EFFECT OF WIND IN THE FIELD OF PLAY FOR ELITE SPRINT KAYAKERS

by

Hali L. Barber

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Department of Mechanical and Aerospace Engineering
Carleton University
Ottawa, Ontario

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Hali L. Barber

The undersigned recommend to
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acceptance of the thesis entitled

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submitted by

Hali L. Barber

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Thesis Co-Supervisor:

Professor Guy L. Larose

Thesis Co-Supervisor:

Professor Metin I. Yaras

Department Chair:

Professor Ron Miller
Department of Mechanical & Aerospace Engineering

Carleton University

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Abstract

The current thesis investigates the contribution of aerodynamic drag on an elite sprint kayaker as a factor in the outcome of a race, where a thousandth of a second can be the increment of success. For kayaking, field of play conditions are an important consideration, as the overall aerodynamic drag on a kayaker comes from the kayaker's forward motion and local atmospheric boundary layer (ABL) winds.

The drag on a kayaker due to ABL winds depends on the wind speed, which is expected to follow a non-uniform profile. To establish the reliability of a theoretical profile for wind over water at a sprint kayaking venue, field testing has been carried out showing that the wind speed profile within the height of a kayaker followed the theoretical logarithmic curve for over 80% of tests in light winds.

The aerodynamic drag of a model kayaker was then measured in a wind tunnel, where a range of inflow profiles were used to confirm that the kayaker's aerodynamic drag coefficient, C_D , is primarily sensitive to velocity profile, with a small sensitivity to Re for the subcritical range from 1.0×10^5 to 2.7×10^5 . The confirmation of the dominance of the velocity profile in comparison to other airflow effects including turbulence, multi-component flow interaction and shape effect, was shown by normalizing the C_D for each inflow condition. For an inflow profile representing the prevailing ABL logarithmic profile confirmed from field testing, the normalized C_D was found to collapse towards the uniform-flow C_D to within 1%.

The wind-tunnel findings with respect to the trends in the aerodynamic drag coefficient were then applied to a single case for a men's K1 200 m race. Results showed that for a calm atmosphere a reduction in air drag coefficient of 10% can correspond to a decrease in finish-time of 0.1 s. When ABL wind drag is added, results imply that for a headwind ranging from

2 m/s to 10 m/s, the race time results can increase from 0.8 s to 8 s. A method for predicting change in race finish-time, which includes aerodynamic drag due to forward motion and field of play ABL winds, gives athletes and coaches the ability to: i) assess the value of reduction in the athlete's body-shape-driven drag and ii) apply a time-correction for the purpose of comparing race results for a range of local field of play ABL winds.

I dedicate this work to my daughter Freya,
who loved science through the eyes of an artist.

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List of Symbols

Symbol	Description	Units
a	Acceleration	[m/s ²]
A	Charnock constant	[-]
A_f	Frontal area	[m ²]
c	Phase speed	[m/s]
C_D	Drag coefficient	[-]
C_{10}	Surface drag coefficient for a reference velocity at 10 m above surface	[-]
d	Upstream rod diameter	[m]
D	Diameter	[m]
f	Frequency	[Hz]
f_c	Coriolis parameter	[rad/s]
F_A	Aerodynamic drag	[N]
F_{Am}	Aerodynamic drag - kayaker forward motion	[N]
F_{app}	Apparent force	[N]
F_{Aw}	Aerodynamic drag - atmospheric boundary layer headwind	[N]

F_H	Hydrodynamic resistance	[N]
F_{Hf}	Hydrodynamic resistance - forward motion	[N]
F_{Hr}	Hydrodynamic resistance - wave reflection	[N]
F_P	Propulsive force	[N]
F_x	Streamwise force	[N]
g	Gravitational acceleration	[m/s ²]
h	Kayaker head height (1 m above water line)	[m]
H_{max}	Maximum wave height	[mm]
H_w	Manometer water height	[m]
H_{wc}	Corrected manometer water height	[m]
I_{uu}	Streamwise turbulence intensity	[%]
k	Wavenumber	[1/m]
K	Alternate Charnock constant = $\ln \left[\left(\frac{1}{A} \right)^{\frac{1}{\alpha}} \right]$	[-]
l	Local length scale	[m]
l_{sl}	Surface layer length scale	[m]
L	Monin-Obukhov length	[m]
L_u^x	Streamwise integral length scale of turbulence	[m]
m	Mass	[kg]
P_a	Atmospheric pressure	[Pa]
P_s	Static pressure	[Pa]

P_0	Stagnation pressure	[Pa]
ΔP	Differential pressure	[Pa]
Q	Dynamic pressure	[Pa]
R	Specific gas constant	[kJ/gK]
Re	Reynolds number	[-]
Ri	Richardson number	[-]
St	Strouhal number	[-]
$S_{uu}(f)$	Streamwise power spectral density for wind speed	[m ² /s]
$S_{uu}(k)$	Streamwise power spectral density for wavenumber	[1/m ³]
t	Time	[s]
t^*	Non-dimensional settling time, Equation (E.1)	[-]
T	Temperature	[K]
$\bar{T}$	Time-averaged value of temperature	[K]
u_*	Friction velocity	[m/s]
U	Streamwise velocity	[m/s]
$\bar{U}$	Time-averaged streamwise velocity	[m/s]
U_a	Streamwise air velocity	[m/s]
U_{cup}	Cup anemometer velocity reading	[m/s]
U_h	Atmospheric boundary layer headwind velocity	[m/s]
U_k	Kayak air speed in course oriented direction	[m/s]

U_{p-s}	Pitot-static probe calibration velocity reading	[m/s]
U_w	Streamwise water velocity	[m/s]
$\bar{U}_{ref}$	Time-averaged streamwise velocity at reference height	[m/s]
$\bar{U}_z$	Average streamwise velocity at height z	[m/s]
U_1	Atmospheric boundary layer headwind velocity at 1 m above water	[m/s]
$\bar{U}_1$	Time-averaged U_1	[m/s]
$\Delta\bar{U}_1$	Change in $\bar{U}_1$	[m/s]
U_{10}	Atmospheric boundary layer streamwise velocity at 10 m above water	[m/s]
x	Streamwise distance	[m]
y^+	Viscous normalized wall-normal distance	[m]
z	Height above surface	[m]
z_0	Surface roughness length	[m]
z_i	Atmospheric boundary layer thickness	[m]
w	Test section width	[m]
$\langle wT \rangle$	Vertical temperature difference	[K]
α	von Kármán constant (0.41)	[-]
β	ψ_m variable for $z/L \leq 0$, Equation (2.19)	[-]
Γ	Neutral temperature gradient (0.0098)	[K/m]
θ	Angle	[rad]

λ	Wavelength	[m]
μ	Dynamic viscosity	[kg/(m·s)]
ν	Kinematic viscosity	[m ² /s]
ρ	Density	[kg/m ³]
ρ_a	Density of air	[kg/m ³]
ρ_w	Density of water	[kg/m ³]
σ_u	Standard deviation of streamwise velocity	[m/s]
τ_w	Wall shear stress	[Pa]
ϕ_m	Momentum correction factor, Equation (2.20)	[-]
ψ_m	Atmospheric stability correction function, Equation (2.19)	[-]
Ω	Angular velocity	[rad/s]

Chapter 1

Introduction

Sports science research has a long history of investigation into the efficiency of sprint paddle sports equipment, apparel and technique. Technology is directly related to the reduction of resistance, which for a kayaker, includes hydrodynamic and aerodynamic drag. According to Robinson et al [1], sports engineering is now considered as important to an athlete's performance as psychological preparation and physical conditioning, and is in part responsible for the reduction in high-performance sports finish times. For sprint kayaking, the world record finish time for the men's single 1000 m is now just under 3.5 minutes, which has dropped by over a minute from 1948 to 2015.

For self-propelled on-water sports, hull and paddle optimization have been the focus for research with some acknowledgement that aerodynamics contribute to the balance of forces. The aerodynamic drag is considered small in comparison to hydrodynamic resistance and therefore details of the aerodynamics and how they affect race results for different athletes and varying wind conditions have not been investigated.

Whether the wind effect is caused by the motion generated by the athlete, or is present in the field of play due to atmospheric condition, the aerodynamic drag of the kayaker contributes to the overall resistance to forward motion. For competitive sprint kayaking, the winning margin is often determined by hundredths of seconds. Consequently, every factor in the force balance of the kayaker is significant.

1.1 Motivation - sprint kayaker wind effects

The two mechanisms of aerodynamic drag, including the kayaker's self generated forward motion, and the local atmospheric boundary layer (ABL) winds, are of interest to athletes and coaches for two reasons. One is for gaining advantage by reducing an individual's aerodynamic drag, the other is for cross comparison of results for races that have taken place at different times and venues.

The kayaker's aerodynamic drag during a single race, where competitors are experiencing nearly the same atmospheric condition, depends on the shape of the athlete, her/his form while kayaking and the decisions that the athlete makes with regards to the shape of her/his equipment and apparel. Therefore, reducing the athlete's unique aerodynamic drag is of interest as it will improve performance and be an individual's advantage over a competitor.

The aerodynamic drag caused by ABL winds that the kayaker has to overcome for the duration of a race is also of interest to the kayakers and coaches. The reason for this is that, when comparing competitors or assessing an athlete's progress, a correction for local atmospheric winds is needed for a fair comparison of results between races that have taken place at different times and different venues. For example, if an athlete is competing in trials to improve her/his standing on a national team, if the local conditions are not considered, results may misrepresent the capabilities of the athlete. For this cross race comparison, the contribution of the aerodynamic drag includes the kayaker's unique shape dependent drag and the added aerodynamic drag due to local winds.

Therefore, to include all wind effects during a race, a method is needed where aerodynamic drag generated by the forward motion of the athlete and aerodynamic drag caused by local atmospheric winds are taken into account.

For this study, the parameters set out by race regulations and field of play conditions are important for understanding the factors that may affect the kayaker's aerodynamics.

1.2 Kayaking equipment regulations

The kayaker's unique drag coefficient is mainly determined by the kayaker's body shape and apparel, as the equipment is regulated. At the elite level, sprint kayaking equipment and race rules are regulated by the International Canoe Federation (ICF). Official rules that may play a part in the aerodynamics of the kayaker include the specifications for the boat construction, including length, shape, and weight. The shape of the hull must have no longitudinal lines that are concave and the deck shape must have its maximum height at the front edge of the cockpit. These basic constraints have led to an optimized design with little room for variation.

The rules also govern innovation by prohibiting any additional foreign part that may be used to give unfair advantage. Any changes to the clothing, equipment, or boat must be presented to the ICF for evaluation and made available to all competitors if accepted. With this fairness rule in place, the kayakers must look to subtle changes in existing features that may be of some aerodynamic advantage.

1.2.1 Equipment and terminology

The components making up the above-water portion of the kayaker affect the kayaker's aerodynamic flow and will therefore be referred to throughout this thesis using terminology and geometric datums illustrated in Figure 1.1 and defined in Table 1.1.

Figure 1.1: Kayaker terminology and reference datums

Table 1.1: Kayaking related definitions

Name	Definition
AWL	above water line
BWL	below water line
blade	paddle end, typically a curved plate, approximately 0.6 m x 0.2 m
coaming	structural up-stand and lip surrounding seat region
cockpit	opening in deck for kayaker to sit
D	upper torso diameter
deck	upper surface of kayak starting at sheer
displacement	weight of water displaced by kayaker, including kayaker and all equipment
draft	maximum depth of hull below water line (BWL)
h	height of kayaker, approximately 1 m above water line (AWL)
hull	bottom surface of kayak starting at sheer
K1	single person kayak
LOA	length over all
pole	paddle handle, typically 32 mm diameter
sheer	intersect of hull and deck
skirt	cloth cover, fitting tightly to kayaker waist and cockpit coaming, typically used to prevent water ingress
stem	leading edge of kayak

1.3 Kayaking course regulations

The ICF also regulates the standard kayak course where the current course lengths include 200 m, 500 m and 1000 m with 8 (Olympic games) or 9 (World Championships) lanes. Each lane is required to be straight and 9 m wide with a minimum water depth of 2 m. Beyond these dimensions, there are no rules on the surrounding shoreline shape, shoreline structures or maximum water size. This allows for a wide range of venues including man-made basins, lakes, and lagoons. Since 1976, the Olympic sprint kayak venue has been held on a range of venues as shown in Table 1.2. This large variation in venue affects local wind patterns which are influenced by topography, resulting in a change in air drag on a kayaker for each race when the local air is not still.

Table 1.2: Olympic sprint kayak/canoe venue

Venue	Length (km)	Width (m)	Depth (m)	Water
Rio (2016)	2.3	2250	10	brine lagoon
London (2012)	2.2	110	3.5	fresh water lake
Beijing (2008)	man-made multi-event basin			fresh water
Athens (2004)	2.5	120	3.5	spring fed basin
Sydney (2000)	2.3	170	5	man-made lake
Atlanta (1996)	large reservoir		80	river fed
Montreal (1976)	2.2	110	2.5	man-made basin

1.4 Thesis approach

For an initial understanding of the overall contribution of wind effects to the balance of forces acting on a kayaker, the force of the natural outdoor winds on the kayaker and the aerodynamic drag generated by the kayaker's own forward motion are needed.

To determine the natural outdoor wind force, the velocity profile of the wind within the height of a kayaker above water is required. Literature has been found that provides a theoretical profile for wind above water [2, 3, 4], but no experimental results were found for the height of interest, for inland open water representative of a kayak race venue. Therefore, the reliability of the theoretical profile for wind over water is established by field testing where the ABL wind velocity profile is measured within the height above water of a kayaker. By measuring temperature and instantaneous velocity, the field tests also add information on other atmospheric conditions specific to air above small bodies of water including turbulence characteristics and atmospheric stability. The approach to the field testing is to gather as much information on the characteristics of the local atmospheric conditions as possible for the purpose of considering all flow conditions that may have an effect on the aerodynamics of a kayaker.

Velocity with a constant magnitude with respect to height is termed a uniform velocity profile, which is representative of the flow from the kayaker's own forward motion. The added air motion due to ABL winds is expected to be non-uniform, or changing in magnitude with

distance from the water surface. If the natural wind velocity profile in the field of play is determined to follow the non-uniform theoretical profile, the sensitivity of the kayaker's aerodynamic drag to a change from uniform to a non-uniform velocity profile is also of importance. Therefore, the drag force for an air-velocity profile with vertical uniformity and vertical ABL profile are needed for a range in wind speeds typical of an elite kayaker's speed performance and expected ABL winds. To study the change in air force on the kayaker with respect to the vertical profile of the air velocity, controlled testing using a wind tunnel was determined to be most practical, where the flow conditions could be manipulated for flow over a scaled model while drag is measured.

If the non-uniform velocity profile is known for wind over water, and the aerodynamic drag on a kayaker for uniform and non-uniform ABL profile can be determined, a force balance equation which incorporates the findings and predicts variation in finish time due to the kayaker's unique aerodynamic drag and added atmospheric wind effects can be established.

Simplification to the force balance equation is necessary for an initial investigation of wind effects in the field of play on a kayaker for the scope of this thesis. A kayaker's movement is complex with the cyclic rotation of the paddle, taking place in both the water and air, where winds on the field of play can change in magnitude and direction instantaneously. Therefore, a single wind orientation at constant speed with respect to the kayaker, and a single posture for a K1 competition were chosen as explained in further detail in the following chapters.

1.5 Thesis objectives

To fulfill the overall objective, which is to investigate the wind effects on the field of play for an elite sprint kayaker, the current thesis uses experimental methods including field and wind tunnel testing. This resulted in a thesis with two experimental objectives, where the experimental results are used for the final objective of performance analysis. The experimental objectives are: i) to measure the reliability of the theoretical ABL wind-over-water velocity profile and ii) to determine the uniform flow aerodynamic drag on a kayaker and to establish a method for calculating the aerodynamic drag force which includes the non-uniform flow

profiles, found in the ABL above water. The overall objective of this research work is to determine the contribution of a kayaker's aerodynamic drag to the total resistive forces acting against the kayaker's forward motion for the duration of a race based on the findings of the experiments. A secondary overall objective is to quantify the effects of a reduction in aerodynamic drag and the presence of atmospheric winds on the race finish time.

1.6 Thesis structure summary

This thesis is divided into eight chapters. Background on bluff body aerodynamics and a survey of literature with respect to sports aerodynamics and ABL profile above water is presented in Chapter 2. The experimental method and setup that was applied for the field testing is described in Chapter 3, with results following in Chapter 4. Chapter 5 explains the wind tunnel setup for the scaled model kayaker. The model kayaker flow characteristics, drag coefficient theory, and experimental results are presented in Chapter 6. Chapter 7 explains the method used to determine the aerodynamic contribution and finish time performance of a K1 sprint kayaker using the results from the experimental work to include field of play headwind effect. The final chapter summarizes findings and identifies areas where the research for the current thesis established specific unresolved questions which would advance the understanding of wind effects on elite sprint kayakers.

To compliment the information contained in the chapters of the thesis, Appendix A presents the calibration and uncertainty for the field testing. Appendix B presents time series field test data including wind speed and wave height measurements. Appendix C and D present the wind tunnel calibration and inflow grid details. Finally, Appendix E presents the numerical simulation setup and results used to expand on the wind tunnel experiments.

Chapter 2

Literature review

To investigate the effect of wind on elite sprint kayaking, flow conditions for a calm and a windy atmosphere were considered for this research using a predominantly experimental approach. Although some literature makes reference to the contribution of air drag for paddle sports, no literature has been found on experimental or computational results for sprint kayaker aerodynamics. Therefore, this chapter will start with a review of fluid dynamics for bluff body shapes in uniform flow, including sports aerodynamics research and multi-component flow interaction. Since the focus of this study is on wind effects on the kayaker for field of play conditions, non-uniform velocity profile and wind-wave effects due to the atmospheric boundary layer (ABL) over water for the height of a kayaker must be defined to determine aerodynamic drag. The ABL velocity profile within a kayaker's height over small bodies of water has not been clearly defined in literature, although theoretical and experimental studies have been found for open water and heights outside of the range of interest.

2.1 Multi-component bluff bodies in uniform flow

2.1.1 Flow analysis for bluff bodies

According to Hoerner [5], during the deceleration of fluid particles approaching an obstacle, the particle momentum is transferred into static pressure. The increment, Q , of this pressure is defined as:

$$Q = 0.5\rho U^2 \tag{2.1}$$

where ρ is the fluid density and U is the streamwise fluid velocity, which is the equivalent of a dynamic quantity and is therefore called dynamic pressure. It is observed that fluid dynamic forces increase with the size of the frontal area, A_f , of a bluff body obstacle. Therefore, a ratio, or drag coefficient, C_D , between measured streamwise force, F_x , dynamic pressure and frontal area is a standard way to compare resistance for a specific bluff body shape defined by the following:

$$C_D = \frac{F_x}{Q A_f} = \frac{F_x}{0.5 \rho U^2 A_f} \quad (2.2)$$

Since the drag is dependent on body shape and flow speed, C_D is dependent on the flow characteristics around the body which are influenced by the non-dimensional Reynolds number. The Reynolds number, Re , represents the ratio of inertia and viscous forces in the flow field of the body:

$$Re = \frac{UD}{\nu} \quad (2.3)$$

where U is free-stream velocity, D is a relevant characteristic length of the bluff body, and ν is kinematic viscosity of the fluid.

The total drag on a body also includes friction drag, but for bluff body shapes, the form drag (or pressure drag) is dominant. For example, friction drag was found to be less than 2% of the total drag for $6 \times 10^4 \leq Re \leq 4 \times 10^6$ in experiments with circular cylinders performed by Achenbach [6], which is representative of the range for a kayaker's bluff body components.

Bluff body components of a kayaker include the flat-plate paddle blade and the cylindrical shapes including paddle pole, arms, torso and head of the athlete. For a flat-plate blade in cross-flow, Hoerner [5] finds that the extreme geometric discontinuity at the sharp edge forces the flow to detach creating a fixed separation point, independent of flow Reynolds number. For the cylindrical shapes, the flow behaviour is Reynolds number dependent. From results found on circular cylinders in cross-flow by Schewe [7], the C_D decreases slightly with increase

in Re for the kayaker's Re range, as seen in Figure 2.1. This region with high C_D is termed subcritical, as it is located prior to the critical regime where the C_D drops significantly due to pressure dependent flow separation characteristics.

Figure 2.1: 2D circular cylinder in cross flow; experimental results adapted from Schewe [7]; grey zone represents expected kayaker torso flow regime (calm atmosphere)

For the subcritical region, the separation location shows some migration depending on the Reynolds number of the flow as illustrated schematically in Figure 2.2. As Re increases, the angle of separation also increases, moving the separation point further downstream, decreasing the width of the wake thereby reducing the C_D .

Figure 2.2: Circular cylinder flow separation angle; adopted from Achenbach [6]

At separation, a shear layer forms that continues on aft of the body, forming the perimeter of the wake. For the subcritical Re range, vortex shedding is also expected, where each side of the bluff body alternates in releasing a vortex in a periodic pattern as illustrated in Figure 2.3.

Figure 2.3: Subcritical vortex street shedding; adapted from Blevins [8]

The shedding frequency is related to the the fluid velocity and cylinder size through the non-dimensional Strouhal number, St :

$$St = \frac{fD}{U} \quad (2.4)$$

where f is shedding frequency, D is body diameter, and U is the undisturbed mean fluid velocity.

For the kayaker's cylindrical components, the shedding frequency can be estimated using a St value of ~ 0.2 as suggested by Achenbach and Heinecke [9] for a smooth 2D cylinder in the subcritical Re region, but may differ due to the asymmetric and multi-component configuration of the kayaker.

