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Drag levels and energy requirements on a SCUBA diver

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Drag levels and Energy Requirements on a SCUBA Diver.

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ABSTRACT

The popularity of sport diving has increased rapidly since its inception in the 1950's. Over this period, the trend has been to increase the amount of equipment carried by the diver. There are many undoubted safety advantages associated with the additional kit, but under some conditions, it can impose an additional burden in the form of increased drag.

The purpose of this paper is to identify the drag penalties for a number of simple SCUBA configurations. This is achieved through scale model experiments conducted in a wind tunnel. Some comments on the associated energy requirements are made, and from these, the effect on a diver's bottom time is briefly addressed. The configurations tested include a study of the effect of the equipment configuration and the effect of small changes to the diver incidence.

The tests show that the addition of a pony cylinder gives a 10% increase in drag compared to a conventional octopus set-up. When a dive knife, large torch and a Surface Marker Bouy (SMB) are also added this increases to 29%. Over the range tested, the average effect of swimming at a head up incidence to the flow is to increase the drag coefficient by 0.013/degree. This amounts to 16% at 5 degrees and 49% at 15 degrees. Estimates of the effect of the drag changes on bottom time show that particularly at the higher speeds the drag increases result in approximately similar percentage reductions in bottom time. Some simple suggestions for drag reduction are proposed.

KEYWORDS

diver, drag, SCUBA, energy requirement, drag reduction

NOTATION

A	Projected frontal area (m)
C_D	Coefficient of drag
D	Drag force (N)
E_t	Endurance time (mins)
l	Model characteristic length (m)
P_{in}	Input power (W)
(Re)	Reynolds number
t	Time (secs)
U	Tunnel freestream speed (m/s)
α	angle of incidence (degs)
η	mechanical efficiency
ρ	fluid density (kg/m^3)
μ	absolute viscosity (Ns/m^2)
υ	kinematic viscosity (m^2/s)

subcripts

a	air
fs	full scale
m	model
w	water

INTRODUCTION

Prior to the 1950's the exploration and enjoyment of the underwater world was limited to a very few professional divers, generally undertaking commercial operations. The invention in 1951 of the Self Contained Underwater Breathing Apparatus (SCUBA) opened up the possibility of the development of a new and exiting sport. The numbers of people participating in this activity has expanded steadily and today more than 2 million people world-wide regularly go diving. The sport has grown into a mature industry with voluntary and commercial operations providing training, the arrival of diving package holidays and a plethora of equipment manufacturers.

In the early days, the SCUBA gear was essentially very simple. The diver strapped on a cylinder containing compressed air which was fitted with a first stage regulator and a second stage mouthpiece. A reserve system told the diver when air was running low. Weights were added to assist the descent and the diver wore a mask and a pair of fins. The development and expansion of the sport has led to a much better understanding of physiological factors associated with the sport and also to the development of safe diving practices. Some of the latter have focused on the equipment used; in particular related to the provision of some form of backup air supply. This may be in the form of an additional regulator (octopus) attached to the same cylinder, for use by another diver or a second completely independent air source. More adventurous diving has also led to the requirement to carry other additional equipment items.

One of the potential disadvantages of the added equipment is the load they impose on the diver under swimming conditions. The additional drag incurred will inevitably increase the workload and hence consumption of air. The problem is particularly important when the diver must make headway against a natural current. The degree to which the additional energy consumption is an important effect is unknown but it is a function of the increase in drag and the relative swimming speed of the diver. Any increase in oxygen consumption inevitably reduces the time that the diver will be able to remain submerged but also increases the risk of decompression sickness.

The purpose of this paper is to identify the drag penalties for a number of simple SCUBA configurations. This is achieved through scale model experiments conducted in a wind tunnel. Some comments on the associated energy requirements are made, and from these the effect of on a diver's time submerged (bottom time) is briefly addressed. The configurations tested include a study of the effect of the equipment configuration and the effect of small changes to the diver incidence.

THE DIVING ENVIRONMENT

The conditions under which diving takes place can vary considerably; it includes fresh or seawater and a wide range of temperatures from around 4°C to temperatures in excess of 30°C. Consequently the fluid properties also vary considerably, but for the purposes of this study, it is clearly convenient to adopt some reference conditions. This is taken to be seawater

at 15°C. The average salinity of the oceans is around 3.5% making the density approximately 1026kg/m^3. The kinematic viscosity at this temperature is 1.246x10^{-3} Ns/m^2, Hoerner (1958).

