

Structural and fluid dynamics

Designing a paddle blade

Fluid flow assessment

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1 Introduction

This document is about researching the flow around a paddle blade and showing what effects it and the flow. It also includes other information about paddle blades, such as the different types of blades and their significance, the processes of making the blades, including the materials used, in addition to the testing procedures used when testing the fluid flow around the blade.

2 The significance of Reynolds Number

Reynolds number is the ratio of inertial forces to viscous forces, (Rehm & Schubert, 2008), represented by:

$$Re = \frac{\rho u L}{\mu}$$

where:

- ρ is the density of the fluid in kg/m^3
- u is the flow speed of the fluid in m/s
- L is the characteristic linear dimension in m
- μ is the dynamic viscosity of the fluid in kg/ms

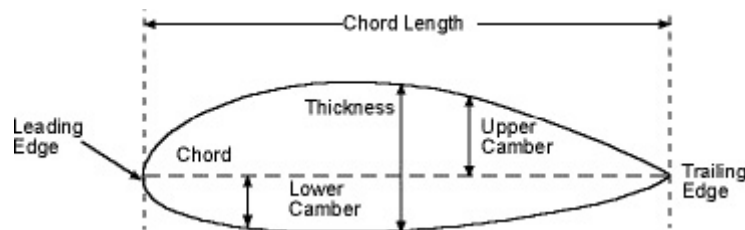
Reynolds number effects the type of flow of the water around the paddle blade. There is either turbulent flow, which is flow that is unsteady and unpredictable, or there is laminar flow which is steady and easy to predict the movement of the flow. The above equation shows which factors affect the turbulence of the flow, which is one way of estimating the turbulence of flow, (Benson, 2021).

Once the units are rearranged, you can see that they all cancel out, so Reynolds Number is unitless. This means that it cannot measure something but describe it instead, and it describes how streamlined the flow is around an object. However, it is important to recall that this is only a prediction of how smooth the flow will be and is not 100% accurate when applying it to reality.

When the Reynolds number is small, there is laminar or smooth continuous flow, whereas the flow is more turbulent and unsteady when the Reynolds number is large. In other words, the smaller the Reynolds number, the smoother the flow, (Burkit, 2020).

Since we are dealing with water, the density should remain somewhat constant where $\rho=1000kg/m^3$ for pure water. If we are dealing with sea water, then the density will increase somewhat to roughly about $1023kg/m^3$, with a maximum of $1240kg/m^3$, as this is the density of the dead sea, (Lensky, Dvorkin, & Lyakhovsky, 2005). This higher density will increase the Reynolds number which in turn makes the flow more turbulent.

If the water and the boat are stationary (such as in a lake), then the flow speed should be zero. When the boat is moving relative to the water, there is now a flow speed, which will be approximated to zero. If it were not approximated, then the flow speed against the paddle would be however fast the kayaker paddles plus the relative velocity of the vessel to the water (these two values could either be positive or negative depending on the direction of either). The maximum flow speed of the paddle can be obtained as 3m/s from the stroke a kayak world champion, (Sumner, Sprigings, Bugg, & Heseltine, 2003). In the article the data also showed that the average flow speed of the blade can be approximated to around 1m/s .



The length L depends on which surface faces the flow of fluid. The dimensions have been given to us with the height, width and thickness of the paddle via a model on CAD. The height will not be used for the paddle as the flow of water will not be travelling upwards. The scenario most likely to happen is when the flow is perpendicular to the greatest surface area of the paddle, as that is how the kayaker will maximise the force exerted. In order to apply this to an equation, the flow can be approximated to travel perpendicular to the leading edge of the blade when it first comes into contact, which makes it travel along the chord length, (Burkit, Wing parameters. Introduction to Aerospace Engineering, 2019). This assumption fits in with the Reynolds number equation as a longer length leads to a more turbulent flow, (David Darling, 2016). From the data given, the maximum chord length is 194mm .

The dynamic viscosity is inversely proportional to the Reynolds number, whilst all the other values above are directly proportional to it. This means that if you increase the viscosity, the Reynolds number decreases (and vice versa), whilst if you increase either density, flow speed or chord length, then the Reynolds number will also increase. According to Engineers Edge, the dynamic viscosity of water varies with temperature, but between 0°C and 20°C , the viscosity is $1.787 \times 10^{-3}\text{kg/ms}$ and $1.002 \times 10^{-3}\text{kg/ms}$ respectively (or Ns/m^2), (Edge, Engineers, 2021). Engineers Edge also gave other values greater than 20°C , but for the sake of assuming the maximum temperature of water stays between $0\text{--}20^\circ\text{C}$ the other values will not be provided. These values can be plugged in as maximum and minimum values into the Reynolds number equation to find estimates for the maximum and minimum Reynolds number. The dynamic viscosity of the dead sea is $3.6 \times 10^{-3}\text{kg/ms}$ at 20°C , (Weisbrod, Yechieli, Shandalov, & Lensky, 2015).

