Effects of fluid stratification on swimming, rowing and paddling

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Abstract

The impact of a fluid's density stratification on the ability to swim, row or paddle is investigated. Experimental results show that stratification may hamper the ability to push against water, thus decreasing propulsion, i.e. the reaction force on swimmer or boat. Possible reasons are that hand or paddle motion is 'wasted' by creating internal gravity waves and by turbulent mixing instead of providing thrust.

1 Introduction

In the absence of strong wind, tidal mixing or wave breaking, open water can be stratified in density along the vertical due to variations in temperature and salinity (salt content). Variations in temperature are usually due to solar insolation while in estuaries and at sea variations in salinity occur due to river run-off. The question we want to address is whether a fluid's stratification has an impact on the ability to swim, row or paddle? While other hydrodynamic conditions, such as currents, and surface gravity waves often play a role in the propulsion efficiency, the impact of stratification is not widely studied. We speculate that it may not only be relevant to competitive swimming, rowing and paddling, but might also be a key factor that could potentially at times make recreational swimming hazardous.

The reason to look into the possible effect of stratification is because it is well-known that stratification may seriously hamper the motion of ships that are propelled by wind or engine. This effect, known as 'dead-water', has been discovered by Fritdjof Nansen [1], and was subsequently analysed and explained by Ekman [2]. Section 2 describes the phenomenon and discovery of dead-water; section 3 investigates whether dead-water may also affect swimming and section 4 discusses experiments on paddling.

2 Dead-water

The sudden slow-down of a ship in stratified water is referred to as the ship encountering 'dead-water'. The first likely mention of dead-water dates back as far as the work of historian Pliny the Younger, who attributed slow-down of ships to *Remora* (sucking fish) [2]. According to Pliny, such anomalous slow-down may have caused the defeat of the fleet of Mark Antony and Cleopatra, at the Battle of Actium (31BC). During his epic voyage in search of the North Pole, Fridtjof Nansen repeatedly observed the sudden slowdown of his sailing ship, the Fram, due to an encounter with dead-water [1]. On returning, he reported the Fram's occasional loss of speed (up to a factor five) to Vilhelm Bjerknes, the towering meteorologist of those days. Bjerknes hypothesized that the ship was sailing on a stratified sea and, on the interface between salt Atlantic and fresh melt water, was generating *subsurface* waves. These interfacial gravity waves are restored by a reduced gravity, $g' = g\Delta\rho/\rho$, which is the acceleration of gravity, g, multiplying the density difference across the interface, $\Delta\rho$, divided by the average density, ρ. Bjerknes stimulated his student, Vagn Walfrid Ekman, to study this hypothesis in more detail. In a lengthy study Ekman subsequently confirmed the hypothesis: in stratified water, when a ship moves with its keel near the interface at the same speed as the interfacial gravity waves, moving at velocity $c' = \sqrt{g'h_1h_2/(h_1+h_2)}$, it will experience more resistance [2]. Here $h_{1,2}$ denote the upper and lower layer thicknesses. Energy intended for propulsion is thus lost by generating interfacial gravity waves [2, 3, 4]. But these interfacial waves, while similar to surface gravity waves, are (nearly) invisible at the surface, except for lending the water over an extensive region behind the ship a glassy, tranquil look. This made the water appear 'dead'.

Figure 1: Fire brigade filling cold (17°C) swimming pool with warm (28°C) water from adjacent pool. After filling the floating 'blanket' is removed, leaving a sharp interface at a depth up to 40 cm.

3 Do swimmers suffer from dead-water? A swimming pool experiment

Following anecdotal evidence from local Dutch newspapers reporting on a swimming accident, it was speculated that dead-water could perhaps also explain enigmatic drowning [5]. Remarkably, (near) drowning sometimes occurs in lakes under good environmental circumstances (i.e. during warm, sunny and calm, windless days). Moreover it sometimes concerns able, healthy swimmers. According to some of the survivors, near-drowning resulted not from hypothermia but rather from excessive exhaustion.

