Foreword

The scientific and engineering principles that underlie chemical engineering can also be used to understand a wide variety of other phenomena, including in areas not thought of as being central to our profession. As such applications might be of interest to our readers, we will consider brief submissions for publication in this category as R&D notes. These submissions will undergo review, and novelty will be an important factor in reaching an editorial decision.

The first such article, "Will Humans Swim Faster or Slower in Syrup?" by Brian Gettelfinger and associate editor Ed Cussler, appears in this issue.

Stanley I. Sandler
Editor

FLUID MECHANICS AND TRANSPORT PHENOMENA

R&D NOTE

Will Humans Swim Faster or Slower in Syrup?

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When one of us was training for the 100 m butterfly in the U.S. Olympic Trials, we began to discuss fluid mechanics of swimming. We noted that swimmers go faster in salt water than in fresh water because they are more buoyant. We argued about how drag could be minimized coming off a turn. Most of all, we wondered whether swimmers would go faster or slower if the viscosity of the fluid was increased.

We discussed this with our colleagues, but found no consensus. Most, including some who were experts in fluid mechanics, felt that the swimmers would go more slowly. Some said the swimmers would go faster, because of increased drag on the hands. A few suggested that there would be no change.

We decided to measure swimming as a function of viscosity. The experimental details are as follows: We chose to thicken water with guar gum because it is readily available in a food grade and causes few allergic reactions. Xanthan was not as available to us; and corn syrup, offered as a donation, must be added at such high concentrations that it would strain the municipal sewage system. We slowly poured 310 kg of guar (Aqualon Supercol, Hercules Chemical, Wilmington, DE) into a 0.15 m^3 garbage can stirred with 1 kW motor through which pool water was pumped at a rate of about 0.01 m^3/s. The resulting dispersion flowed into a 650 m^3 swimming pool, where it was stirred for 36 h with three submersible pumps, each moving at least 0.05 m^3/s. After this mixing, the viscosity of the aqueous guar solution was $(1.92 \pm 0.05)\ 10^{-3}$ Pa s, or about twice that of water. This viscosity did not vary over 16 different positions in the pool. Because the viscosity at this dilute concentration (0.05%) is Newtonian, it gave the same readings in several capillary viscometers and with different spindles of a Brookfield viscometer. The density of these guar solutions was within 10^{-4} g/cm^3 of that of water, so buoyancy changes were insignificant.

We asked 10 competitive swimmers and six recreational swimmers to swim one 25 yard length in a 1,000 m^3 water-filled pool, two 25 yard lengths in the 650 m^3 guar-dosed pool, and (after a shower) one 25 yard length in the water-filled pool. The swimmers rested 3 min between each length. Some competitive swimmers swam several sets, sometimes with different strokes. We recorded each swimmer's lap times, gliding time off the wall, and number of strokes. We recognize that the pools have different shapes, and that smaller, shallower pools are often felt to retard swimming. We tried to minimize these

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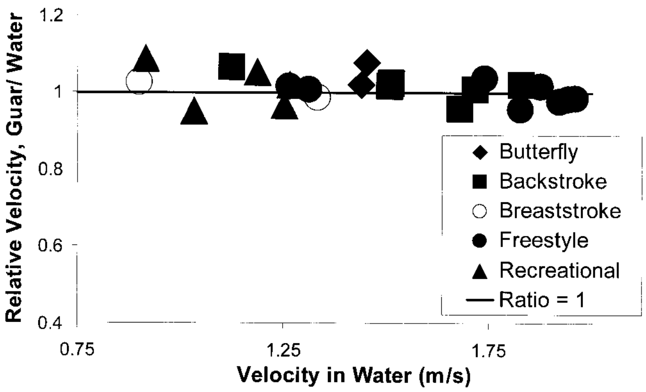

Figure 1. Swimming speed in guar solution is the same as in water.

effects by having only one swimmer at a time in a fairly quiet pool, swimming in a lane next to the wall.

