Abstract:
The purpose of this research, the experimental measurement of a biofilm in a heat exchanger, was to determine the relationship between the biofilm thickness and certain flow parameters. Four test runs were conducted using four different test sections to determine the effect a biofilm produces on the friction factor, the wall shear stress, and the pressure fluctuations in a heat exchanger. The change in the friction factor and the growth of the biofilm approximated the theoretical work, with slight discrepancies in the induction time and maximum values at the conclusion of each test run. The results of the wall shear stress were promising, with the maximum wall shear stress similar for all four test runs in all four flow loops. The pressure fluctuations proved inconclusive in the research, with a random variation of frequencies occurring throughout the investigation. The results of the detachment phase showed a linear relationship between the test parameters and the fluid velocity for the range tested.
EXPERIMENTAL MEASUREMENT OF BIOFILM 
IN A HEAT EXCHANGER

by

Douglas Wayne Heal

A thesis submitted in partial fulfillment 
of the requirements for the degree

of

Master of Science

in

Mechanical Engineering

MONTANA STATE UNIVERSITY
Bozeman, Montana

June, 1989
APPROVAL

of a thesis submitted by

Douglas Wayne Heal

This thesis has been read by each member of the thesis committee and has been found to be satisfactory regarding content, English usage, format, citations, bibliographic style, and consistency, and is ready for submission to the College of Graduate Studies.

June 28, 89  Henry W. Towns  Chairperson, Graduate Committee

Approved for the Major Department

6-29-89  Mitchell Hull  Head, Major Department

Approved for the College of Graduate Studies

July 5, 1989  Henry L. Parsons  Graduate Dean
STATEMENT OF PERMISSION TO USE

In presenting this thesis in partial fulfillment of the requirements for a master's degree at Montana State University, I agree that the Library shall make it available to borrowers under rules of the Library. Brief quotations from this thesis are allowable without special permission, provided that accurate acknowledgement of the source is made.

Permission for extensive quotation from or reproduction of this thesis may be granted by my major professor, or in his/her absence, by the Dean of Libraries when, in the opinion of either, the proposed use of the material is for scholarly purposes. Any copying or use of the material in this thesis for financial gain shall not be allowed without my written permission.

Signature  Douglas Koel
Date       6-30-89
ACKNOWLEDGEMENTS

The author is indebted to the following persons for their assistance in this investigation.

Carl Hoerger, for his guidance and encouragement throughout all phases of the experimentation.

Harry Townes, for his advice and assistance in completing the project.

Pat Vowell and Gordon Williamson, for their advice and assistance in the construction and design of the laboratory equipment.

Alan George, for his advice and assistance in the experimentation.

The staff of the Mechanical Engineering Department at Montana State University for their assistance in all aspects of the experimentation.

The National Science Foundation, for their financial assistance throughout the project. Grant No. CBT-8707821

Deanna Walker, for her assistance in proofreading the final version of the thesis.
# Table of Contents

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>List of Tables</td>
<td>vii</td>
</tr>
<tr>
<td>List of Figures</td>
<td>viii</td>
</tr>
<tr>
<td>Nomenclature</td>
<td>xi</td>
</tr>
<tr>
<td>Abstract</td>
<td>xiv</td>
</tr>
<tr>
<td>1. Introduction</td>
<td>1</td>
</tr>
<tr>
<td>2. Review of Previous Literature</td>
<td>5</td>
</tr>
<tr>
<td>Summary of Previous Findings</td>
<td>5</td>
</tr>
<tr>
<td>Implications for this Investigation</td>
<td>11</td>
</tr>
<tr>
<td>3. Outline of Investigation</td>
<td>13</td>
</tr>
<tr>
<td>Objectives</td>
<td>13</td>
</tr>
<tr>
<td>Scope of the Investigation</td>
<td>13</td>
</tr>
<tr>
<td>Facilities and Equipment</td>
<td>14</td>
</tr>
<tr>
<td>Test Matrix</td>
<td>20</td>
</tr>
<tr>
<td>For Growth Phase</td>
<td>21</td>
</tr>
<tr>
<td>For Detachment Phase</td>
<td>22</td>
</tr>
<tr>
<td>4. Pressure Measurements</td>
<td>23</td>
</tr>
<tr>
<td>Experimental Apparatus and Procedures</td>
<td>23</td>
</tr>
<tr>
<td>Friction Factor for Growth Phase</td>
<td>23</td>
</tr>
<tr>
<td>Friction Factor for Detachment Phase</td>
<td>29</td>
</tr>
<tr>
<td>5. Wall Shear Stress Measurements</td>
<td>34</td>
</tr>
<tr>
<td>Experimental Apparatus and Procedures</td>
<td>34</td>
</tr>
<tr>
<td>Wall Shear Stress Results for Growth Phase</td>
<td>34</td>
</tr>
<tr>
<td>Wall Shear Stress Results for Detachment Phase</td>
<td>40</td>
</tr>
<tr>
<td>TABLE OF CONTENTS—Continued</td>
<td></td>
</tr>
<tr>
<td>----------------------------</td>
<td></td>
</tr>
<tr>
<td>6. BIOFILM MEASUREMENTS</td>
<td>45</td>
</tr>
<tr>
<td>Experimental Apparatus and Procedures</td>
<td>45</td>
</tr>
<tr>
<td>Biofilm Thickness for Growth Phase</td>
<td>46</td>
</tr>
<tr>
<td>Biofilm Thickness for Detachment Phase</td>
<td>52</td>
</tr>
<tr>
<td>7. CONCLUSIONS AND RECOMMENDATIONS</td>
<td>57</td>
</tr>
<tr>
<td>Summary of Results for Growth Phase</td>
<td>57</td>
</tr>
<tr>
<td>Summary of Results for Detachment Phase</td>
<td>58</td>
</tr>
<tr>
<td>Recommendations for Further Investigation</td>
<td>59</td>
</tr>
<tr>
<td>REFERENCES CITED</td>
<td>61</td>
</tr>
<tr>
<td>APPENDICES</td>
<td>64</td>
</tr>
<tr>
<td>Appendix A—Calibration of Turbine Flowmeters</td>
<td>65</td>
</tr>
<tr>
<td>Appendix B—Calibration of Pressure Transducers</td>
<td>73</td>
</tr>
<tr>
<td>Appendix C—Data Reduction Program</td>
<td>80</td>
</tr>
<tr>
<td>Appendix D—Oxygen Level Measurements</td>
<td>89</td>
</tr>
<tr>
<td>Appendix E—Fluid Nutrient Measurement</td>
<td>92</td>
</tr>
<tr>
<td>Appendix F—Temperature Variation Measurements</td>
<td>95</td>
</tr>
<tr>
<td>INDEX</td>
<td>101</td>
</tr>
</tbody>
</table>
# List of Tables

