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6. AUTHOR(S)
Michael P. Schultz and Lawrence J. Borne

7. PERFORMING ORGANIZATION NAMES(S) AND ADDRESS(ES)
Harbor Branch Oceanographic Institution
5600 U.S. Highway One, North
Ft. Pierce, FL 34946

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9. SPONSORING / MONITORING AGENCY NAMES(S) AND ADDRESS(ES)
Office of Naval Research
Program Officer Kelvin T. Higa
Ballston Centre Tower One-800 N. Quincy Street
Arlington, VA 22217-5660

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The development of novel, fouling-release surfaces has led to the need for test methods to better quantify their efficacy. Of considerable interest is the attachment strength of microfouling to these surfaces. The objective of the present project was to design, construct, and calibrate a water channel facility for the screening of novel fouling-release coatings to be used by Prof. J. Callow and Dr. M. Callow at the University of Birmingham, UK. A high aspect ratio (15:1) channel accommodating sixstandard glass slides coated with candidate formulations was designed. At present, fabrication of the water channel is approximately 80% complete. Upon completion, the channel will be tested and calibrated. Delivery of the apparatus to the University of Birmingham is planned for early June, 1999.

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DESIGN, CONSTRUCTION, AND CALIBRATION OF A WATER CHANNEL FACILITY FOR THE SCREENING OF FOULING-RELEASE SURFACES

Michael P. Schultz and Lawrence J. Borne
Division of Engineering R&D
Harbor Branch Oceanographic Institution
5600 US 1 North
Fort Pierce, Florida 34946

30 April 1999

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Prepared for:

OFFICE OF NAVAL RESEARCH
Program Officer Kelvin T. Higa
Ballston Centre Tower One
800 North Quincy Street
Arlington, VA 22217-5660

TABLE OF CONTENTS

LIST OF FIGURES

Abstract

The development of novel, fouling-release surfaces has led to the need for test methods to better quantify their efficacy. Of considerable interest is the attachment strength of microfouling to these surfaces. The objective of the present project was to design, construct, and calibrate a water channel facility for the screening of novel fouling-release coatings to be used by Prof. J. Callow and Dr. M. Callow at the University of Birmingham, UK. A high aspect ratio (15:1) channel accommodating six standard glass slides coated with candidate formulations was designed. At present, fabrication of the water channel is ~80% complete. Upon completion, the channel will be tested and calibrated. Delivery of the apparatus to the University of Birmingham is planned for early June, 1999.

Keywords/Phrases

Enteromorpha, shear stress, adhesion strength, polymers, hydrodynamics, biofouling

1 INTRODUCTION

The attachment strength of microbial fouling organisms under flow has been studied extensively (e.g. Fowler & Kay, 1980; Pedersen, 1982; Milne & Callow, 1985; Hyde *et al.*, 1989; Woods & Fletcher, 1991; Arrage *et al.*, 1993; Callow *et al.*, 1993). However, an accurate, repeatable means of determining the shear stresses required for the detachment of microfouling from fouling-release surfaces is lacking. The goal of this project was to design, construct, and calibrate a flow apparatus to meet the following minimum requirements:

- Provide a rapid, repeatable screening test for fouling release surfaces.
- Maintain a well characterized flow over the range of velocities tested.
- Operate at a range of flow velocities compatible with the size and attachment strength of *Enteromorpha* zoospores.
- Accommodate six replicate standard glass microscope slides per test.

Prior to commencing the design of the water channel, a literature review was conducted to identify flow facilities that had been used in previous research in biofilm adhesion. Several flow cell designs have been used for this purpose. These include the radial flow chamber (RFC), laminar channel flow cell, fully-developed turbulent pipe flow, and the annular flow cell.

The RFC (Figure 1) has been by used by a number of researchers to assess the relative attachment strength of a variety of organisms to a range of test surfaces (e.g. Fowler & Kay, 1980; Milne & Callow, 1985; Hyde *et al.*, 1989; Woods & Fletcher, 1991; Callow *et al.*, 1993).

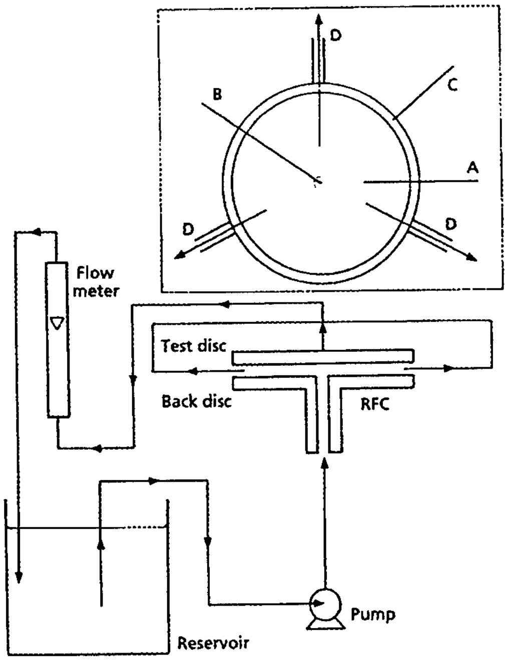

Figure 1 Schematic of the radial flow chamber of Callow *et al.*, 1993.

Callow *et al.* (1993) used an RFC to study the adhesion of the marine diatom *Amphora coffeaeformis*. The wall shear stresses required to remove half of the diatoms from a glass surface and a silane-coupled hydrophobic coating were 5.5 Pa and 12.2 Pa, respectively. It was noted that while the RFC provided a quick method of comparing the attachment strength on various surfaces, critical shear stress values should be used with caution. It was also noted that flow non-uniformity led to anomalies near the center of the cell and at its midpoint. It is our opinion that these observations are due to a stagnation point at the cell's center and the lack of sufficient outlet pipes at the periphery of the cell. Further complicating the situation is the laminar-turbulent transition that occurs on the test surface.

