A computational and experimental investigation of flow inside branched coral colony

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1. Motivation and objective

Coral reefs have the highest biodiversity of any marine ecosystem. Though they cover only 15 percent of the ocean surface between the depth of 0 to 30 meters (Smith, 1978), coral reefs shelter nearly a quarter of all marine life. The host of organisms that thrive in the reef system, of which only about 10 percent have been described, bears tremendous potential for modern medicine (Serageldin 1998). Furthermore, coral reefs are important economic resources, serving as fisheries and breakwaters for coastal communities. In spite of their ecological and economic significance, 30 percent of the world's coral reefs are severely damaged, and 60 percent are projected to be lost by 2030 (Wilkinson 2002). Overfishing, agricultural pollution, and coastal development alter the species and nutrient balance in the water, making corals less competitive against fleshy seaweed (Hughes 1994; McClanahan *et al.* 2002). Warming of the seawater caused by global climate change overheats the coral, which is extremely temperature sensitive. The coral, in response, expels its symbiotic algae, zooxanthellae, such that the coral itself becomes white, or bleached. Prolonged bleaching episodes, which have been observed to increase in frequency and magnitude in the last 30 years (Hughes *et al.* 2003), cause coral death throughout reef systems.

Given both the importance and the fragile state of coral reefs, understanding the mechanisms for coral growth is crucial to the survival and possible recovery of the remaining reef systems around the world. Corals are able to flourish in low-nutrient, oligotrophic waters because of their ability to efficiently use their limited resources for growth. In this work we hope to explore the role of hydrodynamics in coral growth through innovative computational and experimental methods.

Hydrodynamics directly affect coral growth, energetics, and health. Sessile organisms such as corals rely on water flow to deliver their nutrients, and consequently the nature of the flow plays an important role in determining nutrient availability. Coral has two metabolic roles that have functional dependence on flow: one as a zooplankton-ingesting heterotroph, another as a benefactor of symbiotic autotrophs. As heterotrophs, the coral polyps capture zooplankton that is carried by the flow for sustenance. As autotrophs, the symbiotic algae zooxanthellae depend on the concentration gradient of inorganic nutrients established by the diffusive boundary layer. Additionally, the structural integrity of the coral is susceptible to the amount of force the moving fluid imposes on the geometry. Clearly, hydrodynamics plays a crucial role in coral subsistence.

Corals live in a variety of hydrodynamic conditions, with flow velocities ranging from 5 cm/s in the fore reef up to 100 cm/s in the surf zone (Sebens 1997). Consequently, corals have adapted structurally, resulting in morphologies that vary in branch-spacing

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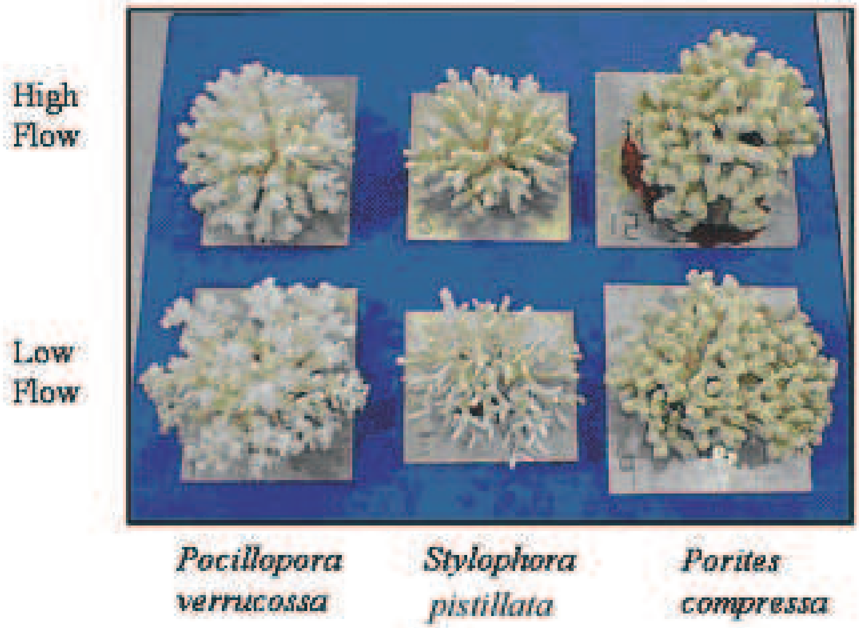

