5.7 maximum deposition of grease particles occurs at the bottom wall of the duct (samples C’ and D’). Fig 5.10 shows the grease deposited per unit area
Table 5.6: Effect of Scotch on the weight of stainless steel substrates

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Tare Weight (g)</th>
<th>Weight after Tape removal (mg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A’</td>
<td>4.6563</td>
<td>4.6563</td>
</tr>
<tr>
<td>2</td>
<td>B’</td>
<td>4.7302</td>
<td>4.7303</td>
</tr>
<tr>
<td>3</td>
<td>C’</td>
<td>4.7034</td>
<td>4.7035</td>
</tr>
<tr>
<td>4</td>
<td>D’</td>
<td>4.5921</td>
<td>4.5921</td>
</tr>
<tr>
<td>5</td>
<td>E’</td>
<td>4.7873</td>
<td>4.7873</td>
</tr>
<tr>
<td>6</td>
<td>F’</td>
<td>4.6491</td>
<td>4.6491</td>
</tr>
<tr>
<td>7</td>
<td>G’</td>
<td>4.7642</td>
<td>4.7642</td>
</tr>
<tr>
<td>6</td>
<td>H’</td>
<td>4.5947</td>
<td>4.5948</td>
</tr>
</tbody>
</table>

Table 5.7: Amount of grease deposited on the stainless steel substrates

<table>
<thead>
<tr>
<th>S.No</th>
<th>Sample</th>
<th>Weight after three experiments (g)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>A’</td>
<td>0.0702</td>
</tr>
<tr>
<td>2</td>
<td>B’</td>
<td>0.0540</td>
</tr>
<tr>
<td>3</td>
<td>C’</td>
<td>0.9668</td>
</tr>
<tr>
<td>4</td>
<td>D’</td>
<td>0.6305</td>
</tr>
<tr>
<td>5</td>
<td>E’</td>
<td>0.0422</td>
</tr>
<tr>
<td>6</td>
<td>F’</td>
<td>0.0244</td>
</tr>
<tr>
<td>7</td>
<td>G’</td>
<td>0.0113</td>
</tr>
<tr>
<td>6</td>
<td>H’</td>
<td>0.0049</td>
</tr>
</tbody>
</table>

inside the duct.

Fig 5.10 shows that maximum deposition takes place in the bottom wall. This is in correspondence with theory as gravitational settling aids other deposition mechanisms on the bottom wall. We are concerned only with deposition occurring on the side walls as that is where our sensors have been placed. Proceeding on similar grounds as in the case for aluminum substrates, the average thickness of grease deposits is found out. Detailed calculations are shown in Appendix B.

5.7 Comparison of Grease Thickness obtained by the 2 substrates

Table 5.8 shows that the average grease deposit thickness on the rear and front walls inside the duct at the end of 3 experiments.
Figure 5.10: Grease deposition per unit area obtained by the steel substrates

Table 5.8: Comparison of grease dep. thickness from the two types of substrates

<table>
<thead>
<tr>
<th>S.No</th>
<th>Average Grease deposition Thickness</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Aluminum Substrates (µm)</td>
</tr>
<tr>
<td>1</td>
<td>26.40</td>
</tr>
</tbody>
</table>

We notice that the results obtained by the two substrates are in close agreement. One of the possible reasons for the discrepancy is the difference in least count of the Micro balance and the Sartorious Balance. Nevertheless a good value of the average grease layer thickness corresponding to the output signal of the photo resistor is obtained.

## 5.8 Conclusions

The cylinder/strain gage technique needs to be further looked into to achieve success with this method. Vibrations produced inside the duct during the cooking process might have been one of the reasons for the possible failure of the strain gage technique. The LED photo resistor proved to be successful in measuring grease thickness deposits in
kitchen exhaust ducts. A proof of concept was developed during the investigations. A further step would be to convert the resistance values given out by the photo resistor into a voltage reading. Thus a correlation could be developed between the average grease build up inside the duct and the voltage reading from the sensors.
Chapter 6

Conclusions and Recommendations for future work

The modeling results provide a good estimate of the amount of grease deposition that can be expected inside kitchen exhaust ducts. Grease deposition on the side walls of the duct are in close correspondence to the deposition on the windows installed on opposite duct walls. The LED sensor technique provided promising results for measuring grease deposits inside a duct. The photo resistor was very sensitive to minute changes of grease deposition layers. It would be beneficial to inspect the output signal of the photo resistor for greater thickness of grease deposits. The fact that this method is non intrusive and cheap is a promising factor is considering further development of this technique. The LED and photo resistor can be placed at different locations inside the duct to find out the variation in grease deposits along the length of the duct.