Laminar flow cells have also been used in the study of biofilm attachment strength (e.g. Pedersen, 1982; Arrage *et al.*, 1993). The flow cell used by Pedersen (1982) is shown in Figure 2.

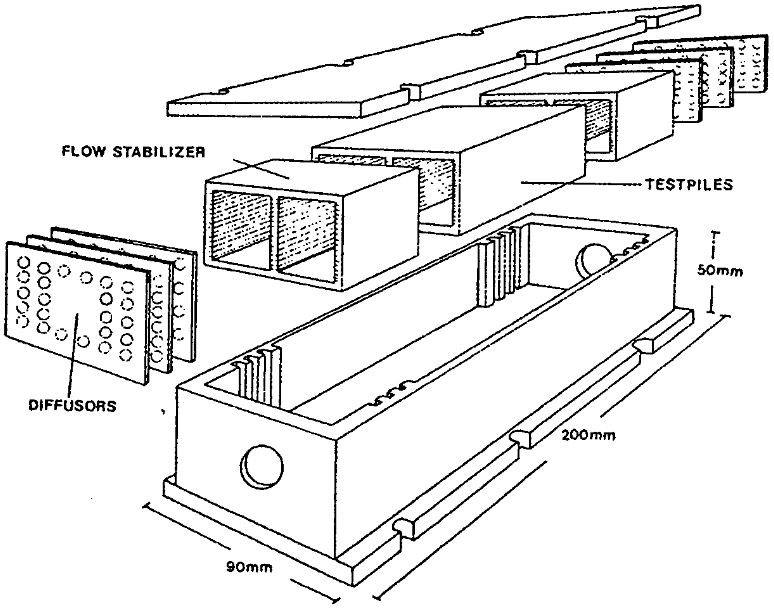

Figure 2 Laminar flow cell of Pedersen, 1982.

This arrangement was designed to allow settlement assays on a number of microscope cover slips. It should be noted that some care was given to the hydrodynamics in this set up. The diffusers and flow stabilizer were incorporated to increase flow uniformity and reduce large-scale vorticity. Flow visualization studies confirmed that the flow in the test cell was quite uniform. Although there are some attractive features to this design, its use in the present investigation would be hampered by several factors. First, the stacked design would present problems with testing coated slides. Differences in the gap between the slides could lead to an order of magnitude difference in the shear stress. Also, there is not adequate development length to allow the flow to become fully-developed. The term fully-developed refers fact that given sufficient development length (~60 pipe diameters in the case of turbulent flow) the velocity profile in the pipe remains constant in the streamwise direction. Since the flow is not fully-developed in this design, there is a variation in the shear stress along the length of the slide.

The laminar flow cell used by Dr. D.C. White's group at the University of Tennessee is shown in Figure 3.

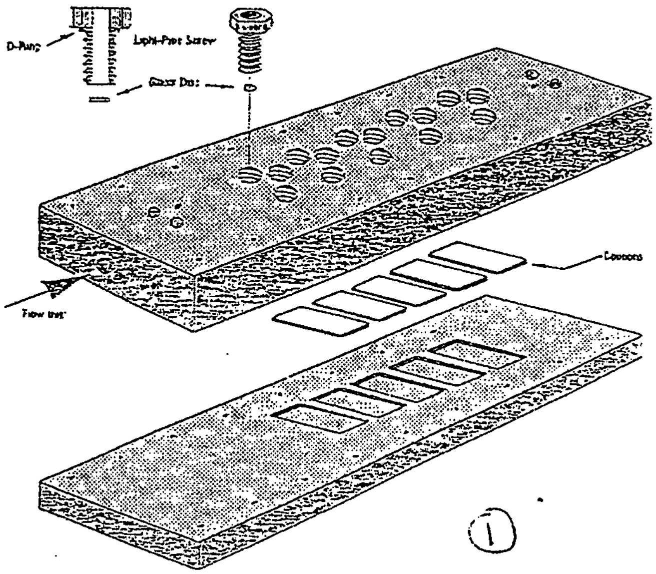

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Figure 3 Laminar flow cell (from Arrage *et al.*, 1993).

In this flow cell, five test coupons are arranged streamwise along a high aspect ratio channel. The design does allow some development upstream of the coupons, although it is not clear that it is sufficient for fully-developed laminar conditions. The channel height is 1 mm. This would make its use in the present investigation difficult. The effect of a slight misalignment of the glass slides or irregularity of the test surface would be magnified in this flow cell. For example, a slide placed upstanding of the channel wall by only 0.1 mm would cause an increase in the local mean velocity of 10% and an even greater change in the wall shear stress. And, since the slides are arranged streamwise, the flow conditions over a single slide affect the flow over the slides downstream.

Fully-developed turbulent pipe flow was used by Characklis and co-workers (Zelver, 1979; Picologlou *et al.*, 1980) to study the effect of bacterial biofilms on frictional resistance. Picologou *et al.* (1980) found that bacterial biofilms did not significantly alter the wall shear stress over first 35 hrs of settlement but subsequently led to a marked increase. The use of a fully-developed pipe flow design allowed the accurate determination of the wall shear stress from a simple measurement of the pressure drop along the pipe. High aspect ratio rectangular channels offer similar advantages and also have well defined flow characteristics (e.g. Tiederman *et al.*, 1985; Characklis, 1990; Durst *et al.*, 1998). The fully-developed, turbulent channel flow facility of Tiederman *et al.* (1985) is shown in Figure 4.