Although the incidence of drowning is reasonably well studied (see e.g. [6, 7]), its relation to the water's stratification (water quality) is currently lacking (personal communication: *Maatschappij tot Redding van Drenkelingen*, Dutch Society for saving drowning victims). Therefore the possible effect of stratification on swimming was experimentally investigated in a swimming pool [5]. Two stratifications with temperature jumps of about 10 degrees were considered, both of upper-layer depth, h_1, less than 40 cm, see Fig. 2. The purpose was to establish the possible role of a swimmer as 'displacement vessel'. However, no retardation was found. Swimming (at a typical speed of 1.5 m/s) appeared to be much faster than interfacial wave propagation (0.15 m/s), apparently explaining a lack of coupling.

Figure 2 : Swimming in stratified pool.

3.1 A curious phenomenon and an experiment with deeper upper layer

It was subsequently speculated that a retarding effect might perhaps result when the upper layer depth approaches the arm length of a swimmer (70 cm, say), as it might be caused by *hand* rather than body motion. The reason to do so is twofold. Fistly, the presence of an interface near the location where the hand moves backward, allows the pressure difference set up across the hand to relax instantaneously. The interface can simply be displaced upward (downward) behind (in front of) the hand. This contrasts with the response to motion of a hand in a homogeneous fluid, where the cross-hand pressure difference, governed by an elliptic Laplace equation, is unable to escape. It drives a flow, but its establishment, being due to a viscous process, needs more time.

Secondly, hand motion is the acknowledged mechanism by means of which most swimmers (mainly) propel themselves [8]. Moreover, in contrast to the swimmer's body, in an absolute frame of reference the hand speed does necessarily change from positive (into swimming direction) to negative. Therefore, during part of a swimming cycle, it approaches the interfacial wave speed at which coupling to interfacial waves might occur.

While contemplating these issues, the author was on holiday with his family at the gently sloping beach of a pocket bay in the Bay of Douarnene, south of Brest (France). As that vacation in 2006 was during the heat wave that struck Europe, the water was noticeably stratified in temperature as soon as water depth exceeded approximately 1 m. This offered the possibility to compare front-crawl swimming in homogeneous and stratified conditions. Picking a water depth at which the temperature transition occurred at arm-depth (approximately 70 cm), remarkably, there was a strange sensation during swimming, independently confirmed by the author's son. While making a single front-crawl stroke in the stratified fluid, the fingers of the hand started vibrating laterally. Surprisingly, the water does not 'see' the hand as a single paddle, but, rather as an arrangement of parallel cylinders. While moving the hand, water was pressed *through* rather than around the hand (i.e. it was squeezed in between the fingers). In stratified conditions this apparently occurred at a speed *above* the threshold beyond which von K´arm´an vortices are shed, but in homogeneous water no lateral vibration was felt, the water apparently moving around the fingers symmetrically, suggesting the speed of the hand was then *below* that threshold. This threshold occurs approximately at Reynolds numbers, $Re = Ud/\nu > 49$, see [9]. For finger diameter $d = 1.6$ cm and viscosity $\nu = 10^{-6}$ m^2/s, this suggest vortex shedding occurs behind a moving finger above a surprisingly small hand speed $U > 3$ mm/s. One can actually find this threshold and sense this instability in homogeneous water too, namely by comparing a stroke while standing fixed on the floor of the water basin to one while swimming. The absence of the lateral finger vibration during swimming in homogeneous water suggests that during the push phase, the backward directed hand speed is nearly identical to the forward-directed body speed, such as to find nearly the 'ideal' of a fixed point within the fluid.

To investigate the possible consequence of this further, a second, smaller-scale, salt-stratified swimming experiment was performed [10]. Indeed, with a deeper upperlayer, the swimming velocity was significantly reduced (by 15%), comparing swimming over a 5 m stretch in stratified and homogeneous water. The exact way and extent over which this coupling works was however not clearly discerned.

