Propeller Guard Designs

An investigation using CFD

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Statement Of Contribution

- I summarised and expanded upon the pro and con arguments for propeller guards using the list created by Gary Polson as a starting point.
- I carried out the survey of the propeller guard market
- I carried out the survey of current propeller guard research
- I used ANSYS Fluent 13 to run the simulations and was helped in the setup by my supervisor Dr Armfield.
- I carried out the performance, safety and cost analyses, influenced by my supervisor Dr Armfield.

The above represents an accurate summary of the student's contribution

Signed……………..Student………………..Supervisor

Acknowledgements

I'd like to acknowledge my supervisor Steve Armfield for providing me with much valuable assistance during my thesis and also Julian Todd for his support.

Abstract

This study investigated three aspects of propeller guards: performance efficiency, safety and cost. The efficiency of the guards was measured using ANSYS Fluent to model the guards and an actuator disk to model the propeller. Solid circular and octagonal guards were found to be approximately equal with an efficiency of ~80% each, whereas the mesh guard testing was found to be inconclusive owing to an inability of the simulation to correctly capture the interaction between the flow and the mesh. The safety of each of the guards was analysed by inspection and deduction resulting in the development of an objective 'danger rating' system, ordering the guards from Lidded mesh, mesh, then circular and octagonal in their ability to minimise the severity of injuries (highest to lowest). The cost issues involved with propeller guards were described including the initial costs (guard and potential replacement propeller) and ongoing costs and savings (fuel, maintenance) though the quantification of this trade-off between short term costs and long term savings was not carried out. Further research could focus on empirical testing of propeller guards to help validate the CFD trials conducted and also run simulations using an actual rotating propeller as opposed to an actuator disk.

Contents

List of Figures

List of Tables

1. Introduction

Boat propellers can be the cause of serious injuries, even death, and so it is of interest to investigate the methods by which these occurrences might be minimised. One fairly intuitive solution to the problem is the attachment of a guard which surrounds the propeller and prevents a person from coming into physical contact with it. The main problem with this solution is that it reduces the performance of the propeller. Little research is available that provides quantitative data on this problem and this thesis is an attempt to fill that void; specifically to use computational fluid dynamics (CFD) to measure the head loss induced by certain guard types. More details are available in section 8. The safety and cost issues involved with propeller guards will also be explored.

In addition, propellers and guards, what they are and how they work, will be briefly reviewed; as will the current debate over their use with the main arguments on each side being described and summarised; the propeller guards available in the market will also be documented and categorised as will other relevant propeller safety devices and then, the available research will be discussed. The basic principles of CFD will be mentioned as well.

2. Propellers and Guards

A propeller is a device that converts rotational energy into forward thrust. As it spins, the blade displaces water whose previously occupied space is then filled with new incoming water. This action creates a pressure differential between the two sides of the propeller blade as seen in Figure 2.1, and this pressure differential forces water to travel from the low pressure side (near the boat) to the high pressure side (away from the boat) at an increased velocity, thereby creating momentum and, by Newton's third law, generating forward thrust (Mercury Marine, 2011).

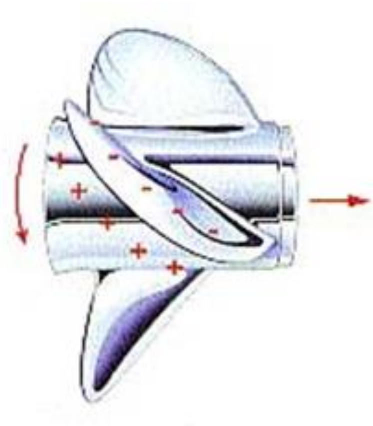


Figure 2.1 Pressure distribution around propeller blade [1]

There are many different varieties of guard (see section 4); a typical design is shown in Figure 2.2. It can be easily deduced from observation that the attachment of a guard will necessarily interfere with the accelerated water flow coming from the propeller by causing a reduction in its velocity due to drag, and therefore a decrease in momentum and forward thrust.

Drag is the force on a body acting in the opposite direction to the body's motion (Fox et al., 2009). There are two main components of drag: friction and pressure. Friction drag, as the name suggests, is caused by the friction that occurs between the body and its surrounding fluid. Pressure drag is caused by an adverse pressure gradient forming along the body; this pressure differential creates a force acting against the body's motion (Fox et al., 2009). It is expected that the friction drag will only have a

[1] http://www.mercurymarine.com/propellers/about/how-propellers-work/

negligible impact on the flow and that pressure drag will be the cause of the majority of any head loss. The third component of drag, wave drag, is also considered negligible.

The presence of the propeller guard itself will negligibly increase the friction drag experienced by the boat through the water in a forward direction, but could conceivably create more significant interference with boat handling and direction changes.

Figure 2.2 Typical propeller ring guard- circular, no lid, with holes [2]

[2] http://www.allinflatables.com/shopping/custom/guards.htmlBackground

3. Background

On April 5 2010, a United States jury found the boating manufacture Brunswick Corp partially liable (66% responsible) for injuries received by a teenager from an unguarded propeller and ordered them to pay $3.8 million USD to cover medical expenses and in compensation for the injury he suffered (Plohetski, 2010). The plaintiff's attorney described the verdict as the first ever successful action brought against the boating industry by a victim of a motor induced injury and the decision will certainly force a re-evaluation within the industry of their stance regarding the installation of propeller guards.

From a more general perspective, Table 3.1 shows the statistics gathered by the United States Coast Guard on the incidence of propeller related injuries in recreational boating from 2005-2009 within the US (USCG, 2010). As can be seen, the total amount and also the proportion of deaths to injuries have remained relatively stable over the five year period with a slight decrease in more recent years. The damages incurred are relatively minor, though the decision from the Brunswick Corp case in 2010 will result in a meteoric rise in the associated damages of unguarded propellers and presumably a similar rise in the attention paid to the debate over propeller guard usage and design.

Year	Accidents	Deaths	Injuries	Damages (USD)
2005	239	31	237	246539.90
2006	234	28	227	176144.10
2007	176	24	166	75090.00
2008	181	21	176	89100.00
2009	184	25	182	58950.00

Table 3.1 Injury statistics on Propeller related incidents from 2005-2009

4. **The Debate** over Propeller Guard Usage

Propeller guards are a somewhat controversial item with strong advocates on both sides of the issue. The issues discussed below relate to the desirability of adopting OH&S regulations and the like for propeller guards, and also the general pros and cons of propeller guards of interest to the individual consumer trying to decide whether or not to purchase one.

4.1 For

The primary argument for the use of propeller guards and for more stringent regulations is simple- safety. A leading advocate of propeller guard usage, Julian Todd, uses the analogy of a bladed propeller rotating in a workshop- it would need to have a guard, so why not the same thing on a boat? (J. Todd**.** Pers.Comm., 15/3/2011).

Several other benefits of prop guards include the protection of the actual propeller from damage, protection of sea flora and fauna and preventing rope/line entanglements in the propeller (**<**www.propellerguards.net>). It has also been suggested that in the long run, propeller guards save money as they reduce the number of replacement propellers bought (J. Todd**.** Pers.Comm., 15/3/2011).

4.2 Against

The arguments against are much more diverse and can be grouped as follows.

Performance: Propeller guards result in intolerable head loss for the propeller flow, interfere with the boat's handling and increase fuel consumption. The guards are also described as being easy to foul, further reducing performance.

Safety: It is argued that propeller guards actually increase the likelihood of propeller injuries because, firstly there is the possibility of becoming 'trapped' in the guard and suffering further injuries because of that, secondly, the guard increases the contact area of the gearbox unit and therefore there is greater likelihood of collision, and thirdly that captains will have an inflated sense of safety from the use of a propeller guard and engage in high risk actions resulting in more injuries (Polson, 2011).

Cost: Propeller guards are costly. These extra costs come from three main sources: firstly the cost of the guard itself, secondly, the increased fuel consumption and thirdly, the potential need to buy a new propeller that matches the engine once the guard is attached.

Manufacturing: The number of propellers, motors etc are too numerous and diverse as to create too many problems in designing, manufacturing etc a guard for each one (Polson, 2011).

Innovation and the Free Market: Mandatory propeller guards would stifle innovation and could prevent the development of potentially superior solutions to the problem such as the “Safety Propeller” (see section 5.2.3). Furthermore, existing propeller safety devices that aren’t classified as guards could be unfairly hurt by such legislation.

Individual autonomy: The government should not be involved in this issue and it is each person’s decision as to whether they should attach a propeller guard or not.

4.3 Summary

The performance problems imposed by prop guards are generally accepted, but the objections to it as a safety device seem highly spurious. In the absence of hard data and statistics on which to base a judgement, it can only be assumed that most people would, when swimming in the vicinity of a rotating propeller, prefer it to be guarded than not. On the other hand, it is important to realise that the improvements in safety are not wholly inherent properties of the guard, as its effect on performance and its cost are, but instead only play a factor when a propeller related injury would actually occur. The majority of the time, only performance and cost are of concern. There appears to be a trade-off between short and long term costs with the unguarded propeller being cheaper in the short term but potentially more expensive in the long term depending on whether increased fuel costs or decreased maintenance costs predominate. This is an empirical question and requires further research for a solution. Still, the issue essentially becomes one of a weighing of performance and cost on the one hand, and safety on the other.

The objection on the ground of manufacturing and design problems is not compelling and, on inspection, actually a possible argument for, rather than against, the need for regulations in order to "correct" this case of market failure. In any case, the existence of companies specialising in selling propeller guards (Safe Marine Ltd, Prop Guard Marine, Hydro-Shield, Lyfgard) sufficiently refutes the point.

The arguments from innovation and individual autonomy are weightier. With regard to innovation, it would be necessary that any regulations do not "pick winners" and exclude other viable devices from the market. Of course, this is easier said than done, but one solution could be to focus primarily on the question of liability and the amount of damages obtainable from the responsible party. This would still leave individuals with the ability to make their own trade-offs between cost and performance with safety but introduce the interests of the injured party into the equation and significantly shift the balance.

Following such a course it would still be important to determine what would constitute a sufficient effort to minimise propeller related dangers and also who would actually be held responsible. And if the Brunswick Corp case is any indication, it seems that the boating manufacturers may be, rather than the owner or passengers of the boat who arguably have accepted known risks by getting aboard.

In conclusion, the value of a propeller guard boils down to a trade off between providing safety verses increased cost and decreased performance. The variables in this equation need to be known for any progress to be made in the propeller guard debate.

5. Market Survey

Although the propeller “safety device” market is still relatively small and undeveloped, there is already diverse range of products available for that purpose. In addition to the propeller guards already discussed which essentially isolate the propeller from any nearby objects or persons, several other approaches to propeller safety have been explored including modifying the propeller itself and even replacing the propeller with a safer thrust producing mechanism.

The propeller guards themselves are available in a number of different designs. These will be catalogued in this section.

5.1 Propeller Guards

The standard propeller encircling guard is the simplest and most intuitive approach to propeller injury prevention. The most obvious problem with these devices as discussed above is the negative impact they have on propeller performance. To that end, the guards are designed in such a way so as to minimise this impact and there have been several approaches towards achieving this aim including

- Modifying the standard guard shape and size so as to minimise interference with propeller flow
- Use of a nozzle to provide compensating thrust
- “Rough mesh” guards

5.1.1 Standard Propeller Guards

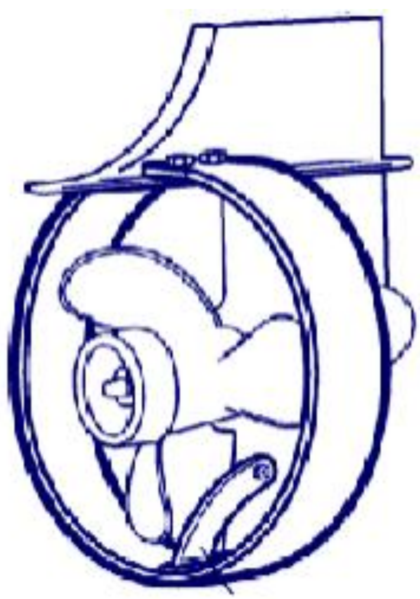
Due to the difficulty experienced in obtaining detailed specific information from companies about their prop guards, no actual guards are profiled, but instead the propellers were categorised according to their most salient features: the shape of the ring, the use of a “lid” and the existence of design features on the ring itself such as holes or meshing. Table 5.1 shows the various configurations of guards currently available on the market and Figure 5.1 shows some of these configurations.

Shape	Lid	Design
Circular	Yes	Solid
Octagonal	No	Holes
-	-	Mesh

Table 5.1 Propeller guard configuration matrix

a

b



c

Figure 5.1 Mesh configurations

a) Ring guard- circular, mesh lid, mesh[3] b) Ring guard- circular, cross lid, mesh[4] c) Ring guard- circular, no lid, solid[5]

[3] http://www.propellerguards.net/

Preliminary Analysis

A preliminary analysis of the configurations can reveal some fairly obvious conclusions about their relative merits.

With regard to shape, the effect cannot be stated with certainty as the greater surface area of the octagonal guard could have an offsetting effect by providing greater clearance between itself at its corner sections and the propeller.

The use of a lid would clearly impede the flow more than not using one but just as clearly increases the safety provided by the guard. Of interest is the head loss imposed by meshes of varying density and also a comparison with a "cross" lid (Figure 4).

It would be expected that holes in the ring or an actual ring mesh would create less head loss than a solid ring as the water flow will be less obstructed. It would be interesting to compare the varying head losses generated by the holes and the mesh as well.

Other Design considerations

In addition to the general shape etc outlined above, the quality of each guard will be affected by the following factors where relevant.

Clearance: The distance between the tips of the propeller blades and the guard will have a considerable influence on the impact the guard will have on propeller performance. Intuitively it can be seen that the stream flow of the water will expand after it passes through the propeller, the closer the guard, the sooner it will come into contact with the guard and the greater will be the associated head loss.

On the other hand, too large a clearance will limit the effectiveness of the guard as a safety device making it much easier for a limb to be inserted in between the guard and the propeller. Furthermore, increasing the size of the guard will increase the chances of making impact with someone in the water. Performance itself could suffer negatively with a larger guard interfering more with the handling of the boat than would a tight fitting guard. Lastly, the cost of the guard would increase due to the larger amounts of material needed to make the guard and potentially greater manufacturing costs.