The strain gage technique did not prove successful to measure grease deposition inside a duct. This technique has to be further looked into. Probably a better design to shield the strain gage from grease deposits should be considered. Also a technique to prevent uncontrollable vibration of the cylinder has to be investigated. Further research work is required in understanding the physics of particle deposition in large horizontal ducts. A different approach might be required in representing deposition results in terms
of non dimensional parameters.
References


Appendix A

Uncertainty Analysis

A.1 Deposition Flux

We know that the deposition flux is given by Eqn A.1

\[ N = \frac{m_s}{A_s t} \]  

(A.1)

where \( N \) is the deposition flux, \( m_s \) is the mass of oleic acid deposited on the substrates, \( A_s \) is the area of the substrates and \( t \) is the time taken for the particles to deposit. \( m_s \) is given by Eqn A.2

\[ m_s = m_u R_{nv} \]  

(A.2)

where \( m_u \) is the mass of uranine deposited on the surface and \( R_{nv} \) is the mass ratio of non-volatiles to uranine in the generated particles. \( m_u \) is given by Eqn A.3

\[ m_u = V_{dil} M_{fluoro} X_{adj} \]  

(A.3)

where \( V_{dil} \) is the volume of 0.0013 N NaOH dilution solution. \( M_{fluoro} \) is the calibration slope of the flurometer and \( X_{adj} \) is the fluorometer reading.

Combining Equations A.2 and A.3 we get

\[ N = V_{dil} M_{fluoro} X_{adj} R_{nv} \]  

\[ \frac{A_s t}{A_t} \]  

(A.4)

Thus the uncertainty associated with Eqn A.4 is given by

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\[
\frac{\Delta N}{N} = \sqrt{\left(\frac{\Delta V_{\text{dil}}}{V}\right)^2 + \left(\frac{\Delta M_{\text{fluro}}}{M_{\text{fluro}}}\right)^2 + \left(\frac{\Delta X_{\text{adj}}}{X_{\text{adj}}}\right)^2 + \left(\frac{\Delta R_{\text{nv}}}{R_{\text{nv}}}\right)^2 + \left(\frac{-\Delta A}{A}\right)^2 + \left(\frac{-\Delta t}{t}\right)^2}
\] (A.5)

The absolute uncertainty in \(V_{\text{dil}}\) is estimated to be ±0.3 ml based on the uncertainty of the 25 ml pipette used to measure \(V_{\text{dil}}\). The absolute uncertainty in \(M_{\text{fluro}}\) is assumed to be negligible as a constant slope was obtained every time the flurometer calibration was performed. The uncertainty in area, \(\Delta A\) is estimated to be ±0.048 inches\(^2\). These are based on the bias and precision errors of the caliper used to measure the dimensions of the steel substrate and the random precision error associated with three samples taken. The uncertainty in time was taken to be ±15 seconds. The variables \(X_{\text{adj}}\) and \(R_{\text{nv}}\) were calculated as follows. \(X_{\text{adj}}\) is given by Eqn A.6

\[
X_{\text{adj}} = X_s - X_b
\] (A.6)

where \(X_s\) is the value read by the flurometer when a sample is tested and \(X_b\) is the value read by the flurometer for a blank sample. The absolute uncertainty thus associated with \(X_{\text{adj}}\) is given by Eqn A.7

\[
\Delta X_{\text{adj}} = \sqrt{\left(\Delta X_s\right)^2 + \left(\Delta X_b\right)^2}
\] (A.7)