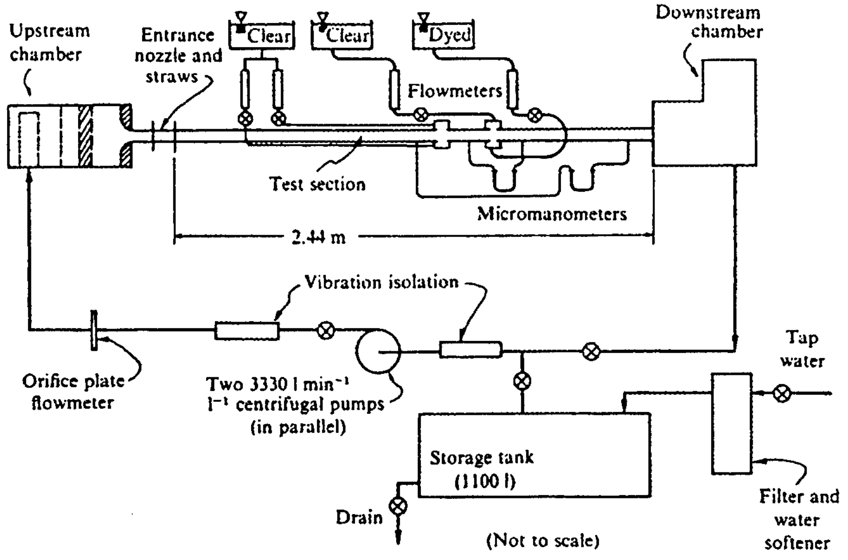

Figure 4 Schematic of a fully-developed, turbulent channel flow facility (from Tiederman *et al.*, 1985).

This facility was designed for accurate determination of the wall shear stress. One should note the considerable care given to inlet flow management. The use of a setting chamber with perforated plate diffusers, honeycomb flow straighteners, screens, and large contraction ratio provides the necessary inlet conditions for accurate and repeatable shear stress measurements in the test section.

Annular flow cells have also been used to study the attachment of microbes (Characklis, 1990). A schematic of an annular flow cell is presented in Figure 5.

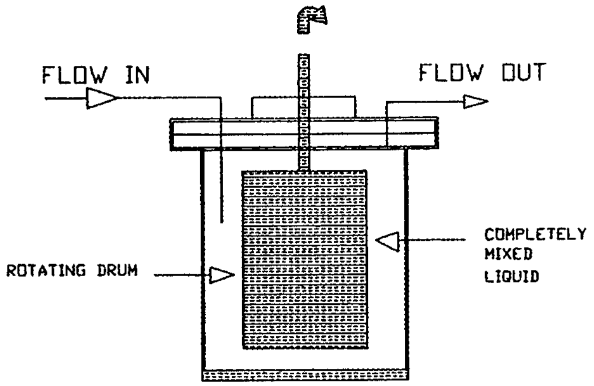

Figure 5 Schematic of an annular flow cell (from Characklis, 1990).

These flow devices consist of concentric cylinders in which the gap is filled with water. The inner cylinder rotates at a rate that is varied based on the shear stress desired. The wall shear stress is determined using the applied torque and the rotation rate. Removable coupons can be mounted on the wall of the outside cylinder to conduct biofilm sampling. The simplicity and the fairly well defined flow pattern generated make this a desirable design. However, the use of standard glass slides in this type of flow cell would be problematic. The coupons would have to be curved and mounted flush if an accurate shear stress determination was to be made.

Based on the literature review and the aforementioned system requirements, it was concluded that the best design would be a fully-developed, turbulent channel flow. The following were the major determining factors in this decision:

- Fully-developed flow allows accurate determination of the wall shear stress that the spores are exposed to.
- A high aspect ratio channel facilitates the mounting of the slides and reduces secondary flows that can lead to variation in the shear stress across the channel.
- Turbulent flows allow higher wall shear stresses to be generated. Dr. M. Callow (personal communication) believes that *Enteromorpha* spores may require a significantly higher shear stress than the (5 –12 Pa) necessary to remove *Amphora* (Callow *et al.*, 1993). To generate these stresses in a manageable system, turbulent flow is required. Furthermore, turbulent flow is more realistic since ships operate in the turbulent flow regime (e.g. Saunders, 1957; Patel, 1998). And, as previously mentioned, considerable care needs to be given with inlet conditions to maintain a laminar flow.

2 WATER CHANNEL DESIGN AND FABRICATION

2.1 General Information

The design chosen for the evaluation of the strength of adhesion of *Enteromorpha* to fouling-release surfaces was a fully-developed, turbulent channel flow facility. A schematic of the water channel design is shown in Figure 6. System components include: centrifugal pump, magnetic flowmeter, settling chamber, test section, digital manometer, discharge tank, and piping. The approximate overall dimensions of the system are 1 m in height, 2.5 m in length, and 1 m, in width. The design velocity range in the test section is 0.5 – 3.0 m/s. The resulting wall shear stress ranges from approximately 1 – 30 Pa.