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[4] http://www.propguardinc.com/
[5] http://www.propsavers.com/Prop%20Saver.html

Denseness of mesh: The denseness of the mesh represents a clear trade off between increasing safety and increasing drag, i.e. the finer the mesh the more the performance of the propeller will deteriorate. Without statistics that reveal the relative incidence of injuries, it cannot be said with certainty that diminishing returns would occur, with little to be gained beyond a mesh size fine enough to obstruct a child's hand, although it seems reasonable to conclude such.

Method of attachment: The way in which the guard attaches to the propeller or gearbox will determine the extent to which it affects the flow of incoming water. Naturally, minimal interference is desired.

Placement/size/shape of holes: The shape of the holes in the guard e.g. circular or rectangular strips will have different affects on the flow of water as it passes through the propeller as too will their size and location.

5.1.2 Kort **Nozzle**

Several guards make use of a Kort nozzle (see Figure 5.4) to provide additional thrust in an attempt to compensate for some of the losses incurred by the presence of the guard. The principle of the Kort nozzle is quite simple: assuming incompressible constant mass flow of a liquid, then between regions 1 and 2 as seen in Figure **5.3**, mass flow in equals mass flow out. In other words

$$\rho 1A1V1 = \rho 2A2V2$$

Figure 5.2 Ring guard incorporating a Kort Nozzle[6]

As the liquid is incompressible, the densities are equal and a clear inverse relationship is seen between the area and the velocity- decreasing the area increases the velocity; and the aerofoil cross section of the Kort Nozzle (Figure **5.5)** can be seen to be doing exactly that. By speeding up the water entering the propeller, it improves its efficiency. Furthermore the increased velocity, according to Bernoulli's equation, results in a decrease in pressure within the nozzle while leaving the pressure outside the nozzle unchanged. This pressure differential results in a force acting on the nozzle of which the forward component is thrust (Carlton, 2007).

[6] http://www.propguard.co.nz/

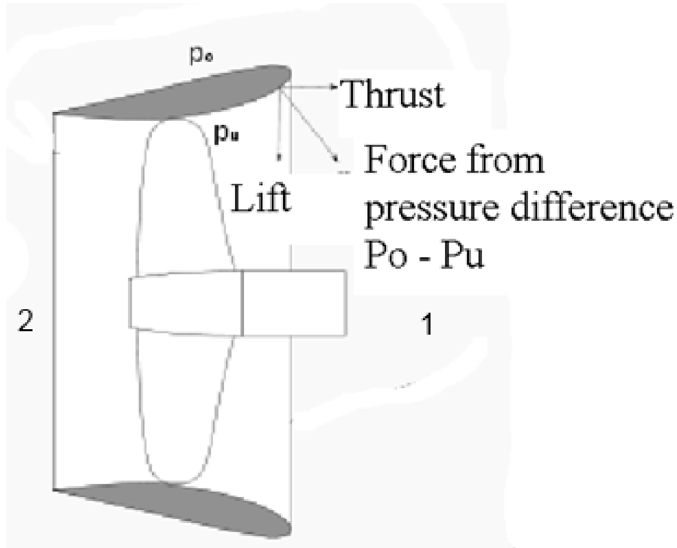

Figure 5.3 Pressure forces around a Kort Nozzle[7]

Propeller guards incorporating the Kort nozzle are in theory superior to those that don't; however, the question still remains as to precisely how superior they are and whether that superiority is worth the additional cost involved in the manufacturing of a much more complicated product.

5.1.3 Proposed- Rough Mesh Guards

This idea proposes to take advantage of the large decrease in the drag coefficient at high Reynold's numbers (see Figure 5.6). In theory, the rough rods that make up the mesh will cause the water flowing past it to go turbulent, allowing for the large reduction in the drag coefficient at low Reynold's number (Polson, 2011).

[7] http://bigben2k.wordpress.com/

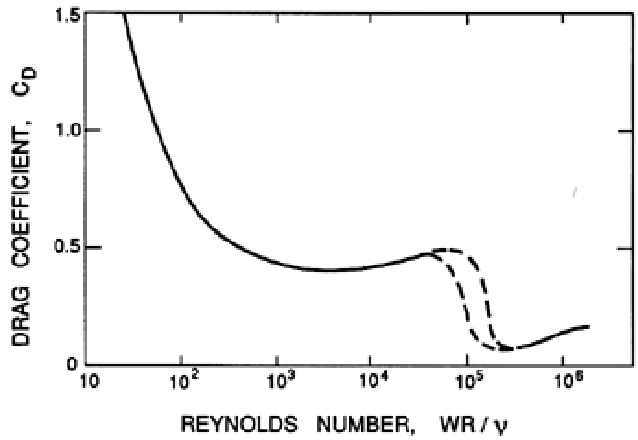

Figure 5.4 Drag coefficient vs Reynolds Number.

Note the large drop around Re = 10^5[8]

Obviously this idea requires testing before it can be properly evaluated. While there is merit in the idea, it seems that there are too many practical problems with the design. The large drag during low Reynold's number times is the major problem and this would limit its application purely to boats travelling predominantly at high speeds. The reduction in drag and resulting increase in propeller performance would also need to be measured to determine whether it would have any significant practical effect.

5.2 Other Propeller Safety Devices

5.2.1 Manatee Guards

Manatee guards are similar to propeller guards except that they don't completely encircle the propeller but instead act more as a buffer underneath it as seen in Figure 5.7. These are not classified with the other guards because they rely on the principle of deflection rather than separation.

The guard appears to be sufficiently far from the propeller so as to minimise its interference with the flow but the actual guard seems to alter the geometry of the boat itself significantly and this could have an impact on boat handling and also increase the friction drag of the boat through the water.

[8] http://caltechbook.library.caltech.edu/1/4/chap5.htm

Figure 5.5 Manatee guard attached to bottom of boat [9]

5.2.2 Jet Pump Propulsion

Rather than use the spinning propeller blades to generate thrust directly, the propeller is contained within jet pump housing. Water is drawn into this housing and then forced out the back of the housing through a nozzle. The expulsion of this water generates the forward thrust as seen in Figure 5.8 (Carlton, 2007).

In addition to greater safety, jet pump propulsion is also superior for high-speed or shallow water applications, though they are generally more expensive than propellers and are less efficient at low speeds. Whether they are less efficient than a propeller with a prop guard on it is unknown and of great interest.

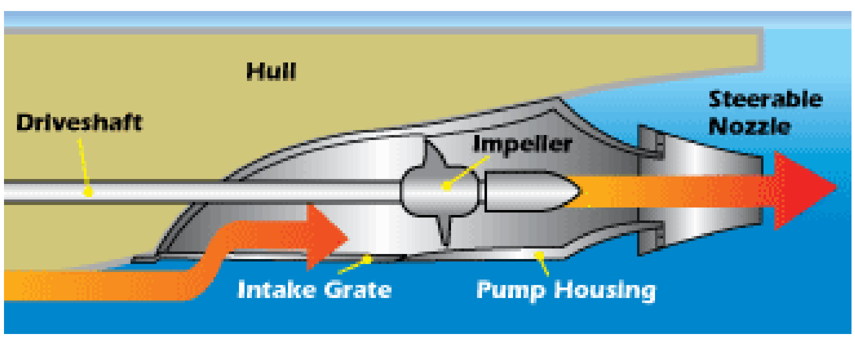

Figure 5.6 Inner workings of a jet pump propulsion system [10]

[9] http://www.lyfgard.com/index.php?option=com_content&task=view&id=49&Itemid=91
[10] http://www.fish.state.pa.us/boatcrs/03boathandbook/chap4_01_pwc.htm

5.2.3 Safety Propeller

The safety propeller "looks and works like a normal propeller" (**<**www.abc.net.au/tv/newinventors/txt/s2736928.htm**>)** but its design has been modified slightly so that it is possible to insert one's arm in between the blades rotating at high rpm without sustaining any injuries (see Figure 5.9). This device won "Invention of the Year" for 2009 on the ABC show "The New Inventors".

The crux of the design is the blunt striking surface which lacks the cutting capabilities of the 'thin edge' surface found in typical propellers; and since the changes to the design are minimal, it is claimed that it can be manufactured from slightly modified ordinary propeller moulds and also that this can be done for the entire range of motor sizes from 2HP to a container ship. Even more significantly, the design change is claimed to have a negligible effect on performance.

On the other hand, the injuries resulting from head contact with the propeller would still be considerable, if less lethal, and the effects on performance still need to be tested much more rigorously; as do too the assertions as to its ease of manufacturing. Preliminary testing has indicated that the propeller is not as safe as originally thought (C. Chamberlain**.** Pers.Comm., 10/5/2011).

Figure 5.7 The award winning Safety Propeller[11]

[11] http://www.fishpo.com.au/safety-propeller-wins-invention-of-year-2009.php

6. Research on Propeller Guards

There has been little investigation, whether theoretical or experimental into the subject of propeller guard performance.

Nakamura et al. (1998) examined the Prop Buddy (circular ring guard) in order to determine its optimal configuration with regard to ring thickness, clearance from the propeller and width. By field testing the various guards, they measured the velocity, RPM reduction and the increase in fuel consumption. The results were inconclusive with all guards yielding a similar percentage reduction in velocity (~15%) and no systematic effect on RPM. The guard with maximum clearance, minimum width and minimum thickness increased the fuel consumption the least, but the difference with the other guards was not large. This study was conducted more than a decade ago and the Prop Buddy website (www.propbuddy.com) is no longer up.

Two studies posted on Prop Guard Inc website investigated the performance of their propeller guard which incorporates the Kort nozzle described above. Schulz Engineering (Prop Guard, 2011) ran several field tests in 1998 measuring the speed of several boats (with and without another boat in tow) with and without a guard. The limited information available indicates that the use of the propeller guards did create gains in thrust though the gains decreased with increasing motor RPM to a modest 12.6% gain at 100%. Figure 6.1 is posted on the website and although it does not label the x-axis, assuming it is the speed obtained by the boat at the specified RPMs, sometimes the boat without the guard appears able to achieve higher speeds at the same RPM and sometimes the reverse. Without additional labelling it is unclear what changing parameter the different plots represent.

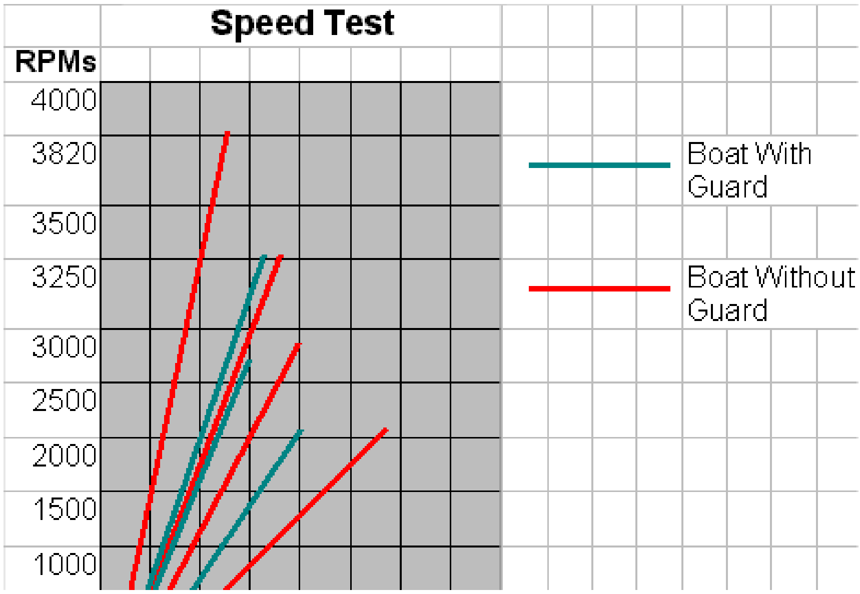

Figure 6.1 Results of Prop Guard Speed Test

Prop Guard (2011) ran the same tests in 2003 with the two different boats (no towing) and reported "higher cruising speed" clocked at an average increase of .5mph over the range of RPM values tested.

Both studies also reported greater handling and complete protection. The actual reports of these studies need to be viewed and their results verified before they can be considered conclusive.

7. Measuring Propeller Guard Efficiency using CFD

The efficiency of each propeller guard is defined for this study as the proportion of total head which remains once the flow has passed through the guard compared to the head directly after passing through the actuator disk.

Guard Efficiency = Postguard head / Preguard head

This will be measured using CFD and specificallyANSYS Fluent 13.0.

Simply put, CFD uses computers to solve equations relating to fluid flow. These equations are too difficult to be solved analytically and therefore the only way to gain approximate solutions is through numerical methods, and their complexity means that this can only practically be done though computer simulations. Several important components of CFD will be explained below with reference to the current study.

