Towards Small Scale Sensors for Turbulent Flows and for Rarefied Gas Damping

by

Amin Ebrahiminejad Rafsanjani
B.Sc., University of Tehran, 2014

A Thesis Submitted in Partial Fulfillment of the Requirements for the Degree of

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Supervisory Committee

________________________________________
Dr. Rustom Bhiladvala, Supervisor
(Department of Mechanical Engineering)

________________________________________
Dr. Afzal Suleman, Departmental Member
(Department of Mechanical Engineering)
Abstract

This thesis makes contributions towards the development of two different small-scale sensing systems which show promise for measurements in fluid mechanics.

Well-resolved turbulent Wall Shear Stress (WSS) measurements could provide a basis for realistic computational models of near-wall turbulent flow in aerodynamic design. In aerodynamics field applications, they could provide indication of flow direction and regions of separation, enabling inputs for flight control or active control of wind-turbine blades to reduce shock and fatigue loading due to separated flow regions. Traditional thermal WSS sensors consist of a single microscale hot-film, flush-mounted with the surface and maintained at constant temperature. Their potential for fast response to small fluctuations may not be realized, as heat transfer through the substrate creates heat-exchange with fluid, leading to loss of spatial and temporal resolution.

The guard-heated thermal WSS sensor is a design introduced to block this loss of resolution. A numerical flow-field with a range of length and time and scales was generated to study the response of both guard-heated and conventional single-element thermal WSS sensors. A conjugate heat transfer solution including substrate heat conduction and flow convection, provides spatiotemporal data on both the actual and the “measured” WSS fluctuations calculated from the heat transfer rates experienced due to the WSS field. For a single-element sensor in air, we found that the heat transfer through the substrate was up to six times larger than direct heat transfer from the hot-film to the fluid. The resulting loss of resolution in the single-element sensor can be largely
recovered by using the guard-heated design. Spectra for calculated WSS from heat transfer response show that high frequencies are considerably better resolved in guard-heated sensors than in the single element sensor.

Nanoresonators are nanowires (NWs) excited into mechanical vibration at a resonance frequency, with a change in spectral width created by gas damping from the environment, or a shift in the resonance peak frequency created by added mass. They enable a wide range of applications, from sensors to study rarefied gas flow friction to the detection of early-stage cancer. The extraordinary sensitivity of nanoresonators for disease molecule detection has been demonstrated with a few NWs, but the high cost of traditional electron-beam lithography patterning, have inhibited practical applications requiring large arrays of sensors. Field-directed assembly techniques under development in our laboratory enable a large number of devices at low cost. Electro-deposition of metals in templates yields high-quality single nanowires, but undesired clumps must be removed. This calls for separation (extraction) of single nanowires. In this work, single nanowires are extracted by using the sedimentation behavior of particles. Based on numerical and experimental analyses, the optimum time and region for extracting samples with the highest fraction of single nanowires ratio was found. We show that it is possible to take samples free of large clumps of nanowires and decrease the ratio of undesired particles to single nanowires by over one order of magnitude.
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DEDICATION

To my beloved parents for their nonstop trust and support:

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Chapter 1

Introduction

This document uses the thermofluid sciences in the development of microsensors with diverse applications. It discusses two types of flows while dealing with small-scale structures in both types. In the first, a guard-heated thermal microsensor capable of resolving wall-shear stress fluctuations over a range of scale in turbulent flow is examined, along with a numerical model for evaluation of its performance. In the other research area, fluid mechanics at microscale (low Reynolds number) is used to help in the development of nanowires as nanoresonators used for sensing. These sensors can be used in different applications, such as molecular mass detection for early diagnosis of disease and experimental studies of gas damping in the transition regime of rarefied gas flow.

In the method where the microsensor with applications in turbulence is proposed, the new guard-heated sensor design is evaluated in numerically simulated flow-fields with the characteristics of turbulence. This sensor is designed to resolve small-scale fluctuations of the wall shear stress (WSS) without the large errors that single-hot-film sensors are prone to. This area of the thesis is identified as “guard-heated WSS sensing”.

In the other work, low Reynolds number fluid mechanics is used to help separate high quality, low-cost template-synthesized nanowires. Nanowire devices have typically been fabricated with high dimensional accuracy using relatively costly top-down methods. For large arrays of devices spanning large areas, the fabrication cost has been the main problem restricting their introduction to commercial use. Low-cost fabrication of nanowires will enable the use of nanowires in new and innovative applications. Synthesis of rhodium nanowires by electrodeposition in commercially available polycarbonate nanoporous templates is a method which was investigated by Moghimian et al. [1] for
low-cost synthesis of high-quality rhodium nanowires. The main drawback of this method is the occurrence of nanowire clumps and particles with unwanted shapes, which are mixed in with the desired straight, high-quality, single nanowires. The second area of this thesis focuses on separating single nanowires from the fabricated batch in a fluid medium by analyzing sedimentation of particles in the medium. Therefore, any part of this thesis that is focused on this topic is called “nanowire separation”.

1.1 Thesis Aim and Questions

1.1.1 Aim and Questions of the WSS Sensing Section

Aim: The main aim of this section is a comprehensive discussion and detailed analysis of adding guard-heating to the conventional flush-mounted hot-film WSS sensors. A comparison of different WSS measuring methods is presented, and the characteristic of thermal sensors which can specifically make them useful for measuring WSS in turbulent flows for in-situ applications is described. Then, the proposed design of guard-heated thermal WSS sensors is discussed. Subsequently, the way that the new design can reduce the errors of the conventional thermal WSS sensors, and make them more capable of measuring fluctuations in turbulent flows is described. In general, we have tried to provide a clear picture of the current possible methods for turbulent WSS measurements, based on which the advantages of the new design are argued.

This section emphasizes the practical applications of thermal WSS sensors in wind turbine control systems – how the information that a capable thermal WSS sensor provides for the control system of wind turbines can be used to avoid flow separation, and consequently, prolong the life span of wind turbine blades, is discussed in detail. Moreover, by reviewing the most current research papers on the available information about fluctuations of WSS in turbulent flows, it is argued that Direct Numerical Simulations methods have not yet been completely successful in giving us a clear view of WSS fluctuations. Reliable measurement methods can still help us in having a better understanding of turbulent structures, as well as being helpful field instruments for flow control system input. In general, this document will discuss and clarify the advantages of measuring WSS for small time and length scales.
**Question:** How well does the new sensor design respond to small scale WSS fluctuations, compared to conventional single-hot-film sensors?

In a previous study, Etrati et al. [2] numerically evaluated such sensors in sinusoidally-varying shear at different frequencies, to computationally evaluate the temporal resolution. In this thesis we extend the previous studies for a better evaluation of the capabilities of the new design. Here we have evaluated guard-heated thermal WSS sensor design using computational simulation in a flow which resembles the turbulent flow that the sensor might experience when being used on a wind turbine blade.

In this thesis, we have moved this evaluation a big step forward to analyze the sensor response under the condition which is similar to real world turbulence conditions and contains fluctuations with a range of length scales and frequencies. This document presents the simulation of the heat transfer of the thermal WSS sensors mounted on a glass substrate and exposed to a flow field resembling real turbulence. The velocity flow field containing fluctuations in a wide range of spatial and temporal scales is created using a two-dimensional large eddy simulation (LES). A conjugate heat transfer problem including conduction through the solid wall and convection in the fluid, is then solved numerically to evaluate heat transfer from the conventional and guard-heated thermal sensors, in response to the WSS fluctuations. The response of conventional and guard-heated thermal sensors is then compared to evaluate the improvements provided by guard heating.

### 1.1.2 Aim and Questions of Nanowires Separation Section

**Aim:** The main aim of this section is to propose and evaluate a method to separate high-quality single nanowires fabricated by electrodeposition in polycarbonate membranes, from a variety of other unwanted particles produced in the synthesis process, by the use of fluid mechanics techniques. The primary focus is to separate clumps of nanowires that are the main problematic particles for using nanowires in sensor applications. In this work, the focus is on inexpensive methods in order to keep the whole nanowire fabrication process at low-cost.

**Questions:** What is the best quality sample, with the highest ratio of single nanowires to unwanted particles, that can be extracted from a batch of particles fabricated by
electrodeposition of Rhodium in polycarbonate membranes by low-cost methods? What is the best experimental procedure to obtain it?

To answer this question, different common microfluidic channels designs are discussed and their use for this purpose is argued to be impractical, or as of now, impossible. This discussion is followed by the method of analyzing the motion of particle in a sedimentation process, in order to find the extent of improvement in sample quality that can be achieved by using a sedimentation approach.

Experiments using sedimentation of particles were completed to find the best sample that can be taken from a specific location at a given time, from a suspension of particles in a test tube; the particles were assumed to be distributed homogenously in the test tube at the start time. A fluid mechanics model is used to verify and complement the experimental results. Based on the simulations and experimental results, a time range and location range with a stable ratio was found for the sampling process.

### 1.2 Thesis Content

In this thesis, the introductory Chapter 2 discusses the significance of the “WSS sensing” work. Chapter 3, is in the format of a research paper, describes methods for solving the problem and the results in details. The same structure is repeated for the “nanowires separation” work. Chapter 4 discusses the importance of this work; it is followed by a research paper manuscript style Chapter 5 discussing the methods used for solving the problem and the results. The final Chapter 6 summarizes the conclusions and contributions of the whole thesis.

Chapter 2 of this thesis presents the background leading to the idea of a guard-heated thermal WSS sensor and its use for measuring fluctuations in turbulent flows. First, the definition and importance of WSS is discussed, then the structures and complexities of turbulent flows are discussed, and successively, WSS in turbulent flows is discussed in more detail. The common approaches for measuring turbulent WSS are then discussed and compared, with a focus on the thermal WSS sensors and the idea of adding guard-heaters to these sensors. This chapter also reviews and compares the most recent information about WSS fluctuations in turbulence using direct numerical simulation (DNS) simulating turbulent boundary layer in zero pressure gradient flows. Based on this,
we describe how an accurate small-scale WSS sensor can be used for validating numerical results, to help us better understand the turbulent structures. Additionally, this second chapter presents the details of a large eddy simulation approach used to create the flow field for evaluation of the guard-heated WSS sensor. This chapter discusses the models that have been used in this approach and the reasons for their choice.

The results of the numerical simulations of the guard-heated WSS sensor in turbulent flows are presented in Chapter 3. This chapter first describes the advantages of a reliable thermal WSS sensor. It clarifies the improvements that a fast response WSS sensor can make to the control system of wind turbines. Then, it describes the numerical method used for evaluation of the guard-heated WSS sensor and presents the results. Here, the heat transfer response of both the conventional single element sensor and the new guard-heated sensor are analyzed and compared, using a velocity field with the characteristics of real turbulence.

Chapter 4 of the thesis clarifies the aim and purpose of separating nanowires from the batch of nanoparticles, fabricated using electrodeposition in polycarbonate membranes. This chapter introduces the wide range of applications of nanowires, focusing on the use of nanowires as nanoresonators. It introduces the idea of using nanowire cantilevers as gas damping sensors in transitional rarefied gases and describes feasible low-cost methods introduced for manufacturing nanowires. By comparing the quality of fabricated nanowires using polycarbonate membranes with the other available methods, we discuss how extracting single nanowires from other particles by the sedimentation method can help us in achieving high-quality nanowire device arrays at low-cost.

Chapter 5, in research manuscript format, details how nanowires may be separated using the difference in their sedimentation behaviour compared to other particles in ethanol suspension. Different approaches for fabrication of nanowires, and different kinds of microfluidic channels for separating nanowires are discussed. Finally, we argue for using sedimentation for separation of nanowires. Results of experimental and numerical methods for sampling from the suspension medium and particles, without agitation, are presented. This chapter then discusses the extent of success achieved by this method and proposes an optimal time and location for taking samples.

Chapter 6 summarizes the main conclusions of the whole document.
Chapter 2

Sensing WSS fluctuations in Turbulent Flows

This chapter describes the idea of WSS, WSS in turbulent flows, the difficulties of measuring WSS fluctuations of turbulent flows, and the need to measure these fluctuations. Discussion of different types of WSS sensors is included in this chapter and the special characteristics of thermal WSS sensors are discussed in detail.

2.1 What is WSS?

WSS is the local tangential force per unit area exerted on the wall (solid) because of the flow of a fluid relative to the wall. Equally, WSS is the tangential force in the fluid at the wall. From scientific and engineering perspectives, the WSS is an essential quantity to compute. Time-averaged of this quantity is an indicative of the global state of the flow on the surface, which is used to determine averaged properties like the skin friction drag. The time-resolved part of WSS can be a measure of the unsteady structures in the flows, which are responsible for the momentum transfers and are indicative of the coherent portion of the turbulence activities [3]. Figure 2.1 illustrates the WSS on the wall resulting from the relative motion of the fluid. The magnitude of WSS is proportional to the velocity slope and viscosity of the fluid. For a Newtonian fluid, WSS can be defined as:

\[ \tau_w = \mu \frac{\partial u}{\partial y} \bigg|_{y=0} \]  

(2.1)
In steady laminar fluid flow, WSS is not fluctuating and it can be determined by knowing the velocity profile at the wall. However, in turbulent fluid flows, WSS fluctuates and its instantaneous value is different from its average value. Fluctuating element is shown by \( \tau'_w \) and the average value is shown by \( \bar{\tau}_w \):

\[
\tau'_w = \tau_w - \bar{\tau}_w
\]

Figure 2.1 WSS due to the relative motion of fluid flow with respect to the solid surface.

The fluctuating behaviour in turbulent flows makes these flows more complicated and calls for time responsive measurement methods.

2.2 Turbulent Flow Structures

Although apparent randomness of structures can be observed in high Reynolds turbulent flows, they are far from being completely uncorrelated. In turbulent flows, there are eddies with large spatial scales, which can be seen with approximately the same spatial structures. These structures that continue to exist considerably longer than their turn-over time scale, are considered as coherent structures. The fluctuations of turbulent flows in time and space are proved not to be completely random and they are statistically correlated. [4]

Fluid motion in turbulent flows creates a large range of fluctuations which cause transport phenomena. Velocity fluctuations are considered as the sum of contributions due to anisotropy, acceleration fluctuations and stochastic forcing [5]. Anisotropy fluctuations vary from flow to flow; these fluctuations are affected by body forces and
boundary effects. The underlying logic is that Navier-Stokes equations are isotropic and anisotropy enters only through boundary conditions and body forces. Large-scale turbulence structures demonstrate anisotropic structures arising from the interaction of flow and boundaries: they are geometry dependent [6].

The structure of small scales in turbulence is considered to be universal and independent of the boundary layer; hence, they have isotropic structure arising from equations of motion. This is the general idea of Kolmogorov’s first similarity hypothesis. Kolmogorov’s first similarity hypothesis states that in every turbulent flow at sufficiently high Reynolds number, the statistics of small-scale motions have a universal form [7]. These small-scale eddies are dependent on the rate of energy that they receive from larger scales, approximately equal to the rate of dissipation $\varepsilon$, and the viscous dissipation, that is related to the kinematic viscosity $v$ [6].

The Kolmogorov theory describes that the turbulence consists of eddies with different sizes, and it describes how energy is transferred from large scales to smaller scales. The largest scales in turbulence are defined by the scale of the flow and the boundary creating instabilities in the flow field while the smallest scales are defined by molecular scales and molecular mean free pathways. Based on the energy spectrum of turbulent flows, the energy decreases at higher wave numbers, most of the energy is stored at large eddies or lower wave numbers. Eddies with the largest sizes are characterized by $l_0$, and this length scale can be compared with the integral length scale $L$. Integral scale can be considered as the spatial scale over which the velocities are correlated. 

"$l_0$" can be derived from the following equation [4] [8]:

$$l_0 \propto \frac{k^{3/2}}{\varepsilon}$$  \hspace{1cm} (2.3)

where $k$ is the kinetic energy and $\varepsilon$ is the dissipation rate.

Here the turbulent kinetic energy is defined as:

$$k = \frac{1}{2} \langle u_i' u_i' \rangle = \frac{1}{2} (\overline{u'^2} + \overline{v'^2} + \overline{w'^2})$$  \hspace{1cm} (2.4)

Large eddies are unstable and they are vulnerable to break down to smaller scale eddies and transfer their energy to them. At this scale, eddies are generated by mechanisms such as external forces and they break down by inviscid mechanisms. Breakdown of large eddies leads to the picture of the energy cascade, which continues until the molecular viscosity...
is sufficient in dissipating their kinetic energy. At this point, the molecular viscosity converts the energy of the eddies to heat.

Shear stress in the flow causes dissipation of energy which means that dissipation of energy is more at the locations where the instantaneous gradient of velocity is higher. Consequently, in turbulent flows, dissipation of energy is concentrated in eddies with smaller scales. In the reverse process of energy cascade, smaller eddies converting to larger eddies is also possible, but it is not statistically significant in three-dimensional turbulence.

Dissipation of eddies by viscous forces happens at the smallest scales in the flow. Therefore, in the smallest scales, it can be assumed that the convection and viscous forces are balanced. If the basic incompressible, Newtonian Navier-Stokes equation is considered, equation (2.5). $\nu, \eta, \tau$ are considered as smallest velocity scale, length scale, and time scale, respectively.

$$\left(\frac{\partial u}{\partial t} + u \cdot \nabla u\right) = -\frac{1}{\rho} \nabla P + \nu \nabla^2 u \tag{2.5}$$

$$u \cdot \nabla u \approx u_\eta^2/\eta \tag{2.6}$$

$$\nu \nabla^2 u \approx \nu u_\eta/\eta^2 \tag{2.7}$$

Assuming that the left hand side of equation (2.6) is equal to the left hand side of equation (2.7), we can conclude that:

$$\frac{u_\eta \eta}{\nu} = Re_\eta = 1 \tag{2.8}$$

The smallest length, velocity, and time scales in the turbulent flow are called Kolmogorov microscales, which can be defined by the following equations:

$$\eta \equiv \left(\frac{\nu^3}{\varepsilon}\right)^{1/4} \tag{2.9}$$

$$u_\eta \equiv (\varepsilon \nu)^{1/4} \tag{2.10}$$

$$\tau_\eta \equiv (\nu/\varepsilon)^{1/2} \tag{2.11}$$

The difference between Kolmogorov scales and integral scale increases by increasing the Reynolds number. Taylor scale lies between the integral scale and Kolmogorov scales is an indication of where the flow structures shift from isotropic to anisotropic or vice versa. In the inertial range, energy is transferred to smaller scale eddies by non-linear interactions. Since energy is dissipated, the amount of energy transferred at this scale is
equal to the amount of energy generated and it is equal to dissipation rate which can be expressed by the following equation:

$$\varepsilon_I \approx \frac{u_0^2}{l_0/u_0} = \frac{u_0^3}{l_0}$$  \hspace{1cm} (2.12)

Knowing the value of Reynolds number for the smallest scale and considering equation (2.12), we can find the ratio of smallest scale and largest scale in the flow as a function of large scales Reynolds number [4]:

$$\eta \approx Re_L^{-3/4}$$  \hspace{1cm} (2.13)

In conclusion, a large range of scales are embedded in the turbulent flows and this range will increase by increasing the Reynolds number. Largest scales, or integral scales, are generated by external effects such as boundaries, so they depend on the geometry and environment. Consequently, these large eddies cannot be universal and differ from one turbulent flow to another. The energy of these large eddies is transferred to smaller eddies and this energy transfer of energy continues until they are small enough to be dissipated by the viscous forces. At this scale, the kinetic energy of flow is dissipated by the molecular forces and it is converted to heat energy. This is the smallest scale known as Kolmogorov scale. In this scale, the flow patterns are known to be isotropic and defined by two unique parameters of $\nu$, $\varepsilon$.