The results, summarized in Figure 1, show that swimming in guar does not change swimming speed. This figure plots the swimmer's speed in water on the abscissa, where the recreational swimmers are slower than the competitive swimmers. It plots the speed in guar divided by the speed in water on the ordinate. The standard deviation between lengths for the recreational swimmers is 3.2%, but that for the competitive swimmers is 2.4%, the same as that recorded by their coaches in normal workouts. The smaller deviation of the competitors is probably a reflection of their superior skill and physical condition.

The results in Figure 1 seem to us consistent with the expectation that form drag is the key to human swimming. This is different than the swimming of microorganisms, which are so small that the flow is laminar. It is different than the swimming of fish, which is explained by assuming the fish are two-dimensional (2-D) vortex generators without frontal area. Flow in human swimming is turbulent. To make this argument more quantitative, imagine a swimmer going 2 m/s who is 1.8 m tall with a frontal area of 0.1 m^2 and a wetted area of 2 m^2. The flow around this swimmer is described by a Reynolds number, defined as (dv/ν), where d is a characteristic length, v is a velocity, and ν is the kinematic viscosity of the fluid (White, 1999; Schlichting and Gersten, 2000). We expect that the characteristic length is roughly the square root of a swimmer's frontal area. Thus, the Reynolds number in water based on this area is

$$\frac{dv}{\nu} = \frac{(0.1m^2)^{1/2} 2m/\text{sec}}{10^{-6} m^2/\text{sec}} = 600{,}000$$

Such a Reynolds number is highly turbulent, so that the drag coefficient is nearly constant, and the force which the swimmer exerts is in fact proportional to the velocity squared. By similar arguments, we can show that the viscous drag around the swimmer is less than 10% of the form drag. Viscous forces are significant in the laminar boundary layer which forms near the swimmer's head, but lasts only about 0.1 m (Schlichting and Gersten, 2000).

The results above are striking because the experiment cannot be as completely defined as most academic studies of fluid mechanics. For example, the swimmers are not all the same size or shape. Their angle in the water is not the same, and their metabolic rate may be different. In addition, the assumption that drag is independent of viscosity along long, smooth surfaces is an approximation. The swimmer's body may be moving steadily, but his hands almost certainly are not. Each of these differences could cause the swimming speed to change in some uncertain way. The fact that the speeds are so nearly constant is evidence that the simple argument above is approximately correct.

The evidence that turbulent flow is key raises two other questions which merit discussion. First, what change in viscosity would be required to have an effect? Second, are the results consistent with what swimming coaches believe?

Fluid mechanics predicts that, to have an effect, the viscosity must increase at least 1,000 times. Such an increase would reduce the Reynolds number enough to give a viscosity dependent drag coefficient. Of course, the increased drag caused by the frontal area of the body would be at least partially balanced by the increased drag on the hands and forearms (Toussaint et al., 2000; Voronstsov and Rumyantsev, 2000). We are not sure which increase would be greater. At the same time, large decreases in viscosity could conceivably allow a swimmer to go faster. These decreases could potentially promote boundary layer separation on the body, reducing its drag; but retain the unseparated boundary layers on the hands and forearms. Tight, ridged swimming suits attempt to exploit this effect (Toussaint et al., 2002; Benjanuvatra et al., 2002), which is also important to sharks, America's Cup ocean racers, and golf balls (Bechert et al., 2000; Childress, 1981).

Finally, these results are consistent with at least one empirical observation by swimming coaches. This observation, suggested by J. E. Counsilman (1968), is the "theoretical square law, " which states that "the resistance [to a swimmer's motion] varies with the square of his velocity." This dependence of resistance on the square of velocity, and not on the first power of velocity, is characteristic of highly turbulent flow. Our experiment supports Counsilman's axiom. Coaches have made good judgments about fluid mechanics.

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