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School of Engineering

Designing a paddle blade Fluid flow assessment

Structural & Fluid Analysis

ACMA6010

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1 Introduction

This report will focus on the fluid flow over a paddle blade of which a SLDPRT file has been provided. Within section (2) the Reynolds number will be discussed to explain how the definition between turbulent and laminar flow and the influences this had when moving the paddle through fluid. Continuing from this; how that fluid flow interacts around the blade will be discussed and in turn how that helps facilitate the paddling motion. Finally, the Reynolds number will be drawn to discover whether a paddle allows for turbulent or laminar flow.

Section (3) will discuss the boundary flow around the blade. Here boundary flow separation will be discussed and compared with various paddles on the market to discover why certain blades are shaped the way that they are. Continuing from this (4) will focus on the materials that have existed in paddle blade manufacture and how they may affect the fluid flow. In section (5) modelling and simulation methods will be highlighted that exist to assist in analysis of fluid flow. Finally, section (6) will focus on how a prototype can be tested and compared to that of the simulation in section (5)

2 Reynolds number

2.1 Discussion

In microfluidics, the Reynolds number is one of the most important dimensionless quantities. It connects the forces of inertia with viscous forces. Reynolds first described the Reynolds number in 1883 (Rapp, 2017). To achieve this Reynolds injected a dye stream into a running liquid conduit. The resulting straight streak showed laminar flow in some cases, whereas dispersal of the streak suggested turbulent flow in others. The change was abrupt, both in terms of placement in the pipe and in terms of the flow characteristics. Several methods were discovered to induce the flow to change from laminar to turbulent: (Vogel, 2020)

For model tests in wind tunnels or water channels, the Reynolds number is also critical. Accurate results in the model experiment that can be translated to reality can only be produced if the Reynolds numbers in the model experiment correspond to the real Reynolds numbers. The characteristic length L for computing the Reynolds number corresponds to the length of the item in the direction of flow in the case of objects around which flow occurs (Tec-science, 2020). The formula is as follows:

$$Re = \frac{\rho v l}{\mu}$$

Where:

Re = Reynolds number, a dimensionless number

ρ = density of the fluid

l = Characteristic length or chord width.

v = velocity of the fluid.

μ = Dynamic viscosity of the fluid.

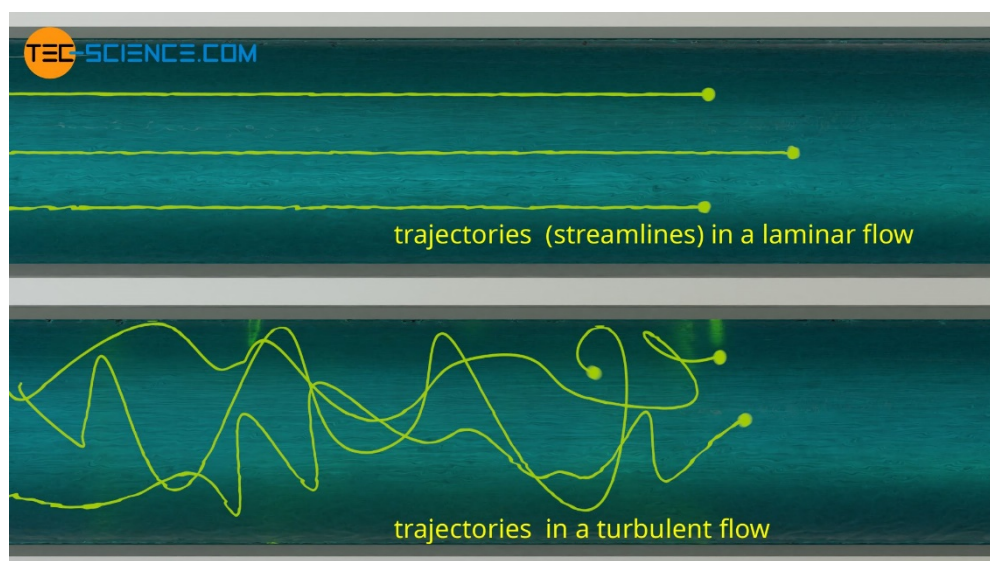
Note that all parameters are presented in the same units, resulting in the Reynolds number having no units when multiplied together (Upp, 2014).