<table>
<thead>
<tr>
<th>Table</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Entrance Length Specifications</td>
<td>16</td>
</tr>
<tr>
<td>2. Test Section Specifications</td>
<td>19</td>
</tr>
<tr>
<td>3. Turbine Flowmeter One Calibration Statistics for 0.8-8 GPM</td>
<td>67</td>
</tr>
<tr>
<td>4. Turbine Flowmeter Two Calibration Statistics for 0.8-8 GPM</td>
<td>68</td>
</tr>
<tr>
<td>5. Turbine Flowmeter Three Calibration Statistics for 0.1-1 GPM</td>
<td>69</td>
</tr>
<tr>
<td>6. Turbine Flowmeter Four Calibration Statistics for 0.1-1 GPM</td>
<td>70</td>
</tr>
<tr>
<td>7. Resolution of Frequency Counters</td>
<td>71</td>
</tr>
<tr>
<td>8. Resolution and Accuracy of Turbine Flowmeters</td>
<td>72</td>
</tr>
<tr>
<td>9. Pressure Transducer One Calibration Statistics</td>
<td>75</td>
</tr>
<tr>
<td>10. Pressure Transducer Two Calibration Statistics</td>
<td>76</td>
</tr>
<tr>
<td>11. Pressure Transducer Three Calibration Statistics</td>
<td>77</td>
</tr>
<tr>
<td>12. Pressure Transducer Four Calibration Statistics</td>
<td>78</td>
</tr>
<tr>
<td>13. Resolution of Pressure Calibration Equipment</td>
<td>79</td>
</tr>
<tr>
<td>14. Resolution and Accuracy of Pressure Transducers</td>
<td>79</td>
</tr>
<tr>
<td>15. Nutrient Content of Test Fluid</td>
<td>94</td>
</tr>
</tbody>
</table>
### LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Diagram of Flow Loop and Instrumentation</td>
<td>15</td>
</tr>
<tr>
<td>2.</td>
<td>Diagram of Pressure Tap</td>
<td>18</td>
</tr>
<tr>
<td>3.</td>
<td>Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches</td>
<td>25</td>
</tr>
<tr>
<td>4.</td>
<td>Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches</td>
<td>26</td>
</tr>
<tr>
<td>5.</td>
<td>Friction Factor v. Time for Growth Phase with a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches</td>
<td>27</td>
</tr>
<tr>
<td>6.</td>
<td>Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches</td>
<td>28</td>
</tr>
<tr>
<td>7.</td>
<td>Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches</td>
<td>30</td>
</tr>
<tr>
<td>8.</td>
<td>Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches</td>
<td>31</td>
</tr>
<tr>
<td>9.</td>
<td>Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches</td>
<td>32</td>
</tr>
<tr>
<td>10.</td>
<td>Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches</td>
<td>33</td>
</tr>
<tr>
<td>11.</td>
<td>Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches</td>
<td>36</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>12.</td>
<td>Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches</td>
<td>37</td>
</tr>
<tr>
<td>13.</td>
<td>Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches</td>
<td>38</td>
</tr>
<tr>
<td>14.</td>
<td>Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches</td>
<td>39</td>
</tr>
<tr>
<td>15.</td>
<td>Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches</td>
<td>41</td>
</tr>
<tr>
<td>16.</td>
<td>Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches</td>
<td>42</td>
</tr>
<tr>
<td>17.</td>
<td>Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches</td>
<td>43</td>
</tr>
<tr>
<td>18.</td>
<td>Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches</td>
<td>44</td>
</tr>
<tr>
<td>19.</td>
<td>Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.885 Inches</td>
<td>48</td>
</tr>
<tr>
<td>20.</td>
<td>Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.625 Inches</td>
<td>49</td>
</tr>
<tr>
<td>21.</td>
<td>Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.370 Inches</td>
<td>50</td>
</tr>
<tr>
<td>22.</td>
<td>Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.275 Inches</td>
<td>51</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>--------</td>
<td>-----------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>23</td>
<td>Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.885 Inches</td>
<td>53</td>
</tr>
<tr>
<td>24</td>
<td>Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.625 Inches</td>
<td>54</td>
</tr>
<tr>
<td>25</td>
<td>Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.370 Inches</td>
<td>55</td>
</tr>
<tr>
<td>26</td>
<td>Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.275 Inches</td>
<td>56</td>
</tr>
<tr>
<td>27</td>
<td>Data Reduction Program</td>
<td>84</td>
</tr>
<tr>
<td>28</td>
<td>Oxygen Level In Test Fluid</td>
<td>91</td>
</tr>
<tr>
<td>29</td>
<td>Variation in Fluid and Room Temperature for a Fluid Velocity of 1 ft/sec</td>
<td>97</td>
</tr>
<tr>
<td>30</td>
<td>Variation in Fluid and Room Temperature for A Fluid Velocity of 1.25 ft/sec</td>
<td>98</td>
</tr>
<tr>
<td>31</td>
<td>Variation in Fluid and Room Temperature for a Fluid Velocity of 1.50 ft/sec</td>
<td>99</td>
</tr>
<tr>
<td>32</td>
<td>Variation in Fluid and Room Temperature for a Fluid Velocity of 1.75 ft/sec</td>
<td>100</td>
</tr>
</tbody>
</table>
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>Area</td>
</tr>
<tr>
<td>$A_e$</td>
<td>Cross-Sectional Area</td>
</tr>
<tr>
<td>C</td>
<td>Circumference</td>
</tr>
<tr>
<td>$c_t$</td>
<td>Coefficient of Friction</td>
</tr>
<tr>
<td>D</td>
<td>Diameter</td>
</tr>
<tr>
<td>DMS</td>
<td>Data Monitoring Software</td>
</tr>
<tr>
<td>DO</td>
<td>Dissolved Oxygen</td>
</tr>
<tr>
<td>e</td>
<td>Average Depth of Roughness</td>
</tr>
<tr>
<td>e/D</td>
<td>Relative Roughness</td>
</tr>
<tr>
<td>F</td>
<td>Degrees Fahrenheit</td>
</tr>
<tr>
<td>f</td>
<td>Friction Factor</td>
</tr>
<tr>
<td>$f_{10,000}$</td>
<td>Friction Factor for a Reynolds number of 10,000</td>
</tr>
<tr>
<td>ft</td>
<td>Feet</td>
</tr>
<tr>
<td>FFT</td>
<td>Fast Fourier Transform</td>
</tr>
<tr>
<td>g</td>
<td>Acceleration Due to Gravity</td>
</tr>
<tr>
<td>gm</td>
<td>Gram</td>
</tr>
<tr>
<td>GPM</td>
<td>Gallons per Minute</td>
</tr>
<tr>
<td>$h_f$</td>
<td>Head Loss Due to Friction</td>
</tr>
<tr>
<td>hr</td>
<td>Hour</td>
</tr>
<tr>
<td>Hz</td>
<td>Cycles per Second</td>
</tr>
</tbody>
</table>
### NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>in</td>
<td>Inches</td>
</tr>
<tr>
<td>k</td>
<td>Average Depth of Roughness</td>
</tr>
<tr>
<td>Khz</td>
<td>Kilocycles per second</td>
</tr>
<tr>
<td>L</td>
<td>Length</td>
</tr>
<tr>
<td>Lbf</td>
<td>Pounds-Force</td>
</tr>
<tr>
<td>m</td>
<td>Meter</td>
</tr>
<tr>
<td>mm</td>
<td>Millimeters</td>
</tr>
<tr>
<td>MHz</td>
<td>Megacycles per Second</td>
</tr>
<tr>
<td>min</td>
<td>Minute</td>
</tr>
<tr>
<td>MSU</td>
<td>Montana State University</td>
</tr>
<tr>
<td>( \dot{m} )</td>
<td>Mass Flow Rate</td>
</tr>
<tr>
<td>P</td>
<td>Pressure</td>
</tr>
<tr>
<td>PPM</td>
<td>Parts per Million</td>
</tr>
<tr>
<td>PSI</td>
<td>Pounds-Force per Square Inch</td>
</tr>
<tr>
<td>( P_{\text{dyn}} )</td>
<td>Dynamic Pressure</td>
</tr>
<tr>
<td>r</td>
<td>Radius</td>
</tr>
<tr>
<td>Re</td>
<td>Reynolds number</td>
</tr>
<tr>
<td>s</td>
<td>Seconds</td>
</tr>
<tr>
<td>T</td>
<td>Temperature</td>
</tr>
<tr>
<td>t</td>
<td>Time</td>
</tr>
</tbody>
</table>
## NOMENCLATURE