Figure 1. Low and high flow morphologies of several corals from Eilat, Israel.

and width (Fig. 1), from plate-like to massive. For instance, coral geometries with denser branching tend to divert more flow to the exterior, establishing a larger stagnant region in the core of the geometry and greater shear above the colony due to a higher exterior velocity. For the same flow condition, coral geometries with sparser branching will allow more flow through the interior, resulting in greater force imposed upon the interior branches by the flow. Quantifying the functional dependence of the resulting flow field on coral morphology and hydrodynamic environment will significantly contribute to understanding nutrient transport.

Hydrodynamics also directly affect the corals' requirements for structural stability. As the large-scale physical damages to coral reefs by hurricane-driven waves attest, the structural integrity of the coral structure is susceptible to damage due to the amount of force the moving fluid places on it (Sebens 1997). Corals that live in wavy, high-energy environments need more robust branches and lower surface area to volume ratios in order to prevent breakage. In slower flows, corals can afford structurally weaker morphologies to optimize for nutrient and feeding priorities. Conversely, some species take advantage of periodic storm events by having thin branches that break off, and then recolonize elsewhere on the seafloor (Sebens 1997). No matter what the adaptive behavior is, the force that the flow imparts on the coral structure deems particular morphologies more suitable for one versus another hydrodynamic environment.

Additional complexity arises from the fact that the hydrodynamics throughout the colony, defined as one skeletal unit, e.g. one head, are locally variable and therefore cannot be adequately modeled with bulk flow and roughness parameters at the scale important for these processes. The coral geometry acts as a bluff body that perturbs the flow, resulting in recirculation zones and regions of localized acceleration, deceleration, and stagnation (Chamberlain & Graus 1975). Such spatially and temporally variable flow in turn leads to differential local nutrient concentrations and boundary layer thicknesses throughout a coral colony, which, after a long enough time, may induce localized calcification for a single coral head resulting in a specific preferential growth form (Oliver *et al.* 1983; Lesser *et al.* 1994; Bruno and Edmunds 1997). The resulting new geometry then interacts with the flow in a slightly different way, which once again has direct consequences on local nutrient availability and coral growth (Kaandorp & Kűbler 2001).

To better address this complex interaction, we believe that it is possible to create a comprehensive model of corals based on first principles, *i.e.* a virtual coral. This model would simulate numerically the flow and mass transfer in and around a coral colony, given the specific geometry of the coral. Since the geometry of the coral itself depends on local calcification rates, the rates would be calculated using model representations of the chemistry of calcification and of photosynthesis by the zooxanthellae. This comprehensive approach would require models of the light field incident on the coral surfaces, including among other physics the focusing effects of surface waves. When complete, this model should be capable of testing hypotheses relating changes in flow, morphology, nutrient, light level, and temperature to the coral's physiological response, *e.g.* calcification rates and pattern, photosynthesis rates, or bleaching. As the first step in the development of the virtual coral model, we will perform detailed calculations of flow through a single coral head, allowing for the explicit computation of local stresses, forces, and mass transfer rates at every point on the surface of a coral head. Specifically, we propose to:

- Compute and validate through comparisons with experiments the variability of stress and velocity fields throughout a single colony, including the interstitial area between the branches.
- Assess the effect of the flow conditions (*e.g.* variable velocities, unidirectional versus oscillatory flow) on mass transport.
- Assess the effect of roughness on mass transport, considering both
    - large-scale geometric roughness as characterized by morphologies from different species and flow regimes;
    - small-scale surface roughness as characterized by the mucus membrane and polyps attached to the large-scale geometry.