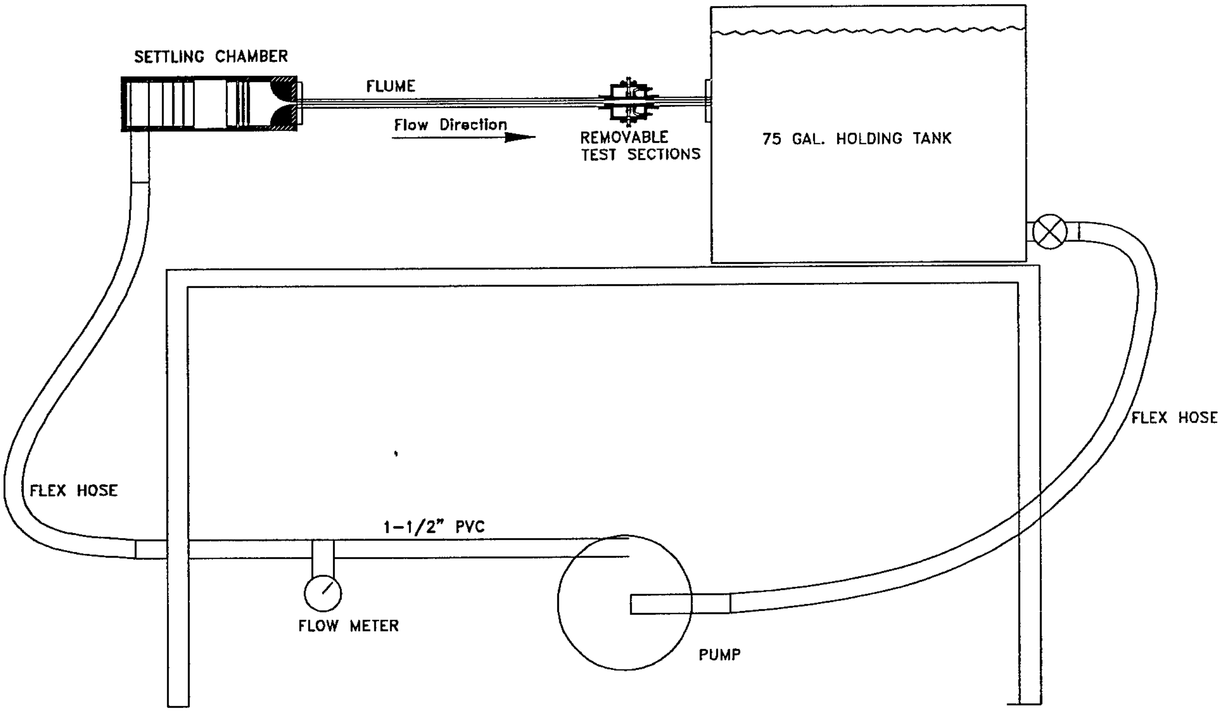

Figure 6 Schematic of the water channel design.

2.2 Centrifugal Pump

A 0.56 kW (¾ hp) thermoplastic centrifugal pump capable of delivering 151 liters per minute (40 gpm) at 9 m of head is used to drive the flow in the water channel. The motor is single phase and operates on 230V. A picture of the centrifugal pump is shown in Figure 7.

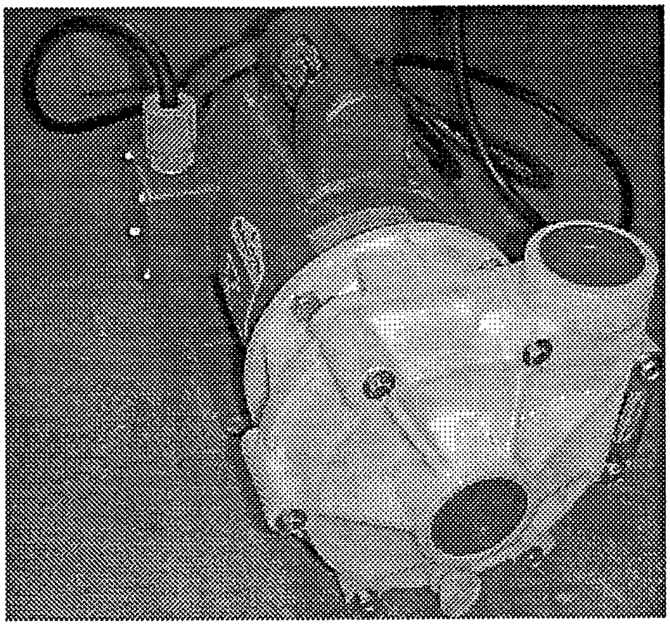

Figure 7 Centrifugal pump.

2.3 Magnetic Flowmeter

A magnetic flowmeter placed downstream of the pump monitors the flow rate through the system. The flowmeter is an ABB MagMaster model #MFE4ER140311 transmitter with a model #MFE400372801004ER magnetic sensor. The accuracy of the flowmeter is ±0.2% of the reading over the design range of 23 to 132 liters per minute (6 to 35 gpm). This allows the bulk mean velocity in the test section to be determined to a similar accuracy. Figure 8 shows the magnetic flowmeter.

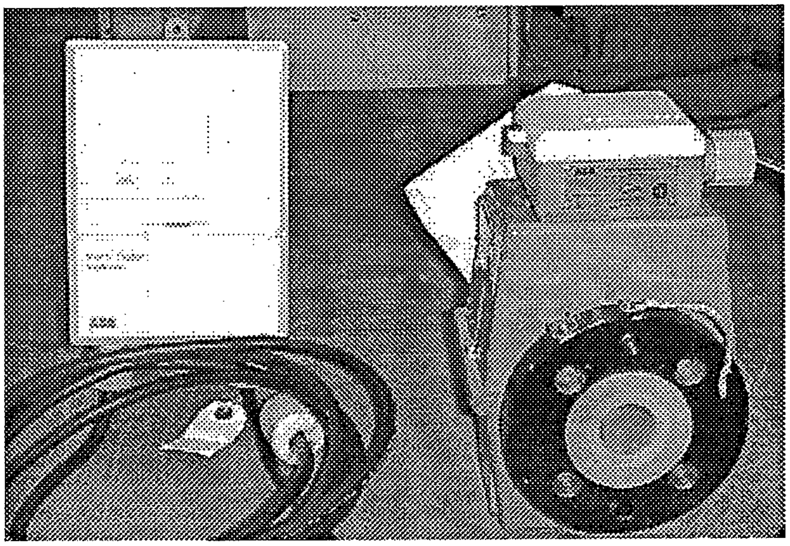

Figure 8 Magnetic flowmeter.