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFM</td>
<td>Turbine Flowmeter</td>
</tr>
<tr>
<td>$u_0$</td>
<td>Uncertainty</td>
</tr>
<tr>
<td>$v$</td>
<td>Velocity</td>
</tr>
<tr>
<td>$v_0$</td>
<td>Versus (in comparison to)</td>
</tr>
<tr>
<td>$z$</td>
<td>Elevation</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Absolute Viscosity</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Specific Weight</td>
</tr>
<tr>
<td>$\pi$</td>
<td>3.14</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Standard Deviation</td>
</tr>
<tr>
<td>$\tau_w$</td>
<td>Wall Shear Stress</td>
</tr>
<tr>
<td>$\tau_{10,000}$</td>
<td>Wall Shear Stress for a Reynolds number of 10,000</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic Viscosity</td>
</tr>
<tr>
<td>$d(\cdot)$</td>
<td>Differential Quantity</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Mass Density</td>
</tr>
</tbody>
</table>
The purpose of this research, the experimental measurement of a biofilm in a heat exchanger, was to determine the relationship between the biofilm thickness and certain flow parameters. Four test runs were conducted using four different test sections to determine the effect a biofilm produces on the friction factor, the wall shear stress, and the pressure fluctuations in a heat exchanger. The change in the friction factor and the growth of the biofilm approximated the theoretical work, with slight discrepancies in the induction time and maximum values at the conclusion of each test run. The results of the wall shear stress were promising, with the maximum wall shear stress similar for all four test runs in all four flow loops. The pressure fluctuations proved inconclusive in the research, with a random variation of frequencies occurring throughout the investigation. The results of the detachment phase showed a linear relationship between the test parameters and the fluid velocity for the range tested.
CHAPTER 1

INTRODUCTION

One of the major problems facing industry today is the effect of fouling upon heat exchangers. Fouling refers to the formation of an unwanted substance on the surface of a heat exchanger. This formation, or film, can greatly reduce the overall efficiency of the heat exchanger by lowering the heat transfer rate and increasing the pressure drop within the heat exchanger. As the film continues to enlarge, it will continue to lower the efficiency and may eventually restrict the flow of fluid in the heat exchanger completely. The annual cost from this lowered efficiency due to fouling has been estimated by Marner and Suiter [1] to be four to seven billion dollars per year for the United States industrial sector alone.

There are several types of fouling which may affect a heat exchanger. Precipitation fouling occurs when soluble salts which are suspended in the heat exchanger fluid precipitate onto the heat exchanger surface. Particle fouling occurs when suspended particles accumulate on the inside of the heat exchanger. Chemical reaction fouling is caused by the attachment of the products of a chemical reaction onto the heat exchanger surface. Corrosion fouling is caused by the deposition of corrosion products onto the heat exchanger surface. Finally there is biological fouling, or biofouling, which results from the attachment and growth of microorganisms on the heat exchanger surface.
According to Strauss and Puckorius [2] the two recognized forms of industrial biofouling are microbiological fouling of heat exchangers and macrobiological fouling of intake and discharge canals. The former is caused by both plant and animal organisms such as algae and bacteria. The latter stems primarily from invertebrate life such as mussels or clams. This research was concerned exclusively with the investigation of the first, microbiological fouling.

Currently no satisfactory method exists to control the effect of the fouling in heat exchangers. One method is simply to wait until the heat exchanger performance has been substantially reduced, which is indicated by a decrease in the temperature rise across the heat exchanger surface or by reduced condenser vacuum, and then to stop the process and physically remove the deposits. These indicators are very poor in reflecting the fouling occurring within the heat exchanger and irreparable damage may have already occurred before the indicators show that a problem exists. A second method is to add to the heat exchanger fluid chemicals which inhibit any type of potential growth. Periodic chlorination of the water is a common example of this method. Unfortunately, government regulations have severely limited the level of chlorine in heat exchanger fluid discharges, which in turn makes this procedure illegal in many areas. Velocity excursions may be used to remove some of the fouling, but this method does not remove the fouling from the heat exchanger completely and the deposition from fouling quickly returns, causing the efficiency of the heat exchanger to be reduced again. Mechanical cleaning may be used, but the cost of this type of removal is high. Recently a thermal
backwash technique has been experimented with at power plants on the West and East coasts. Thermal backwash, however, must be done frequently enough to kill marine organisms in the juvenile stage. This technique's success depends on the organisms' acclimatization temperatures and thus has met with little success when implemented.

The above control strategies have three major weaknesses according to Turakhia [3]:

1. Process instrumentation is not accurate enough to adequately sense fouling. It may give erroneous information as to the presence of fouling, and by the time that a deposit has been sensed, it may be too late to control it by methods other than stopping the process and physically cleaning the heat exchanger.

2. Indirect methods of determining the cause of the deposit may suggest a variety of potential factors. Often an effective treatment program can only be determined by trial and error.

3. Diagnosis of the problem and prescription of the treatment program require a knowledge of not only fouling in general, but also the past history of the particular treatment. Such knowledge must be developed over time for each application because of the complex interactions which may contribute to fouling.

The problem of determining the type of fouling occurring within the heat exchanger also poses a dilemma. It may be evident that the heat exchanger has a film buildup, but identification of the film may be difficult if not impossible.
The biofilm composition may be determined visually, but it is then again necessary to shut the heat exchange process down, since shutting down is costly, this method is not appealing. This leaves examination of the heat transfer fluid and past consideration of the heat exchanger as the predominant methods for biofilm identification. These methods are inexact and unreliable in most applications.

The current research investigated the possibility of deriving a relationship between the biofilm thickness and various flow parameters such as the friction factor and the wall shear stress. This correlation would then be used to create a fouling "monitor" which would be capable of taking continuous data on the biofilm. The monitor would then use the information to create a base of information to help in determining the biofilm thickness and type. Corrective measures could then be implemented by the individual to remove the biofilm while the heat exchanger is still in operation.
CHAPTER 2

REVIEW OF PREVIOUS FINDINGS

Summary of Previous Findings

Although there has been a great deal of investigation into the effects of surface roughness on fluid flow, most previous work was based upon the assumption of a uniform surface roughness and a constant inside pipe diameter. Unfortunately, a biofilm is constantly changing its physical characteristics as it matures and grows.