To achieve these goals, we will use a numerical simulation technique based on the Immersed Boundary (IB) method to calculate the flow and mass transfer around a single coral colony. The IB technique has proven to be effective and efficient for computing flows around complex geometries (Iaccarino *et al.* 2003; Iaccarino & Verzicco 2003; Grigoriadis *et al* 2004). The coral morphology and flow conditions can be varied in the simulations to determine the effects on the flow field and on nutrient transport. The results will be validated using a combination of Magnetic Resonance Velocimetry (MRV) for the interstitial flow and Particle Image Velocimetry (PIV) for the wake region of the coral.

2. Experimental setup

2.1. *Coral geometry acquisition*

In order to mimic the flow around corals in the field conditions, we need to incorporate realistic geometries in our experiments. For this purpose we have selected *Stylophora pistillata*, a Red Sea coral found more commonly in slower, unidirectional flow regimes, for this purpose.

The coral need to be digitally represented so that the geometry can be built using rapid prototyping manufacturing and imported into the computational flow domain.

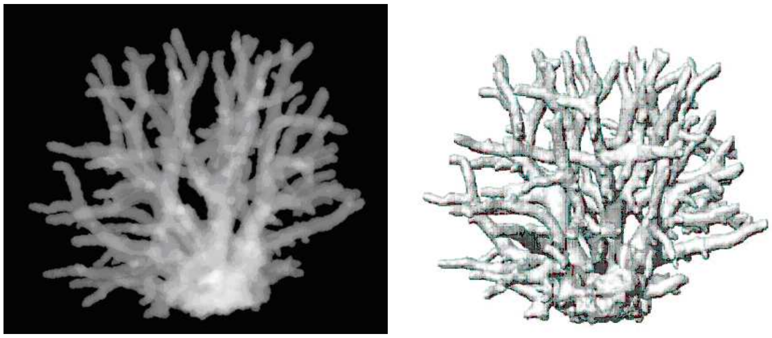

FIGURE 2. *Stylophora pistillata*, low flow morphology. (a) CT scan: This image is a compilation of 245 images taken at every 0.7 mm (in the direction out of the page). The pixel size is 0.35 mm x 0.35 mm with an 18 cm by 18 cm field of view, resulting in a 512 x 512 matrix of intensity values for each image. (b) Postprocess with MIMICS to create a three-dimensional representation in stl format.

The digital format is obtained by scanning the coral skeletons using x-ray computed tomography (CT). This medical technology is ideal for our purpose; the method is able to effectively image calcium carbonate, the basis for both bones and coral skeletons, and render occlusions in the contorted coral geometries. Two-dimensional images (Fig. 2a) are constructed from linear projections of x-rays taken at many different angles along a single plane, which then are shifted by a small distance (thickness) perpendicular to the image plane to acquire the next set of projections (Bushberg *et al.* 1994). Each image then has an associated thickness.

2.2. *Coral model and setup*

The size of the experimental facility is limited by the MRV system. In order to accommodate the restriction, a 75% model of the coral colony was built by Dr. Ryan Wicker at University of Texas at El Paso (UTEP) using a fused deposition manufacturing system (Figure 8 shows the 100% model, Figure 9 shows the 75% model in the channel). MRV-compatible resin manufactured by DSM Somos was layered with water-soluble supports for the overhanging branches. The supports were then dissolved to create the final model. To house the model, a unidirectional flow laboratory setup (3) has been designed and constructed to create an inlet flow condition that is as uniform as possible (see *e.g.* Vogel, 1983). To fit inside the 26 cm diameter head coil, the channel is confined to the maximum size of 19 cm wide by 17 cm tall. Attached to the front of the channel is a diffuser with three differential pressure drops (50% void ratio in the center region, 75% around the perimeter) to prevent the flow from stalling. The inlet contains two additional screens and a baffle for the same purpose. The outflow releases into a reservoir, which is connected to a pump and then recirculates to the inflow. The velocity in the channel with the current set up is approximately 5 cm/s.