The range of water speeds encountered by a diver can also vary considerably. In still water, it is simply a question of the swimming speed of the diver, which can be controlled to prevent fatigue. But, when there is a naturally occurring current the diver may be forced to work at a particular rate, and it is in these circumstances that the drag on the diver becomes potentially important. In commercial situations, it is generally agreed that the effective work of a diver ceases at a current of 1.8 to 2.0 knots (approx. 1m/s) IAUECA (1987). A similar value can be associated with a swimming diver, anecdotal evidence would suggest that a current of 2 knots would quickly bring about fatigue. This would suggest that for the purposes of this work the upper speed limit should be 2.0 knots or 1.0m/s.

EXPERIMENTAL DESIGN

The primary non-dimensional parameter of concern in low speed flows of the type under consideration here is the Reynolds Number (Re). This parameter represents the ratio of inertial to viscous forces in the flow. If the Reynolds number of the wind tunnel experiment matches that seen for a diver in water then the results will be directly applicable, as the flow fields will be similar. Reynolds number is defined as:

$$(\mathrm{Re}) = \frac{\rho U l}{\mu} = \frac{U l}{\upsilon}$$

Where U is the free-stream speed, and υ is the kinematic viscosity. The characteristic length (l) can be selected as convenient but in this case, the length of the diver including fins is employed. This avoids the complication of changing the reference length as the frontal area is modified with the changes in configuration. Therefore to match the real world and wind tunnel Reynolds numbers:

$$(\mathrm{Re}) = \frac{U_w l_{fs}}{\upsilon_w} = \frac{U_a l_m}{\upsilon_a}$$

Where the subscript *w* refers to water, *a* to air, *m* to model and *fs* to full scale.

In many cases, particularly when considering bodies with large scale flow separations the drag coefficient C_D is reasonably independent of Reynolds number once a critical value is exceeded. In the case of a complex shape, such as a SCUBA diver, where there are many external protuberances there is less chance of this overall independence, as different parts of the equipment will have different critical Reynolds Numbers. As the diver may be exposed to a range of flow speeds, it may be necessary to simulate a range of Reynolds Numbers to get a more complete picture of the loads that the diver will encounter.

The wind tunnel used for the measurements is a simple closed circuit design with an open working section. The working section dimensions are approximately 1.0m by 0.75m with a length of 2.0m. To avoid distortions to the flow-field the blockage must be limited to typically less than 5%, though smaller ratios are desirable. Blockage ratio is defined as:

$$Blockage\ Ratio = \frac{model\ \ frontal\ area}{tunnel\ cross\ sectional\ area} x100$$

The model dimensions can be determined by combining the factors above, along with the requirement that the scale must be sufficiently large for the details to be accurately manufactured. In this work, a one-third scale 50th percentile male figure is used. The main dimensions of the model and diving equipment are listed in Appendix 1. The Reynolds number data is shown in table 1, the reference length is 0.74m.

Sea Water			Air
Speed (knots)	**Speed (m/s)**	**Reynolds number**	**Speed (m/s)**
0.5	0.257	4.66×10^5	9.3
1.0	0.514	9.32×10^5	18.6
1.5	0.772	1.40×10^6	27.9
2.0	1.029	1.86×10^6	37.1

Table 1. Reynolds Number comparisons.

The maximum tunnel working speed is approximately 35m/s so in practice the highest equivalent swimming speed is of the order 1.9 knots.

The frontal area of the model when in the swimming position (prone) is 0.015m^2. This represents a blockage in this tunnel of only 2%. As the model incidence is increased, the blockage increases to a little under 5% at an incidence of 15°.

Diver configurations

With the huge range of designs of equipment now on the market it is clearly not possible to test every conceivable configuration. The tests have therefore been limited to three main configurations followed by tests of subsidiary equipment. The baseline diver consists of a single 12 litre cylinder fitted with a first stage regulator, plus a standard waistcoat style buoyancy control device (BCD) with air supply hose, contents gauge and hose, single regulator and hose, weight belt, mask and fins. Note that the cylinder capacity is quoted in terms of its water capacity as cylinders have various working pressures when charged with compressed air. This configuration is shown in Figure 1. Although there are many designs of BCD in regular use, the one selected for this work is a generic version of the type most commonly found.

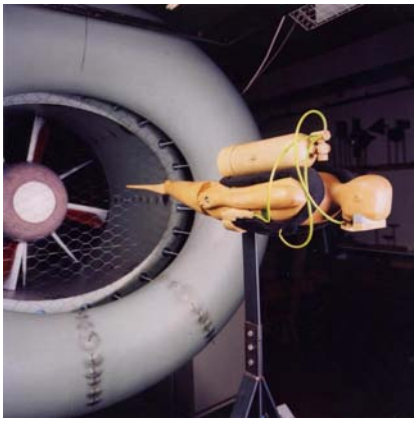


Figure 1 Baseline diver

The second and third configurations represent two alternative methods of improving safety.