7.1 Modelling

7.1.1 Governing Equations

Many viscous flows can be modelled using the Navier-Stokes (NS) equations which refer to the continuity, momentum and energy equations of a fluid; the first two being of relevance to this study are presented below:

Continuity[12]:

$$\frac{\partial \rho}{\partial t} + \frac{\partial(\rho u)}{\partial x} + \frac{\partial(\rho v)}{\partial y} + \frac{\partial(\rho w)}{\partial z} = 0$$

X-momentum[13]:

$$\frac{\partial(\rho u)}{\partial t} + \frac{\partial(\rho u^2)}{\partial x} + \frac{\partial(\rho uv)}{\partial y} + \frac{\partial(\rho uw)}{\partial z} = -\frac{\partial \rho}{\partial x} + \frac{1}{Re}\left[\frac{\tau_{xx}}{\delta x} + \frac{\tau_{xy}}{\delta y} + \frac{\tau_{xz}}{\delta z}\right]$$

[12] http://www.cfd-online.com/Wiki/Standard_k-epsilon_model
[13] ibid

Y-momentum[14]:

$$\frac{\partial(\rho v)}{\partial t}+\frac{\partial(\rho u v)}{\partial x}+\frac{\partial(\rho v^2)}{\partial y}+\frac{\partial(\rho v w)}{\partial z}=-\frac{\partial \rho}{\partial y}+\frac{1}{Re}\left[\frac{\tau_{xy}}{\delta x}+\frac{\tau_{yy}}{\delta y}+\frac{\tau_{yz}}{\delta z}\right]$$

Z-momentum[15]:

$$\frac{\partial(\rho w)}{\partial t}+\frac{\partial(\rho u w)}{\partial x}+\frac{\partial(\rho v w)}{\partial y}+\frac{\partial(\rho w^2)}{\partial z}=-\frac{\partial \rho}{\partial w}+\frac{1}{Re}\left[\frac{\tau_{xz}}{\delta x}+\frac{\tau_{yz}}{\delta y}+\frac{\tau_{zz}}{\delta z}\right]$$

Where x,y,z = spatial coordinates, u,v,w = velocities in those respective directions, t = time, Re = reynold's number, τ = stress tensor

The flow of interest for this study is turbulent and therefore the equations must be modified otherwise an approximate solution would require an incredibly fine mesh and excessive computing power (Armfield, 2011). This can be done in several ways but for this study, only averaged variables are needed and so the Reynolds Averaged Navier Stokes (RANS) method will be used. This method separates the instantaneous variables of the NS equation into a mean (over time) and fluctuating part resulting in the following equations-

[14] ibid
[15] ibid

$$\frac{\partial V_x}{\partial x} + \frac{\partial V_y}{\partial y} + \frac{\partial V_z}{\partial z} = 0$$

$$\rho\left(\frac{\partial V_x}{\partial \tau} + V_x\frac{\partial V_x}{\partial x} + V_y\frac{\partial V_x}{\partial y} + V_z\frac{\partial V_x}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\frac{\partial^2 V_x}{\partial x^2} + \mu\frac{\partial^2 V_x}{\partial y^2} + \mu\frac{\partial^2 V_x}{\partial z^2} - \rho\frac{\partial \overline{v'_x v'_x}}{\partial x} - \rho\frac{\partial \overline{v'_x v'_y}}{\partial y} - \rho\frac{\partial \overline{v'_x v'_z}}{\partial z} + S_x$$

$$\rho\left(\frac{\partial V_y}{\partial \tau} + V_x\frac{\partial V_y}{\partial x} + V_y\frac{\partial V_y}{\partial y} + V_z\frac{\partial V_y}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\frac{\partial^2 V_y}{\partial x^2} + \mu\frac{\partial^2 V_y}{\partial y^2} + \mu\frac{\partial^2 V_y}{\partial z^2} - \rho\frac{\partial \overline{v'_y v'_x}}{\partial x} - \rho\frac{\partial \overline{v'_y v'_y}}{\partial y} - \rho\frac{\partial \overline{v'_y v'_z}}{\partial z} + S_y$$

$$\rho\left(\frac{\partial V_z}{\partial \tau} + V_x\frac{\partial V_z}{\partial x} + V_y\frac{\partial V_z}{\partial y} + V_z\frac{\partial V_z}{\partial z}\right) = -\frac{\partial P}{\partial x} + \mu\frac{\partial^2 V_z}{\partial x^2} + \mu\frac{\partial^2 V_z}{\partial y^2} + \mu\frac{\partial^2 V_z}{\partial z^2} - \rho\frac{\partial \overline{v'_z v'_x}}{\partial x} - \rho\frac{\partial \overline{v'_z v'_y}}{\partial y} - \rho\frac{\partial \overline{v'_z v'_z}}{\partial z} + S_z$$

[16]

Where Vx, Vy, Vz = the time averaged velocities in their respective directions.

This averaging introduces new unknowns into the equation (outlined in red): Reynold's Averaged stresses, with the result that there are now more unknowns than there are equations. This means that a turbulence model must be used to approximate the new stresses (Armfield 2011).

7.1.2 Turbulence models

There are a variety of turbulence models available and the model picked will be dependent on the kind of flow being studied. The eddy viscosity model is a common and robust method suitable for the current study. This model represents the characteristics of the small eddies in a flow en masse through the following equations:

$$-\left(\overline{U'_i U'_j U'_k}\right) = \nu_t\left(\overline{U_{i,j,k}} + \overline{U_{j,k,i}} + \overline{U_{k,i,j}}\right) - \frac{2}{3}k \times \partial_{i,j,k}$$ [17]

Where the equation is in tensor notation such that $\overline{U_i}$ is the mean velocity component and U'_i is the fluctuating velocity component, ν_t = eddy viscosity, k = kinetic energy of turbulence.

[16] ibid
[17] ibid

As seen, this is not a final solution but introduces still more unknowns into the equation: ν_t , the eddy viscosity and k, the kinetic energy of the turbulence.

To model these, another model is needed and once more there are a variety of models available. The k-ε model is widely accepted as a relatively robust and accurate model and, excepting some kind of particularity in the flow, can be safely used. With no particularities in the present study, the k-ε model is chosen. It models ν_t and k using the following equations:

$$\nu_t = C_\mu \times \frac{k^2}{\varepsilon}$$ [18]

Where C_μ = adjustable constant, ε = turbulence dissipation

Now to find k the following equation is used:

$$\frac{\partial}{\partial t}(\rho k) + \frac{\partial}{\partial x_i}(\rho k u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_k}\right)\frac{\partial k}{\partial x_j}\right] + P_k + P_b - \rho\epsilon$$ [19]

and ε:

$$\frac{\partial}{\partial t}(\rho\epsilon) + \frac{\partial}{\partial x_i}(\rho\epsilon u_i) = \frac{\partial}{\partial x_j}\left[\left(\mu + \frac{\mu_t}{\sigma_\epsilon}\right)\frac{\partial \epsilon}{\partial x_j}\right] + C_{1\epsilon}\frac{\epsilon}{k}\left(P_k + C_{3\epsilon}P_b\right) - C_{2\epsilon}\rho\frac{\epsilon^2}{k}$$ [20]

Where

$$\mu_t = \rho C_\mu \frac{k^2}{\epsilon} \qquad P_k = -\rho\overline{u_i'u_j'}\frac{\partial u_j}{\partial x_i} \qquad P_b = \beta g_i \frac{\mu_t}{\mathrm{Pr}_t}\frac{\partial T}{\partial x_i}$$

$$\beta = -\frac{1}{\rho}\left(\frac{\partial \rho}{\partial T}\right)_p$$ [21]

Where 'g_i' is the gravitational vector

[18] ibid
[19] http://www.cfd-online.com/Wiki/Standard_k-epsilon_model
[20] ibid
[21] ibid

Table 7.1 shows the values of the adjustable constants used in the ANSYS simulation.

Constant	Value
Cmu	0.09
C1-epsilon	1.44
C2-epsilon	1.92
TKE Prandtl	1
TDR Prandtl	1.3

Table 7.1 Constant values from ANSYS 13[22]

Then through computer simulations, each equation can be worked through successively to ultimately solve the RANS equations. Of course, the beauty of CFD is that only a cursory familiarity with the above equations is necessary for the practically minded engineer to begin simulations.

7.2 Discretization

The Finite Difference method used in this study defines a numerical grid or mesh on the domain with each node representing a unique point. The model equations are then discretized and converted into algebraic form using a specified discretisation scheme relating the variable at one node to those of its neighbouring nodes (Ferziger & Peric, 2002).. The schemes used were the first and second order upwind scheme.

In ANSYS Fluent, the first order upwind scheme assumes that the cell-centre values (φ) of each variable represent a cell-average value that is the same for the whole cell. In other words, the face value (φ_f) equals the cell centre value-

$$\varphi_f = \varphi$$ [23]

For second order upwind schemes, Taylor series expansions are used to calculate more accurate face values-

$$\varphi_f = \varphi + \Delta\varphi.\mathbf{r}$$ [24]

[22] ANSYS Fluent 13 Help Database
[23] ibid
[24] ibid

Where **r** is the displacement vector from the upstream cell centroid to the face centroid.

The first order upwind scheme lacks accuracy but is very stable. Because of this superior stability it was used to begin the calculations to achieve relatively accurate results before switching to the second-order upwind scheme, which has superior accuracy but was unable to converge when applied using the initial conditions (Ferziger & Peric, 2002).

7.3 Solution Method

The simulation begins with given initial values at the boundary and, through the discretisation scheme chosen above, calculates the conditions at the rest of the nodes in the domain. The process is therefore iterative and will stop once the cumulative difference in calculated values of a node between iterations is less than a specified value. This value is known as the residual (Ferziger & Peric, 2002).

7.4 Accuracy

To ensure accuracy, several parameters need to be checked. The three most important are the sizes of the domain, the grid and the residual.

The domain of a theoretically unbounded 3D flow must be large enough such that boundaries imposed by the domain do not affect the flow

The grid must be fine enough such that the particular characteristics of the flow are captured.

The residual must be small enough such that subsequent iterations do not significantly alter the obtained result.

All these are measured using convergence tests which compare the results of a nominated variable over several domain, grid and residual sizes. From these it can be determined whether the solution can be considered accurate (Ferziger & Peric, 2002).

7.5 Actuator disk theory

The idea behind actuator-disk theory is the replacement of an actual (and incredibly complex) three dimensional rotating propeller by an infinitely thin circular disk across which a “pressure jump” is defined (Figure 7.1).

This considerably simplifies the situation to be modelled and makes the following assumptions (Rajagopalan, 2002)

- The flow is steady and incompressible
- The rotation imparted to the flow is ignored
- Flow outside the stream tube has constant stagnation pressure
- The cumulative impact of the propeller on the incoming water is treated as occuring at one single point (the middle)
- Pressure varies discontinuously and velocity varies continuously (Figure 7.2)
- Flow is unobstructed up and downstream (e.g. the boat hull is ignored)

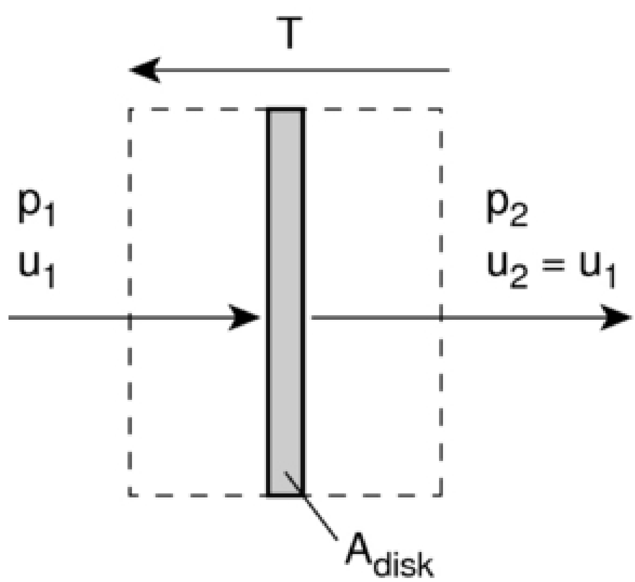

Figure 7.1 Pressure around an actuator disk[25]

[25] http://mit.edu/16.unified/www/FALL/thermodynamics/notes/node86.html

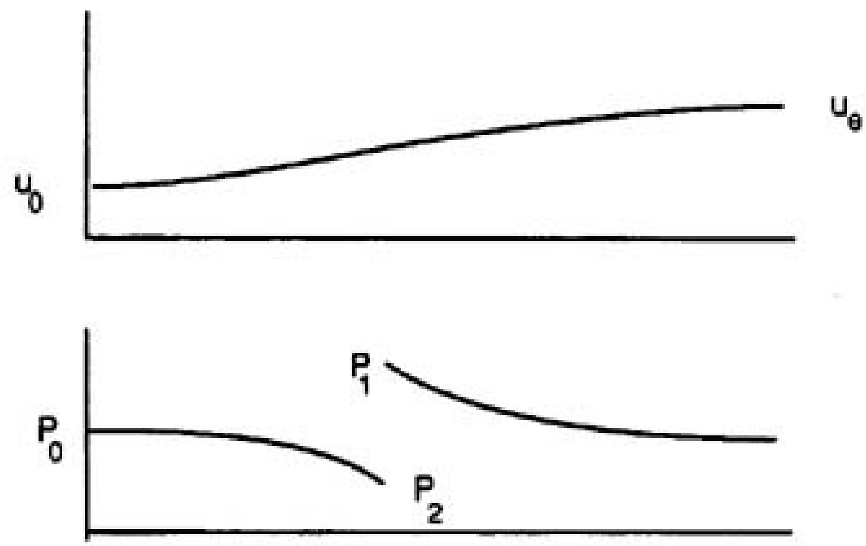

Figure 7.2 Velocity and pressure paths through the actuator disk[26]

The most conspicuous failing of the actuator disk model is that the resulting flow will look very different to that induced by a rotating propeller. However, the primary purpose of the AD model is in the estimation of power loss for which the exact "mirroring" of the flow is not essential as long as the required conditions of the flow (head) are adequately captured. As the purpose of this study is the measuring of head loss induced by a surrounding guard, the actuator disk is deemed likely to be a valid model.

[26] ibid

8. Objectives

The limited information about the effectiveness of propeller guards has meant that the debate over their use has rested mainly on unproved or vague assertions. This study aims to begin the development of a comprehensive research effort into propeller guards and will take a broad approach, examining the primary propeller guard design features in order to provide usable information on their actual and comparative effectiveness. This information is essential if appropriate steps are to be taken in the development of policy and regulations concerning propeller guards. It will also allow people to make informed decisions about the tradeoffs between performance and safety in the available propeller guard designs.

The current project will look at the guard configurations and comparisons seen in Table 8.1, assess the degree of safety they provide and evaluate the impact they have on propeller performance. Although this approach does not allow for direct comparison of existing propeller guards, it will provide practical data which will help to inform such comparisons and more importantly will provide a greater systematic understanding of propeller guard design.

	Subject 1			**Subject 2**		
	Shape	**Lid**	**Design**	**Shape**	**Lid**	**Design**
Test 1	Circular	No	Solid	Octagonal	No	Solid
Test 2	Circular	Yes	Fine Mesh	Circular	Yes	Coarse Mesh

Table 8.1 Proposed CFD simulations

Test 1 will investigate whether a circular or octagonal guard is superior, and test 2 the difference in head loss produced by different mesh sizes. Obviously all configurations can be compared with one another as well.