The absolute uncertainties in the flurometer readings, \(\Delta X_s\) and \(\Delta X_b\) are estimated to be one half of the finest graduated marking on the flurometer. \(R_{\text{nv}}\) which is the ratio of non volatiles to uranine in the final solution is given by Eqn A.8

\[
R_{\text{nv}} = \frac{m_o + m_u}{m_u}
\] (A.8)

where \(m_o\) is the mass of oleic acid in the final aerosol solution and \(m_u\) is the mass of uranine in the final aerosol solution. The absolute uncertainty in \(R_{\text{nv}}\) thus is

\[
\Delta R_{\text{nv}} = \sqrt{\left(\frac{1}{m_u^2}(m_o^2\Delta m_o^2 + m_u^2\Delta m_u^2)\right)}
\] (A.9)

A Sartorius balance was used to weigh uranine and thus it was estimated the uncertainty in \(m_u\) and \(m_o\) to be ±0.01 grams based on the resolution of the balance.
A.2 Deposition Velocity

We know that the deposition velocity for particles deposited in given by the Eqn A.10

\[ V_{dep} = \frac{N}{C} \]  (A.10)

where \( V_{dep} \) is the deposition velocity, \( N \) is the deposition flux and \( C \) is the total aerosol concentration measured by the Moody at the duct centreline. \( C \) is given by Eqn A.11

\[ C = \frac{m_m}{Q_m t} \]  (A.11)

where \( m_m \) is the mass collected on all the stages of the Moody, \( Q_m \) is the flow rate of the Moody impactor and \( t \) is the sample time. \( m_m \) is given by Eqn A.12

\[ m_m = V_{dil} M_{fluoro} X_{adj} \]  (A.12)

Combining Eqns A.11 and Eqn A.12 we get

\[ C = \frac{V_{dil} M_{fluoro} X_{adj} R_{nv}}{Q_m t} \]  (A.13)

The relative uncertainty in \( V_{dep} \) is given by

\[ \frac{\Delta V_{dep}}{V_{dep}} = \sqrt{\left( \frac{\Delta N}{N} \right)^2 + \left( \frac{\Delta C}{C} \right)^2} \]  (A.14)

where

\[ \frac{\Delta C}{C} = \sqrt{\left( \frac{\Delta V_{dil}}{V} \right)^2 + \left( \frac{\Delta M_{fluoro}}{M_{fluoro}} \right)^2 + \left( \frac{\Delta X_{adj}}{X_{adj}} \right)^2 + \left( \frac{\Delta R_{nv}}{R_{nv}} \right)^2 + \left( \frac{-\Delta Q_m}{Q_m} \right)^2 + \left( \frac{-\Delta t}{t} \right)^2} \]  (A.15)

The flow rate was measured using a TSI mass flow meter 4000 series. Thus the uncertainty in \( Q_m \) was estimated to be 2 percent of the reading. The uncertainties in the other variables have been discussed in the previous section.
A.3 Dimensionless Deposition Velocity

Dimensionless deposition velocity is given by Eqn A.16

\[ V^+ = \frac{V_{dep}}{u^*} \]  

(A.16)

where \( u^* \) is the friction velocity and is given by Eqn A.17

\[ u^* = U_{avg} \sqrt{\frac{f}{8}} \]  

(A.17)

where \( U_{avg} \) is the average velocity inside the duct and \( f \) is the Moody friction factor.

The uncertainty associated with \( V^+ \) is given by Eqn A.18

\[ \Delta V^+ = \sqrt{\left(\Delta V_{dep}\right)^2 \left(\frac{8}{f U_{avg}^2}\right) + \left(\Delta U_{avg}\right)^2 \left(\frac{8 V_{dep}^2}{f U_{avg}^4}\right) + \left(\Delta f\right)^2 \left(\frac{2 V_{dep}^2}{f^2 U_{avg}^2}\right)} \]  

(A.18)

The uncertainty in \( V_{dep} \) has been determined earlier. The uncertainty in \( f \) is estimated to be 2 per cent (Gerstler et. al). The uncertainty in \( U_{avg} \) is based on the bias error of the hot film anemometer which is 3 percent of the indicated reading.