2.4 Settling Chamber

A settling chamber is placed upstream of the test section. The purpose of the settling chamber is to improve the flow uniformity, remove any large scale vorticity induced by the pump, and to lower the background turbulence intensity in the test section. A schematic of the settling chamber is given in Figure 9.

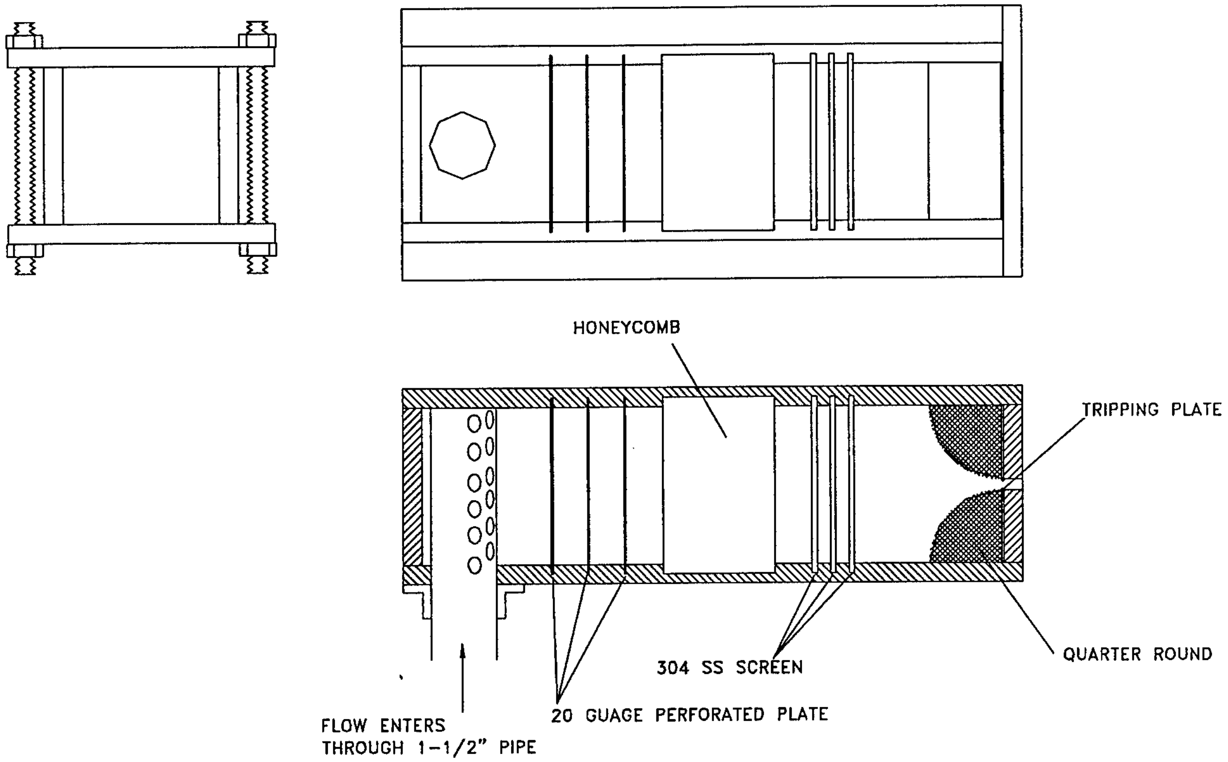

Figure 9 Schematic of the settling chamber.

Flow enters the settling chamber by means of a perforated pipe and then passes through three perforated plates, which act as diffusers. These are constructed of 20 gauge 304 stainless steel and have open area ratios of 40%, 51%, and 63%, respectively. A polycarbonate honeycomb (6 mm openings and a length of 75 mm) and a series three screens (#24 mesh, 60 % open area ratio) further reduce large scale vorticity and freestream turbulence levels. At the end of the settling chamber, a two-dimensional nozzle (contraction ratio of 15:1) accelerates the flow and reduces the relative magnitude of the background turbulence. Just downstream of the contraction, tripping plates are placed. These are ~ 0.5 mm in height (~15% blockage as recommended by Durst *et al.*, 1998) and insure that the flow in the test section becomes a fully-developed turbulent flow at the lower Reynolds number range. A picture of the settling chamber is presented in Figure 10.