Of course the pioneering nature of this study means that in addition to the specific questions being investigated mentioned above, the validity of CFD as a tool for studying propeller guards, and in particular the Actuator Disk concept as implemented using ANSYS Fluent, is also under investigation.

Using the study of Nakamura (1998) as a basis, it is hypothesised that the circular ring guard will cause ~ 20% loss in available head. It is further hypothesised that there will be no significant differences in the head loss caused between the circular and octagonal guards, that the unlidded mesh ring guard will cause significantly less head loss than either and that the finely meshed lidded mesh ring will cause more head loss than the coarsely meshed lidded mesh ring.

While an authoritative answer to the latter hypotheses is dependent on the confirmation of the first, some insight may still be gained by an examination of the flows generated and of the proportional head loss caused by the two degrees of meshed lids.

9. Design

This study will investigate the head loss incurred by a variety of guards attached to a .275m diameter, .3m pitch propeller spinning such that the boat which it is powering is travelling at 21.6km/hr or 6m/s. The propeller is attached to a 15hp, 80% efficient engine.

The propeller will be modelled using an actuator disk on ANSYS Fluent 13.0. The specs of the computer used to run the simulation are as follows-

Intel ® Core (TM)i 7CPU 950@3.07GHz, 3.06GHz, 6.00GB of RAM.

9.1 Model Set-Up

9.1.1 Domain

The domain consists of the water immediately surrounding the propeller including the upstream and downstream. It was made by inserting a "primitive box" with the dimensions as seen in Figure 9.1 and Table 9.1.

.

Domain	a	b	c (upstream)	d (downstream)
A	1.2	1.2	1.4	3.6
B	1.3	1.3	1.5	4
C	1.5	1.5	1.75	5

Table 9.1 Domain configurations and results

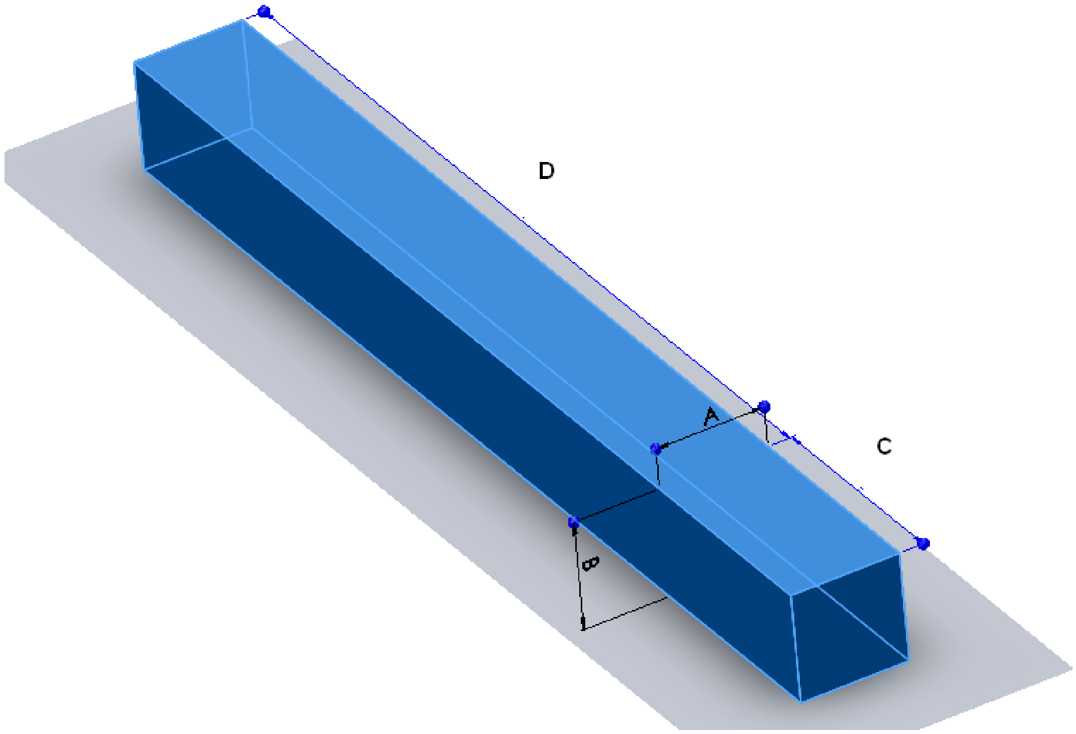

Figure 9.1 Domain dimensions

"Add Frozen" was selected as the operation type and the body was designated as a fluid.

9.1.2 Actuator Disk

The actuator disk was simply a circular surface of diameter .275m. It was made using the following steps

- Sketch a circle on the inlet face of the domain in the corresponding position on the x-y plane as the desired final position of disk (centre).
- Extrude it the necessary length (length "c" in the above domain dimensions) selecting "slice material" in the Extrude type option
- In the dialogue tree, select the box and the extrusion, right click and select form new part.

9.1.3 Propeller Guards

The guards were positioned concentrically with the actuator disk and such that the disk was located at the half way point (between the two flat faces) of the guard.

9.1.3.1 Circular Ring

The circular ring guard was made using SolidWorks. The dimensions can be seen in Figure 9.2.

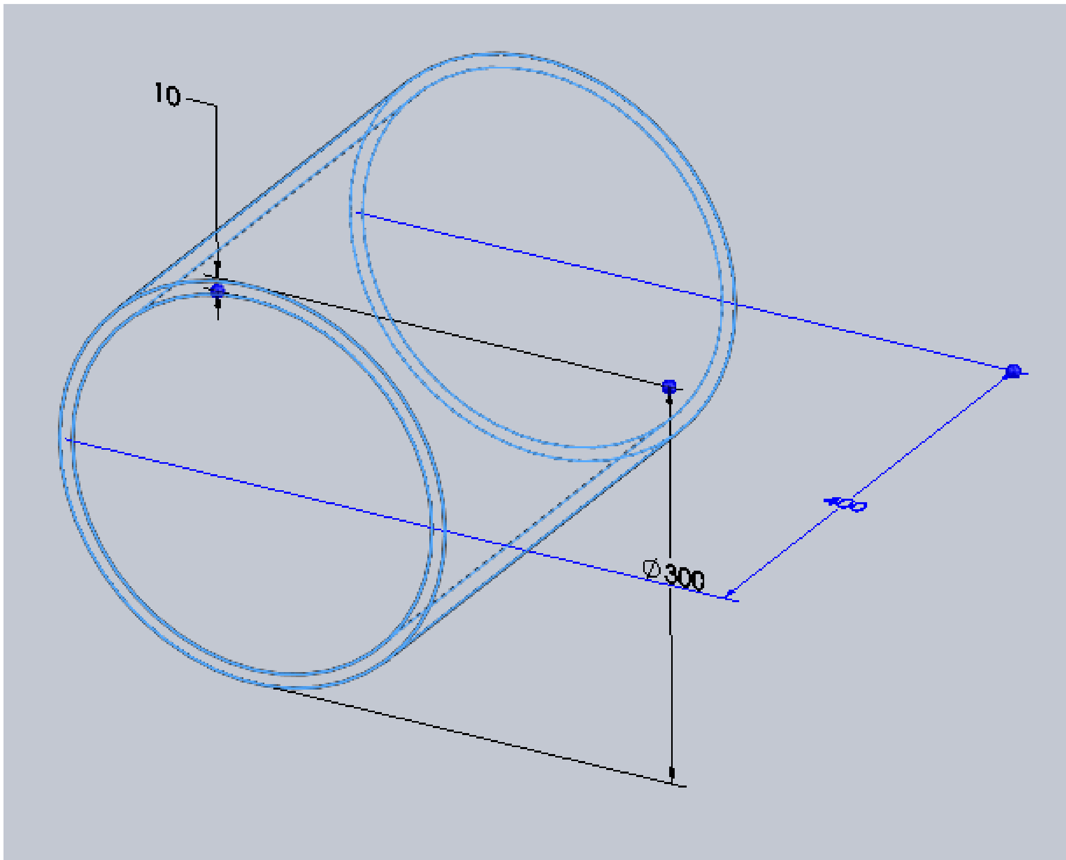

Figure 9.2 Circular ring guard design.

Diameter = 300, Length = 400

9.1.3.2 Octagonal Ring

The octagonal ring guard was made using SolidWorks. The dimensions can be seen in Figure 9.3.

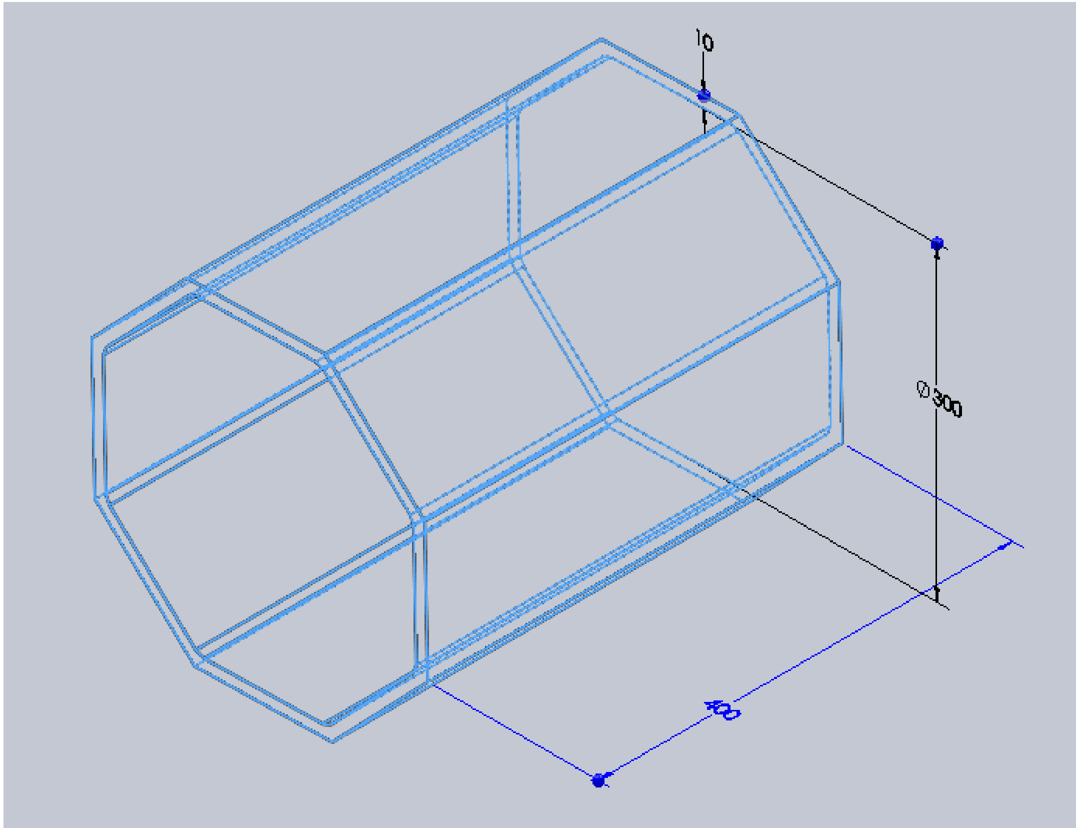

Figure 9.3 Octagonal ring guard design

9.1.3.3 Mesh Guards

The mesh guards were made using the assembly function of solid works. The mesh base can be seen in Figure 9.4 and its dimensions in Table 9.2.

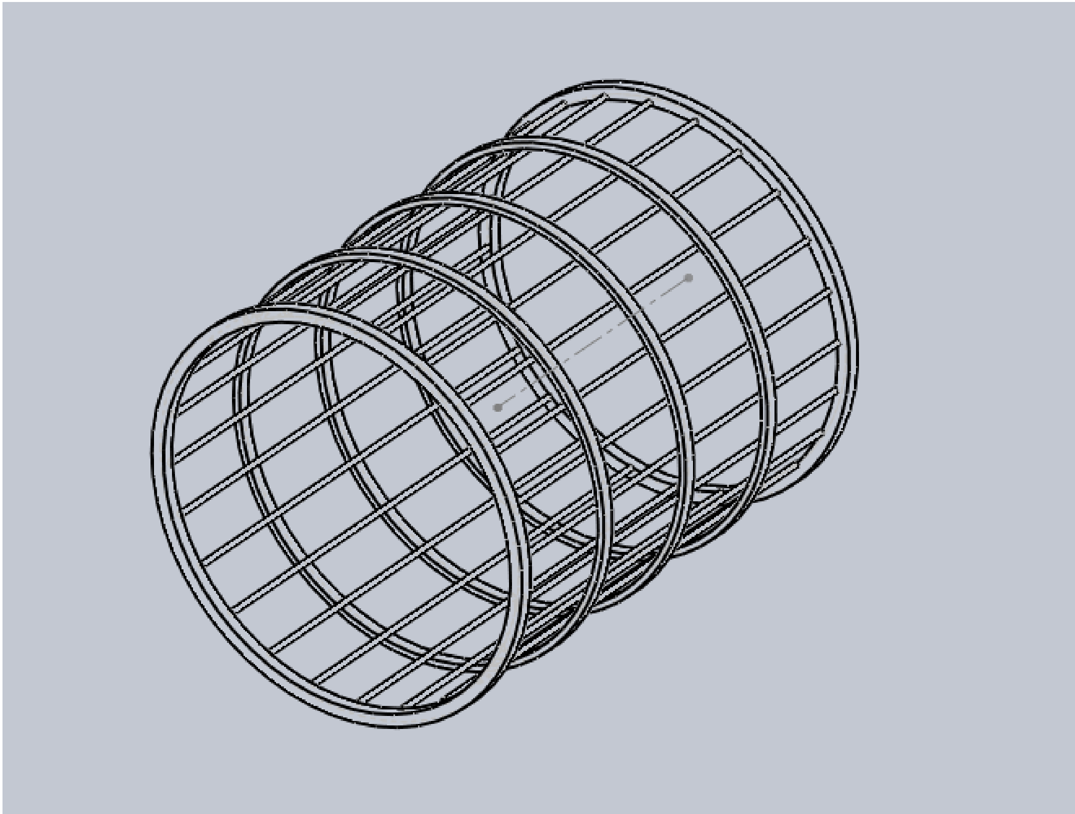

Figure 9.4 Mesh Ring guard design

Part	Dimesnsion	Value	Unit
Outer Ring	Outer Diameter	320	mm
	Inner Diameter	55	mm
	Thickness	10	mm
Inner Ring	Outer Diameter	320	mm
	Inner Diameter	310	mm
	Thickness	10	mm
Rod	Diameter	4	mm
	Length	30	mm
Assembly	Distance between rings	87.5	mm
	Angle between rods	15	degrees

Table 9.2 Mesh Ring guard dimensions

The mesh lids used can be seen in Figure 9.5, and their dimensions in Table 9.3.