An item with a higher Reynolds number can force its way through a flow field, even across the streamlines. A huge vessel or ship (with Reynolds numbers in the range of 10^9) against a folded

origami or paper boat is an excellent example: the massive vessel can force its way through the current and waves, whereas the light paper boat would not be able to. It must instead follow the streamline and will be dragged along (Rapp, 2017)(Figure 1).

	<i>Reynolds Number</i>
A large whale swimming at 10 m s^{-1}	300,000,000
A tuna swimming at the same speed	30,000,000
A duck flying at 20 m s^{-1}	300,000
A large dragonfly going 7 m s^{-1}	30,000
A copepod in a speed burst of 0.2 m s^{-1}	300
Flapping wings of the smallest flying insects	30
An invertebrate larva, 0.3 mm long, at 1 mm s^{-1}	0.3
A sea urchin sperm advancing the species at 0.2 mm s^{-1}	0.03
A bacterium, swimming at 0.01 mm s^{-1}	0.00001

However, at large flow rates, turbulence occurs in fluids, and laminar flow is no longer possible. A turbulent flow is used in this situation. Disturbances in the well-ordered flow, which are always present, generate turbulent flow. However, a relatively strong internal cohesion of the fluid can compensate for these disruptions to some extent, allowing the flow to remain laminar (Tec-science, 2020)(Figure 2).



If the Reynolds numbers are larger than 100,000, a turbulent flow is expected when a fluid passes over a flat plate. The critical Reynolds values in agitated vessels are around 10,000. Turbulent flows don't have to be a disadvantage in this scenario; they help with speedy mixing (Tec-science, 2020). When considering the paddle blade this would assist in the propulsion forwards, however in the case of automobiles or aeroplanes, turbulent flows are generally undesirable since they result in energy dissipation. Therefore, these objects should be created in a streamlined manner to avoid turbulence (Tec-science, 2020).

2.2 Influences on flow around the blade

When considering the paddle, the forces attributed to the momentum of a moving fluid are referred to as inertial forces. As a result, a particle of fluid, urged on by its inertia, continues to do its regular thing to the extent that it stays unmolested. The second factor is viscous forces, which were previously overlooked. Fluid's dislike being sheared; if shear occurs, viscous forces will fight the motion's persistence, just as friction opposes the movement of one solid across another (Vogel, 2020). The viscosity will tend to smooth out any internal flow abnormalities (Vogel, 2020).

So, if the relative importance of inertial and viscous forces separates various flow regimes, it would imply that the relative importance of inertial and viscous forces distinguishes different flow regimes. The former keeps things moving, whereas the latter brings them to a halt. In this instance the paddle stroke would ideally be turbulent as turbulence is favoured by high inertial forces, which are inevitably accompanied by high shear rates (Vogel, 2020).

2.3 Reynolds number for the fluid flowing around the blade

From the paddle blade concept provided (*Figure 4*) data was retrieved to find the chord width of the paddle (*Figure 3*)