Some of the earliest work in fluid dynamics was done by Sir Issac Newton who theorized that for straight and parallel motion of a fluid, the tangential stress, $\tau$, between the two adjacent layers was proportional to the velocity gradient, $\partial u / \partial y$, in a direction perpendicular to the layers, $\partial y$. This gives the relationship:

$$\tau = \mu \frac{\partial u}{\partial y}$$

(1)

The coefficient of proportionality $\mu$ is now known as the absolute viscosity of the fluid.

In 1840, G. H. L. Hagen [4] and J. L. M. Poiseuille [5] studied laminar flow in circular pipes. Hagen experimented with the flow of water through small brass tubes. His results showed that loss of head for a given length of pipe...
was directly proportional to the rate of flow and inversely proportional to the
diameter of the tube to the fourth power. Poiseuille also arrived at the same
conclusion working with small capillary tubes. This relationship between the
pressure loss and flow parameters was termed the Hagen–Poiseuille relationship
and is defined by the equation:

\[ p_1 - p_2 = 8\mu l \frac{Q}{\pi R^4} \]  \hspace{1cm} (2)

In 1883, Osborne Reynolds [6] investigated the characteristics of laminar
and turbulent flow. Reynolds performed a series of experiments in which dye
was injected into water flowing through a glass pipe. Reynolds experiments and
his analytical work showed that the nature of pipe flow depends on a dimension­
less parameter which he called the Reynolds number. This parameter was deter­
mined by the relationship:

\[ Re = \frac{\rho u_m D}{\mu} \]  \hspace{1cm} (3)

where \( \rho \) is the mass density of the fluid, \( u_m \) is the mean velocity of the fluid,
\( D \) is the hydraulic diameter, and \( \mu \) is the absolute viscosity of the fluid. With
his experimental and analytical work he showed that the Reynolds number was
characteristic to both laminar and turbulent flow. From his work, he concluded
that the transition between laminar and turbulent flow occurred at a Reynolds
number of 2000. If special precautions were taken not to disturb the fluid,
Reynolds found that this transition period was delayed to Reynolds numbers as
high as 3000.

In 1933, J. Nikuradse [7] investigated the relationship between surface
roughness and the pressure loss in pipes. In his research, Nikuradse obtained and classified sand grains of various sizes. He then glued these sand grains to the inside of various pipes to produce a desired roughness and the pressure drop was then determined for different values of Reynolds numbers. In his experiments observations were made on the loss of head (pressure drop), velocity distribution in the test pipe, discharge quantity and the temperature of the water. From this information, Nikuradse was able to determine a relationship between the Reynolds number and the friction factor of the pipe. This relationship had three distinct regions. The first region consisted entirely of laminar flow within the pipe and extended from Reynolds numbers from 0 to 2,000. In this region, the friction factor was related to the Reynolds number by the relationship:

\[ f = \frac{64}{Re} \]  (4)

This first region was predicted analytically by Hagen and Poiseuille and was characterized by the linear relationship between the friction factor and the Reynolds number. The second region was termed the transition region and extended from Reynolds numbers of 2,000 to 100,000. The smoother the pipe used for experimentation, the higher the transition Reynolds number. For extremely rough pipes transition occurred at a Reynolds number of 4,000. For extremely smooth pipes, this region would last to Reynolds numbers nearing 100,000. The friction factor in the latter region was related to the Reynolds number by the relationship:

\[ f = \frac{0.316}{(Re^{\frac{1}{8}})} \]  (5)
The final region was classified as the fully rough region and started with Reynolds numbers ranging from 4,000 to 100,000, depending upon the roughness of the pipe. In this region the friction factor was independent of the Reynolds number and was determined using the relationship:

\[
f = \frac{1}{(1.74 + 2 \times (\log r/k))^2}
\]  

(6)

This last region was characterized by the dependence of the friction factor upon the r/k ratio instead of the Reynolds number. This r/k ratio is the inverse of the relative roughness k/r which was used in early experiments. Recently more literature has assigned the relative roughness as e/D. Each notation is found in literature.

The findings of Nikuradse help in the development of semi-empirical theories of fluid friction factors. In 1935, L. Prandtl developed the following formula for the friction factor in turbulent flow in smooth pipes:

\[
\frac{1}{\sqrt{f}} = 2.0 \log(Re\sqrt{f}) - 0.8
\]  

(7)

At about the same time, T. von Karmen developed the following relation for friction factor for completely turbulent flow:

\[
\frac{1}{\sqrt{f}} = -2.0 \log\left(\frac{e/D}{3.7}\right)
\]  

(8)

Both of these relationships are the limited in their application to Nikuradse's work to the completely laminar or completely turbulent region.
In 1939, C. F. Colebrook [8] developed a formula that combined the laminar and turbulent limits and also covered the transition region. This relationship stated:

\[
\frac{1}{\sqrt{f}} = -2.0 \log \left( \frac{e/D + 2.51}{3.7 \cdot Re} \right)
\]  

Colebrook’s equation allowed a single relationship to relate the entire range for the friction factor. The drawback to the equation was that the friction factor was implicit with respect to \( f \).

Shortly after Nikuradse and Colebrook published their works, Lewis Moody [9] realized the importance of these findings. In his paper, he plotted the experimental results of Nikuradse and Colebrook. This plot has since been termed the Moody Diagram. The diagram plotted the relationship between the Reynolds number, the friction factor, and the relative roughness of a pipe. If any two of these pieces of information were known, the third could be determined by using the diagram. Since data already existed on the relative roughness of most industrial piping, it was relatively easy to calculate the friction factor that would exist within a pipe for a certain Reynolds number. The Darcy-Weisbach equation:

\[
gh_f = f \frac{Lv^2}{d^2}
\]

where \( f \) is the friction factor, \( v \) the fluid velocity, \( L \) the length of the pipe, \( d \) the diameter of the pipe, and \( g \) the acceleration due to gravity, may then be used to solve for the resulting head loss in the pipe. The Moody diagram greatly simplified pipe flow calculations and is still in wide use today.
In recent years, many researchers, such as Characklis [10,11,12], Turakhia [3], and Trulear [10] have realized the importance for investigation into the effects of biofouling on fluid dynamics. Many researchers have helped to define the basic processes involved in biofouling. For example, Trulear and Characklis [10], in their work 'Dynamics of Biofilm Processes', helped to define the basic processes occurring in biofouling. Their research found that the processes which contribute to the overall biofilm accumulation are:

1. Organic adsorption.
2. Transport of microbial particles to the surface.
3. Microorganism attachment to the surface.
5. Reentrainment of biofilm by fluid shear.

Strauss and Puckorius [2] recently investigated the different types of fouling occurring in industrial heat exchangers. Their research helped to classify the different types of fouling depositions which may possibly occur within industrial heat exchangers. They investigated three major types of depositions which were precipitation fouling, biological fouling, and corrosion fouling. This work helped to give the reader a better understanding of the processes involved in these types of fouling and possible methods to remove the fouling.

