Since the early 1980s, there has been an exponential growth in the quantity of seafood produced by aquaculture and, in the near future, this production will account for half the world’s global harvest of fish. With ever-growing demand, fish farms are trying to expand. Countering this expansion is growing concern, globally, on the potential environmental impact of larger aquaculture farms. As a result, many governments are becoming reticent to grant new concessions to aquaculture developments in coastal waters. Consequently commercial producers of marine finfish have been seeking alternative locations to coastal bays, fjords or other areas to locate larger net-pen farms. Moving further offshore appears to be the logical alternative, making farms invisible from the coast, reducing their ecological and environmental impact on coastal marine life and also enabling the installation of wider and deeper pens.

Inevitably this expansion raises a number of new requirements: increased operating costs, on-site maintenance personnel, energy use and net-pen design. Existing pens may be unsuitable for the harsher conditions found in the open ocean, where mooring lines must resist large fluctuating forces and high induced drag generated by waves and currents. Exploiting wave action to provide autonomous wave-powered energy system for aquaculture farms is being explored currently (Meggitt 2014). Failure of mooring lines caused by overloading often leads to net loss, resulting in ‘ghost nets’ that can pose a threat to marine life and a navigation hazard. Furthermore, an increase in climatic variability seems likely to lead to an increase in ocean wave states.

Considering future changes in environmental conditions, the compounding problems of increasing pen size and the lack of natural shelter in the open ocean, new farms must increase their capabilities to withstand degradation and major mechanical fatigue. The interaction of the net with water flow from waves and currents govern the resulting forces. This is an area where efforts can be made toward optimizing the net structure (mesh/twine composition or ‘weave’) and the relative location of a pen within a concession.

In addition to the mechanical action of water flow, there is the associated problem of bio-fouling, which can serve to reduce net porosity by over 50 percent, with direct consequences for fish health through a reduction in the rate of oxygen supply. Another major impact of biofouling is the resulting drastic increase of drag forces on the structure, increasing tension in mooring lines or towing cables.

These combined factors have motivated a deeper study of aquaculture net drag and how it may be minimized. The considerations presented here must be taken together with certain practical issues such as the constraint of the mesh void size in relation to fish size and the need of the twine thickness of the mesh to support mechanical stress.

**Technical Aspects**

Within the Faculty of Engineering at the University of Auckland, we are undertaking a study of the impact of net density on flow dynamics and drag, where variations in the mesh void (i.e. the space between two consecutive twines) and twine thickness are being investigated. To better quantify the effects of design changes, a small-scale experimental investigation was conducted within our Fluid Mechanics Laboratory, where changes can be evaluated under well-defined and controlled flow conditions.

Experimental data were acquired using a recirculating flume with a measured turbulence intensity of less than 3 percent. The flume cross-sectional area is 0.4 m by 0.4 m, with a length of 4 m and an operational flow rate between 2 and 50 cm/s. Under these controlled conditions, it has been possible to obtain detailed measurements of the flow dynamics for a range of models with varying mesh and twine dimensions.

Rather than studying a section of a net, we manufactured...
small-scale models mimicking a simplified aquaculture net pen. The models were manufactured using the low-cost, rapid prototyping capabilities offered by modern 3D-printing technology, capable of a spatial resolution of 20 µm. This method guarantees precision and regularity of twines and mesh, allowing us to modify the geometry by microns. Thirty circular pen models, with a surface porosity varying from 0.56 to 0.90, were manufactured (Fig. 1). As a point of reference, typical aquaculture nets have a porosity of about 0.80. Data were acquired using dye visualization, Particle Image Velocimetry and unidirectional load cell measurements.

**Observations**

Despite using a small-scale model at low inflow velocity, the observed flow behavior was in good agreement with larger-scale experiments and numerical simulations (Klebert 2013). Varying the net-pen porosity serves to vary the bleed flow velocity (Wood 1967), designated as $U_1$, which is the reduced velocity flow in the wake of the model as a result of the flow through the porous surface at the back side of the obstruction. Our models are able to recreate the types of flow expected in the wake of this kind of geometry:

- Regime 1 flows - A laminar steady wake with a bleed flow velocity ($U_1$) that is close to the free flow velocity ($U_\infty$).
- Regime 2 flows - A steady wake of finite length that evolves into an oscillating shear layer and subsequent vortex shedding.
- Regime 3 flows - The bleed flow velocity is a small fraction of the free flow velocity, resulting in high velocity gradients and a shear layer developing into the classic von Kármán vortex shedding pattern (Williamson 1996).

The mechanism for generation of a particular flow regime is related to the porosity of the net pen. A very porous pen will have regime 1 flow (Fig. 2 top) and a nearly solid pen will generate a regime 3 flow (Fig. 2 bottom). However, porosity is not the only parameter determining the wake, as two net-pen models of identical porosity but different twine/mesh ratio can produce different flow dynamics and significantly different drag.

**Environmental Aspects**

The netting density of a pen, usually imposed by the need to retain fish of a specified size, plays an important role in the operation of a net pen. It dictates the oxygen supply rate to the pen from inflowing water and the rate that wastes are flushed through the pen. The dispersion of biosolids is directly related to the flow regime and the magnitude of the bleeding flow. Net-pen models with the first flow regime have the fastest diffusion time, whereas models with the third flow regime tend to trap particles in their wake for an extended period. To consider the issue of waste, this may have an impact on fish health, as in the case of waste returning to a net pen with a turning tide, which is not preferable.

**Impact on Drag**

We conducted multiple experiments, each varying only one parameter: twine thickness, the mesh void or porosity. The results indicate the following trends:

- An increase in the mesh void tends to result in a reduction of drag. However, a void that is too small induces more drag than a completely opaque net (Fig. 3).
- A reduction of twine thickness does not necessarily lead to a reduction of drag. Regardless of twine thickness, it is always possible to identify a net-pen model porosity with a greater drag than an opaque net (Fig. 4).
- An increase in net porosity does not necessarily induce less drag. The same drag was obtained with models of surface porosity varying by over 40 percent (Fig. 5).

Based on these results, we infer that the induced drag on a net pen produced by the net cannot be determined by the surface porosity parameter alone. Although mesh void is the dominant parameter driving the mechanism, generating drag, the effect of twine thickness cannot be overlooked.

We are currently revising the mathematical model which, if verified on a larger-scale aquaculture net-pen model, could
help optimize aquaculture netting used in future applications. Extrapolating our small-scale results to a 20-m diameter net pen in open-ocean conditions, a 10-mm increase of the mesh void can lead to a 0.4 GN reduction in the drag force.

Conclusions

With net-pen farms increasingly situated farther offshore, it has become even more important to understand flow dynamics around aquaculture pens to predict the load forces applied to the net and to optimise the farm environment. We have observed that a change in surface porosity can result in drastically different flow dynamics and changed dispersion rates of particulate matter through nets.\footnote{Levy, B., H. Friedrich, J.E. Cater, R.J. Clarke and J.P. Denier. 2014. Impact of twine/mesh ratio on the flow dynamics through a porous cylinder. Experiments in Fluids (submitted).}

A change in surface porosity has an impact on the drag force, as expected. However, porosity alone is not the main factor in determining the level of drag, but that it is primarily imposed by the mesh void size and to some lesser extent by twine thickness.

These results provide a better understanding of the fluid-structure interaction on a porous structure similar to those used in commercial net-pen aquaculture and provide a starting point for net-pen design optimization.

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Notes

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