A.4 Dimensionless Relaxation time

The dimensionless relaxation time is given by Eqn A.19

\[ \tau^+ = \frac{\tau u^*}{\mu} \]  

(A.19)

The relative uncertainty in \( \tau^+ \) can be written as

\[ \frac{\Delta \tau^+}{\tau^+} = \sqrt{\left(\frac{\Delta \tau}{\tau}\right)^2 + 2 \left(\frac{\Delta u^*}{u^*}\right)^2 + \left(\frac{\Delta \mu}{\mu}\right)^2} \]  

(A.20)

The relative uncertainty in the friction velocity is given by Eqn A.21

\[ \frac{\Delta u^*}{u^*} = \sqrt{\left(\frac{\Delta U_{avg}}{U_{avg}}\right)^2 + 0.25 \left(\frac{\Delta f}{f}\right)^2} \]  

(A.21)

We know that relaxation time of a particle is given by Eqn A.22
\[ \tau = \frac{\rho_p d_p^2 C_c}{18\mu} \]  
(A.22)

Thus the relative uncertainty in the relaxation time can be represented as

\[ \frac{\Delta \tau}{\tau} = \sqrt{\left(\frac{\Delta \rho_p}{\rho_p}\right)^2 + 2 \left(\frac{\Delta d_p}{d_p}\right)^2 + \left(\frac{\Delta C_c}{C_c}\right)^2 + \left(\frac{\Delta \mu}{\mu}\right)^2} \]  
(A.23)

Uncertainties in \( \rho, C_c \) and \( \mu \) are not taken into account. Standard deviation obtained during the several tests was used as the uncertainty associated with \( d_p \).
Appendix B

Sample Calculations

Sample calculations for deposition onto a cylinder due to impaction, diffusion, thermophoresis and vapor transport have been performed at a bulk air velocity of 7.62 m/s (1500 ft/min), cylinder diameter of 0.02 m (0.78 inches) and a particle diameter of 10 \( \mu \text{m} \).

B.1 Particle Impaction onto a circular cylinder in cross flow

The mass deposition rate per unit length per unit mass concentration is given by

\[
M_{\text{impac}} = \eta U_{\text{avg}} \pi d_b
\]  \hspace{1cm} (B.1)

where \( \eta \) is the collection efficiency, \( U_{\text{avg}} \) is the bulk air velocity and \( d_b \) is the cylinder body diameter. The collection efficiency is obtained using the plot shown by Fig 3.1. Thus the mass deposition rate per unit length per unit mass concentration by impaction for a particle diameter of 10 \( \mu \text{m} \) is

\[
M_{\text{impac}} = 0.067 \times 7.62 \frac{m}{s} \times \pi \times 0.02m = 0.01 \frac{m^2}{s}
\]  \hspace{1cm} (B.2)

B.2 Particle Diffusion onto a circular cylinder in cross flow

Convective heat transfer correlation for a cylinder in cross flow is given by
\[ Nu = 0.26Re^{0.6}Pr^{0.37} \] (B.3)

Assuming most of the grease deposition takes place on the front side of the cylinder, the average heat transfer coefficient for the front side is approximately twice the value for the entire cylinder. Assuming a heat and mass transfer analogy Eqn B.3 can be written as

\[ Sh = 0.52Re^{0.6}Sc^{0.37} \] (B.4)

\[ \frac{h_md_b}{D} = 0.52 \left( \frac{U_d}{\nu_{fluid}} \right)^{0.6} \left( \frac{\nu_{fluid}}{D} \right)^{0.37} \] (B.5)

where \( h_m \) is the mass transfer coefficient, \( d_b \) is the cylinder body diameter, \( D \) is the particle diffusivity and \( \nu_{fluid} \) is the kinematic fluid viscosity.

The particle diffusivity, \( D \) is given by

\[ D = \frac{kTC_c}{3\pi\mu d_p} \] (B.6)

where \( k \) is the Boltzman’s constant, \( T \) is the temperature, \( C_c \) is the slip correction factor and \( d_p \) is the particle diameter.