Either a second (octopus) regulator is added which, in an emergency can be used by another diver. Or a second *pony* cylinder (water capacity 3 litres) with a separate contents gauge and regulator is added. Similarly this could be used by another diver in an emergency, but has the added advantage that it acts as a completely independent air source, and may therefore be used by the diver carrying it. This arrangement can be seen in Figure 2 and Figure 3. These figures also show the additional items of equipment; a large torch, reel for a surface marker buoy (SMB) and a knife. The additional items were tested as additions to the baseline configuration and in a number of combinations to determine interference effects.



Figure 2 Fully equipped diver - right view

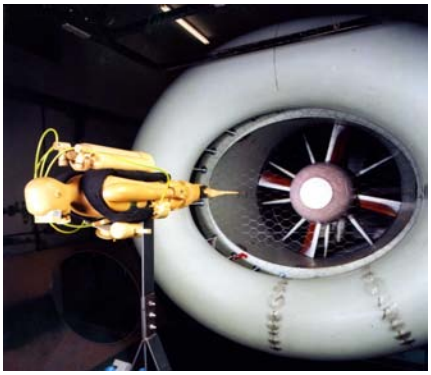


Figure 3 Fully equipped diver - left view.

The diver model is largely constructed from wood, with securing pins to attach the diving equipment. The Buoyancy Control Device was manufactured from a relatively fine weave material, and stuffed to take up the appropriate shape. Once the shape was achieved the BCD was attached to the diver using Velcro and given a coating of lacquer. As it is recognised that the routing of hoses will have a noticeably effect on the results obtained, all hoses were made from 5mm diameter PVC tubing over soft copper rods. This construction allowed the hoses to be bent into a representative position and tests reliably repeated. For the tests reported here the divers limbs were not articulated.

Experimental procedure

The model is mounted on a support sting attached to the under-floor balance and the tunnel run for a short period to stabilise the temperature. With the tunnel switched off a tare reading is taken and all transducers zeroed. Drag measurements are then recorded across the speed range of interest. The speed is taken from a pitot-static mounted at inlet to the working section and connected to a differential pressure transducer. While making measurements it is

unnecessary to match the speeds exactly as the data is subsequently used to calculate non-dimensional coefficients. All data were acquired using a PC based data acquisition system sampling at a rate of 100Hz for 60 seconds. The data is then averaged to eliminate the effects of any unsteadiness in the flow. The averaged values were stored for further analysis.

As the model is supported in the flow by a sting, the influence of this must be established and the data corrected to determine the diver-only drag. With the support mounted to the balance and the model mounted separately from above in order to generate the interference effect, the contribution of the support sting to the total drag reading can be determined. This method of correction allows for the direct contribution of the support and the interference effect of the model on the support but does not account for the interference effect of the support on the flow around the model. To minimise this latter effect the support is made from a thin section bar with rounded leading edge and tapered trailing edge.

The balance used was a three component virtual centre strain gauged balance, located under the working section. The balance is capable of providing lift, drag and pitching moment, though in this case the study is limited to drag.

The averaged drag data is converted to a drag coefficient (C_d) using the following definition.

$$C_d = \frac{D}{\frac{1}{2}\rho A U^2}$$

Where D is the drag force and ρ is the air density. The reference area (A) used is the projected frontal area and in this work it is recalculated for each configuration. This ensures that the drag coefficients can be compared to determine which is the most efficient shape, but when assessing the additional load on the diver the product C_dA, or *drag area* should be used. This is the standard approach when considering what are essentially different shape bodies. In each case, the reference area is calculated from the working drawings produced for the model manufacture.

RESULTS AND DISCUSSION

Reynolds number effects and overall accuracy

Before considering the effect of equipment changes on the drag of the diver the issue of Reynolds number sensitivity is addressed. This is important because if the tests are independent of Reynolds number we can reduce the experimental work to a single tunnel speed and compare the configurations through a single drag coefficient or drag area value. A test of the baseline configuration, across the full speed range of the tunnel, allows a plot of drag coefficient against Reynolds Number; Figure 4.