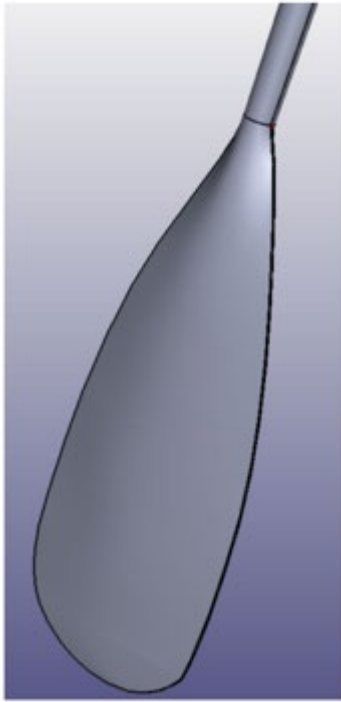


Figure 4 – Paddle CAD

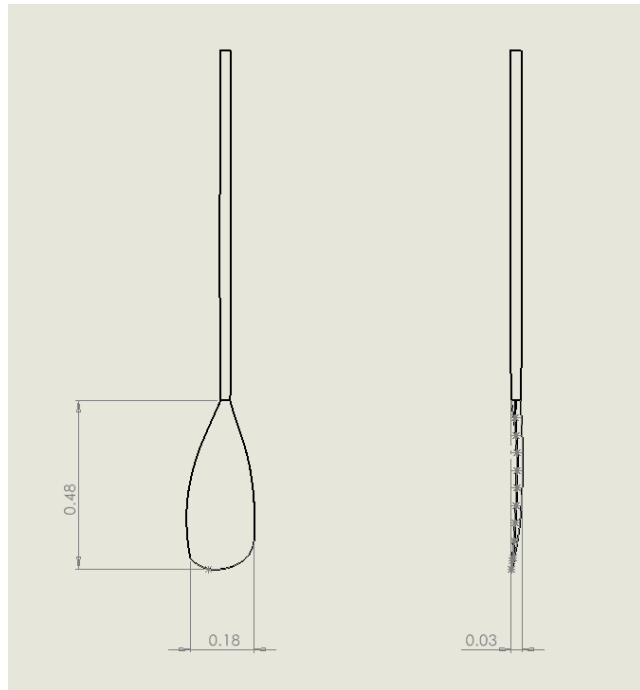


Figure 3 – Technical Data of Part

With a chord width of 0.18m we can show the characteristic length as:

$$l = 0.18m$$

For the velocity of the fluid the average paddling speed of 1.53m/s was considered (kayakingnear, 2020)

Thus:

$$v = 1.53 \text{ m/s}$$

Knowing that the density of water is 1000 kgm^{-3} the dynamic viscosity of the fluid can be found in (Figure 5)

Temperature [°C]	Viscosity [mPa·s]
10	1.308
20	1.002
30	0.7978
40	0.6531
50	0.5471
60	0.4658
70	0.4044
80	0.3550
90	0.3150
100	0.2822

Figure 5 - Dynamic Viscosity of water - (Engineersedge, 2015)

Thus:

$$\mu = 1.308 \times 10^3$$

Using the equation:

$$Re = \frac{\rho v l}{\mu}$$

$$Re = \frac{(1)(1.53)(0.18)}{(1.308 \times 10^3)}$$

$$\underline{Re = 210.486}$$

So, it can be stated that the fluid flow would be turbulent.

3 Boundary Flow and application

It's clear that there are various aspects to consider when determining what is the "optimal" paddle form, depending on differing viewpoints and applications. Manufacturers vary in their ability to provide great form alternatives for kayak paddle blades within their product lines (Watson, Basic Kayak Paddle Shapes, 2013). Modern paddlers can choose from the traditional form as well as a variety of alternative shapes that have changed as technology and paddling styles have progressed. Each is intended to make moving a kayak through the water more efficient and powerful (Watson, Basic Kayak Paddle Shapes, 2013).

With the fluid flow across the paddle has been defined as turbulent (2.3) a closer look will be taken at how it moves through the water. A flow can follow a body's shape if the transitions are smooth, and the fluid's viscosity is high enough to resist inertial forces. Around the body, a typical hydrodynamic boundary layer forms, the thickness of which is mostly determined by viscosity (Tec-Science, 2020)(Figure 6).