In 1987, Carl Hoerger [13,14] began the study of heat transfer modeling for the control of fouling in heat exchangers. The theoretical work of Hoerger attempted to simulate biofilm parameters, such as growth rates and fouling factors, within a heat exchanger. These analytical simulations were then used to predict actual conditions within a heat exchanger.
Implications for this Investigation

The findings of the previous investigators were used to determine the basic variables for this experiment. The implications from the previous work are summarized as follows:

1. The major form of fouling currently affecting industrial heat exchangers was biological fouling. Due to that fact, this was the form of fouling that was investigated in this research.

2. The major factor affecting the fluid in the heat exchanger was the surface of the biofilm. Therefore, only the thickness of the biofilm and the surface conditions were investigated in this research. The biofilm characteristics were assumed constant throughout its thickness.

3. Since the important surface characteristics were those of the biofilm, the material of the pipe was unimportant. For this reason, glass tubing was used throughout the experimentation. This was done for ease in the observation and measurement of the biofilm thickness.

4. Since isolation of a single type of film is possible only if the entire system can be sterilized, the biofilm was seeded from microorganisms within the air and in the Bozeman water system. Currently methods such as autoclaving are available for sterilization of some test apparatus, but unfortunately this process is limited to dimensions significantly smaller than the test apparatus used for this experimentation. The water was exposed to air throughout the experimentation to allow any microorganisms present in the air to enter the flow loop. The flow loop was supplied with tap water to allow it to be seeded...
with any microorganisms present in the Bozeman water system.

5. The only factor allowed to change the fluid temperature was a change in the temperature of the surrounding room air.

6. The oxygen level would be held constant throughout the investigation. Since the oxygen saturation point is dependent upon temperature, this point would fluctuate slightly as the temperature of the test fluid varied.

7. The nutrient level would be held constant for all of the four test runs in the investigation.

8. For ease in data reduction, the elevation of the entire test section remained the same throughout the investigation.

9. The biofilm thickness was neglected in determining the diameter of the glass in the test section. For all calculations, the diameter of the pipes was assumed constant throughout the research. For data reduction, the biofilm thickness would change the pipe diameter roughly 1 percent at the maximum biofilm thickness.

10. To determine a dimensional correlation, the diameter of the test sections would vary from that of an actual heat exchanger, roughly 7/8 inch diameter, to a diameter of 1/4 inch. This gives a variance in the cross-sectional area of ten, with the maximum area 0.615 square inches and the minimum area 0.0594 square inches.
CHAPTER 3

OUTLINE OF INVESTIGATION

Objectives

The objectives of the experimental research for predictive modeling of a biofilm had two major areas of concern. The first was to investigate the relationship between the friction factor and the biofilm thickness, and the second was to investigate the effect of the biofilm thickness on the heat transfer coefficient. It was felt that by combining these two pieces of information, a predictive model of the biofouling could be determined while the heat exchanger was still in operation. The research for this thesis was concerned primarily with the change in the friction factor as the biofilm grew.

Scope of the Investigation

During the initial design of the experiment, it was determined that the experimental variables to be investigated should be applicable to the conditions affecting heat exchangers. Therefore, the investigation varied the velocity of the fluid to the point of detachment of the biofilm from the surface of the pipe. Investigation beyond this point was considered unnecessary.
Four separate flow loops were used to determine the relationship between the pipe diameter and the flow parameters. The addition of more than one pipe diameter allowed investigation into the possibility of non-dimensionalizing the final results.

The biofilm thickness in the test section was allowed to vary from an initial condition of no biofilm to a final state of a fully matured biofilm within the test section.

Facilities and Equipment

All of the experiments and test runs performed were conducted at Montana State University in Ryon Laboratory, Room 21, Laboratory Station 1. The laboratory design consisted of four individual flow loops. All of the flow loops were identical except for the diameter of the pipe used in the entrance length and test section. Figure 1 gives a schematic drawing of one of the flow loops used in the experimentation.

All four flow loops were supplied by a thirty-gallon tank of fluid located on the floor of Ryon Laboratory. The lower tank was placed near the entrance to the test section for ease in operation. The lower tank was lined with plastic to stop corrosion by the biofilm. A pump located on the side of the tank was then used to supply fluid to a suspended tank, which was elevated to a height of approximately thirty feet. This upper tank rested upon a platform which was suspended on top of a support tower located in the laboratory. The
water level in this upper tank was held constant by placing an overflow pipe on the side of the tank. The overflow from this upper tank was then returned to the lower tank to recycle again.

![Diagram of Flow Loop and Instrumentation.](image)

Figure 1. Diagram of Flow Loop and Instrumentation.

Hoses were attached to the bottom of the suspended tank to allow the water in the tank to gravity feed. By placing the tank at an elevation of thirty feet, a wide range of velocities could be measured. The supply hoses consisted of roughly thirty-five feet of 5/8 inch diameter garden hose. This eliminated any possibility of picking up vibrations which may have been caused by the building itself.

Once the hoses reached the support table, they were connected to gate
valves. These valves allowed control of the velocity of the fluid through the hoses. Locating these valves at the beginning of the support table was to reduce the difficulty in operation and access.

After passing the valves, the water entered a bubble trap. Removing the air bubbles from within fluid helped to give a more uniform growth pattern to the biofilm in the test section. The bubble trap consisted of an enlarged pipe tee with a valve located at the top to allow the trapped air to be removed.

After passing the bubble trap, the water was allowed to enter a section of pipe of the same diameter as the test section. This produced an entrance length which allowed the water to reach steady state conditions by the time it reached the test section. The entrance lengths and the length to diameter ratios (L/d) for the flow loops are listed in Table 1.

Table 1. Entrance Length Specifications

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>Entrance Length (inches)</th>
<th>Entrance Length Pipe Diameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>40.3</td>
<td>75.8</td>
</tr>
<tr>
<td>2</td>
<td>44.6</td>
<td>111.5</td>
</tr>
<tr>
<td>3</td>
<td>45.6</td>
<td>149.0</td>
</tr>
<tr>
<td>4</td>
<td>47.4</td>
<td>169.3</td>
</tr>
</tbody>
</table>
The minimum L/D ratio used was 75. According to Incropera and Dewitt [15], the minimum ratio necessary for fully developed conditions is between 10 and 60. Therefore, for all four flow loops fully developed conditions were assumed.

After leaving the entrance length, the test fluid passed through a plastic pressure tap. This pressure tap consisted of five inches of two-inch diameter polycarbonate plastic. Figure 2 gives a drawing of the pressure tap used in the research. The entire length of the plastic tap was bored to the inside diameter of the test pipe, and the first inch and last inch were bored so a brass sleeve could fit into the pressure tap. The sleeves were then sealed to the plastic pressure tap. This design of the pressure taps allowed the glass piping to be placed within the tap while maintaining a constant inside pipe diameter. The brass sleeve allowed the glass test section to be sealed to the plastic pressure tap. This was done by placing plastic tubing over the sleeve and glass test section and clamping. The sleeve was necessary since the plastic tap could not be clamped.

This pressure tap design allowed an average pressure reading to be taken as the fluid entered the test section. The pressure tap took readings from the top, bottom, and from both sides of the pipe and then averaged these readings. This averaged pressure reading was then transmitted to a pressure transducer. The pressure transducer was placed in parallel with the test section by connecting the pressure taps to the transducer with plastic tubing. Plastic tubing was used so that any air not removed by the bubble traps could be detected visually and removed. The pressure transducer was placed on the support table.
by the test section and between the pressure taps. These pressure transducers were then attached to pressure indicators. The pressure transducer, pressure indicator, and connectors were calibrated as one unit and kept together throughout the experiment. Appendix B gives the results of the initial and final calibrations, with the resulting accuracies and resolutions.