The remaining kayaker component is the above waterline streamlined kayak. The kayak aerodynamic drag is considered to be small, but not insignificant, in comparison to the bluff body parts. Its high-aspect-ratio elliptical shape allows the flow to stay attached for a longer streamwise distance, separating closer to the trailing edge, thereby minimizing the form drag. When the flow around the kayak is assumed to be similar to a standard elliptical shape, an empirical formula for a 10:1 length-to-width aspect ratio by Hoerner [5] evaluates the C_D in the subcritical Re range to be ~ 0.3 based on the frontal area of the above water part of the kayak.

Although the kayaker components have individual drag characteristics, studies have found that when bodies are placed within a limited distance to one another, flow interaction takes place, changing the overall flow pattern.

2.1.2 Multiple body proximity

Several studies have been carried out to determine the effect on flow patterns around similar and dissimilar uniform shapes due to proximity to one another. A study on circular cylinder drag reduction with the use of an upstream rod by Wang et al [10] found that the mechanism of decreased drag was due to the rod wake interacting with the flow around the cylinder. The upstream rod was placed in-line and in staggered positions, showing that the wake from the rod either shielded the cylinder or caused the wakes of both bodies to combine. In wind tunnel experiments with the configuration illustrated in Figure 2.4, the rod reduced the drag force on the cylinder for stagger angles, θ , up to 5° , and the rod wake impinged on the cylinder wake for angles ranging from 5° to 10° .

Figure 2.4: Wang et al [10] rod/cylinder experimental setup diagram

The rod/cylinder investigation included a range of diameter ratios (d/D) from 0.1 to 0.5, and distance ratios (x/D) from 1.5 to 4.0 for subcritical Re of 8.2×10^4 .

Flow visualization was carried out to supplement the wind tunnel findings, where hydrogen bubble structures were photographed for a Re value of 4800 with results shown in Figure 2.5.

Figure 2.5: Upstream rod wake effect on circular cylinder for stagger angles, a1: $\theta = 0^\circ$, b1: $\theta = 2.5^\circ$, c1: $\theta = 7.5^\circ$, d1: $\theta = 12.5^\circ$, adapted from Wang et al [10]

For the pole-to-torso diameter ratio ($d/D \sim 0.14$) and the pole-to-torso distance ratio ($x/D \sim 1.5$) of the kayaker, these findings would imply that a region exists where the pole may reduce drag on the torso and that the flow interaction between the closely grouped components will have some impact on the overall C_D .

2.1.3 Sports aerodynamic modelling

A study by Jackson [11] on Olympic kayaker peak race speed used a C_D value of 1.0 according to Blevins [8] of an average man in seated or crouching position in cross flow. This estimation was used to determine the aerodynamic drag contribution for a K1 male kayaker to be 7% at peak speed, with an estimated possible reduction of 20%. The author's argument for the high variation is that the kayaker's bluff body form drag can more likely be reduced, due to a reduction of frontal area for example, than the well defined hydrodynamically efficient hull. It was also noted that the estimation was for calm atmosphere and that aerodynamic resistance increases rapidly for headwind conditions.

A study by Sharobaiko et al [12] into the use of computers for performance analysis developed software to model the forces on the stroke cycle of a canoeist which included wind magnitude and direction. Although details of the algorithm were not presented, the noted requirement of a retrofit correction to account for the difference between field results and the

simulation suggests that the study was incomplete. However, the authors acknowledge that the power of the wind is an important factor for a paddler.

More recent studies in sports science have used wind tunnel testing to obtain specific drag coefficients with smaller uncertainty. From these tests, aerodynamic drag has been found to be influenced by posture, equipment and apparel, with results being used to improve performance. For example, Jansen et al [13] measured drag of a mannequin in sailing posture for three angles of attack with an array of racing apparel. The study was used to determine the contribution of the athlete's body drag in comparison to all other resistive forces and showed that savings in total drag on a solo sailor of 1.2% could be obtained by changing the clothing of the athlete.

An investigation by García-López et al [14] found that posture and equipment had an influence on the aerodynamic drag. The authors used wind tunnel tests to measure aerodynamic drag of professional cyclists in full gear for four unique postures with and without pedalling. Results showed a change of $\sim 14\%$ in aerodynamic drag due to posture, demonstrating that the aerodynamic interaction of the flow around the athlete and their equipment is different than for each part individually, and therefore the athlete is best represented when the posture and equipment are modelled.

Wind tunnel turbulence has also been found to influence the aerodynamic drag of athletes. A study by D'Auteuil [15] on speed skater boundary layer transition found that when turbulence in the wind tunnel flow was matched to indoor speed skating oval conditions with turbulence intensity of $\sim 3\%$ in the longitudinal, vertical and lateral directions, for a range of 0.1 to 100 Hz, flow around the skater's body changed and influenced the drag when compared to laminar flow. For modelling of outdoor atmospheric conditions, Irwin [16] suggests that the full turbulence spectrum is difficult to duplicate as the wind tunnel test section is typically not large enough to simulate the large scale turbulence, even with scaled models. Experiments comparing field results to wind tunnel tests for a 6 m cube by Richards et al [17] found that the free-stream high-frequency end of the turbulence spectrum needs to be simulated as it interacts directly with the local flow around the body, modifying its behaviour. For wind over a large lake, measurements by Donelan et al [18] suggest that close to the height

of the kayaker and expected wind speeds, the high-frequency range will be approximately 10^{-1} Hz to 10^2 Hz.

For modelling of athletes, past experimental testing related to sports science has relied on wind tunnels, finding that posture, equipment, and flow conditions are important for accurately determining aerodynamic drag. For the sprint kayaker, all above-water components in representative orientation are therefore expected to be integral to the model setup. The flow conditions should also match the field of play wind, including velocity profile and frequency spectrum, where the high-end turbulence frequencies have been shown to be most important for the proper formation of the local flow field behaviour around the bluff body.

2.2 Wind on the field of play

Theoretical models for wind over water available in published literature demonstrate that the atmospheric condition has variability due to water surface roughness and atmospheric stability. Such models could be used to predict the velocity profile and turbulence characteristics for a kayaker in headwinds.

2.2.1 Wind profile above water

Atmospheric turbulence shapes the wind profile. There are two types of turbulence in the atmosphere that can be present close to the surface of the earth. One is mechanically developed turbulence, where the wind is slowed down due to surface friction inducing shear and therefore creating turbulence. The other type of turbulence is convectively developed turbulence, which is created due to vertical temperature variation according to Mann [2]. Convective and mechanical turbulence shape the wind profile near the surface of the earth extending upward for hundreds of metres. This region is known as the atmospheric boundary layer (ABL), with a thickness defined by ESDU Data Item 85020 [19] as:

$$z_i = \frac{u_*}{6f_c} \quad (2.5)$$

where z_i is the boundary layer thickness, u_* is friction velocity, and f_c is the Coriolis parameter.

Friction velocity relates the velocity profile to the fluids behaviour at a no-slip boundary using the kinematic viscosity of the fluid. Therefore, although friction velocity has units of metres per second, it is not a measure of flow speed, but a relationship developed from the definition of surface shear stress as expressed by Donelan [3]:

$$\tau_w = \mu \frac{dU}{dz}; \quad \mu = \nu \rho \quad (2.6)$$

$$\frac{\tau_w}{\rho} = u_*^2 = \nu \frac{dU}{dz} = \text{constant} \quad (2.7)$$

where τ_w is wall shear, μ is viscosity, U is streamwise velocity, z is distance from the wall, ρ is density and ν is kinematic viscosity.

From Equation (2.7), it can be seen that velocity changes with height according to the friction velocity value. Since friction velocity is a function of wall shear, the surface shape and roughness of the adjacent denser material influences the velocity profile.

The Coriolis parameter accounts for an effect on global wind patterns. Linear velocity, due to the rotation of the earth, is faster at the equator than near the poles, causing a twist in wind patterns longitudinally. The Coriolis parameter, f_c , is defined by ESDU Data Item 85020 [19] as:

$$f_c = 2\Omega \sin\theta \quad (2.8)$$

where Ω is the angular rotation of the earth (72.9×10^{-6} rad/s) and θ is the angle of latitude at location.

Within the ABL, layers exist, the characteristics of which are governed by different properties. At the surface interface a thin viscous layer exists where the velocity is linearly proportional to the height when normalized using the friction velocity. Next is a buffer layer which smoothly transitions to the overlap layer above it. The overlap layer, or surface layer, follows a logarithmic velocity distribution when normalized using the friction velocity. Above the surface layer is the outer layer which extends to the boundary layer height. Dyrbye and Hansen [20] suggest that the logarithmic surface layer has been found to represent the ABL

velocity profile up to 100 m above the surface of the earth. Therefore, it is expected that the velocity profile of interest for the present study will be logarithmic, and that the viscous and buffer layers, which are less than 10 mm in thickness for the range of wind speeds a kayaker will face, are negligible with respect to the height of a kayaker.

Mann [2] states that the logarithmic profile is commonly expressed for a neutrally stratified atmosphere, where convective turbulence is considered absent, as:

$$\frac{U}{u_*} = \frac{1}{\alpha} \left[\ln \frac{z}{z_0} \right] \quad (2.9)$$

where α is the von Kármán constant (0.41) and z_0 is the roughness length of that surface.

Elements considered to be roughness are features on a surface with enough steepness to initiate flow separation on their lee side, creating form drag. As explained by Donelan [3], the aerodynamic effect of roughness is dependent on spacing and steepness of the surface features. For water, the shape of the air-sea interface determines the roughness.

In a study by Donelan [3] on air-sea interaction, the author states that experimental work has found that the surface of oceans can be ultra smooth or very rough, with a roughness length, z_0 , ranging from 10^{-6} mm to 10 mm. In comparison to the roughness over land which remains nearly constant as wind increases, the roughness on the water surface changes with the dynamic interaction of the water with the wind as suggested by Wüest & Lorke [4] and Mann [2]. Difficulty in determining a specific open water roughness length led to an experiment by Charnock [21] where an 8 m wind profile above a $1 \text{ km} \times 1.6 \text{ km}$ water reservoir was compared to laboratory experiments. Based on the results, a relation between friction velocity, gravitational acceleration, g , and roughness length was proposed by Charnock as follows:

$$z_0 = A \frac{u_*^2}{g} \quad (2.10)$$

where the coefficient, A , has been termed the Charnock constant. Mann [2] describes the Charnock constant as a local value due to the dynamic nature of water, which responds readily to the local wind field. Many experiments have found local Charnock constants which

deviate from the original value, $A = 0.007$. Wind over water measurements by Garratt [22] determined $A = 0.0144$ from ocean data, whereas Peña et al [23] have used $A = 0.012$ for Danish North sea studies.

There are two commonly used presentations of the Charnock constant. The first directly incorporates roughness length, by substituting Equation (2.10) into Equation (2.9). The second approach isolates the Charnock constant, K , while incorporating gravity and friction velocity within the logarithmic profile:

$$\frac{U}{u_*} = \frac{1}{\alpha} \ln\left(\frac{gz}{u_*^2}\right) + K \quad (2.11)$$

where A and K are related as follows;

$$K = \ln\left[\left(\frac{1}{A}\right)^{\alpha^{-1}}\right] \quad (2.12)$$

The first method is more direct, but the second shows the relation to the law of the wall for the equilibrium turbulent boundary layer profile. A Charnock constant, K , of 5.7 has been found experimentally for light winds and is used for the following drag coefficient method proposed by Wüest & Lorke [4].

An alternate method of determining wind profile over water is to compare surface drag coefficient with respect to a referenced wind velocity, U_{10} , at 10 m above water surface.

Instead of determining the roughness length and friction velocity, the coefficient of drag, C_{10} is found as follows:

$$C_{10} = \frac{\tau_w}{\rho U^2} = \left(\frac{u_*}{U_{10}}\right)^2 \quad (2.13)$$

Measured values of C_{10} can be used to determine friction velocity, which is then substituted into Equation (2.11) to determine a velocity profile.

Donelan [3] observed a large scatter of experimental results for C_{10} from studies for wind over water ranging from young laboratory and field waves to mature field waves. According to Emeis [24], when the wind begins to apply force on the water, if the water has

previously settled, there is a time period where the waves are developing before they come to an equilibrium with the wind speed. More specifically, the phase speed of the wave does not reach its maximum for the prevailing wind forces. For this initial stage, the waves are considered to be young waves. Wüest & Lorke [4] have studied C_{10} as it relates to winds on inland lakes, discussing the difference between open ocean waves and waves found on smaller bodies of water. For small bodies of water, waves are typically young, making them steep and short with a higher frequency. For light winds, this causes the surface to be rougher than for older waves, increasing the drag coefficient and suggesting the surface roughness length is wave age dependent. Donelan [3] , Geernaert et al [25], Wüest & Lorke [4] and Yelland & Taylor [26] have found that the drag coefficient of the wind-wave surface, C_{10} , has a minimum around 5 m/s as shown in Figure 2.6.

Figure 2.6: Wind-wave drag coefficient; adapted from Wüest & Lorke [4]

According to Wüest & Lorke [4], to incorporate the wave age effect into the logarithmic velocity profile, the drag coefficient can be modified for wind speed as follows:

$$C_{10} = \begin{cases} 0.0044U_{10}^{-1.15}, & U_{10} < 3\text{m/s} \\ 0.001, & \geq 3\text{m/s } U_{10} \leq 5\text{m/s} \\ u_*/U_{10}, & U_{10} > 5\text{m/s} \end{cases} \quad (2.14)$$

suggesting that a single equation for all wind speeds is not suitable for wind over smaller bodies of water and that a range in the neutral ABL profile exists which depends on wave conditions for wind above water. This theory adds to a general consensus that the ABL profile above bodies of water is dependent on wave age, which is determined by the size of the water surface and the consistency of the wind.

Figure 2.7 shows the effect on velocity profile within the height of the kayaker when using the three-part C_{10} method proposed by Wüest & Lorke in comparison to the roughness method by Mann [2] ($A = 0.0144$).

Figure 2.7: Wind profile comparison: $U_{10} = 2, 4, 6, 8, 10$ m/s, solid: $A = 0.0144$; dashed: three part Wüest & Lorke [4] method ($K = 11.3$ or $A = 0.01$)

The deviation shows that at low reference wind speeds, the higher C_{10} reduces the wind speed in the region of the kayaker. At higher reference wind speeds, the lower Charnock constant used by Wüest & Lorke, predicts a smoother surface and therefore a higher velocity. The maximum deviation between the methods at the kayaker's shoulder height is 0.25 m/s for a 10 m/s reference wind speed.

Atmospheric stability

For a kayaking event, the atmosphere may not be neutral, therefore the impact of atmospheric stability on the velocity profile is also a consideration. If the vertical temperature gradient does not follow the neutral stratification of $\Gamma \equiv -dT/dz = 0.0098$ K/m, where dT/dz is the gradient of mean temperature in the height direction, the atmosphere is considered either unstable or stable. An unstable condition is initiated as the sun heats the surface of the earth. As the air above the surface warms, it becomes lighter and pushes upward. According to Mann [2], the higher colder air will drop downward as it is heavier, creating a turbulent motion. Inversely, if the temperature increases with height, lighter air is above heavier air and the stratification is stable. The variation in stability condition is seasonally and diurnally dependent above water, where the air temperature gradient is affected by the lag in temperature change of the water compared to the air.

A common method used to determine whether the atmospheric stratification is neutral, unstable or stable is the Richardson number, Ri :

$$Ri = \frac{g}{T} \frac{dT/dz + \Gamma}{(dU/dz)^2} \quad (2.15)$$

where g is gravitational acceleration, T is temperature at the height of interest, Γ is the neutral temperature gradient (0.0098 K/m), dU/dz is the wind speed gradient over the change in height. If the atmosphere is unstable, $Ri < 0$, if the atmosphere is stable, $Ri > 0$, and for neutral stratification, $Ri = 0$.

Another method for determining the atmospheric condition is by determining the Monin-Obukhov length, L :

$$L = -\frac{T}{g\alpha} \frac{u_*^3}{\langle wT \rangle} \quad (2.16)$$

where T is absolute temperature at the height of interest, u_* is friction velocity, g is gravitational acceleration, α is the von Kármán constant (0.41), and $\langle wT \rangle$ is the vertical temperature difference from the water surface to z . For a neutral atmospheric condition, $|L| \geq 200$. For the non-neutral atmosphere L is incorporated into the logarithmic profile as described below.

In studies on wind profile over water, Donelan [3], Mann [2] and Peña et al [23] use an empirical correction function, ψ_m , to correct a wind profile for convection effects. The method by Peña et al adjusts the neutral atmospheric profile as follows:

$$U_{unstable} = \frac{u_*}{\alpha} \left[\ln \frac{z}{z_0} - \psi_m \left(\frac{z}{L} \right) \right]; \quad (-200 \leq L \leq -50) \quad (2.17)$$

$$U_{stable} = \frac{u_*}{\alpha} \left[\ln \frac{z}{z_0} - \psi_m \left(\frac{z}{L} \right) \left(1 - \frac{z}{2z_i} \right) \right]; \quad (10 \leq L \leq 200) \quad (2.18)$$

where ψ_m is defined by Mann [2] as:

$$\psi_m \left(\frac{z}{L} \right) = \begin{cases} -5 \frac{z}{L}, & \frac{z}{L} > 0 \\ \ln \left\{ \left[(1 + \beta^2)/2 \right] \left[(1 + \beta)/2 \right]^2 \right\} - \arctan \left[(1 - \beta)/(1 + \beta) \right], & \frac{z}{L} \leq 0 \end{cases} \quad (2.19)$$

where $\beta = \left(16 \frac{z}{L} \right)^{0.25}$

Open ocean wind profile studies by Peña et al [23] found that the neutral and unstable formulae compared well to measured results, but that the stable expression over predicted the wind speed.

Figure 2.8: Wind profile for $U_{10} = 6$ m/s, $A = 0.0144$

To observe the sensitivity of the velocity profile to the theoretical atmospheric conditions, the profiles over the height range of a kayaker for a reference wind of 6 m/s at 10 m above water line is shown in Figure 2.8. The unstable condition is predicted to increase the wind speed at the kayaker's head height by 0.2 m/s, whereas the stable condition reduces the velocity at head height by 0.1 m/s according to Equation (2.17) and (2.18), respectively. A Charnock value $A = 0.0144$ was used to determine the roughness length.

Stability is also expected to alter the wind length scale and turbulence intensity. For a neutral atmosphere, Peña et al [23] state that the local turbulence length scale is assumed to be isotropic and equal to the distance from the open water surface. For the stable and unstable conditions, an atmospheric stability momentum correction factor, ϕ_m , is used to modify the local neutrally stable length scale as follows:

$$l = \frac{l_{sl}}{\phi_m} = \frac{z}{\phi_m} \quad (2.20)$$

where l is local length scale and l_{sl} is surface layer length scale.

ϕ_m is defined by Högström [27] as following a power law trend with respect to the non-dimensional stability relation, $\frac{z}{L}$, with coefficients, p, q, r , quantified through field experiments:

$$\text{unstable: } \phi_m = \left(1 - q \frac{z}{L}\right)^p \quad (2.21)$$

$$\text{neutral: } \phi_m = 1 \quad (2.22)$$

$$\text{stable: } \phi_m = \left(1 - r \frac{z}{L}\right) \quad (2.23)$$

where $p = \frac{1}{3}$, $q = 12$ and $r = 4.7$ have been found to produce an expression that compares well to direct calculation using open ocean measurements by Peña et al [23].

The impact of the atmospheric condition on the local turbulence length scale at 1 m AWL according to the stability correction factor is listed in Table 2.1, suggesting that the eddy size would vary by 0.064 m with respect to the chosen L .

Table 2.1: Atmospheric stability turbulence length scale at 1 m AWL

Stability condition	Monin-Obukhov length, L	l (m)
unstable	-150	0.975
neutral	1	1
stable	125	1.039

2.2.2 Wind-wave effect on hull resistance

If ABL wind effects are considered in the force balance for the kayaker in windy conditions, the effect of the wind-waves on the hull resistance should be considered. The effect of wind on the water includes surface drift and wind-waves.

Wind induced surface drift

Shemdin [28] suggests that surface drift is caused by the tangential portion of the momentum transfer at the air-water interface. As the friction creates the waves, a horizontal

force on the side of the wave appears. Shemdin used a paper disc neutral buoyancy test to measure the dispersion profile of floating discs in water for wind speeds ranging from 3 m/s to 9 m/s, with results showing a logarithmic profile as illustrated in Figure 2.9. The experiments concluded that surface drift speed is 3% of the free-stream air velocity, U_{10} , or $0.6u_*$.

Figure 2.9: Air-sea logarithmic velocity profile schematic

If the wind-induced surface current is assumed to be 3% of the U_{10} wind speed for a 10 m/s headwind, the surface current would be 0.3 m/s. Resistance prediction curves and tow tank testing results by Scragg & Nelson [29] for eight-oared rowing shells suggest that for a streamlined hull of similar displacement, the resistance at 0.3 m/s is negligible compared to the viscous hull resistance at racing speeds.

Reflected wave resistance

A study by Kwon [30] considers the reflection of short waves ($0.2 < \lambda/LOA < 1.2$) as added hull resistance when they collide with the hull. Scaled model experiments in a tow tank found that the added resistance increased as the wavelength to wave height decreased, suggesting that for young, closely spaced waves, the reflected wave resistance can be a factor. It should be noted that the results by Kwon are from experiments on a model with ship form, where the hull shape is far less streamlined than a kayak, but that the results do agree with a K1 kayak experimental test by Tzabiras et al [31]. The purpose of the experiment

by Tzabiras et al was to quantify the added resistance on a K1 Olympic kayak using a tow tank and regular sinusoidal waves at a range of frequencies. The results have shown that for wavelengths longer than the kayak, there was little added resistance, but for higher frequency waves, more representative of short fetch wind waves, there was an increase in hull resistance of up to 12%.

