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Collaborative Proposal: Form and function of phytoplankton in unsteady, low Reynolds-number flows

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Principal Investigator: Jumars, Peter A.
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Project Participants

Senior Personnel

Name: Jumars, Peter
Worked for more than 160 Hours: Yes
Contribution to Project:
P. Jumars has general oversight responsibility as PI and has taken charge of both the theoretical and numerical modeling aspects of the work.

Name: Karp-Boss, Lee
Worked for more than 160 Hours: Yes
Contribution to Project:
Lee has taken major responsibility for the experimental components of the work, comprising three components: unsteady settling of spheres, unsteady settling of objects shaped like phytoplankton and transport of phytoplankton cells in turbulent flow.

Post-doc

Graduate Student

Undergraduate Student

Name: Pritchard, LeAnn
Worked for more than 160 Hours: Yes
Contribution to Project:
Ms. Pritchard participated in data collection and analysis for the unsteady settling experiments.

Technician, Programmer

Other Participant

Research Experience for Undergraduates

Name: Klingler, Elisa
Worked for more than 160 Hours: Yes
Contribution to Project:
Elisa has been producing models for trial in our large Couette, experimenting with varying shapes and material properties to identify phytoplankton shapes and mechanical properties that might be of interest to test further in the cone-and-plate Couette.

Years of schooling completed: Junior
Home Institution: Same as Research Site
Home Institution if Other:
Home Institution Highest Degree Granted(in fields supported by NSF): Doctoral Degree
Fiscal year(s) REU Participant supported: 2004
REU Funding: REU site award

Organizational Partners

University of Washington

Danny Gr³nbaum (School of Oceanography) and James J. Riley (Mechanical Engineering) have been working on direct numerical simulation of turbulence (DNS) to characterize the shear history of small water parcels such as those occupied by diatom chains. We will be using their results to define target environments for simulation in our cone-and-plate couette device produced for this project by Steve Wereley of Purdue.

Purdue University

Steve Wereley (Mechanical Engineering) with his student, Peter Grant, has produced the cone-and-plate couette device that will be used in our unsteady-flow experiments to simulate conditions experienced by phytoplankton in turbulent marine waters. They also have produced the large couette device that will be used in the summer 2004 effort to develop curricular materials on low Reynolds number flows for secondary schools.

Other Collaborators or Contacts

We have collaborated with Mimi Koehl (Integrative Biology) at the University of California at Berkeley to publish a review and prospectus on algal biophysics.

We collaborate with Thomas Ki°rboe and Andy Visser at the Danish Institute for Fisheries Research and with Tim Pedley at Cambridge. They help us check web presentations and preprints for rigor and generality to other subfields of fluid dynamics and biological oceanography.

We have initiated a collaboration with Lisa J. Fauci of the Mathematics Department at Tulane University (New Orleans) and her Ph.D. student, Magda Musielak. Using realistic, coupled fluid and solid dynamics, they have begun modeling phytoplankton chains of varying flexibilities in steady shear. Prior to Hurricane Kristina, they had completed 2D modeling with predictions of shapes that would be observed as a function of varying chain rigidity. We resumed this collaboration in summer 2006 and have extended it to unsteady shear.

Activities and Findings

Research and Education Activities:

We have completed data collection for an effort to reconcile theory, numerical modeling (via the COMSOL physics modeling package) and experimental measurements of acceleration of a sphere from rest at low Reynolds number. Numerical modeling for more complex phytoplankton shapes is still in progress. These results were delayed considerably because we were pushing the low-velocity noise limits of particle imaging velocimetry. We overcame this problem by working with scaled-up models of phytoplankton in unsteady settling.

Major reasons for project extension were the results of some preliminary experiments conducted by L. Karp-Boss at Johns Hopkins University in spring of 2006.á They promise to connect our results in simple flows to behavior of real phytoplankton embedded in three-dimensional turbulence.á Working from methods and in apparatus developed by Friedman and Katz (2002) for oil droplets, we are testing the hypothesis (based on their oil-droplet results) that negatively or positively buoyant phytoplankton will have a sinking or rising rates near 25% of the root-mean-square turbulent velocity rather than a rise rate or settling rate related to their still-water velocity.á The potential environmental significance is very large, implying that diatoms could go up and down in the water column much faster than had been supposed, with only minor changes in buoyancy between slightly positive and slightly negative, respectively.á The approach involves tracking individual cells over significant distances through multiple exposures of a digital camera with a pulsed laser.á Fluorescent microspheres provide a passive control for lower Stokes numbers (than for the phytoplankton) and are used to visualize the flow field.á Our initial experiments show that the ability to track individual diatom cells is highly variable among species, and our remaining task is to acquire more tracking data over a wider range of species.á We believe that this final study has the potential to deliver even more than we had anticipated in the proposal, in terms of environmental relevance.