### 2.3 Current Understanding of WSS in Turbulent Flows

For understanding the behaviour of the turbulent boundary layer (TBL) flow should be analyzed in the smallest scales in both experimental measurements and numerical simulations. A flow with Zero Pressure Gradient (ZPG) on a flat plate is considered as benchmark and there have been experimental and numerical attempts to understand the structure of these TBL flows. Despite advances in experimental methods, the accuracy of these methods is not enough for representing turbulence in smallest scales. Moreover, the measured flows in these experiments cannot be considered as fully ZPG. [9]

In recent decades, there have been noticeable advances in simulating ZPG TBL down to the smallest scales using direct numerical simulation (DNS). DNS is a type of
simulation in computational fluid dynamics in which the Navier-Stokes equations are numerically solved without any turbulence model. This means that the whole range of spatial and temporal scales of the turbulence must be resolved. All the spatial scales of the turbulence must be resolved in the computational mesh, from the smallest dissipative scales, Kolmogorov microscale [10]. Therefore, the computational effort is high for this approach, and it is not commonly used for engineering problems. However, this method provides us with valuable information in fundamental research in turbulence.

DNS has gained high reliability and also consistency with experimental results for the case of channel flows. As a result, it has been considered as a reliable source for turbulent structures in ZPG flow on a flat plate. However, a study by Schlatter et al. 2010 [9] which has reviewed the published DNS results for ZPG TBL, reports large differences in the results of different simulations using different approaches.

This study compares the results from seven different sources and compares the skin friction coefficient and fluctuating magnitude of WSS. Results were compared with the empirical 1/7-power law using the equation of $C_f = 0.024 \text{Re}_\theta^{-1/4}$ with 5% tolerance. The outcomes are not completely coherent; while some of them obey the 1/7-power law quite well others do not. Differences of more than 15% in skin friction value at the same Reynolds numbers can be seen in results from different studies. Furthermore, the rate of change of skin friction with respect to the Reynolds number varies. [9]

The other parameter which is analyzed in this study is the reported RMS value of WSS. Results are quite close to each other in three of those seven studies, but the deviation in the other studies is more obvious. These three studies offer the equation of $\tau_{w,rms}^+ = 0.298 + 0.018 \ln(\text{Re}_\tau)$, which quite agrees with the results which were reported by the experimental study by Alfredsson et al. [11]. Although these three studies agree with one another and with reported experimental results, deviations in the reported results of the other studies show that the DNS results are still questionable and should be verified. Here $\tau_{w,rms}^+$ is defined as:

$$\tau_{w,rms}^+ = \frac{\tau_{w,rms}'}{\overline{\tau}_w} = \lim_{y \to 0} \frac{u'}{U}$$

(2.14)

In addition, in an experimental study by Colella et al. [12], wall-mounted hot films were used for measuring WSS and it was shown that the RMS value of $\tau_{w}^+$ was decreased
by increasing the Reynolds value. However, in the numerical studies by Örlü [13], the RMS value of $\tau_w^+$ was clearly increasing with increase in the Reynolds number. This contradiction shows that besides the numerical methods, experimental techniques cannot yet accurately measure the fluctuations of the WSS.

Örlü [13] tried to clarify the previous contradictions on the WSS RMS value in ZPG flows. Based on the results of their simulations, RMS value of $\tau_w^+$, decreases by increasing the probe length. This value was decreased from 0.42 to 0.3 when the length was increased from $4L^+$ to $60L^+$, at $Re_0= 3969$. This work further shows that $\tau_w^+$ increases slightly with increase of the Reynolds number. This study and other experimental studies show that the RMS value of $\tau_w^+$ is about 0.4 for the smallest probe length used [11] [13].

2.4 Methods of Measuring WSS

Several methods have been proposed and established for measuring WSS. Also, microfabrication technology has facilitated construction of smaller and more precise sensors [14]. In this section, we are going to discuss some of the main developed sensor technologies for measuring WSS: micropillar sensors, floating-element probes, electrochemical sensors, and thermal sensors. Some of the less common methods will be quickly described at the end of this section. Finally, an overview of the characteristics of different sensors will be given to make a conclusion on the current capability for measuring turbulent WSS fluctuations.

2.4.1 Micropillar

MicroPillar Shear-Stress Sensor (MPS$^3$), has a good ability to measure the two-directional dynamic wall-shear stress distribution [15]. The MPS$^3$ is based on cylindrical microstructures positioned on the wall, a schematic of the concept is presented in Figure 2.2. The micropillars are exposed to the fluid motions which cause them to bend depending on the WSS value. Hence, the measurement technique belongs to the indirect group of measurement techniques since the WSS is obtained from the relation between velocity profile and the local surface friction [16].
The pillars are usually manufactured with diameter of microns, using the elastomer polydimethylsiloxane (PDMS, Dow Corning Sylgard 184). They are flexible enough to be deflected by the fluid forces and ensure a high sensitivity of the sensor [15]. Brücker et al. [17] proposed using sensor films with arrays of flexible micropillars for sensing the WSS by their bending in the flow. This method uses standard optical imaging and image processing techniques and can provide the tip displacements simultaneously over all sensing elements.

Figure 2.2 Schematic of the micropillar WSS sensor. Adapted from Brücker et al. [17].

Calibration of micropillars is necessary for a reliable and accurate measurement. A static calibration is necessary to correlate the deflection of the micropillars with the local WSS. The sensor is placed in a Couette flow where the sensor is exposed to a known linear velocity profile. Consequently, the sensor length should be limited to the thickness of the viscous sub-layer when being used in turbulent flows. In other words, the sensor should be exposed to a linear velocity in practical applications since it has been calibrated in a linear flow. [16]

The dynamic calibration by magnetically exciting the sensor structure is another concept that is proposed by Brücker et al. [17]. Since the MPS$^3$ itself is not magnetic, a permanent magnet is attached to the pillar tip. An electromagnetic coil with a ferrite core is used to excite the pillars harmonically. The response of the micropillar to the excitation function is recorded at an adequate temporal resolution with a high magnification optical system. The input function, which is necessary to determine the pillar behavior, is
determined by measuring the magnetic field strength simultaneously with the pillar reaction.

**Advantages and disadvantages:** Firstly, due to the cylindrical geometry of this sensor, it is equally sensitive to both wall-parallel WSS components and does not suffer from cross-axis sensitivity. Consequently, the micropillar deflection can be considered to be representative of the exerted forces in magnitude and angular orientations. [16]

The main limitation of this sensor is that it can work only in limited Reynolds numbers in turbulent flows. First, as the Reynolds number increases, the thickness of viscous sublayer decreases. Our measurements of micropillar sensors can only be accurate when the sensor is still in the viscous region of flow. Thus, the sensor can work in a range of Reynolds number in which the viscous sublayer thickness is greater than pillar’s height.

Secondly, if the Reynolds number \( \text{Re}_{D_p} \) reaches a certain level, Stokes or Oseen flow around the structure can no longer be assumed and a detachment of the flow field on the sensor causes additional differential pressure force contributions on the sensor structure, as shown in Figure 2.3. Since typical Reynolds numbers are \( \text{Re}_{D_p} < 1 \), the Stokes condition can be assumed valid such that the flow field should symmetrically follow the pillar contour allowing us to determine the total drag forces exerted by the local flow field around the sensor structure. [15]

![Figure 2.3](image)

(a) \( \text{Re}_{D_p} < 4 \)  
(b) \( \text{Re}_{D_p} = 4 \)  
(c) \( \text{Re}_{D_p} = 9 \)  
(d) \( \text{Re}_{D_p} = 13 \)

Figure 2.3 Two-dimensional flow field around a circular object. \( \text{Re}_{D_p} \) is the Reynolds number based on the diameter, \( D_p \), and the local velocity \( U \). At \( \text{Re}_{D_p} \geq 4 \) the flow detaches. Adapted from Grosse et al. [15].

Using this sensor in airflow can be misleading since the dynamic transfer function of the sensor structures shows a strong resonance due to low damping. The current results demonstrate that as long as frequencies of turbulent wall-shear stress fluctuations are below the eigenfrequency the measurements can be favorable. [17]
There are other sources of errors for these sensors including sensor misalignment; an offset between the sensor and the surface that it is mounted on. Besides, a non-parallel orientation of the sensor ‘chip’ and the surrounding surface causing a one-sided vertical misalignment is possible. Another cause of the error is yielding-induced drift; elastic materials tend to yield under constant stress causing the sensitivity of the sensor to change over time. It can be expected that changing mechanical properties and yielding would influence the mean WSS measurements [15]. Other sources of errors include dust contamination, sensor aging, sensitivity to acceleration, vibration and thermal expansion [18].

2.4.2 Floating-Element Probe

In floating-element probe, a measurable change in capacitance is created when the tethered top plate moves by an applied shear stress. A typical design of floating element shear stress sensor is illustrated in Figure 2.4. The structure of the sensor can be divided into three layers. The bottom of the structure is the substrate. The middle layer is sacrificed layer; the gap between the device layer and substrate. The top layer is the device layer; the floating element, tethers, fingers and anchors are all fabricated at this layer. [19]

When fluid flows over the top surface of the sensor, it exerts shear on the floating element sensor and tethers. As a result, the floating element with movable fingers moves along the fluid direction, while the fixed fingers do not move. This movement changes the capacitance between the fixed fingers and the movable fingers. Capacitance can be measured and calibrated by applying a known shear stress. [19]

Each tether is modeled as a fixed-guided beam, fixed at one end to the substrate and guided at the other end [20]. The principle of measuring the displacement of the floating element is based upon differential parallel plate capacitance measurements and it assumes that the displacement x is small compared to the initial gap. The motion of the floating element in the indicated direction increases one capacitance and correspondingly decreases the other.
Since the fabrication of these sensors is complicated, the majority of the research work is focused on different methods for enhancing fabrication and detecting the defects in the structure after fabrication. If the structure is fabricated without defects, when a DC voltage is applied to the sense fingers, there will be an electrostatic force in the gap between the adjacent fingers; then, the movable fingers can be attracted to the fixed fingers. This motion will be captured by the CCD camera and showed on the screen obviously. If the motion is not obtained from the screen, there exist defects in the structure. The applied load is not only limited to DC voltage; if AC voltage is loaded, whether the floating element can move dynamically is an indicator for judgment. [19]

**Advantages and Disadvantages:** One problem of these sensors is their large scale. A nominal sensor made by microfabrication technology has 500-μm floating-element size, 10 μm tether thick and width. [19] The width and the thickness of cantilever is 400 μm and 15 μm, respectively. This can be considered high in comparison with the length scales in high Reynolds turbulent flows which will lead to low spatial resolution.

After the device is fabricated, there might be some shortcomings inside the structure which cannot be observed by the naked eye. The stiction problem is incomplete release and the breakage of tethers, and it can lead to the invalidation of the sensor completely. Stiction includes two aspects: the adherence of adjacent sense fingers; and the adherence between the floating element and the substrate. [19]

The main source of measurement errors for floating-element shear stress sensors is related to the effect of pressure gradients around the floating element. Figure 2.5
illustrates the phenomena causing errors in the measurement. The use of a floating-element type sensing structure necessitates the presence of gaps around the element. The presence of gaps and cavities affect the sensor performance, but if the gap size is less than a few viscous length-scales, it will not noticeably disturb the flow. [19]

Figure 2.5 Schematic diagram illustrating the forces acting on the floating-element in a pressurized channel flow. $\tau_g =$ shear stress acting on the bottom face of the element, $\tau_w =$ shear stress acting on the upper face of the element, and $p =$ pressure acting on the cross section of the floating element. Adapted from H. Lv et al. [19].

### 2.4.3 Electrochemical (Electro-Diffusion) Sensor

The electrochemical method, also known as electro-diffusion method, is a non-intrusive technique used for the measurement of the local WSS. By solving the convection–diffusion equation in a steady regime without the axial diffusion term, a solution, the “Lévêque solution”, relating the limiting diffusion current and the wall shear rate was proposed for high Péclet numbers [21]. Figure 2.6 shows a configuration which was used to measure WSS by electro-diffusion probes. In the test, there are two parallel plate disks, one of them is fixed and the other is rotating. A servo-motor and its controller were used to generate oscillatory torsional flow between the two coaxial disks [21].

The reduction of ferricyanide ions on a platinum cathode is the most common electro-diffusion reaction [22]:
\[
\text{Fe(CN)}_6^{3-} + e^- \rightarrow \text{Fe(CN)}^{-4}
\]  

(2.15)

Figure 2.6 An example of experimental configuration for measurement with electro-diffusion sensor. Adapted from Böhm et al. [21].

**Advantages and disadvantages:** Electro-diffusion sensors have been successful in determining the mean velocity. These sensors have also been successful in determining the fluctuation of WSS [23]. Due to their small size, they are capable of measuring small-scale fluctuations. This is a great advantage when it comes to the measurements of the fluctuation of turbulent flows.

The main problem of electrochemical probes is their limitation to laboratory applications. These sensors are dependent on using ionic solutions and this fact makes their use for in-situ applications almost impossible. Another source of error in electrochemical sensors is their thermal sensitivity. Temperature can affect the reaction in these probes and add error to the measurements.

### 2.4.4 Thermal Sensor

Thermal flow sensors are based on the ability of fluid flows to affect thermal phenomena by the heat transfer. This heat transfer is transduced into a varying electrical signal which is the sensor response to flow change. Thermal sensors using Constant Temperature Anemometry (CTA) measure turbulent fluctuations by sensing the changes in heat transfer from a small, electrically heated sensing element exposed to the fluid motion. One may expect that their small size should allow high spatial resolution and frequency response, which would make them especially suitable for studying details in turbulent flows. Figure 2.7 shows a schematic of a conventional hot film sensor, consisting of a single-element hot film flush-mounted on a solid substrate. [14]
In thermal hot-wire sensors, a fast Wheatstone bridge circuit is used to maintain the sensor at constant temperature. As shown in Figure 2.8, by adjusting the voltage using the Wheatstone bridge, the electrical resistance of the probe is kept constant. Materials with high temperature coefficient of resistance (TCR) are chosen for the wire to obtain a stronger correction to deviation from constant temperature. Therefore, Wheatstone bridge is capable of keeping the temperature of the probe constant. The fast response of this sensor enables sensitivity to high frequency fluctuations. The overheat of the sensor, which is its temperature difference from the cold fluid, can be adjusted by varying the resistance of adjustable resistor, shown as R3 in Figure 2.8.

The same Wheatstone bridge circuit is used for flush-mounted hot film sensors. As the flow crosses the hot film, heat is transferred from the hot film to the flow. Since the heat
is generated from the current which goes through the hot film, the transferred heat can be measured by measuring the current. The rate of heat transfer through the sensor is related to the WSS by the following equation [14]:

\[ \tau_w \sim Q_f^3 \]  
Equation (2.16)

The underlying assumptions for the use of this relation for turbulent WSS measurement are that the thermal boundary layer is contained within the viscous sublayer, streamwise and spanwise diffusion are negligible and no heat conduction to the substrate occurs [14]. However, the heat transfer to the substrate can be considerable, specifically when the fluid’s density or the shear rate is low.

**Advantages and disadvantages:** Sensors made as single-element hot films flush-mounted with the wall have several characteristics desired from an ideal instantaneous WSS measurement in turbulent flows. Low thermal inertia of thin films allows a high-frequency response, they can be small in size to enable good spatial resolution, and they are insensitive to pressure variations and not prone to dust contamination or fouling. Thermal sensing using constant temperature anemometry (CTA) has provided a significant portion of the experimental data on which quantitative models in turbulence are based on by achievement of high spatial and temporal resolution and insensitivity to pressure fluctuations. [14]

However, thermal WSS sensors have sources of errors that considerably affect their performance. The main source of error of these sensors is the heat transfer to the substrate. Ideally, sensors should be thermally isolated from the wall, so only heat transfer to the flow can occur. However, there are other energy pathways, such as heat transfer through substrate, which result in thermal losses and degrade sensor performance.

There have been attempts to minimize the heat conduction to the substrate. In one method, as shown in Figure 2.9, the sensor consists of a polysilicon thin-film resistor on a silicon nitride or Parylene diaphragm that are suspended from the substrate by a vacuum or an air cavity. An electric current is passed (via aluminum metallization) through the resistor which functions as a hot wire. A vacuum or air cavity underneath the diaphragm is used to maximize thermal isolation [25]. However, the results from this sensor were not acceptable when it was tested in a wind tunnel under known shear rates. Problems
like a change in the flow pattern due to the cavity underneath the sensor, and fabrication difficulties are associated with this method. Therefore, development of this method did not continue.

![Diagram](image)

Figure 2.9 Schematic of a design that was used for minimizing the heat transfer to the substrate. Adapted from Lin et al. [25].

Using guard-heated sensors is one idea that has been proposed for reducing the errors in thermal sensors. The guard-heaters are thin films that are maintained at the same temperature as the sensor and they can be used around and beneath the main sensors. By this method, heat conduction to the substrate will tend to zero and the assumption of negligible axial heat transfer would become more realistic [26]. This is the main idea of WSS sensing section of this thesis and it will be discussed in more details in section 2.5.