4 Swimming, rowing and paddling

Swimming of humans should distinguish the behaviour of the body from that of its appendages (hands and legs). These two form, however, a coupled system; the appendages and body serving different purposes [11]. A similar statement can be made with regards to rowing and paddling. For optimal forward speed, body or boat need to minimize form, frictional and wave drag. But, in order to optimize thrust (propulsive force), the hand, oar or paddle actually needs to *maximize* that drag. For this reason, in the pull-phase, the paddle (as we will now collectively call hand, oar and paddle) is oriented perpendicular to the propulsion direction, not parallel, giving a paddle 'grip' on the water. The debate whether thrust is generated by lift or by drag forces is not finished [12]. Probably both will contribute. Lift appears most effective during (small angle of attack) insweep and outsweep, when the paddle velocity is positive relative to the water. Drag must be effective during pull (in the intermediate phase), when the paddle is near its lowest, vertical position, moving backwards horizontally and having a negative velocity relative to the water. Note that this paddle-based drag interpretation of propulsion does provide a rationale for understanding retarding effects due to stratification, even when propulsion speed itself is supercritical. Such a rationale is lacking when boat and paddle are perceived as a single object, moving at 'supercritical' speed, i.e. faster than the interfacial gravity wave.

To support this interpretation, we discuss two paddlewheel carriage experiments, comparing propulsion in homogeneous to that in stratified water. A dramatic reduction of propulsion speed occurred in the stratified case (see movie on Dead-water at www.nioz.nl/maas). Swimming occurs by pushing fluid backwards in order to generate a forward reaction-force on the body (thrust). This requires vortex shedding that takes backward directed momentum with it [13]. Unsteady hand motion may play a decisive role as it helps thinning the boundary layer around the hand, promoting vortex shedding. Also, it creates an along-arm pressure difference, leading to pumped-up propulsion [14]. However, in stratified fluids, vortex shedding and the creation of drag may be interrupted, especially near an interface.

Fluid may become trapped to the hand, resulting in a dipolar displacement of fluid: at the palm side of the backward moving hand excess pressure pushes lighter fluid down wards, while at the back of the hand, heavy fluid is sucked upwards. This dipole need not be shed away at all, but in contrast, might stick to the hand.

4.1 Effect of single stroke

For this reason, another experiment was performed in which the body, the 'displacement vessel', was actually taken out of the water [10]. The swimmer was put on a carriage above a pool that was either filled with homogeneous or stratified fluid (Fig. 3). The carriage could ride along the two sides of the pool. The carriage plus swimmer was given an initial velocity, by means of a rope, pulley and weight system. The rolling motion at the start emulated regular swimming. While rolling, the 'swimmer' performed a single stroke in the water, in front of a camera. The gain in kinetic energy ΔE of the carriage plus swimmer was monitored. Since also the pressure difference across the hand was measured, this gain could be related to the effort (the work done, W). Figure 4, shows the results for two swimmers, one recreational (left) and one competitive (right) swimmer. It shows that multiple experiments were performed by both swimmers, differing from each other by the exact amount of work performed during each stroke. When we just compare the effect of the fluid's state, i.e. compare strokes in homogeneous (x) versus those in stratified (o) water, it is clear that the gain in kinetic energy is much reduced in the stratified fluid. It suggests that during outsweep, dense lower-layer fluid appears to be dragged upwards, against gravity [10].