3. Computational study

The Immersed Boundary (IB) technique enables numerical simulations of the flow around very complex geometries to be performed on simple Cartesian grids with local grid refinement. In the present application the coral is not physically present in the computational domain when the mesh is generated and its presence is accounted for via modifications to the governing equations. These modifications take the form of a forcing

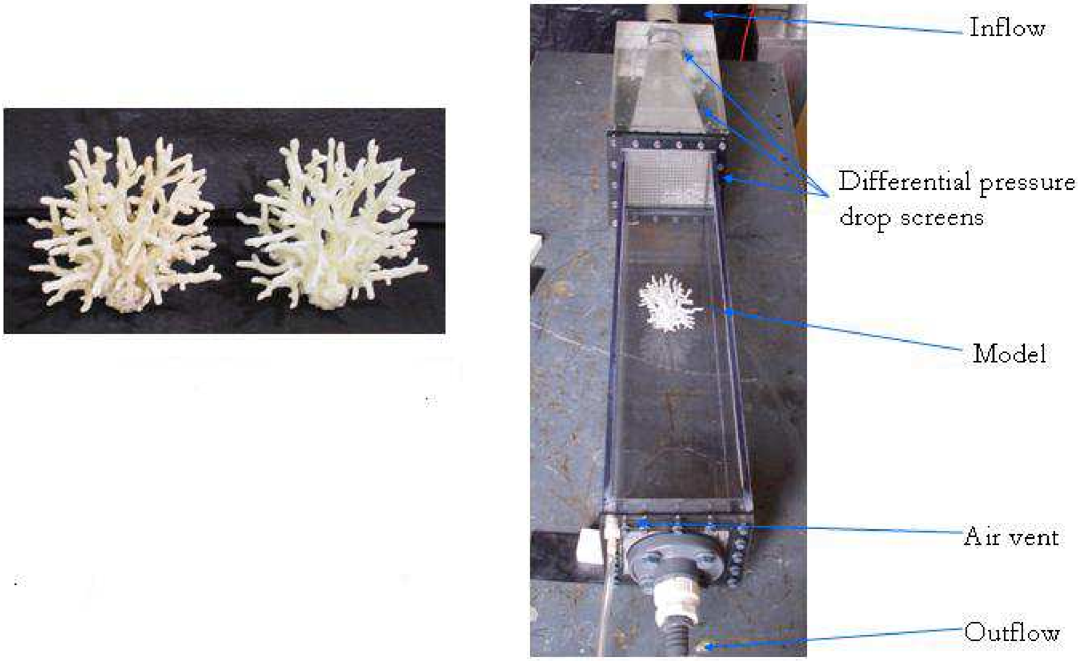

FIGURE 3. *Stylophora pistillata* skeleton (left) and rapid-prototyped model (center). Channel set-up for MRV and PIV (right)

term which mimics the effect of the physical boundary conditions enforced on the coral surface. In the present implementation of the IB approach the solution in the vicinity of the coral is reconstructed on the basis of the computed flow away from the body and the no-slip condition on the surface. Inverse distance interpolation is used (Iaccarino & Verzicco 2003). Although the objective is to ultimately perform Large Eddy Simulation with the IB technique, we have carried out some preliminary simulations with a Reynolds Averaged Navier-Stokes (RANS) model to gather initial solutions to be compared to experiments and to investigate the grid resolution requirements for capturing the details of the flow. The computation code used, namely IBRANS, is based on the solution of the three-dimensional, steady-state RANS equations using a finite volume, collocated discretization where all the flow variables (*e.g.* pressure and velocity) are defined at the center of each grid cell (see Iaccarino *et al.* 2003 and Iaccarino & Verzicco 2003 for details). The SIMPLE (Semi-Implicit Method for Pressure-Linked Equations) pressure-correction algorithm is used. The continuity equation is converted into a discrete Poisson equation which subsequently is used to correct the momentum equations. A second-order accurate discretization is used to solve the governing equations; the solution is computed iteratively using a fully implicitly scheme. The boundary conditions are treated explicitly, where no slip is assumed along the immersed boundary of the solid surface.