Another concern is the sensitivity to ambient temperature and humidity. With constant shear stress, changes in temperatures and humidity will cause changes in the heat drawn from the film, which could spuriously be interpreted as fluctuations in WSS. At low temperatures, below 35 °C, the effect of humidity will be small since the amount of water vapor that the air can absorb is not significant. However, humidity change at higher temperatures can affect the heat transfer [27]. Measurement and correction of these quantities should therefore be considered.
Another limit on the sensor length is imposed by the assumption of negligible axial diffusion. The sensor must be larger than a certain value, depending on the fluid properties and shear strength, for the negligible axial diffusion assumption to be reasonable. In physical terms, because of the sudden change in temperature near the leading and trailing edges of the hot film, the neglected terms become significant and the heat transfer would be dominated by edge effects. [14]

### 2.4.5 Other Methods for Measuring WSS

Usually, it is not possible to measure the fluid velocity close enough to the wall to determine the WSS from the directly measured velocity gradient at the wall. However, some approaches have been used to obtain the WSS from velocity measurements very close to the wall. A common approach is to use mean velocity measurements at distances from the wall. The simplest application of this idea is when a well-defined region exists where the mean velocity is varying with the logarithm of distance from the wall. Law of wall argument suggests that in this region [28]:

\[
\frac{d\bar{U}}{dy} = \frac{u^*}{k_y}
\]  

(2.17)

Where \(u^* = \sqrt{\frac{\tau_w}{\rho}}\) is the friction velocity and \(k\) is the von Karman constant, which is usually taken as approximately equal to 0.40.

However, this method uses models for the average turbulent velocity to predict the average velocity gradient at the wall, and there is no accurate model for predicting instantaneous velocity at the wall using the velocity data further from the wall.

Using oil-film gage is another proposed method mostly used in aerodynamics applications. The behavior of the air layer very close to the surface of a body in the flow may be modeled by placing an oil film on the surface, which is blown back by the air flow. These can be related to the surface streamline pattern and the skin friction distribution. For visualization of surface flow, oil, often mixed with white powder, has frequently been used. When applied to the surface, the oil moves in the direction of the surface streamlines leaving streaks showing the streamline direction. Surface flow phenomena such as separation and reattachment lines and points can be clearly shown by this method. [29]
However, the oil-film gage is used for illustration of WSS and finding the pattern of WSS around an object. Since this method cannot respond fast to velocity variations, it can only be used for measuring the average WSS or variations in large time scales.

**2.4.6 Unresolved Problem of Sensing WSS Fluctuations**

As a summation of WSS measurement methods, all of the proposed methods for measuring WSS have serious limitations and sources of errors which make the exact measurement of WSS a challenging issue. These limitations become even more severe when it comes to measuring the fluctuations in turbulent flows. As mentioned, micropillars and floating element sensors are not accurate enough in terms of spatial and temporal resolution, also micropillars sensor is highly limited in terms of Reynolds number working range.

Electrochemical and thermal sensors demonstrate significantly better small-scale resolution, mostly due to their small sizes. However, electro-diffusion sensors are limited to specific applications under controlled condition, and thermal WSS sensors suffer from severe errors due to the heat transfer to the substrate. Hence, it can be argued that the technology of a reliable sensor for measuring WSS fluctuations in turbulent flows for engineering applications has not been developed yet, and needs more dedication and investment. Such a sensor can open up a wide range of engineering applications, specifically in aerodynamics and wind turbine industries. These applications will be discussed more in chapter 3.

**2.5 Idea of Guard-Heated Thermal WSS Sensor**

As discussed in the previous section, thermal WSS stress sensors have ideal characteristics for measuring small-scale fluctuations in turbulent flows; however, they suffer from a significant source of error which is the heat transfer to the substrate. Eliminating this source of error can be a milestone in sensing WSS in turbulent flows.

Guard-heaters are basically heated elements surrounding the sensor in the substrate region that are kept at the same temperature as the sensor. Guard-heaters can almost eradicate any heat transfer from the sensor to the substrate by forcing zero temperature gradient around the sensor using guard-heaters. A schematic of heat transfer from thermal
WSS sensor without guard heaters (single-element WSS sensor) and thermal WSS sensor with guard-heaters (guard-heated WSS sensor) is shown in Figure 2.10.

Figure 2.10  Illustration of a) single-element WSS sensor and its heat transfer to the surrounding, b) guard-heated WSS sensor and its heat transfer to the surrounding.

As seen in the Figure 2.10, heat from single-element WSS sensor transfers to both solid substrate and fluid flow while an accurate measure of the WSS signal need to be dependent only on the fluid flow. In this case, the measured current which goes through the sensor is a measure of heat transfer to both solid and fluid, and therefore, cannot be an accurate measure of the actual WSS. It is not straightforward to predict the amount of heat transfer to the substrate since the substrate temperature field is affected by fluid temperature and velocity.

In guard-heated design, the sensor is surrounded by guard-heaters maintained at the same temperature as the sensor by a separate bridge circuit, which makes a zero gradient temperature field around the sensor in the solid substrate. The heat transfer to the substrate occurs from the guard-heaters instead of the sensor. Because the sensor and guard-heaters are connected to separate electrical circuits, the current going through the sensor can be translated as the amount of heat transfer to the fluid only, and it can be an accurate measure of WSS. In this design, there should be an electrically isolating material between the sensor and guard-heaters to ensure that the current does not travel from sensor to the guard-heaters and vice versa.

Former studies have shown the better performance of guard-heated WSS sensors in capturing smaller temporal scales, but not in a velocity field representing the real-world condition. In a numerical study by Etrati et al. [2], guard heated thermal WSS sensor and
single element thermal WSS sensor were exposed to a sinusoidally varying linear velocity profile at different frequencies and the heat transfer responses were compared.

The results in this study [2] showed that the heat transfer response of the single-element sensor to velocity fluctuations dropped significantly at low frequencies while the guard-heated sensor was acceptably responsive at considerably higher frequencies, in the order of 10^5 times higher than the single element sensor. This is due to the fact that single-element heat transfer is highly affected by the substrate heat-transfer. In other words, for the single element sensor not only the sensor should be responsive to fluctuations, but also the substrate should be responsive since most of the heat transfer goes to the substrate when the working fluid is air.

However, when the working fluid was changed from air to water in this study [2], the frequency response of both sensors were considerably increased at the same Péclet number—Péclet number is defined as the ratio of advective heat transfer to diffusive heat transfer. When the working fluid changed from air to water, the limiting frequency of single element increased by about 10^5 times, and the limiting frequency of guard-heated sensor increased by about 10 times. It can be concluded that single-element sensors can still be used for sensing flow fluctuations if the working fluid has considerably higher density and thermal conductivity compared to air.

The aforementioned work [2] was limited to a simple linear velocity profile with sinusoidal variations in velocity profile. The amplitude of the shear rate variations was constant with a step by step variation in frequency. However, turbulence fluctuations are more complicated and they happen in a combination of different frequencies, different length scales, and different magnitudes. This makes the prediction or calculation of the actual heat transfer from the sensor more complicated. Consequently, to have a better evaluation of the performance of guard-heated WSS sensors used on a wind turbine blade, a simulation of the response of a sensor exposed to a velocity closer to real turbulence is needed.

The purpose of WSS sensor simulations in this work was to create a turbulence field with fluctuations of different scales and real-work phenomena like separation and intermittency. To achieve this, a 2-dimensional simulation of high velocity air flowing through a channel was simulated by large eddy simulation with a relatively fine mesh.
The resulted velocity field showed desirable behaviour with fluctuations over a wide range of frequencies and sudden kicks. The total heat transfer from both single element and guard-heated WSS sensor was calculated for a comprehensive comparison.

### 2.6 Possible Turbulence Simulation Approaches

Realm of CFD is extensively concerned with the numerical representation and computation of partial differential equations which govern the motion of fluids. This is divided into two main areas: the development of numerical methods, and then, the creation of algorithms to implement these methods. CFD generally offers three approaches for simulating turbulent flows: direct numerical simulation, large eddy simulation, and Reynolds averaged Navier-Stokes methods.

#### 2.6.1 Direct Numerical Simulations (DNS) Approach

DNS is a method which fully solves Navier-Stokes equations. By this method, full range of spatial and temporal scales of the turbulence are resolved from the smallest scales in which eddies start to dissipate, up to the integral scale $L$ [10]. Therefore, the memory storage requirement is very high and it grows significantly with increasing the Reynolds number.

In addition, the integration of the solution in time is done by an explicit method. This means that in order to be accurate the integration for most discretization methods must be done with a time step small enough that a fluid particle moves only a fraction of the mesh spacing, $h$, in each time step—or Courant number is less than one. Since the number of floating-point operations required for completing the simulation is proportional to the number of mesh points and the number of time steps, the number of operations grows as $Re^3$. [10]

Therefore, the computational cost of DNS is very high and it increases dramatically with the Reynolds number. For the Reynolds numbers encountered in most industrial applications, the computational resources required by a DNS would exceed the capacity of the most powerful computers. This type of simulation is mostly used for the fundamental research using simple geometries, such as flat plate, for better understanding of turbulence.


2.6.2 Reynolds Averaged Navier-Stokes (RANS) Approach

Engineering turbulent flows are usually computed using simpler averaged descriptions instead of resolving all length scales and time scales of the flow field. Approaches based on the Reynolds-Averaged Navier-Stokes (RANS) equations are the most common methods. These methods separate the chaotic turbulent fluctuation terms and use turbulent models for computing (estimating) them. Common approaches of modeling the Reynolds stresses term incorporate the Boussinesq hypothesis. Based on this hypothesis, the Reynolds stress tensor can be related to the mean strain tensor or the mean rate of deformation. [30]

The incompressible Navier-Stokes equations can be decomposed into mean and fluctuating quantities considering the components in all three directions [31]:

\[ u = \bar{u} + u' \]  \hspace{1cm} (2.18)
\[ v = \bar{v} + v' \]  \hspace{1cm} (2.19)
\[ w = \bar{w} + w' \]  \hspace{1cm} (2.20)

By substituting the decomposed velocity values into Navier-Stokes equations and averaging over the results considering the rules of time averaging, the tensor equation of the results would be [31]:

\[ \rho \frac{D\bar{u}_i}{Dt} = F_i - \frac{\partial P}{\partial x_i} + \mu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \rho \left( \frac{\partial u_i' u_j'}{\partial x_j} \right) \]  \hspace{1cm} (2.21)

The last term arises from the turbulent fluctuations terms and it can be written as [31]:

\[ \rho \left( \frac{\partial u_i' u_j'}{\partial x_j} \right) = \frac{\partial}{\partial x_j} \left[ \rho (u_i' u_j') \right] \]  \hspace{1cm} (2.22)

The right hand term in the bracket is called turbulent shear stress or Reynolds stress. By the Boussinesq hypothesis, this expression can be expressed as [31]:

\[ -\rho (u_i' u_j') = \rho \left[ \nu_T \left( \frac{\partial U_i}{\partial X_j} + \frac{\partial U_j}{\partial X_i} \right) - \frac{2}{3} k\delta_{ij} \right] \]  \hspace{1cm} (2.23)

Different RANS methods are mostly distinguished based on the model that they use for calculating turbulent kinematic viscosity, \( \nu_T \). These methods are categorized as zero-equation (algebraic closure), one-equation models, and two-equation models. The number of equations is actually the number of PDEs that must be solved for finding, \( \nu_T \). [32]
An example of a zero-equation model is the mixing length model, in which no PDE is solved for calculating the turbulent kinematic viscosity value. In this model, it is assumed that kinematic turbulent viscosity can be expressed as \( \nu_t = l_m^2 \left| \frac{\partial \bar{u}}{\partial y} \right| \), where \( l_m \) is the mixing length. This model is incapable of modeling flows with circulation and separation and it is rarely used nowadays.

In Spalart-Almaras model one conservation equation with convective and diffusive terms is solved for finding the kinematic turbulent viscosity. This method usually work relatively well for wall-bounded flows with mild separation and circulation. [33]

\( k-\varepsilon \) model is an example of two equations method. The total turbulent kinetic energy \( k \) is calculated as the mean kinetic energy and the instantaneous kinetic energy, and one equation is solved for \( \varepsilon \) as the rate of dissipation of the turbulent kinetic energy. \( k-\omega \) is another two equations model in which \( k \) is the turbulent kinetic energy and \( \omega \) is the specific dissipation that has the unit of time inverse. \( k-\omega \) model leads to more accurate results for the flow structures close to the wall; therefore, it is better to be used if the heat transfer from the wall is being simulated. These methods are valid for fully developed turbulence and they have poor predictions for flows with strong separation and swirling and rotating flows. [33]

In general, simulations using RANS methods are based on averaging over time, and consequently, they cannot capture the time-dependent turbulent fluctuations. These equations are generally used to obtain the mean value of the turbulent flows. Although these methods can also be used as unsteady in time-dependent flows while taking into account the variations overtime, this time dependency is regardless of the turbulent chaotic structures and they only take into account the variations in the mean properties. In other words, time steps that are resolved are significantly larger than the turbulence fluctuations time scales.

### 2.6.3 Large Eddy Simulations (LES) Approach

Besides DNS and RANS models, Large Eddy Simulation (LES) is intermediate in complexity between DNS and RANS. LES directly computes the large energy-containing scales while modeling the influence of the small scales using sub-grid scale (SGS) models [34]. Therefore, LES acts like a DNS model for scales larger than the grid size,
and it acts like RANS model for scales smaller than the grid size. In recent years, LES is receiving more attention in the wind energy wake simulations, because of its capability to handle unsteady, anisotropic turbulent flows dominated by large-scale structures and turbulent mixing.

This is a significant advantage over RANS methods, but the drawback is that the computational requirements for LES are considerably higher than for RANS, especially at higher Reynolds numbers. However, LES has the advantage of capturing turbulent fluctuating structures while the computational effort is much less than DNS method. Due to the fact that in LES sub-grid structures are modeled by SGS models, the results from the LES method are mesh dependent; the result get more accurate as the mesh gets finer.

Based on Kolmogorov theory, the small scale motions are isotropic and they are formed by the mean of energy cascade from the large scale motions; therefore, it was envisioned that small scales could be successfully approximated by turbulence models. Furthermore, large scales of motion contain most of the flow energy and are responsible for most of the transport phenomena. Moreover, larger scales are directly affected by the geometry and boundary conditions. As a result, modeling them regardless of the specific condition of the problem can result in significant errors. Consequently, Smagorinsky [35], structured the basis of LES method based on solving the larger scale of motions directly from Navier-Stokes equations and modeling smaller scales.

In LES method, eddies smaller than the grid are modeled with a subgrid-scale model, and the filter is usually applied by filtering scales smaller than cube root of cell volume multiplied by a coefficient. The SGS models are based on the assumption that the smallest eddies in the flow have relatively universal characters that does not depend on the flow geometry. The main criterion for SGS models is to be able to mimic the process of extracting energy from the resolved scales [36]. Mathematically, this scale separation is carried out by spatially filtering the velocity field, splitting it in a resolved (also called large-scale, simulated or filtered) velocity and an unresolved (small scale) part [32]. Different LES methods usually vary in the method that they use for modeling the sub-grid scales.

The Smagorinsky model is an algebraic LES model, which offers a straightforward method for filtering and calculating the sub-grid scales. In this model, it is assumed that
rate of dissipation of energy in sub-grid scales is equal to the rate of energy received from the larger scales, at all times. The Smagorinsky length scale is defined as, \( l_s = C_s \Delta \), where \( \Delta \) is the cube root of cell volume, and \( C_s \) is the Smagorinsky coefficient which is determined by isotropic turbulence decay and it ranges from 0.1 to 0.3 \([7], [37]\). Smagorinsky model implements the Boussinesq hypothesis in order to compute the turbulent viscosity values:

\[
\nu_t = (C_s \Delta)^2 \sqrt{2\bar{s}_{ij} \bar{s}_{ij}} = (C_s \Delta)^2 |S| \quad (2.24)
\]

\[
\bar{s}_{ij} = \frac{1}{2} \left( \frac{\partial \bar{u}_i}{\partial x_j} + \frac{\partial \bar{u}_j}{\partial x_i} \right) \quad (2.25)
\]

The equilibrium assumption in Smagorinsky model can lead to inaccurate results in cases that the equilibrium is not established; for example, turbulence impinging the leading edge of an airplane wing or turbulent flow with strong buoyancy effects. A more advanced Smagorinsky model (Dynamic Smagorinsky) has been proposed by Germano et al. \([38]\), in which the Smagorinsky coefficient is a function of space and time and the value can vary depending on the flow structure.

“One-equation model” is another LES method with differential SGS model, which is also based on the eddy viscosity, but it includes solving a transport equation for kinetic energy and dissipation rate in addition to the Smagorinsky model, equation 2.26. A study by Fureby et al. \([39]\), has shown the superiority of the one-equation models over the Algebraic methods for channel flows. However, the one-equation model assumes isotropy for the unresolved scales, which can be unrealistic. If the grid is not small enough, the modeled scales would still have anisotropic behavior \([7]\):

\[
\frac{\partial K}{\partial t} + \nabla \cdot (K \bar{u}) = \nabla \cdot [(v + v_{SGS}) \nabla K] - \varepsilon + \tau^r_{ij} \bar{s}_{ij} \quad (2.26)
\]

where \( \tau^r_{ij} \) is the anisotropic residual-stress tensor \([7]\):

\[
\tau^r_{ij} = \tau^r_{ij} - \frac{2}{3} k_r \delta_{ij} \quad (2.27)
\]

In this equation \( \tau^r_{ij} \) is the residual stress tensor.

\( v_{SGS} \) is the SGS eddy-viscosity and \( \varepsilon \) is the rate of dissipation which can be defined as:

\[
v_{SGS} = C_k K^{1/2} \Delta \quad (2.28)
\]

\[
\varepsilon = C_\varepsilon K^{3/2} / \Delta \quad (2.29)
\]
2.6.4 The Selected Approach for our Simulations

In this work, the purpose was simulating well-resolved velocity fluctuations and finding the temperature distribution and heat transfer in the velocity field. Therefore, RANS models could not be used due to the intrinsic time averaging approach of these models. DNS method was not use feasible due to the heavy computational cost and the limitations of time and computational resources. Finally, LES Smagorinsky model was chosen for approaching the problem in this work. Smagorinsky model was chosen because of requiring less computational effort compared to other LES methods like “dynamic Smagorinsky” and “one equation” models. Moreover, the fact that we are seeking for well-resolved fluctuations rather than accurate velocity distribution, for the specific geometry, makes Smagorinsky model more desirable.

2.7 The Intrinsic Conjugate Character of Thermal WSS Sensor Problem

In the case of thermal WSS sensor, if heat transfer from the thermal WSS sensor to the substrate is negligible compared to its heat transfer to the fluid, a single element sensor can be well responsive to the turbulent fluctuations and correlation between WSS and heat transfer can be approximated using the “Lévêque solution”. However, thermal WSS sensor exposed to the turbulent flow of low viscosity and conductivity fluid like air, cannot be isolated enough from the substrate in a manner that heat transfer to the solid is negligible compared to the heat transfer to the fluid. Therefore, heat transfer to the fluid happens from both sensor and substrate.

The coupled heat transfer, between the solid and the fluid, brings in complexities in experimental and numerical methods. In this condition, there exist different governing equations for the heat transfer in the solid region and heat transfer in the fluid region while these two regions interact with each other from the interface.