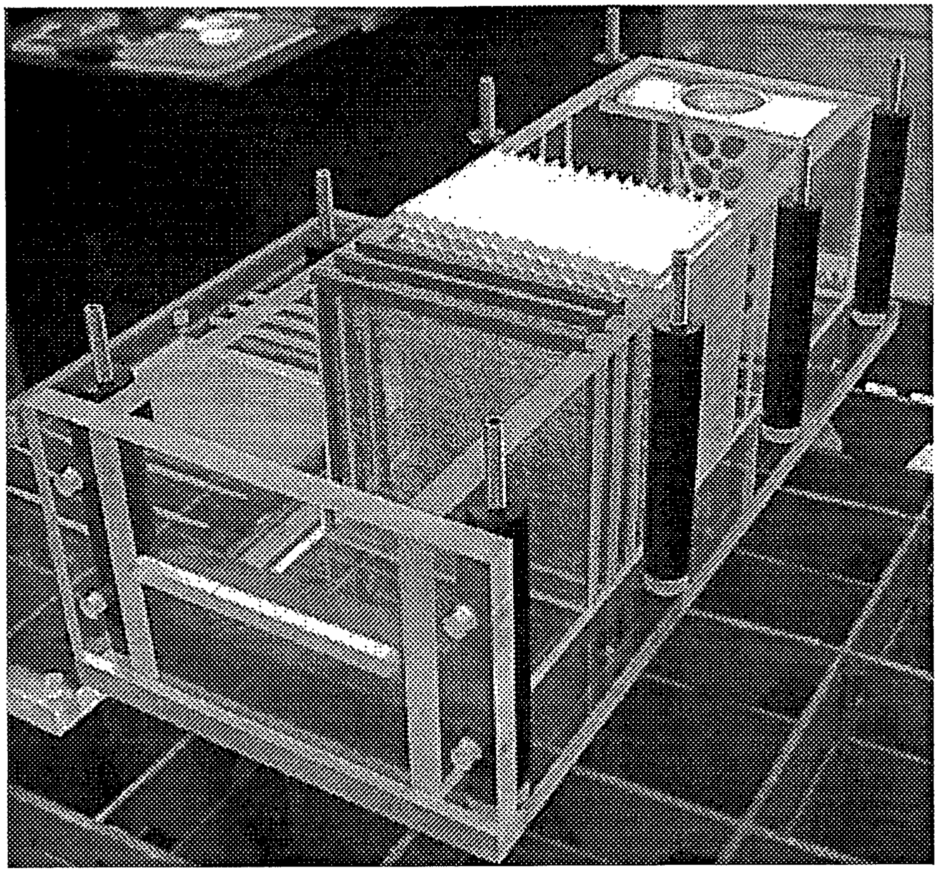

Figure 10 Settling chamber.

2.5 Test Section

The test section is 7 mm in height (H), 105 mm in width (W), and 1000 mm in length (L) (15:1 aspect ratio). The section is constructed of acrylic to allow optical access for viewing the experiment or for flow measurements with laser-Doppler velocimetry (see Figures 11 & 12).

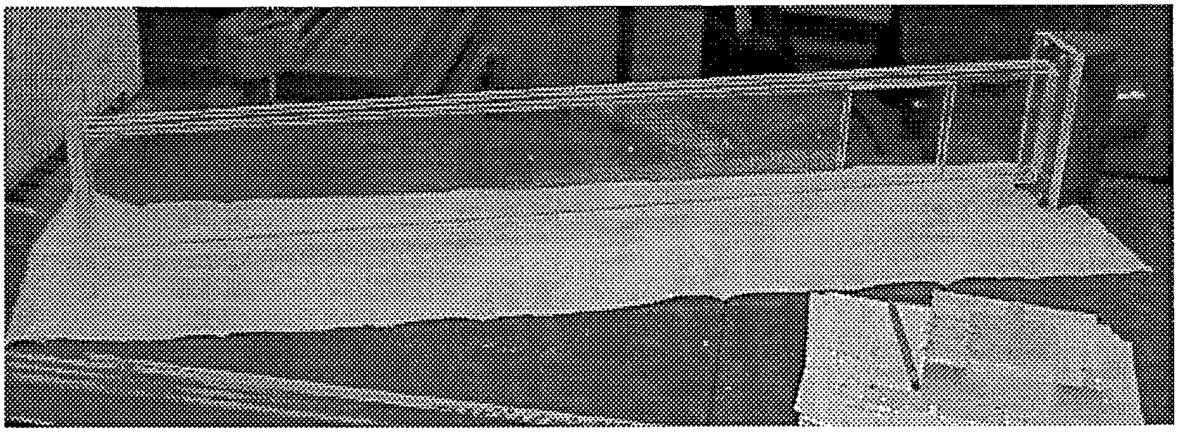

Figure 11 Acrylic test section.

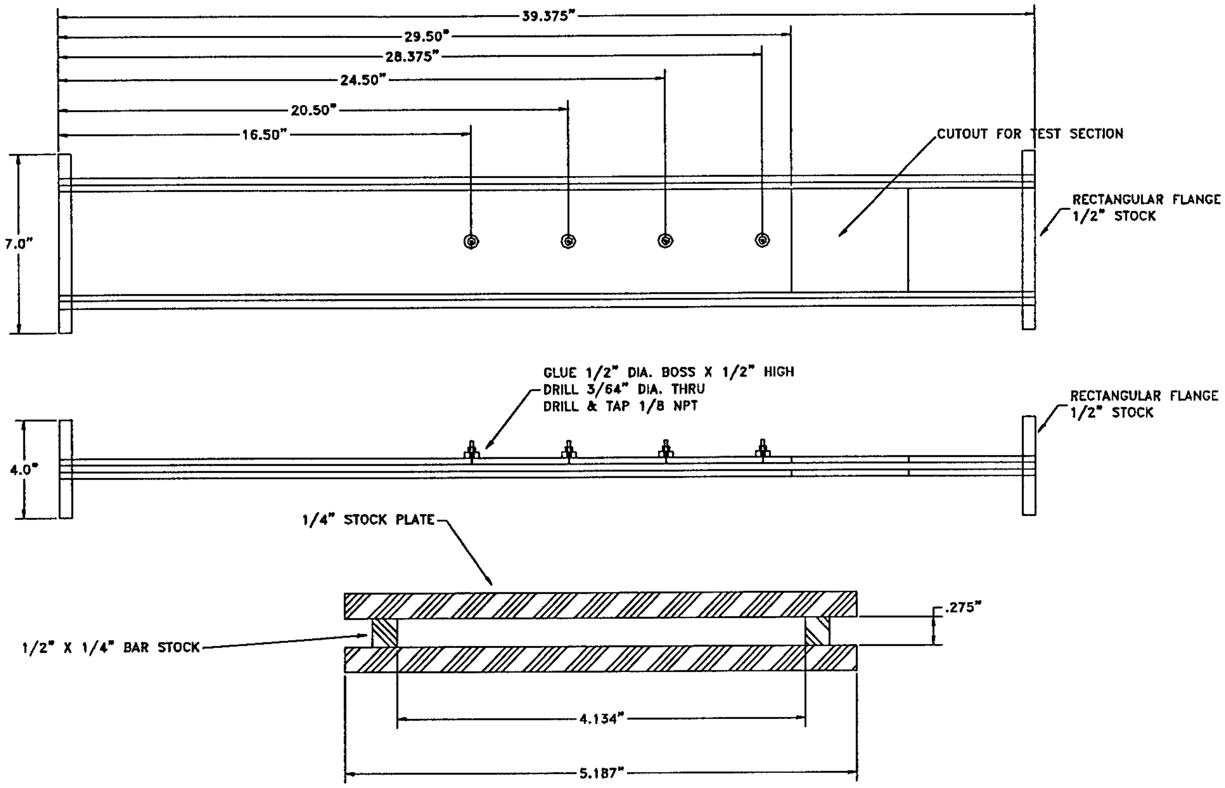

Figure 12 Schematic of the test section.