Mass deposition rate per unit length of cylinder per unit mass concentration for various body diameters is given by

\[ M_{diffusion} = h_m\pi d_b \] (B.7)

For a temperature of 298 K particle diffusivity as given by Eqn B.21 is

\[ D = \frac{1.38 \times 10^{-23} \frac{J}{K} \times 298K \times 1}{3 \times \pi \times 0.0000181 \frac{kg}{m^3} \times 0.00001m} = 2.41 \times 10^{-12} \frac{m^2}{s} \] (B.8)

The mass transfer coefficient as given by Eqn B.21 is

\[ \frac{h_m \times 0.02m}{2.41 \times 10^{-12} \frac{m^2}{s}} = 0.52 \left( \frac{7.62 \frac{m}{s} \times 0.02m}{1.53 \times 10^{-5} \frac{m^2}{s}} \right)^{0.6} \left( \frac{1.53 \times 10^{-5} \frac{m^2}{s}}{2.41 \times 10^{-12} \frac{m^2}{s}} \right)^{0.37} = 5.16 \times 10^{-6} \frac{m}{s} \] (B.9)
The mass deposition rate per unit length of cylinder per unit mass concentration thus is

\[ M_{\text{diffusion}} = 5.16 \times 10^{-6} \frac{m}{s} \times \pi \times 0.02m = 3.24 \times 10^{-7} \frac{m^2}{s} \]  \hspace{1cm} (B.10)

### B.3 Particle Thermophoresis onto a circular cylinder in cross flow

Thermophoretic velocity is given by

\[ V_{\text{thermo}} = -\frac{3\mu C_v H \Delta T}{2 \rho_{\text{fluid}} T} \]  \hspace{1cm} (B.11)

where \( H \) is given by

\[ H = \left( \frac{1}{1 + 6 \frac{k_a}{k_p}} \right) \left( \frac{k_a}{k_p} + \frac{4.4 \lambda}{1 + 2 \frac{k_a}{k_p} + 8.8 \frac{k_a}{k_p}} \right) \]  \hspace{1cm} (B.12)

Heat transfer at the cylinder from conduction and convection can be equated to obtain the temperature gradient at the cylinder surface as follows

\[ \frac{dT}{dx} = \frac{h_{b-c} (T_b - T_c)}{k_a} \]  \hspace{1cm} (B.13)

where \( h_{b-c} \) is the heat transfer coefficient between the free stream and cylinder surface, \( T_b \) is the bulk temperature, \( T_c \) is the cylinder temperature and \( k_a \) is the thermal conductivity of air. \( h_{b-c} \) is calculated as given by Eqn B.6 and is

\[ \frac{h_{b-c} \times 0.02m}{0.026 \frac{W}{mK}} = 0.52 \left( \frac{7.62 \frac{m}{s} \times 0.02m}{1.53 \times 10^{-5} \frac{m^2}{s}} \right)^{0.6} (0.7)^{0.37} = 148.39 \frac{W}{m^2K} \]  \hspace{1cm} (B.14)

The temperature gradient for a bulk temperature of 35 degree C and a cylinder body temperature of 25 degree C as given by Eqn B.13 is

\[ \frac{dT}{dx} = \frac{148.39 \frac{W}{m^2K} \times (298K - 308K)}{0.026 \frac{W}{mK}} = -57073.08 \frac{K}{m} \]  \hspace{1cm} (B.15)

\( H \) as given by Eqn B.16 is
$$H = \left( \frac{1}{1 + 6^{0.066 \mu m / 10 \mu m}} \right) \left( \frac{0.026 \frac{W}{mK}}{0.17 \frac{W}{mK}} + 4.4 + \frac{0.066 \mu m}{10 \mu m} \right) = 0.127 \quad (B.16)$$

Thus the thermophoretic velocity as given by Eqn B.11 is

$$V_{thermo} = \frac{-3 * 0.0000181 \frac{kg}{ms} * 1 * 0.127 * -57073.08 \frac{K}{m}}{2 * 1.176 \frac{kg}{m^3} * 308K} = 5.43 * 10^{-4} \frac{m}{s} \quad (B.17)$$

The mass deposition rate per unit length of cylinder per unit mass concentration due to thermophoresis is given by

$$M_{thermo} = V_{thermo} \pi d_b \quad (B.18)$$

For a cylinder body diameter of 0.02m the mass deposition rate per unit length of cylinder per unit mass concentration due to thermophoresis is

$$M_{thermo} = 5.43 * 10^{-4} \frac{m}{s} * 0.02m = 3.41 * 10^{-5} \frac{m^2}{s} \quad (B.19)$$