In the realm of CFD, problems including both solid and fluid equations with the two regions interacting with each other through the interface are inherently-coupled problems that are called conjugate problems. The Fluid Solid Interactions (FSI) and Conjugate Heat Transfer (CHT) are the most common examples of conjugate physics problems. In
these problems, governing physics are different at each region while they affect each other. There are two methods for solving these problems: monolithic and partitioned.

In the monolithic method, a solution in the universal domain is obtained by solving the governing equations within each domain and the interface equations simultaneously [40]. In this method, a single matrix of equations would be solved. The other approach is the partitioned approach where the flow and the structural equations are solved separately; this means that the flow does not change when the solution of the structural equations is calculated and inversely [41]. The solutions in the domains are related to each other at the interface with boundary conditions to satisfy the interface equations. Usually one boundary condition is applied to the solid region and the other is applied to the fluid region.

In the partitioned method, it is possible to use single interface iteration that is called staggered or loosely-coupled. However, a more reliable approach is to check for convergence within each time step that is called strongly-coupled approach. If the interaction between the regions at the interface is weak, the staggered method can be used. However, if the interaction at the interface is strong, the staggered method may not converge or lead to accurate results. [41] [42]

While using CFD, the time can be discretized using an implicit or an explicit method. In explicit method, the solution is obtained by solving each time step separately and there is no coupling between time steps. However, in the implicit method the equations at different time steps need to be solved simultaneously. In practical applications, implicit method is more prevalent since it can reduce the time step restrictions and facilitate the convergence. In conjugate problems, when implicit time discretization is used, Dirichlet condition is applied to one region and Neumann condition is applied to the other region to satisfy the interface equations. [43] [44]

In CHT, two conditions couple the fluid–solid interfaces: continuity of temperature and continuity of the heat flux. In 1997, Gils [45] applied a particular discretization and proved that the Dirichlet condition—continuity of the temperature—should apply to the fluid domain, and the Neumann condition—continuity of the heat flux—should be applied to the solid domain for better stability of the numerical method. Also, in this research Giles showed that critical time-step for the conjugate problem can be smaller
than the critical time step for sub-domains. This can depend on the relative sizes of the heat capacities and grid spacing.

To define interface condition of CHT problem, the interface is considered as a very thin layer while the thickness tends to zero. As a result, the heat capacity of the layer will tend to zero; hence, it cannot store any heat. Therefore, the continuity of energy would imply that the amount of energy going into the layer should be equal to the amount of energy going out from the layer, Figure 2.11.

\[
\text{Fluid} \quad \downarrow \quad \text{Solid}
\]

Figure 2.11 Illustration of the boundary condition at the solid-fluid interface for CHT problems.

Therefore, the following equation is implied:

\[
C = m \times c_p = \rho A dt \times c_p \xrightarrow{dt \to 0} C \to 0 \xrightarrow{c \to 0} Q_{in} = Q_{out}
\]  

(2.30)

Using heat transfer equations for fluid and solid we will have:

\[
k_s \frac{\partial T}{\partial y} \bigg|_s = k_f \frac{\partial T}{\partial y} \bigg|_f
\]  

(2.31)

Continuity of temperature imposes that there cannot be a sudden jump, or step, in the temperature. Consequently, an equal temperature in the solid and fluid at the interface is the boundary condition.

\[
T_f = T_s
\]  

(2.32)

In OpenFOAM the solver “chtMultiRegionSimpleFoam” is programmed for solving steady CHT problems and “chtMultiRegionFoam” is programed for solving unsteady CHT problems. These solvers use partitioned approach with strongly coupled method (using internal iterations). It is possible to define a specific turbulent simulation approach for each of the fluid regions within this solver.

In this work, first, the steady solver “chtMultiRegionSimpleFoam” with the LES Smagorinsky approach for the fluid flow was used for obtaining the developed temperature field in the solid region. This was done since the unsteady method would require considerable amount of time, with relative to the simulation time, to let the
temperature field develop in the solid region. Hence, steady solver was used to find the developed temperature distribution in the solid region in order to reduce the computational costs. Then, using the obtained temperature field for solid region, and using the same method, domain, and boundary conditions, the problem was solved by the unsteady solver “chtMultiRegionFoam”.

2.8 Details of the Computational Approach

In this work, flow of air through a channel with a step at the beginning of the channel was chosen to obtain the desired flow characteristics like fluctuations at different frequencies, separation, and instabilities. No slip (wall) condition was imposed at the bottom of the channel and slip wall condition was imposed at the top of the channel. As the WSS sensor necessitates, a substrate was considered underneath the fluid domain with the properties of the glass material. In the physical world, the sensor will be mounted on the substrate, but in the simulation world, the sensor was separated from the substrate by different boundary conditions and physical properties. Figure 2.12 shows the dimensions and geometry of the domain used for solving this problem.

![Figure 2.12 Dimensions of the simulation field (dimensions are not in scale, and the sensor and guard-heaters are exaggerated for better illustration).](image)

In wall bounded flows, the shear stress from the wall is the source of turbulence eddies and vorticities in the flows. The transition to turbulence can be initiated by perturbations in the flow regime. In reality, the perturbation is provided by the physical imperfections such as the surface roughness or vibrations. In the computational simulations, the aforementioned perturbation does not exist. In this case, the perturbation in the flow
velocity can be caused by numerical errors, e.g. truncation errors, and cause the initiation of transition. However, numerical errors are small which can significantly delay transition to turbulence and increase the computational cost of simulation. [36]

Adding structured vorticities is one method, which is commonly used in for faster transition to turbulence [36]. However, in this work, not only turbulent structures were favorable, but also the more complex structures over a large body like large airfoils were desired. As discussed in section 2.1, abundance of sudden events in the atmospheric turbulence and its interaction with the rotating wind turbine blades creates complex flows. Therefore, in these simulations, the perturbation from turbulent inlet velocity was combined with a step in the simulation domain to create various instabilities. The step in the domain creates larger vorticities which can be a representative of larger atmospheric fluctuation. This step also results in time-to-time flow separation over the sensor; this is desired since the sensor is aimed at detecting flow separation in practical applications on the wind turbine blades.

For generating the mesh, “blockMeshDict” tool form OpenFOAM software was used, and then “topoSetDict” was used for defining different regions (air, substrate, sensor, guard-heaters) in the simulations. “blockMeshDict” is a tool in OpenFOAM designed for creating parametric meshes with grading and curved edges. In this problem, hexahedron mesh was used all over the domain. In LES method, if the larger cells, farther from critical regions like walls and the edges, are considerably larger than the smaller cells in the domain, near the critical regions, small scales in the flow can be lost by using SGS models in the larger cells. Consequently, the accuracy in the whole domain can decrease and the small scales can be lost even near the walls where the cells are small. [36]

In this problem, the hexahedron was the most desired type of mesh at the sensor—very close to the wall—due to the structured geometry and considering the 2-dimensional problem. It should be noted that OpenFOAM uses 3-dimensional meshes even for 2-dimensional problems; the only difference is that only one cell is defined in the third direction. The structured geometry of hexahedron would result in better calculation of the velocity structures, velocity gradient, and temperature gradient very close to the wall. In this problem, since it was intended to limit the cell size growth farther from the sensor to
preserve the small-scale data, hexahedron mesh was used all over the domain to keep the grid structured and simple, and keep the grid size in the whole domain acceptably small.

In the “blockMeshDict” tool, the ratios in horizontal direction were varied in a way to get the finest mesh over the sensor and guard-heaters; also, to obtain a relatively fine mesh at the step and at the inlet. The ratios in the vertical directions were varied in a way to get the finest mesh at the walls. In addition, the variations were planned in a way to keep the length to width ratio (cell aspect ratio) for all of the cells in the domain less than 4 and larger than 0.25 to avoid numerical errors during integration over surfaces of the cells. The manner that the ratios were defined to achieve the aforementioned conditions can be found in “blockMeshDict” in Appendix B. The whole domain including all regions had 600,000 cells. The significantly low ratio of the sensor size to the domain size resulted in the increased number of cells.

Figure 2.13 shows the mesh in the substrate and fluid regions around the sensor and guard heaters. The two vertical black lines in the picture are the imaginary lines which separate the sensor from the in plane guard-heaters. In the real world, the black lines are electrical insulations, silicon oxide or silicon nitride, between the sensor and the guard-heaters. For the case of single element sensor, the mesh is the same. The only difference is that the guard-heaters are not defined and they are a part of solid region.

Figure 2.13 The mesh structure around the sensor and guard heats in substrate and fluid regions.

For the Boundary Conditions (BCs), solid regions needed only temperature BCs and the fluid region needed temperature, velocity, and pressure BCs. Figure 2.14 shows how the BCs were defined for the temperature for the case of guard-heated sensor.
For temperature BCs at the interface of solid and fluid, the boundary condition of “turbulentTemperatureCoupledBaffleMixed” has been used. This is a boundary condition for temperature, to be used for heat-transfer on back-to-back baffles without considering the radiation effects. OpenFOAM can emulate heat transfer across thin solid structures, or “baffles”. Baffles are represented as boundary patches of the mesh. Thermal conductivity is the only parameter that is needed to be defined for this BC.

Figure 2.15 shows the boundary conditions defined for velocity.
For the inlet velocity, “turbulentInlet” was used as the BC. This is an inlet condition, which generates a fluctuating inlet condition by adding a random component to a reference (mean) field.

\[ x_p = (1 - \alpha) x_p^{n-1} + \alpha (x_{\text{ref}} + C_{\text{RMS}} x_{\text{ref}}) \]  \hspace{1cm} (2.33)

- \( x_p \): Boundary values
- \( x_{\text{ref}} \): Reference value or the mean value of the boundary
- \( n \): Time level
- \( \alpha \): Fraction of new random component added to value at the previous time
- \( C_{\text{RMS}} \): RMS coefficient

In these simulations, \( \alpha \) and \( C_{\text{RMS}} \) were chosen as 0.2 and 0.1, respectively.

Pressure boundary condition was defined as zero gradients on all of the fluid region boundaries except for the outlet that was defined as constant value of 100 kPa.
Chapter 3

Evaluation of the Guard-Heated Thermal WSS Sensor in a Turbulent Flow Created by 2-Dimensional Large Eddy Simulation

Abstract

Wall mounted thermal films use the same idea of Constant Temperature Anemometry (CTA) to measure wall shear stress (WSS) at the wall. However, previous studies have proven the significant errors of the conventional single element WSS thermal sensors when used in air due to the considerable amount of heat transfer to the substrate. The idea of surrounding the thermal WSS sensor with hot films at the same temperature with the sensor has been proposed recently. These hot films are called guard-heaters, and they eradicate sensor’s heat transfer to the substrate by forcing zero gradient temperature in this region. A reliable thermal WSS sensor can be specifically advantageous for the feedback control system of wind turbines and fundamentals research in turbulence.

In this work, we have calculated the heat transfer of both single element and guard-heated WSS sensors exposed to a flow resembling real turbulence with instabilities obtained by 2-dimensional (2-D) Large Eddy Simulation (LES) of airflow in a channel. It is concluded that even at relatively high shear rate, the heat transfer to the substrate is about 6-7 times larger than the heat transfer to the air for the single element sensor which can cause significant errors in the WSS measurements. Moreover, it is shown that the response of single element sensor drops at high frequency fluctuations while this problem is solved by using guard-heaters.
3.1 Introduction

WSS is defined as the tangential element of the force that is exerted by the fluid on the solid substrate (wall) per unit of area. In turbulent flows, WSS fluctuates over a wide range of frequencies and length scales. Finding an appropriate method for sensing small-scale fluctuations of turbulent flows has always been a challenge. Most of the available methods are capable of measuring mean velocity and large fluctuations, but when it comes to the small-scale fluctuations, they have shortcomings like spatial averaging due to their large size and temporal averaging due to their slow response.

Using microscale hotwires (thermal anemometry) has been a successful method for sensing small-scale velocity fluctuations in turbulent flows. In this method, the heated element (sensor) is maintained at a constant temperature which is higher than the fluid’s temperature by using an electrical circuit (Wheatstone bridge). Any change in the velocity will lead to a change in the heat transfer coefficient, which will in turn change the heat transfer from the sensor to the environment. Since the sensor temperature is constant, any heat transfer from the sensor should be equal to the energy that is given to the sensor by the electrical current. As a result, by knowing the fluid properties, the fluid velocity can be correlated to the electrical current going through the sensor. By benefiting from the small size, low heat capacity, and fast responding electrical circuit, these sensors demonstrate the aptness for sensing small-scale variations. [46], [47]

Like hotwires for thermal anemometry, hot films mounted on the surfaces were considered as a reliable method for measuring the small-scale fluctuations of WSS. Using the same concept, hot films correlate the variations of heat transfer from the sensor to the variations of WSS; their main difference is that the hot films are mounted on the wall. However, studies have proved that using hot films is not a reliable method for sensing small-scale WSS variations, more so when it is used in air.

This unreliability stems from the fact that heat transfer from the sensor is not limited to the heat transfer to the fluid by convection, but a considerable portion of heat can be transferred to the solid substrate by conduction. Heat transfer to the substrate extends the effective heat transfer region to the fluid from the sensor to the whole heat affected zone in substrate; the heat affected zone can be hundreds times of the sensor size. The enlarged
heat transfer region has relatively large size and heat capacity which would result in low spatial and temporal resolutions.

In numerical studies by Meunier et al. [48], and Etrati et al. [2], hot films were exposed to varying velocity at different frequencies. It was shown that as the frequency increases, the sensor response to the fluctuations will considerably drop even at fairly low frequencies if the working fluid is air, even if the substrate material is glass which has relatively low thermal conductivity. Furthermore, in wind tunnel experiments done by Alfredsson et al. [11], for measuring WSS by thermal sensors, considerable differences between $\tau_{\text{w rms}}/\bar{\tau}_w$ values at the same Reynolds numbers was found.

Some researchers have tried to insulate the sensor from the substrate. Ruedi et al. [49], Lin et al. [25], and Yamagami et al. [50] tried to insulate the sensor by placing it on a diaphragm on a vacuum, but none of these studies analyzed the effect of heat transfer to the diaphragm. Ruedi et al. [49], shows that the insulated sensor has a higher frequency response compared to the conventional hot films. However, when the response was compared to the response of hot-wire of the same size, it was found that the frequency response dropped at lower frequencies compared to the hotwire.

Electro-chemical sensor, also called Electro-Diffusion Method (EDM), is another type of WSS sensor which has the potential of measuring small-scale WSS fluctuations. In this method, WSS causes reduction of ions on the cathode which will in turn cause a measureable current. Studies show the ability of these sensors to measure small-scale fluctuations with acceptable accuracy [22], [51]. However, application of these sensors is constrained to the research and laboratory applications due to the chemicals involved in the structure of this sensor.

As a result, all of the currently available WSS measuring methods have serious limitations when it comes to measuring small-scale fluctuations. A capable sensor in sensing small-scale WSS fluctuations can be a breakthrough in turbulence WSS measurements with various engineering applications e.g. aerospace engineering and renewable energies. Besides, a reliable sensor in sensing small-scale fluctuations can lead into a better understanding of WSS in turbulent flows. Precise measurements can be used by scientists for better modeling of turbulent boundary layers and verification of numerical methods.
3.2 Idea of Guard-Heated Thermal WSS Sensor

The general idea of using guard-heaters for thermal WSS sensor is covering the sensor with hot films at sensor’s temperature in the substrate in order to impose zero gradient temperature around the sensor. If this method is implemented correctly, all of the heat transfer from the sensor would be transferred to the fluid region, and the amount of heat transfer can be a more accurate representative of the WSS on the sensor. In this case, the heat energy transferred to the substrate is provided from the guard-heaters which are connected to a separate electrical circuit. Therefore, the heat travelling through the substrate would not affect the signal which is received from the sensor.

In the previous studies [2], [18] two approaches of guard heating were examined. In the first method, sensor was surrounded by guard-heaters just from the side, termed one-plane guard-heated (GH1P) sensor. In the second method, sensor was covered with guard-heaters from sides and underneath, termed two-plane guard-heated (G2HP) sensor. The results of the previous studies have showed that the GH1P is not an effective method in blocking the heat transfer to the substrate, and a sensor covered with guard-heaters just from the sides cannot be responsive to small scale fluctuations. Hence, only GH2P method is considered in this work. Both G1HP and G2HP are illustrated in the Figure 3.1.

Figure 3.1 Illustration of one-plane guard-heated sensor and two-plane guard-heated sensor.

3.3 Why Sense Small Scale Fluctuations?

As mentioned, a reliable sensor for measuring small-scale WSS fluctuations can open up a broad range of applications. One of the proposed applications is incorporating the sensor in aerodynamic control systems. These sensors can be installed on the
aerodynamic devices for sensing the WSS and providing their control system devices with valuable information [52].

This type of sensor can be specifically advantageous for wind turbine control system due to the significant effects of atmospheric turbulence on the wind turbines. The idea is using an array of small-scale WSS sensors, mostly at the positions that are vulnerable to flow separation. The data from an array of the sensors can be processed and be provided to the active control system of wind turbines to avoid separation and sudden load shocks on the blades more effectively.

Based on wind turbulence characteristics, intermittent fluctuations can have significant magnitude compared to the average relative velocity of the blade with respect to the air—these extreme fluctuations are called gusts. In other words, the probability density function (PDF) of velocity increments is heavy tailed rather than following Gaussian distribution due to the strong fluctuations found in atmospheric wind. [53], [54]

The fluctuating wind velocity can significantly change the load on the blades by resulting in flow separation on the blades due to the sudden velocity changes. The sudden changes not only cause changes to the electrical power output, but also can cause shock loading and fatigue for the wind turbine blades and powertrain. These can decrease the life span of turbine components, reducing cost competitiveness; in addition, accidents could lower public confidence, and reduce competitiveness with other commonly used power generation methods.

Studies show that the intermittent behaviour of atmospheric turbulence can be found in the load changes of the wind turbines. It has been shown in a study by Mücke et al. [55] that the load fluctuations on the wind turbine corresponds to the wind characteristics with extreme events; both distributions are heavy-tailed. The load on wind turbines demonstrate a dynamic behaviour stemming from turbulent behaviour of atmospheric wind. This relation exists even in short-time dynamics [56]. It is worth mentioning that the extreme events are usually not considered in standard algorithms for turbulence and it is necessary to consider higher moments to correctly reproduce the long-tailed PDF of wind turbulence [55].

The correlation between the wind PDF and load PDF suggests that sensing local fluctuations can provide us with crucial missing data for better comprehension of the
atmospheric wind turbulence and its relation to blade loading. Consequently, it is envisioned that measuring the small-scale local load can help us with prediction of the sudden load changes on the blades. Strategic locations of arrays of WSS and pressure sensors over a tiny fraction of the blade area would need to be determined in scaled down laboratory experiments. This can provide a signal to the control system to take preemptive boundary layer action to enhance the blade life span by reducing shock loads.

