Engineering Notes

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Testing of Unpowered Advanced Underwater Vehicles at Very High Reynolds Numbers

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DRAG of well-designed, fully submerged underwater vehicles is, in accordance with d'Alembert's principle, primarily due to skin friction. The obvious desirability of reducing drag and boundary-layer noise has stimulated considerable interest in advanced vehicles employing some form of boundary-layer control to maintain laminar flow over a large part of the vehicle surface. Existing experimental facilities and test techniques are not satisfactory for scale model tests at Reynolds numbers of about 10^8 when facility induced transition from laminar to turbulent flow cannot be tolerated. This is in contrast to conventional models on which transition has to be artificially induced to approximate the prototype flow conditions.

Experiments in water tunnels generally cannot reach the required Reynolds numbers and pose the serious problems of tunnel wall boundary-layer noise as well as tunnel blockage which results in pressure gradients. While these effects are relatively minor on models of conventional turbulent flow vehicles, they can nullify the results of a laminar flow vehicle. When operating at 100 ft/s and length Reynolds numbers of 10^8, a tunnel flow rate of about 6000 ft^3/s would eliminate wall effects but the problems of noise and turbulence would still have to be considered. Thus the practicality of using water tunnels in these applications is somewhat doubtful. Tow tank testing of such models requires large, high power, expensive facilities and introduces the problem of possible premature transition caused by the vibration of the carriage. These problems have been avoided in buoyant vehicles which ascend to the surface propelled only by the buoyant forces. Unfortunately, the net buoyant forces are relatively low, and high Reynolds numbers can be achieved only when large, expensive models are used. Hydrodynamic studies using powered free-running vehicles incur high initial cost and also high operating expenses. Alternate approaches have to be sought because transition prediction techniques are not developed to the point where a commitment of large expenditures on development of vehicles without model tests can be justified.

The method suggested here is related to the buoyant vehicle scheme, but rather than depending on forces corresponding to specific gravity differences ranging from 1 to 0 (weightless, finite volume vehicle), weighted vehicles will be used. Now the forces correspond to differences between a specific gravity of 1 and up to about 20, which would approximate a model made of depleted uranium. Quick estimates of the performance of such models can be obtained when the specific gravity of water and the vehicle drag coefficient are assumed to be constant. The equation of motion is

$$V\rho_V \frac{du}{dt} = Vg(\rho_V - \rho_\infty) - \tfrac{1}{2}\rho_\infty u^2 C_D V^{2/3} \tag{1}$$

with V being the volume, u the velocity, C_D the volume drag coefficient, and where ρ_V, ρ_∞, the vehicle and ambient densities, respectively, can be integrated directly to yield

$$\phi = (1-e^{-s})^{1/2} = \tanh\theta \tag{2}$$

with

$$\phi = u/u_T \qquad \gamma = \rho_v/\rho_\infty \qquad \Delta = \rho_v V^{1/3}/C_D$$

$$s = x\rho_\infty/\Delta \quad \text{(distance)} \qquad \theta = t\left(\frac{\rho_\infty g}{\Delta}\,\frac{\gamma-1}{2\gamma}\right)^{1/2} \quad \text{(time)}$$

The terminal velocity u_T is given by

$$u_T = \left(\frac{2(\gamma-1)}{\gamma}\,\frac{\Delta g}{\rho_\infty}\right)^{1/2} \tag{3}$$

The parameter of principal interest here is the Reynolds number based on the terminal velocity and the vehicle length, $Re_\infty = u_T L/\nu$. For design purposes it is interesting to know the vehicle length in terms of the desired Reynolds number. The relation is

$$L = Re_\infty \frac{\Delta}{\rho_\infty} \Big/ Re^* \tag{4}$$

with

$$Re^* = \left(\frac{2(\gamma-1)}{\gamma}\,\frac{\Delta^3 g}{\rho_\infty^3 \nu_\infty^2}\right)^{1/2} \tag{5}$$

The present study is intended to be an indication of the feasibility of testing laminar flow vehicles using the gravitational force for propulsion. Obviously, the assumption of constant drag coefficients is an approximation so that the results presented here are estimates of the potential of utilization of the method in underwater vehicle testing. In order to illustrate the characteristics of the problem, calculations were performed for a range of drag coefficients and density ratios with water density and viscosity evaluated at 15°C. The Reynolds number at the terminal velocity is taken as the independent variable. Results are presented in dimensional form for easy assessment of the physical quantities involved.

Vehicle lengths and terminal velocities are shown in Fig. 1 for a wide range of drag coefficients and density ratios. The depth at which 99% of the terminal velocity is achieved is shown in Fig. 2. It should be noted in Fig. 3 that very high Reynolds numbers, on the order of 10^8, can be achieved with vehicles weighing only 120-150 kg (260-330 lb).