2.3 Conclusions

Kayaker component shapes and flow interaction is expected to influence the aerodynamic drag of a sprint kayaker, creating a unique C_D , which is sensitive to flow regime and therefore velocity profile and turbulence characteristics. To simulate sprint kayaker aerodynamics reliably, similarity of posture, body shape, equipment and free-stream flow conditions are required. For simulation of the free-stream flow, high frequency turbulence and velocity profile should be matched to the local field of play. With large local variability for wind over water characteristics, theoretical logarithmic profiles provide an estimate that is useful for prediction but may differ from experimental measurements. For small lakes and basins where kayak races take place, limitations to fetch and water depth narrow the variability of the wave development, but the local shoreline structures and atmospheric stability may change considerably between venues.

Chapter 3

Experimental setup for ABL field measurements

To better understand wind characteristics on the field of play for a kayaker, including the instantaneous profiles of velocity, turbulence intensity and length scale over 1 m height from the water surface, field testing was carried out. Wave height, wind direction, location along the course and time of day were also recorded for comparison of wind consistency and to observe the parameters that may affect a kayaker's performance. Although it is expected that variation between venues would affect results, a single site was chosen for practical reasons. The site was at a natural body of water with some current, where shoreline topography varied over the length of the course, which represented the complexity that can be found at competitive sprint kayaking venues.

The test setup, instrumentation details and measurement uncertainty are explained in the following.

3.1 Site details and test setup

The tests took place at a river with a slow current that is approximately 5 m deep, where an official sprint kayaking course is set for training and race purposes. Tests were run on days with no precipitation during the month of July, 2017.

Figure 3.1: Field test site: Mooney's Bay, Ottawa

Figure 3.1 shows site details and measurement locations with the course lanes represented by dashed lines which are marked on site by permanently anchored buoys. The buoys were used to locate the research platform at the predefined locations A-B-C.

The platform was anchored during testing and allowed to self align with headwinds before measurements were taken. During the tests at each location, wind direction did fluctuate for portions of a sample period, but not for long enough to move the test platform.

A twin pontoon platform was used for testing, with sensor apparatus mounted in flow undisturbed by the platform at the end of a bow pole and on a mast as shown in Figures 3.2, Figure 3.3 and Figure 3.4.

The test matrix was designed to collect data during the time of day expected for kayak races, with rotation of the test sequence for the predefined locations to improve random sampling within the overall daily time frame. The wind profile measurement system included three pressure sensors mounted on a bow apparatus and a wind speed cup anemometer mounted on a midship mast. The wave height distance sensor was also mounted on the bow apparatus.

Figure 3.2: Field test: elevation and plan view of the research platform setup

Figure 3.3: Mooney's Bay field setup, July 2017

Figure 3.4: Bow apparatus details

A data acquisition device (DAQ) with three single-ended inputs was used for the bow apparatus, therefore two configurations were required to collect data from the four bow apparatus sensors. Configuration-1 collected wind speed data at four heights and configuration-2 collected wind speed data at three heights and wave height. At each test location, data sets were taken for both configurations, one immediately after the other.

All bow apparatus tests had a sample rate of 256 Hz for 120 s. The sample frequency was chosen to record the turbulence spectrum found by Donelan et al [18] for wind over an inland lake. The duration of the tests was chosen to capture the low spectrum of the expected high-frequency turbulence while remaining within the datalogging capacity of the wireless DAQ and the number of expected daily tests. The Table 3.1 test plan shows the test matrix used for data collection from the bow pole apparatus for wind speeds ranging from 1 m/s to 6 m/s at 1 m above water line (AWL). Data from the mast anemometer were collected throughout the test period at a preset sample rate of 1 Hz and were limited to collecting wind speeds above 1.5 m/s.

Table 3.1: Field test matrix

Test	Location sequence	Date	Configuration
1	BC, CB*	July 4	1,2
2	ABC, CBA	July 6	1,2
3	B,BC,B**	July 12	1,2***
4	B,CC,BB*	July 25	1,2

* data collection prevented at location *A* by platform shifting due to river current

** data collection sequence interrupted by rain and insufficient wind speed

*** wave height measurements missing due to disconnected cable

3.2 Instrumentation

The bow apparatus measured wind pressure within one metre of the water surface at three heights along with wave height. The system included three vertically equidistant Pitot-static probes and a laser distance sensor. The cup anemometer, mounted 2.5 m AWL on a mast, was considered supplemental to the bow apparatus and used to extend the wind profile data by increasing the number of points defining the velocity profile shape.

Surface water temperature and air temperature at 1 m AWL were also measured for each test period using an immersion thermometer. Hourly reports from a local weather station located at the Ottawa International Airport were used for atmospheric pressure and temperature. The weather station is 5 km SE of the test site with measurements recorded at a height of 10 m above ground.

A spirit level on the platform was used for regular monitoring of the platform balance during testing. Mechanical interference due to the boat stability and apparatus wracking was assumed to be negligible as no peaks at the natural frequencies of the boat were observed in the response spectra of the data. Notes during testing were taken when external disturbances were noticed such as boat traffic, precipitation, or anchor rode interference. This information was correlated with the time series data to provide a proper interpretation of the results.

3.2.1 Bow apparatus system

The bow apparatus had a vane/buoy assembly designed to provide an unobstructed view of the wind which measured the in-line horizontal component of local velocity. The vane/buoy system consisted of the pressure sensor rake which could swivel on a shaft fixed to a buoy. The sensor rake was aligned with the main wind direction using a vane and bearing system which had the ability to follow wind direction for $\pm 180^\circ$ during a test as illustrated in Figure 3.5.

Figure 3.5: Side and plan view of the bow apparatus illustrating the vertical and yaw motion

The pressure sensor assemblies were in fixed alignment with one another, connected by carbon fibre tubing which was also used as wiring conduit. The height of the probes above waterline was maintained by the buoy which was constrained horizontally, but allowed to bob vertically.

A site test, where the bow apparatus was placed beside the cup-anemometer, with upper probe at the same height as the cups, was used to confirm that the time response to wind direction change was suitable for the requirements of the test. The test had a 256 Hz sample rate for 10 minutes. The velocity results from the upper pressure probe of the bow apparatus showed that the sensor followed the change in wind speed measured by the directionally independent cup anemometer within the instrument cut-in range (above 1.5 m/s for the cup anemometer) as shown in Figure 3.6. The magnitude of the wind measured by the upper pitot-static probe during the dock test covered the full range of wind speeds measured during the field tests at 1 m AWL.

Figure 3.6: Pitot-probe versus cup anemometer dock test results

Although the dock test showed that the upper Pitot-static probe was responding well to wind speed change, the lower probe may not be in-line with the wind due to the location of

the vane on the bow apparatus. A twist in the velocity profile is not compatible with the operating range of the bow apparatus and if present would cause a lower reading on the local wind, especially at the height of the lower probe.

The Pitot-tube angle of attack could also be affected by small changes in the setup angle due to platform motion. The platform motion would include pitch and heel, which would cause misalignment of the probe angle of attack in the vertical and horizontal orientation. The wavelength of the short waves expected on small lakes was assumed to be too small to cause significant pitching or heeling of the anchored 5 m test platform. This was observed to be true and therefore the misalignment of the wind to the Pitot-static probes due to platform motion was within $\pm 10^\circ$. The Pitot-static tube probe, with blunt nose, is considered similar to a small-bore cylindrical tube, which according to Gracey [32] is insensitive to angles of attack up to $\pm 11^\circ$ for subsonic flow, where the error is the same for misalignment of flow in the vertical and horizontal plane for the symmetrical shape. To confirm the insensitivity range, error due to an angle of attack of 10° was determined by testing the sensor rake in a Carleton University wind tunnel. Results found an error of less than 1% for the maximum tested wind speed of 10 m/s.

For the vertical wave motion measurements, a distance sensor was mounted on the end fitting of the bow pole with the laser beam directed downward towards the top of the buoy. The alignment of the distance sensor to the buoy was fully constrained, allowing movement in a single direction, and therefore results were not affected by platform motion.

To ensure the displacement of the buoy placed the water line at the desired location, a weight estimate was carried out, which showed that the system needed to be as light as possible, resulting in a bow apparatus weight of 0.7 kg. The lightweight system was also expected to minimize wave damping and reduce probe alignment delay.

A 12-bit MicroStrain V-Link-LXRS wireless DAQ was used for the vane/buoy system data collection, which corresponds to 4096 discrete values between 0 V and 3 V and a voltage resolution of 0.0007 V. The DAQ also provided a regulated 3 V DC supply to the pressure transducers.

The V-Link wireless DAQ configuration and datalogging was controlled by a MicroStrain WSDA-base connected to a laptop computer on the research platform as seen in Figure 3.7.

Figure 3.7: Bow apparatus DAQ system

Pressure sensors

Sensirion SDP800 series analog differential pressure transducers with a range of 0 Pa to 125 Pa were used. The sensors have a patented CMOSens technology utilizing a micro-thermal flow sensor embedded within a silicon chip that the air passes over.

Figure 3.8: Bow apparatus pressure sensor assembly

The sensors were connected to 100 mm long Eagle Tree Systems Pitot-static probes with 4 mm outside and 1 mm inside diameters using 150 mm of Tygon tubing. All sensor/probe assemblies were mounted within a custom printed P400 Acrylonitrile butadiene styrene (ABS plastic) casing for environmental protection and mechanical arrangement as shown in Figure 3.8. The pressure sensors were calibrated in a Carleton University wind tunnel to determine individual calibration curves for the field testing wind speed range. Results and a detailed description of the wind tunnel calibration tests are presented in Appendix A.

Distance sensor

The distance sensor was a Wenglor CP35MHT80 which was supplied with 24 V DC excitation power using a DDC30 Series XP power converter connected to a 12 V platform battery. The 10 V sensor output was reduced to 2.5 V to meet the maximum 3 V input requirement of the V-Link DAQ using a 0.25 resistor ratio divider.

The arrangement of the distance sensor on the bow apparatus is shown in Figure 3.9.

Figure 3.9: Bow apparatus wave height sensor setup

A laboratory static calibration was carried out as described in Appendix A which found results to be within ± 1 mm. During field testing, it was observed that systematic error, due to bow apparatus linear bearing resistance and wave/buoy interaction, caused the measured

distance results to be lower than observed by visual inspection. Uncertainty due to the field test environment is described in more detail in the uncertainty analysis section of this chapter.

3.2.2 Mast cup anemometer

Figure 3.10 shows the Inspeed Vortex 3-cup wind speed sensor at the mast head, which was an autonomous system with an internal DAQ. The wind direction sensor did record data, but was not used, as direction was noted at the platform by reading of a compass. A USB connection allowed for downloading of wind velocity and time stamp data at a 1 Hz sample rate for each test duration. The unit was considered supplementary to the primary pressure sensor rake, and therefore details on the internal hardware or software are not reported here.

Figure 3.10: Cup anemometer setup

3.2.3 Calibration and data reduction

Pressure transducer data and velocity calculations

Prior to field testing, wind tunnel testing was used to determine zero offset and pressure to output voltage calibration curves for each pressure transducer using a 10:1 inclined chamber volume manometer with a Pitot-static probe. A unique curve and zero offset was determined for each sensor as reported in Appendix A.

The sensitivity within a 10° cone was also measured in the wind tunnel and added to the field test uncertainty to account for Pitot-tube misalignment with the field test water-plane and/or wind direction.

Using the wind tunnel calibration results, field test data were converted to differential pressure, ΔP , after each test which was used to determine velocity for each time series as follows:

$$U = \left(\frac{\Delta P}{0.5\rho} \right)^{0.5} \quad (3.1)$$

where U is the instantaneous streamwise velocity and ρ is air density.

Density was found using the ideal gas law:

$$\rho = \frac{P_a}{RT} \quad (3.2)$$

where P_a is atmospheric pressure from an hourly local weather station report, R is the specific gas constant for air, and T is the temperature measured 1 m AWL at the platform.

The streamwise velocity was determined from an average of the instantaneous velocity over the length of a steady wind interval found for each time series at each Pitot-probe height. Detail on the criteria used to determine the length of a steady wind interval is explained in Chapter 4, where raw data for velocity are presented. Notes taken during testing were also used to filter out any non-representative data due to boat traffic, anchoring issues or unsuitably low wind speeds.

Wave height data

The wave height sensor was statically calibrated while mounted on the bow apparatus, where incremental heights were measured from the laser to the top of the buoy using a standard tape measure with accuracy of ± 1 mm. The calibration results presented in Appendix A provided a linear voltage-to-displacement relation which was used to estimate maximum wave height for each field data series.

Cup anemometer data

The cup anemometer was calibrated in a wind tunnel using the same setup as for the pressure transducer calibration. Results showed that a correction was required to the manufacturer's calibration as presented in Appendix A. Results from the cup anemometer were synchronized to the bow apparatus data using a manually recorded timestamp with a 1 s resolution taken at the start of sampling. The mean wind speed from the cup anemometer results was then selected for the same 20 s interval chosen from the pressure transducer results.

3.3 Pitot-probe rake velocity uncertainty analysis

To determine systematic and random error, all known instrumentation and equation propagation error was determined. For the uncertainty calculations, the root-sum-squares (RSS) method was used as follows [33]:

$$\mu_x = \sqrt{\mu_1^2 + \mu_1^2 + \dots + \mu_k^2} \quad (3.3)$$

where μ_x is the total system uncertainty and μ_{1-k} are instrumentation errors.

3.3.1 Wind profile error

Since wind speed is a function of differential pressure and air density, error is present for each of the bow apparatus velocity measurements as described in the following.

Pressure transducer

The known systematic error for the pressure transducers comes from the DAQ quantization error, μ_Q , zero offset drift, μ_0 , and temperature shift, μ_T . Temperature sensitivity was not tested and therefore the manufacturer's specification of $< 0.5\%$ of reading per 10°C was used. The zero offset was checked regularly throughout the field testing by running a test with crimped Tygon tube sleeves covering the probes. The maximum zero offset change during testing was then used for the zero drift error.

For random error, the calibration tests were used to determine a 95% confidence interval error, μ_{95} , with a $\pm 10^\circ$ angle of attack tolerance, μ_{10} .

The total known systematic error, μ_B , and random error, μ_S , were used to determine the differential pressure error, $\mu_{\Delta P}$, as follows:

$$\mu_{\Delta P} = \sqrt{\mu_B^2 + \mu_S^2} \quad (3.4)$$

where

$$\mu_B = \sqrt{\mu_Q^2 + \mu_0^2 + \mu_T^2} \quad (3.5)$$

and

$$\mu_S = \sqrt{\mu_{95}^2 + \mu_{10}^2} \quad (3.6)$$

3.3.2 Error propagation

For error propagated through the calculation of velocity from equation (3.1), the polynomial and fractional relations are accounted for as follows:

For polynomial equations, where:

$$X = Y^n \quad (3.7)$$

the error is found by:

$$\mu_X = |n| \frac{\mu_Y}{Y} |X| \quad (3.8)$$

For fractional equations, where:

$$X = \frac{Y}{Z} \quad (3.9)$$

the error is found by taking the partial derivatives as follows:

$$\mu_X = \sqrt{\left(\frac{\partial X}{\partial Y} \mu_Y\right)^2 + \left(\frac{\partial X}{\partial Z} \mu_Z\right)^2} \quad (3.10)$$

The resulting equation for the propagation of error for the velocity, μ_U , is therefore:

$$\mu_U = 0.5 \left[\sqrt{\left(\frac{\partial U}{\partial \Delta P} \mu_{\Delta P} \right)^2 + \left(\frac{\partial U}{\partial \rho} \mu_{\rho} \right)^2} \right] \quad (3.11)$$

where $\mu_{\Delta P}$ is differential pressure error and μ_{ρ} is density error. As density is a function of atmospheric pressure and temperature, the error is a result of changes in atmospheric conditions on site. Atmospheric pressure had a maximum deviation for a test period of 160 Pa, where air temperature was found to vary over the 1 m AWL region by no more than 1 °C. Therefore, error in density was calculated for that range of deviation and included in the propagation of error calculations.

The resulting total error in the velocity, measured by the mid-height Pitot-probe on the bow sensor rake, is presented in Table A.3.

Table 3.2: Mid sensor velocity uncertainty

Output (V)	U (m/s)	μ_U (m/s)	% error
0.01	1.564	0.171	11.0
0.02	2.209	0.122	5.5
0.05	3.477	0.081	2.3
0.10	4.881	0.065	1.3
0.15	5.932	0.061	1.0
0.20	6.797	0.060	0.9
0.25	7.540	0.061	0.8
0.30	8.193	0.062	0.8
0.35	8.778	0.063	0.7
0.40	9.307	0.064	0.7
0.45	9.788	0.065	0.7
0.50	10.230	0.066	0.6
0.55	10.636	0.066	0.6
0.60	11.010	0.067	0.6
0.65	11.358	0.067	0.6

The error results for all of the pressure sensors are presented in Appendix A.

3.4 Wave height uncertainty

Although the distance sensor is a high-precision device which gives a direct result with calibration accuracy found to be within ± 1 mm, the test setup and field environment added error. For large regular waves created by the wake from other boats, pitching motion was observed and data excluded. Platform motion was not observed for the short wind-waves, but other mechanical and alignment errors were observed. The wind-waves were not organized into a single continuous wave, but typically formed a pattern of short span waves with irregular amplitudes as shown in Figure 3.11 and 3.12.

Figure 3.11: July 6, location B, maximum wind speed, $U_1 = 6$ m/s

Figure 3.12: July 25, location C, $U_1 = 3.5$ m/s

Therefore, the buoy measurement system was not aligned with the peaks and troughs continuously and an assumption was made that within the 120 s time series, a maximum peak-to-trough height was captured. Damping due to some resistance in the linear bearing at the bow pole fitting was also noted. Therefore, the results from the wave measurements are considered useful for a general relationship between wind speed and wind-waves for the test location with an observed uncertainty of +20 mm to account for underestimation of wave height.

Chapter 4

Field measurement results for wind over water

The vertical profile of wind was measured over a small inland body of water at an official sprint kayaking course to determine whether the velocity profile follows a theoretical logarithmic curve for atmospheric wind over water. Turbulence intensity and length scale were determined from the measurements to understand better the turbulent structures within the atmospheric boundary layer (ABL) above water for light winds. Wave height was also measured to show the state of the water surface with respect to the magnitude of winds on the field of play.

4.1 Time series data reduction

At the test site, four days during the month of July had conditions favourable to testing with light winds and no precipitation for the length of a test period. Over the four testing periods, data were collected for two sensor configurations to measure wind profile and wave height. The wind profile sensor array included measurements taken with a Pitot-probe rake at 0.2, 0.6 and 1.0 m above water line (AWL) and with a cup anemometer speed sensor at 2.5 m AWL. Data measured with the four wind sensors has been named configuration-1. For measuring the wave height, a second setup, configuration-2 was used. For configuration-2, the sensor at 0.6 m was disconnected from the data acquisition system to provide a data acquisition channel for the wave height sensor. Figure 4.1 shows an example of a time series collected for the two configurations, where the average wind speed for the full duration of the

time series is noted on the left and the height above water level of each sensor is labelled at the right of each configuration. Appendix B presents the full range of configuration-1 and configuration-2 data sets for the tests where wave height data were extracted.

a) Configuration-1

b) Configuration-2

Figure 4.1: An example of the configuration-1 and configuration-2 time series results

For configuration-1, all time series were visually inspected to locate a steady wind interval lasting 20 s to ensure that post processing of the turbulence characteristics was representative of the fluctuating velocity component and not a result of short duration wind speed changes. Given that the lower end of the high-frequency turbulence activity is expected to be around 1 Hz according to wind over water measurements by Donelan et al [18], having 20 s of data captures a sufficient number of the large turbulent structures for a sound statistical result. For the high frequency end of the spectrum, the turbulence is expected to be around 100 Hz, which was assumed to be within the frequency response of the pressure transducers connected to the Pitot probes which have a manufacturer's response specification of more than 200 Hz, and were shown to capture frequency at 256 Hz. Fluctuating pressure signal distortion due

to a possible resonance in the tubing connecting the Pitot-probes to the pressure transducers was assumed negligible as the length of tube was less than 150 mm. For the steady wind interval, the standard deviation from the mean wind speed was not more than 20% for the three heights measured. From 19 time series, 16 were found to have a 20 s steady wind interval.

For configuration-2, wave height time series were collected for 11 tests, with 9 time series having wave data for which height and frequency trends were extracted.

During each test period, the measurements were taken at three locations, designated as A, B and C, along the 1000 m kayak course, with a distance between A and B of 400 m and between B and C of 600 m. Although the intention was to measure at each location sequentially, the anchoring system did not work when winds were opposing the river current at location A. Therefore, more samples were obtained from locations B and C. For a detailed map of locations the reader may refer to Chapter 3, Figure 3.1.