Furthermore, the complicated motion of the blades with respect to air makes it more complex to find the instantaneous relative velocity. In addition, in wind turbine farms the flow on the blades is affected by wakes that are generated by other turbines in the farm that additionally makes the calculation of the velocity at the blades complicated [57]. Therefore, sensing what happens on the surface of blades can significantly deepen our insight of flow characteristics on the blades, and help the scientists in computational simulations of the blades.

One may ask why sense at small length scales while the load on the blades arises from larger scale flow structures? In turbulence small scale fluctuations are not random and disorganized, although they may seem random at the first glance. Small-scale fluctuations are connected to the large-scale fluctuations by the means of the energy cascade. Even though it is not straightforward to find the correlation and predict larger scale structures based on the small-scale fluctuations, we know the correlation exists [4].

The idea is that data from an array of small-scale sensors and data from the load on the blades/turbine can be scrutinized to find the correlation between the load and the local fluctuations/trend of the small scale WSS. Considering the definite correlation between small-scale fluctuations and large-scale behaviour, and also the capability of these sensors to sense what happens on the surface of blades, it is expected to be able to find valuable data in small scale which will be a clue to large-scale separation and sudden shock on the blades.

Besides using WSS sensors for avoiding separation, coarse-grained data from these sensors can be used to store the history of sudden load shocks on the blades for maintenance purposes. Blades in a wind farm go through different load shocks based on their location in the farm and effects such as the wake flow of wind turbines upstream.
Therefore, tailoring blade maintenance and replacement plans based on the load history of each blade can significantly optimize the maintenance costs.

### 3.4 Computational Approach

In this work, the heat transfer from guard-heated and single element thermal WSS sensors exposed to a turbulence flow are calculated and the responsiveness to the WSS fluctuations is evaluated. To create the turbulent field, flow of air with an inlet velocity of 100 m/s in a channel with the total length of 0.0625 m with no slip boundary condition at the bottom wall and slip condition at the top wall is simulated with 2-D LES method.

Previous work [2] has investigated response to harmonic forcing and showed strong improvement in spatial resolution and in frequency response by using guard-heaters. Here we have worked with a time-varying velocity field with several characteristics of real turbulence. We know that turbulence is an inherently a 3-dimensional phenomenon. Since LES directly solves larger scales of turbulence by directly solving Navier-Stokes equations, 2-D LES simulations results in neglecting some real characteristics of turbulence. Reported by Rodi [58], 3-dimensional simulations does result in more reliable results compared to 2-D simulations.

However, 2-D simulations were capable of representing of the turbulence characteristics and fluctuations that are desired in our case. We sought the comparison between the shear stress evaluated from this velocity field, which resembles some characteristics of turbulence, and the computational analog of "measured" WSS by evaluating the heat transfer from the thermal sensor to this value. We compared the performance of the single-element and guard-heated sensors using this evaluation.

The simulations were carried out with OpenFOAM-2.4 open source software. Solver “chtMultiRegionFoam” was used to handle the conjugate heat transfer between solid and fluid regions. LES Smagorinsky approach was used as the turbulence model for the fluid region. Hexahedron mesh was used for the whole domain with the finest mesh size of 10×12.5 µm for the sensor and guard-heaters, and on top of them in the fluid region. Figure 3.2 shows the dimensions of the simulations field and the mesh around the sensor and guard heats.
A step was added to the beginning of the channel in the fluid region in order to create disturbance for triggering the turbulence on the plate. In addition, the step results in wake and instabilities which will lead into vorticities and separation further down the plane. The vorticities and separation are desired in this problem since the real application of the sensor is envisioned to be on the wind turbine blades where the flow is affected by atmosphere turbulence, flow of the air on the wind blades at different angles of attack, circular motion of the blades with respect to the air, wakes from other turbines, and etc.

To conduct the simulations in a fully-developed temperature condition in the solid region, first the steady-state simulations were carried on with the same boundary condition and simulations approaches. Using the results for the temperature distribution in the solid as the initial condition, the unsteady simulations were done for 4 ms and the results for $t=2$ ms to $t=4$ ms with a writing step of 2 µs were analyzed.

The calculated boundary layer thickness at the sensor was found to be 3.3 mm from steady state simulations, and the Reynolds number based on this boundary layer was $2.6 \times 10^4$. The critical Reynolds number based on the boundary layer thickness for the case of airflow on a flat plate with the same condition is $1.3 \times 10^4$. Therefore, the flow on top of the sensor is expected to be turbulent. Also, for airflow on a flat plate with the same condition and boundary layer thickness of 3.3 mm, the Kolmogorov length scale is found to be 1.8 µm. Therefore, the finest grid in the problem, above the sensor, is expected to resolve scales about 14 times larger than the Kolmogorov length scale.
3.5 Results and Discussion of the Simulations

In this work, single element and guard-heated thermal sensors were simulated. Here, the results of heat transfer for three cases are presented: 1. Total heat transfer from guard-heated sensor 2. Total heat transfer from single element sensor 3. Heat transfer from the single element sensor to the fluid region assuming that it is possible to separate the heat transfer to the fluid region from the heat transfer to the solid region. This case is called “quasi-ideal case” by the authors. The ideal case would be no heat transfer to the substrate; in the quasi-ideal case the heat transfer to the substrate exist, but it is assumed that it can be separated from heat transfer to the fluid. This assumption is not plausible, but this case is modeled for better understanding of the effect of the heat transfer to the substrate.

Figure 3.3 shows a sample of the streamwise velocity and the vorticity distribution in the fluid field, and the temperature distribution in the solid field at \( t = 2.8 \) ms for the guard-heated sensor case. Phenomenon like vorticities, wake and separation can be seen in the flow.

![Sample of streamwise velocity and vorticity distributions](image)

Figure 3.3 Sample of streamwise velocity and vorticity distributions for the fluid region and temperature distribution in the solid region at a specific time in the simulation domain. a) Streamwise velocity, unit= m/s b) Vorticity magnitude, unit=1/s

To evaluate the response of the sensor to the velocity fluctuations, first, the WSS over the sensor and the heat transfer from the sensor per unit depth are calculated and plotted
versus time. It should be noticed that the WSS is not exactly the same in the simulations for the single element sensor and guard-heated sensor, but they have the same general characteristics, trend, and behavior. The $\tau_{\text{w rms}}/\bar{\tau}_w$ value for the guard-heated sensor simulations was 0.9 while this value for the single element sensor was 0.86 over the 4 ms of simulations.

Thermal WSS sensors are blind to direction changes and only respond to the WSS magnitude. In other words, thermal WSS sensors cannot measure whether the WSS is in positive direction or negative direction. Therefore, if the reverse flow happens at the wall, the thermal WSS sensor cannot sense it. However, these sensors can potentially sense the transition to reverse flow (separation) by a drop in the heat transfer due to the drop in WSS magnitude. Figure 3.4 shows the WSS on the sensor and the WSS magnitude on the sensor for the case of guard-heated sensor for the analyzed time.

![WSS & Absolute Value of WSS for the Guard-Heated Sensor](image)

Figure 3.4 Comparison between the WSS on the sensor and the WSS magnitude on the sensor from the simulations for guard-heated sensor.

As a result, thermal WSS sensors are evaluated based on their response to WSS magnitude. Figure 3.5 shows the WSS magnitude on the sensor and the heat transfer from the sensor versus time. In these plots, whenever WSS magnitude curve reaches the absolute zero, a direction change happens in the flow.
Figure 3.5 The WSS magnitude and the heat transfer response of the sensors over time. a) The heat transfer of the single element sensor only to the fluid region, or quasi-ideal case. b) The total (real) heat transfer of the single element sensor to both fluid and solid regions. c) The total heat transfer of the guard-heated sensor. In these plots the heat transfer axis starts at zero and ends at the maximum heat transfer in order to illustrate the variations of heat transfer compared to the total heat transfer. $q'$ is the heat transfer from the sensor per unit of depth.
The trend of heat transfer from the single element sensor to the fluid region, Figure 3.5.a, corresponds well with the magnitude of WSS. However, in reality the signal received from the single element sensor is the total heat transfer, which is depicted in Figure 3.5.b. In this case, the total heat transfer is significantly larger than the heat transfer fluctuations due to the WSS fluctuations. The average heat transfer to the substrate is found to be 6-7 times larger than the average heat transfer to the fluid.

The total heat transfer from the single element sensor is much higher than the guard-heated sensor, but this heat transfer does not represent the heat that the fluid is picking up from the sensor. This heat transfer is the summation of the heat transfer to both regions which will finally be transferred to the fluid through the extended heat affected zone. In this case, the small portion of heat transfer to the fluid is faded in the larger portion of heat transfer to the solid.

Guard-heated thermal sensor demonstrates noticeable variations of heat transfer resulting from the WSS variations. In practice, the signal that we receive from this sensor is the heat that the fluid is picking up from the sensor, which is directly correlated to the WSS magnitude. It worth to notice that there is a sudden drop in heat transfer shortly after the WSS reaches absolute zero, in every instance. This fact potentially enables us to spot the local separations with guard-heated WSS sensor.

We know that if the ideal 2-D heat transfer with no heat conduction to the substrate is considered, the heat transfer and the WSS are correlated together by, $|\tau_w| \sim Q_f^3$. Since the conjugate heat transfer happens in our problem, we have used a third order curve with the equation of, $|\tau_w| = (A_1 + A_2Q)^3$ [59], to fit the WSS data to the heat transfer data. Afterwards, this curve is used as the regression curve to back calculate the WSS from the heat transfer response. Figure 3.6 shows the Power Spectral Density (PSD) of the real WSS magnitude calculated from the velocity field and the predicted WSS magnitude from the heat transfer response for both single element (total heat transfer) and guard heated sensors. In these plots, WSS magnitude and frequency are non-dimensionalized with the following equations:

$$\omega^* = \frac{\omega L_s^2}{\alpha_f} \quad (3.1)$$
\[ |\tau_w|* = \frac{2 |\tau_w|}{\rho_f U_0^2} \] (3.2)

Where \( L_s \) is the sensor’s length, \( \alpha_f \) is the fluid’s thermal diffusivity, \( \rho_f \) is the fluid’s density, and \( U_0 \) is the average fluid’s velocity outside of the boundary layer.

Figure 3.6 PSD of WSS magnitude in logarithmic scale as a function of frequency in logarithmic scale for a) single element sensor and b) guard-heated sensor. The blue lines show the real WSS magnitude calculated from simulations and the orange lines show the predicted WSS magnitude calculated from the heat transfer response and the regression curve equation.

Figure 3.6 shows that for the single element sensor, the high frequency WSS fluctuations are not represented well in the predicted WSS from heat transfer while these fluctuations are represented considerably better by the guard-heated sensor. This arises from the low frequency varying heat transfer to the solid region from the single element sensor. The added low frequency heat transfer decrease the effect of fast fluctuation. In other words, fast fluctuations are only represented in the heat transfer from the fluid
which is only a small portion of the total heat transfer. Therefore, due to the enlarged and slow responding heat transfer area, single element sensors suffer from low resolution in high frequencies, like most of the WSS measuring methods. The results from the simulations in this work, plotted in Figure 3.6, shows that this problem can be solved by using guard-heaters around the sensor.

Figure 3.7 shows the variations in the heat transfer of the single element sensor to both fluid region and solid region.

![Fluid Heat Transfer Vs. Substrate Heat Transfer of the Single Element Sensor](image)

Figure 3.7 Heat transfer to the fluid region and heat transfer to the solid region of the single element sensor as a function of time.

In Figure 3.7, points 1 and 1’, and points 2 and 2’ show the response of heat transfer to both regions, to a specific fluctuation. The heat transfer change is in the same direction for both regions; for example, an increase in the WSS magnitude will result in the increased heat transfer from the sensor to both regions. However, the heat transfer response of solid substrate has more delay (phase lag) compared to the heat transfer to the fluid region. Moreover, comparison between these points shows that this phase lag is not constant and can vary based on the condition. The superposition of the responses with different phase lags makes prediction of the real WSS more complicated and less accurate. Among ten heat transfer response that were compared together, the maximum
time difference between fluid response and solid response was 64 times higher than the smallest time scale in the flow (Kolmogorov time scale) and the minimum difference was 17 times higher than the Kolmogorov time scale while the average was 38 times higher than this time scale.

Points 3,4 in Figure 3.7 show the response of the heat transfer to the fluid due to the high frequency fluctuations of WSS, but there is no corresponding point in the heat transfer to the solid. These fast fluctuations are not sensed by the solid due to the temporal averaging which arises from the slow temporal response of the substrate. The temporal averaging in the solid substrate results in poor response of single element sensor at high frequencies which is illustrated in Figure 3.6.

One may argue that it might be possible to calculate the amount of heat transfer to the substrate, and then, subtract this amount from the total heat transfer from the sensor in order to find the net heat transfer to the fluid. Alternatively, one may argue that the variations in the heat transfer to the substrate are not significant and it would not drastically change the results. These arguments are implausible since the heat transfer to the substrate is not stable or insignificant, but it changes over time scales larger than the small turbulence fluctuations.

The low frequency (large time scale) fluctuations are not very well captured in the simulations in this work since the inlet velocity was defined as constant. However, such fluctuations are significant in real flows of interest e.g. the velocity far from wind turbine blades shows change over large time scales due to the nature of the wake and the change in the wind velocity. To find the heat transfer to the solid, we need to know the average velocity over larger time scales and its history. Moreover, since the heat transfer to the solid for the single element sensor is several times larger than the heat transfer to the fluid, small errors in calculation of the heat transfer to the substrate can lead to large errors in the calculation of the heat transfer to the fluid.

### 3.6 Conclusions

In this work, the advantages of guard-heated WSS sensors were explained and feasible applications of a reliable thermal sensor were argued. Then, the heat transfer from a single element and guard-heated WSS sensors exposed to a turbulent field were
calculated and compared together. For the particular case, we showed that the average heat transfer to the fluid region is less than one-sixth of the average heat transfer to the substrate which makes sensing small fluctuations implausible with the conventional single-element sensor. Also, we showed that the guard-heated WSS can measure changes in the flow direction by a stronger response in terms of the total heat transfer.

Moreover, the spectrum of measured WSS magnitude from heat transfer response of the sensors was compared to the PSD of the real WSS magnitude. The results show that for single element sensor we obtain unrealistically low measurements for the magnitude of high frequency fluctuations. The intensity of small scale fluctuations predicted by guard-heated sensor was more than 10 times closer to the real intensity compared to the single element sensor. As a result, we suggest that single element WSS sensors should not be used if the heat transfer to the substrate is significant. Moreover, using guard-heaters can solve the problems of single element sensors at high frequencies.
Chapter 4

Fabrication of Nanowires Using Electrodeposition in Polycarbonate Membranes

This chapter discusses the applications of single nanowires, and shows the significance of fabrication of a large quantity of single nanowires at low-cost. It also includes an overview of different methods of nanowire fabrication and discusses the advantages of electrodeposition in hard-templates. At the end, a review on the published results of nanowire growth in two different hard-templates is presented. Finally, the importance of separation of single nanowires from fabricated particles by electrodeposition in polycarbonate membranes is argued.

4.1 Applications of Nanowires

One application of nanowires relates to the applications of semiconductor nanowires. By the increased focus on microelectronics industry there is an increased demand on semiconductor nanowires. Among all semiconductor nanowires silicon is the best choice for this field since it has been used for electronic applications for many years and the technology has been well developed for this material. Fabrication of field effect transistors and device miniaturization are examples of the application of semiconductor nanowires in microelectronics. [60]

Nanowires can also be used as thermoelectrics. Thermoelectrics convert thermal energy to electrical energy and vice versa, since the process is reversible. Therefore, nanowires can be used for electricity generation and solid-state coolers. Bulk thermoelectrics
currently have limited applications due to low efficiency. In a study by Boukai et al. [61], a 100-fold improvement was reported compared to the bulk silicon thermoelectrics.

Moreover, fabrication of chained nanowires between predesigned gaps have applications in photovoltaic solar cells, light-emitting diodes, and liquid crystal displays. In a study by Sam et al. [62], a disordered suspension of nanowires was ordered by using external forces from controlled electric field gradients. This enables the fabrication of transparent electrodes for solar and display applications. In this study, rhodium nanowires were fabricated using aluminum oxide templates and the fabricated nanowires were chained between assembly electrodes with different gap sizes of 180 and 240 µm.

One of the most significant applications of nanowires, and the application that we are dealing with in this study, is their use as nanoresonators. Nanoresonators are sub-micron diameter structures that are clamped at one side or both ends and set into mechanical vibration around one of their chosen resonance frequencies. The extraordinary resolution of nanoresonators for detecting small mass and damping forces has led them to a wide range of applications in biomedical sensor research and sensors for small-scale flow studies. Nanoresonators have been reported to be able to detect mass in the order of yoctogram ($10^{-24}$ g) [63] [64].

In research by Sioss et al. [65], an array of hundreds of nanowires was successfully used for detection of a few base pairs of RNA, identified as prostate cancer biomarkers, from circulating tumor cells (CTCs). It is shown by biomedical studies that CTCs are released even in the early stage of cancers. Due to the small mass and high frequency of the nanoresonators, their resonance frequency can change measurably upon the addition of a small mass ($\sim 10^{-18}$ g) of specific biomarker molecules; hence, biomarkers can be detected by detecting the shift in the frequency [66] [67].

Besides all of the aforementioned applications for nanoresonators, the application that is particularly important to us is using nanoresonators as fluid mechanics sensors in the realm of rarefied gases environments [68], [69]. When using nanoresonators as mass detectors, the nanoresonator interaction with the fluid is considered as a problematic phenomenon due to the damping forces applied to the resonators by the fluid. In this regime, the inertia forces of fluids can be neglected in most of the cases and it is the drag force of the fluids which increases the damping of resonance. Increased damping will
decrease the quality factor of the nanoresonator, which will, in turn, decrease the accuracy of peak measurement.

However, the emphasis is on the capability of nanoresonators as sensors in various fluid mechanics applications, as proposed by Bhiladvala [63]. The high sensitivity of thin, long nanoresonators to the small masses and capability of them to measure small-added masses is proven, but when it comes to fluid mechanics applications, their sensitivity to the damping forces from the fluid becomes important. For this application, nanoresonators with known Q-factors at high vacuum (no fluid damping) should be used. It is known that the interaction of the nanoresonator with fluids will change the Q-factor and the resonance peak frequency. Accordingly, these two parameters can be measured and used to determine damping due to the fluid.