### B.4 Vapor Transport

The diffusion coefficients of the four compounds taken into consideration is given by Table 3.1. Using a heat mass transfer analogy as in the case of particle convection/diffusion, the vapor mass transfer coefficient is calculated. This equation is given by

$$\frac{h_v d_b}{D_v} = 0.52 \left( \frac{U d_b}{\nu_{fluid}} \right)^{0.6} \left( \frac{\nu_{fluid}}{D} \right)^{0.37} \quad (B.20)$$

where $h_v$ is the vapor mass transfer coefficient. Considering Naphthalene for the sample calculations the vapor transfer coefficient is found out to be

$$\frac{h_v * 0.02m}{8.36 * 10^{-6} \frac{m^2}{s}} = 0.52 \left( \frac{7.62 \frac{m}{s} * 0.02m}{1.53 * 10^{-5} \frac{m^2}{s}} \right)^{0.6} \left( \frac{1.53 * 10^{-5} \frac{m^2}{s}}{8.36 * 10^{-6} \frac{m^2}{s}} \right)^{0.37} = 0.068 \frac{m}{s} \quad (B.21)$$
The mass removal rate per unit length per unit mass concentration by vapor transport is given by

\[ M_{\text{vapor}} = h_v \pi d_b \]  \hspace{1cm} (B.22)

Substituting the values the mass removal rate per unit length per unit mass concentration for Naphthalene is

\[ M_{\text{vapor}} = 0.068 \times \pi \times 0.02m = 4.27 \times 10^{-3} \frac{m^2}{s} \]  \hspace{1cm} (B.23)

### B.5 Deposition Flux

Deposition flux on the substrate on the bottom wall is considered. The reading of the fluorometer, \( X_{\text{adj}} \) given by Eqn A.6 was 29 after adjusting for the blank sample reading. \( V_{\text{dil}} \) the volume of 0.0013 N NaOH dilution solution used was 25 ml. \( M_{\text{fluro}} \) the calibration slope of the fluorometer was 0.0027. The area of the substrate over which deposition took place was 9 inches\(^2\). Thus solving for Eqn A.3 we get

\[
N = \frac{25 \text{ml} \times 0.0027 \frac{\text{uguranine}}{\text{ml}} \times 29 \times 200 \frac{\text{ugnon-vol.}}{\text{uguranine}}}{9 \text{inches}^2 \times 25 \text{min}} = 125.344 \frac{\text{ugnon-vol.}}{\text{ft}^2\text{min}} = 22.49 \frac{\text{ugnon-vol.}}{\text{m}^2\text{s}}
\]  \hspace{1cm} (B.24)

The uncertainty associated with \( X_{\text{adj}} \) is given by

\[ \Delta X_{\text{adj}} = \sqrt{0.5^2 + 0.0025^2} = \pm 0.50 \]  \hspace{1cm} (B.25)

The mass of uranine is the final solution was 0.9 g and the mass of oleic acid was 179.91 g. The mass of iso propyl alcohol added to the solution was 78.99 g and the mass of DI water in the final solution was 40.2 g. Thus \( R_{nv} \) is given by

\[ R_{nv} = \frac{179.91 + 0.9}{0.9} = 200 \]  \hspace{1cm} (B.26)

The uncertainty in \( R_{nv} \) given by Eqn A.9 is

\[ \Delta R_{nv} = \sqrt{\left( \frac{1}{0.9^2} (179.91^2 * 0.01^2 + 0.9^2 * 0.01^2) \right)} = \pm 0.01 \]  \hspace{1cm} (B.27)
Thus the relative uncertainty in the deposition flux, $\Delta N$ as given by Eqn A.4 is

$$\frac{\Delta N}{N} = \sqrt{\left(\frac{0.3}{25}\right)^2 + \left(\frac{0}{0.0027}\right)^2 + \left(\frac{0.50}{29}\right)^2 + \left(\frac{0.01}{200}\right)^2 + \left(\frac{0.048}{9}\right)^2 + \left(\frac{0.25}{25}\right)^2} = \pm 0.024$$