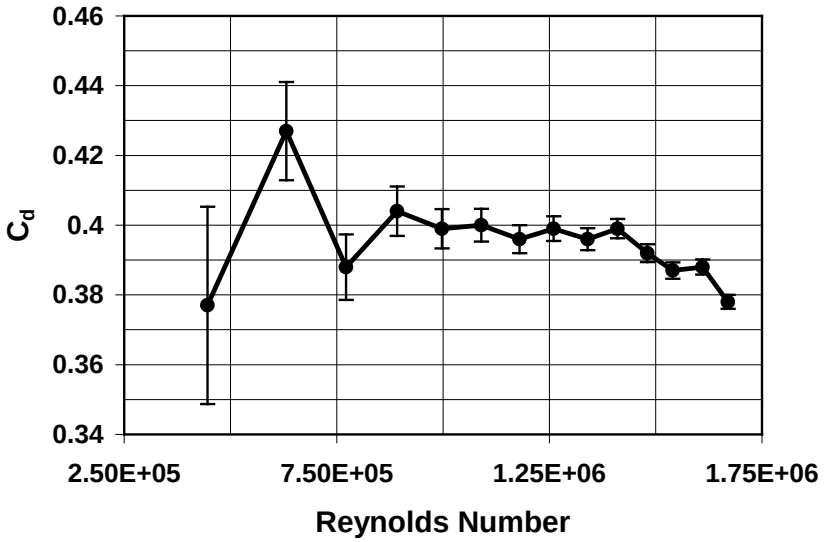


Figure 4 Baseline diver - Reynolds number run.

The variation exhibited arises from two sources. At the lowest Reynolds numbers tested the measured drag force is very small so the errors associated with the tunnel speed measurement and balance linearity and repeatability can result in a relatively large error in the drag coefficient. This is illustrated by the error bars given on the figure. However, where the uncertainty is greatest the drag on a real diver is small so it does not present the load problem seen at higher speeds. It is therefore concluded that the remainder of the tests should be restricted to Reynolds Number above 7.5×10^5. The second source of variation arises because the complex nature of the body under test ensures that different parts of the model pass through transition at different tunnel speeds, giving rise to coefficient changes across the range. This suggests that all configurations should be tested across the range rather than at a single tunnel speed.

Diver configurations and accessories

In Figure 5 the three main diving configurations are compared.

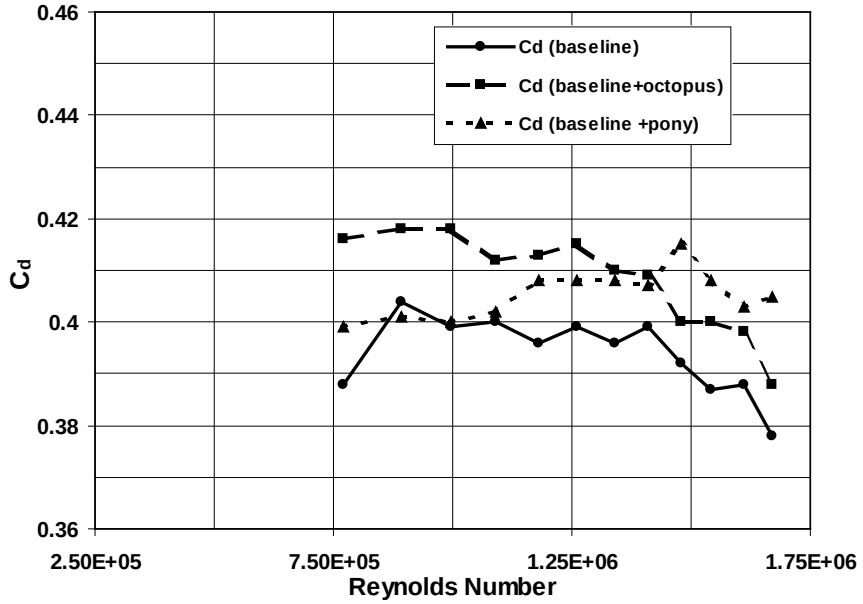


Figure 5 Main configurations against Reynolds number.

The addition of the octopus rig to the baseline increases the drag coefficient across the range tested, this is expected as the configuration involves the simple addition of an exposed hose and demand valve. The effect of this could be reduced if the hose was more carefully routed, but as an item of safety equipment, it must remain readily available. The potential for improvement by careful routing of hoses is covered briefly later in the paper. The addition of the pony cylinder produces an interesting result. In practical terms, it constitutes the addition of a spherically tipped cylinder into the region next to the main cylinder. The local Reynolds number based on freestream velocity and pony cylinder diameter ranges from 5×10^4 to 1.1×10^5. However, with the local flow accelerations likely in this region it falls into a critical Reynolds Number range. The influence of this is likely to be a slow rise in C_d possibly followed by a drop as transition to a turbulent boundary layer occurs, however this occurs as a contribution to the overall characteristic seen in the figure.

The data presented represents the efficiency of each of the configurations, but does not indicate the effect they have on the drag on the diver. The drag area is therefore plotted against water speed in Figure 6.