![Diagram of Pressure Tap](image)

**Figure 2. Diagram of Pressure Tap.**

After passing the pressure taps, the water entered the glass test section. The test section was designed to be rotated to allow observations to be made on any side of the piping without changing any of the flow characteristics. The lengths and diameters of the test section are listed in Table 2. At the end of the test section the glass piping entered another pressure tap as described above. This allowed the pressure drop across the section to be calculated.
Table 2. Test Section Specifications

<table>
<thead>
<tr>
<th>Loop Number</th>
<th>Test Length (inches)</th>
<th>Inside Diameter (inches)</th>
<th>Outside Diameter (inches)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>35.6</td>
<td>0.532</td>
<td>0.625</td>
</tr>
<tr>
<td>2</td>
<td>36.0</td>
<td>0.400</td>
<td>0.475</td>
</tr>
<tr>
<td>3</td>
<td>36.0</td>
<td>0.306</td>
<td>0.392</td>
</tr>
<tr>
<td>4</td>
<td>36.0</td>
<td>0.280</td>
<td>0.352</td>
</tr>
</tbody>
</table>

Once the water passed the second pressure tap, it entered a six inch length of piping with the same diameter as the test section. The fluid then entered a turbine flow meter. The turbine flowmeter was connected to a frequency counter located on the equipment table. The calibrated turbine flowmeter readings from the frequency counter were used to calculate the velocity of the fluid passing through the test section. Appendix A gives the calibration statistics and the accuracy and resolution of the frequency counter and turbine flowmeters. Immediately after the turbine flowmeter, a T-type thermocouple was installed within the fluid flow. The thermocouple was connected to the computer to allow a constant recording of the temperature of the fluid exiting the test section. This recording could be taken at any time or averaged over a given time period. Tests of the temperature variation along the entire length of the flow loop showed identical temperature readings through all points of the flow loop. Therefore, the temperature probe was placed at the end of the test.
section for ease of installation and maintenance. After passing the thermocouple, the fluid entered drain hoses which returned the water to the tank located on the floor.

The valves, entrance lengths, test sections, turbine flowmeters, and thermocouples of all four flow loops were held rigid by mounting the flow loop to a support stand. The support stand was elevated from the table to allow a microscope to be placed underneath the glass test section so that biofilm thickness measurements could be taken with greater ease. The piping was placed in circular plastic rings which were clamped to the support structure. This design lowered the possibility of breaking the glass tubing by reducing the radial movement of the test apparatus. A twenty-four inch viewing section was cut into the support structure underneath the test section to facilitate placing a microscope under the test section.

Test Matrix

Due to the length of time necessary for a single test run, it was decided during the initial stages of the research that only two major areas of concern were to be investigated. The first area was the characteristics of the initial growth of the biofilm in the test section, the second was the study of the characteristics of the biofilm in the test section during detachment from the pipe wall. It was felt that these two areas would give a much better understanding of biofouling processes occurring in heat exchangers. The test matrix used for the research was split into two areas of investigation. The first test
matrix was called the growth phase, and the second test matrix was termed the detachment phase. Throughout the thesis, the results for both phase will be listed. The test matrix for both phases follows.

For Growth Phase

1. Pressure measurements were taken to determine the pressure drop across the test section. From this information, the friction factor caused by the biofilm in the glass piping could be calculated.

2. Velocity measurements would be taken to determine the wall shear stress on the biofilm in the test section. The velocity would be held constant at 1.00, 1.25, 1.50, and 1.75 ft/sec for test runs one through four respectively. The corresponding Reynolds numbers varied from 2,800 to 17,000.

3. The temperature in the test section would be measured to determine the properties of the fluid.

4. The biofilm thickness in the test section would be measured to determine any correlation between the measured variables and the biofilm thickness.

5. Four individual flow loops would be used to determine the effects of the variation of pipe diameter on the results.

6. The oxygen level would be held constant throughout the experimentation. This level would be measured once every twenty-four hours during the test runs.
7. The nutrient level would be held constant throughout the experimentation. It would be determined at the beginning of each of the four test runs for comparison.

8. All data would be recorded at maximum intervals of twelve hours. The time between test points would be reduced as the growth of the biofilm increased.

For Detachment Phase

The second stage of the investigation was the detachment phase. The test matrix for the detachment phase was as follows:

1. The velocity would be varied from the growth velocity to 3 ft/sec.

2. All other pertinent information would be recorded as in the growth phase.
CHAPTER 4

PRESSURE MEASUREMENTS

Experimental Apparatus and Procedures

Pressure readings were taken in all four flow loops using 1.0 psi full scale pressure transducers. Table 14 in Appendix B gives the resolution and accuracy of the pressure transducers used in the experimentation. These measurements were taken for the purpose of determining the friction factor for the biofilm in the test section.

Friction Factor for Growth Phase

Figures 3 through 6 plot the relationship between the friction factor and test time during the growth phase for flow loops one through four respectively. To make an accurate comparison between data points, it was necessary to plot the friction factor at similar Reynolds numbers. To accomplish this, the relative roughness, e/D, was calculated for the data point. This relative roughness was used to determine the friction factor at a Reynolds number of 10,000. The value of 10,000 for the Reynolds number was chosen arbitrarily. Appendix C gives a description of the exact method used to accomplish this.

As can be seen from the results, the friction factor maintains a constant
value of roughly 0.033 between thirty-six and fifty-seven hours for test velocities of 1.0, 1.25, and 1.50 ft/sec. For a test velocity of 1.75 ft/sec, the friction factor did not change throughout the test run.

After the initiation stage, the friction factor increased linearly in relation to time for approximately one hundred and ninety hours for a test velocity of 1.0 ft/sec, to one hundred hours for a test velocity of 1.50 ft/sec.

Following the growth stage, the increase in the friction factor declined. Data was taken approximately eighteen hours into this plateau stage before the test run was ended. The maximum friction factor ranged from approximately 0.1 for a test velocity of 1.0 ft/sec, to 0.048 for a test velocity of 1.50 ft/sec.
Figure 3. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches

Growth Velocities

- * = 1.00 ft/sec
- □ = 1.25 ft/sec
- ○ = 1.50 ft/sec
- △ = 1.75 ft/sec
Figure 4. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches
Friction Factor \( \times 10^{+2} \)

Growth Velocities
- \( \ast \) = 1.00 ft/sec
- \( \square \) = 1.25 ft/sec
- \( \circ \) = 1.50 ft/sec
- \( \triangle \) = 1.75 ft/sec

Figure 5. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter Of 0.370 Inches
Figure 6. Friction Factor v. Time for Growth Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches
Friction Factor for Detachment Phase