In order to maximise the Reynolds number, the numerators must be maximised whilst the denominators are required to be minimised. Since we have found each maximum and minimum value, the value can now be interpreted by implementing the values into the equation.

For the maximum Reynolds number within the dead sea:

$$Re = \frac{(1240)(3)(0.194)}{3.6 \times 10^{-3}}$$

$$Re = 200,466.66$$

This value has decreased dramatically, due to the large change in viscosity.

For the maximum Reynolds number within normal seawater:

$$Re = \frac{(1023)(3)(0.194)}{1.002 \times 10^{-3}}$$

$$Re = 594,197.6$$

This is the largest Reynolds number, mainly due to the larger flow speed, and the smaller change in viscosity.

For an average Reynolds number in normal water:

$$Re = \frac{(1000)(1)(0.194)}{1.307 \times 10^{-3}}$$

$$Re = 148,431.52$$

This Reynolds number is the smallest due to the approximations of the average densities and flow speeds viscosity (which is largely changed due to approximations in average temperatures).

3 About the boundary flow and the different types of blades

The boundary flow around the blade is important to consider. It is when the viscosity comes into effect, otherwise the fluid flows smoothly around the object. As a fluid flows around an object, the flow slows down as it gets closer to the surface of the object. It can be approximated that at the surface the fluid flow is 0, as it decreases to 0 from the outside of the boundary layer, which is at the current flow speed, (Benson, Boundary Layer, 2021).

The boundary thickness is dependent on the Reynolds number. The smaller the Reynolds number, the smaller the boundary layer, which makes the flow more laminar. Higher boundary layers mean a more turbulent flow, which leads to chaotic swirls inside the boundary layer.

Separation is when the boundary layer lifts off from the shape of the body, causing turbulence. This can occur when there is a high change in pressure, due to the fact that the boundary flow has relatively low energy compared with the laminar flow. In other words, there is a lot of drag or friction between the two. This can happen at high angles of attack, which causes wings to stall in terms of aerodynamics, creating large swirls of air or water, (Benson, Boundary Layer, 2021).

Separation, which is “largely influenced by the viscosity”, can also happen with sharp changes in direction, as well as smooth changes if the boundary layer fluid velocity is low enough, (tec-science, 2020).

Paddle blades can come in many forms, as they serve different purposes for traversing different water bodies. Some of the many applications to water-based activities include kayaking, canoeing, rafting and paddle boarding which share some similarities but differ in numerous ways. These activities all require the blade to push water away, exerting a force to push the user forwards or backwards. But the situations of each activity require a different blade, (Moore, 2019).

Kayaking requires a fast, cycle-like movement of the arms, where a double-sided blade pops in and out of the water on each cycle, one side at a time. To maximise the push of the water, the blade is asymmetrical (slightly longer at the end furthest from the paddler), as each end only needs to ever be on one side of the boat, as seen as an example in figure 2 below.



Figure 2 shows an image of a kayak blade, (Conwy Kayaks, 2021).

Canoeing on the other hand only has one blade on the shaft, which means the blade must be symmetrical, otherwise there will be an uneven force exerted on one side of the user, such as in the figure below.

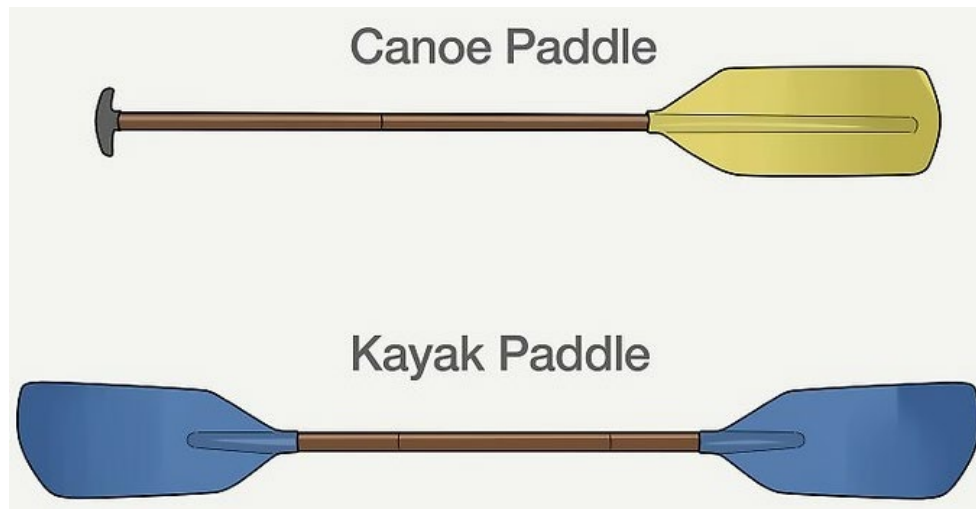


Figure 3 shows some of the differences between a kayak and canoe paddle, (How to Tell the Difference Between a Kayak and Canoe, 2021).