4.1.1 Atmospheric stability condition

For the velocity measurements, the instantaneous velocity was averaged over the 20 s steady wind interval for each height. The results were then overlaid onto the theoretical logarithmic profile for comparison. To determine whether an atmospheric stability correction to the theoretical neutral logarithmic profile was needed, the air temperature at the test platform was measured at $z \sim 0.02$ m and 1 m above water. The Richardson number, Ri , was then used to determine the stability condition as follows:

$$Ri = \frac{g}{\bar{T}} \frac{d\bar{T}/dz + \Gamma}{(d\bar{U}/dz)^2} \quad (4.1)$$

where g is gravitational acceleration, $\bar{T}$ is mean temperature at 1 m AWL, $d\bar{T}/dz$ is the gradient of mean temperature, Γ is the neutral temperature gradient (0.0098 K/m) and $d\bar{U}/dz$ is the wind speed gradient over the noted height. Ri is negative for unstable conditions, positive for stable conditions, and zero for neutral conditions. For the atmosphere, the magnitude of absolute Ri values increases with altitude. Therefore, for the measurement at 1 m AWL, Ri

is expected to be small. From a study on the Ri by Hansen [34], a large data set was used to establish Ri with respect to altitude. For measurements at 3 m above ground, the average Ri was 0.1 for the stable condition and -0.03 for the unstable condition.

For the field tests, a range in Ri from -0.005 to 0.002 was found for the temperature gradient between the water surface and 1 m AWL. The unstable condition ($Ri = -0.005$) was present at the start of tests on July 25, at 11:30 am, after a low overnight air temperature. The unstable temperature gradient within 1 m AWL did not last for more than an hour after the start of testing. The range of Ri values for the tests suggests that the atmospheric condition was shifting during the field testing, but for the height of interest, was nearly neutral.

Alternatively, the Monin-Obukhov length, L , may be used for stability classification:

$$L = -\frac{\bar{T}}{g\alpha} \frac{u_*^3}{\langle wT \rangle} \quad (4.2)$$

where $\bar{T}$ is the mean value of absolute temperature at 1 m above water, u_* is friction velocity, g is gravitational acceleration, α is the von Kármán constant (0.41), and $\langle wT \rangle$ is the vertical temperature difference between $\bar{T}$ and the air at the water surface. To determine the friction velocity, u_* , Equation (6.2) was used, as explained in the next section, where the measured average steady wind velocity at 1 m was used.

The resulting L from the field results ranged from -0.12 to 0.45, which does not fit within stability classification. According to Peña et al [23] the stability classification starts at $L \geq 10$ for stable conditions and $L \leq -50$ for an unstable atmosphere.

The stability evaluation results for both methods suggest that the vertical temperature difference during tests, which was no more than 2.5 °C within 1 m AWL, does not have a significant impact on the theoretical velocity profile for the height of interest. Therefore, the atmospheric condition was deemed to be neutral during all tests and no stability correction to the neutral logarithmic profile was made for the comparison of the measured data to the theoretical ABL velocity profile.

4.1.2 Theoretical ABL velocity profile

To compare the velocity data to the theoretical logarithmic profile for wind over water, a measured reference velocity at a specific height is needed. For many applications, the height at 10 m is appropriate. For the kayaker, where local wind is of interest, a reference height within the height of the kayaker, measured during a race, is more relevant and practical. As noted in the previous section, an added benefit to using a reference wind speed at 1 m AWL is that the deviation of the velocity profile caused by stability conditions is minimized because the range of interest is small. Therefore, when calculating the logarithmic profile, the friction velocity, u_* , is found using a reference height of 1 m in the following equation:

$$u_* = \left[\left(\frac{1}{\alpha \bar{U}_1} \right) \ln \left(\frac{zg}{A u_*^2} \right) \right]^{-1} \quad (4.3)$$

where $\bar{U}_1$ is the measured time-averaged streamwise velocity at $z = 1$ m AWL.

The friction velocity is then used in the theoretical logarithmic ABL profile for wind over water according to the following equation:

$$\bar{U} = \frac{u_*}{\alpha} \left[\ln \frac{z}{z_0} \right]; \quad \text{where} \quad z_0 = A \frac{u_*^2}{g} \quad (4.4)$$

where $\bar{U}$ is the average wind speed at height z , α is the von Kármán constant (0.41), u_* is the friction velocity, z is height above water, z_0 is the surface roughness length, g is gravitational acceleration and A is the Charnock constant (0.0144).

4.2 Results of steady wind velocity profile measurements

Daily results for the average of each 20 s steady wind interval are shown in Figures 4.2 to 4.5 with the z -axis extending to 3.0 m. Although the 2.5 m AWL cup anemometer measurement system was not in use for July 4 or July 6 for technical reasons, the z -axis has been kept consistent for all velocity profile graphs.

Figure 4.2: July 4, 16:30 - 17:30

Figure 4.3: July 6, 13:30 - 15:00

Figure 4.4: July 12, 10:00 - 12:00

Figure 4.5: July 25, 11:30 - 12:30

For July 12, the cup anemometer results were not useful for two of the profiles due to low speed cut-out. The cup anemometer data points are represented by a triangle pointing towards the theoretical curve belonging to the data set, with uncertainty error bars.

The measurements taken at $z = 0.2, 0.6$ and 1.0 m are the average velocity for the 20 s steady wind interval measured by the Pitot-probe rake system installed at the bow. The resulting data points are denoted by a diamond marker with wind uncertainty error bars.

Test location (A,B,C) and theoretical wind speed at $z = 10$ m, U_{10} , are noted at the top of each velocity profile curve. The U_{10} wind speed has been shown to provide a perspective on the approximate magnitude of the wind speed at standard weather station height at most airports.

Pitot-probe rake results

The results show a range of U_{10} wind speeds from 2.0 m/s to 7.1 m/s for test periods ranging from 1 to 2 hours in length. The Pitot-probe rake results follow a logarithmic profile within the measurement uncertainty for 81% of the steady wind intervals.

For the 19% of Pitot-probe rake data sets that do not fall onto the theoretical profile, most show a higher wind speed at 0.6 m with a lower wind speed at 0.2 m. The curve where this pattern is most evident is for July 6, at location C, with a $U_{10} = 4.7$ m/s. For the data points that do not fall on the theoretical curve, the maximum deviation is 0.1 m/s. The deviation could be an actual change in the profile shape or a result of unknown systematic error. One systematic error unaccounted for is due to the vane system. The rigid vane setup, which aligns the Pitot-probe rake with the wind direction, was not sensitive to twist in the wind profile. If twists were present, the lower probe is expected to be most affected and underestimate the wind speed as the vane is located between the mid and upper probes.

July 6 had the largest range of wind speeds since the wind was increasing throughout the 1.5 hour testing period. A range of 4 m/s at $z = 1.0$ m was measured during the test period for the 20 s steady wind intervals, which had a mean standard deviation of less than 18%. For kayak races, which include heats, semifinals and finals, a kayaker may race at a different

time within a day, than an opponent. The wind speed results for this test period demonstrate that the wind speed can change significantly between races within a short time frame.

For the 16 steady-wind velocity profiles, 2 sets were found with the same magnitude for different days. For July 6, a set at location A and C (1000 m apart) was measured for the 1.5 hour time frame. The second set was found at a single location, B, within a 10 minute time frame. For the remainder of the measurements, the steady wind velocity was found to vary in magnitude for each time series and for each location.

Cup anemometer results

The cup anemometer results showed deviation up to 0.5 m/s from the logarithmic profile. Whether the variation in results for the 2.5 m AWL height are due to instrumentation error or the real ABL profile, is not certain. The cup anemometer is non-directional in the horizontal plane. Therefore, if momentary side winds were present they are included in the measurement whereas the bow apparatus vane system limits the Pitot-probe measurements to a narrow dominant wind angle which was observed to be less than 10° . Typically, the addition of a side wind force and higher turbulence intensity would increase the over-speeding of the cup anemometer in comparison to the calibration done in a wind tunnel, according to Hansen et al [35]. The over-speeding is caused by the non-linear response to wind fluctuations, where the cup anemometer geometry causes the sensor to increase in speed with wind readily, but shows a delay in deceleration when winds decrease. From the dock calibration test reported in Appendix A, where ABL side winds and high turbulence intensity were present, the cup anemometer reading was typically higher than the Pitot-probe readings. When compared to the theoretical logarithmic profile prediction for that height, some of the cup anemometer results were higher, but most showed a velocity that was slower. This suggests that the results which were slower than predicted by the logarithmic profile were not due to instrumentation error, but were in response to the wind speed at the cup anemometer height, $z = 2.5$ m.

With respect to a kayaker, where the height of interest including the upright paddle blade, is within 1.4 m AWL, the cup anemometer results do not present enough of a deviation from the logarithmic profile to disprove the theoretical profile within the height of interest.

Further testing of the cup anemometer system would be necessary to shed light on the noted discrepancy between the cup anemometer and Pitot-probe velocity measurements.

4.2.1 Velocity profile for unsteady wind

For measurement of wind speed at a kayaking event, it is not likely that data will be reviewed to determine a steady wind interval. Therefore, the results from each time series for configuration-1 have been averaged for the full 120 s sample to compare to a logarithmic profile where the reference velocity is the measured $\bar{U}_1$ and $A = 0.0144$. For the full range of 19 samples, 84% had results which fell on the logarithmic profile within the sensor uncertainty.

Figure 4.6: Velocity profiles for a 120 s time series average

Selective profiles shown in Figure 4.6 demonstrate the results. Although the streamwise wind speed fluctuated by as much as 7 m/s within a single 120 s time series, the logarithmic profile appears to be maintained while the wind changes in magnitude.

4.2.2 Wind speed sensitivity to location and time

To observe the sensitivity of the average velocity over the 120 s sampling duration to a constant time lapse and location, the results for configuration-1 and configuration-2 have been compared. The configuration-2 test was started 4 minutes (on average) after configuration-1. Table 4.1 shows the change, $\Delta\bar{U}_1$, in the measured average wind speed over 120 s at 1 m AWL between the configuration-1 and configuration-2 results.

Table 4.1: Change in $\bar{U}$ at $z = 1$ m within 4 minutes

Day in July	Location	$\Delta\bar{U}_1$ (m/s)
4	B	0.71
4	C	1.17
6	A	0.24
6	A	0.32
6	B	0.69
6	B	0.06
6	B	0.91
6	C	0.21
6	C	0.23
12	B	0.00
12	B	0.28
12	C	0.26
25	B	0.61
25	C	0.50
25	C	0.51

All but one comparison showed a change in wind speed at 1 m AWL for the 4 minute time lapse, with a maximum deviation observed at location C of 1.17 m/s. Although some location-specific consistency in $\Delta\bar{U}_1$ was found on a single day, a larger sample would be required to identify trends.

4.2.3 Wave height results

For each 120 s time series of wave height data, the results were visually inspected to find the maximum wave height, which was typically found for two to three wave periods at separate times within each sample. From 11 tests, 9 were used to determine wave height. Two tests were rejected after observation during testing of interference between the buoy and anchor rode. The results for the maximum wave height are expected to be underestimated by as much as 20 mm due to buoy/wave misalignment and mechanical resistance. It was observed that the vertical motion of the bow apparatus was not always smooth, appearing to pause momentarily. This could have been a result of the misalignment of the irregular wave peaks with the buoy, or from mechanical resistance at the linear bearings. For either systematic error, the results would have underestimated the wave height. The results are shown in Table 4.2 where H_{max} refers to the maximum wave height and T refers to the wave period for the maximum wave height, but was also found to represent the wave period for the duration of the time series by ± 0.3 s. The fetch is an estimation of the distance between shoreline and sensors with respect to the wind direction measured at the test platform for each sample and is expected to be within 30 m of the actual distance. $\bar{U}_1$ refers to the average wind speed for the 120 s duration of the time series measured at 1 m AWL and U_{10} refers to the approximate magnitude of the wind speed at standard weather station height.

Table 4.2: Wave measurement results

Location	H_{max} (mm)	T (s)	Fetch (m)	$\bar{U}_1$ (m/s)	Theor. U_{10} (m/s)
B	15	0.5	120	2.5	3.0
C	15	0.8	270	2.5	3.0
C	20	0.5	200	3.5	4.3
A	20	0.5	230	2.8	3.4
C	30	0.8	170	3.3	4.0
A	40	0.4	200	3.2	3.9
B	40	0.4	280	3.1	3.8
C	80	0.6	120	3.9	4.8
B	90	0.5	170	5.9	6.7

Rather than the expected positive correlation between wave period and wave height, a mix of heights between 15 mm and 90 mm were measured for a small range in wave period of 0.4 s to 0.8 s or a frequency range of 2.5 Hz to 1.25 Hz.

For the estimated range of fetch from 100 m to 280 m, it was found that wave height was not related to fetch. For the 15 mm wave height in Table 4.2, where the 120 s wind speed average at $z = 1$ m is the same for the two cases, the difference in fetch is 150 m. The fetch and duration of preceding winds is expected to affect the development of the waves, or wave age. For the short fetch across a small body of water, the waves may not have enough distance for their phase speed to accelerate up to the speed of the wind above the water, and therefore reach maximum height. This characteristic of wave development over short fetch has not been considered, as the duration and magnitude of preceding winds was not measured, but may be contributing to the inconclusive relationship between wave height and fetch.

The only observed relationship was found between wave height and the average wind speed at 1 m AWL, $\bar{U}_1$, where the wave height increases with the wind speed as shown in Figure 4.7.

Figure 4.7: Wave height versus wind speed at 1 m AWL

The error bars represent the estimated systematic uncertainty during testing. Although the data points show an increase in wave height with an increase in wind speed, a larger data set is necessary to determine a trend with a level of confidence.

4.3 Wind turbulence characteristics

Turbulence characteristics were found through the instantaneous velocity measurements at a sample rate of 256 Hz. The results have been used to determine the turbulence spectrum, turbulence intensity and the turbulence length scale as described in the following.

4.3.1 Turbulence spectrum

The turbulence spectrum for two 20 s steady wind intervals is shown in Figure 4.8, for a $\bar{U}_1$ wind speed of 1.7 m/s and 5.7 m/s. The energy corresponding to each frequency is shown in a one-sided spectral density, $S_{uu}(f)$, versus frequency, f , plot. The spectral density follows an inertial subrange decay of $-5/3$ out to 100 Hz for the lower wind speed.

Figure 4.8: Turbulence spectra: for measured steady wind cases with minimum and maximum speed

For the higher wind speed, the decrease in spectral density with increasing frequency follows a rate of -5/3 at lower frequencies and a rate of -3 at higher frequencies.

Turbulence spectrum for all of the 20 s steady wind intervals and the full 120 s time series showed a spectral density trend similar to the two shown in Figure 4.8.

4.3.2 Turbulence intensity and integral length scale

The turbulence intensity and integral length scale were determined from the instantaneous velocity for each 20 s steady wind interval. The steady wind interval was used to ensure the changing wind speed did not influence the turbulence results.

Turbulence length scale

The integral length scale, which is a measure of the dominant gust size, can be found from the instantaneous velocity data using the “spectral fit” technique described by Teunissen [36] where the peak in the wavenumber spectrum is used to determine the integral length scale from the following relationship:

$$k = \frac{2\pi f}{\bar{U}} \quad (4.5)$$

where f is frequency and $\bar{U}$ is mean velocity. The dominant wavenumber for the spectra provides the integral length scale or wavelength, λ , defined as:

$$\lambda = \frac{1}{k} \quad (4.6)$$

Figure 4.9 illustrates the method, where the wavenumber spectrum is shown, with a resulting integral length scale, L_u^x , of 0.8 m. The figure also represents a general shape found for most of the results, where a broad crest in the spectrum suggests that a range of gust size exists at similar magnitude to the dominant gust size, or integral length scale.

Figure 4.9: Field measurement wavenumber spectrum: July 6, $z = 0.2 \text{ m}$

The average length scale from the steady wind data are graphed in Figure 4.10 with error bars representing the standard deviation from the mean at each height.

Figure 4.10: Field test integral length scale results at $z = 0.2, 0.6, \text{ and } 1.0 \text{ m}$

The axis ratio in Figure 4.10 has been set to 1:1 to show the anisotropy of the eddies. The measured average length scale of approximately 1 m, is expected to be constant for wall normal distribution within the logarithmic region [37].

Turbulence Intensity

The streamwise turbulence intensity, I_{uu} , is defined as the ratio of the standard deviation of velocity fluctuation, σ_u , to the average wind speed, $\bar{U}_z$, at height, z :

$$I_{uu} = \frac{\sigma_u}{\bar{U}_z} \quad (4.7)$$

To determine the turbulence intensity, the steady wind interval of 20 s was used, eliminating the temporal effect of change in magnitude of the wind in the ABL.

Figure 4.11: Average field measurement turbulence intensity at $z = 0.2, 0.6$, and 1.0 m

Turbulence intensity corresponding to the steady wind configuration-1 field test data are shown in Figure 4.11. The average longitudinal turbulence intensity is not uniform with

respect to height, with the highest level found closer to the water surface, which is expected within the logarithmic region of the boundary layer. All results were within a range of 8% to 17%. For the wind speeds measured, no apparent trend was found between the magnitude of I_{uu} and wind speed.

The turbulence results are within reason when compared to results from open sea ABL tests carried out by Solov'ev and Ivanov [38], where turbulence intensity was found to range from approximately 15% to 23% at a height of 1.7 m AWL measured for a wind speed range from 1.5 m/s to 20 m/s with an offshore fetch range from 0.6 km to 2.0 km.

4.4 Summary

The field test results from measurements taken during the month of July at an official kayaking course on a small inland body of water, show that the wind profile within the height above water of a kayaker and the associated waves have the following characteristics:

- The atmospheric velocity profile followed a logarithmic growth with height for over 81% of the measurements, where the roughness length was determined using a Charnock number of 0.0144 and the reference velocity was taken as the measured streamwise wind speed at $z = 1$ m. A roughness length range of 3×10^{-6} m to 9×10^{-5} m was found for the 1 m AWL wind speed range of 2 m/s to 6 m/s, which fits within the range of 10^{-9} m to 10^{-2} m suggested by Donelan [3] for an air-sea wind excited surface.
- An average of the unsteady velocity data for each height over a full 120 s sample period was also shown to fit a logarithmic profile for 84% of the data set, showing that the logarithmic profile is maintained on average during unsteady ABL winds.
- Turbulence characteristics for 20 s steady wind intervals, with a mean wind speed standard deviation of less than 20%, were analyzed to understand the turbulent structures creating the ABL velocity profiles. Turbulence intensity results showed a range from 8% to 17% with an increase closer to the water surface. The average integral length scales, Lu^x , were approximately 1 m at $z = 0.2$, 0.6 and 1.0 m.

- Results showed a range in wave height from 15 mm to 90 mm for a wind speed at kayaker head height, $\bar{U}_1$, of 2.5 m/s to 5.9 m/s. The measurements were intended to give a general wave height range at an inland lake kayaking venue for light winds. A larger sample size is needed to confirm the trend of the positive correlation between wave height and wind speed.

Chapter 5

Experimental setup - wind tunnel

Tests were performed on a $\frac{1}{6}$ model elite sprint kayaker in a low-speed wind tunnel at Carleton University for a Reynolds number range of 1.0×10^5 to 2.7×10^5 based on the torso diameter taken at mid torso height.

Variation of the drag force on the model was evaluated for three flow conditions: uniform velocity profile with low turbulence and two non-uniform velocity profiles with turbulence.

Details of the experiment including wind tunnel setup, instrumentation, model information, flow conditioning measurement and measurement uncertainty are presented in the following.

5.1 $\frac{1}{6}$ Model kayaker experiment

The closed-loop 0.76 m x 0.51 m wind tunnel used for this experiment was designed for blunt bluff body testing with a maximum flow speed at the 1.83 m long test section of 60 m/s. Velocity distribution at the test section inlet is uniform to within 0.4% with a measured 0.15% longitudinal turbulence intensity. The test section inlet uniformity and low turbulence level is achieved using a 12:1 contraction ratio with flow straightening honeycomb screens upstream of the test section.

To produce the non-uniform velocity profiles for the model kayaker tests, grids with varying dowel diameter and spacing were placed at the test section inlet.

5.1.1 Test section sensor and model arrangement

Two wind tunnel test section setups were required to determine the kayaker's aerodynamic drag. The first test setup measured the test section velocity profile for each of the three flow conditions. The second test was set up to measure aerodynamic drag of the model kayaker, for each flow condition.

Flow condition test setup

The flow condition test setup included a traversing Cobra Probe, fixed location pitot-static tube and flow conditioning grids. The Cobra Probe was used to measure the flow velocity and turbulence profiles at the leading edge of the kayak. As the Cobra Probe system would obstruct the flow upstream of the model kayaker, it could not be present for the drag measurements. Therefore, a datum, or reference velocity, was required that would measure flow speed for the flow condition tests and the aerodynamic drag tests. A Pitot-static probe was placed in the same plane as the kayaker body and used to determine reference velocity for all testing.

Aerodynamic drag test setup

The aerodynamic drag test setup included the fixed location Pitot-static tube, $\frac{1}{6}$ model kayaker, load cell and flow conditioning grids. The kayaker model was located at the downstream end of the test section to maximize fetch length between the tunnel inlet grids and the leading edge of the model kayaker.

Figure 5.1 and 5.2 illustrate the test section layouts with dimensions relative to the model head height, h , and tunnel width, w .

For flow conditioning grid geometry refer to Appendix D.

Figure 5.1: Test section setup: flow condition measurements

Figure 5.2: Test section setup: aerodynamic drag measurements

5.1.2 Instrumentation

All measurement systems were connected to a National Instruments USB-6251 A/D 16-bit data acquisition device (DAQ) through a Turbulent Flow Instrumentation Ltd (TFI) interface unit. Dedicated TFI Device Control software was used to set sampling rate and collect data for the flow and drag measurements.

DAQ setup

To configure the TFI sampling rates, two terms are used. The acquisition scan rate and the data output rate. The frequency that the raw data is sampled at per channel is the acquisition scan rate. The frequency that the data is output to file, is the data output rate. The TFI system uses down-sampling and low-pass filtering to process the raw data acquired at the acquisition scan rate into the output rate data. This prevents aliasing caused by frequencies in the sampled signal that are larger than half the sampling frequency and reduces measurement noise, while outputting data at a lower desired frequency.