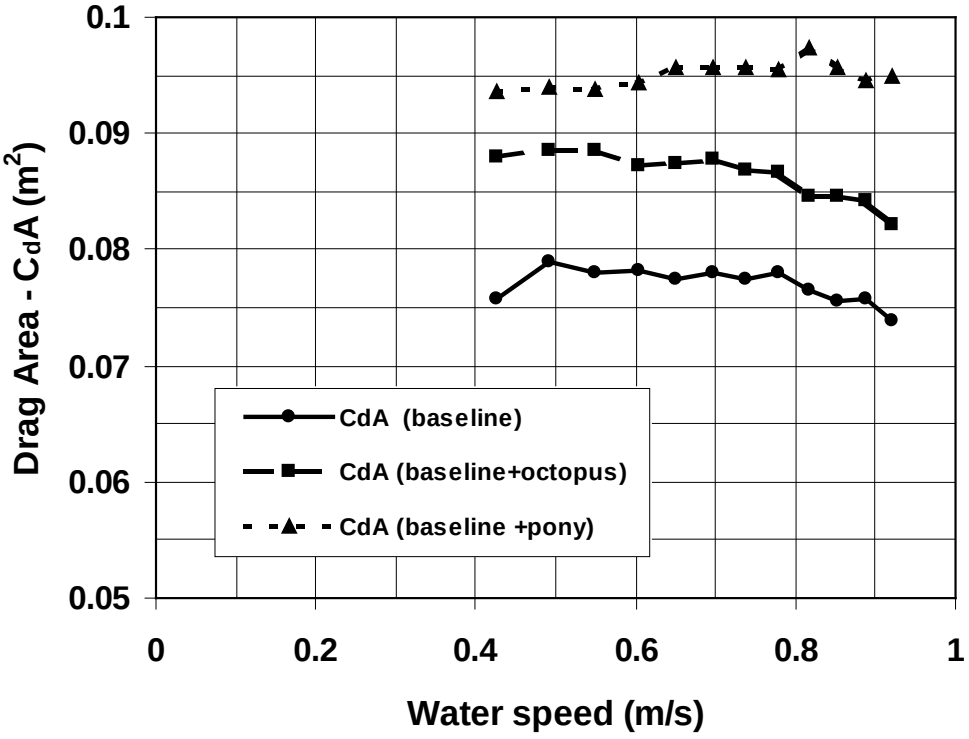


Figure 6 Drag area against water speed for main configurations.

This clearly illustrates the penalty associated with the additional equipment. The increased frontal area in the case of the pony cylinder counteracting the efficiency advantage it has over the octopus rig. The average increase, across the Reynolds number range tested, in drag area and therefore drag force, is 12% for the octopus rig and 24% for the pony rig over the baseline configuration. Assuming that in the interest of safety no divers would use the baseline configuration then the pony rig gives a 10% increase in drag compared to the octopus set-up.

The effect of extra equipment items is illustrated in Figure 7. Each item has been tested as an addition to the baseline diver. The knife is located on the outside of the lower leg, the torch

and SMB are attached to the chest area. These locations can be seen in Figure 2 and Figure 3.

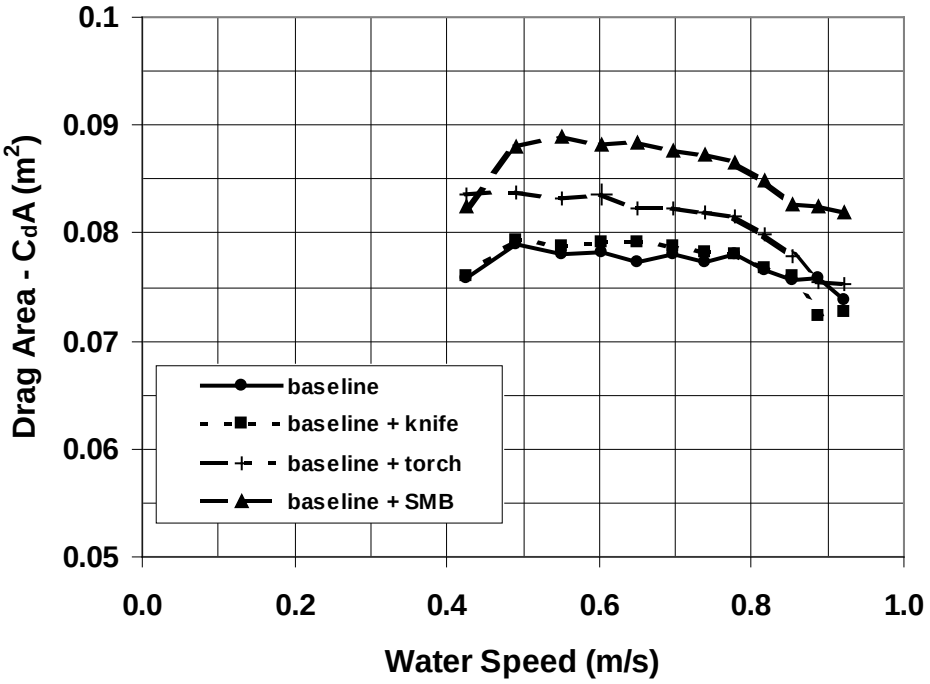


Figure 7 Drag area against water speed for auxiliary equipment.