(B.28)

### B.6 Deposition Velocity

The total aerosol concentration measured by the Moody at the duct centreline, $C$ as given by Eqn A.13 is

$$C = \frac{25 ml \times 0.0027 \mu g\text{uranine}}{30 \text{pm} \times 25 \text{min}} \times 471.34 \times 200 \frac{\mu g\text{nonvol.}}{\mu g\text{uranine}} = 240.13 \frac{\mu g\text{nonvol.}}{ft^3} = 8480.11 \frac{\mu g\text{nonvol.}}{m^3}$$

(B.29)

The relative uncertainty in $C$ as given by Eqn A.15 is

$$\frac{\Delta C}{C} = \sqrt{\left(\frac{0.3}{25}\right)^2 + \left(\frac{0}{0.0027}\right)^2 + \left(\frac{0.50}{471.34}\right)^2 + \left(\frac{0.01}{200}\right)^2 + \left(\frac{0.6}{30}\right)^2 + \left(\frac{0.25}{25}\right)^2} = \pm 0.025$$

(B.30)

Thus the deposition velocity as given by Eqn A.10 is

$$V_{dep} = \frac{125.344 \frac{\mu g\text{nonvolatiles}}{ft^3\text{min}}}{240.13 \frac{\mu g\text{nonvolatiles}}{ft^3}} = 0.520 \text{fpm} = 0.00264 \frac{m}{s}$$

(B.31)

and the uncertainty in deposition velocity, $\Delta V_{dep}$ is

$$\frac{\Delta V_{dep}}{V_{dep}} = \sqrt{(0.024)^2 + (0.025)^2} = \pm 0.034$$

(B.32)

### B.7 Dimensionless Deposition Velocity

The uncertainty in the dimensionless deposition velocity as given by Eqn A.18 is

$$\Delta V^+ = \sqrt{(0.01248)^2 \left(\frac{8}{0.0244 \times 1500^2}\right) + (45)^2 \left(\frac{8 \times 0.520^2}{0.0244 \times 1500^4}\right) + (0.000488)^2 \left(\frac{2 \times 1500^2}{0.0244^3 \times 1500^2}\right)}$$

(B.33)

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\[ \Delta V^+ = \pm 0.18 \quad (B.34) \]

### B.8 Dimensionless Relaxation Time

The friction velocity as given by Eqn B.35 is

\[ u^* = 1500 \sqrt{\frac{0.0244}{8}} = 82.44 \text{ fpm} = 0.418 \frac{m}{s} \quad (B.35) \]

The relative uncertainty in friction velocity as given by Eqn A.21 is

\[ \frac{\Delta u^*}{u^*} = \sqrt{\left( \frac{45}{1500} \right)^2 + 0.25 \left( \frac{0.000488}{0.0244} \right)^2} = \pm 0.032 \quad (B.36) \]

The particle relaxation time as given by Eqn B.37 is

\[ \tau = \frac{0.9 \frac{g}{cm^3} \times 0.000205 \frac{cm^2}{s} 	imes 1.13}{18 \times 1.81 \times 10^{-4} \frac{g}{cm^3}} = 1.31 \times 10^{-5} s \quad (B.37) \]

The relative uncertainty in relaxation time as given by Eqn A.23 is

\[ \frac{\Delta \tau}{\tau} = \sqrt{\left( \frac{0}{0.9} \right)^2 + 2 \left( \frac{1.92}{2.05} \right)^2 + \left( \frac{0}{1.13} \right)^2 + \left( \frac{0}{0.000181} \right)^2} = \pm 1.32 \quad (B.38) \]

Thus the dimensionless relaxation time as given by Eqn A.19 is

\[ \tau^+ = \frac{1.31 \times 10^{-5} s \times 0.418^2 m^2}{1.53 \times 10^{-5} m^2 s} = 0.146 \quad (B.39) \]

And the uncertainty in dimensionless relaxation time as given by Eqn A.19 is

\[ \frac{\Delta \tau^+}{\tau^+} = \sqrt{(1.32)^2 + 2 (0.032)^2 + \left( \frac{0}{0.000181} \right)^2} = \pm 1.32 \quad (B.40) \]