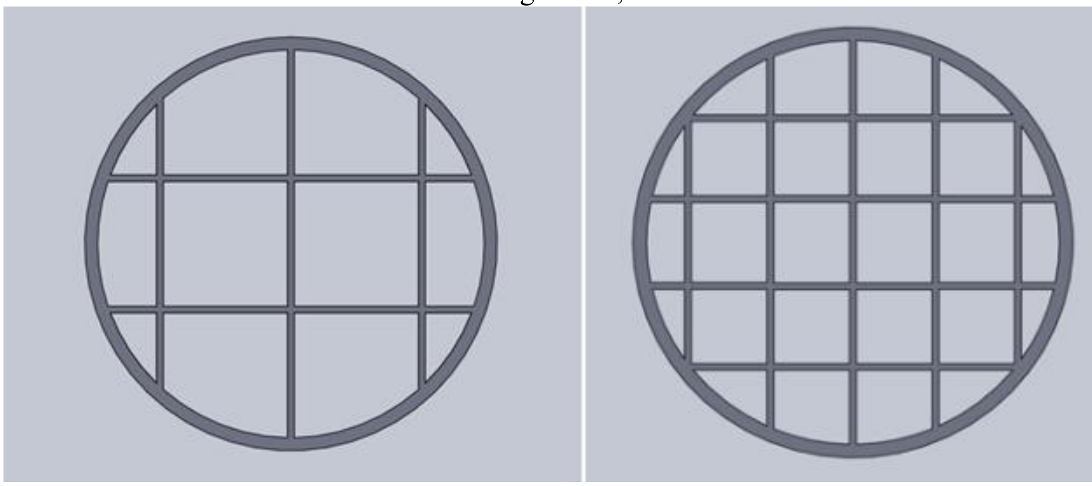

Figure 9.5 Mesh lid designs: Mesh-4 on left, Mesh-6 on right

Mesh	Outer Diameter (mm)	Inner Mesh Size (mm)
Mesh-4-lid	320	96.67
Mesh-6-lid	320	55

Table 9.3 Mesh lid dimensions

9.1.4 Model Validation

Table 9.4 shows the maximum velocities obtained using three different domain sizes. As can be seen, by increasing the size of the domain from B to C, less than a 0.07% difference in values is found, and therefore Domain C can be considered to be sufficiently large to obtain domain independence. Domain testing was carried out using the circular ring guard. As all relative distances were the same regardless of the guard used, the testing is considered valid for all guard configurations.

Domain	a	b	c (upstream)	d (downstream)	Max. Vel. (m/s)	%Change
A	1.2	1.2	1.4	3.6	9.593	n/a
B	1.3	1.3	1.5	4	9.613	0.208
C	1.5	1.5	1.75	5	9.619	0.062

Table 9.4 Maximum Velocity results

9.2 Grid

9.2.1 Inflation

Inflation was used around the areas of interest (actuator disk and guard) to minimise the computing time required to achieve accurate results. The inflation parameters were the same for both areas and can be seen in Table 9.5.

Inflation Option	Smooth Transition
Transition ratio	0.272
Maximum Layers	5
Growth rate	1.2
Inflation Algorithm	Pre

Table 9.5 Mesh inflation parameters

9.2.2 Sizing

Sizing parameters for all configurations are shown in Table 9.6.

Configuration	Element Sizing (mm)	Max size (mm)	Max Face size (mm)	Min Size (mm)	No. Nodes	No. Elements
A	0.02	0.04	0.04	0.02	372760	2129038
B	0.01	0.04	0.04	0.01	388179	2206869
C	0.005	0.04	0.04	0.005	427580	2406377
D	0.0025	0.04	0.04	0.0025	564074	3074144

Table 9.6 Element sizing parameters

9.2.3 Mesh

Figure 9.6 shows a cut scene of the mesh using configuration C. Note the inflation around the actuator disk and guard.

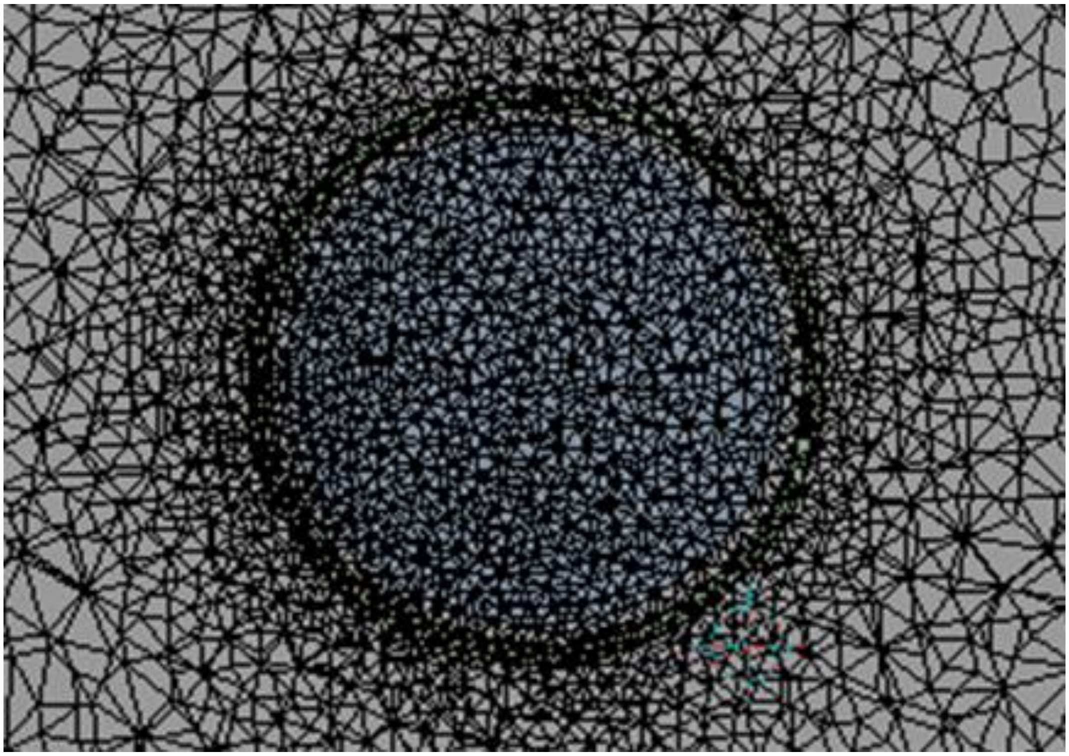

Figure 9.6 Clip scene of the inflated grid

9.2.4 Convergence

As can be seen from Figure 9.7, convergence is not achieved using any of the configurations, and lack of computing power and time meant that finer grids could not be used. However, considering the difference in results obtained by the varying mesh sizes is in the magnitude of 1e-02, it simply means that for the results to be meaningfully discussed, any analysis must be restricted to a magnitude difference of at least 1e-01. Mesh tests were conducted for the circular ring guard and the mesh-6-lid guard. As no significant changes occur when switching the octagonal guard for the circular guard, or the mesh-6-lid guard for the mesh-4-lid guard, the respective results are considered to hold for all.

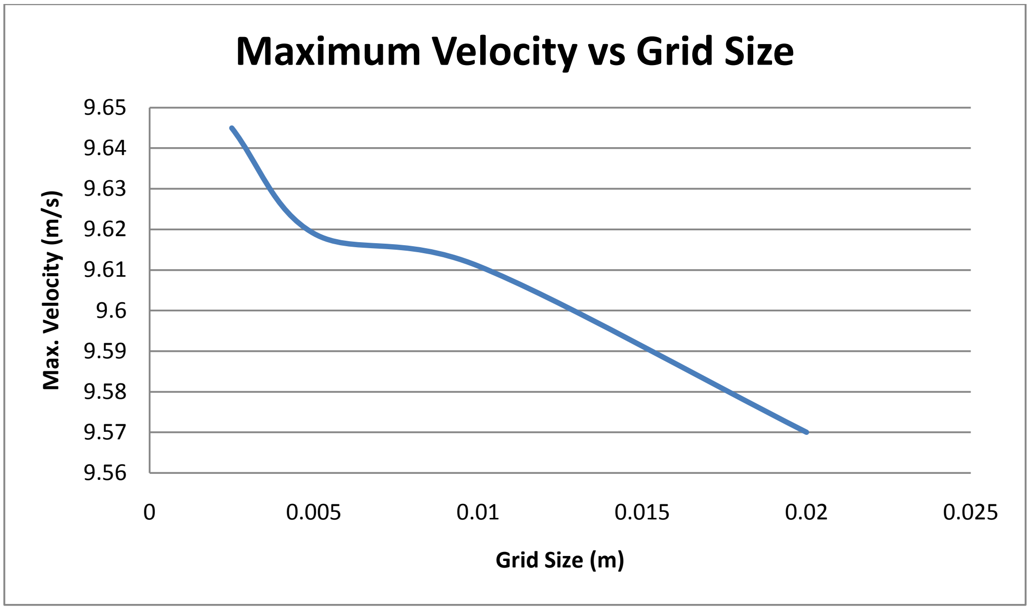

Figure 9.7 Plot of Maximum velocity vs Grid Size

Grid Size (m)	0.02	0.01	0.005	0.0025
Vel. (m/s)	9.57	9.611	9.619	9.645
Approx. Time (hrs)	10	16	24	40

Table 9.7 Velocity values for respective grid sizes

It should be noted that the approximate times given assume continuous operation; however, as first order upwind simulation were run first and only then followed by second order upwind, the building opening hours (7:00am-9:00pm) and outside-of-thesis commitments meant that any simulation that took 12 hours to run as first order upwind, could only be continued on the following day. Essentially this doubled the approximate running time of the simulations.

9.3 Boundary Conditions

9.3.1Named Selections

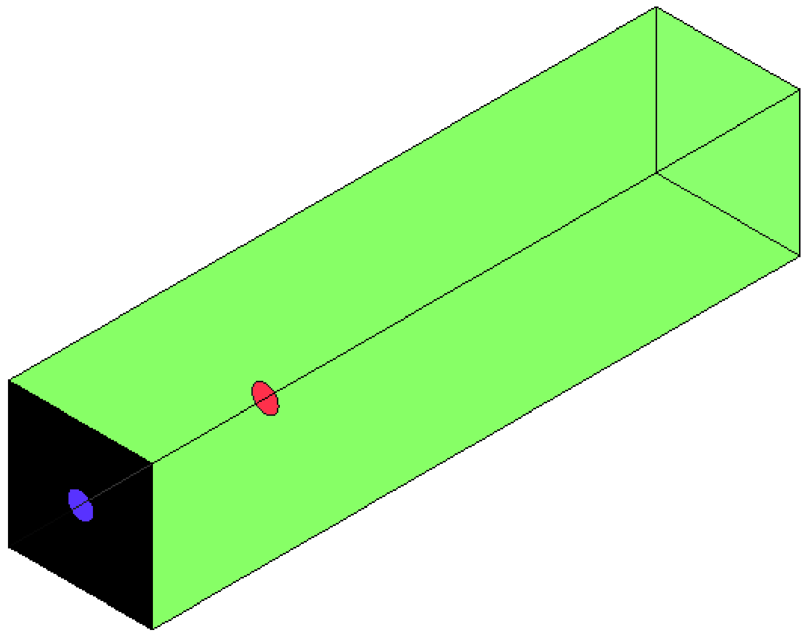

Figure 9.8 Named selection areas

Colour	Name
Red	Disk Outlet
Black	Inlet
Blue	Disk Inlet
Green	Symmetry

Table 9.8 Selection names

All areas of interest were given names as seen in Figure 9.8 and Table 9.8. The unlabelled face opposite the Inlet was named “Outlet” and when a guard was used, all faces of the guard were selected at the same time and named “Guard”. The part of the domain connecting the disk inlet and outlet was not named as it did not need to be treated individually.

9.3.2 Set up

All non-default parameters in the Set-up section are shown in Table 9.9

Section	Parameter	Value
Fluent Launcher	Options	Double Precision
Models	Viscous	Standard k-ε, standard wall functions
Cell-zone conditions	part-solid	Fluid-water-liquid
	solid	solid- steel
Boundary Conditions	Disk inlet	Velocity-inlet, 6m/s
	Disk outlet	Fan- 37.55 kPa constant pressure jump
	Inlet	Velocity-inlet, 6m/s
	Outlet	Pressure-outlet
	Guard	Wall
	Symmetry	Symmetry
Solution Method	Momentum	1st order upwind, then second order upwind
	Turbulent Kinetic Energy	1st order upwind, then second order upwind
	Turbulent Dissipation Rate	1st order upwind, then second order upwind
Monitors	Residuals	1.00E-05
Solution Initialisation	Z-velocity	6m/s
	Turbulent Kinetic Energy	18*
	Turbulent Dissipation Rate	.09 x TKE^1.5/(inlet height/2)[27]

Table 9.9 Set-up parameters

*TKE[28] = (Inlet Velocity) ^{2}/2

[27] Armfield. AMME 4210: Computational Fluid Dynamics, lecture notes, University of Sydney

9.3.3 Pressure Jump

To find the pressure jump across the actuator disk required some calculations. Firstly, the corresponding velocity difference needed to be found and this was done by considering the thrust (assumed constant) required to move a small boat at the nominated velocity of 6m/s using the 15hp, 80% efficient engine. This was calculated as (Spakovszky, 2007):

$$\text{Thrust} = \text{Power x efficiency/velocity} = 1493.33\ \text{N}$$

Then equating that calculation with an alternate formulation of the thrust generated by a propeller (Spakovszky, 2007), namely:

$$\text{Thrust} = \pi/4 \text{ x diameter}^2 \text{ x (velocity} + \Delta\text{velocity}/2) \text{ x density x } \Delta\text{velocity}$$

Yielded the following solution after rearranging and subbing in the known values below:

$$\Delta\text{velocity} = 4.54\text{m/s}$$

where

Power = 15hp = 11.2Kw
Boat velocity = 6m/s
Efficiency = .8
Diameter = .275m
Density = 998.2kg/m^3

Now considering the flow on either side of the actuator disk, the pressure jump was calculated by applying Bernoulli's equation to the upstream and downstream flows:

[28] ibid

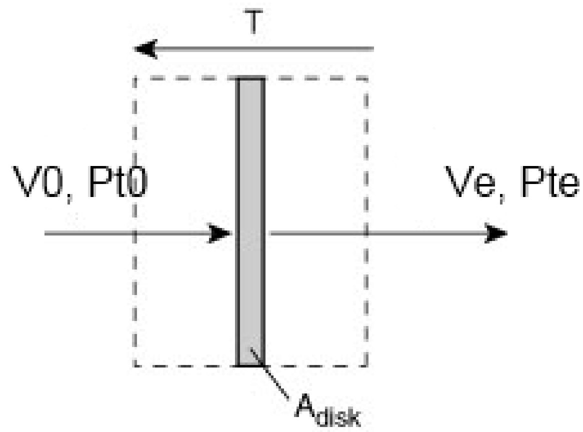

Figure 9.9 Pressure and velocity around actuator disk[29]

Pt_0 $= p_0 + .5 \times \text{density} \times v_0^2$

Pt_e $= p_0 + .5 \times \text{density} \times v_e^2$

Δp $= pte - pt0$

$= .5 \times \text{density} \times (v_e^2 - v_0^2)$

$= .5 \times 998.2 \times (10.54^2 - 6^2)$

$= 37.55 kPa$

Where p_0 is the surrounding pressure.