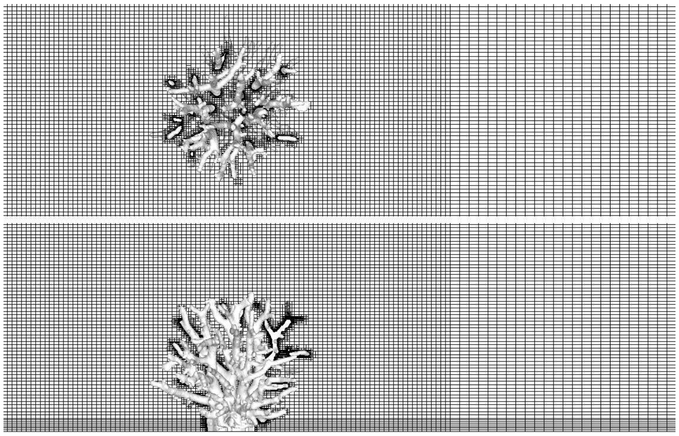

FIGURE 4. Computational grids generated for the RANS simulations. Horizontal plane at 1/3 the coral height (top) and vertical plane at midspan of the duct (bottom). The mesh contains ≈ 2 million cells

Computational grids are generated automatically starting from the CAD definition of the coral geometry (in stereo-lithography format); the duct described previously is modeled without the inlet diffuser; the flow is assumed to be uniform at the inlet and no-slip boundary conditions are specified on the duct walls. The mesh size is specified on the coral surface and grid resolution is achieved through local grid refinement. Three grids have been generated and their cross-sections (corresponding to a longitudinal plane halfway through the duct) are reported in Fig. 4.

4. Experimental study

MRV is a non-invasive experimental technique which allows the acquisition of the entire three-component mean velocity field in a three-dimensional flow domain a medical Magnetic Resonance Imaging (MRI) scanner. MRI is a medical technology that uses magnetic field and sequences of radio frequency pulses to extract images inside an object. The method relies on the atomic structure of the object being imaged. In the absence of a magnetic field, the spin and charge distribution of the individual atoms result in magnetic dipoles that is randomly oriented due to thermal energy. The MRI coil imposes an external gradient magnetic field such that the net magnetic moment of the atoms in the sampled object aligns itself with the field, while each individual dipole precesses around the orientation of the magnetic field such that at any given time its position can be described by a phase. When motion is present, the location of fluid parcels are marked based on their phase, which then can be reconstructed with Fourier transform. This method has been used to measure turbulent flow in a highly complex internal flow geometry modeling the internal cooling passage of a gas turbine engine blade (Elkins *et al.* 2003). The data have been validated against PIV measurements on selected planes and have also been used to validate a numerical simulation of the same geometry using the IB technique (Iaccarino *et al.* 2003).

The setup shown in Fig. 3 was placed in the MRI chamber and preliminary measurement were collected. The flow-meter indicated the flowrate as 81 L/min, which is equivalent to 5.2 cm/s for the channel. The resolution is approximately 1.25 mm by 1.25 mm in the xy plane, with 1 mm thick slices along the z axes. Total scan time was 9.35