Four pressure taps are placed from 60H to 100H downstream of the tripping plates. Durst *et al.* (1998) have found that 60H is a sufficient length to obtain fully-developed, turbulent channel at Reynolds numbers >3000. In fully-developed flow, the wall shear stress is related to the pressure drop in a high aspect ratio channel by Equation 1 (Hussain & Reynolds, 1975):

$$\tau_w = -\frac{H}{2}\frac{dp}{dx} \qquad (1)$$

where: τ_w = wall shear stress
H = channel height
dp/dx = streamwise pressure gradient

The mounting apparatus for the six replicate slides is placed 750 mm downstream of the tripping plates. The slides are placed side by side, with their long axis aligned with the flow. Three are placed on the top of the channel and three on the bottom. Each slide mounting port has an articulating positioning mechanism. This allows the slide to be positioned flush with the channel wall and allows variation in coating thickness to be accommodated. The mounting port uses a vacuum applied to the reverse side of the slide to hold it in place (see Figures 13 & 14).

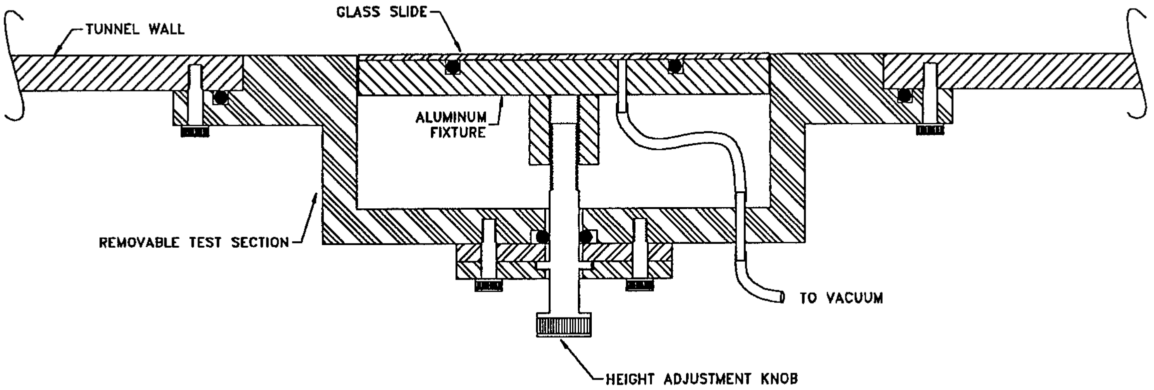

Figure 13 Schematic of slide mounting apparatus.

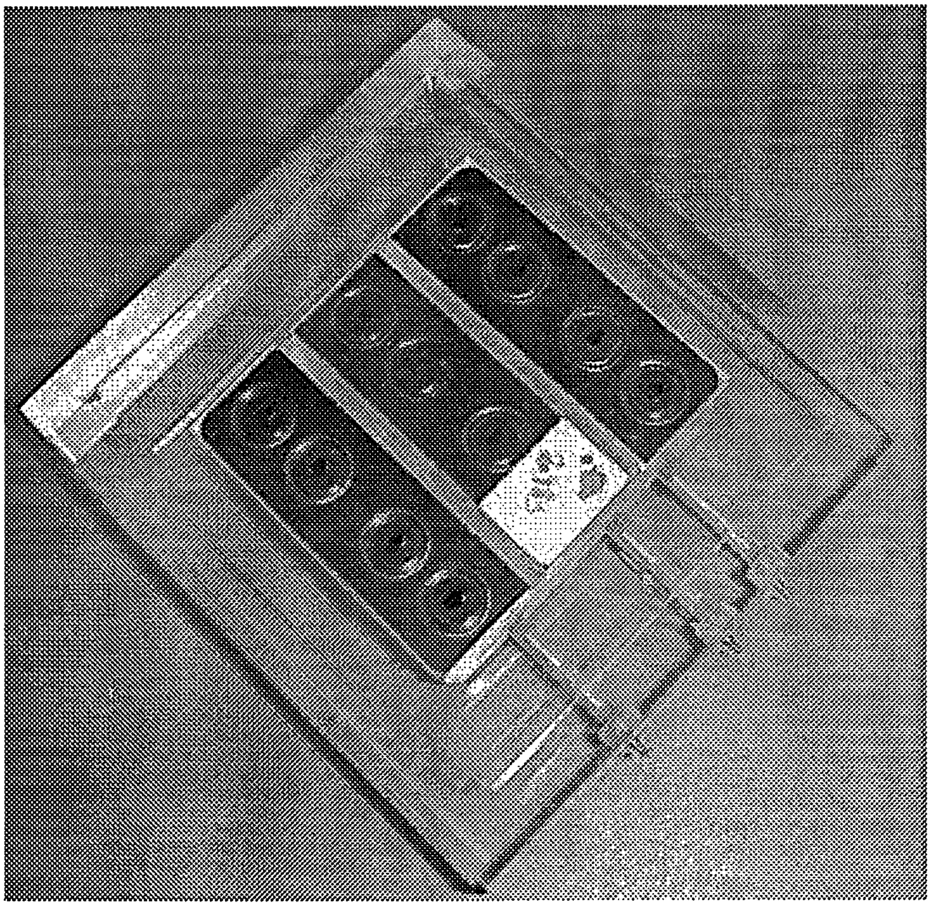

Figure 14 Slide mounting apparatus.