9.3.4 Material selection

From the survey of available propeller guards, it was found that steel was a common material used to make them. Water was chosen as the liquid. Although sea-water might have been more appropriate, the net effect was expected to be negligible and not worth the time of creating a new material. The properties for each were taken from the ANSYS database and are shown in Table 9.10.

Material	Density(kg/m3)	Viscosity (kg/m/s)
Water-liquid	998.2	0.001003
Steel	8030	-

Table 9.10 Material Properties

[29] ibid

9.4 Residual Test

The results of the turbulence tests are seen in Table 9.11. There is no difference in the calculated maximum velocities and therefore the residual value of .0001 is used for the remaining calculations.

Residual	Max. Velocity (m/s)
0.00001	9.619
0.0001	9.619

Table 9.11 Results of residual test

10. Results

10.1 Model Validation using Flow Fields

Figure 10.1 presents the vector z-velocity plots of the flow generated when a circular ring guard is attached. (For zoomed out vector plots of the other guards, see the Appendix) with the black lines representing the approximate position of the guard and the red line, that of the actuator disk. The flow is as expected, with a velocity increase seen immediately after the actuator disk, the formation of the wake once it becomes free of the guard's constraint and the gradual diffusion of the flow. The flow for all guards is essentially identical and Figures 10.2-6 show magnified images of the vector velocity plots for the different guards.

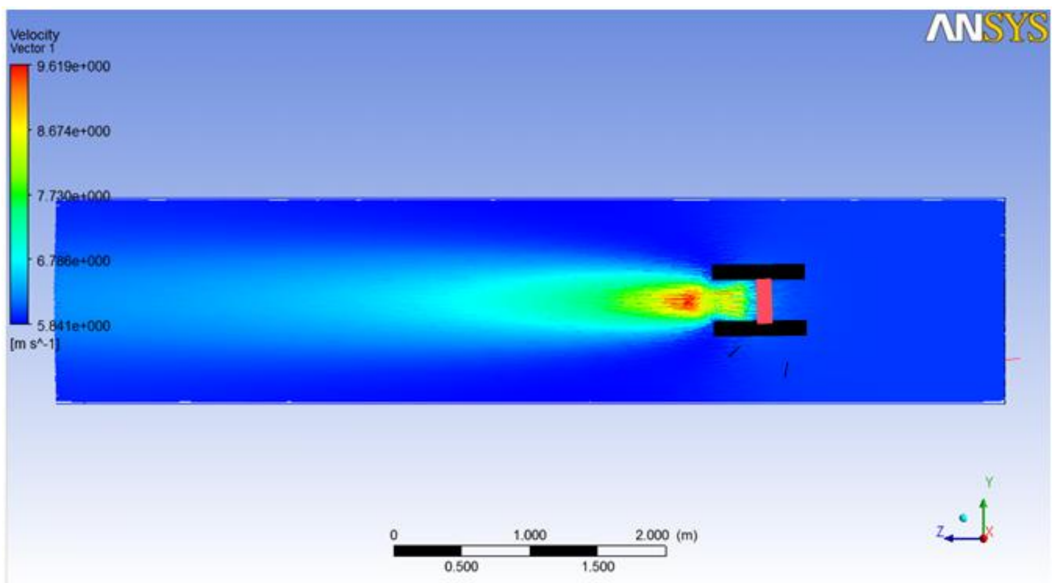

Figure 10.1 Circular Ring vector z-velocity plot

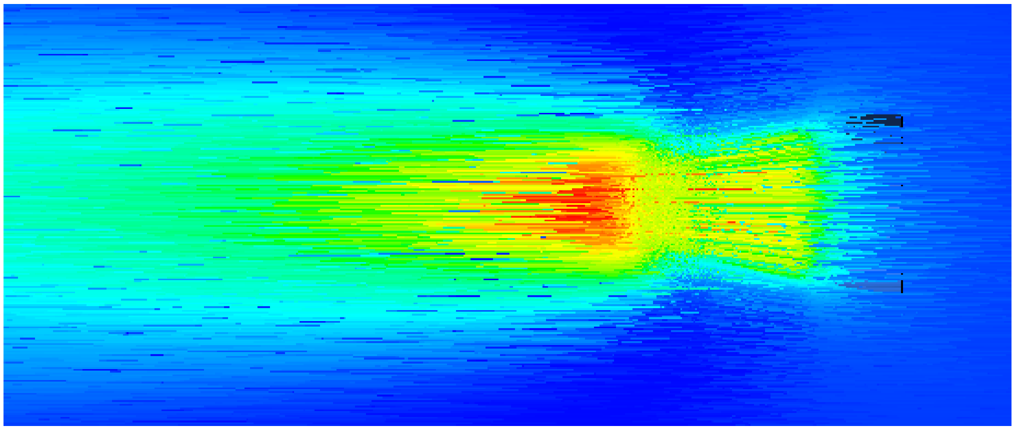
Figure 10.2 Circular Ring Close Up vector z-velocity plot

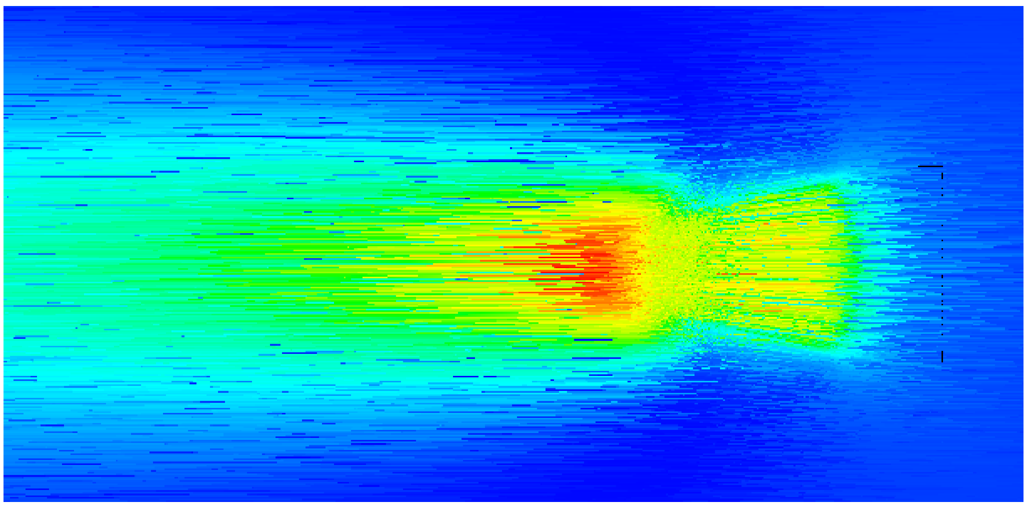
Figure 10.3 Octagonal Ring Close Up vector z-velocity plot

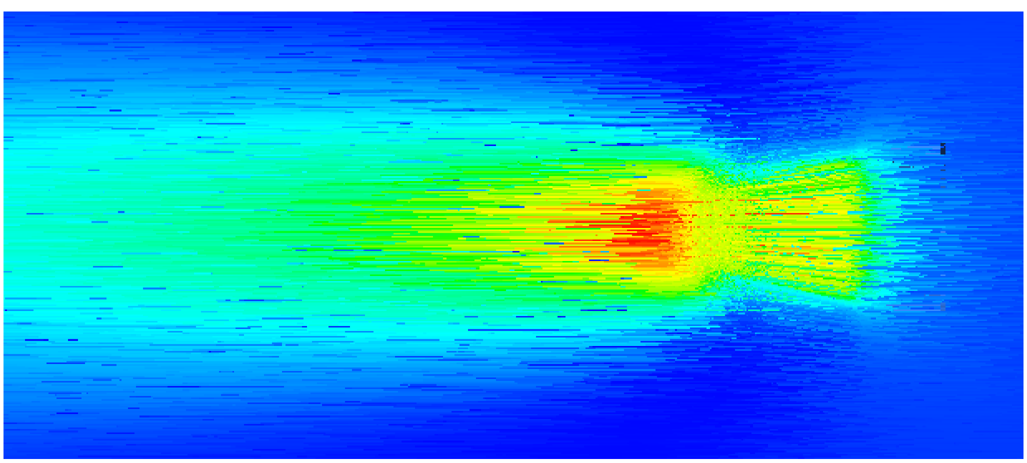
Figure 10.4 Mesh Ring Close Up vector z-velocity plot

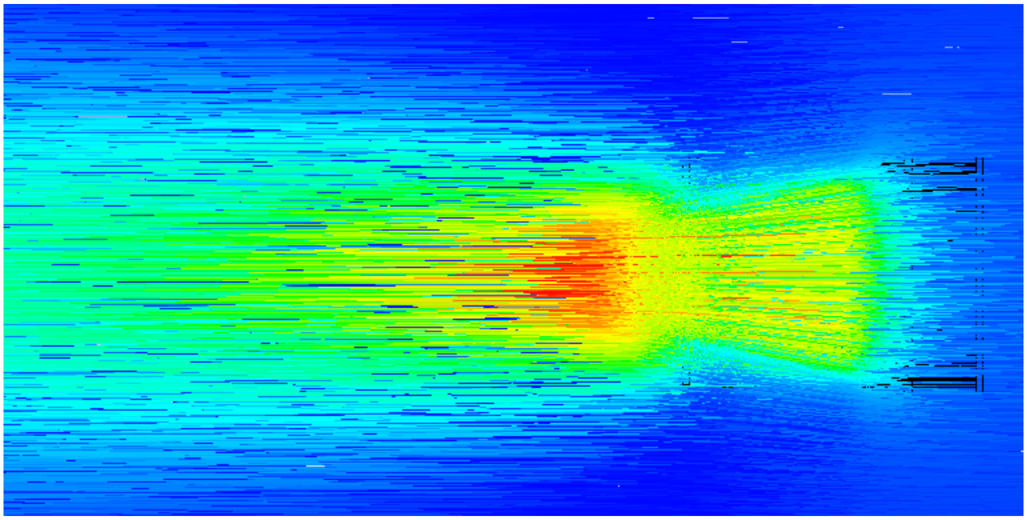

Figure 10.5 Mesh-4 closeup vector z-velocity plot

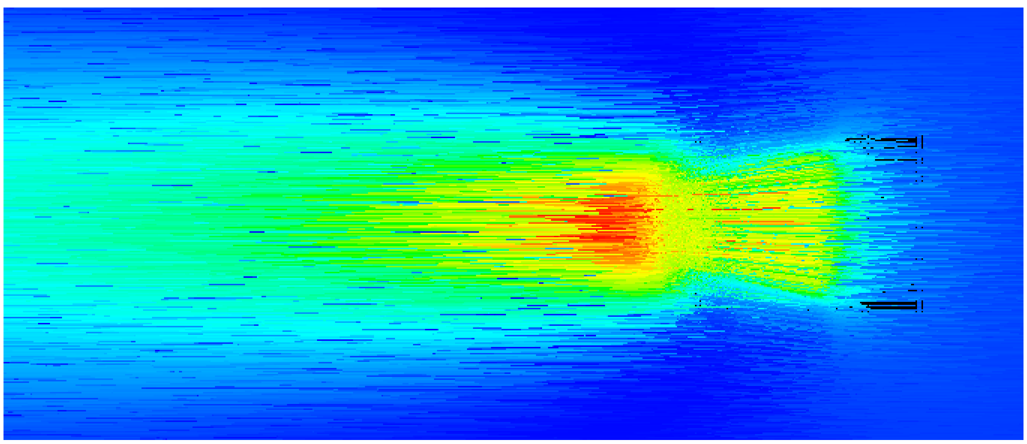

Figure 10.6 Mesh-6 ring closeup vector z-velocity plot

Other than some variation in the pattern of the high velocity turbulent wake region, there is little difference. The only characteristic of interest is the failure of the flow to pass through the curved section of the meshed guard, instead remaining bounded by it just as much as by the solid circular guard.

The flows generated by the actuator disk and guard interface are as expected for the solid guards and can be considered valid in that regard. The flow for the meshed guards did not capture the ability of the flow to pass through the mesh and therefore is considered invalid.

10.1.2 Actuator Disk Validation

The expected head gain from the propeller detailed in section 8.5.3 is

$$(37500/998.2 + 4.54^2/2)/9.81 = 4.87\text{m}$$

The head gain provided by the actuator disk model was 2.54m, ~52% of the theoretical value.

The velocity produced by the actuator disk was 8.95m/s, ~85% of the velocity (10.54m/s) from which the pressure jump was calculated in section 8.5.3.