For the flow condition measurements, the DAQ sampling was set to 2 kHz output rate, with a 1024 block size, which fixed the sampling time for the desired 15 s to an exact value of 15.36 s, with 30,720 samples.

For the aerodynamic drag measurements, the DAQ sampling was set to 1 kHz output rate as required by the return rate of the load cell raw data to the receiver. For the selected 1024 block size, the sample time was 15.36 s, with 15,360 samples.

Traversing Cobra Probe

The Cobra Probe, manufactured by Turbulent Flow Instrumentation Ltd (TFI), was used to measure the mean velocity and turbulence profiles. The probe is a 4-hole temperature compensated pressure probe with 0.5 mm taps located on the probe head facets. The head is mounted on a support stem which is connected to the body as illustrated in Figure 5.3 a. Tubing inside the support stem connects the pressure taps to four pressure transducers housed within the body. The Cobra Probe used for this experiment has a specification operating

range of 2 m/s to 55 m/s with a velocity accuracy within ± 0.5 m/s and a flow angle accuracy of $\pm 1.0^\circ$, for flow that resides within $\pm 45^\circ$ of the x-axis, as illustrated in Figure 5.3 b).

Figure 5.3: Cobra Probe schematic: a) side view, b) head inflow orientation and axis definitions; adapted from TFI [39] (all dimensions in mm)

The Cobra Probe is fully calibrated by the manufacturer to ensure accuracy from the transducers, tubing frequency response, and head geometry. TFI provides software that applies the calibration to the raw voltage signals measured by the four pressure transducers. Tests to verify the flow velocity and pitch angle accuracy of a Cobra Probe have been reported by D'Auteuil [15] with results found to be within the manufacturers specifications.

For the Cobra Probe results, the TFI software used the static pressure measured by a static tap placed at the side wall of the test section, a manually input atmospheric pressure

and a manually input temperature, to determine velocity. The atmospheric pressure was taken from a local hourly weather station report. The temperature was measured using a Fisher-brand liquid-in-glass thermometer placed at the centre of the test section outlet, with the bulb positioned 50 mm from the top wall. Readings were taken at the start and end of each test, with a maximum 1 °C temperature increase for the duration of a test. For each test, the software outputs an instantaneous velocity data set file and a configuration summary file containing atmospheric pressure, static pressure, pitch, and yaw results.

The Cobra Probe results reported that the local flow direction was misaligned with the probe by $< 5^\circ$ pitch and $< 1^\circ$ yaw. No corrections were made as the measurements were used for relative velocity profiles and not absolute comparison. Where comparison is made to field of play ABL profiles, the shape of the profile is the only comparison made and therefore also relative.

The Cobra Probe was mounted on the lower end of a manually dialed traversing gear bar. For the flow profile data points, the instantaneous wind velocity was time-average from each sample for 15 mm incremental heights between 15 mm above the wind tunnel floor and the maximum traversing height, $\bar{U}_{ref}$ (0.1 h to 1.9 h). Measurements were taken for each flow condition for the range of flow speeds in ascending and descending order.

Preliminary measurements of the flow within the wind tunnel test section were performed to check the Cobra Probe mean velocity output with the Pitot-static tube and Datametrics measurements. The probes were placed at various locations within the test section to measure and confirm that the streamwise mean velocity results from the two systems were in agreement within the Cobra Probe specification accuracy. The locations included centre of the inlet cross section, flow condition setup location, and the cross-stream symmetry location. For probe calibration and flow analysis test details the reader may refer to Appendix C.

Pitot-static tube/pressure transducer system

The stainless steel Pitot-static tube was connected to a Datametrics 1400 (2500 Pa) pressure transducer which measured stagnation (total) pressure with a tap in-line with the flow,

and static pressure with eight taps perpendicular to the flow. Figure 5.4 illustrates the Pitot-static probe configuration.

Figure 5.4: Pitot-static tube elevation schematic

The exit ports of the tube, accessible above the test section, were connected with 2 m of Tygon tubing to the pressure transducer. The height of the probe was determined by the physical limitations of the Cobra Probe and the location of free-stream flow. The Pitot-static tube needed to match one of the data points measured by the Cobra Probe, to provide a reference velocity. The maximum Cobra Probe height was chosen. The Pitot-static tube was offset from centre, on the opposite side to the paddle blade, to capture free-stream air velocity. The flow speed was tested to ensure it was in agreement with that measured by the upstream Cobra Probe. The tests were carried out with and without the kayaker model in place to ensure that the presence of the model kayaker did not alter the reference flow speed. The test results are presented in Appendix C.

The TFI output file for the Datametrix transducer was in volts, which was converted to velocity during post processing using the temperature and atmospheric pressure values from the thermometer and Cobra Probe readings.

Load cell system

For the aerodynamic drag force experiments, a JR3 Multi-Axis Load Cell Technologies 30E12A4-U562-EF mFS 100 N load cell, placed under the model kayaker measured streamwise force, while the Pitot-static tube and Datametrix 1400 system measured streamwise dynamic air pressure. Although the load cell measures three force components and three moment components, for the purpose of this experiment, the x-axis, or streamwise force component

was the only output used for calculation. During post processing, a calibration matrix supplied by the manufacturer was used to remove any cross-coupling between axis and convert the TFI voltage output into force.

Prior to the model kayaker measurements, tests were performed to calibrate statically the load cell streamwise force results and to measure drag coefficient, C_D , for a 2D circular cylinder mounted to the load cell. The load sensor C_D test was used to confirm that the results were within reason when compared to published C_D , for a similar Re number. Detailed flow characteristics, cylinder setup and surface details were not considered. The static calibration and cylinder C_D comparison results may be found in Appendix C.

5.1.3 Model kayaker and load cell arrangement details

The model scale was determined to be $\frac{1}{6}$ for the following reasons: to avoid wall interference effects by keeping blockage below 5%; to fit within the traversing probe range; to reach the full scale Reynolds number; and for manufacturing costs. The 3D model was printed with P400 Acrylonitrile butadiene styrene (ABS plastic). The shape was developed using a 3D modelling program with dimensions taken from an elite kayaker in paddling posture. The posture of the model represents a significant phase within the stroke cycle for elite sprint kayaking. Plagenhoef [40] decomposed the paddle stroke into four phases giving a percentage of total stroke time to each phase. The position taking up the largest time was found to be the pull phase (26 - 46%), where the paddle transitions from vertical to steering as the upper hand moves forward. Although each phase is important, a position with the paddle blade tip at its peak height is assumed to be an important aerodynamic posture. The posture also matched previous full scale tests which are presented here only for the purpose of comparison.

Details of the model kayaker construction and load cell arrangement are illustrated in Figure 5.5. The centroid of the model kayaker was aligned with the centre of the load cell to avoid any moment effects due to longitudinal weight distribution.

Figure 5.5: $\frac{1}{6}$ model kayaker elevation

5.2 Flow condition velocity at reference height

For the three flow conditions, including uniform (no grid), grid-1 and grid-2, velocity profiles were measured for a fan speed range from 1800 to 3000 rpm. With the blocking of flow, due to the grids, a range in reference velocity was found as seen in Table 5.1.

Table 5.1: Fan speed reference velocity, $\bar{U}_{ref}$, for flow condition tests

Fan speed (rpm)	$\bar{U}_{ref}$ uniform (m/s)	$\bar{U}_{ref}$ grid-1 (m/s)	$\bar{U}_{ref}$ grid-2 (m/s)
1800	31	26	24
2100	36	31	29
2400	41	35	33
2700	(2640)* 45	39	36
3000	-	44	-

* Cobra Probe maximum pressure warnings, therefore fan reduced to 2640 rpm, or measurements not taken

For the aerodynamic drag force measurements, the fan speed range was increased to the maximum, 3600 rpm, to extend the range of wind speed to a full scale wind of 10 m/s which equates to a 4 m/s headwind if the kayaker is paddling at an assumed 6 m/s.

As the $\bar{U}_{ref}$ changes with fan speed and flow condition, non-dimensional values for the flow characteristics, Re and velocity ($\bar{U}/\bar{U}_{ref}$), were required for comparison of the results. Height, z , was non-dimensionalized with respect to the head height, h , of the model kayaker (z/h).

5.3 Instrumentation and measurement error

The systematic and random error for the flow conditioning measurements included error from the Cobra Probe and the Datametrix pressure transducer systems. The error calculated for the Cobra Probe measurements for the inflow profiles during the flow conditioning tests was included in the error calculation for the drag tests under the assumption that the velocity profiles were maintained for the same reference height velocity.

Cobra Probe system

For each wind speed with the uniform flow setup, a test was carried out for the full traverse range in ascending and descending order for three runs, resulting in six tests. The results were used to determine a 95% confidence interval for each data point using the student-t method. The maximum uncertainty was found to be 2.3% of $\bar{U}_{ref}$ and located within the test section bottom boundary layer where turbulence was highest. The maximum uncertainty was then applied to all flow condition measurements for random error calculations.

For the systematic error, the manufacturers specification of ± 0.5 m/s was used after confirmation from calibrations as described in Appendix C.

Pitot-static tube/pressure transducer system

The precision error of the Datametrix system was found using a 95% confidence interval of mean pressure for six tests at each wind speed.

Systematic error including quantization error and sensitivity error was found for the reference pressure measurements. For the ± 10 V output signal with the 16-bit DAQ, quantization error was found to be 0.0003 V. The Datametrix unit is professionally calibrated by Alpha

Controls & Instrumentation on a yearly basis. A calibration report was used to determine the 0.012% sensitivity error.

Pitot-tube yaw and pitch misalignment error was not calculated as the apparatus was fixed for the duration of flow condition and drag testing and therefore the measurements were considered relative.

Load cell system

For the JR3 load cell results, a 95% confidence interval of mean force for six samples was used to determine precision error.

The systematic error was determined for sensitivity and quantization. A calibration test was used to determine sensitivity error of 1.3% of reading. The quantization error was found to be 0.0003 V for the ± 10 V output, which equates to 0.0015 N for the 100 N range. The total systematic error including sensitivity and quantization was found to be 1.3% of reading.

5.4 Uncertainty analysis

5.4.1 Uncertainty analysis method

To determine systematic and random error, all known instrumentation and equation propagation error was found. For the uncertainty calculations, the root-sum-squares (RSS) method was used as follows [33]:

$$\mu_x = \sqrt{\mu_1^2 + \mu_1^2 + \dots + \mu_k^2} \quad (5.1)$$

where μ_x is the total system uncertainty and μ_{1-k} are instrumentation errors.

Further, uncertainty propagates through the calculation for determining drag coefficient, C_D . Details on the definition and methods for determining C_D are found in Chapter 6. For the purpose of explaining uncertainty calculations the accepted definition of C_D is used here and defined as:

$$C_D = \frac{F_x}{0.5\rho U^2 A_f} \quad (5.2)$$

where F_x is the streamwise force on the model kayaker, ρ is the air density, U is the streamwise air velocity, and A_f is the frontal area of the model kayaker.

The propagated uncertainty was determined by taking the partial derivatives of the drag coefficient equation with the RSS method. For simplification of the error propagation equation, the velocity variable can be replaced by dynamic pressure, Q , as follows:

$$U^2 = \frac{2Q}{\rho} \quad (5.3)$$

which results in the following drag coefficient equation:

$$C_D = \frac{F}{QA_f} \quad (5.4)$$

Taking the partial derivatives with the RSS method results in the error propagation equation:

$$\mu_{C_D} = \sqrt{\left(\frac{\partial C_D}{\partial F_x} \mu_{F_x}\right)^2 + \left(\frac{\partial C_D}{\partial Q} \mu_Q\right)^2 + \left(\frac{\partial C_D}{\partial A_f} \mu_{A_f}\right)^2} \quad (5.5)$$

5.4.2 Propagation of C_D calculation error

Using the method from equation (5.5), the propagated systematic error from the C_D is defined as follows:

$$\mu_B = \sqrt{\left(\frac{1}{QA_f} \mu_{F_{xB}}\right)^2 + \left(\frac{-F_x}{A_f Q^2} \mu_{Q_B}\right)^2 + \left(\frac{-F_x}{A_f^2 Q} \mu_{A_f}\right)^2} \quad (5.6)$$

where μ_B is systematic error, $\mu_{F_{xB}}$ is load cell systematic error, μ_{Q_B} is pressure sensor systematic error and μ_{A_f} is the frontal area error due to the model printing tolerance.

Equation (5.6) must include the integration of the local pressure and area for the integrated C_D calculations as follows:

$$\mu_B = \sqrt{\left(\frac{1}{\sum(Q_i A_{f_i})} \mu_{F_{x_B}}\right)^2 + \left(\frac{-F_x}{\sum(A_{f_i} Q_i^2)} \mu_{Q_B}\right)^2 + \left(\frac{-F_x}{\sum(A_{f_i}^2 Q_i)} \mu_{A_f}\right)^2} \quad (5.7)$$

For the random error, μ_S , the frontal area of the model does not change and therefore is not included, reducing the propagated random error to:

$$\mu_S = \sqrt{\left(\frac{1}{\sum(Q_i A_{f_i})} \mu_{F_{x_S}}\right)^2 + \left(\frac{-F_x}{\sum(A_{f_i} Q_i^2)} \mu_{Q_S}\right)^2} \quad (5.8)$$

where $\mu_{F_{x_S}}$ is load cell random error and μ_{Q_S} is pressure sensor random error. The total uncertainty including systematic and random error is then found as follows:

$$\mu_{C_D} = \sqrt{\mu_B^2 + \mu_S^2} \quad (5.9)$$

The maximum μ_{C_D} was found to be ± 0.005 for the uniform flow condition. The following tables present the integrated C_D uncertainty for each flow condition. All presented results pertain to the specific model with systematic errors affecting the overall drag coefficient values. Since the measurement system is consistent for all flow conditions, the relative error is expected to be negligible.

Table 5.2: C_D uncertainty: uniform flow condition

Re (10^5)	C_D	μ_{C_D}	% error
1.45	0.634	0.005	0.45
1.71	0.628	0.004	0.42
1.96	0.621	0.004	0.40
2.21	0.614	0.004	0.39
2.46	0.608	0.004	0.38
2.71	0.602	0.004	0.38

Table 5.3: C_D uncertainty: grid-1 flow condition

Re (10^5)	C_D	μ_{C_D}	% error
1.10	0.651	0.004	0.41
1.29	0.641	0.004	0.40
1.48	0.632	0.004	0.40
1.66	0.623	0.004	0.39
1.85	0.616	0.004	0.38
2.04	0.610	0.004	0.38
2.23	0.605	0.004	0.38

Table 5.4: C_D uncertainty: grid-2 flow condition

Re (10^5)	C_D	μ_{C_D}	% error
0.85	0.723	0.005	0.49
0.99	0.708	0.005	0.49
1.14	0.699	0.005	0.48
1.28	0.689	0.005	0.47
1.42	0.681	0.005	0.46
1.57	0.675	0.005	0.46
1.71	0.671	0.005	0.45

Chapter 6

Wind tunnel results for a model sprint kayaker

6.1 Model kayaker upstream flow characteristics

The $\frac{1}{6}$ model kayaker was tested to establish sensitivity of the drag coefficient, C_D , to Reynolds number, headwind velocity profile and turbulence by modifying the inflow conditions of the wind-tunnel test section. The uniform inflow was modified using grids which are described in detail in Appendix D.

Grid-1 was used to develop a headwind representing a velocity profile similar to those prevailing under field of play conditions that a kayaker would experience. The contribution of the natural headwind to the overall kayaker aerodynamics is in addition to the aerodynamic drag force, created by the kayaker's forward movement in water. From the 2016 RIO Olympics men's K1 200 m sprint kayak event, results published by the International Canoe Federation show that the kayaker can reach a speed of 6 m/s relative to water. With a wind tunnel air speed limit of 60 m/s and a $\frac{1}{6}$ scaled model, the maximum wind tunnel apparent wind is 10 m/s, resulting in a maximum headwind of 4 m/s, which represents a common wind speed in the field of play.

A second grid, grid-2, was designed to produce a higher velocity gradient than grid-1, where the near-floor wind speed was reduced to 55% of the velocity measured at the full height of the velocity profile. As the atmospheric boundary layer (ABL) wind within the kayaker's height has been demonstrated to follow a logarithmic profile (see Chapter 4), the non-logarithmic profile is not expected to represent field of play conditions, but was included

in the present study to expand the conditions and thereby establish the sensitivity of the aerodynamics of a kayaker in headwind to the head-wind profile.

6.1.1 Streamwise characteristics of velocity and turbulence

Before measuring drag force on the model kayaker, the wind profile for all flow conditions was measured at the kayak leading edge on centre. The results were used to determine velocity profile, turbulence intensity profile and turbulence length scale.

Time-averaged velocity profiles

The grid-1 velocity profile was intended to follow a logarithmic profile specific to wind over water according to Mann (1992), which corresponds to the following equation:

$$U = \frac{u_*}{\alpha} \left[\ln \frac{z}{z_0} \right]; \quad \text{where} \quad z_0 = A \frac{u_*^2}{g} \quad (6.1)$$

where U is the wind speed at height z , α is the von Kármán constant (0.41), u_* is the friction velocity, z is the height above water line, z_0 is the surface roughness for wind over water, g is gravitational acceleration and A is the Charnock constant. A Charnock constant of 0.0144 was used which has been confirmed from the field of play measurements (see Chapter 4). The friction velocity, u_* , was found through a series of iterations, where an initial u_* is input along with U , A , g and z to find a resulting u_* as follows:

$$u_* = \left[\left(\frac{1}{\alpha U} \right) \ln \left(\frac{zg}{A u_*^2} \right) \right]^{-1} \quad (6.2)$$

where u_* was found to be 0.0562 m/s for $U = 2$ m/s at $z = 10$ m.

Figure 6.1 shows the measured velocity profiles, where the velocity is non-dimensionalized by the reference velocity, $\bar{U}_{ref}$, measured at $z = 2h$, where h is the height of the kayaker as shown in Chapter 5: Figure 5.2. The grid-1 profile was found to deviate from the desired logarithmic profile by a maximum of $\pm 0.02 \bar{U}/\bar{U}_{ref}$, which was considered acceptable for prediction of the field of play ABL profile in consideration of the maximum deviation measured during field testing of $\pm 0.04 \bar{U}/\bar{U}_{ref}$.

As noted in Figure 6.1, the grid-2 velocity and turbulence profiles enable the experiment to cover a broader range of headwind conditions as intended. The inflections seen in the grid-1 and grid-2 profiles are a result of the turbulence grid designs used for the study.

Figure 6.1: Test section undisturbed velocity profile at $x = 5.6 h$; $\bar{U}/\bar{U}_{ref} = \pm 0.02$

Turbulence intensity profiles and normalized spectrum

For wind tunnel testing, matching turbulence characteristics to full scale outdoor spectrum has limitations due to model scaling and tunnel size according to Irwin [16]. For this experiment, turbulence characteristics were not expected to match field of play conditions for any turbulence characteristics, but were measured to provide a better understanding of the possible reasons for a difference in drag on the model kayaker for each tested flow condition.

The longitudinal turbulence intensity, I_{uu} , for each flow condition is defined as the ratio of the standard deviation of the streamwise velocity fluctuation, σ_u , to the average wind speed, $\bar{U}_z$ at a specified height, z , above the test floor:

$$I_{uu} = \frac{\sigma_u}{\bar{U}_z} \quad (6.3)$$

Figure 6.2 shows the measured turbulence intensity profiles for the three flow conditions, which were found to deviate from the mean turbulence intensity by a maximum of 0.6%.

The field test results have been added to Figure 6.2 to show that the turbulence intensity is expected to be higher on the field of play. The error bars represent the standard deviation from the mean turbulence intensity for the field test data. For wind over water, Miyake et al [41] found an average $I_{uu} = 9.4\%$, at 400 m offshore and 5 m above water, suggesting that the measurements taken at Mooney's Bay, within 1 m above water are reasonable.

Figure 6.2: Test section undisturbed flow turbulence intensity at $x = 5.6 h$; with uncertainty in $I_{uu} = \pm 0.6\%$

To further examine the structure of the grid-1 and grid-2 turbulence, frequency spectrum of the fluctuations in the longitudinal velocity component is compared to experimental field results from Chapter 4, published experimental measurements, and theoretical predictions in Figure 6.3. The figure shows the normalized magnitude versus frequency spectrum. The one-sided power spectral density, $S_{uu}(f)$, of the instantaneous velocity is normalized by the frequency, f , and the mean velocity squared, $\bar{U}^2$. The abscissa shows frequency normalized by the height above water, z , and time-averaged velocity, $\bar{U}$, for comparison of frequencies

measured at different heights and wind speeds. The specific height and mean wind speed for each spectrum can be found in the legend. For the wind tunnel results, the spectrum at height of the kayaker, $z = h$, was chosen.

The published comparisons include a study by Donelan [18] where wind over a lake for a comparable height and similar average wind speed was measured and a theoretical von Kármán model of the atmospheric turbulence close to the ground for neutral atmosphere according to ESDU 85020 [19].

The comparison shows that the grids used for the wind tunnel tests produced a spectrum with a similar shape but significantly lower magnitude than the theoretical and field data for the spectrum measured. The wind-tunnel drag results and their relation to field conditions have to be interpreted in this context.