References cited

Friedman, P.D., and J. Katz. 2002. Mean rise rate of droplets in isotropic turbulence. Physics of Fluids 14: 3,059-3,073.

Ruiz, J., D. MacÝas and F. Peters. 2004. Turbulence increases the average settling velocity of phytoplankton cells. Proc. National Acad. Sci. U.S.A. 101: 17,720-17,724.

Findings:

Because the time scale of unsteady responses is determined by the diffusion of momentum (specifically the kinematic viscosity divided by the length scale), larger phytoplankton such as diatom chains are strongly influenced in unsteady flows. We find that in cylindrically shaped chains, unsteady flows are particularly effective in eroding diffusive boundary layers and alleviating diffusive limitations. For cells above about 10 micrometers in radius, nutrient uptake should be enhanced and sinking rate decreased by adopting a non-spherical morphology.

For spherical objects in unsteady motion at low Reynolds number, theory, numerical models and experiments demonstrate the increasing importance of the history term with increasing sphere radius.

Experiments in turbulent flow with phytoplankton cultures (done at Johns Hopkins in J. Katz' lab) suggest that phytoplankton with specific gravities different from seawater have their net upward or downward velocity increased to roughly 0.25 times the rms turbulent velocity.

Training and Development:

The theoretical work has contributed substantially to Jumars' graduate and undergraduate teaching, particularly in a course (SMS 481) called 'Design of Marine Organisms' that focuses on momentum, mass and information transfer and is taught as a hands-on, lab class to juniors and seniors. This experience, in turn has been the basis for beginning a book on low-Reynolds number flow and biology and for beginning to develop teaching approaches and materials for secondary-school students. Dennis Levandoski and Jen Fox used these materials to develop teaching materials for high school students during a month-long session at the Darling Marine Center in July-August 2004. They continued to work on and used these materials in preparation for presenting them (Jen in Seattle and Dennis in Maine) to larger groups of high school teachers.

The group in summer 2005 in Maine comprised Dennis and five other high school teachers, with primary skills and interests in teaching high school physics. They used the two-week session (in collaboration with L. Karp-Boss and P. Jumars) to develop standards-relevant curricular materials that deal with pressure buoyancy and drag, including low Reynolds-number cases.

In February 2006 Dennis Levandoski summarized his experiences with fellow teachers at a special symposium in education and outreach at the Ocean Sciences Meeting. In AY2005-2006, undergraduate LeAnn Pritchard participated actively in the experimental components of the work and is pursuing graduate work in oceanography at another institution (University of Rhode Island).

Outreach Activities:

We suggested that low Reynolds number phenomena would be ideal as means to interest biologically oriented students in physics and mathematics and vice versa. The original focus was on high-school curricula. We recruited two high school teachers Jen Fox (Garfield High School, Seattle, WA) and Dennis Levandoski (Westbrook High School, Portland, ME). Altogether we spent about a month on developing curricular materials. The group actively involved included Steve Wereley (Purdue, who visited also to lend his expertise to tank and PIV operation), Tansy Clay (a graduate student with Danny Gr³nbaum), Lee Karp-Boss and Pete Jumars as well as the two teachers. All participants brought candidate materials, but much of the time was spent examining curricular materials evolved for Pete Jumars' course on Design of Marine Organisms (SMS 481 <http://www.marine.maine.edu/~jumars/classes/SMS_481/index.html> and modifying them for secondary school use. Jen teaches marine biology in high school and could incorporate much of the material directly in her classes. She has been doing so with strong student enthusiasm. Dennis Levandoski, who also has taught middle school, pointed out that interdisciplinary material was much easier to offer at this level than in high school, where AP courses' curricula already are jam packed. Accordingly, we worked to make the materials maximally accessible. As a parallel strategy, we visited websites that treat fluid dynamics and asked whether we could develop simpler yet rigorous explanations, and the answer was often affirmative. Karp-Boss, Clay and Jumars iterated by electronic means to optimize web explanations, supplementary teacher materials and student activities (with instructions and materials lists presented on the web). We then moved to recruit 12 more teachers (six from Washington and six from Maine) for workshops in summer 2005 to quality control this material and develop more. Levandoski and Jumars presented back-to-back a one-hour session entitled 'Using Marine Biology to Demonstrate Concepts in Physics' at the Maine Science Teachers Association Annual Conference (October 2004, Gardiner, Maine), where we gave demonstrations and explained the approach. Jen Fox and Tansy Clay each presented at the 2005 ASLO Aquatic Sciences Meeting in Salt Lake City.