At this point, it is appropriate to remark briefly on some practical engineering aspects of the exploitation of the outlined concept. The terminal values of Reynolds numbers, depths, and speeds are convenient parameters which need not be reached since the sinking rates of the vehicles can be monitored by pitot-static or inertial instruments and transmitted to the surface by acoustic links, wires, or optical fibers. The latter two can unwind from spools inside the vehicle and thus will add no hydrodynamic drag. Vehicles with $C_D = 0.007$ and $\gamma = 10$ reach 99% of the terminal speeds at depths of about 1.6 km (1 ml), which corresponds to a pressure of about 160 atm. Such depths are easily found in the

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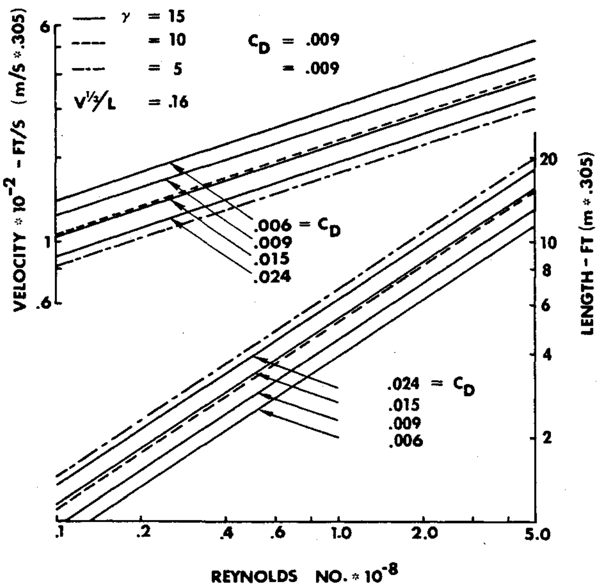

Fig. 1 Vehicle terminal velocities and lengths.

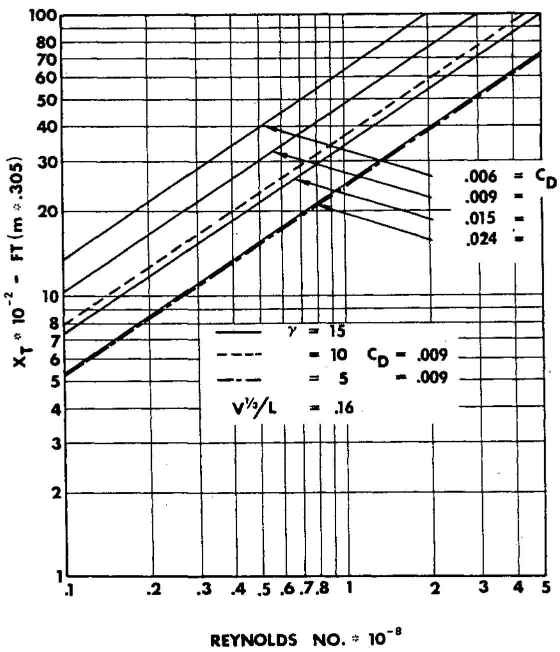

Fig. 2 Depth at which 99% of the terminal velocity is achieved.

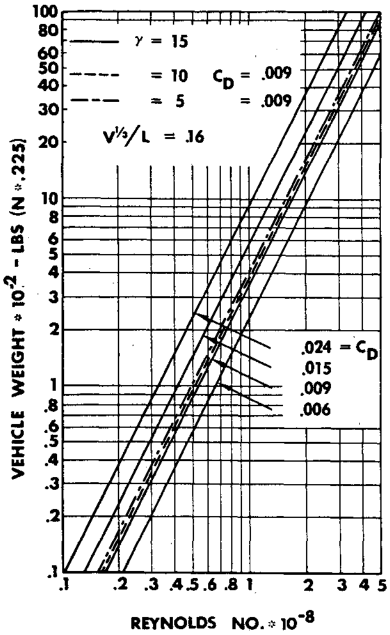

Fig. 3 Total vehicle weights.

oceans, but are not really needed since about 80% of the terminal speed is reached at dimensionless depth $s=1$ or about 275 m (900 ft). This is approximately within reach of the U.S. Navy DTNSRDC Lake Pend Oreille, Idaho facility, which is used for buoyant ascent tests from depths of 800 ft (244 m). When feasible, dropping such vehicles from heights of 30-40 m (100-130 ft) would reduce the depth requirements for 80% of the terminal speed by a factor of 2. Structural requirements are readily estimated from the relation for the collapse pressure W_c, cylinders of diameter D, thickness a, and elastic modulus E, which Ref. 1 gives as

$$W_c = KE(a/D)^3 \tag{6}$$

The coefficient K is a function of the length-to-radius ratio and is presented by Ref. 1 in graphical form. For an aluminum cylinder $E=700{,}000$ atm, $K=3$ for length-to-radius ratios greater than 16. Taking $a/D=0.05$, the collapse pressure is calculated to be 260 atm. With some internal stiffening and meridional curvature even thinner shells could be used safely. The vehicles could be abandoned, or recovered, by several means. For example, at a preset depth, the internal ballast could be ejected or a ballast section could be separated by explosive bolts. The part of the vehicle containing instruments, or even onboard recording equipment, would then be recovered at the surface.

The vehicle weight and size requirements appear to be quite reasonable. Test facilities, particularly with an air drop, can be easily found, and recovery of parts of the vehicle does not present any major problems. The concept could be used for hydrodynamic research, or as a very high speed delivery system.

Reference

[1]Baumeister, T., Avallone, E. A., and Baumeister III, T., eds., *Marks' Standard Handbook for Mechanical Engineers,* 8th ed., McGraw-Hill Book Company, New York, pp. 5-50.

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Portable Servoactuator Test System

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Nomenclature

A = piston area
B = load viscous damping
F_L = load force
I = servovalve current
K = load, spring (if any)

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