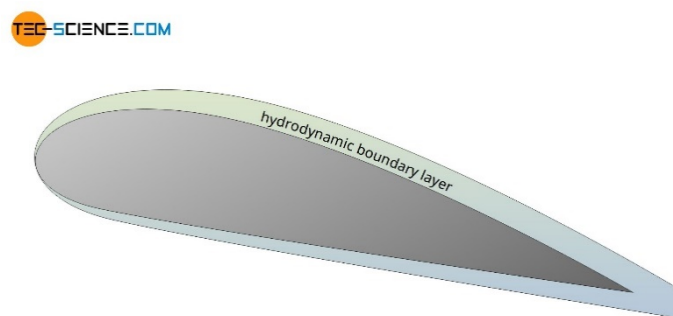


Figure 6 – Hydrodynamic Boundary Layer (Tec-Science, 2020)

However, when the fluid encounters sharp transitions or flows around blunt bodies, it is frequently unable to follow the profile. The boundary layer, or flow, starts to separate from the body surface. The separation of the boundary layer or flow is referred to as a boundary layer separation or flow separation. Vortices frequently occur downstream of the separation point, resulting in a turbulent flow. (Tec-Science, 2020). This in turn benefits the paddle as it enables for more control over the

steering and power output of the stroke. When all other factors are equal, a larger surface will push more water. Because a shorter paddle is used for a vertical/high stroke, the blade is usually shorter but wider than those used for a longer, horizontal stroke. A broader, shorter blade is more efficient and effective in achieving the need/use of power in the high stroke (Watson, Basic Kayak Paddle Shapes, 2013).

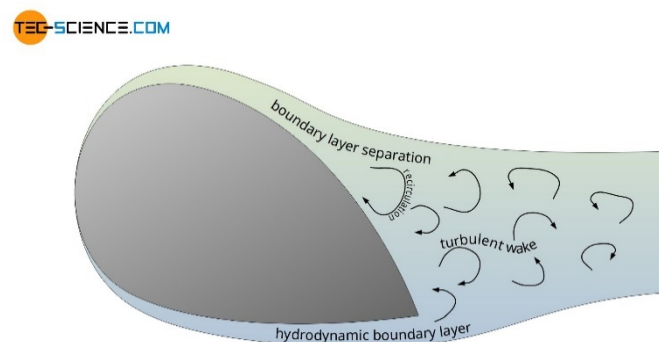


Figure 7 – Boundary Layer Separation (Tec-Science, 2020)

Because it explains the relationship between existing inertial forces and operating viscous forces in a fluid, the Reynolds number is critical. The greater the inertia compared to viscosity, the greater the probability of boundary layer separation. Even with streamlined bodies, flow separation will eventually occur if the Reynolds numbers are high enough (Tec-Science, 2020). So

For this reason, when considering the choice of paddle, a lower chord width would prove more advantageous to a longer day paddling as compared to a greater width within more competitive scenarios. Wider blades provide for faster, more powerful strokes, allowing you to accelerate quickly. Therefore, many kayaking surfers choose them (Paddling-Magazine, 2016). Whereas a longer, narrower blade generally enters the water more gently and gives the paddler better control and skill. Shorter, wider blades, on the other hand, have more power and are better suited to

shallow water (Ashes-Still-Water-Boats, 2019). This can be seen in (Figure 8) where the widths are greater in Whitewater applications as opposed to touring.

			Weight - Blade set in grammes +/- 3%							
	Paddle blade design	Primary Usage	SF	LF	N12	CC Standard	CC Light	Area	Width cm	Length cm
Ribbed Blades	Cybi Bach	Sea Touring - Children	620		730			560	16.5	50
	Kinetik touring 600	Sea Touring	650		770	560	490	600	17	50
	Kinetik touring 650	Sea Touring	690		830	570	500	650	18	50
	Kinetik touring 700	Sea Touring	750		850	590	510	700	19	50
	Archipelago	Sea Touring - recreation	660		780	570	500	650	17	50
	Nordkapp	Sea Touring	760		860	600	520	725	19.5	50
	Reef	Surf			850	600	520	715	19	50
	Power	Whitewater			820	590	510	625	19.75	48.5
Dihedral	Xti	Whitewater		870	860			675	21.5	48.5
	Fusion - Polymer	Whitewater - Surf		860	850			700	20.5	47.5
	Mania	Whitewater/Packrafting		870	860			650	19.75	48.5