Figures 7 through 10 plot the relationship between the friction factor and the fluid velocity for the detachment phase. As in the growth phase, the friction factor was plotted with respect to a Reynolds number of 10,000. The friction factor exhibited two tendencies in the research. In the test runs with slower velocities, 1.00 and 1.25 ft/sec, the friction factor decreased linearly with respect to the fluid velocity, with two distinct regions occurring. The first region is marked by a large coefficient of friction for the test section, which decreases slightly with an increase in velocity. The second region is marked by a drastically reduced coefficient of friction within the test section, approaching clean pipe conditions. As the velocity is increased in the test section, the friction factor continues to approach ideal conditions. The two regions are separated by a detachment region. At this point a critical wall shear stress has been reached causing a large portion of the biofilm to detach from the surface, thereby significantly lowering the friction factor. The second tendency observed occurred in the higher velocity test runs, 1.50 and 1.75 ft/sec. In these test runs, the friction factor decreased linearly throughout the entire range of velocities and paralleled the slower velocities after the detachment of the biofilm.
Figure 7. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches
Figure 8. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 inches
Figure 9. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches
Growth Velocities

* = 1.00 ft/sec
□ = 1.25 ft/sec
○ = 1.50 ft/sec
△ = 1.75 ft/sec

Figure 10. Friction Factor v. Velocity for Detachment Phase With a Reynolds Number of 10,000 and a Pipe diameter of 0.275 Inches
CHAPTER 5

WALL SHEAR STRESS MEASUREMENTS

Experimental Apparatus and Procedures

The wall shear stress was determined during both phases of the experimentation. Readings were taken during the growth phase at the same time that visual observations were made on the biofilm. The wall shear stress was calculated at the initial clean pipe conditions, and results were calculated as the biofilm grew and matured within the test section. The data reduction program used to calculate the wall shear stress is listed in Appendix C.

Wall Shear Stress Results for Growth Phase

The relationship between the wall shear stress and the growth time for the individual flow loops are shown in Figures 11 through 14. To make an accurate comparison between the data points, it was necessary to determine the wall shear stress at a fixed Reynolds number. To accomplish this, the relative roughness, e/D, was determined at the data point. The relative roughness was used to determine the friction factor at a Reynolds number of 10,000. The velocity of the fluid was then calculated for a Reynolds number of 10,000 and
the wall shear stress determined.

As can be seen from the results, the wall shear stress exhibited three distinct regions. The first region was evident by a constant value for the wall shear stress. This value ranged from 0.008 lbf/ft\(^2\) for a test velocity of 1.0 ft/sec to 0.024 lbf/ft\(^2\) for a test velocity of 1.75 ft/sec. This period lasted between thirty-six and fifty-seven hours. After this time, the wall shear stress increased linearly to a value between 0.024 and 0.026 lbf/ft\(^2\). This limit on the biofilm shear stress was representative of all four test runs and all four test loops.
Figure 11. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches
Figure 12. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches
Figure 13. Wall Shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches
Figure 14. Wall shear Stress v. Time for Growth Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches
Wall Shear Stress Result for Detachment Phase

The values for the wall shear stress on the biofilm in the test section during the detachment phase are plotted in Figures 15 through 18. The value of the wall shear stress was determined at a Reynolds number of 10,000 using the method described in the growth phase. As can be seen from the figures, the shear stress increases linearly as the velocity is increased, with all four test runs exhibiting similar tendencies. The wall shear stress increased from a value of 0.025 lbf/ft
2 to values of approximately 0.80 lbf/ft
2.
Figure 15. Wall Shear Stress v. Velocity for Detachment Phase For a Reynolds Number of 10,000 and a Pipe Diameter of 0.885 Inches
Figure 16. Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.625 Inches
Figure 17. Wall shear Stress v. velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.370 Inches
Figure 18. Wall Shear Stress v. Velocity for Detachment Phase for a Reynolds Number of 10,000 and a Pipe Diameter of 0.275 Inches
CHAPTER 6

BIOFILM MEASUREMENTS

Experimental Apparatus and Procedures

Examination of the biofilm in the test section was accomplished using a Bausch and Lomb optical microscope which allowed measurements of the biofilm thickness to be made to the nearest micrometer. The biofilm thickness was measured using the principle of optical microscopy, as outlined by Bakke and Olsson [16]. This method involved focusing a microscope first on the biofilm-fluid interface and then on biofilm-substratum surface, and measuring the difference between the two points. The actual distance is related to the measured distance by the relationship:

\[ L_f = k_f y_f \]  \hspace{1cm} (11)

Where \( y_f \) is the distance measured by the microscope and \( k_f \) is a proportionality constant given by the relationship:

\[ k_f = \frac{n_f}{n_m} \]  \hspace{1cm} (12)

Where \( n_f \) is the refractive index of the biofilm and \( n_m \) is the refractive index of the medium interfacing the film at its top surface, which is the surface of the glass for this experimentation. Since the refractive index of glass is between 1.5 and 1.55 [17] and the refractive index of the biofilm is 1.5 [16], the
proportionality constant was approximated as one and the distance measured by the microscope was the actual thickness of the biofilm.

Measurements on the biofilm thickness were taken at twelve locations in the test section. The biofilm measurement were taken at two inch intervals starting at the beginning of the second pressure tap. These twelve readings were taken to reduce the influence of local thickness fluctuations.

**Biofilm Thickness for Growth Phase**

Biofilm thickness measurements were taken for the growth period starting at the initial input of the test fluid into the flow loop. To eliminate the effects of residue biofilm left from previous experimental runs, the drain hoses, upper and lower tanks and test section for all four flow loops were cleaned with a bristle brush to remove any biofilm not removed by the velocity excursions. This process was done before each of the four test runs used in the research. This process allowed all four test runs to start from a clean pipe situation. Figures 19 through 22 show the biofilm thickness v. time for the growth stage of the biofilm for flow loops one through four respectively. As can be seen from the figures, all growth rates follow a similar pattern throughout the entire growth cycle. The growth cycles for all cases consist of three stages. The first stage is termed the induction phase. At this stage the glass pipe is clean, and the biofilm must build a base upon the pipe from which to grow. This stage is marked by a lack of any significant growth in the pipe and lasts between thirty-six and fifty-seven hours.
The second stage is the growth stage. At this stage, the biofilm has successfully attached itself to the pipe wall. This stage is marked by a linear rate of growth for the biofilm. This linear region lasts between one hundred and ninety hours for a test velocity of 1.00 ft/sec, to one hundred hours for a test velocity of 1.50 ft/sec.