Another style of kayak blade is the Greenland paddle, which is usually a lot slimmer and slightly longer. Compared with the common type of blades, such as the Euro paddle, the Greenland paddle doesn't have a wide blade at the end. Users may prefer this type of blade for longer distances, as kayakers are found to travel at similar speeds even with the dissimilarities between the blades. On the other hand, kayakers might find that the larger blades are better for fast and sudden aquatic adjustments, which would prove more useful for white water kayaking as opposed to the Greenland paddle, (Moore, 2019). The differences that effect the Reynolds number in the types of blades are the chord lengths and the flow speeds, if the user can paddle faster with a different blade (largely due to the change in chord length).

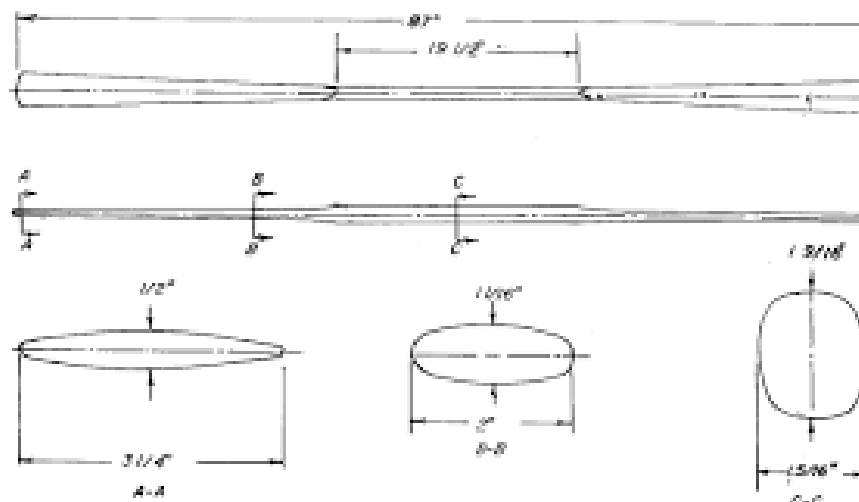


Figure 4 shows some dimensions of a typical Greenland paddle, (David).

4 Material used, being used and that will be used for paddle blades

The history of seafaring has changed dramatically over the years, whilst the methods have also changed as well. As you would imagine, many paddles used before plastics came around would have been wood, due to it being a common material and it being easy to manipulate at the time, such as seen by the Duvensee paddle said to be a sign of the earliest use of a paddle. This was found in the early 1900s, dating back to the Mesolithic age (roughly around 15000-8000BP), (Wander, n.d.).

Nowadays materials such as plastic, fibreglass and metals, aluminium for example, are common for a paddle blade to be made from. They each have different properties, and as a result each has their own positives and negatives, as noted in the table below.

Material	Pros	Cons
Wood	-Lightweight -Durable -Can be sourced from different types of trees	-Uncommon -Maintenance needed
Aluminium	-Affordable -Durable -Tough against rocks	-Heavy
Plastic	-Affordable -Common -Durable	-Fragile during construction -Heavy -Tough but brittle (prone to snapping)
Fiberglass	-Lightweight -Popular -Durable -Strong	-Expensive -Prone to scratches and chips from rocks
Carbon Fibre	-Lightweight -Durable -Strong	-Expensive -Uncommon -Prone to scratches from rocks

Table 1 shows the materials used when making a paddle blade, (Silent Wake Crew, 2019), (Kayak Help, 2021).

The material used is given, which is glass fibre reinforced plastic, which essentially means that a plastic paddle is covered with a layer of glass fibre and then coated with resin to hold it all together. From this, we can estimate its purpose and performance.

Glass fibre reinforcement increases the durability as the fibres are strong and resistant to large cracks, but are susceptible to the seabed and rocks. Plastic is less efficient, owing to the flexibility of the material when displacing the water. This elasticity is somewhat cancelled out by the rigidity of the glass fibre coating, making the blade more efficient, (Kayak Help, 2021).