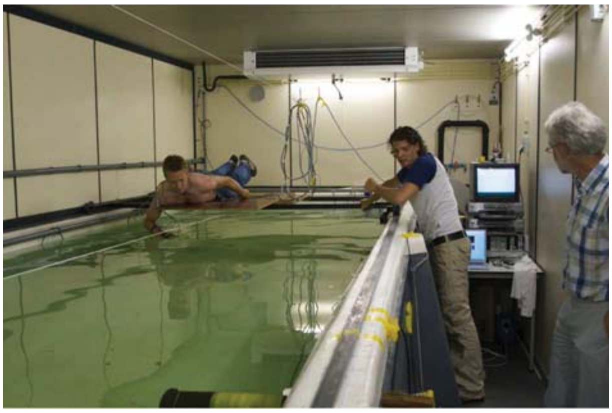

Figure 3: 'Swimmer' on moving carriage, performing single stroke in homogeneous or stratified water. The camera is visible near the bottom of the image (black).

In fact, looking at one particular experiment, shows a surprising feature in the

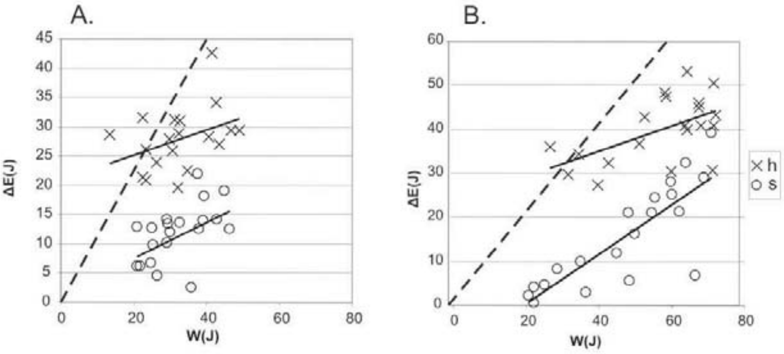

Figure 4: Gain in kinetic energy ΔE versus work W performed by (a) recreational and (b) competitive swimmer in homogeneous (x) and stratified (o) water (from [10]).

latter case. Fig. 5, displays carriage versus horizontal hand velocity (both monitored by video) in homogeneous (solid) and stratified (dashed) circumstances. Hand and carriage motion start in the lower right hand corner of this figure; during the in-sweep the hand speed is still into the (positive) 'swimming' direction. But, as time progresses one moves left and upwards along these curves. When the out-sweep starts (i.e. when the hand decelerates), in homogeneous water the carriage continues to accelerate (solid line) while in stratified water it *decelerates* abruptly (dashed line). This anomalous retardation of the carriage in stratified circumstances must be due to the hand displacing heavy fluid, sticking to the hand, against gravity when moving upwards during out-sweep. This appears to invoke a reaction force (torque), pivoting around some place on the arm, that seems responsible for pulling the carriage backwards. Were it not for the support of the carriage by the tanks sides, this would, in fact, also pull it downwards. Replacing the carriage in this experiment by a swimmer, lacking such a support, it transpires that this may be one of the decisive factors making an encounter with dead water potentially hazardous, see [15].

4.2 Paddle wheel experiment

To study this effect further, a similar experiment was carried out in a 2 m long glass container, but now using a LEGO paddle wheel carriage, shown in Fig. 6. The carriage was started from rest and was pulling itself forward. This carriage was powered with a LEGO power supply that was kept fixed during comparison of the experiment in homogeneous versus that in stratified water. In the stratified case, green food color was added to the fresh top layer, which was subsequently put on top of a salty lower layer. The upper layer was 2 cm thick, which was the depth to which each of the four