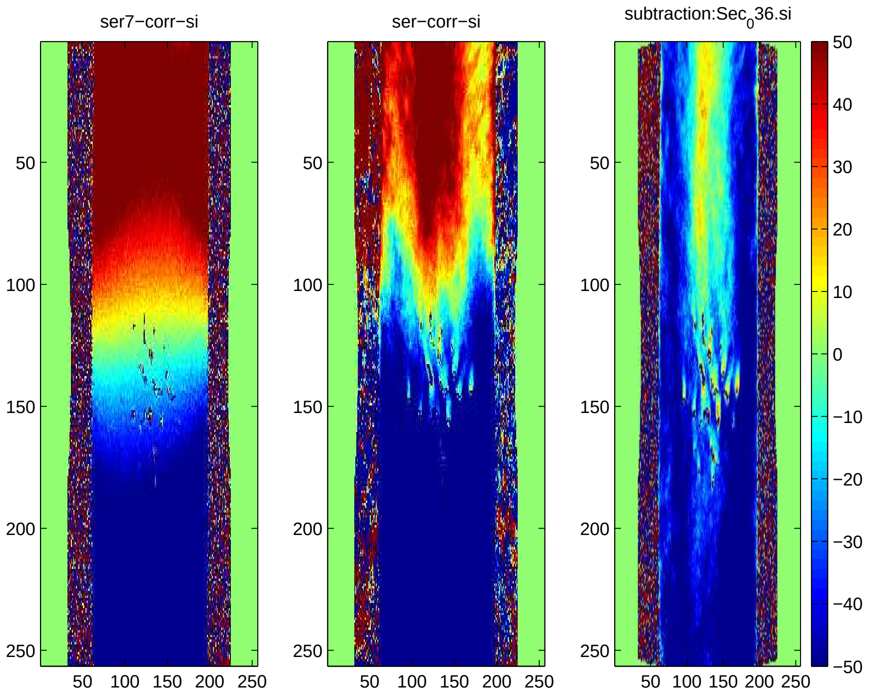

FIGURE 5. MRV velocity result at approximately 1/3 of the height of the coral. The images are scans flow off, flow on, and flow off subtracted from flow on, respectively. Flow is going from bottom to top. The color gradation is an indication of streamwise velocity in mm/s. The velocities are inverted; negative velocity indicate upward direction, and conversely, positive velocity indicate downward or reverse direction.

minutes. A 0.5% by volume gadolinium solution was used to enhance the signal. An example of the results is shown in Fig. 5. The MR signal of the setup with the pump on and off were recorded, such that the flow off condition can be subtracted from the flow on condition such that the signal would only be from the flow.

The preliminary result clearly show a wake behind the coral geometry as a whole, as well as effects of the coral branches itself. Because of the size of the channel, which in effect occupy the entire space in the magnet coil, the edges of our domain, where the magnetic field lines curve, require more refined reconstruction.

5. Preliminary analysis of the flow field

Preliminary calculations and measurements are compared in a vertical plane corresponding to the duct mid-span and in an horizontal plane at 1/3 of the coral height (in Fig. 6 and Fig. 7, respectively). The Reynolds number, based on the coral height and the inflow bulk velocity, is $Re = 4,700$. The (steady-state) calculations indicate the presence of a rather large wake with maximum negative velocities twice v_{inflow}. The structure of the wake is highly three-dimensional and the branch distribution is clearly visible through the presence of high velocity spots. The comparison between MRV and IB data is, at this point, not satisfactory. It must be noted that from visual observation during the measurements, the flow has a strong unsteady nature. This is neglected by the current steady-state calculations and can lead to substantial overpredictions of the wake