The average increase over the range tested is 0% for the knife, 5% for the torch and 11.5% for the SMB. Finally, the items were tested in combination yielding the results shown in table 2. All configurations tested are summarised in this table.

Configuration	Average Cd	Frontal area (m^2)	Drag area (m^2)	Drag increase(%)
Baseline	0.394	0.195	0.0770	-
Octopus rig	0.408	0.212	0.0864	12.3
Pony rig	0.405	0.234	0.0951	23.5
Baseline + knife	0.395	0.195	0.0771	0.2
Baseline + torch	0.393	0.206	0.0809	5.1
Baseline + SMB	0.414	0.207	0.0858	11.5
Baseline + knife + torch	0.394	0.206	0.0812	5.5
Baseline + knife + SMB	0.404	0.207	0.0837	8.8
Baseline + torch + SMB	0.411	0.218	0.0896	16.4
Baseline + knife + torch + SMB	0.413	0.218	0.0898	16.8
Octopus rig + knife + torch + SMB	0.433	0.234	0.1015	31.8
Pony rig + knife + torch + SMB	0.433	0.260	0.1112	44.5

Table 2. Summary of Results

In the final configurations tested it is seen that the Octopus rig with all accessories adds an additional 32% drag and the pony rig with all accessories adds an additional 45%. Compared to the octopus set-up the fully equipped diver using a pony cylinder suffers a 29% increase in drag. The significance of this for the diver will be considered later.

Incidence effects

In the final programme of tunnel tests the incidence of the diver to the oncoming flow is considered, Figure 8. This is an attempt to simulate the usual requirement for the diver to swim in a slightly head up configuration though in this case, as there is no articulation in the model, the complete diver is inclined. In practice most divers swim head up at a slight incidence. Only the baseline diver is considered, and in line with usual practice the drag coefficient is calculated using the baseline diver frontal area. It is therefore unnecessary to consider the drag area.

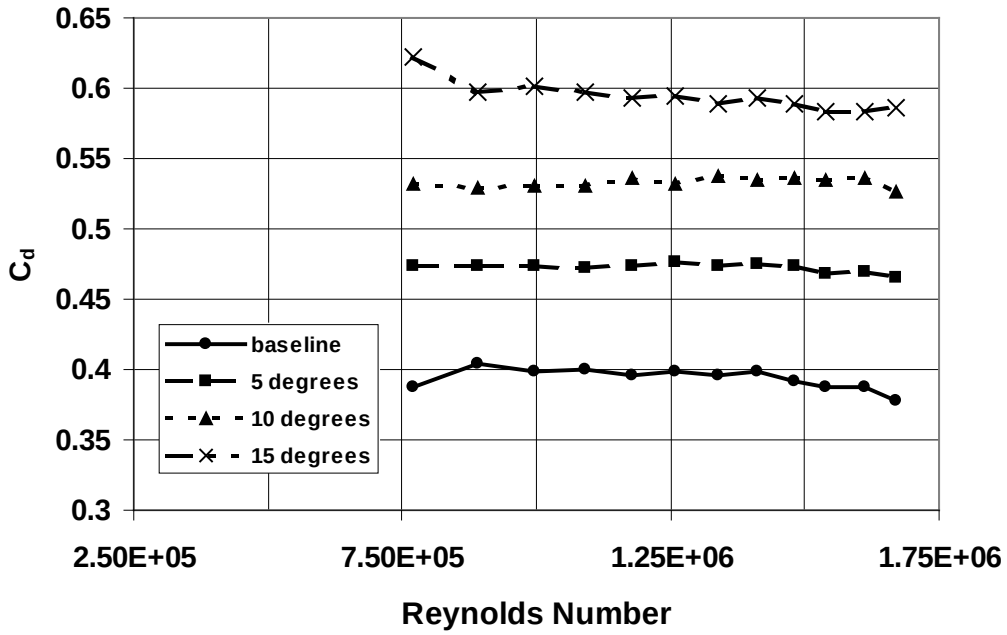


Figure 8 Effect of incidence.

Over the range tested the average effect of incidence is to increase the drag coefficient by 0.013/degree. This amounts to 16% at 5 degrees and 49% at 15 degrees.