It should be noted that from a fluid mechanics perspective it would be desirable to have the flow develop entirely over a spore fouled surface. In that case, the effect of the spores on the wall shear stress could be evaluated. However, since the spores are small (~5 μm) and the logistics of 1000 mm test specimens is unmanageable for a rapid screening test, it will be assumed that the flow is virtually unaltered by the presence of the spores. This appears to be a valid assumption since estimates of the viscous length scale range from much greater than to approximately equal to the size of the spores over the range of velocities to be tested. To ensure this is the case, the spores should not be given a significant growth period. Biofilms that were allowed to grow as little as 96 hrs have been shown to significantly increase the wall shear stress and turbulence structure in boundary layer flows (Schultz & Swain, 1999).

2.6 Digital Manometer

A digital manometer is used to measure the pressure drop in the test section. The meter is a Validyne differential model #PS309D-1-N-1 with nickel plated stainless steel wetted parts for corrosion resistance. Its range is 0-150 mm H_2O with an accuracy of ±0.25% of full scale. The use of several pressure tap spacings allows the manometer to operate in the upper part of its range and give more accurate pressure measurements. This should allow the wall shear stress in the test section to be determined to within ±4% over the entire velocity range.

Figure 15 Digital manometer.

2.7 Discharge Tank

The flow from the test section exits into a diffuser pipe and into a discharge tank. The tank has a large volume (265 liters) that will increase the time necessary for all of the fluid to make a complete circuit of the water channel. This should help reduce the buildup of heat in the seawater. Its relatively large size should also allow flow exiting the test section to settle before being recirculated. If the test runs are going to be conducted over long periods of continuous operation (say >20 min.), a cooling coil may be necessary to further reduce heating of the seawater. A thermometer is mounted in the discharge tank to allow monitoring of the seawater temperature during the experiments.

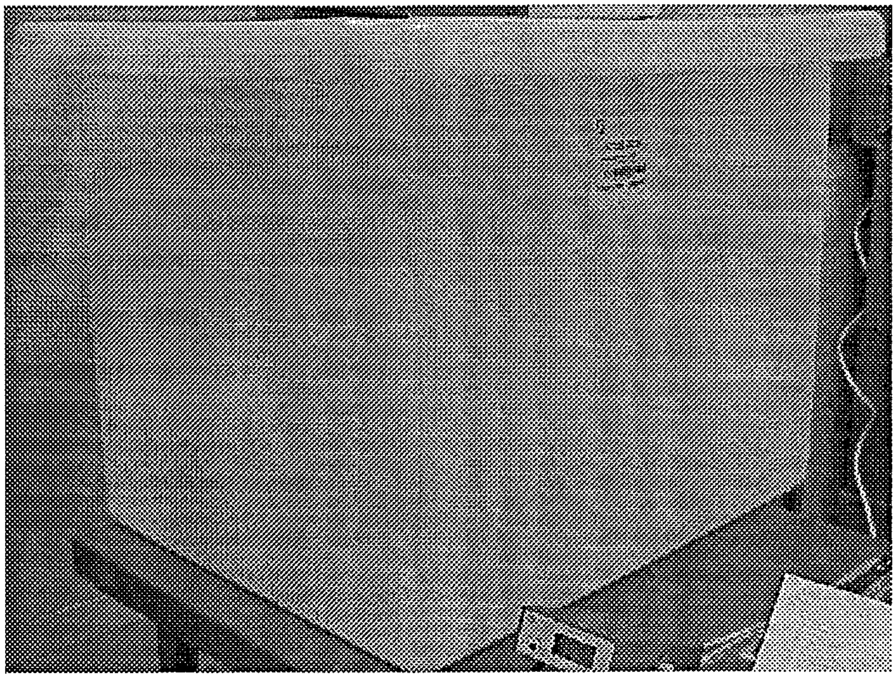

Figure 16 Discharge tank.

2.8 Piping

The piping for the system will be a combination of standard schedule 40, 1-1/2" (38 mm) diameter pipe and 1-1/2" (38 mm) flexible hose. This allows for corrosion resistance, easy fabrication, and inexpensive system alterations. The flexible hose serves to isolate any pump vibration from the rest of the system.

3 SYSTEM CALIBRATION, DELIVERY, AND SETUP

3.1 System Calibration

System calibration is to be conducted at Harbor Branch Oceanographic Institution. This will occur following the final stages of fabrication and assembly, which are projected to be completed in the first week of May 1999. The calibration will consist of proofing the system to check for leaks and confirm proper operation. The pressure drop in the test section will be measured over the entire range of design flow velocities. A calibration curve of wall shear stress versus flow rate will be generated. This will allow a simple means for the researchers at the University of Birmingham to quickly estimate the wall stress in their experiments. However, deviations from the calibration salinity and temperature will likely occur. These will affect the wall shear stress. For a more accurate determination of the wall shear stress, it is recommended that the pressure drop measurements be made during the experiments as well. Calculation of the wall shear stress given the pressure drop in the test section can be made using Equation 1.

3.2 System Delivery and Setup

The calibrated water channel will be delivered and setup at the University of Birmingham by Dr. M. Schultz and L. Borne, P.E. of Harbor Branch. The setup will include three days of system orientation for Prof. J. Callow, Dr. M. Callow, and their research assistant. Operation of the system will be demonstrated and preliminary measurements of the adhesion strength of *Enteromorpha* will be made. System delivery and setup are planned for the first week in June 1999.

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