

Polymer Drag Reduction and Bioluminescence Reduction

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LONG-TERM GOALS

Bioluminescence represents an operational threat to U.S. Navy nighttime operations because of the vulnerability risk due to detection because of flow-stimulated light emission from naturally occurring plankton. Conversely, bioluminescence presents additional capabilities for detecting moving objects at night, particularly in the littoral zone where conventional acoustic surveillance is severely challenged. We are interested in the hydrodynamic conditions that stimulate bioluminescence, the resulting bioluminescence signatures, how to estimate signatures based on levels of bioluminescence potential, and how to mitigate these signatures.

OBJECTIVES

Dinoflagellate bioluminescence, the most common emission source in surface waters, is stimulated by flow agitation. We have used several independent flow fields to demonstrate that the intensity of bioluminescence is correlated with the magnitude of fluid shear stress. Values of shear stress that stimulate bioluminescence are present within breaking waves and associated with the flow fields of swimming organisms, but are orders of magnitude greater than other naturally occurring flows. Thus the motion of any object moving through the ocean will generate a bioluminescence signature, increasing the risk of vulnerability in the context of nighttime naval operations. Consequently, there is growing interest in exploring mitigation strategies in bioluminescence reduction in the context of Navy special operations, swimmer delivery vehicles (SDV's), and other underwater vehicles.

The objective of this project is to test two hypotheses concerning the effect of polymer drag reducing solutions on bioluminescence stimulation in bounded and unbounded flows. (1) The well-documented reduction of turbulent skin friction in polymer solutions of polyethylene oxide (PEO) is hypothesized to also result in a similar reduction of flow-stimulated bioluminescence. Turbulent pipe flow tests with concentrations of 10 ppm PEO provide about 50% reduction in turbulent skin friction in the pipe. Consequently, for the same pipe and volume flow rate a 50% reduction in flow-stimulated bioluminescence is predicted. Turbulent pipe flow is characterized based on flow rate and pressure drop, and provides a direct comparison between wall shear stress and flow-stimulated bioluminescence. (2) There is also evidence that low concentrations of PEO will affect the turbulent structure of jet flow, resulting in the absence of the smaller turbulent length scales. It is hypothesized that the absence of these smaller “eddies”, which are associated with larger shear stresses in the flow, would result in less bioluminescence stimulation. Jet turbulence is an unbounded flow that is more similar to that of a turbulent boat wake and provides insight into the effect of polymer treatment on the size of a bioluminescence signature. Jet flow stimulated bioluminescence will be measured within a spherical light collector, with and without trace quantities of PEO (10 ppm). Together, these

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approaches will provide information on whether the use of drag-reducing polymers causes a decrease in turbulent flow-stimulated bioluminescence. If so, then polymer addition could represent a much-needed strategy to reduce bioluminescence signatures of naval relevance.

Objective 1: Determine the effect of the drag-reducing polymer PEO on dinoflagellate bioluminescence: stimulation in the absence of flow and bioluminescence potential.

Prior to interpreting the results of flow tests with PEO, it is necessary to determine its effect on the bioluminescent system of the dinoflagellates. Tests in the absence of flow stimulation will determine if PEO affects the level of naturally occurring “spontaneous” bioluminescence in dinoflagellates and total bioluminescence capacity as measured by acid treatment.

Objective 2: Measure changes in stimulated bioluminescence intensity in fully developed turbulent pipe flow upon addition of the drag-reducing polymer PEO.

Using fully developed turbulent pipe flow, an unbounded flow, the project will investigate if polymer solutions that result in significant drag reduction will also reduce bioluminescence. Polymer drag reduction of 50% or more has been observed for dilute (e.g., 10 ppm) solutions of PEO in turbulent pipe flows with high values of wall shear stress (order of $10\text{--}100\text{ N m}^{-2}$). Our previous work has shown that for fully developed turbulent pipe flow, bioluminescence intensity generally increases linearly with wall shear stress (Latz and Rohr 1999). If the polymer reduces wall shear stress at a given flow rate, then bioluminescence intensity should be similarly reduced. PEO does not have drag reducing properties in laminar flow so no changes in bioluminescence for laminar flows is expected.

Objective 3: Measure changes in the bioluminescence intensity and size of the bioluminescence signature produced by a submerged turbulent jet upon addition of the drag-reducing polymer PEO.

Using a turbulent jet (an unbounded flow), the project will investigate whether dilute concentrations of polymer affect bioluminescence stimulated by a turbulent jet. Low polymer concentrations (30 ppm PEO) are known to result in conspicuous changes in the appearance of a water jet discharging into a tank of the same fluid because smaller turbulent eddies are not found in the PEO jets. High-speed photographs of a water jet in air with and without polymer (200 ppm PEO) have shown remarkable differences in flow structure, particularly the lack of spray in the jet polymer solutions. The tendency for the jet to cavitate is also reduced by the presence of trace amounts of polymer. Imaging of bioluminescence stimulated by a turbulent jet will assess whether trace amounts of polymer affects the intensity of the stimulated bioluminescence and the size of the luminescent signature.