### B.9 Grease Thickness for bench LED experiments

Bernoulli’s principle was used to calculate the density of lard used for the bench experiments. Mass of lard inserted into a container containing DI water was 293 g. The volume of DI water displaced was 265 ml. The density of lard thus is
\[
\rho_{\text{lard}} = \frac{M_{\text{lard}}}{V_{\text{displaced}}} = \frac{0.293\text{kg}}{265 \times 10^{-6}\text{m}^3} = 1105.67 \frac{\text{kg}}{\text{m}^3} \tag{B.41}
\]

Diameter of substrate paper used was 2.8 cm and the weight of lard deposited onto the substrate paper was 0.378 g. Density of lard deposited onto the substrate paper is given by Eqn B.43

\[
\rho_{\text{lard}} = \frac{M_{\text{lard}}}{\pi d_{\text{sub}}^2 t_{\text{sub}}} \tag{B.42}
\]

where \(d_{\text{sub}}\) is the diameter of the substrate paper and \(t_{\text{sub}}\) is the thickness of the substrate paper.

Thus the thickness of grease deposit as given by Eqn B.43 is

\[
1100 \frac{\text{kg}}{\text{m}^3} = \frac{0.378\text{g}}{0.028\text{m}^2 t_{\text{sub}}} = 550 \mu\text{m} \tag{B.43}
\]

**B.10 Average grease thickness layer on Aluminium Substrates**

Three experiments were performed and the amount of grease deposited on the aluminium substrates on the front and the rear walls at the end of each experiment was determined. The density of grease was assumed to be 900 kg/m\(^3\).

Average mass deposition on the front wall was 6.337 mg and the back wall was 6.167 mg. Diameter of the Aluminium substrate used was 4.4 cm. Thus the thickness of grease deposit on the front wall as given by Eqn B.43 is

\[
900 \frac{\text{kg}}{\text{m}^3} = \frac{6.337 \times 10^{-6}\text{kg}}{0.044\text{m}^2 t_{\text{sub}}} = 4.63\mu\text{m} \tag{B.44}
\]

Similarly the thickness of grease deposit on the back wall is 4.51 \(\mu\text{m}\). Thus the average grease thickness layer after one cooking run was 4.57 \(\mu\text{m}\) per wall and the total grease thickness deposit after 3 cooking runs was 13.2 \(\mu\text{m}\) per wall.
B.11 Average grease thickness layer on Stainless Steel Substrates

Proceeding on similar lines as in the previous section the average mass of grease deposited on the stainless steel substrate on the front wall at the end of three experiments was 62.1 mg and the rear wall was 33.3 mg. The area of the stainless steel substrate used was 49.28 \( cm^2 \). Thus the thickness of grease deposit on the front wall is

\[
900 \frac{kg}{m^3} = \frac{62.1 \times 10^{-6} kg}{0.004928 m^2 l_{sub}} = 14.0
\]

Similarly the thickness of grease deposit on the rear wall 7.5 \( \mu m \).
Appendix C

ASHRAE 1375 RP concentration data

Table C.1: Average Conveyor Broiler Duct PCI Mass Concentration Data

<table>
<thead>
<tr>
<th>Stage</th>
<th>Cni, mg/m³</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combined</td>
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<tr>
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<td>4</td>
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Table C.2: GC-MS results

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<th>Compound</th>
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<tr>
<td>Acenaphtylene</td>
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<td>Pyrene</td>
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<td>Phenanthrene</td>
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Table C.3: Average Conveyor Broiler Duct SMPS Mass Concentration Data

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<th>$D_p, \mu m$</th>
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Appendix D

Solidworks Detailed Diagrams
Figure D.1: Cylinder Assembly
Figure D.2: Feed through with window attachment
Figure D.3: LED fixture
Figure D.4: Modified feed through with LED installed
Figure D.5: Photoresistor fixture
Figure D.6: Modified feed through with Photoresistor installed
Appendix E

Flurometer calibration
Figure E.1: Fluorometer Calibration

\[ y = 0.3626x - 0.0177 \]

\[ R^2 = 0.9889 \]