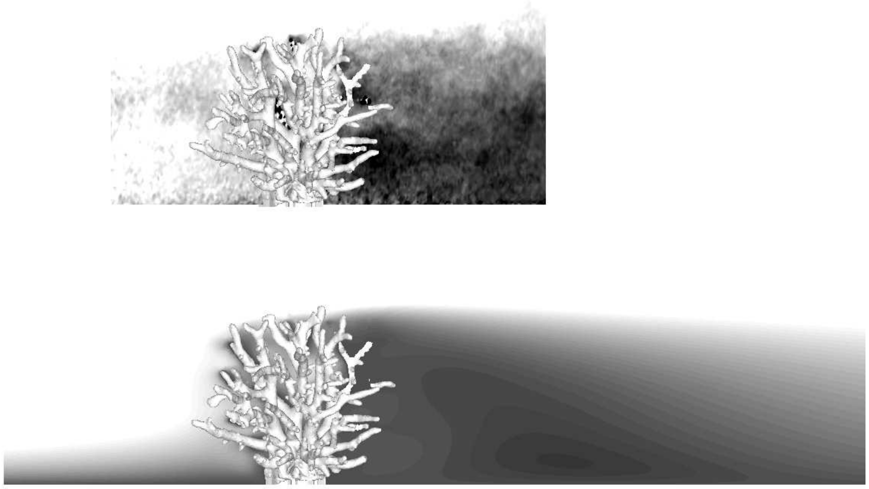

FIGURE 6. Comparison of experimental (MRV, top) and numerical (IB, bottom) results for a vertical plane at the duct mid-span section. Streamwise velocity shown.

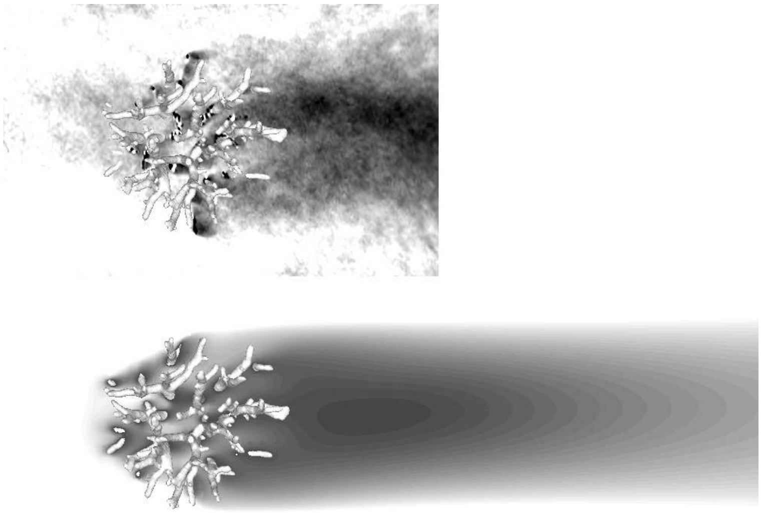

FIGURE 7. Comparison of experimental (MRV, top) and numerical (IB, bottom) results for a horizontal plane at 1/3 height of the coral. Streamwise velocity shown.

strength and size (Durbin, 1995). In addition, the MRV data are collected in frequency space over ≈ 10 minutes. For this reason, the collected data might not represent correctly neither the time-averaged or the instantaneous flow field. Moreover, flow rate measurements show large discrepancies during the testing. These difficulties in the acquisition of satisfactory experimental and simulation data are currently being addressed.

6. Conclusion

Coral reefs are clearly of great ecological significance, and as is often the case with ecosystems of importance, the health and survival of coral reefs are threatened. In order to diminish the degree of degradation and even possibly facilitate the recovery of coral reefs, a better understanding of coral biology must be developed, within context of the environment that so greatly influences its fate. As shown repeatedly in the literature, basic aspects of coral ecology, growth, and health, can strongly depend on flow.

In order to examine this dependence, this work has spanned a wide array of techniques. The acquisition of a real coral geometry in digital format required scanning the coral skeleton using CT; the same model is then used for both the computations and the measurements as a physical model of the coral (not the actual skeleton) must be used. For the construction of this model, a complex rapid-prototyping technique (Iyengar *et al.* 2004) was utilized due to the very complex geometry with many occlusions and overhangs. The model was placed in a channel built for this experiment and the velocities were extracted using MRV. The numerical technique IB was used for its efficiency with complex geometries, resulting in some preliminary computational results to compare with the experimental results.

These innovative computational and experimental methods will elucidate previously unresolved dynamics on the scales important to mass transfer. As hydrodynamics continue to change due to increased storm events resulting from climate change and continued human manipulation of the coastline by dredging and building infrastructures such as breakwaters, understanding the interactions between hydrodynamics and coral will be crucial for preserving the remaining coral reefs.

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