There are two conditions where nanoresonators can be used as a sensor in fluid mechanics application. One is measurements in Stokes flows where the viscous forces dominate the inertial forces, e.g. external oscillatory flows, fluid behaviour in high frequencies. The other one is in the transition regime of rarefication. In this case, nanoresonators can become specifically useful to provide data in this regime, where neither continuum fluid equations, nor the rarefied gas equations apply [63].

The wide range of nanowire applications makes their fabrication cost an important variable, as it will affect the cost of all of the devices and sensors that integrate nanowires in their structures. In addition, applications like using an array of nanowires for cancer detection and nanowire chaining for transparent electrodes demand a high quantity of nanowires, or low-cost and high-yield methods for fabrication of nanowires in large groups. Low-cost fabrication can make the aforementioned applications feasible for practical use.

Moreover, low-cost fabrication of nanowires can open up new potential applications to the continuously growing nanowires field to integrate nanowires into applications that are currently inhibited due to the costly fabrication methods. Finally, low-cost fabrication can facilitate research on the mechanical and electrical properties of nanowires, which will in turn provide us with more information about their behaviour, and properties.
4.2 Nanowire Fabrication Methods

Fabrication of nanowires and nanoresonators can be done using top-down or bottom-up methods. In top-down methods, nanoparticles are fabricated by etching into a bulk material to obtain the final desired shape. Focused-Ion Beam (FIB) and Electron-Beam Lithography (EBL) are top-down methods which can be used for fabricating nanostructures with controlled size of tens of nanometers. These methods have been quite successful and precise in creating nanostructures. [66]

However, there are serious problems associated with top-down methods that call for development alternative methods. First of all, using top-down methods demands using FIB and EBL machines for long times which results in high costs, since operating costs of these devices is high [66]. Moreover, particles fabricated by beam etching methods are left with residual thermal stresses in doubly-clamped beams or geometric distortion in cantilevered beams. These can be strongly disabling for sensor applications. [70]

The other category of nanostructure fabrication methods are bottom-up methods which include fabricating nanostructures from smaller particles and molecules, mostly by Chemical Vapor Deposition (CVD) means [71]. These methods do not demand etching by devices like EBL and FIB, and thus generally reduce the costs.

The electrodeposited material can be directed to the desired shape by using soft-templates or hard-templates. In soft-template growth methods, no physical template exists, but chemical components in a solvent are used to orient the deposited material [72] [73]. In hard-template growth, a physical template with the desired shape is used as the target for electrodeposited material [74], [75]. This template acts like a mold for the electrodeposited materials. After electrodeposition, the template is dissolved and the micro/nano particles are left in suspension.

The specific advantage of electrodeposition in hard-templates is the fact that it can be done at room temperature and pressure, without the high capital costs of CVD equipment and a cleanroom environment. Therefore, this method can be considered as a promising low-cost and high-volume nanofabrication method. The electrodeposition method also offers other advantages such as the capability of fabricating nanowires out of different materials by changing the electrodeposition materials in order to get the desired nanowire properties. Another capability of this method is the control over nanowires properties by
changing the electrodeposition parameters such as electrodeposition voltage or using additives [76].

4.3 Electrochemical Deposition in Hard Templates: Polycarbonate Templates versus AAO Templates

As it was mentioned previously, electrodeposition deposition into templates can be used for fabricating of nanowire structures at low cost. In general, the reduction of dissolved metal ions in electrolyte by changing their oxidation state using stimulus is what happens in the electrodeposition method. In this method, the target ion source is the electrolyte, and the target deposition site is the cathode, where the reduction reaction takes place. The reduction happens by using a stimulus such as an electric potential; the amount of deposited material can be controlled by controlling the stimulus. Electrochemical method is versatile and it can be done not only by metal, but also by semiconductors and conductive polymers such as oxides and phosphides. [77], [78]

In electrochemical synthesis a 3-dimensional template can be used as the cast for the deposited material, this technique is called template synthesis technique. For example, a template with nanowire shaped pores can help the reduced metal ions to get the shape of nanowires. A wide range of materials can be used as templates; porous Anodized Aluminum Oxide (AAO) templates and track-etched membranes are two of the most common templates. [76], [79]

4.3.1 AAO Templates

Porous AAO membranes are one of the common membranes with hexagonal shaped pores. When aluminum is anodized in an acidic environment, the aluminium can be etched in a porous structure with high porosity. These membranes are mostly used as filters, although they have been successfully used as nanowire electrodeposition membrane.

**Advantages and disadvantages:** These membranes are commercially available with very high pore densities as high as $10^{11}$ pore per square centimeter, which is a noticeable advantage for mass-production of nanowires. Moreover, the mechanical properties and chemical resistivity of these membranes is acceptable, better compared to polycarbonate
membranes. However, these templates are commercially fabricated in limited pore sizes. Pore sizes as small as 5 nm diameter have been reported by Martin [80]. In addition, the pores in these membranes are reported to be branched, non-uniform, and not straight. [79], [80]

### 4.3.2 Polycarbonate Templates

Track-etched membranes are the other types of membranes which are created by bombarding the desired template with fission fragments to create tracks in the template. Afterwards, these tracks are etched by chemical techniques to create the pores. Polycarbonate and polyester are the two most common commercially available track-etch membrane materials while other track-etch materials such as Teflon and polyethersulfone are also available. [76]

**Advantages and disadvantages:** These templates are commercially available in a wider range of pore sizes compared to the AAO materials. Moreover, these templates are reported to have uniform, cylindrical and straight pores. However, compared to AAO membranes, these membranes have a lower pore density, up to $10^9$ pores per square centimeter. Furthermore, the pores in track-etch membranes are not structured and generally not perpendicular to the membrane surface which usually results in the systematic connection of fabricated nanowires. [76], [79]

### 4.4 Need for Separation of Nanowires Grown in Polycarbonate Templates

In a study by Moghimian [76], both AAO and polycarbonate templates were used for electrodeposition of Rhodium nanowires and the results were compared together. In this study AAO membranes with two different pore sizes and polycarbonate track-etch membranes at five different pore sizes from different suppliers were used. In this study, the fabricated nanowires were mainly aimed to be used as nanoresonators. Due to the difficulties in resonator chip fabrication process, it is easier to use longer nanonanowires as nanoresonators; therefore, thicker membranes were used in this study.

Based on the results from this study, most of the pores in AAO membranes had a branched region used for filtration, but the branches were not limited to the branched
region of the membrane and they existed throughout the membrane with lower density. If these branches exist on the pores which are used for nanowire growth, the result would be nanowires with branches deviating from cylindrical shape.

In addition, this study found that non-uniform diameter is a frequent defect in nanowires deposited in AAO membranes. In general, AAO pores exhibit low cylindricity and nanowires with non-perfect shapes. Moreover, there is a deformed region in AAO membranes in which the pores are not perpendicular to the membrane, and these pores can result in nanowires with smaller lengths. Even if well-shaped and cylindrical nanowires are present in the batch fabricated by growth of nanowires in AAO membranes, it would not be feasible to separate them from other less cylindrical or branched nanowires. [76]

As mentioned, pores in polycarbonate membranes can be at different angles with respect to the membrane surface and they are mostly not perpendicular to the surface. The angled pores cause pore connections in the 3-dimensional structure of membrane which results in connected or clumped nanowires. The abundance of clumped nanowires in the fabricated batch of nanowires using polycarbonate templates, results in low yield of desired single nanowires. In addition, considering the lower pore density of polycarbonate membranes compared to AAO membranes, the quantity of fabricated single nanowires, in the same area of electrodeposition, using polycarbonate membranes would be considerably less than what we achieve by using AAO membranes. [76]

However, fabricated nanowires using polycarbonate membranes do not demonstrate issues like branching. For this reason, single nanowires coming out of polycarbonate membranes have a more uniform shape and better degree of cylindricity. The acceptable cylindricity makes nanowires fabricated by polycarbonate membranes more suitable for precise applications such as sensor applications. Moghimian [76], has used various AAO and polycarbonate membranes in his work and he has concluded that polycarbonate membranes are more suitable for fabricating nanowires for nanoresonator applications.

However, these cylindrical nanowires need to be separated from the fabricated batch for post-processing and being practically used for precise applications. Since the fabricated batch contains particles in various dimensions and geometries, separating single nanowires from this batch can be challenging. Figure 4.1 shows the nanowires
fabricated by AAO and polycarbonate membranes along with the clumped nanowires made by polycarbonate membranes [76].

Figure 4.1 Fabricated particles by using AAO and polycarbonate membranes. a) A typical nanowire fabricated using AAO membrane b) A typical nanowire fabricated using polycarbonate membrane c) An example of what is obtained from polycarbonate membrane before post processing and purification d) Clumped nanowires obtained from polycarbonate membranes from top view. Adapted from Moghimian [76].

To sum up, using AAO membranes can result in a higher quantity of nanowires and the resulting batch will be nanowires, no or fewer unwanted particles, but the quality and geometry of nanowires are less reliable. AAO membranes can be used when the geometry precision is not the first priority. For example, in the use of chained nanowires for making transparent electrodes, where the quantity is more important than the quality, AAO membranes have been used for fabrication of nanowires [62].
Polycarbonate membranes will result in lower quantity of nanowires, the resulting batch will contain a high volume of unwanted particles, mostly clumped nanowires, but the quality and the geometry of single nanowires is more consistent and reliable. Therefore, these membranes are more desired when reliability and precision is the priority.

Therefore, electrodeposition in polycarbonate templates can be a reasonable substitute for fabrication of nanowires using high-cost methods like EBL or FIB. However, separation of single nanowires from other particles fabricated in the membrane, particularly unwanted clumps, is needed to make this method a practical approach for fabrication of single nanowires. That being the case, in this thesis it is tried to propose the best method for extracting the single nanowires from the batch.

In Chapter 5 of this thesis, different possible methods for purification of single nanowires are discussed and the best method, with the focus of keeping the process at low-cost and time-efficient, is proposed. The final results show a significant increase in the ratio of single nanowires to clumps. As a result, the process of fabrication of Rhodium nanowires in polycarbonate templates proposed by Moghimian [76], combined with the single nanowire extraction process described in chapter 5 of this thesis, provides a comprehensive guideline for fabricating and extracting high quality single nanowires at low cost.
Chapter 5

Purification of Rhodium Nanowires Fabricated by Electrodeposition in Hard Templates: Analysis of the Sedimentation Behavior

Abstract

Electrodeposition in hard templates is a simple and low-cost method for fabrication of nanowires for nanosensor and nanoresonator applications. However, formation of clumps of nanowires can reduce the production yield and interfere with device fabrication. Therefore, post-processing steps for separating single nanowires from other particles is needed for their use in practical applications. In this article, the shape and size of all of the synthesized particles from electrodeposition of rhodium in polycarbonate templates are analyzed. An analytical method using a bi-disperse suspension model is proposed for analyzing sedimentation behavior of the particles falling in a vial. This is complemented by taking samples from the vial and measuring the distribution of particles in each sample. By uniting the analytical and experimental results, the combination of particles at different regions of the vial as a function of time is determined. It was found that it is possible to decrease the ratio of clumped particles to single nanowires from 0.77 initial ratio to 0.053 and to remove all of the huge clumps by the low-cost and straightforward sedimentation approach.
5.1 Introduction

Directed assembly is defined as organizing a disordered system and generating orientation-dependent field [81], [82]. In nanofabrication, the term “directed assembly” refers to a group of methods used for spatial and temporal control of fields for positioning arrays of particles onto their predetermined locations on the substrate [62], [83]. Directed assembly of single nanowires (NWs), using external fields on large-area chip devices at low cost has enabled new applications including detection of cancer at early stage in research lab scale [65] and study of fluid flows, e.g. Stokes flow, and different regimes of rarefication [63]. These applications require low-cost synthesis of a large number of uniform NWs. The template for electrodeposition may be chosen from a variety of porous materials such as commercially available track-etched polycarbonate or anodized aluminum oxide membranes [76], [80], [84], [85].

In the track-etching process [86], one ion creates one track, which in turn becomes one pore. Anodization of aluminum in an acidic solution causes the metal to etch in a fashion that leaves a porous structure. These pores have cylindrical shapes in a hexagonal array [79].

The disks of anodized alumina have higher pore density with pores aligned in the normal direction to the membrane disk plane [86], [87]. In the case of polycarbonate, most pores are angled with respect to the normal disk plane. Moreover, the polycarbonate membrane pores show a much higher degree of cylindricity [76].

Nanoresonator devices [63], [65], [81] which are made for studying rarefied gas dynamics and other fundamental fluid mechanics problems are well-served by template synthesis of straight cylindrical NWs. Polycarbonate membrane can provide the best quality of NWs for a nanomechanical resonator device. This choice enables fabrication of highly-cylindrical NWs for reliable resonance measurement and deduction of material mechanical properties [76]. Figure 5.1 shows samples of straight cylindrical nanowires obtained after dissolving the polycarbonate membrane. The nanowires are few microns different in length, but all of them are straight and uniform.
Figure 5.1 High quality cylindrical single NWs obtained from electrodeposition in polycarbonate membranes. Scale bar = 5 µm.

However, polycarbonate and anodized alumina templates each have one major problem associated with them. NWs grown in commercially made anodized alumina are branched and not perfect cylinders. Although there is a branched region known for filter purposes close to the membrane surface, there are other random branching and pore distortions throughout the membrane. The main problem with the polycarbonate membrane is that the numerous pore intersections make many groups of bundled NWs forming big clumps (see Figure 5.2). The presence of such NW clumps in batch of synthesized NWs has several disadvantages, e.g. interrupts the NW positioning on sensor devices.

Figure 5.2 (a) Top view of NWs after dissolving a polycarbonate template reveals pore angles. (b) Numerous large NW clumps formation confirms systematic pore connections. The inset shows a closer view of these pore connections. (c) Combination of different particles, including smaller clumps and single NWs, found in the solution after dissolving the template. Scale bars mark 2, 50 and 50 µm, respectively from left to right.

Although single NWs grown from polycarbonate membrane have much higher quality (no branching and better cylindricity), their fraction in a NW batch is much smaller than single NWs obtained from the anodized aluminum oxide membrane. Therefore, further
processes such as particle separation and purification (enrichment) methods are required for high yield NW resonator chip fabrication.

If a batch containing clumps is used for fabrication of nanoresonators, issues such as clamping of unwanted particles emerge. Figure 5.3 shows clumps that are clamped as nanoresonators when non-purified sample was used for directed assembly of nanoresonators.

![Figure 5.3 Clamping of clumps when non-purified samples where used for fabrication of nanoresonators. a) Clamped single nanowire with clamped clumps next to it b) Sample of undesired big clump clamped instead of single nanowires.](image)

There have been studies on purifying single NWs after fabrication since creation of unwanted products is a common problem in NWs fabrication. In a study by Akbulut et. al. [88], separation of gold nanorods from a batch containing NWs, small spherical particles, and larger particles was done by centrifugation in aqueous multiphase system. In other studies, copper and silver NWs were purified in multiphase aqueous solutions [89], [90]. Pradel et al. [91] separated Ag NWs from small particles by cross flow in hollow fiber micro filter.

However, none of the aforementioned researches have studied separation of NWs from the clumps, but they were focused on combination of NWs and smaller particles, mostly spherical. Furthermore, the previous studies were mostly dealing two or more distinguishable type of particles. In this case we are dealing with particles in different ranges, or a continuous variation of particles.
Using microfluidic channels is a common and well-developed method for separating particles with different sizes and densities. However, some characteristics of NWs batch—mixture of single and clumped NWs—make use of microfluidic channels complicated.

Existence of particles with wide range of sizes is the first issue. Dimensions of microfluidic channel have to be large enough to avoid blocking by bigger particles while large dimensions would decrease the accuracy of separation for smaller particles. Dimension requirements for some microfluidic channels are discussed in Ref [92]. The immediate possible solution to this problem can be using multi-step separation with channels at different sizes. However, the separation should be reliable to ensure separation of biggest particles in each step in order to avoid clogging in the next steps.

Low sphericity of particles is the other problem which decreases the effectiveness of separation by microfluidic channels. There exist effective methods like Deterministic Lateral Displacement (DLD) [93], [94], Pinched Flow Fractionation (PFF) [95], [96] and Hydrodynamic Separation [97], [98], for separating spherical particles with different sizes or different densities, but these methods become less efficient when the particles deviate from spherical shape.

The third problem is the difference in shape of particles with clumps at different width-to-length ratios. In other words, the microchannel should be efficient in separating various sizes and shapes. The final problem of these particles is their sharp edges which limits use of the PDMS as microfluidic channels’ material. If soft PDMS with low shear modulus [99] is used as the inner surface of microfluidics channels, sharp-edged particles may stick to the surface and ruin the channel, so it is necessary to use materials such as silicon in the microfluidic channel.

Considering the limitations of the microfluidic channels, it is reasonable to look for other possible alternative methods. Theoretically, it is known that particles with different sizes and densities sediment with different velocities. Thus, NWs batch containing particles with a wide range of sizes and densities would have considerably different ratio of clumped NWs to single NWs (clumped-to-single ratio) at different times and at different positions within the test tube. As a result, it would be advantageous to, first, know the population of particles with different sizes and densities in the solution, and
find the distribution of these particles at different times. As a result, we can find out what would be the quality of the best sample that can be obtained without bothering to use any microchannel.

5.2 Experimental

5.2.1 Experimental Method

Rhodium NWs were made in polycarbonate membranes (Sterlitech) with thickness of nominal 20 µm and 400 nm pore diameter. A commercial rhodium sulfate (Rh225D, Technic) with pH=1.1 was used. Electrodepositing was performed at -400 mV with respect to an Ag/AgCl reference electrode at room temperature (for a detailed synthesis protocol see [76]).

A test tube with 2 mm diameter was filled with a suspension of the particles in ethanol to the height of 3.2 cm. In this work, this height was considered as 4 regions, from top: three 1 cm regions which were called upper third, middle third, and lower third, respectively. The last 0.2 cm, at the lowest level, where the all the sediments settle, was called sediment region. In this article, the first 3 cm is considered as the working region and last 0.2 cm is excluded from the discussion. Particles, which have left the three upper regions, were gone to the 0.2 cm sedimentation region.

The experiment started with shaking the test tube containing the solution of NWs to have a homogeneous solution along the tube. To ensure that the final homogeneity of the solution was acceptable, a repeatable combination of shaking by hand and high frequency shaking, (42 kHz) with FS20H Ultrasonic Cleaner was used. The sedimentation process was started when the test tube was immobilized in its holder.

Samples from each of the aforesaid regions were taken after specific times; shaking process was done separately before taking each sample. Samples were poured on microscope glass slides and 5 min was given to the ethanol to dry. Then, the samples were analyzed under the microscope to find the number of the single NWs and clumps, structure of the clumps, and their shape and size. Both 2 µl and 0.8 µl samples were tried and there was no noticeable difference between the results.
5.2.2 Categorization of Particles Based on Experimental Results

First, particles’ shape was analyzed based on the pictures obtained from samples. Single NWs were almost cylinders with 0.4 μm diameter and 10 μm height, NWs with few micrometers more or less in height were observed as well. Most of the clumps formed rectangular cubes in a way that NWs’ length was the height of the cubes. For clumps, number of NWs in each particle, density (mass fraction of NWs) of the clumps, and their frontal area was analyzed.