Figure 6.3: Normalized longitudinal wind turbulence spectra

Turbulence length scales

In addition to the turbulence intensity spectrum, the longitudinal length scale of turbulence can be used to compare gust size. For the wind tunnel flow conditions, the x-direction

integral length scale, L_u^x , was estimated using the “spectral fit” technique described by Teunissen [36], where the peak in the wavenumber spectrum is used to determine the integral scale from the following relationship:

$$k = \frac{2\pi f}{\bar{U}} \quad (6.4)$$

where f is turbulence frequency and $\bar{U}$ is the time-averaged velocity. The dominant wavenumber for the spectra provides the length scale or wavelength, λ , defined as:

$$\lambda = \frac{1}{k} \quad (6.5)$$

Figure 6.4 illustrates the method, where the wavenumber spectrum for grid-2 is shown, with a resulting integral length scale, L_u^x , of 0.03 m, at kayaker chest height.

Figure 6.4: Wind tunnel flow wavenumber spectrum: grid-2

For a grid dowel diameter of between 0.01 m and 0.02 m placed 0.93 m upstream, the resulting eddy size is reasonable. It can also be seen that a range of frequencies exist close to the chosen maximum. Therefore, the results are expected to estimate the dominant eddy size,

where a range of eddies exist at similar wavenumber and magnitude, which is a characteristics also found from the Chapter 4 field measurements. When compared to ABL winds, the wind tunnel length scale represents a natural wind gust of 0.2 m. For the field conditions from Chapter 4, the gust size at kayaker chest height, $z = 0.6$ m, was found to range from 0.1 m to 2.2 m, with an average of 1.0 m.

For wind tunnel testing, Irwin [16] notes that modelling natural wind turbulence is difficult when the model is large with respect to the tunnel. For ABL wind tunnel testing of buildings, the scale is commonly in the order of 1:500. For the case of the model kayaker, the scale is large at 1:6, which was required to match full scale Re at the kayaker's torso, where Re is based on wind tunnel speed and torso diameter.

Therefore, the combination of the required scaling and the single-plane flow conditioning grid method was not ideal for representing scaled ABL turbulence intensity, but did match turbulence length scales within the order of magnitude of the measured field of play conditions. The non-uniform profiles were primarily used to observe the effect of velocity profile on the kayaker's drag coefficient, C_D , with the understanding that the model and the flow conditions are simplified for the purpose of understanding some, but not all effects that the ABL may have on a sprint kayaker. Later in this chapter, discussion on the effects of turbulence intensity and length scale on the kayaker's drag force are presented.

6.2 Drag coefficient theory

For determining the C_D of the model kayaker two methods have been used. The first method is commonly used for bluff bodies in uniform flow. The second method integrates velocity with respect to height of the kayaker to account for the effect of the non-uniform velocity profile on the kayaker's drag. Each method uses the same experimental drag result, F_x , but the reference dynamic force in the denominator is modified.

1) C_D : reference velocity method

For the first method, velocity profile is not considered to be an influence and $\bar{U}$ is taken to be the mean measured reference velocity as follows:

$$C_D = \frac{F_x}{0.5\rho\bar{U}^2A_f} \quad (6.6)$$

where F_x is the streamwise force on the model obtained from a load sensor, $\bar{U}$ is the mean velocity at the reference height of $1.9h$, and A_f is frontal area.

2) C_D : integrated velocity method

The second method applies an integration over the height of the model, where local $\bar{U}$ for each measured data point is used to determine the local dynamic pressure, the product of which with the corresponding segment of frontal area is then summed up over the total height to obtain the reference force for normalizing the drag force as follows:

$$C_D = \frac{F_x}{0.5\rho(\sum \bar{U}_i^2 A_{f_i})} \quad (6.7)$$

where $\bar{U}_i$ is measured at a specific height and A_{f_i} is the frontal area at that location as illustrated in Figure 6.5.

Figure 6.5: Schematic of velocity measurement location and corresponding frontal area

6.3 Model kayaker experimental C_D results and discussion

6.3.1 C_D : reference velocity method

Model validation

For validation of the model setup, the results are compared in Figure 6.6 to unpublished C_D of a full scale elite sprint kayaker based on wind tunnel tests with uniform flow. The C_D results were provided to the author by the National Research Council Canada. For the $\frac{1}{6}$ model, the uniform-flow C_D results are lower than the full scale elite kayaker C_D , with the difference being comparable to that seen between the two data points for the full scale kayaker C_D . Therefore the model results are reasonable, but may be lower than the full scale test results due to different flow conditions and/or model details.

Figure 6.6: Kayaker C_D ; reference velocity method

The two tunnels have a similar turbulence level of 0.15%, but the blockage and relative floor boundary layer thickness were not the same. Since the blockage for the full scale test was corrected and the blockage for the $\frac{1}{6}$ model was less than 5%, the difference in blockage is considered negligible. However, with the kayaker sitting at the floor level, the floor boundary

layer thickness covered a different portion of the kayaker as a result of scaling. For the full scale tests at the National Research Council, the floor boundary layer was less than 10% of the kayak height at the kayak leading edge. For the $\frac{1}{6}$ model, the full kayak height and skirt were within the boundary layer where velocity is lower, resulting in a reduced measured drag force, F_x , and therefore a lower C_D .

The model details which may also account for the lower value of C_D for the model include body shape, details in equipment geometry, surface roughness and posture which were not an exact match with the full scale kayaker.

$\frac{1}{6}$ Model C_D results: reference velocity method

The C_D results for wind tunnel cases of the present study show a decrease as the velocity profile deviates from uniform. The C_D is 21% lower for grid-1 and 44% lower for grid-2 when compared to the uniform flow at $Re = 1.7 \times 10^5$. These results demonstrate that for a kayaker in the field of play, the velocity profile which includes headwinds is expected to alter the kayaker's C_D , when C_D is defined as per the reference velocity method. Therefore when determining C_D for apparent headwind speeds greater than the athlete's maximum propulsion speed, where an ABL headwind accounts for a portion of the aerodynamics, a velocity profile has an effect.

C_D baseline

The C_D results for the uniform flow condition are not expected to change significantly as a result of calculation method because starting at a height of 15% of the velocity profile (outside of the wind tunnel floor boundary layer thickness) the flow velocity does not vary by more than 0.7% between measured heights. Therefore, the uniform-flow C_D results for the reference velocity method have also been shown in the integrated-method C_D plot as a datum for comparison.

6.3.2 C_D : integrated velocity method

When the integrated method is used for the non-uniform flow cases, there is a shift of the C_D towards the uniform flow case as seen in Figure 6.7.

Figure 6.7: Kayaker C_D ; integrated velocity method

There is also a reduction in Re for the non-uniform cases as the wind velocity measured at the upper chest, instead of reference velocity, is used for the Re calculation. For all flow conditions, the C_D results showed some dependence on Re , with the C_D decreasing with increasing Re .

For the uniform flow case, where a thin region of non-uniform flow is present at the test section floor, the integrated method caused an upward shift in C_D of 0.001 as shown between the open and closed square data points in Figure 6.7.

With the collapse of the C_D results towards the uniform-flow condition, obtained with the integrated velocity method C_D , the integrated method has accounted for flow effects to within 1% and 7% for the grid-1 and grid-2 flow conditions, respectively.

A numerical model as described in Appendix E was setup to replicate the wind tunnel experiments with the three flow conditions for cross validation. The numerical model results

produced the same trend where the reference velocity method C_D values collapsed towards the uniform-flow C_D values when the integrated velocity method was used to within 6% and 11% for the grid-1 and grid-2 flow condition, respectively.

The difference in the C_D values for the non-uniform and uniform-flow conditions using the integrated velocity method C_D for the experimental and numerical investigations show that the velocity profile effect is the primary flow effect on the aerodynamic drag of the kayaker model and that small secondary effects exist, causing the variations amongst the results.

Although the wind tunnel turbulence intensity is significantly lower than the level measured in the field of play, the variation amongst the turbulence intensity levels for the wind tunnel cases suggests that turbulence has a minimal effect. The collapse of the C_D for the two non-uniform, higher turbulence (approximately 6%) flow conditions, onto the C_D for the uniform velocity profile with negligible turbulence (0.15%), implies that the turbulence does not alter the kayaker's pressure drag, and therefore wake, in a significant way. Therefore, although a full dynamic similarity between the field and wind tunnel turbulence levels has not been achieved, the favourable agreement of the C_D using the integrated method implies that if turbulence effects exist, the effect on the kayaker's aerodynamic drag is small and secondary for the level of turbulence considered.

The smaller secondary effects could be a result of small changes in the pressure distribution due to large scale turbulence at the paddle blade, multi-component wake interaction and/or component shape C_D contribution.

Turbulence length scale with respect to the kayaker model

If turbulence was causing the small effects, the variation between the grid-1 and grid-2 C_D results would be caused by the turbulence levels at the paddle blade height. For the non-uniform flow conditions, the turbulence intensity up to $z/L = 1$, which represents the height between the floor and the top of the kayaker's head, is similar. From $z/L = 1$ to 1.4, which includes the paddle blade only, the grid-2 turbulence intensity is higher. It is possible that the turbulence length scale which is similar in size to the paddle blade, causes an instantaneous angle of attack that increases the mean drag. The paddle blade is oriented

with a pitch of 16° from vertical and a yaw of 20° from perpendicular to streamwise flow. From research on a full size flat-plate paddle blade by Sumner et al [42], where wind tunnel tests were used to compare the effect of pitch and yaw on C_D of various blades, it was found that the maximum C_D was present when the flat-plate blade was perpendicular to the flow. Therefore, the potential exists for an increase in C_D for the paddle blade if the flow were to have an intermittent perpendicular angle of attack caused by large scale turbulence. For the grid-2 case, where a larger magnitude of turbulence intensity exists at the height of the blade, this effect is expected to be greater than for grid-1 if the increased energy were present at the integral length scale which represents the large scale turbulence in this case.

Multi-component shape effect

Although the integrated method normalizes the velocity profile effect on the kayaker's C_D , it assumes that the form drag is solely dependent on velocity and not the shape of the individual components. The bluff body components, causing the form drag, are made up of cylindrical shapes, except for the paddle blade, which resembles a flat-plate. If the drag of each component were to be measured independently, each would have a unique C_D depending on shape, size, and flow related orientation. For the flat-plate paddle blade, the expected C_D is around 1.6 [42], whereas according to Blevins [8] the C_D of a cylindrical protuberance with similar height to diameter ratio as the kayaker torso is expected to be much lower at approximately 0.75.

It is possible that the larger velocity gradient of the grid-2 flow condition caused a larger drag force on the kayaker. For the same torso Re , the streamwise velocity at the height of the centroid of the paddle blade was 20% higher for the grid-2 flow than the grid-1 flow, resulting in a higher pressure on the blade as supported by numerical results for the pressure distribution on the windward side of the kayaker presented in Appendix E. Therefore, although the C_D is associated with the entire group of kayaker components, the paddle blade may be contributing to the overall C_D disproportionately in comparison to the other components.

Multi-component wake interaction

Another effect each flow condition may have on the kayaker is the location at which the boundary layer separation of flow from the body occurs. As this would be a difficult measurement to obtain from the model kayaker using the present wind tunnel setup, the numerical model is used to study the location of separation. For each flow condition, the separation location was found at about mid-torso height, $0.4 h$, which included flow around the pole and lower arm as well as the torso. Results showed that separation did not occur at the same location on the arm or torso due to upstream components where wake interaction may have caused a change in flow pattern as shown in Figure 6.8. This indicates that at some locations, the interaction of the flow between components may alter the overall flow pattern and therefore the C_D for the same value of Re .

Figure 6.8: Numerical model separation location at $z = 0.4 h$; square = uniform, diamond = grid-1, triangle = grid-2

Wake interaction between the kayaker components is also evident through observation of the pressure distribution across the kayaker's chest. According to the numerical model results, presented in Appendix E, the pressure distribution across the width of the kayaker's chest is asymmetric as a result of the location of the pole.

6.4 Summary

Wind tunnel experiments, where a range of inflow profiles were used to measure aerodynamic drag on a $\frac{1}{6}$ model kayaker, confirmed that the kayaker's aerodynamic C_D is primarily sensitive to velocity profile, with a small sensitivity to Re for the subcritical range from 10^5 to 3×10^5 measured at the kayaker's torso. The confirmation of the dominance of the velocity profile in comparison to other flow effects including turbulence, multi-component flow interaction and shape effect was shown by normalizing the C_D . This was done by integrating the wind speed with respect to kayaker height for a corresponding frontal area segment for the non-uniform flow profiles. Results from the normalized kayaker C_D are listed in the following:

- For an inflow velocity profile representing the ABL for wind over water, the kayaker's C_D was normalized towards the uniform-flow C_D to within 1%. The importance of this finding is that when the relationship is applied inversely, the uniform-flow C_D can be used to determine the ABL wind drag force on a kayaker if the logarithmic velocity profile for wind over water is integrated with frontal area over the height of the kayaker.
- For an inflow condition representing a velocity gradient higher than that of an ABL profile, the kayaker's C_D was normalized towards the uniform-flow C_D to within 7%. This supports the C_D results for the ABL inflow profile by following the same trend, and also implies that other flow effects do contribute to the kayaker's aerodynamic drag but account for a small percentage.
- The small percentage of variation in normalized C_D for the range of inflow conditions may be due to turbulence intensity effect. Although the wind tunnel ABL flow condition did not match the turbulence intensity measured on the field of play, it did present a large increase (approximately 6%) in comparison to the uniform-flow case (0.15%) suggesting that although full dynamic similarity was not achieved, the turbulence intensity effects are not a primary influence on the aerodynamic drag for a kayaker.

Chapter 7

The contribution of aerodynamics to the overall drag of a kayaker

The hydrodynamics of kayaks, canoes, and rowing shells have been studied extensively for shape optimization [43, 29], as the hydrodynamic contribution to total resistance for the boat for the respective sport is much higher than the aerodynamic portion [11]. However, as the hulls are now well designed, there is growing interest in the aerodynamics for elite racing where a race can be won by a very small margin. For competitive sprint kayaking, finish times are measured to the thousandth of a second. Therefore an improvement in finish time by such an increment is considered to be the minimum requirement for a meaningful reduction of aerodynamic drag.

As aerodynamic drag is the result of the forward motion of the kayaker and the atmospheric wind conditions, two avenues of study are of interest. For a calm atmosphere, the aerodynamic drag due to forward motion is generated mostly by the kayaker's body shape and surface roughness of her/his apparel. On a windy day, the kayaker's aerodynamic drag is also influenced by wind speed and direction. Therefore, there is interest in: i) determining whether the reduction in body-shape-driven aerodynamic drag can reduce race time significantly, and ii) how the aerodynamic drag contribution changes with atmospheric winds. For a calm atmosphere, hereafter called case-1, the environmental factors affecting the kayakers are small and therefore represent a comparison between competitors for a race where each kayaker is expected to experience a similar environment. For a windy atmosphere, hereafter

called case-2, the atmospheric wind drag and the associated wind-wave resistance are added to the forces affecting the kayaker's forward motion. The two cases will be investigated to evaluate the contribution of aerodynamics to total drag and to finish-time results for a men's K1 200 m race, with simplifications as explained in the following.

The kayaker's interaction with the air and water is complex, with counter forces on the kayaker coming from the unsteady motion of paddling, the location of the air-water interface on the hull of the kayak, and local characteristics of the air and water within the field of play.

The unsteady motion of the kayaker follows a cyclic surging movement with a forward speed that has been reported to deviate up to 4% from the mean kayak speed during a stroke cycle [11]. The paddler's own motion also creates pitch, roll and yaw which the kayaker strives to eliminate. For this study, it will be assumed that the kayak is moving in a smooth forward motion without any paddle stroke effects.

Under the stated assumptions, the resistance acting on the submerged hull due to the smooth forward motion of the kayak are due to skin-friction, form-driven flow separation and bow-wave resistance. The bow wave is created by displacement as the hull parts the water in its path. Additional resistance due to local water and air conditions can also be a factor. Wave resistance amplification due to shallow-water waves can be present for typical kayak basin depths at peak speeds [44]. Hull resistance also increases with secondary effects from wind. As the wind builds, an atmospheric boundary layer above the water is developed, creating wind-waves and wind-induced surface drift. The wind-waves reflect off the hull and interact with the bow wave of the hull, thereby contributing to the hydrodynamic resistance. For the purpose of this study, the forces acting on the hull are simplified by excluding the effects of the water depth and surface drift. There does not appear to be published information on these effects for the kayak application, and quantifying these effects as part of the present study would yield too broad a research scope. The excluded surface drift and shallow-wave effects are considered factors to be investigated in future work on this topic.

The atmospheric wind patterns within the field of play are affected by shoreline obstacles, and atmospheric stability. The resulting aerodynamic drag force on the kayaker depends on magnitude and direction of the wind along the course. For this study, it will be assumed that

the winds are steady headwinds for the entire length of the course and follow a logarithmic boundary layer profile for neutral conditions.

Temperature of the water and air is also linked to aerodynamic drag and hull resistance, where the temperature directly affects fluid density. The aerodynamic drag is directly proportional to air density, where a change of 1 °C in temperature would change the air resistance at peak kayak speeds by approximately 0.3%. The hydrodynamic resistance is directly proportional to water density by affecting hull skin-friction resistance and hull wetted surface area. For a change in water composition from fresh water to brine, the hydrodynamic resistance changes by approximately 1%; for a temperature change of 10 °C, the change in hydrodynamic resistance is approximately 0.2%. Density is therefore a significant secondary factor in the force balance for a kayaker, but will be assumed constant for the purpose of determining the wind speed effects for this study.

After the noted simplifications, the remaining forces acting on the kayaker are illustrated in Figure 7.1, with the forces defined as:

- F_{app} is the apparent or resultant force that the athlete exerts beyond the resistance of the fluid drag forces
- F_P is the kayaker's propulsive force transmitted through the paddle to the kayak
- F_A is aerodynamic drag on the kayaker
 - F_{Am} is aerodynamic drag due to forward kayaker motion through stagnant air
 - F_{Aw} is aerodynamic drag due to moving air (wind)
- F_H is total hydrodynamic drag on the hull and appended rudder
 - F_{Hf} is skin-friction, form-driven flow separation and bow-wave resistance
 - F_{Hr} is added hull resistance due to the reflection of wind-waves

Figure 7.1: Kayaker force diagram

For case-1 and case-2, the contribution of aerodynamic drag to the overall resistive forces will be evaluated using the simplified forces identified in Figure 7.1. The forces will then be used in an equation of motion to evaluate change in a 200 m K1 race finish-time for each case.

7.1 Case-1-Kayaker aerodynamics for calm atmosphere

For a calm atmosphere, all competitors are assumed to face similar environmental conditions. Although a kayaker's aerodynamics may be affected by the wake of adjacent competitors and lane position, the conditions vary less than between different venues. The difference in drag forces then becomes mainly a factor of the total kayaker shape, above and below the waterline.

For this study, the aerodynamics has been measured for a single posture which represents the largest aerodynamic drag and is named the pull phase, which accounts for 26% - 46% of a paddle stroke cycle [40]. In reality, the kayaker cycles through a series of postures which may

cause a fluctuation in aerodynamic drag and influence the overall results. This dynamic effect would also vary between kayakers depending on their unique body shape and technique.

For the purpose of comparing the aerodynamic drag to the overall resistance, a percentage of contribution is found for a single speed, which is considered a static drag ratio. Expanding the analysis by including the speed variations of the kayaker for the duration of the race allows for an evaluation of the aerodynamic contribution in terms of finish-time. Both methods are explained in the following and used to determine the relative influence of aerodynamic drag on the kayaker.

7.1.1 Static aerodynamic drag

Aerodynamic and hydrodynamic testing has been carried out at the National Research Council Canada for an elite Canadian kayaker. The unpublished data including hydrodynamic hull resistance and aerodynamic drag was provided to the author. Aerodynamic drag was measured with an athlete in static posture in a wind tunnel while hydrodynamic forces were recorded by traversing a weighted kayak in a tow-tank. The results indicate that at 6 m/s there is a $6.4 \pm 0.6\%$ contribution from aerodynamic drag to the total resistive force.

This result is comparable to the results of a study where the aerodynamic contribution of a male K1 kayaker was theoretically estimated at 6.9% for a 4.8 m/s kayak speed [11]. In another study involving wind-tunnel testing of an elite solo sailor, with the portion of the body above a low-profile deck being comparable to that of a kayaker, the aerodynamic contribution to the total resistance was approximately 10% [13].

7.1.2 Balance of the forces in the equation of motion

The balance of forces in an equation of motion is used to establish the time profile of the propulsive force that a kayaker exerts during a race. Under the assumption that the kayaker will maintain the propulsive profile for a variation of body-shape-driven aerodynamic drag, the propulsive profile is used to establish the sensitivity of the race time to changes in aerodynamic C_D for a calm atmosphere.

To determine the time variation of the propulsive force, F_P , a longitudinal equation of motion is used, where acceleration in an inertial reference frame balances the opposing forces as per Newton's second law as follows:

$$F_{app}(t) = ma = m \frac{dU_k}{dt} = F_P(t) - F_A(t) - F_H(t) \quad (7.1)$$

where m is total kayaker and kayak mass, a is rate of acceleration, U_k is air speed of the kayak, and t is time.

Rearranging Equation (7.1) to solve for the kayaker's propulsive force, F_P , provides the total force the athlete is expected to exert to maintain the desired rate of acceleration. Solving for F_P requires the time variations of the athlete's speed and resistive forces. Elite level sprint kayakers have a unique speed profile that is recorded by a sensor mounted to the kayak. Typically kayakers will reach a maximum peak force as quickly as possible which they will attempt to maintain for the duration of the race. Due to exhaustion, the peak force is difficult to maintain and therefore the speed decreases with time.