APPROACH

For objective 1, the effect of PEO on spontaneous bioluminescence is investigated in the dinoflagellate *Lingulodinium polyedrum*, which exhibits spontaneous flashes and glowing in the absence of flow stimulation. Bioluminescence is measured in an integrating light collector using a photon-counting photomultiplier. Bioluminescence potential is measured in a commercial luminometer, with total light emission released by chemical stimulation using acetic acid to bypass the mechanical transduction pathway and directly activate the luminescent chemistry.

For objective 2, a new pipe flow apparatus was fabricated with complementary financial and engineering support from SSC San Diego. The apparatus consists of a clear acrylic pipe with an internal diameter of 0.635 cm, the same dimension used previously (Rohr et al. 1990, Latz and Rohr

1999, Latz et al. 2004). Flow through the pipe is regulated by a computer-controlled pump system located downstream of the pipe. Upstream of the pipe is a tapered nozzle to assure laminar flow at the inlet even at high flow rates. Flow rate is measured by a mass flow meter downstream of the pump and the pressure drop within the pipe is measured by a pair of ports connected to a differential pressure transducer. Bioluminescence is measured by a photomultiplier detector located 200 pipe diameters downstream of the inlet where the flow is fully developed. All flow and bioluminescence measurements are taken directly by computer. The volume of water measured is kept constant for all flow rates tested. Dinoflagellate cultures are diluted into filtered seawater to achieve desired cell concentrations, and for polymer treatments the polymer Polyox (polyethylene oxide) was premixed into the seawater to achieve final concentrations of 10 or 30 ppm.

For objective 3, bioluminescence stimulated by a turbulent jet is measured using an apparatus previously used for ONR-funded work. Bioluminescence stimulation occurs as a result of high speed flow through a 2 mm nozzle into a tank containing a known species and concentration of luminescent dinoflagellates. The tank is positioned within an integrating light collection chamber where bioluminescence intensity is measured by a photomultiplier detector and the spatial pattern of bioluminescence simultaneously measured by a low-light video camera. This mode of stimulation is extremely repeatable allowing a comparison between no polymer and polymer treatments.

WORK COMPLETED

(1) Initial tests last year demonstrated that there was no effect of polymer on fluid density or fluid dynamic viscosity. Tests of the effect of polymer on bioluminescence potential per cell of *L. polyedrum*, based on measurements of bioluminescence stimulated by acid treatment, showed no significant difference compared to seawater controls.

(2) The pipe flow apparatus was completed, tested, and calibrated last year. The apparatus was designed with a valve assembly so that the pipe could be backfilled by having the pump push water through to remove all air. Then the valve arrangement was switched to allow the pump to pull water through the pipe for bioluminescence tests. The pipe inlet was positioned within an 80 L vat filled with the desired concentration of dinoflagellate. A homogeneous distribution of organisms throughout the vat was accomplished using a modified Archimedes screw design to achieve adequate mixing with minimal prestimulation.

(3) The pipe flow apparatus was used last year in tests of the effect of polymer treatment on flow-stimulated bioluminescence of the coastal dinoflagellate *Lingulodinium polyedrum*. PEO concentrations of 10 and 30 ppm were tested for a dinoflagellate cell concentration of 10 cells/ml.

(4) Drag reduction by the polymer occurs only in turbulent flow. Tests in laminar flow, where polymer is not expected to affect flow properties, were used as a control to normalize the turbulent flow results and to evaluate whether polymer treatment affected flow sensitivity of dinoflagellates.

RESULTS

Last year's tests confirmed that polymer treatment resulted in as much as a 50% reduction in friction factor. As friction factor is directly proportional to pipe wall shear stress, this inferred that pipe wall shear stress was also reduced by as much as 50%. Thus we expected that bioluminescence intensity of

L. polyedrum stimulated in turbulent flow would be reduced. Surprisingly, there was no noticeable effect on bioluminescence intensity. Perhaps *L. polyedrum* is being maximally stimulated regardless of the reduction in wall shear stress that PEO provides. Polymer treatment increased bioluminescence intensity in laminar flow (Figure 1, left). This result was unexpected because PEO has no drag reducing properties in laminar flow. Thus polymer treatment may be causing a physiological change in the dinoflagellates resulting in enhanced flow sensitivity. There was no significant effect of 10 ppm or 30 ppm PEO treatment on bioluminescence potential per cell. One possibility is that the polymer is causing an osmotic imbalance resulting in cell swelling, which causes increased flow sensitivity in *L. polyedrum* (Chen et al. 2007). Measurements of cell size with a Coulter Counter showed no significant difference between the equivalent spherical diameter of 10 ppm PEO-treated (37.5 μm) and seawater control (37.3 μm) cells (Figure 1, right). Thus increased flow sensitivity due to cell swelling was ruled out although PEO exposure appears to cause other physiological changes resulting in increased flow sensitivity.