The simulated values represent an increase in head and velocity and therefore can be considered as validly modelling the gross behaviour of the propeller. However, the specific scenario that was being modelled: that of a boat travelling at 6m/s and the propeller providing the necessary thrust, has not been accurately captured and therefore the results can only be spoken of in a general sense and not with regard to the scenario outlined above.

10.2 Head Loss

Table 10.1 shows the available head at various times in the flow and also the percentage loss.

	Head (m)			
Guard	**Initial**	**Pre Guard**	**Post Guard**	**% Loss**
Circular	1.733	4.271	3.435	19.6
Octagonal			3.445	19.3
Mesh			3.435	19.6
Mesh-4-lid			3.435	19.6
Mesh-6-lid			3.435	19.6

Table 10.1 Available head at various points in the flow

Initial and pre guard head was the same for all configurations as would be expected. Similarly, post-guard head for circular and mesh rings was the same, again as expected after the examination of their flows revealed the failure of the simulation to accurately model the flow-mesh interaction. A small difference is noted in the head loss incurred by an octagonal as opposed to a circular guard.

Head loss was calculated by applying Bernoulli's equation to two circular planes, .15m diameter, directly in front of the actuator disk and the end of the guard as seen in the cut scene Figure 10.7. This was valid as no flow from within the streamtube (flow emanating from the actuator disk) ever passed through the guard and therefore all elements present in the first plane were captured by the second plane.

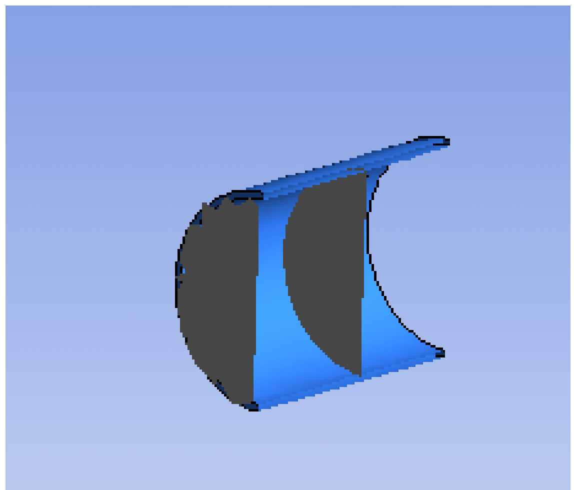

Figure 10.7 Cut scene of planes used to calculate head loss

11. Discussion

11.1 Performance Analysis

The first hypothesis was confirmed with head loss for all guards approximating 20%. Similarly, while the head loss for the octagonal guard was slightly smaller than that for the circular, it was insignificant being a mere .3%. It is important to consider what this efficiency decrease means in real terms.

The loss of efficiency essentially means that for the motor engine putting in the same amount of work, the boat is receiving that much less thrust. This has the obvious result that desirable speeds may become unattainable, or attainable only with much greater fuel consumption. Furthermore, a propeller is selected such that the engine it is coupled with can satisfy its Wide-Open-Throttle rating. An inability to do so can result in several negative consequences including engine damage and cooling problems (D'Antonio, 2010). Naturally the attachment of a propeller guard will render any previous calibration invalid and therefore a different propeller would need to be purchased to satisfy the WOT requirements. The next step would be to quantify the effects of a decrease in efficiency in these terms- speed reduction, fuel consumption and WOT requirements.

As already discussed, the Mesh ring guard seems to have been treated by the simulation as a solid circular guard, and even the addition of the lids does not seem to have had any impact on the flow. Even though inflation was used around these guards it does not seem to have inflated the fineness of the cells around it to a sufficient degree to capture its effect on the flow. Having said that, even the uninflated grid size of .04m or 4mm would seem to be small enough for a 5mm diameter rod to have some kind of effect on and so the problem could lie elsewhere. Considering that the denseness of the mesh already used required a computing time of over twenty four hours, the use of a grid fine enough to capture it must wait until the investigation of propeller guards becomes of interest to those with access to much larger computing power than is available for undergraduate students.

Alternatively, the actuator disk might not have caused the flow to diffuse to such a degree as would be expected from an actual propeller. This could be remedied by experimenting with other positions of the actuator disk, such as at the beginning of the guard, to see if that gives the flow sufficient time to dilate. However, if this is the case, it does not explain why the lidded mesh guards did not influence the head loss as the flow definitely passed through them.

The 20% head loss figure, while in line with the expected value, is still of doubtful validity owing to the absence of empirically obtained data against which it could be compared. Perhaps a CFD study of propeller guards was premature and it would be more appropriate to first compile a database of empirically gathered efficiency data against which any future CFD might be compared. Then, after the use of CFD in accurately modelling propeller guards has become firmly grounded, it would be useful to use it to investigate the exact effect of each of the countless possible guard design parameters on efficiency.

11. 2 Safety Analysis

The lack of specific detail (affected body part etc) in the statistics gathered for propeller related injuries means that it is not possible to empirically determine the degree to which each guard would be able to prevent injuries. However, by careful consideration of typical scenarios and the application of patient thought, it is not unreasonable to assume that a fairly valid understanding of their relative safety merits could be obtained.

From the debate over propeller guard usage summarised above, it is known that as the guard gives with its left hand, so does it take away with its right, and therefore the degree to which injuries are reduced by shielding the propeller must be counterbalanced by the introduction of new injuries from the presence of the guard.

To determine the "rating" of each guard, I will be comparing it to an unguarded propeller with a base rating of 100 (though adjusted later; see section 11.2.1). This rating will then be modified depending on how each guard would change the severity or occurrence of the injury. If, for example, it prevented ½ of the potential injuries, it would be rated at 50, or if it changed the injury from one of laceration to one of blunt trauma, it would be modified by a factor of .5. This system attempts, therefore, to reflect and quantify two important considerations: that not all propeller related injuries will be prevented by the guard and that the injuries will not disappear but will be replaced by injuries of differing severity.

No pretence of scientific truth is assumed by this calculation of quantitative ratings to multiple decimal places, only that of an objective methodology. Although the weightings are necessarily somewhat arbitrary, they will be applied consistently and the weightings are explicit. This, firstly, makes it clear exactly what is meant when describing the relative safeties of each guard and secondly, will allow for the progressive development of a more valid propeller guard rating system which will benefit from the input of those more experienced in the area and also from the collection of more detailed statistics.

Thus the "formula" for calculating a guard's danger rating can be written as

$$\Sigma(\text{Proportion of injuries of type Z x severity rating of injuries of type Z})$$

With the proportions differing for each type of guard and the severity ratings as shown in Table 11.1.

Injury	Rating
Laceration	1
Blunt (solid)	0.5
Blunt (mesh)	0.3
Death	3

Table 11.1 Injury severity ratings

Again I stress the "non-ultimate" status of these ratings and in particular the rating of death. Of course one would feel that the suffering induced by death is more than three times worse than the suffering induced by lacerations, however horrendous, and possibly infinitely so, but such a rating would serve no practical use in evaluating the comparative safety benefits of each guard and a rating had to be assigned that would attempt to reflect as accurately as possible the trade-offs that people do in fact make everyday, assigning to death a value and weighing it against other costs and benefits.

11.2.1 Unguarded

The number of injuries caused by an unguarded propeller will be the standard by which the proportions of each injury caused are calculated for the guards. From the statistics presented above, approximately 90% of the injuries involve lacerations while 10% involve death. This calculated to a danger rating of

$$90 \times 1 + 10 \times 3 = 120$$

11.2.2 Solid

Circular Ring

The circular guard would mean that any injury caused by the propeller would require some part of the person coming into contact with it directly on its end face. Considering the typical scenario of someone being run over by a boat and propeller, it is clear that in the majority of cases, this would stop any contact from occurring and the only time contact would take place would be if a person's limbs were outstretched and directly in line with the propeller, or if they were horizontal in the water and the diameter of their head was smaller than that of the propeller guard.

The guard itself would not create any new injuries and by that I mean it would not create an injury when there would not have been one had there not been a guard (the guard itself only increasing the surface area of the propeller by an insignificant degree). Instead, it would change the nature of the injury from one involving laceration and cutting, to one of blunt trauma; and in the worst case scenario, unconsciousness leading to death by drowning. The degree to which it does this would depend on the size of the propeller. A larger propeller would mean a larger exposed area and more chance of someone coming into contact with it.

In summary, the guard does not affect the occurrence of injuries and so no modification will take place on that account. I estimate that 80% + size_factor (see Table 11.2 for size factor ratings) of the injuries would be changed to the blunt trauma kind and that 1% of these would result in death from unconscious drowning. Therefore the final danger rating for an average size guard is:

$$20 + 79.2 \times .5 + .8 \times 3 = 62$$

Guard	Size_factor
Small (<.3m Dia)	10
Medium (<.6m Dia)	0
Large (>.6m Dia)	-15

Table 11.2 Size factors

The probability of death caused by the circular guard, and all other guards is considered so small compared to the empirically based unguarded propeller probability because, as mentioned, death would in the first case be incredibly unlikely to occur from the impact alone but instead arise only from drowning. This would mean that for death to occur, the accident would, in general, have to take place when that person was alone and unable to be aided by any nearby person. Speaking from pure conjecture, it seems reasonable to assume that when a lone person is injured by a propeller it would not be travelling at high speed, if moving at all (with no one piloting the boat) and therefore the impact would probably not be of sufficient force to cause unconsciousness.

Octagonal ring

I do not see that the octagon shape offers any significant advantages or disadvantages with regard to safety and so it will be given the same rating as the circular guard.

11.2.3 Meshes

Unlidded

The unlidded mesh guards are essentially the same as the circular guards except that the injury caused by their impact with a person would be considerably less, the surface area of impact and stiffness of the guard being significantly less than the solid circular guard, and therefore will have a modification factor of .3. The chance of knocking someone unconscious is similarly less and is estimated at .02. Naturally the gaps in the mesh mean that hands can come into contact with the propeller from every angle but this will depend on the size of the mesh used and any mesh size that prevents an average size hand from entering would be little different to a solid wall. The likelihood of a hand actually going inside the mesh, in any case, is considered highly unlikely and will therefore be ignored for this study. Therefore the danger rating of an unlidded mesh guard is calculated to be:

$$20 + 79.84 \times .3 + .16 \times 3 = 44.43$$

Lidded

Lidded mesh guards have the same benefits as the unlidded type but almost completely prevent contact with the propeller and therefore all chance of laceration is prevented. Their rating is calculated as

$$99.84 \times .3 + .16 \times 3 = 30.432$$

11.2.4 Summary

Table 11.3 summarises the safety analysis

Guard	Size	Danger Rating
Circular/octagonal	Small	57
	Medium	62
	Large	69.5
Unlidded mesh	Small	37.4
	Medium	44.4
	Large	54.9
Lidded mesh	-	30.4
Unguarded	-	120

Table 11.3 Guard danger rating

The greater danger rating of the solid guards compared to the unlidded mesh guard is noteworthy as it is somewhat counter intuitive. It relies on the assumption made regarding the negligible likelihood of any part of a person penetrating through the guard and coming into contact with a propeller. If that assumption is true, then the result is sound. Considering the difficulty of inserting part of one's body through a mesh, even a large one, when it is travelling at high speeds lends weight to the validity of the assumption.

11.3 Cost Analysis

It is often imprudent to engage in abstract theorising over the potential cost and difficulties involved in the manufacture of any product owing to the large number of unknowns in any market based speculation, but it would be remiss in an undergraduate honours thesis not to exhaust all avenues by which the application of serious thought and contemplation might be displayed. To that end, let several general maxims be applied upon which, then, appropriate caveats will be attached.

First, the more material used in the guard, the more expensive it will be and similarly, the more complicated the design, the greater the expense. Applying these two maxims, it is seen that the circular and octagonal guards require more material while the meshed guards are harder to manufacture. Therefore it is a matter of determining the relative importance of each factor. While dependent on the kind of material used, I think in general the total cost involved in the making of the guard, including labour, any capital equipment and so on would be by far the more significant contributor.

It must also be recognised that economies of scale will eventually play a factor, assuming either a grassroots up swell in, or government mandated, enthusiasm for propeller safety, and the extent to which these reduce the comparative costs will be dependent on the number being made which is impossible to know at this time. The existence of manufacturing processes already in existence that could be easily converted to propeller guard production is another unknown that would render all speculation almost practically worthless.

The trade-off between the upfront costs of the guard and the costs saved by lower maintenance and replacement costs is another weighty consideration. As too are the increased petrol costs that will be incurred by an efficiency hampering guard.

Lastly, the importance of the cost must, of course, be reconciled with the perceived value of the guard. No one would want, or want to actually buy, a perfectly safe, 100% efficient guard for an exorbitant price just as surely as no one would want to even use a moderately safe, highly inefficient guard that was provided free of charge.

In summary, the meshed guards will tend to be more expensive than the non-meshed guards, but the actual price can only be determined by the actual making of it, and as part of an ongoing manufacturing operation. The ratings determined by this analysis are shown in Table 11.4.

Guard	Cost
Circular/Octagonal	Low
Unlidded Mesh	Medium
Lidded mesh	High
Unguarded	Zero

Table 11.4 Guard cost designations

Whether or not the price is inhibitive will depend on consumer preferences, which, as the market is still undeveloped, is essentially unknown; though one might consider its lack of development as strong evidence that the size of the "inhibitive" cost is fairly small.

12. Conclusion

12.1 Summary

The findings of this study may be summarised as follows:

Firstly, the use of CFD in measuring propeller guard efficiency received support, but more importantly several key limitations were identified, namely the requirement of large amounts of computing power to model mesh guards and the need for further empirical research for comparison. Secondly, the efficiency of circular and octagonal guards was measured as 80%. Thirdly an objective method of defining the safety value of each design was developed and applied to each of the guards considered and fourthly, the primary cost issue, the trade-off between upfront costs and ongoing petrol and maintenance costs, was described. The above data is presented in Table 12.1 below.