The speed profile from a race, $U_k(t)$, can be used along with the kayaker's C_D for the above-water portion and the below-water portion, respectively, to determine the aerodynamic drag, F_A , and the hydrodynamic resistance, F_H , from the following:

$$F(t) = 0.5\rho C_D A_f U_k^2(t) \quad (7.2)$$

where ρ is the respective fluid density, A_f is the frontal area for either the above water or below water portion of the kayaker and U_k is the longitudinal velocity from the speed profile.

7.1.3 The effect of Aerodynamic C_D on race time

For the men's K1 final event at the 2016 RIO Olympics, discrete speeds at 10 m increments were published by the International Canoe Federation (ICF) [45]. For the present study, this data for one of the competitors was used to determine the rate of acceleration along the length of the course, based on which the time variation of the propulsive force exerted by the kayaker, F_P , was computed.

Manipulation of the speed profile data

The time derivative of $U_k(t)$, dU_k/dt , was used to determine F_{app} , and $U_k(t)$ was used to determine F_A and F_H , where the resistance was calculated according to Equation (7.2), and the frontal area, A_f , and drag coefficients, C_D , were based on experimental tests. The resulting propulsive force was then determined according to Equation (7.1). Figure 7.2 shows all forces and demonstrates the relative contribution of each force to the total propulsive force. An aerodynamic C_D value at maximum kayak speed was used for the entire race. This approach is expected to provide a more conservative aerodynamic drag calculation considering the wind tunnel results from Chapter 6 show that C_D increases at a small rate with decreasing velocity in this flow regime.

Figure 7.2: The components of force for a kayaker in a 200 m race

Converting propulsive acceleration into velocity and distance

Once the kayaker's propulsive force, F_P , is known, acceleration is isolated for the purpose of determining velocity and distance, where all forces are aligned with the course oriented velocity vector, as follows:

$$a(t) = \frac{1}{m} [F_P(t) - F_A(t) - F_H(t)] \quad (7.3)$$

Integrating the acceleration in time provides the time variation of velocity, and integrating twice provides the distance, where initial conditions for velocity and distance are set to zero. The results are shown in Figure 7.3.

Figure 7.3: Propulsive force (F_P), velocity (U) and distance (x) over time for a 200 m race

The initial purpose of determining the distance is to ensure that the variation in time of acceleration places the kayaker at 200 m for the recorded finish-time for the known variables including mass, frontal area, aerodynamic C_D and hydrodynamic C_D . When that has been established, it is assumed that the curvature of the variation in speed which passes through

the discrete speeds at 10 m spacing matches the curvature of the actual speed profile between the discrete speeds sufficiently. The changes in race finish-time can then be determined for changes in the aerodynamic drag, assuming that F_P represents a consistent effort by the athlete.

Sensitivity of the race results to aerodynamic C_D reduction

A reduction in body-shape-driven aerodynamic C_D of 5% - 10% has been reported in sports science literature [13, 15]. Therefore, sensitivity of the finish time for a 200 m race to changes in the aerodynamic C_D was established by performing calculations with an aerodynamic C_D value that ranges from 0.1% to 10% lower than its nominal value obtained from wind tunnel testing. A reduction in finish time, Δt , ranging from 0.001 s to 0.106 s was found, following a linear trend of:

$$\Delta t = \frac{\%C_D \text{ reduction}}{94.727} \quad (7.4)$$

This linear relation is unique to the time variation of velocity used for this study, but shows that the body-shape-driven aerodynamics contribute to the overall force balance at a magnitude that is relative to the margin of success for a winning race time.

7.2 Case-2-Kayaker aerodynamics for headwind conditions

If the effect of headwinds are included in the mathematical model described in the foregoing, one would be able to compare the finish time of races performed under different wind conditions. At the elite level, sprint kayak competitions take place worldwide, where the environment may vary greatly. The purpose of this multi-condition comparison is to monitor the progress of the athlete's performance and compare competitors who may not race at the same event.

For analysis of this case, aerodynamic and hydrodynamic forces due to headwinds are added to the analysis described in Section 7.1.2. In this instance, F_A includes the aerodynamic drag from the forward motion, F_{A_m} , and atmospheric wind, F_{A_w} . During the 2016 RIO

Olympics, strong winds on the field of play at the sprint canoe/kayak and rowing venue were reported to have reached 10 m/s without cancellation of the race.

Due to the waves initiated by the headwind, F_H also includes added resistance due to hull wave reflection, F_{H_r} , along with the flat water resistance from case-1, F_{H_f} . The equation of motion presented for case-1 in Equation (7.1) can be accordingly modified as follows:

$$F_{app}(t) = ma = m \frac{dU}{dt} = F_P(t) - [F_{A_m}(t) + F_{A_w}] - F_{H_f}(t) - F_{H_r}(t) \quad (7.5)$$

where the method for summing the time-dependent forward motion aerodynamic drag and the constant headwind drag, $[F_{A_m}(t) + F_{A_w}]$, is described in the following.

F_{A_w} -Aerodynamic drag due to atmospheric headwind

For natural wind, which is non-uniform over the height of the kayaker, a logarithmic neutral atmospheric velocity profile for wind over water has been confirmed in Chapter 4. In Chapter 6, it was found that the calculation of F_{A_w} as per the following equation is successful in capturing the effect of velocity non-uniformity on this drag force:

$$F_{A_w} = 0.5\rho C_D \left(\sum U_{h_i}^2 A_{f_i} \right) \quad (7.6)$$

where ρ is air density, C_D is the uniform-flow drag coefficient, U_{h_i} is the local headwind speed at height, i , as per a logarithmic profile, and A_{f_i} is the frontal area corresponding to U_{h_i} .

F_A -Aerodynamic drag due to forward motion and atmospheric headwind

To determine the total aerodynamic drag, the headwind velocity, U_h , is added to the kayak air speed, U_k , as follows:

$$F_A(t) = F_{A_m}(t) + F_{A_w} = 0.5\rho C_D \left(\sum [U_k(t) + U_{h_i}]^2 A_{f_i} \right) \quad (7.7)$$

where the aerodynamic drag, F_A , is scaled with the square of the resultant velocity which is relative to the kayaker.

F_{H_r} -Hydrodynamic resistance due to atmospheric headwind

To determine whether the headwind-waves measured during the Chapter 4 tests would add significant resistance to the kayaker's motion and therefore be considered as an additional field-of-play wind effect, a laboratory experiment which measured added hull resistance due to waves is considered. Water channel experiments were carried out by Tzabiras et al [31] to determine the added resistance on an Olympic class K1 kayak hull due to waves aligned perpendicular to the kayak direction. Harmonic regular waves were generated using a paddle system for a 5.0 m/s steady hull speed. The authors found that the total hull resistance increased by 2% for a 0.3 Hz wave frequency and 120 mm wave height and 12% for a 0.5 Hz wave frequency and 100 mm wave height. The additional resistance is significant and appears to be sensitive to a number of parameters yet to be investigated including wave height, wave frequency and hull speed. From the results presented in Chapter 4, a single data set was found where wave height was large enough to be comparable to the laboratory regular wave study by Tzabiras et al [31]. For a wind speed of 6 m/s at 1 m above water line (AWL), or $U_1 = 6$ m/s, field of play waves were found to have a peak-to-trough wave height of approximately 100 mm with a 0.5 Hz frequency. Therefore, the following analysis of the wind effects on a kayaker will include an added hull resistance for a single wind speed, U_1 of 6 m/s, to provide a sense of the importance of further investigation into wind-wave effect.

Similar to the case-1 approach, for the purpose of comparing the aerodynamic drag including headwinds to the overall resistance, a percentage of aerodynamic contribution is found for a single peak propulsive force, where the aerodynamic contribution increases as headwind speed increases. The relationship is considered static due to the assumed fixed propulsive force for this ratio between hydrodynamic resistance and aerodynamic drag. The analysis is then expanded to include the speed variations of the kayak for the duration of the race which allows for an evaluation of the changes in finish-time as a result of ABL headwinds.

7.2.1 Static aerodynamic drag including atmospheric wind effects

If the estimated resistance due to headwind, F_{Aw} , is added to the kayaker's aerodynamic drag for the peak propulsive force found for the calm condition at 6 m/s hull speed relative to water (neglecting surface drift), the ratio of aerodynamic drag to the overall drag increases with headwind speed at a non-linear rate as shown in Figure 7.4.

For a headwind at 1 m AWL ranging from 2 m/s to 10 m/s, the contribution of aerodynamic drag to the total resistive force increases, ranging from 11% to 40% respectively.

Figure 7.4 also shows the increase in the resistance due to wind-wave hull resistance for a U_1 wind speed of 6 m/s. Although the resistance is hydrodynamic, it is added to the F_A since it is present as a result of wind effects. If the maximum added wind-wave hull resistance, F_{Hr} , of $0.12F_{Hf}$, measured by Tzabiras et al [31] is added to F_A , the contribution of wind effects to the total resistance increases by over 9%.

Figure 7.4: Contribution of headwind effect to total resistance at a 6 m/s hull speed

Although results show that the increase in ABL wind speed changes the contribution of aerodynamics significantly without the addition of wind-wave hull resistance, the contribution of the wind-wave resistance suggests that the effect wind has on the surface of the water may

be a large factor and that evaluation of the wind effects on the performance of a kayaker should not ignore the state of the water.

Sensitivity of race finish-time results to headwinds

To evaluate the sensitivity of the race finish-time to headwind drag for a 200 m race, the headwind force, F_{Aw} , as per Equation (7.6), has been added to the aerodynamic drag as described in Equation (7.7). Figure 7.5 shows the increase in finish-time with respect to U_1 headwind speed. Results show a finish-time increase ranging from 0.832 s to 7.824 s, for a range of 2 m/s to 10 m/s ABL headwinds at 1 m AWL. This suggests that a light headwind, as low as 2 m/s, adds resistance that is significant to the outcome of a race.

Figure 7.5: Increase in finish time for a K1 200 m race due to wind effects

When wind-wave hull resistance, F_{Hr} , is also included in the balance of forces in Equation (7.5), where the added hull resistance is estimated at 2% and 12% of F_{Hf} , results for a U_1 wind speed of 6 m/s increase finish time by 3.740 s and 5.457 s, respectively. This estimation implies that the kayaker may experience an overall wind effect that increases the finish-time significantly more, with the presence of wind-waves.

Although the present work shows a need for more investigation into added hydrodynamic resistance due to wind effects, the contribution of F_{Aw} to F_A is significant. The method for determining finish time increase can be used to evaluate aerodynamic effects typical for field-of-play light winds for the purpose of comparing results fairly. A time correction could be applied to enable the comparison of finish times of races performed under different wind conditions.

7.3 Summary

To evaluate the changes in finish time for a 200 m K1 kayak race a balance of forces was used in an equation of motion for a specific elite kayaker. The kayaker's propulsive acceleration profile was used to determine change in finish time for a reduction in the kayaker's body-shape-driven aerodynamic C_D and for added headwind drag with results listed in the following:

- A decrease in finish time as a result of reduction in aerodynamic C_D by up to 10% was found to follow a linear rate. The results imply that for a reduction in aerodynamic C_D of 10% the race finish time may change by 0.1 s. Depending on the closeness of a finish, this change in aerodynamic drag could change the final ranking of the race. For the RIO Olympics, the men's K1 200 m final had a finish result range of 1.2 s for eight competitors, with a two way tie for bronze position. Therefore, although the improvement in finish time due to a C_D reduction is small, it is enough to change the final standing of the race. This also implies that a reduction in the body-shape-driven aerodynamic drag for an athlete competing in the K1 1000 m would improve finish time by a larger margin.
- The contribution of aerodynamic drag from the ABL headwinds was found to be significant, with a larger effect on finish time than the aerodynamic C_D reduction. For a headwind range from 2 m/s to 10 m/s at 1 m AWL the finish time is predicted to increase by 0.8 s to 8 s. This is expected to be a conservative estimate, as other factors affecting the kayaker's performance due to the ABL headwind, such as stability correction and added hull resistance also require energy from the athlete.

- For cross comparison of race results for races which have taken place at different venues and times of day, the method in the present work could be used to calculate finish time change due to local ABL winds. The results could then be applied as a time-correction to compare races for a range of field of play wind speeds.

Chapter 8

Conclusions and future work

8.1 Conclusions

The overall objective of this research was to evaluate the effect of wind on an elite sprint kayaker, where wind effects come from the kayaker's forward motion and atmospheric winds on the field of play. Therefore, the reliability of the theoretical logarithmic profile of the atmospheric boundary layer (ABL) over water within the kayaker's height and investigation into the aerodynamics of the bluff body kayaker was an essential part of this research prior to evaluation of the aerodynamic contribution to drag.

Field testing at a kayak course on a river confirmed that the atmospheric velocity profile follows a logarithmic growth with height for steady winds and averaged unsteady winds for over 80% of the measurements.

By modelling the kayaker in a single position at $\frac{1}{6}$ scale, wind tunnel testing was used to determine the kayaker's aerodynamic drag for uniform and non-uniform flow profiles including the logarithmic velocity profile found to prevail during field tests. By suitably normalizing the drag coefficient, it was shown that the primary flow effect on the kayaker's C_D is the velocity profile. With this observation, if a kayaker's uniform-flow C_D is known, and the wind speed within the height of the kayaker is measured, the drag force due to ABL winds can be determined and added to the aerodynamic drag due to forward motion.

A force balance including headwind drag was used to determine aerodynamic contribution and change in finish-time for calm and headwind conditions. The results for a male K1 kayaker

imply that the contribution of the aerodynamic drag to the overall resistance is 6.4% for a calm condition which increases up to 40.0% for a kayaker facing a 10 m/s headwind assuming a constant peak propulsive force.

When the force balance is used in an equation of motion for a 200 m race, results suggest that a reduction from 1% to 10% in the body-shape-driven C_D for a calm atmosphere could reduce finish-time from 0.001 s to 0.1 s respectively, where race results standing can be determined by 0.001 s. Based on this finding, coaches and athletes can evaluate the benefit in reducing body-shape-driven aerodynamic drag as a factor contributing to performance.

If headwinds are present, the equation of motion predicts that for light winds ranging from 2 m/s to 10 m/s race finish-time may increase from 0.8 s to 8 s, respectively. From this evaluation, it has been shown that an ABL wind time-correction would be necessary to monitor a kayaker's performance or compare competitors for races that have taken place at different venues or different times.

8.2 Future work

To broaden the scope of the present research, aerodynamic drag sensitivity to ABL wind attack angle and reflected wind-wave hull resistance should be considered. The state of the water surface as a result of ABL winds is expected to affect hull resistance for the wave height and frequency range found during the present field testing. It is expected that the aerodynamic drag and the hydrodynamic resistance will change as a result of wind direction, and that in addition to the drag forces, propulsive energy will be exerted to maintain hull stability and hull direction when wind-waves with an angle of attack are present.

Amongst the secondary aerodynamic effects not accounted for by the present study, the multi-component flow interaction between the pole and torso may be significant as some shielding of the torso by the pole is expected, where the pole diameter and distance between the components may reduce the kayaker's C_D . The paddle blade is also expected to cause more drag than the cylindrical kayaker shapes, therefore investigation into sensitivity of the overall kayaker aerodynamic drag to shape of the windward blade face is recommended.

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Appendix A

Field test sensor calibration

A.1 Bow apparatus sensor calibration and uncertainty

A.1.1 Pressure sensor calibration for the Pitot-probe rake

A wind tunnel was used to calibrate the pressure sensor rake and vane system, without buoy motion. As seen in Figure A.1, the vertical distance between sensor probes was reduced from 400 mm to 120 mm to fit the apparatus within the free-stream flow of the test section. The pressure sensor and vane apparatus was placed on centre, midway downstream within the test section. The reference pressure Pitot-static tube was placed upstream from the Pitot-probe rake by 175 mm and offset by 130 mm to avoid disturbance of the oncoming flow. A sample time of 20 s at 1024 Hz was used, after a verification that this period of time was sufficient for the conditions to be stationary. Data were recorded for each of the three wind sensors simultaneously, for six runs in ascending and descending order from 0 to 10 m/s in 1 m/s increments. Data for two runs at 10° fixed yaw was also collected. A calibration for each sensor was found using the average voltage result at each wind speed with respect to the dynamic pressure obtained from a Pitot-static tube and chamber volume manometer system. The manometer was set to a 10:1 incline to improve reading resolution and was left to settle for 2 minutes after each wind speed change. Calibration results shown in Figure A.2 are for a single sensor with error bars accounting for manometer reading error.

Figure A.1: View of the pressure rake in the wind tunnel test section used for calibration

Figure A.2: Calibration curve for the mid height wind profiler sensor

A.1.2 Bow apparatus velocity uncertainty results

From the uncertainty analysis described in Chapter 3, results for the three pressure sensors are presented in the following tables.

Table A.1: Lower (0.2 m AWL) sensor velocity uncertainty

Output (V)	$\bar{U}$ (m/s)	μ_U (m/s)	% error
0.01	1.359	0.150	11.0
0.02	1.919	0.107	5.6
0.05	3.026	0.070	2.3
0.10	4.260	0.053	1.2
0.15	5.193	0.048	0.9
0.20	5.967	0.046	0.8
0.25	6.640	0.045	0.7
0.30	7.238	0.045	0.6
0.35	7.780	0.046	0.6
0.40	8.276	0.047	0.6
0.45	8.734	0.047	0.5
0.50	9.159	0.048	0.5
0.55	9.557	0.049	0.5
0.60	9.931	0.050	0.5
0.65	10.282	0.050	0.5

Table A.2: Mid (0.6 m AWL) sensor velocity uncertainty

Output (V)	$\bar{U}$ (m/s)	μ_U (m/s)	% error
0.01	1.564	0.171	11.0
0.02	2.209	0.122	5.5
0.05	3.477	0.081	2.3
0.10	4.881	0.065	1.3
0.15	5.932	0.061	1.0
0.20	6.797	0.060	0.9
0.25	7.540	0.061	0.8
0.30	8.193	0.062	0.8
0.35	8.778	0.063	0.7
0.40	9.307	0.064	0.7
0.45	9.788	0.065	0.7
0.50	10.230	0.066	0.6
0.55	10.636	0.066	0.6
0.60	11.010	0.067	0.6
0.65	11.358	0.067	0.6

Table A.3: Upper (1.0 m AWL) sensor velocity uncertainty

Output (V)	$\bar{U}$ (m/s)	μ_U (m/s)	% error
0.01	1.359	0.194	14.3
0.02	1.919	0.137	7.2
0.05	3.026	0.088	2.9
0.10	4.260	0.064	1.5
0.15	5.193	0.056	1.1
0.20	5.967	0.051	0.9
0.25	6.640	0.049	0.7
0.30	7.238	0.049	0.7
0.35	7.780	0.048	0.6
0.40	8.276	0.048	0.6
0.45	8.734	0.049	0.6
0.50	9.159	0.049	0.5
0.55	9.557	0.050	0.5
0.60	9.931	0.050	0.5
0.65	10.282	0.051	0.5

A.2 Cup anemometer calibration

The cup anemometer was calibrated in a wind tunnel with the same setup as for the Pitot-probe rake calibration tests. The anemometer DAQ system was turned on and left running for the duration of the test. The wind tunnel fan rotational speed was increased in 120 rpm increments from 120 to 720 rpm in ascending and descending order twice. The cups did not rotate below a 120 rpm rotational fan speed. Each fan speed was held for 120 s to obtain a sample of at least 100 data points per speed. The calibration curve in Figure A.3, where the Pitot-static tube wind speed results, U_{p-s} , are graphed with respect to the cup anemometer reading, U_{cup} , shows that a linear correction to the original calibration of the cup was needed.

Figure A.3: Cup-anemometer wind tunnel calibration results

As the wind tunnel flow is limited in direction and speed fluctuation rates, a site test was also used to compare the cup anemometer response and speed to the upper sensor of the bow apparatus Pitot-probe rake. The site test was carried out by mounting the instruments at the

end of a fixed dock as shown in Figure A.4, where the upper Pitot-probe was set at a fixed height of 1.4 m AWL to match the cup-anemometer position.

Figure A.4: Bow apparatus/cup-anemometer dock test setup

The test had a 256 Hz sample rate for 10 minutes. The results are shown in Figure A.5, where the cup anemometer and Pitot-probe readings follow the wind flow pattern in magnitude and direction within the instrument cut-in range (above 1.5 m/s for the cup anemometer).

Figure A.5: Bow apparatus/cup anemometer dock test

The cup anemometer wind speed results are slightly higher than the Pitot-probe pressure sensor, which could be a result of an additional lateral wind component not detectable by the streamwise pressure probe or by increased turbulence not accounted for by the low turbulence wind tunnel cup anemometer calibration tests.

A.3 Distance sensor calibration

The distance sensor was statically calibrated for the required measurement range in ascending and descending order using a standard tape measure with results shown in Figure A.6. Although the static calibration found the error to be within ± 1 mm, additional systematic error observed during field measurements of an estimated +20 mm is shown in the plot to account for the added uncertainty due to the dynamics of the mechanical system for the field setup.

Figure A.6: Distance sensor calibration and field setup uncertainty

Appendix B

Field measurement time series

Figure B.1 through B.6 show times series results for Mooney's Bay field measurements for configuration-1 and configuration-2 for the tests where wave height data were extracted.