Based on the pictures from the particles, dominant frontal area sizes were found and clumps were divided to 8 different types based on their frontal area—except group 3 and group 4 which have the same frontal areas and are divided based on their mass fraction. The grouping was based on the analysis of about 800 particles and results are given in the following table.

<table>
<thead>
<tr>
<th></th>
<th>Type1</th>
<th>Type2</th>
<th>Type3</th>
<th>Type4</th>
<th>Type5</th>
<th>Type6</th>
<th>Type7</th>
<th>Type8</th>
</tr>
</thead>
<tbody>
<tr>
<td>L × W (μm)</td>
<td>80×15</td>
<td>60×10</td>
<td>20×9</td>
<td>20×9</td>
<td>15×6</td>
<td>10×5</td>
<td>7×4</td>
<td>4×3</td>
</tr>
<tr>
<td>population</td>
<td>12</td>
<td>15</td>
<td>11</td>
<td>15</td>
<td>13</td>
<td>12</td>
<td>12</td>
<td>10</td>
</tr>
<tr>
<td>percentage</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>β (mass fraction)</td>
<td>0.57-</td>
<td>0.47-</td>
<td>0.43-</td>
<td>0.33-</td>
<td>0.23-</td>
<td>0.16-</td>
<td>0.13-</td>
<td>0.08-</td>
</tr>
<tr>
<td></td>
<td>0.85</td>
<td>0.58</td>
<td>0.50</td>
<td>0.42</td>
<td>0.29</td>
<td>0.23</td>
<td>0.18</td>
<td>0.16</td>
</tr>
<tr>
<td>$f_{shape}$</td>
<td>1.272</td>
<td>1.248</td>
<td>1.127</td>
<td>1.127</td>
<td>1.132</td>
<td>1.125</td>
<td>1.133</td>
<td>1.158</td>
</tr>
</tbody>
</table>

Table 5.1 Characteristics and population percentage of each type of clump. The third dimension for clumps is single NWs length which is considered the same for all clumps, 10 μm. Last row, $f_{shape}$, will be discussed later.

Clump mass is the number of counted single NWs in the clump multiplied by the mass of each single NW. The mass fraction of a clump is denoted by the constant $\alpha$ and it is defined as:

$$\beta = \frac{N_s M_s}{\rho_{Rh} V_b}$$  (5.1)

$V_b$ is the volume of a filled solid with the same dimensions.

Based on Table 5.1, for smaller clumps mass fraction, $\alpha$, is smaller which means there are fewer particles per unit volume in a clump. Given this, sedimentation of smaller clumps becomes considerably slower. Consequently, sedimentation of some small
clumps was even slower than the sedimentation of single NWs, although their frontal area was larger.

### 5.3 Sedimentation Theory and Model

The total force on each particle in the fluid can be expressed in terms of components as follows [100]:

\[ F_{\text{total},i} = F_{\text{GB},i} + F_{D,i} + F_{\text{Br},i} + F_{\text{vdw},i} \]  \hfill (5.2)

In this equation, only the vertical components of the forces are considered. \( F_{\text{GB},i} \), is the sum of the gravitational and buoyancy forces acting on particle and is equal to:

\[ F_{\text{GB},i} = (\rho_{\text{solid}} - \rho_{\text{fluid}})V_p g \]  \hfill (5.3)

\( V_p \) is the volume of fluid displaced by the particle.

\( F_{D,i} \) is the drag force on a particle due to its relative velocity with respect to the fluid. In order to find drag on the particles, they are considered as spherical particles and an equivalent diameter was calculated for each type of particle. The drag on non-spherical solid particles will also depend on the degree of sphericity, and their orientation to the flow [101]. These two parameters are taken into account by calculating the shape factor, \( f_{\text{shape}} \).

Equivalent radius, \( a_{eq} \), and shape factor, \( f_{\text{shape}} \), for a particle in creeping flow \( (Re_p \ll 1) \) was found based on Ref [101]. Details on how to find \( f_{\text{shape}} \) is discussed in Appendix A. \( f_{\text{shape}} \) for cylindrical single NWs was found to be 1.354 and \( f_{\text{shape}} \) for clumps is given in Table 1. The final effective diameter is equivalent diameter multiplied by the shape factor, \( a = a_{eq} f_{\text{shape}} \).

By computing the equivalent diameter for the particles, they can be treated as spherical particles. Reynolds number \( (Re) \) for particles in type 1, biggest particles, is about 0.2, and this number is considerably smaller for other types. As a result, it is valid to consider creeping flow around particles. Stokes approximation, for \( Re_p \ll 1 \), completely neglects the inertial terms in the Navier-Stokes equation and yields the drag force around a moving sphere based on the equation [102]:

\[ F_D = 6\pi a_{eq} \mu f U_{rel} \]  \hfill (5.4)
Oseen argues that the inertial terms are not negligible in the far field from particle where $\bar{x} = O(1/Re)$. So it makes an approximation for the inertia term and finally the drag for on a moving spherical particle would be found as [102]:

$$F_D = 6\pi\mu_f U_{rel}(1 + \frac{3}{8}Re_p)$$  \hspace{1cm} (5.5)

Both equations lead to the same result at very low $Re$, while at relatively higher $Re$, the Oseen approximation leads to more exact results. In this work, the Oseen approximation has been used for finding drag on particles.

A single particle falling in a fluid without the effect of walls would reach its terminal velocity when buoyancy, gravitational, and drag forces are balanced, $|F_{GB,i}| = |F_{D,i}|$. Micro particles accelerate from stationary position to their terminal velocity in a very short time at low $Re$. Hence, the initial acceleration of particles is not considered in our model. It was found that the biggest clumps reach 99 percent of their terminal velocity in less than 0.4 ms, and this time is less for smaller particles with lower $Re$.

$F_{Br,i}$ is the force associated with Brownian motion acting on the particles. The Brownian motion can cause sudden and random motions of solid particles due to their interaction with fluid molecules. The strength of this effect can be measured by Péclet number ($Pe$) in the context of mass transfer which is defined as the ratio of advective transport to the mass diffusion rate, and it can be written as:

$$Pe = \frac{U_0 a}{D}$$  \hspace{1cm} (5.6)

Where $U_0$ is the terminal velocity, and $D$ is the diffusion coefficient which can be written as [99]:

$$D = \frac{k_B T}{\gamma}$$  \hspace{1cm} (5.7)

$\gamma = 6\pi\mu a$, for a spherical particle and it is called the drag coefficient, and $k_B$ is the Boltzmann constant. By using Stokes approximation for finding terminal velocity and equation (5.6), we can find the $Pe$ number of a spherical particle falling by its terminal velocity as:

$$Pe = \frac{4\pi (\rho_{particle} - \rho_{fluid}) g a^4}{3k_B T}$$  \hspace{1cm} (5.8)
If $Pe >> 1$, the effect of Brownian motion on sedimentation is negligible. In our case, the Péclet number of single NWs is 32. Therefore, Péclet number can result in small effects in the sedimentation of nanowires. The Péclet number of clumps is considerably higher by the higher equivalent radius and the Brownian motion can be neglected for these particles.

Interaction of single NWs with fluid molecules can cause their displacements in the vertical direction and affect their sedimentation pace. The mean squared displacement of a particle by the Brownian motion in terms of elapsed time and diffusivity can be determined by the Stokes-Einstein equation [62], [103]:

$$|\Delta x|^2 = 2Dt$$

(5.9)

Brownian motion was considered in our model by a displacement with a random magnitude from a Gaussian distribution with mean squared value calculated from the equation (5.9) and mean value of zero. Average over all the single NWs considered in our model, the net displacement due to the Brownian motion was found to have less than 0.8% of the total displacement magnitude over 10 mins of sedimentation.

$F_{vdw,i}$, van der Waals forces, is the sum of the attractive or repulsive forces acting on the $i$th particle by other particles. The following equation represents the van der Waals forces acting on two spherical particles with radius $a$ which are separated by center-to-center distance $R$. $A_{PM}$ is the Hamaker constant of two particles in the specific medium. This force highly depends on the distance of particles from each other, and decreases dramatically by the decrease of dilution.

$$F_{vdw} = \frac{A_{PM}}{6} \left[ -\frac{2a^2 \cdot 2R}{(R^2 - 4a^2)^2} \cdot \frac{2a^2}{R^3} + \frac{8a^2}{(R^2 - 4a^2)R} \right]$$

(5.10)

In our case the solution was a dilute system where the volumetric ratio was found to be 0.623%; volumetric ratio is defined as the volume of a portion of the solution occupied by the particles to the total volume of the solution. The diluted solution will result in relatively small van der Waals forces, so this effect was neglected.

Besides aforementioned forces, when a particle falls in an assemblage of other particles, its flow field is affected by other particles. Consequently, its relative velocity is not only a function of its own velocity, but also depends on the field flow.
In this case, suspension was considered as a bidisperse suspension with two types of particles; single NWs and clumps. Characteristics of clumps were averaged between the existing clumps at each time in each region. Based on [102], [104] for a dilute bidisperse suspension the following equation can be used for finding the real terminal velocity:

\[ \langle U_i \rangle = U_{0,i} \left( 1 + \sum_{j=1}^{m} K_{ij} \phi_j + O(\phi_j) \right) \] (5.11)

Where \( U_{0,i} \) is the terminal velocity of \( i \)th particle when it is falling alone, \( K_{ij} \) is the dimensionless sedimentation coefficient, and \( \phi_j \) is the volumetric ratio of \( j \)th particle.

To find the velocity of a single nanowire:

1. The terminal velocity of a particle falling alone was found based on \( |F_{GB,i}| = |F_{D,i}| \).

2. To find the effect of clumps on the single NW, it was assumed that the ratio of the radius of clumps to the radius of single NWs is high, \( \frac{a_c}{a_s} \gg 1 \). Hence, Sedimentation of single NWs is affected by the velocity and pressure gradient induced by the motion of clumps and the following equation can be used [102], [104]:

\[ K_{ij} = -\gamma(\lambda^2 + 3\lambda + 1) + O(\lambda^{-1}) \] (5.12)

Where, \( \lambda = \frac{a_c}{a_s} \), and \( \gamma = \frac{\Delta \rho_c}{\Delta \rho_s} \).

3. The properties of the clumps was averaged in each time step in each region to find \( \lambda \), \( \gamma \), and \( \phi \).

4. To find the effect of other single NWs on a falling single NW, \( K_{ij} \) value for identical particles was used, \( K_{ij} = -5.62 \). [102]

To find the velocity of a clump:

1. The terminal velocity of a particle falling alone was found based on \( |F_{GB,i}| = |F_{D,i}| \).

2. To find the effect of single NWs on the clump, \( K_{ij} \) is considered as a component which increase the viscosity of the fluid since single NWs affect the velocity gradient around the clumps. Therefore [102]:

\[ K_{ij} = -\frac{5}{2} \gamma^{-1} + O(\lambda^{-1}) \] (5.13)

3. To find the effect of clumps on the clumps the data from averaging over clumps was used to find \( \phi \), and \( K_{ij} = -5.62 \) was used.
Based on the results from the numerical model, after a long time (about $t > 2$ hrs) no more particles should exist in the top third and middle third regions, and all of the particles should have settled at the sedimentation region while some of the particles may move up to the bottom region by the mean of Brownian movements. However, our experiments show that this is not the case and small number of particles will remain in the solution even after 2 hrs. This can be due to some strong kicks of the random Brownian motions, or some completely irregular shaped particles, which were not considered in this model. As a result, as the time passes and the concentration decreases, our model would become less accurate since it is not considering rare phenomenon. Therefore, the end time for simulations was defined as when the total number of particles in the specific region equals to three times of the number of particles at $t = 2$ hrs in that region, found by experiments.

5.4 Experimental and Numerical Results and Discussion

The experimental results showed the general enrichment of NWs as the time passes, up to a specific time for each region. The distribution of particles at different times was found by counting single and clumped NWs of samples of each region. Figure 5.4 shows a schematic of the experimental results. The initial ratio of particles in the solution was 0.77 and the minimum ratio found by the experimental measurements was 0.053, in the middle region at $t = 30$ min. This value shows the ability to remove all of the large clumps and decrease the number of smaller clumps by the factor of 14, or decrease their ratio to 5% of population by sedimentation method.

Figure 5.5 shows samples of distribution of particles at specific locations and times. Figure 5.5.a. can be considered as an approximate representative for the initial distribution of the particles. Figure 5.5.b. shows that even in the first 10 seconds, the distribution of particles within the container has considerably changed. The big clumps have large terminal velocities and a considerable number of them sediment even in the first few seconds. Figure 5.5.c. shows the amount of success that was gained in reducing the clumps in the sample by the sedimentation method. Although, a small portion of
particles with undesired shapes still exist in the sample, but it can be assured that all huge clumps are gone, and the ratio of single NWs to undesired particles is high.

Figure 5.4 A schematic of the distribution of particles in different regions after 3 different time intervals. ■ ■ ■, are representative of clumps and, / / /, are representative of single NWs. In the bottom of the container, length of the columns is a representative of the population of the particles. Container’s shape is not in scale.

Figure 5.5 (a) Distribution of particles in the middle of the container at $t = 10$ s (b) Distribution of particles in the sediments region at $t = 10$ s, (c) Distribution of particles in the middle of container at $t = 30$ min. Scale bar = 50 µm.
Figure 5.6 shows the estimated distribution of particles by numerical approach and experimental measurements, as a function of time. As it can be seen, the top third region does not have a stable minimum ratio. In the middle third, the stable minimum ratio is about 0.05 from 25 min to 40 min. At the lower third, a stable minimum ratio of 0.048 happens between 40 min to 60 min. Although the minimum ratios at the bottom and middle are close, the middle region is a better candidate due to less waiting time, and being farther from the sediments region, where most of the clumps are settled.

In general, the smaller time intervals are more desirable for taking samples. Firstly, our experimental measurements show that clumps-to-singles ratio at 2 hrs, is higher or comparable with the measured values at 30 min for all regions. Moreover, a big portion of particles which remain in the upper parts after a long time are undesired particles with irregular shapes. Furthermore, the numerical simulations suggest that all of the good single NWs should have settled in the sediments after about 80 mins.

In addition, as the time passes, the ratio of crushed NWs to single NWs would increase since the terminal velocity of crushed NWs is smaller than single ones and they are affected by the Brownian motion due to their smaller size. Although, crushed NWs are not as problematic as clumps, they are undesired. Also, as the time passes more particles sediment and the concentration of particles decreases which means that we less NWs can be gained per unit of volume. Finally, longer waiting times mean more waste of time; one way to decrease the waiting time is using centrifugal sedimentation instead of gravitational sedimentation.

To evaluate the repeatability of the measurements, taking samples from the middle at 3 min was chosen. To do this, the experimental procedure was done by 3 different operators, 4 times each. Figure 5.7 shows the results of the experiments. The results suggest that the variations between the operators are larger than the variations within the measurements of each operator. This is due to the fact that criteria for counting single NWs and clumps are different in the eye of each operator.
Figure 5.6 Results of the numerical approach along with experimental data: population and ratio of particles in the top third, the middle third and the lower third regions as a function of time.
In this work, an optimized time and region for taking samples with the highest ratio of single NWs was proposed, for this specific mixture. Changes in the method of fabrication of NWs may cause a change in the mixture and especially the concentration and the shape of the clumps. However, the theory shows that the effect of flow field created by the neighbouring particles is small and does not considerably change the sedimentation velocity. Hence, the recommended time and region may slightly differ by a different combination of the particles. However, it would not considerably change until the single NWs' shape and density remains the same, the dilution of the solution is less than 1% volumetric ratio, and the height of the solution in the container is the same. Furthermore, since the minimum ratio is stable during a wide range of time, taking samples at the middle of this time range would also be reliable.

5.5 Conclusions

Electrodeposition of metal NWs in hard templates will generally provide a mixture of high-quality single NWs and undesired clumped NWs. In this article, first, a mixture including single NWs and clumps was analyzed to determine shape and abundance of different particles in the NWs batch. These particles were categorized in 9 groups. Afterwards, sedimentation of particles from an initial homogeneous dilute solution in a test tube was analyzed experimentally and numerically in order to find the distribution of particles as a function of time.
Based on the experiment results, we found that the quality of mixture (singles-to-clumps ratio) in all the 3 regions at 30 min was considerably higher than the quality of mixture at 3 min and 10 sec. Also, we found that by the mean of sedimentation approach we can achieve a sample with no large clumps and reduce the clumps-to-singles ratio by over an order of magnitude. Based on the numerical results from this work, we recommend taking samples after 25 min to 40 min from the middle of the container for smallest clumps-to-singles ratio. The current method was a significant increase in the quality of the mixture by the simple method of the sedimentation of particles.
Chapter 6

Conclusions and Future Work

This work presents studies for two different sensors with applications in fluid flow and other measurements. It uses fluid mechanics knowledge in the realms of high Reynolds number turbulent flows and low Reynolds number Stokes flow. In the first study, evaluation of a new design for thermal sensors of turbulent WSS was presented. This work involved the creation of a numerical flow field with a range of fluctuation length and time scales as would be encountered in turbulent flows and analyzing the sensor’s response to these structures. In the other study, batches of nanoparticles produced by electrodeposition in polycarbonate membranes were considered, to develop a low-cost method for extracting high quality single nanowires from the batch by sedimentation. This study focused on the falling behavior of particles in low Reynolds numbers flow.

Earlier work has reported the limitations of conventional single-element thermal WSS; the limitations are severe in the case of measuring WSS fluctuations for fluids with low-conductivity, such as air. They stem mainly from the heat transfer to the substrate. Therefore, a reliable WSS sensor capable of measuring small scale fluctuations of turbulent flows is yet to be developed. Guard-heater films surrounding the sensor element, maintained at the same temperature by a separate circuit, can almost completely eliminate errors due to heat transfer from the sensor element through the substrate.

A capable and time-responsive WSS sensor can be specifically useful for the control system of wind turbines. Studies have proposed the similarity between the load on the wind turbines and the intermittent behavior of atmospheric turbulence in small scale. Therefore, measuring fluctuations at small scales can potentially help us to use this
correlation and avoid the flow separation on the blades. Additionally, a time-responsive WSS sensor can help us in better understanding of small scale structures of turbulence.

In this work, a flow resembling actual turbulent flow with separation was created by simulating the air flow in a channel with a step at the inlet. The heat transfer fluctuations of both single element and guard-heated sensors were then compared to the known WSS fluctuations to evaluate the responsiveness of these sensors.