Blade Materials

SF - Short fibre Polymer

LF - Long fibre Polymer

N12 - Nylon 12 - Glass filled

CC Standard - Carbon - Glass Composite

CC Light - Carbon - Carbon Kevlar

Weight

Durability

Stiffness

Figure 8 – Celtic Paddle comparison (Celtic-paddles, 2020)

The other consideration can be made when viewing the curve of the blade the bite of a paddle in the water is affected by adding a sweep to the blade, either along the axis of the blade (curve) or through the cross-section (spoon). During the power stroke, the curvature resembles the shape of a swimmer's hand. The curvature is intended to enable a quick catch at the start of the stroke. Because the blade is curved, it should be removed from the water as soon as possible to avoid the curvature lifting water instead of pushing it. The curvature can be placed equally throughout the blade or applied more towards the tip. A spooned blade has a spoon-like form. The lengthwise edge of a spoon paddle, when set flat with its power face above, allows you to add water without it pouring back off like it would on a "curved" blade (Watson, Basic Kayak Paddle Shapes, 2013).

4 Materials and Performance

Paddle blades, like paddle shafts, come in a variety of materials, each with its own efficiency and feel while paddling. While traditional paddles made of wood are still being manufactured, they aren't as durable as well-made synthetic paddles. They can be created in a variety of forms and designs (Moore, 2019). Paddle blades are more expensive as they get lighter and stiffer. Plastic polypropylene blades are the most basic and inexpensive option on the market. These are tough, but they're also a little flimsy, and the blade flex is visible while drawing the blade through the water. During the flexing, some of the energy put into the paddle stroke is wasted. Blades made of polypropylene are likewise quite hefty (Faisey, 2017).



Figure 9 – Glass Fibre paddle (Moore, 2019)

The blade presented in this report is to be manufactured from glass fibre reinforced plastic. Fiberglass is a fibre-reinforced plastic made by infusing glass fibres, which are molten sand that is extruded via brushing to produce a fibre that is woven into glass sheets, with a plastic resin, most often epoxy. It's an adaptable substance with a wide range of applications and beneficial properties. Its capacity to be moulded into complicated shapes that would be impossible to cast with other materials is a crucial advantage. As a result, it's frequently utilised to make storage tanks, boat hulls, and kayak paddles (OBrien, 2021). The raw material, glass fibre, is inexpensive to create, making it a viable commercial choice. Fiberglass is also durable, lightweight, non-rotting, and non-combustible. The sole disadvantage is that it expands with temperature fluctuations or prolonged exposure to sunshine, which can cause the resin or topcoat to break if painted. However, because fibreglass is easily healed, it is not a significant problem unless left untreated (OBrien, 2021).

bladed paddle. More people are upgrading to a fibreglass paddle over a carbon fibre paddle because of this limiting aspect (OBrien, 2021)(figure). Paddles with fibreglass blades have better performance and durability than paddles with carbon fibre blades at a lower cost. In terms of all kayak paddles, they are in the centre of the pricing range (*Figure 10*). The blades on these paddles are more likely to chip than plastic blades, but they rarely shatter completely. These paddles are also more efficient than those with plastic blades due to the extra stiffness of fibreglass (Salisbury, 2021).