Pipe flow represents a bounded flow where polymer treatment affects the interaction of the fluid with the pipe walls. The next phase of testing involves using the polymer with jet turbulence, an unbounded flow with a fully turbulent flow field. With jet turbulence it will be possible to assess the effect of polymer treatment on the size and intensity of the bioluminescence signature.

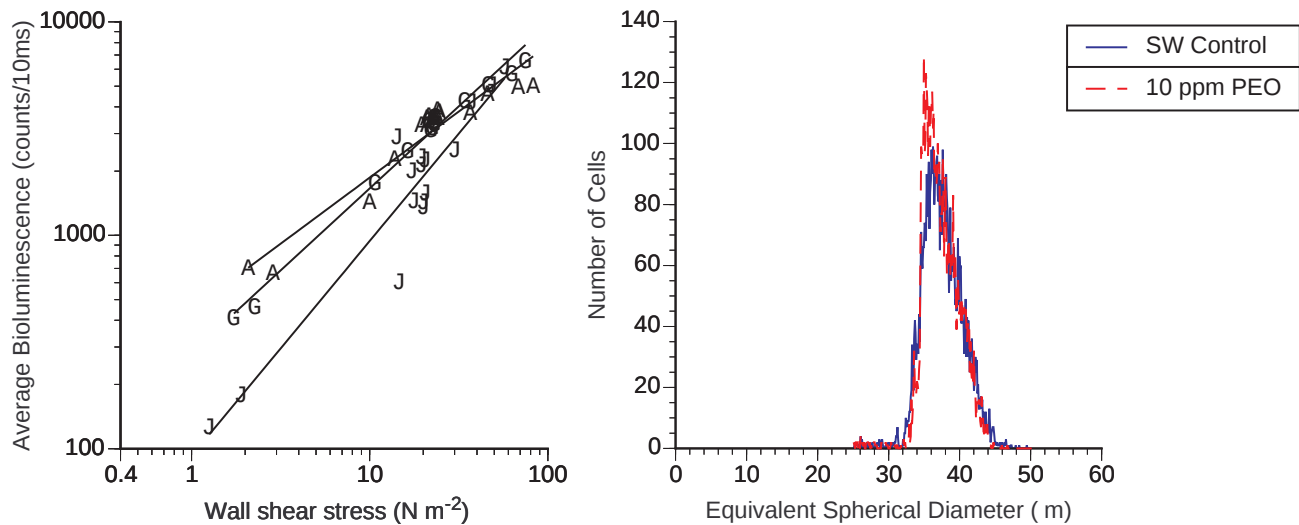


Figure 1. (Left) Effect of polymer treatment tested in laminar and turbulent pipe flow. Solid symbols are for the no polymer condition; open symbols are for two experiments with 30 ppm PEO polymer treatment. Symbols represent average bioluminescence intensity of the dinoflagellate *Lingulodinium polyedrum* as a function of wall shear stress for each flow. Values at wall shear stress values $< 3 \text{ N m}^{-2}$ are for laminar flows. There was no difference in bioluminescence between the polymer and no polymer conditions for turbulent flows, but PEO treatment resulted in greater bioluminescence when tested in laminar flow. (Right) Cell size was not affected by 10 ppm PEO treatment, indicating that that PEO did not result in osmotic changes resulting in cell swelling. These results suggest that the increased bioluminescence in laminar flow was not due to increased flow sensitivity due to cell swelling.

IMPACT/APPLICATIONS

Tests of the effect of drag-reducing polymer treatment on bioluminescence stimulated by turbulent pipe flow, a bounded flow field, showed no evidence for bioluminescence suppression. We are presently exploring: (1) whether cells were maximally stimulated in turbulent flow regardless of whether the polymer was present; (2) why polymer increases flow sensitivity of *L. polyedrum* in laminar flow; and (3) whether cells were stimulated in turbulent pipe flow near the wall where the polymer PEO may have minimal effect.

Work with a turbulent jet, an unbounded flow field, will assess whether the polymer treatment affects the spatial footprint and intensity of a bioluminescence signature. Based on the results of this study, it will be possible to determine whether to further explore polymer-based bioluminescence reduction as a mitigation strategy. This knowledge will be beneficial in the context of potential DARPA projects exploring mitigation strategies for decreasing the amount of flow-stimulated bioluminescence associated with SDV's and other underwater vehicles. This project represents the latest contribution from a productive partnership between academic (SIO) and Navy (SSC San Diego) research. Specifically, SSC San Diego has provided supplemental funding, engineering expertise, and assistance from an ONR NREIP summer intern.

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