It was shown that for the single element sensor, the average heat transfer to the solid was about six times the average direct heat transfer to the fluid, which results in significant errors in the WSS measurements due to spatial averaging and other mechanisms. Therefore, it was proposed that this sensor should not be used for measuring WSS fluctuations when the working fluid is air.

Our simulations showed that using guard-heaters can nearly eliminate the heat transfer from the sensing element to the substrate. It was shown that in this design the sensing element heat transfer is restricted to direct heat transfer to the fluid, directly related to the WSS magnitude above the sensor. In particular, it was shown that any transient direction change in the flow and WSS downstream of the step, was accompanied by a sudden drop in the heat transfer, which shows of the capability of this sensor for measuring local separation.

Afterwards, the fluctuation in the predicted WSS from the heat transfer response was compared to the real WSS obtained from the simulation velocity field. By comparing the power spectral density of the predicted WSS for both sensors, it was shown that the signal strength of the single element sensor drops significantly at high frequencies while the guard-heated sensor stays responsive to high frequency fluctuations.

For future work, it is recommended that both sensors types be numerically tested in a simulated three-dimensional (3D) turbulence field. Turbulence fluctuations are 3D and the errors in measurement of the streamwise component of the WSS due to spanwise fluctuations in the third dimension need to be accounted for.

Future work on the fabrication of guard-heated thermal WSS sensors will be shaped by these results. Single element sensors commercially available should not be used, particularly in air flows, but the guard-heated sensor should be developed as prototype. The developed guard-heated sensor can be compared with commercially available single
element sensors when exposed to a turbulent flow, e.g. in a wind tunnel. This work would be a practical evaluation of effectiveness of using guard-heating.

The other research study in this work presented an inexpensive method for separating single nanowires fabricated by electrodeposition in polycarbonate membranes, from the clumps and fragments also produced. Electrodeposition in hard templates is a promising method for fabricating high-quality cylindrical single nanowires. However, undesired particles produced along with single nanowires are the main drawback of this method.

The single nanowires fabricated by polycarbonate membranes have been analyzed in the previous studies, and their structure reliability and cylindricity have been proven. However, the practical feasibility of extracting the single nanowires that are mixed with other particles, have not been studied in detail before. In this study, different types of existing particles in the resulting batch were investigated by taking several samples, and they were categorized in different groups based on their shape and size by scrutinizing the samples taken from the batch.

The singles-to-clumps ratio of small sample volumes was analyzed numerically and experimentally, for sedimentation behaviour, after the sedimentation starts in an initially homogeneous mixture. In the numerical method, equations derived for bi-disperse mixtures were used to develop a model for the sedimentation of particles. The results demonstrated acceptable correspondence with the results of experiments with more than 40,000 particles counted in total.

Our findings from the analysis and experiments were that the largest clumps, which are the most disruptive, constitute a high volume fraction of all the particles; they fell considerably faster than other particles. None of these particles were observed in any of the samples that were taken from the middle third and the top third of the test tube after 3 mins.

To address reduction of the unwanted smaller clumps from our desired single NWs, we conclude that taking samples from the middle third of the test tube between 20 mins to 45 mins sedimentation time appears to be the best strategy examined. This time and region yields an optimal ‘clumps-to-singles ratio’. It was shown that it is possible to decrease the ‘clumps-to-singles ratio’ to 7% of its initial value. The fraction of clumps was then reduced to below 5% of the number of all particles.
This work facilitated low-cost enrichment of single nanowires for applications demanding high-quality nanowires, e.g. nanoresonators. It offers a low-cost method for high-quality and high-volume fabrication of nanowires by complementing previous research work, in which high-quality single nanowires were fabricated, but the process of enriching the fraction of suitable nanowires was not analyzed or experimentally investigated. The contribution of this work is the creation of an effective method for separation of single nanowires, that allows the whole process, fabrication and separation, to be undertaken at low-cost.

For future work, it is recommended that the outcome of using this separation method for practical applications, e.g. nanoresonators, should be compared with the results of other nanoresonator fabrication methods. This will give us a more comprehensive knowledge of the achievable quality of nanoresonators fabricated by this method. This can be complimented by cost and quality analysis of the fabrication methods.

Another recommended future work is further enrichment by other separation methods. Since it is possible to eradicate all of the huge clumps by this sedimentation process, the output from this sedimentation process can be used in microfluidic channels without concern about the blockage of channels by huge clumps. Microchannel flow could then be used to separate small crushed particles from the single nanowires.
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Appendix A

Finding $f_{shape}$ Parameter for Falling Particles in the Fluid

The general equation for finding $f_{shape}$ is:

$$f_{shape} = \frac{1}{3} \sqrt{A_{proj}^*} + \frac{2}{3} \sqrt{A_{surf}^*}$$  \hspace{1cm} (A.1)

Where for rectangular cuboid:

$$A_{surf}^* = \frac{A_{surf}}{\pi d^2}$$  \hspace{1cm} (A.2)

$$A_{proj}^* = \frac{A_{proj}}{\frac{1}{4} \pi d^2}$$  \hspace{1cm} (A.3)

Where $d$ is the diameter of a sphere with the same volume with particle. $A_{proj}$, is the area of the particle which is perpendicular to the flow of water and $A_{surf}$ is the total surface area of the particle. $A_{surf}^*$, $A_{proj}^*$, are the non-dimensional parameters. For cylinder the following equations can be used for $A_{surf}^*$ and the same equation for rectangular cuboid can be used for $A_{proj}^*$

$$A_{surf}^* = \frac{2E_{cyl} + 1}{(18 E_{cyl}^2)^{1/3}}$$  \hspace{1cm} (A.4)

Since particles falling direction is varying rapidly due to the Brownian motion, an equal probability is assumed for all of the possible falling directions and final, $f_{shape}$, is found by averaging over possible falling angles and directions. Individual cylindrical NWs have one possible falling direction changing from $0^\circ$ to $90^\circ$, horizontal to vertical. Rectangular cuboid clumped NWs have 3 perpendicular configurations in the horizontal
plane and each of the configurations can have a rotation from 0° to 90°, from horizontal plane to vertical plane.
Appendix B

Details of Turbulent Simulations in OpenFOAM

In this appendix, the structure of the solver for OpenFOAM case that can help understanding the model, and the URL links to the case files used for the simulations are presented. Figure B.1 shows the structure of the folder which was used for solving the problem in OpenFOAM.

The case files of my simulations are available to public by the following links.

For guard-heated WSS sensor:

https://drive.google.com/drive/folders/146TL2xML5ZeFZp4_aJcmUnqXJVTXBvT-

For the single element WSS sensor:

https://drive.google.com/open?id=1BDcEDNmarsf2tGTEbJ4ZMpjLORpzwaLu
Figure B.1. The tree chart of OpenFOAM case file, including necessary files which should be defined for solving the problem.
Appendix C

Numerical Code for Modeling the Sedimentation Process

The following code was written in MATLAB for numerical modeling of nanowires sedimentation process based on what has been discussed in Chapter 5.

This MATLAB code can also be accessed through the following link:

https://drive.google.com/open?id=137EAF-11cgSwIFOGHX0PM1GOaQdFonh

c1c
clear
% Defining parameters and matrices
t=0; % Time
n=0; % Counter for each time step
viscosity= 0.0012;
Sdensity= 12410;
Fdensity= 780;
l=zeros(1,8); % Clump's length
W=zeros(1,8); % Clump's width
aMax=zeros(1,8); % Maximum mass fraction
aMin=zeros(1,8); % Minimum mass fraction
Vcube=zeros(1,8); % Volume of the clump
Mcube=zeros(1,8); % Mass of the clump
FBC=zeros(1,8); % Net gravity force on the clump
Deqclump= zeros(1,8); % Deqclump
Fshapeclump= zeros(1,8); % Fshapeclump
FDCconst= zeros(1,8); % FDCconst
UCter= zeros(1,8); % Terminal velocity of the clump
phi= zeros(1,48); % Volumetric ratio of clumps in each time step

% Defining characteristics of each category based on observations from measurements
L(1,1)= 80*10^-6;
W(1,1)= 15*10^-6;
aMax(1,1)=0.85;
aMin(1,1)=0.57;
Deqclump(1,1)= 28.405*10^-6;
Fshapeclump(1,1) = 1.2717;
L(1,2) = 60*10^-6;
W(1,2) = 10*10^-6;
amax(1,2)=0.58;
amin(1,2)=0.47;
Deqclump(1,2) = 22.545*10^-6;
Fshapeclump(1,2) = 1.2475;

L(1,3) = 20*10^-6;
W(1,3) = 9*10^-6;
amax(1,3)=0.50;
amin(1,3)=0.43;
Deqclump(1,3) = 15.0924*10^-6;
Fshapeclump(1,3) = 1.1256;

L(1,4) = 20*10^-6;
W(1,4) = 9*10^-6;
amax(1,4)=0.42;
amin(1,4)=0.33;
Deqclump(1,4) = 15.0924*10^-6;
Fshapeclump(1,4) = 1.1256;

L(1,5) = 15*10^-6;
W(1,5) = 6*10^-6;
amax(1,5)=0.29;
amin(1,5)=0.23;
Deqclump(1,5) = 11.9788*10^-6;
Fshapeclump(1,5) = 1.1322;

L(1,6) = 10*10^-6;
W(1,6) = 5*10^-6;
amax(1,6)=0.23;
amin(1,6)=0.16;
Deqclump(1,6) = 9.8475*10^-6;
Fshapeclump(1,6) = 1.1249;

L(1,7) = 7*10^-6;
W(1,7) = 4*10^-6;
amax(1,7)=0.18;
amin(1,7)=0.13;
Deqclump(1,7) = 8.1168*10^-6;
Fshapeclump(1,7) = 1.1331;

L(1,8) = 4*10^-6;
W(1,8) = 3*10^-6;
amax(1,8)=0.16;
amin(1,8)=0.08;
Deqclump(1,8) = 6.1197*10^-6;
Fshapeclump(1,8) = 1.1575;

% Single nanowire properties
Lcyl= 10*10^-6;
Dcyl= 0.4*10^-6;
Vcyl= 0.25*pi*Dcyl^2*Lcyl;
Mcyl= Vcyl*Sdensity;
FBS = Vcyl*(Sdensity-Fdensity)*9.18;
Deqcyl= 1.3389*10^-6;
Fshapecyl= 1.3538;
USTer = FBS/(3*pi*viscosity*Deqcyl);

%Defining matrices for population of the particles, their position and
%their velocity
% Note: Each of the top 3 regions in the test tube is divided into 16
cells
% plus one cell for the sediments region. Therefore, the test tube is
divided
% into 49 cells in total.
NS = zeros(1, 49);
NC = zeros(8,49);
NT = zeros(1,49);
NS (1,:) = 129;
NC (:,:) = 13;
US= zeros(49,129);
UC= zeros(8,48,13);
UCfinal= zeros(8,48,13);
XS= zeros(49,129);
XC= zeros(8,48,13);
PS= zeros(49,129);
PC= zeros(8,48,13);
XP= zeros(1,48);

% Homogeneous distribution of particles by the cell number
% for single NWs
for j=1:1:48
  for i=1:1:129
    PS(j,i)=j;
  end
end
%For clumps
for z=1:1:8
  for j=1:1:48
    for i=1:1:13
      PC(z,j,i)=j;
    end
  end
end
%Middle position of each cell in the code
for j=1:1:48;
  XP(1,j)= (testtubeL/48)*(j-0.5);
end
%Initial positions of single NWs based on the middle position of each
cell
for j= 1:1:48
  for i=1:1:129
    XS(j,i)= (testtubeL/48)*((j-1)+rand);
  end
end
%Initial positions of clumps based on the middle position of each cell
for z=1:1:8
  for j= 1:1:48
    for i=1:1:13
      XC(z,j,i)= (testtubeL/48)*((j-1)+rand);
% Terminal velocity of each category based on the minimum mass fraction
for i=1:1:8
Vcube(1,i)= W(1,i)*L(1,i)*Lcyl;
FBC(1,i)= aMin(1,i)*Vcube(1,i)*(Sdensity-Fdensity)*9.18;
FDConst(1,i)= 3*pi*Deqclump(1,i)*viscosity*Fshapeclump(1,i);
UCter(1,i)=FBC(1,i)/FDConst(1,i);
end
% Terminal velocity of each clump
for j=1:1:48
for i= 1:1:13
for z=1:1:8
UC(z,j,i)= UCter(1,z)*((aMin(1,z)+rand*(aMax(1,z)-aMin(1,z)))/aMin(1,z));
end
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sedimentation process
for dt=[0.39, 1.4^0.39, 1.4^2*0.39, 1.4^3*0.39, 1.4^4*0.39, 1.4^5*0.39, 1.4^6*0.39, 1.4^7*0.39, 1.4^8*0.39, 1.4^9*0.45]; %Time approach
for q=1:1:100 %Each time interval repeats 100 times
% The time intervals increase gradually
t=t+dt;
n=n+1;
for j=1:1:48
NT(1,j)=NS(1,j)+sum(NC(1:8,j));
end
%%%%%%%%%%%%%%%%%%%%%%%%
% Single nano wires
for j=1:1:48
% finding gamma and lambda for bidisperse model
landatot=0;
gamatot=0;
landaMax=0;
tlandaMax=0;
SNC=sum(NC(1:8,j));
if SNC>0
for q=1:1:8
landatot= landatot+(NC(q,j)/SNC)*Deqclump(1,q);
gamatot= gamatot+(NC(q,j)/SNC)*(aMin(1,q)+aMax(1,q))/2;
phi(1,j)= 0.006*SNC/104;
end
 landa=landatot/Deqcyl;
gama=gamatot;
if landa >landaMax
 landaMax= landa;
tlandaMax= t;
end
else
 gama=0;
 landa=0;
end
% New position of single NWs at the end of time interval
for i=1:1:129
    % Brownian motion displacement
    XBrown = normrnd(0,4*10^-5*(0.4/3600)^0.5);
    US(j,i) = USter*(1-phi(1,j))*gama*(landa^2+3*landa+1);
    XS(j,i) = XS(j,i)+US(j,i)*dt+XBrown;
    % Cell# that the particle is positioned at
    PSupdate = floor(XS(j,i)/(testtubeL/48))+1;
    if PSupdate>49
        PSupdate=49;
    end
    % Updating count of single nanowires in each cell
    if PSupdate==PS(j,i) && PS(j,i)<49
        NS(1,PS(j,i))=NS(1,PS(j,i))-1;
        NS(1,PSupdate)= NS(1,PSupdate)+1;
        PS(j,i)= PSupdate;
    end
end
end
% Brownian motion of single NWs in sediments region
for j=1:1:49
    for i=1:1:129
        if PS(j,i) == 49
            XBrown = normrnd(0,4*10^-5*(0.4/3600)^0.5);
            if XBrown < 0
                XS(j,i)= XS(j,i)+XBrown;
                PSupdate = floor(XS(j,i)/(testtubeL/48))+1;
                if PSupdate>=49
                    PSupdate=49;
                else
                    NS(1,PS(j,i))=NS(1,PS(j,i))-1;
                    NS(1,PSupdate)= NS(1,PSupdate)+1;
                    PS(j,i)= PSupdate;
                end
            end
        end
    end
end
end
%%%%%%%%%%%%%%%%%%%%%%%%%%%
% Sedimentation of conjunct nanowires
for j=1:1:48
    for i=1:1:13
        for z=1:1:8
            UCFinal(z,j,i) = (1-5.62*phi(1,j))* UC(z,j,i); % Corrected terminal velocity by bidisperse assumption
            XC(z,j,i) = XC(z,j,i)+UCFinal(z,j,i)*dt;
            PCupdate = floor(XC(z,j,i)/(testtubeL/48));
            if PCupdate>49
                PCupdate=49;
            end
            % Updated count of clumps in each cell
            if PCupdate==PC(z,j,i) && PC(z,j,i)<49
                NC(z,PC(z,j,i))=NC(z,PC(z,j,i))-1;
                NC(z,PCupdate)= NC(z,PCupdate)+1;
                PC(z,j,i)= PCupdate;
            end
        end
    end
end
end
end
end
end
\[ T(n) = \frac{t}{60}; \]
\[ TTS(n) = \text{sum}(\text{NS}(1, 1:16)); \]
\[ TTC(n) = \text{sum} (\text{sum}(\text{NC}(1:8, 1:16))); \]
\[ TTR(n) = \frac{TTC(n)}{TTS(n)}; \]
\[ MS(n) = \text{sum}(\text{NS}(1, 17:32)); \]
\[ MC(n) = \text{sum} (\text{sum}(\text{NC}(1:8, 17:32))); \]
\[ MR(n) = \frac{MC(n)}{MS(n)}; \]
\[ BS(n) = \text{sum}(\text{NS}(1, 33:48)); \]
\[ BC(n) = \text{sum} (\text{sum}(\text{NC}(1:8, 33:48))); \]
\[ BR(n) = \frac{BC(n)}{BS(n)}; \]

%%%%%%%%%%%%%%%%%%%

Results from the experimental measurements

\[ XTT = \left[ \frac{10, 180, 600, 1200}{60} \right]; \]
\[ YTT = \left[ 0.59, 0.331, 0.209, 0.092 \right]; \]
\[ XM = \left[ \frac{10, 180, 300, 600, 900, 1200, 1500, 1800, 2700, 1800, 1800, 1200, 1800, 2700}{60} \right]; \]
\[ YM = \left[ 0.802, 0.2743, 0.2184, 0.1427, 0.1543, 0.1148, 0.0998, 0.0692, ... \right] \]
\[ 0.0841, 0.0654, 0.0543, 0.0752, 0.0714, 0.2211, 0.0801, 0.0658, 0.2426, 0.2499 \];
\[ XB = \left[ \frac{10, 180, 900, 1800, 2700, 3600}{60} \right]; \]
\[ YB = \left[ 0.85, 1.2*0.38, 0.892*0.22, 0.19*0.38, 0.206*0.38, 0.479*0.19 \right]; \]

% Plotting the results for the middle region

figure
hold on
yyaxis left
set(gca, 'FontSize', 15)
ax=gca;
ax.YColor = 'red'
plot(T, MR, 'color', 'red', 'lineWidth', 1)
plot(XM, YM, 'color', 'red', 'lineWidth', 1)
ylabel('singles to clumps ratio')

yyaxis right
ax.YColor = 'blue'
plot(T, MS*88.372, 'color', 'blue', 'lineWidth', 1)
plot(T, MC*88.372, '-','color', 'green', 'lineWidth', 1)
%Factor 88.372 is to convert the numerical population to real world
%population
xlabel('time (min)')
ylabel('population of particles')
title('population and ratio of particles in the middle region versus
time','fontweight','normal')
hold off