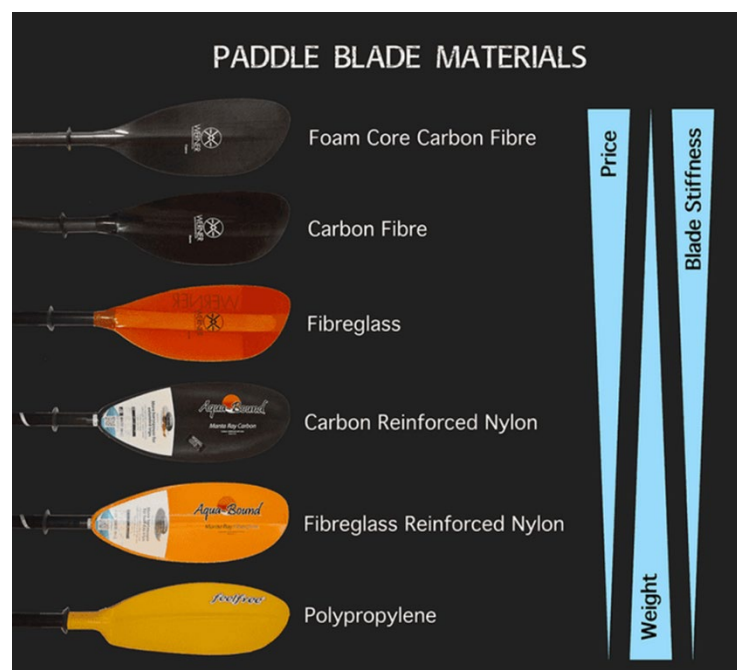


Figure 10 - (Faisey, 2017)

For these reasons carbon fibre paddles have become more popular in recent years. This material produces paddles that are both light and robust. Carbon fibre blades are lighter than fibreglass blades, but they suffer from the same chipping and other issues. Carbon fibre is a fabric formed of yarns spun from exceedingly fine carbon strands, while the word technically refers to the fibres themselves (Moore, 2019).

Consider a long-chain polymer with carbon atoms forming the molecule's major "spine." Remove anything that isn't carbon from the molecule with heat, chemicals, or whatever else you can think of while keeping the spine intact. The resulting fibres are exceedingly fine and strong, outperforming steel in terms of strength and stiffness (Moore, 2019). High strength and rigidity are two of the main features. This allows for the blade to maintain its rigidity when being pulled through the water. One important downside is that, as compared to other FRPs, it has weak impact resistance (Moore,

2019). This in turn means for activities such as Whitewater run a higher risk of causing damage to the paddle. Kayak builders frequently combine carbon fibre with other materials such as Kevlar or fibreglass to solve this problem. Carbon fibre and, say, Kevlar, can be blended in a single fabric by weaving alternate strands of carbon fibre and Kevlar, or by alternating layers of carbon fibre and layers of, example, Kevlar (Moore, 2019).

5 Modelling and simulation

The main modelling technique that could be used to simulate the flow around this blade would be Computational fluid dynamics modelling (CFD). CFD is based on fluid mechanics concepts and employs numerical methods and algorithms to solve fluid flow problems. CFD models aim to replicate the interaction of liquids and gases with boundary conditions defining the surfaces. They also keep track of how solids flow through a system. The Navier-Stokes equations are employed in these models. The equations are then solved iteratively as a steady-state or transient situation, and simulations are run (David A. Tillman, 2012).

So far, no complete fluid dynamic investigations on a rowing blade have been conducted under actual rowing conditions. This type of research would reveal the unstable flow behaviour around a rowing blade in motion, enabling for further exploration into areas for improvement (Sliasas & Tullis, 2009). Due to this the need for CFD modelling can be crucial to the designs of new blades and concepts.

CFD can be broken down into four steps:

Step 1 -The investigated spatial air flow situation is represented in a "3D-CAD" programme with an interface or exchange format to the software used to solve the CFD equations. In order to justify them with boundary criteria, the CAD model assigns an alphanumeric number to all adjacent surfaces (Koeln, 2014).

Step 2 -Tetrahedra, hexahedra, and other base bodies occupy the observed interior volume. The establishment of these control volumes necessitates adherence to a set of guidelines. The length-to-width ratio should not exceed a 1:5 scale, as this may generate unstable simulation circumstances. This stage also includes the definition of all boundary conditions. This could be the perfused volume's surface texture, the inlet and outlet apertures, or the temperature of the fluid being tested (Koeln, 2014).