Figure B.1: Time series results: July 6, location A, early-afternoon
Configuration-1 steady wind interval (s): 60 - 80
Configuration-2 wave height (mm): 20

Figure B.2: Time series results: July 6, location B, early-afternoon
 Configuration-1 steady wind interval (s): 85 - 105
 Configuration-2 wave height (mm): 40

Figure B.3: Time series results: July 6, location B, mid-afternoon
 Configuration-1 steady wind interval (s): 0 - 20
 Configuration-2 wave height (mm): 90

Figure B.4: Time series results: July 25, location C, late-morning
 Configuration-1 steady wind interval (s): non found
 Configuration-2 wave height (mm): 30

Figure B.5: Time series results: July 25, location C, late-morning
 Configuration-1 steady wind interval (s): 75 - 95
 Configuration-2 wave height (mm): 80

Figure B.6: Time series results: July 25, location B, late-morning
 Configuration-1 steady wind interval (s): non found
 Configuration-2 wave height (mm): 15

Appendix C

Wind tunnel measurement system calibration

Preliminary measurements were taken to confirm flow conditions and sensor readings within the test section with and without the model kayaker in place. For the velocity measurements, the vertical traversing measurements were taken using a Cobra Probe and the fixed reference velocity was calculated from measurements taken by a 2500 Pa Datametrics pressure transducer. A load cell was used to measure drag force which was calibrated statically with known weights hung on a pulley system in the streamwise directions and then checked for expected C_D results using a 2D cylinder.

Following are the results of the Cobra Probe and load sensor calibration tests.

C.1 Calibration of the Cobra Probe

To check calibration of the Cobra Probe velocity output values, results were compared to readings taken by a Pitot-static tube and the Datametrics pressure transducer. The Datametrics unit is professionally calibrated by Alpha Controls & Instrumentation on a yearly basis. The calibration report data was used to determine the calibration curve for the Datametrics pressure values. Although the transducer measures pressure, the voltage output is read as inches of water, and named a digital manometer by the manufacturer. Therefore, the calibration theory is explained in terms of water height.

From the calibration report, the calibration curve was determined to be:

$$\Delta H_{wc} = 1.0007\Delta H_w - 0.0026 \quad (\text{C.1})$$

where ΔH_{wc} is the corrected height of water, and ΔH_w is the height of water output by the system.

The pressure, or manometer reading, was converted to velocity, U , using Bernoulli's relation as follows:

$$U = \sqrt{\frac{2(P_0 - P_s)}{\rho_a}} = \sqrt{\frac{2(\rho_w g \Delta H_w)}{\rho_a}} \quad (\text{C.2})$$

where P_0 is stagnation pressure, P_s is static pressure, ρ is density, g is gravity, Δh is inches of water, and subscript a and w represent air and water.

Atmospheric pressure, P_a , was obtained from the Ottawa Airport hourly weather station report and was manually input at the start of each run, which was used with temperature reading, T , to calculate density using the ideal gas law as follows:

$$\rho_a = \frac{P_a}{RT} \quad (\text{C.3})$$

where R is the gas constant for air.

A temperature shift of no more than 1° C during a single run was observed from a Fisher-brand liquid-in-glass thermometer placed at the aft end of the test section. This deviation has negligible affect on velocity results (0.08 m/s). Using the above process to determine velocity, the Datametrics maximum error was 0.50 m/s, which is 0.01% for the calibration range.

A series of tests were done to compare the Cobra Probe to the Datametrics Pitot-static measurements for calibration of the Cobra Probe and to observe deviation due to test setup obstructions. All flow measurement results were time-averaged from an output sample rate of 2 kHz for 15.36 s. Following are the results in sequential order.

C.1.1 At location of pitot-static tube

For the calibration of the Cobra Probe, the Datametrix/Pitot-static tube system was used as the known value. The two probes were located at the test section inlet on centre. While the fan was running continuously, two runs were measured, where the vertical location was shifted for run 2 to capture measurement using the Pitot-static tube at the same height as the Cobra Probe from run 1. The results from Table C.1 show that the Cobra Probe deviates less than 0.28 m/s from the calibrated Datametrix measurements which is within the Cobra Probe manufacturers tolerance of ± 0.50 m/s.

Table C.1: Cobra Probe calibration

Run	Cobra Probe		Pitot-static tube	
	z (mm)	$\bar{U}$ (m/s)	z (mm)	$\bar{U}$ (m/s)
1	315	19.778	193	19.541
2	193	19.775	75	19.510

C.1.2 Pitot-static tube and Cobra Probe at test location

For the flow conditioning and load sensor tests the Pitot-tube was placed at the fixed downstream reference location while the Cobra Probe was placed at the leading edge of the kayak. Without the model in place, measurements were taken to compare Cobra Probe velocity results to Pitot-static tube readings to ensure that the velocity was not changing significantly due to streamwise location.

The test was also run to check test section symmetry where the Pitot-static tube was placed at the reference height for 125 mm to port side and 125 mm to starboard side.

Results from Table C.3 show that the Cobra Probe deviates less than 0.44 m/s from all Pitot-static tube measurements which is within the Cobra Probe manufacturers tolerance of ± 0.50 m/s. Therefore it was assumed that flow was symmetric and within sensor accuracy for the distance the probes were located away from one another.

Table C.2: Pitot-static tube downstream of Cobra Probe ($z = 315$ mm)

Run	Cobra Probe		Pitot-static tube	
	$\bar{U}_{port}$ (m/s)	$\bar{U}_{stbd}$ (m/s)	$\bar{U}_{port}$ (m/s)	$\bar{U}_{stbd}$ (m/s)
1	19.876	19.781	19.583	19.761
2	30.326	30.217	29.943	30.102
3	40.726	40.599	40.290	40.467
4	45.774	45.633	45.464	45.619

C.1.3 Obstruction of flow at the Pitot-static tube

The Cobra Probe traversing support bar and Cobra Probe body were an obstruction of the flow upstream of the Pitot-static tube. Therefore, a test was run to check velocity change read by the Pitot-static tube for the full traversing height of the Cobra Probe. Results found that the velocity was slowed by a maximum of 0.17 m/s when the Cobra Probe body was at the height of the Pitot-static tube. The measurements were found to be more consistent when the Cobra Probe was close to the test section floor. Therefore readings from the Pitot-static tube for final flow condition reference value were taken when the Cobra Probe was at the lowest measurement height.

Table C.3: Pitot-static tube obstruction test

Run	Cobra Probe height (mm)	Cobra Probe $\bar{U}$ (m/s)	Pitot-static tube $\bar{U}$ (m/s)
1	315	45.510	45.506
2	291	45.517	45.483
3	260	45.499	45.436
4	230	45.446	45.354
5	199	45.421	45.311
6	169	45.452	45.318
7	138	45.512	45.351
8	108	45.611	45.440
9	77	45.587	45.521
10	47	45.533	45.500
11	16	41.300	45.599

C.1.4 Model obstruction test

Since the flow condition measurements for the grid profiles would not have the model in place, a test was run to confirm that the presence of the model did not alter the velocity at the Pitot-static tube. Results seen in Table C.5 show that the maximum difference is 0.17 m/s at the highest velocity and is below the reference deviation from the Cobra Probe of ± 0.50 m/s. Therefore, the addition of the model for the final tests is not expected to change the free-stream reference measurement taken by the Pitot-static tube.

Table C.5: Model obstruction test

Run	Pitot-static tube $\bar{U}$ (m/s)	
	with kayaker	without kayaker
1	19.572	19.632
2	29.925	29.858
3	40.265	40.120
4	45.434	45.266

C.1.5 Conclusion

From the test section velocity measurements where calibration of the Cobra Probe was checked, and the consistency of the reference velocity taken by the Pitot-static tube was confirmed, the Cobra Probe measurements of velocity profile can be expected to be within the manufacturers specification of ± 0.50 m/s.

C.2 Calibration of the load sensor

For the drag force measurements, a JR3 100 N 6-axis load sensor was used. Forces were measured in the streamwise (drag) direction (F_x). The load cell data is returned to the receiver at a rate of 8 kHz for all 6-axis, therefore the acquisition rate was set to 8 kHz with an output rate from the DAQ of 1 kHz, sampling each millisecond for 15 s at each data point. The load sensor was calibrated with known weights for a static test, and then tested for drag

coefficient using a 2D circular cylinder which was compared to published values. Results and some details are presented in the following.

C.2.1 Static F_x calibration

With the load sensor mounted in place under the test section floor, known weights covering the expected load range for final use and the 2D cylinder test were hung from a pulley for two arrangements where a uni-directional force was applied in the x-direction. The output data was then processed using Matlab, where a calibration matrix provided by the manufacturer was required to obtain the force values.

Figure C.1 shows the time-average results for each known weight for the streamwise applied force.

Figure C.1: Load sensor F_x calibration curve

The calibration curve correction was applied to all F_x load sensor results, with a sensitivity error (max deviation after calibration) of 1.3% reading.

C.2.2 C_D of a circular cylinder

The measured drag force of a 2D 0.048 m diameter cylinder was compared to published experimental data for similar subcritical flow regime and cylinder aspect ratio. The base of the cylinder was mounted to the load cell in the same location as for the model kayaker setup. There was a 2 mm gap at the top of the cylinder which was assumed to be small enough to prevent flow between cylinder top and test section surface. Tunnel wind speed range and increment was set to match the model kayaker tests.

Figure C.2: Cylinder C_D comparison to digitized data from Schewe (1983)

Results plotted over published values are shown in Figure C.2. The error bars have been determined using the uncertainty analysis technique described in Chapter 5, with a maximum C_D uncertainty of ± 0.07 . The C_D of a circular cylinder can be affected by surface roughness, diameter, eccentricity of the diameter, turbulence intensity and length scales. Therefore, the comparison of the 0.048 m diameter cylinder to the published results has only been used as a preliminary test to confirm the system is providing results that are within reason.

Appendix D

Flow conditioning grids

The grids used to alter the flow through the wind tunnel test section for the $\frac{1}{6}$ model kayaker C_D testing were designed to suit the physical constraints of the tunnel setup. With a fixed length test section directly downstream of the wind tunnel contraction, the flow conditioning was restricted to a short fetch. The kayaker model was placed with the trailing edge at the extreme end of the test section, which set the distance between inlet grid and kayak leading edge to twice the height of the tunnel.

D.1 Grid geometry

No references were found to model the desired profiles. Therefore the grids were developed using an initial calculation of blocked velocity per unit height for 12 mm diameter wooden dowels. This method worked well in the lower boundary layer region, but became less applicable with increased dowel spacing. Trial and error was used for final adjustment of the grid dowel size and spacing, where the traversing Cobra Probe provided the measured velocity profiles. The grid-1 setup with Cobra Probe in place can be seen in Figure D.1, with grid dowel diameter and spacing illustrated in Figure D.2.

Figure D.1: Wind tunnel test section grid flow measurement setup

Figure D.2: Grid dowel diameter and spacing (mm)

D.2 Grid-1 ABL velocity profile

For the grid-1, used to produce a velocity profile representing the prevailing ABL for wind over water, the non-dimensionalized velocity profile, U/U_{ref} , was designed to follow a logarithmic profile for a 2 m/s wind at a reference height of 10 m above water. As the limitations of the wind tunnel speed set the headwind range from 0 to 4 m/s, the 2 m/s value was chosen to represent the middle of the test range. The variation between a normalized velocity profile for a 2 m/s and a 4 m/s for wind over water, where roughness length changes with wind speed, is largest near the surface boundary, and is considered insignificant, as the maximum value is within the uncertainty ($\pm 0.02U/U_{ref}$) of the measured profile shape.

Appendix E

Numerical investigation of sprint kayaker aerodynamics

A numerical study has been carried out to supplement wind tunnel tests of a model kayaker which were used to investigate the sensitivity of coefficient of drag, C_D , to three flow conditions. To calculate the C_D from the wind tunnel aerodynamic drag results, two methods were used, one which used a constant reference air velocity, and the other which integrated the measured velocity profile and area for incremental sections spanning the height of the kayaker. The second, formerly called the integrated method, was assumed to remove effect of the variation in velocity profile for each of the three flow conditions. Although the method reduced the gap between C_D results, some variation remained, suggesting that the velocity profile was not the only flow characteristic affecting the C_D . Therefore the numerical study has been used to observe local effects at the kayaker's body with respect to flow conditions.

As there has been no literature found for the purpose of benchmarking the 3D kayaker model, a numerical investigation by Stringer et al [46] on drag coefficient for a 2D circular cylinder in cross flow for the same Reynolds number range was used for computational method guidance. Modelling of the human body as cylinders for drag coefficient measurements for sports science has been well documented by D'Auteuil [15] and Chowdhury et al [47]. Although the kayaker model also includes the streamline kayak, and the flat plate paddle blade, the majority of the model consists of a grouping of cylinders, with the dominant cylinder being the torso.

The domain inlet was $1 D$ upstream of the kayak leading edge, and $0.5 D$ upstream of the wind tunnel measurement probe location. The closeness of the inlet to the wind tunnel probe location prevented the bottom boundary layer from growing and therefore deviating from the input profiles by the time flow reached the measurement location. Initial simulations confirmed that the inlet was sufficiently far enough upstream of the kayak leading edge to prevent interference with the flow at the kayak.

The outlet was placed at a downstream location where its affect on the flow around the kayaker's bluff body was considered negligible. The outflow boundary was initialized with an average static pressure of $0 Pa$.

The sides and top wall were set to slip condition, with the assumption that the free-stream air flow was not affected by the presence of the kayaker at that distance.

The air density was input as 1.18 kg/m^3 to match the experimental condition.

E.1.2 Meshing

The computational domain was discretized using an unstructured tetra/mixed grid, with prism layers of growth rate 1.1 at the kayaker and bottom wall surfaces. The distance of the first prism layer from the kayaker was set to $y^+ < 1$ which is considered appropriate for circular cylinders in cross flow. The purpose of controlling the first, or shear layer from a non-slip wall is to allow for boundary layer growth by making a geometrical connection between node spacing and shear stress, which in turn provides a boundary layer profile and avoids the automated wall function used by the solver.

Three successively refined grids were generated using ICEM CFD 17.2. The grids were refined from a baseline grid following the basic method for refinement ratio by Celik et al [48] where an overall cell growth rate of 1.3 is suggested. Due to the unpredictability of the automated unstructured meshing, the refinement of the cell size was done by reducing the size of governing element maximum size by 60% for each iteration. The governing elements included the first prism layer height at kayaker and bottom, a density box, and the global maximum element size. The density box included the entire width and length of the domain

with height at the tip of the kayak paddle. The density box was used to reduce the number of elements above the height of the kayaker while ensuring high density in the wake region.

A convergence study on the three grids was done to ensure that the results were independent of the grid element size and organization.

E.1.3 Numerical scheme

ANSYS CFX 17.2 was used for the solution, which uses a finite volume method (FVM) to solve Navier-Stokes equations algebraically. The spatial derivatives are calculated using a second order centre-differencing method, with a second-order Euler backward differencing method used for the temporal derivatives.

The setup solved, incompressible, URANS equations using the two equation turbulence model Shear Stress Transport (SST), which uses the $k - \omega$ model to estimate near wall turbulence and the $k - \epsilon$ model which predicts well away from the wall where the eddies are expected to behave relative to velocity. Stringer et al [46] has found SST to solve drag coefficient of circular cylinders well for a flow regime $Re > 10^5$. For the kayaker model, the Re values for the entire height of the torso for all flow conditions are above 10^5 .

There is also a range of Re from 1.7×10^4 to 1.7×10^5 for the flow around other cylinders within the kayaker model, including pole and body parts, which means Kármán vortex shedding is expected. Using a non-dimensional Strouhal number of 0.2 as suggested by Achenbach and Heinecke [9] for a smooth 2D cylinder in the subcritical Re region, determines the shedding period to be 0.009 s at the model torso. One tenth of the estimated period was used for the timestep to ensure definition of the vortex shedding. Since the shedding frequencies take time to settle into a constant amplitude after the onset of flow, a method confirmed by Stringer et al [46] was used, where a non-dimensional overall time required to settling is found as follows:

$$t^* = \frac{tU}{D} \tag{E.1}$$

where t^* is the non-dimensional time, t is total time, U is fluid velocity and D is cylinder diameter. This method has been used for a large range of Reynolds number to determine that at a value of $t^* = 30$, the onset of shedding frequency settling starts, and that at $t^* = 150$ the shedding pattern is well established. This method was used for the kayaker model resulting in $t = 0.315$ s for $t^* = 150$.

E.1.4 Mesh convergence procedure

For the purpose of determining the mesh dependent errors, simulations on the three successive mesh refinements were run with input inlet boundary profiles for an experimental flow condition. Comparison of variables critical to the investigation of the flow were used for the convergence study including kayaker drag force, flow separation location at the torso, and cross-stream velocity profile 1 D downstream of kayaker torso at chest height, or $z = 0.4 h$.

The simulation is assumed to have good convergence when the mass, and momentum RMS residual calculations have reduced to 10^{-5} . It was found that some local RMS residual momentum values were as high as 10^{-4} . Those cells were isolated to determine location, which was in a small area in the unstable wake, downstream of the kayaker away from the analysis region. For the purpose of this investigation, where pressure drag and separation location are compared for differing flow conditions, the mesh was considered sufficiently converged.

E.2 Numerical results

Simulations were run for the sequentially refined grids with results used to confirm grid independence and final mesh error according to the GCI method by Celik et al [48]. The grid refinement results are shown in Table E.1 where ϕ is used to denote the variable for each column according to the GCI method. With the mesh independent fine grid, the simulation was solved for the three experimental flow conditions to compare drag force results, and C_D with experimental results. The numerical model was also used to investigate flow separation and frontal area pressure distribution for the purpose of comparing the turbulence effect, flow interaction, and velocity assumptions.

E.2.1 Mesh convergence and error study

Table E.1: Grid convergence study results for drag force and separation location

Description		$\phi = \text{kayaker}$ streamwise drag force (N)	$\phi = \text{y-direction}$ separation location, port (m)	$\phi = \text{y-direction}$ separation loca- tion, starboard* (m)
Refining ratio (course to medium)	r_{32}	1.4		
Refining ratio (medium to fine)	r_{21}	1.3		
Variable (fine grid)	ϕ_1	5.694	-0.0315	0.0318
Variable (medium grid)	ϕ_2	5.892	-0.0322	0.0315
Variable (course grid)	ϕ_3	6.821	-0.0325	0.0319
Apparent order	P	5.04	3.30	0.40
Extrapolated ϕ^{21}	ϕ_{ext}^{21}	5.619	-0.0327	0.0347
Approximate relative error	e_a^{21}	3.5 %	0.8 %	1.0 %
Extrapolated relative error	e_{ext}^{21}	1.3%	0.6%	8.2 %
Fine grid convergence index	GCI^{21}	1.7%	0.8%	11.2 %

* starboard = blade up

Figure E.2: Grid convergence study: cross-stream velocity profile 1D aft of torso

E.2.2 Numerical aerodynamic drag

The numerical aerodynamic drag force on the kayaker for $t^* = 150$ is compared to experimental results in Table E.2.

Table E.2: Kayaker aerodynamic drag: experimental and numerical (CFX)

Flow condition	Force (N)		
	Experimental	CFX	Deviation
uniform	5.754 ± 0.133	5.694 ± 0.095	0.060
grid-1	5.420 ± 0.025	5.722 ± 0.097	0.302
grid-2	6.038 ± 0.011	6.208 ± 0.106	0.170

The numerical solution for the drag force on the kayaker compares well to the experimental results with discretization error within the experimental uncertainty for the uniform flow condition. For the grid-1 and grid-2 flow conditions, the numerical drag force results are outside of the experimental uncertainty. Although the dominant length scale, turbulence intensity and velocity profiles were input as inlet boundary conditions, the profiles were interpolated by the solver from discrete incremental values which were averaged from the experimental data. Therefore, the details of the turbulent structures and velocity profile around the downstream bluff bodies may have been predicted differently by the SST solver than were present for the experimental testing.

The experimental results show a drop in the drag force for the grid-1 condition, which was not the case for the numerical results.

E.2.3 Comparison of numerical to experimental C_D

Figure E.3 shows the experimental versus CFX ($t^*=150$) results for C_D calculated using; a) the reference velocity method and b) the integrated velocity method, for the three flow conditions.

Figure E.3: C_D comparison: a) reference velocity method, b) integrated method; square = uniform, diamond = grid-1, triangle = grid-2; solid = experimental, open = CFX

The CFX C_D results show the largest deviation from the experimental C_D for the grid-1 flow condition, with a result 4% higher for the reference velocity method and 6% higher for the integrated method. The integrated method results show a similar trend to the experimental C_D where removal of the velocity profile effect shows that although the gap between the C_D for the three flow conditions decreases, other secondary flow characteristics are present which have a small effect on the C_D .

E.2.4 Numerical model separation location

To observe change in flow pattern between the multiple components of the kayaker, separation location has been found at a horizontal plane cutting through the pole, left arm and torso, as shown in Figure E.4.

Figure E.4: Numerical model separation location at $z = 0.4 h$; square = uniform, diamond = grid-1, triangle = grid-2

For the cross section at $0.4 h$, the leading component is the pole which was found to have flow separation at a constant location for the three flow conditions. For the arm, the grid-1 and grid-2 results showed two closely spaced separation points on the outer side of the arm, whereas the uniform flow showed separation on the inner and outer sides. For the torso, a single location was found for the three flow conditions on the starboard side. For the port side, in way of the arm wake, the separation location was dependent on the flow condition, with the grid-1 result separating at the aft most point. The separation location results for this cross section demonstrate that at some locations, although the Re is the same, the interaction of the flow between components may alter the overall flow pattern.

E.2.5 Frontal area pressure distribution

From Figure E.5, the numerical model shows that the pressure distribution over the frontal area of the kayaker is affected by upstream components as seen by the non-uniform pressure distribution across the width of the kayaker's chest. The proximity of the upstream pole to the kayaker's chest causes wake interaction resulting in an asymmetric pressure distribution within the pole wake region.

Figure E.5: Numerical model frontal area pressure distribution

The pressure distribution also shows that although the Re is the same at the torso, the high pressure region for the grid-2 case is larger than for grid-1 on the flat-plate paddle blade.