Guard	Size	Danger Rating	Performance	Cost
Circular/octagonal	Small	57	80	Low
	Medium	62	-	
	Large	69.5	-	
Unlidded mesh	Small	37.4	-	Medium
	Medium	44.4	-	
	Large	54.9	-	
Lidded mesh	-	30.4	-	High
Unguarded	-	120	100	Zero

Table 12.1 Guard danger, performance and cost summaries

As to the “absolute” or overall value of any particular guard, I can only quote the great Edmund Burke (2006, pg5):

> I cannot stand forward, and give praise or blame to anything which relates to human actions, and human concerns, on a simple view of the object, as it stands stripped of every relation, in all the nakedness and solitude of metaphysical abstraction.

In other words, the value of the guard is dependent upon the individual needs of each person for the particular purpose they wish to use it for.

The lack of definitiveness of this study has been mentioned more than once in passing and as such, only a brief recap will be given here. The use of CFD in investigating propeller guard efficiency is still in its infancy and as such, the results found in this study are provisional only. In addition, the study used many assumptions which could perhaps have a significant impact on the actual efficiency of the propeller guard including-:

- The propeller flow was sufficiently well modelled by an actuator disk
- The presence of the boat was ignored
- The propeller guard attachment to the boat was ignored

The validity of the first assumption has received some support by the findings but remains inconclusive, and the latter two assumptions would most likely result in an overrating of propeller guard efficiency. All three assumptions can be addressed in future research.

Also previously mentioned, the inability of the simulation to model the meshed guards is a serious problem and has meant that no meaningful discussion could be conducted as to their relative efficiency.

12.2 Future areas of research

This thesis notwithstanding, propeller guards remain a fertile source of future research and such research can best be divided into five main areas:

12.2.1 Methodology

The use of CFD in measuring propeller guards still needs further validation. To do this, firstly more empirical testing of propeller guards needs to be done so that meaningful comparisons can be drawn. Then once the soundness of CFD analysis has been established, the tool can be used to investigate in greater detail the effects of the various guard parameters etc that it would be much too involved to test empirically.

The use of a rotating domain in place of an actuator disk should also be explored to determine whether the accuracy of the results obtained is worth the additional effort and expense involved in the set-up.

Lastly, high powered simulations that can deal with extremely fine grid sizes will be needed to model meshed guards.

12.2.2 Guard Design and Parameters

Several of the possible guard designs were tried in this study but many were left untested, with the design of greatest interest being the Kort Nozzle guard. Apart from the overall design, the parameters outlined in the preliminary analysis (Section 5) can be studied in greater depth, for example measuring a wide variety of clearances for the same guard design, or experimenting with various hole placements. The effect of guard size and material needs also to be examined.

12.2.3 Situational Factors

Similarly, the efficiency of the guard across a wide variety of situations has been left unexplored, most importantly, its efficiency at different incoming water speeds and angles and the effect of acceleration. The method of attaching the propeller to the boat and the actual presence of the boat itself upstream of the propeller are factors also worthy of further thought.

12.2.4 Safety

The importance of statistical data in determining the weighting to be given to the danger rating of each guard as mentioned in Section 4 was not explored and future research could investigate the likelihood, for each type of boat, of being involved in a propeller accident. This would provide a more well-rounded idea of the true safety improvements offered by any particular guard. To illustrate the point: a boat with an almost zero percent chance of involvement in a propeller related injury would not benefit greatly from a zero danger rating guard. The danger rating system developed here could be further expanded upon and improved as well.

12.2.5 Cost

Probably the most pressing cost issue is the previously mentioned question of high initial upfront + increased petrol costs versus long term savings via low maintenance costs. Considering a major objection against propeller guards is the fact that they are expensive, the determination of this question would lend some serious weight to the "long-term savings" theory.

A more in-depth analysis could also be conducted into the manufacturing of propeller guards, their current costs, consumer demand and so on.

13. References

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14. Appendix

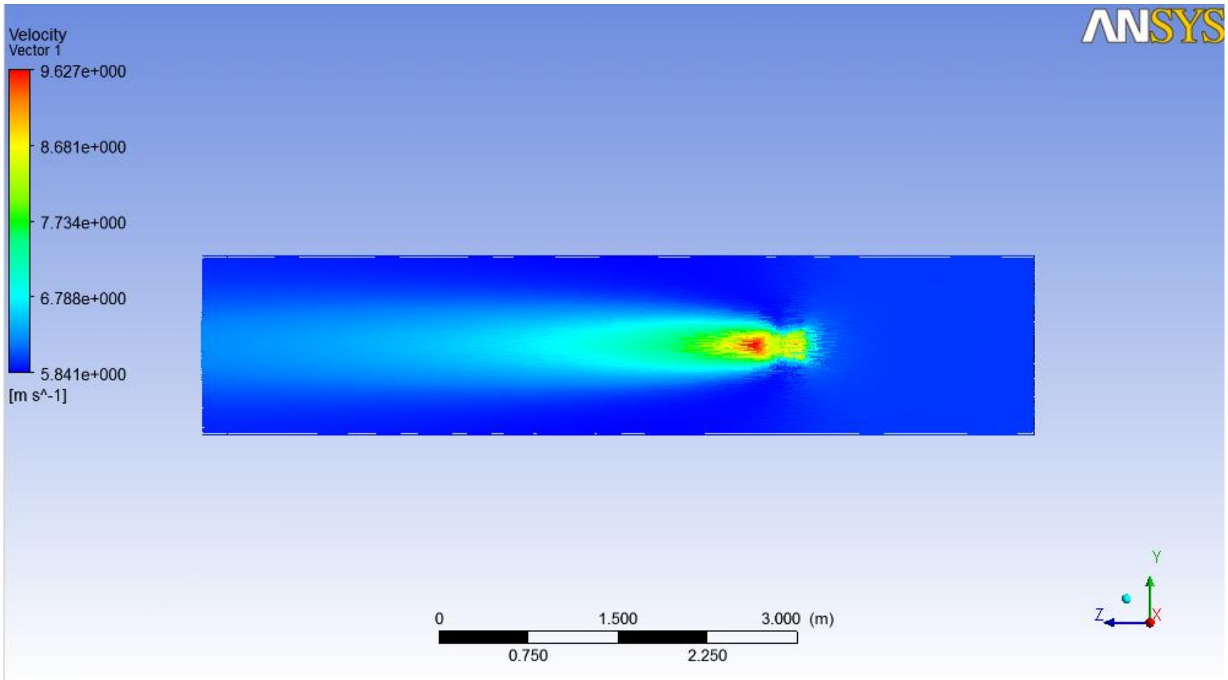

Figure 1 Octagonal Ring

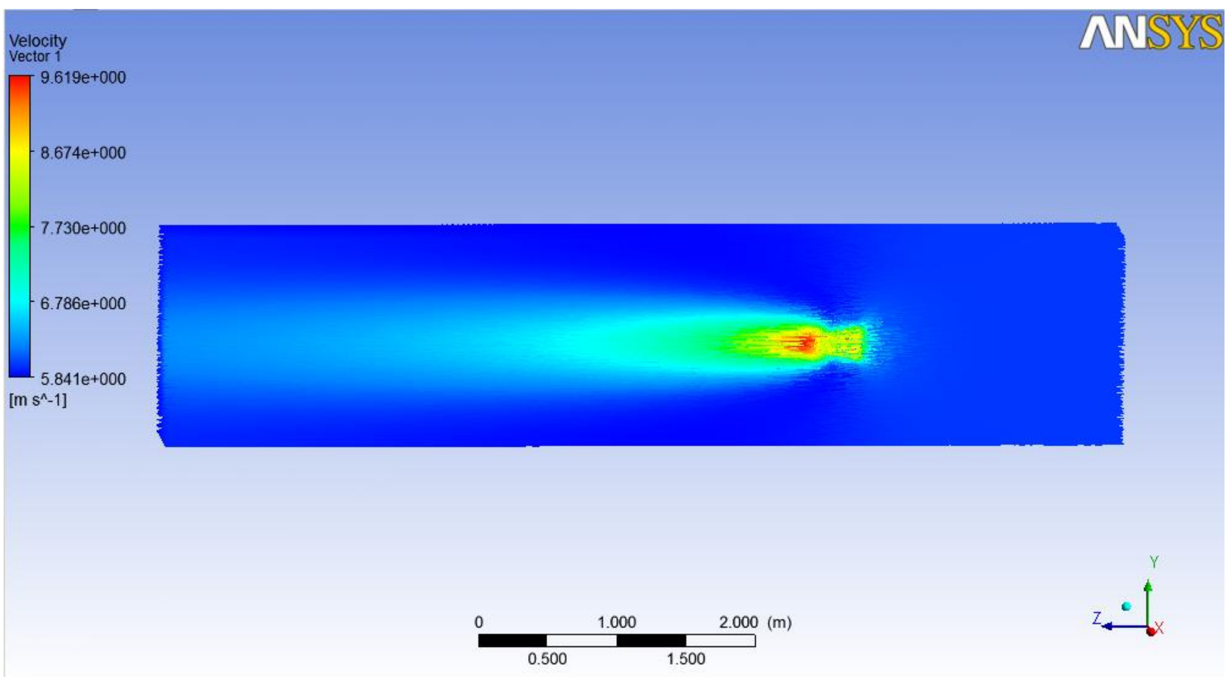

Figure 2 Mesh Ring

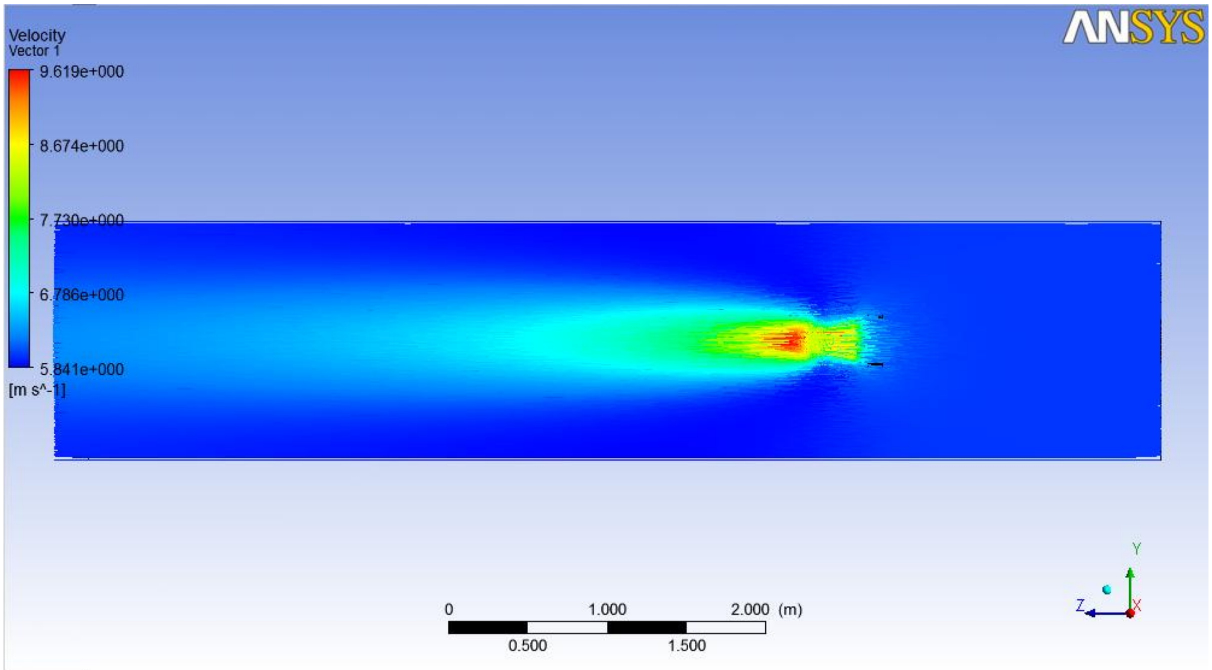

Figure 3 Mesh-4 Ring

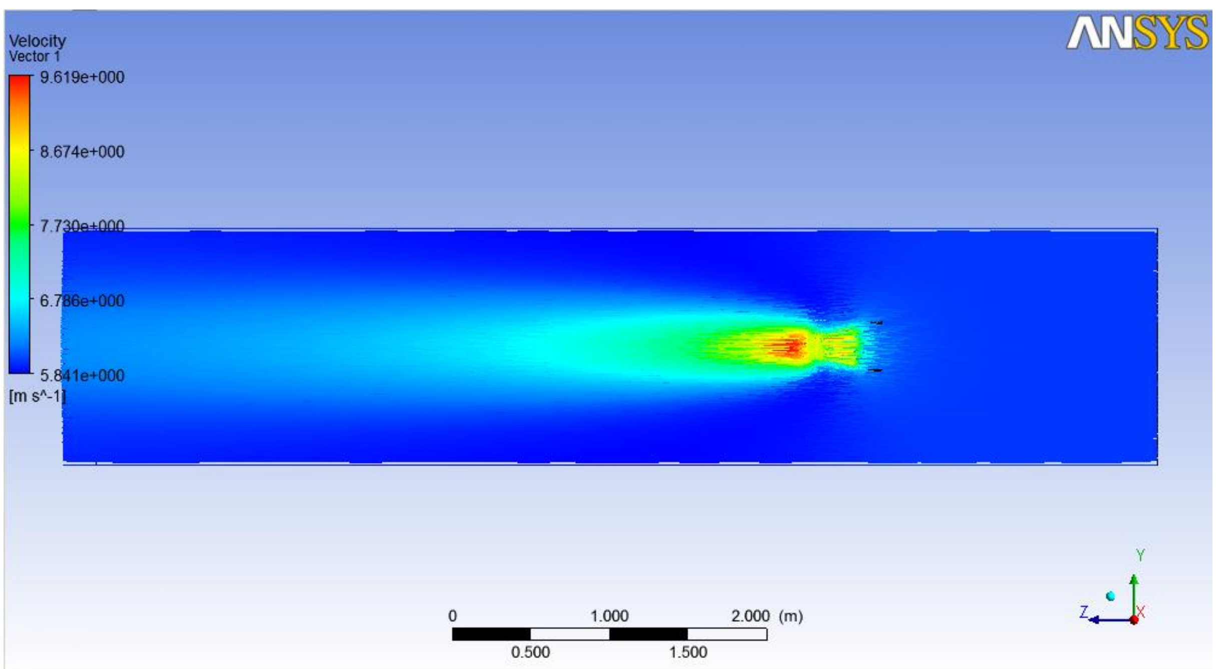

Figure 4 Mesh-6 ring