In the foreseeable future, fibreglass and carbon-fibre blades are presumably the most popular, largely due to their greater longevities and efficiencies. As with most products, the cost of production will undoubtedly decrease as well, making them more appealing to customers.

5 Modelling techniques

There are several methods of measuring the flow patterns around an object. The most common method would be to use a wind tunnel. These can come in the form of open or closed tunnels, and can be quite pricy to build and control. There are two main types of wind tunnel:

- Closed return type
- Open air tunnels

Closed loop advantages:

- best flow quality, flow is usually uniform
- operating costs are low
- quiet operation due to fan needing a lower power

Closed loop disadvantages:

- increased cost of construction, due to the system being closed
 - tunnel might need cooling system, as energy is constantly being provided, thus increasing pressure
 - design is inferior due to the fact that smoke would build up inside, reducing visibility and accuracy
- (Hall, Closed Return Wind Tunnel, 2021)

Open loop advantages:

- construction cost is low
- good for smoke visualisation, as it does not build up

Open loop disadvantages:

- high operating cost, as fan needs to be continually on at a high power
 - very loud
 - air might need to be filtered and pointed in the correct direction, as there could be wind outside
- (Hall, 2021)

The use of the Reynolds number acts as a constant to find the correct parameters needed to find a similar flow pattern when changing the fluid from air to water (or vice versa). This method is very useful when analysing the flow around an aerofoil, or in this case a paddle blade.

Alternatively, a water tunnel could be used to find the flow patterns. In order to keep the Reynolds number constant, the density, flow speed and viscosity must be changed back to work around the water, as opposed to the air. This will provide more accurate data, as the paddle is designed for use in the water, although the exact outcome may vary from time to time due to turbulence in reality being unpredictable and unsteady, (Zahari & Dol, 2015).

Another method could be to use computer software to predict the turbulence of water within a simulation, (Tillman, Duong, & Harding, 2012).

6 Producing the blade and testing the fluid flow

The production of objects varies from material to material, as there are alternative methods for constructing different components. In this case, we are given the materials used for the blade, so the production methods are now limited to only a few. Producing the blade is only one step in the manufacturing process, alongside with the testing afterwards.

Plastic blades could be fabricated by use of injection moulding, but this would not be possible for fibreglass. As a result, the fibreglass will need to be placed on later, after the plastic has set and possibly after it has been attached to the shaft.

To make a paddle via injection moulding, an automated machine would heat thermosetting plastic granulates to be injected into a mould via a large metal screw. The mould will have a 3D outline of a paddle blade, which can be reused after the molten plastic has been set, and then ejected, (Multimedia-Agentur, 2016).

At this stage, the blade is ready to either be coated in fibreglass or attached to the shaft. The paddle blade is made of plastic, but as plastic is prone to snapping, as it is quite brittle, it can be reinforced with fibre glass, which can enforce the plastic, but add to the weight, adding effort for the user, (Bending Branches, 2021).

After injection moulding, the blade can be reinforced with the fibreglass by having someone coat it with a thin layer of fibreglass, covered in resin. Smoothing out the resin over the blade is essential, this is to prevent uneven surfaces, and to ensure that the coating is pressed as close as possible to the plastic. The resin will seep through the fibres, and then set, creating a smooth blanket with the fibreglass safely encased inside, (QuietwaterPaddles, 2014). Despite the added weight, this will greatly increase the durability, longevity and efficiency of the paddle, (Kayak Help, 2021).

An alternate manufacturing process is using the fibreglass reinforced plastic blade is to use a vacuum mould. This would not encase plastic, and it would be hollow, but the outsides would be fibreglass and resin, (Iyer, 2017).

After the resin has set, the excess fibreglass might need to be accounted for, in which case it could be cut off or sanded down. If the blade has not yet been attached to the shaft, it will then go onto that stage. After this, the testing would commence.

Testing could be completed by any of the methods mentioned above in section 6, which include a wind tunnel, a water tunnel, or by using computational methods. The analysis could be completed with the aid of CAD (Computer Aided Design), CAE (Computer Aided Engineering), or CFD

(Computational Fluid Dynamics), (Tillman, Duong, & Harding, 2012). This could be done by applying an average force throughout the paddle, and then analysing the outcomes.

The wind tunnel would give data the same way as the water tunnel, but would need to be adjust the density water to that of air, and then increase the speed to make up for the decrease in density. This will need to be done for the closed air tunnel (Hall, Closed Return Wind Tunnel, 2021), as well as the open-air tunnel (Hall, Open Return Wind Tunnel, 2021).

The water tunnel might provide the best results once analysed, as the blade is designed to live in the water, (Zahari & Dol, 2015).

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