Our outreach and education efforts came to fruition as anticipated. In summer 2005, Dennis Levandoski and five other Maine high school teachers developed standards-relevant teaching materials on pressure, buoyancy and drag. Two papers were presented at Ocean Sciences 2006 (Levandoski et al. 2006 & Jumars et al. 2006). Reviewed teaching materials are posted at <http://aslo.org/education/teaching/fluids.html> and <http://aslo.org/education/teaching/suspension_feeding.pdf> on the ASLO website, which has exceeded an access rate of 10 million hits per year and is doubling roughly annually in this metric. We have recently published a lab exercise based on the simpler aspects of low Reynolds number settling as the flagship ôhands-on oceanographyö teaching feature in Oceanography (Boss et al. 2006). We also have a paper in review (Fox et al.) in Biology Teacher.

References cited:

Boss, E., L. Karp-Boss and P.A. Jumars. 2006. Settling of particles in aquatic environments ùLow Reynolds numbers. Oceanography 19: 151-154.

Clay,T., J. Fox, D. Gr³nbaum, and P.A. Jumars. Integrating mathematics, physics, and biology in the high school classroom: An example focused on the physics that control plankton movement. Biology Teacher, in review.

Jumars, P.A., L. Karp-Boss and D. Levandoski. 2006. Multi-directional teaching and learning: Who reached out? Talk presented in the session on ôReaching Out: WhatÆs in it for scientists?ö 20 February, Ocean Sciences Meeting, Honolulu.

Levandoski, D., P.A. Jumars and L. Karp-Boss. 2006. A partnership between oceanographic researchers and high school teachers. Talk presented in the session on ôMaking Science Fun: Scientist and Educators Working Together Iö 20 February, Ocean Sciences Meeting, Honolulu.

Journal Publications

Boss, E., L. Karp-Boss and P.A. Jumars, "Settling of particles in aquatic environments: Low Reynolds numbers", Oceanography, p. , vol. 19, (2006). Published,

T. Clay, J. Fox, D. Grünbaum, and P.A. Jumars, "Integrating mathematics, physics, and biology in the high school classroom: An example focused on the physics that control plankton movement", Biology Teacher, p. , vol. , (2007). Submitted,

Karp-Boss, L., and P.A. Jumars, "Unsteady settling of spheres and model phytoplankton shapes", Limnology and Oceanography, p. , vol. , (2007). In manuscript,

L. Karp-Boss, E. Boss and P.A. Jumars, "Role of cell shape in phytoplankton ecology", Limnology and Oceanography, p. , vol. , (2007). In manuscript (review paper),

Jumars, P.A., and L. Karp-Boss, "Simulating turbulence in studies of its biological effects: A new cartoon", Marine Ecology PSZN, p. , vol. , (2007). In manuscript,

Books or Other One-time Publications

Koehl, M.A.R., P.A. Jumars and L.
Karp-Boss, "Algal biophysics", (2003). Book, Published
Editor(s): T.A. Norton, Ed.
Collection: Out of the Past
Bibliography: pp. 115-130. British Phycological
Association, Belfast

Web/Internet Site

URL(s):
http://aslo.org/education/teaching/fluids.html,
Description:

Other Specific Products

Contributions

Contributions within Discipline:

We continue to see increasing interest by others in unsteady flow phenomena as a consequence of our presentations and publications. One recent example is the demonstration by workers in Joseph Katz' laboratory, that unsteady motions by small organisms (nauplii) propagate velocity signals much shorter distances than predicted and observed for steady motions.

We look forward in future textbooks to the inclusion of the history term in biological fluid dynamics texts treating unsteady motion.

Contributions to Other Disciplines:

Our focus on unsteady motion crossed over into our studies of burrowing, where we have found (through Kelly Dorgan, a graduate student supported by NDSEG and NSF fellowships) that nereid polychaetes burrow by crack propagation, using subterminal expansions to apply lateral forces that cause forward propagation of a crack. The burrowing method is quite efficient because after the threshold stress is reached the energy for crack propagation comes from release of bond energy, leading to increased entropy. This work is now published (Dorgan et al. 2005).

Dorgan, K.M., P.A. Jumars, B. Johnson, B.P. Boudreau, and E. Landis. 2005. Burrowing by crack propagation through muddy sediment. Nature 433: 475.

Contributions to Human Resource Development:

Our outreach products are already reaching high schools. Quoting from a recent e-mail (fall 2005):
'Just wanted to let you know the density and buoyancy labs went so well
the other chem instructor and I are exchanging lab groups for 2 claases so
his kids get to do them, too. Thanks again. Roxanne Cirrincione (Science Teacher at Lubec Consolidated School, Lubec, Maine)'

Contributions to Resources for Research and Education:

Curricular materials suitable for high school have been reviewed and posted at the American Society of Limnology and Oceanography 'Teaching Tools' website <http://aslo.org/education/teaching.html>.

Contributions Beyond Science and Engineering:

Categories for which nothing is reported:

Any Product

Contributions: To Any Beyond Science and Engineering