Step 3 - The selection of one or more suitable models for the stream is a prerequisite for a successful calculation. It is necessary to distinguish between the types and forms of flow (stationary/non-stationary/laminar/turbulent), the type of conductor (pipe, channels, etc.), and the type of fluid (friction/viscous). Iteratively, the numerical approximation process for partial differential equations

arrives at a solution. It terminates the procedure after it has undercut a defined approximation error. Physical model parameters are approached as a rule to check the answer.

Step 4 - Mass flows or function graphs are common for displaying simulation results, with the resulting parameters (such as flow rate or pressure) on an ordinates axis and position or time on the abscissa. Colourful two- or three-dimensional visuals that depict the pressure or flow velocity of the fluid in the inspection area via a colour spectrum. (Koeln, 2014).

Some advantages and disadvantages of CFD can be seen in (*Table 1*).

Table 1 - Advantages and disadvantages of CFD

Advantages	Disadvantages
Specific physical boundary conditions or effects can be considered in isolation	Errors may occur due to simple flow models or simplified boundary conditions
Simulations provide at any point (of the pattern) measured data, experiments in contrast only a few selected points	Possible uncertainties caused by too little computing values per cell and hence therefore resulting interpolation errors
Many flow parameters are gathered, which are not accessible in experiments	Computation time may extend for large models
In the beginning of the planning process, a variety of prototypes are simulated in order to quickly gather information for further planning	The costs may be much higher due to wrong consulting compared to experiments
Simulations are able to contribute to a greater understanding of the problem than experiments	
The costs are usually much lower compared to experiments	

6 Discussion prototype development

To develop this component a model prototype could be created full scale to be placed within a wind tunnel. When considering this the effect of Reynolds number for the model data to be applied directly to real-life conditions, both geometric (aspect ratio) and dynamic (Reynolds number) similarities must be accomplished, as with any fluid dynamic test requiring the use of scaled models. Within Caplan's experiment geometric resemblance was achieved since the models were scaled exactly from the full-size oar blades (Caplan & Gardner, 2007). By altering the model size or relative free stream velocity, the dependence of the model data on Reynolds number can be determined. If the blade size was increased, the measured force coefficients would be influenced by a reduced average free stream velocity across the frontal area of the blade due to the edge effects of the water flume, with the fluid velocity falling as the edges are approached (Caplan & Gardner, 2007).

(D. Sumner, 2003) Created such an experiment where tests were carried out in a low-speed, closed-return wind tunnel. Outside the test-section-wall boundary layers, the velocity non-uniformity in the middle area of the test section was less than 0.5 percent (D. Sumner, 2003). To help facilitate this a Plexiglas ground plane with a rounded leading edge could be utilised to minimise flow. (D. Sumner, 2003) set a suitable boundary layer profile was installed on the test section floor. The ground plane boundary layer thickness was roughly 30 mm at the area of the kayak blade, although without the blade placed in the wind tunnel (D. Sumner, 2003).

The paddle blades were positioned outside the boundary layer produced on the ground plane due to the end plate and blade mounting apparatus design. The flat plate was positioned vertically from the force balance, as if it were installed on a kayak paddle shaft, in the same way as the paddle blades (D. Sumner, 2003). This guaranteed that the mounting structure and wind tunnel test circumstances for both the flat plate and the kayak paddle blades were identical, allowing for direct comparison of the flat-plate data with the data from the kayak paddle blades (D. Sumner, 2003).

Hydrodynamic studies could also be conducted however as stated in (6) no complete fluid dynamic investigations on a rowing blade have been conducted under actual rowing conditions. One reason for the lack of attention paid to data-based hydrodynamic studies of blade shape design is the difficulty in getting relevant data. It's quite difficult to build an experimental device that can reproduce the blade motion through water caused by an accelerating shell (Sliassas & Tullis, 2009). This kind of flow investigation has not been successful due to the difficulty of obtaining data relating

to the flow around the blade from such tests, as well as the time-consuming procedure of building real blades to be evaluated (Sliasas & Tullis, 2009).

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