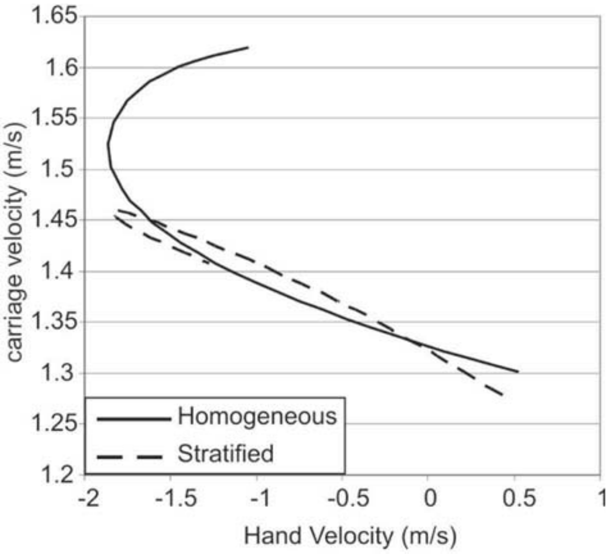

Figure 5: Carriage versus hand velocity during single stroke in homogeneous or stratified water, from [10].

paddles extended.

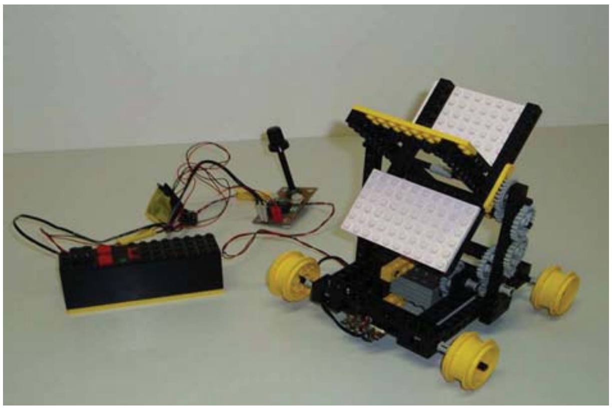

Figure 6: LEGO paddle wheel carriage, used to ride in its inverted position on top of a tank.

In the homogeneous fluid, the carriage was immediately pulling itself forward, but in the stratified fluid it took a while before it started moving, see Fig. 7. (It started to move really at the end of the timespan shown in this figure). In the stratified fluid, before the carriage is able to propel itself forward, fluid is first displaced and mixed, until the paddle is able to 'grab' into the lower layer and then propel itself forward.

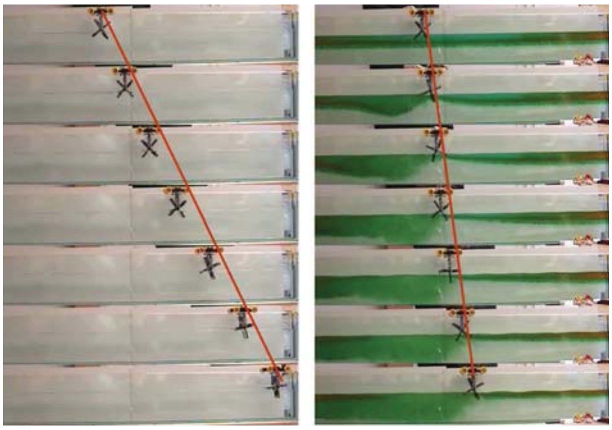

Figure 7: Paddle wheel carriage, starting from rest in the center of a 2 m long basin that is filled with homogeneous (left) or stratified water (right). Shown is the right 1.2 m. The red lines approximately connect the carriage's center. Their difference in inclination indicates that stratification seriously inhibits motion of the paddle wheel carriage in stratified conditions.

5 Conclusions

We have shown that stratification may not only seriously inhibit propulsion of boats (the 'dead-water' effect), but also when propulsion is produced by paddling (such as in swimming, rowing or paddling). The effect has been demonstrated in a number of experimental conditions, all using salt stratification (in general leading to stronger density stratification than occurs due to temperature, given the typical range of temperature differences found in open water). The effect appears to be strong when the paddle stroke is executed in the vicinity of an interface, separating layers of different density. Work is going not only in generating interfacial waves, but also in mixing the fluid. This may lead to reduced thrust and excessive fatigue. Efforts to capture this effect numerically have sofar been unsuccessful [16]. More effort is needed to reproduce the drop in swimming and paddling performance and to probe its full consequences for open water swimming, rowing and paddling.

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