A comparison of the results obtained with published material is difficult, as no study of this type has been previously undertaken to the knowledge of the authors. IAUECA (1987) provide approximate forces on an average diver in the horizontal position derived from water tow tests. The figures quoted are approximately 15% higher than those obtained for the fully equipped diver reported here. However, it is difficult to draw further conclusions, as IAUECA (1987) does not report the exact configuration of the diver tested. It is also important to note that Lyttle et al (1998) report that high degrees of accuracy can be difficult to achieve with the tow test. Lyttles work reports sophisticated tow tests on elite swimmers at a range of depths and speeds. At the deepest depth tested (0.6m), where the wave drag is minimised, the mean drag coefficient found is 0.33 (C_d values are not reported in the paper but have been calculated from the data given). This result refers to the Reynolds number range 2.4 x 10^6 to 4.7 x 10^6. Given this result a final test of the wind tunnel model was undertaken with all SCUBA equipment removed. This approximates to the configuration of the tow tests apart from the divers fins,

which were not removable. The C_d value determined at the highest Reynolds number possible (1.7×10^6) was 0.306. This gives some confidence in the results.

ENERGY REQUIREMENTS.

Although a detailed investigation of the energy requirements of the diver are beyond the scope of this paper, an estimate of the likely increment in energy input associated with the drag changes that have been measured would be useful. The real situation of a diver in water is clearly not directly comparable to the fixed attitude tested in the wind tunnel. In practice, there is a dynamic situation where the means of locomotion, the leg kick, generates vortex structures not seen in the passive case. However, this does not preclude some further analysis.

The oxygen required for the process of respiration is, in the case of a SCUBA diver, limited by the capacity of the compressed air cylinder used. The demand for oxygen depends on the Basal Metabolic Rate (BMR), the efficiency of the diver and the output work rate required. As the output work rate is the product of drag force times relative water speed any increase in speed or drag will increase the required oxygen input, and hence reduce the time that the diver may remain submerged.

BMR has been widely studied; it is subject dependent, being particularly dependent on body mass and fitness and is effected by temperature and pressure. Nadel (1974) shows that not only does the BMR increase with reducing temperature, but the oxygen consumption associated with activity can also increase. The work reported shows that the oxygen consumption of a breaststroke swimmer can increase by up to 60% for a drop in temperature from 33ºC to 18ºC.

The mechanical efficiency of a swimming diver has not been widely reported. Typical values for walking and running are around 20%, McArdle (1999), but Toussaint (1990) suggests that the efficiency of a swimmer is significantly lower than this because of the transfer of kinetic energy to the fluid medium. Toussaint's (1990) measurements on a group of elite swimmers performing front crawl yields efficiencies between 5 and 9.5%, with the higher efficiencies arising at the higher swimming speeds. Toussaint (1988) further suggests that dynamic measurements of the drag during swimming correlate well with passive measurements. It is concluded that the use of the passive drag forces, measured in the wind tunnel, will generate realistic power input and hence oxygen consumption figures if combined with an appropriate efficiency figure (η).

The power input in Watts is calculated as the drag power divided by the efficiency:

$$P_{in} = \frac{\rho A C_D U^3}{2\eta}$$

The oxygen consumption in litres/minute at the surface is the sum of the BMR and the oxygen required to generate the power:

$$O_2(consumption) = BMR + 0.002826 P_{in}$$

Where the constant 0.00286 is the conversion factor between Watts and litres per minute O_2 consumption.

If the breathing gas is compressed air containing 21% oxygen, then the total oxygen available to the diver is:

$$Available\,O_2 = Cylinder\ capacity\ \text{x}(working\ \ pressure - reserve)\text{x}0.21$$

As the ambient pressure increases with depth, at the rate of (approximately) one atmosphere for each 10 metres, the endurance time (E_t) in minutes of the diver at a depth h in metres is given by:

$$E_t = \frac{Available\,O_2}{(1+{}^{h}\!/_{10})O_2(consumption)}$$

In Figure 9 the bottom times (duration of dive) are estimated for the baseline and fully equipped diver at constant depths of 20 and 40 metres. The following assumptions have been made: A 12 litre capacity cylinder with a working pressure of 230 bar and reserve of 50 bar, a Basal Metabolic Rate of 0.37 litres/minute and an efficiency of 5%. The calculation does not account for the increased oxygen consumption associated with exercise at low temperatures, the increase in breathing resistance due to the apparatus and depth, or the increased stress experienced by divers when under high work loads. These factors are likely to reduce the bottom times significantly. The ability of the diver to maintain the required work rate is also not addressed.

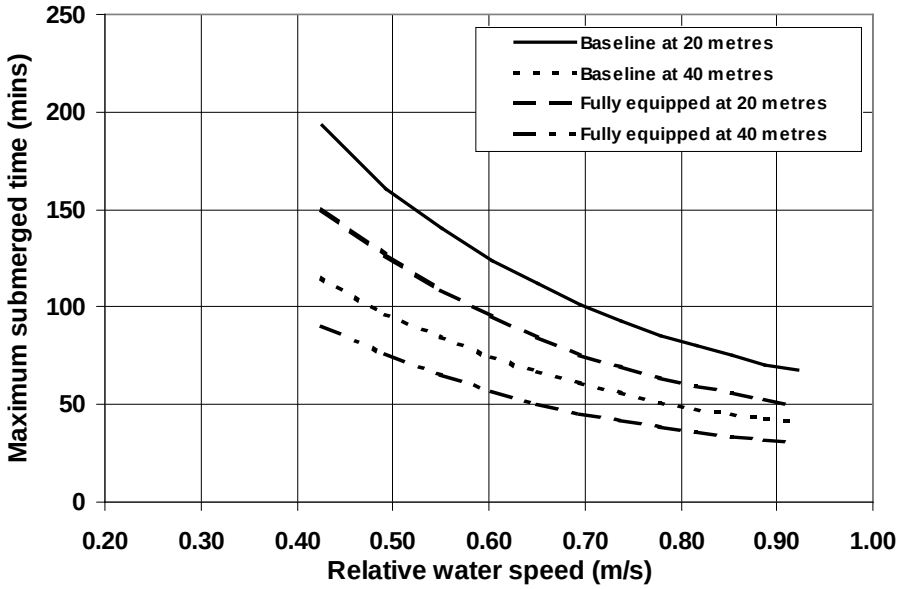


Figure 9 Bottom times for constant depth dives at varying water speeds.

The influence of the additional drag is seen clearly in the graph. The reductions in available dive time are, apart from the BMR, proportional to the increase in measured drag. At the higher speeds, the BMR accounts for approximately 15% of the total Oxygen consumption.

DRAG REDUCTION METHODS

The relatively simple calculations of endurance illustrate the dramatic effect the additional sources of drag can have. Although it has not formed a significant part of this study, it is therefore natural to suggest means by which the effects of the additional equipment may be ameliorated. The effect of the hoses was seen with the addition of the octopus rig to the baseline diver. This resulted in a 12.3% increase in drag. Therefore, this is clearly an area for potential improvement. For each of the three main configurations an alternative configuration

was tested where all the hoses were restrained closer to the body by taping them to the top of the shoulder. Such an arrangement is practical, as it is usual for BCD's to have a number of simple hose restraining points. For the Baseline diver shown in Figure 1 restraining the hoses reduced the drag area by 11%, for the Octopus configuration the drag area is reduced by 6% and for the pony by 8%. Further reductions would be achieved by removing some hoses entirely. For example remote air contents sensors are available which remove the requirement for the console and its connection hose. The further potential for drag reduction is a good area for further work.

CONCLUSIONS

- A wind tunnel model of a SCUBA diver has been tested in an open-section wind tunnel over a representative range of Reynolds numbers, and in a number of configurations.
- Some Reynolds number dependency is seen for all configurations of diver tested.
- Relative to the baseline diver described the addition of an octopus rig increases the drag by 12% and the addition of a pony rig by 24%. Assuming that for safety reasons no divers would use the baseline configuration then the pony rig gives a 10% increase in drag compared to the octopus set-up.
- When added in isolation the addition to the total drag of a diving knife, large torch and an SMB reel were 0%, 5% and 12% respectively.
- The fully equipped diver employing the pony cylinder and all the additional equipment items increased the drag by 45%.
- When tested in a head up configuration the average increase in the drag coefficient is 0.013/degree. This amounts to 16% at 5 degrees and 49% at 15 degrees.
- Some reduction in the drag penalties incurred can be achieved by ensuring that the connecting hoses are secured close to the body.
- The results obtained compare well with the published literature.
- Estimated bottom times have been presented. For a more accurate indication, further work on the efficiency of the swimming diver is required. However, as the BMR contributes a relatively small amount to the total oxygen requirement the drag increases are a good indication of the increase in overall oxygen consumption and hence bottom time.

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APPENDIX ONE - PRINCIPAL MODEL DIMENSIONS

Diver standing height - 0.58m (Representing a 50% percentile male, height 1.75m)
Shoulder width - 0.17m
Fin length - 0.165m (from heel to tip)
Model reference length - 0.74m (total length of model with fins extended as in figure 1
12 litre cylinder - diameter 0.060m - height 0.216m
Pony cylinder - diameter 0.034m height 0.170m