After the growth stage, the increase in the biofilm thickness decreased significantly, with a maximum thickness of 360 micrometers for a test velocity of 1.00 ft/sec to no biofilm growth for a test velocity of 1.75 ft/sec.
Figure 19. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter of 0.885 Inches
Growth Velocities

- * = 1.00 ft/sec
- □ = 1.25 ft/sec
- ○ = 1.50 ft/sec
- △ = 1.75 ft/sec

Figure 20. Biofilm Thickness v. Time for Growth Phase
With a Pipe Diameter of 0.625 Inches
Figure 21. Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.370 Inches
Growth Velocities

- * = 1.00 ft/sec
- □ = 1.25 ft/sec
- ○ = 1.50 ft/sec
- △ = 1.75 ft/sec

Figure 22. Biofilm Thickness v. Time for Growth Phase With a Pipe Diameter of 0.275 Inches
Biofilm Thickness for Detachment Phase

A plot of the biofilm thickness v. the fluid velocity is plotted in Figures 23 through 26. For smaller biofilm growths, those occurring for 1.50 and 1.75 ft/sec, the biofilm detaches linearly with respect to the fluid velocity. For the larger biofilm growths, the biofilm exhibits two regions of detachment. The first region is characterized by a linear decrease in the biofilm thickness as the velocity is increased. At a critical velocity, a vast majority of the biofilm is detached from the surface of the test section. Past this point, the biofilm again decreases linearly with an increase in fluid velocity.
Figure 23. Biofilm Thickness v. Velocity for Detachment Phase with a Pipe Diameter of 0.885 Inches.
Figure 24. Biofilm Thickness vs. Velocity for Detachment Phase with a Pipe Diameter of 0.625 Inches
Figure 25. Biofilm Thickness v. Velocity for Detachment Phase With a Pipe Diameter of 0.370 Inches
Figure 26. Biofilm Thickness vs. Velocity for Detachment Phase With a Pipe Diameter Of 0.275 Inches
CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

Summary of Results for Growth Phase

The results of the investigation of the growth phase support several conclusions. Specific findings of the investigation are summarized in the following statements.

1. The friction factor had three distinct regions which appeared in all four test runs. The first region was characterized by a constant value in the friction factor and lasted approximately thirty to forty hours. Following this region, the friction factor increased linearly with respect to time. This second region lasted approximately one hundred and fifty hours. For the slower test velocities this time was slightly greater, and for the faster velocities, slightly less. The third region was characterized by a stable value for the friction value, with small increases occurring occasionally.

3. The wall shear stress on the biofilm in the test section exhibited similar tendencies to the friction factor. Three distinct regions occurred in the experimentation. The first region was marked by a stable value for the wall shear stress and lasted thirty to forty hours. Following this region the wall shear stress increased linearly with respect to time. This linearly
region continued until a wall shear stress of 0.024 to 0.026 lbf/ft$^2$ was reached. At this value, the wall shear stress stabilized for the remainder of the test run.

3. The growth of the biofilm also exhibited three distinct regions. During the first period, there was no apparent biofilm growth in the test section. This period lasted approximately thirty to forty hours. After this time, the biofilm increased linearly with respect to time for approximately one hundred and fifty hours. As in the results for the friction factor, this time was slightly greater for the slower test velocities, and slightly less for the slower velocities. The third region was evident by a stabilization in the biofilm thickness, with small changes in thickness over time.

**Summary of Results for Detachment Phase**

The results of the investigation of the detachment phase support several conclusions. Specific findings of the investigation are summarized in the following statements.

1. For growth velocities of 1.25, 1.50 and 1.75 ft/sec, the friction factor decreased linearly with an increase in fluid velocity. The values for all three test runs were similar, with a starting value for the friction factor of approximately 0.055 and concluding at a value of 0.36. For a growth velocity of 1.00 ft/sec, the friction factor exhibited two regions. From 1.00 ft/sec to 1.40 ft/sec the friction factor decreased linearly from a value of approximately 0.105 to a value of 0.085. Between 1.40 and 1.60
ft/sec, the friction factor was reduced from a value of 0.085 to a value of roughly 0.058. Beyond velocities of 1.6 ft/sec, the friction factor again decreased linearly, with similar results to the other three test runs.

2. For all cases investigated, the wall shear stress increased linearly with an increase in fluid velocity. In all test runs, the wall shear stress increased from a value of approximately 0.025 lbf/ft\(^2\) to a value of 0.080 lbf/ft\(^2\).

3. For growth velocities of 1.25, 1.50 and 1.75 ft/sec, the biofilm thickness decreased linearly with an increase in fluid velocity. For these three test runs, the biofilm thickness started at an initial value of approximately 120 microns, and decreased to a value of roughly 35 microns. For a growth velocity of 1.00 ft/sec, the biofilm thickness started at an initial value of approximately 300 microns and decreased linearly to a value of 275 microns at 1.40 ft/sec. Between 1.40 and 1.60 ft/sec, the biofilm thickness decreased from 275 microns to roughly 100 microns. Beyond this point, the biofilm thickness again decreased linearly with respect to fluid velocity, and was similar to the results for the other test velocities investigated.

**Recommendations for Further Investigation**

Temperature variations were a slight problem in the investigation. The only factor affecting the fluid temperature was the temperature of the room. Unfortunately, due to the large size of the room and the abundance of windows
facing the sun, the room temperature was highly susceptible to environmental conditions. I would recommend that in further study, a room with the means to stabilize temperature be used.

Since garden hose was used to supply the test section with fluid, it was difficult to determine if the frequent bristle scrubbing fully removed the biofilm growths in this section. For future work, I would recommend using clear plastic tubing so any biofilm growths could be seen more easily.

At the time of this research, efficient methods of in situ biofilm thickness measurement were unknown. This variable contained the greatest degree of inaccuracy. I would recommend in further study that more accurate methods be investigated to determine the biofilm thickness.
REFERENCES CITED


2. Strauss, S.D., Puckorius, P.R., Cooling-Water Treatment for Control of Scaling, Fouling, Corrosion, A Special Report, Power Reprint Department, New York, New York.


APPENDICES
APPENDIX A

TURBINE FLOWMETER CALIBRATION
TURBINE FLOW METER CALIBRATION

The turbine flowmeters used throughout the experimentation were calibrated at the beginning of the investigation and again at the conclusion of the experimentation. Tables 3 through 6 give the data used in plotting the initial calibration for the turbine flowmeters. The turbine flowmeters used in the research allowed two possible ranges to be used. The first range was between 0.1 to 1 GPM and was used entirely for flow loops three and four. The second range was 0.8 to 8 GPM and was used for flow loops one and two. To calibrate the flowmeters, eight test runs were taken at different velocities and the output to the frequency counter noted. The frequency counter used in the calibration of the turbine flowmeter was set at a gate time of ten seconds. Fluid was then passed through the flowmeter for sixty seconds and six readings were recorded. The gallons of fluid per minute of the fluid passing through the flowmeter was then determined and the average frequency counter reading was then compared with the GPM to determine the relationship between these two pieces of information. This relationship was then used in the data reduction program listed in Appendix C. The resolution of the frequency counter used in all calibrations was ± 0.05 and Table 8 gives the accuracy of the equations used.
Table 3. Turbine Flowmeter One Calibration Statistics  
For 0.8–8 GPM Range

<table>
<thead>
<tr>
<th></th>
<th>run 1</th>
<th>run 2</th>
<th>run 3</th>
<th>run 4</th>
<th>run 5</th>
<th>run 6</th>
<th>run 7</th>
<th>run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>reading 1</td>
<td>9.3</td>
<td>18.3</td>
<td>29.0</td>
<td>40.0</td>
<td>50.7</td>
<td>59.5</td>
<td>67.4</td>
<td>76.6</td>
</tr>
<tr>
<td>reading 2</td>
<td>8.8</td>
<td>18.2</td>
<td>29.1</td>
<td>40.1</td>
<td>50.8</td>
<td>59.5</td>
<td>67.4</td>
<td>76.5</td>
</tr>
<tr>
<td>reading 3</td>
<td>8.6</td>
<td>17.3</td>
<td>29.1</td>
<td>40.0</td>
<td>50.8</td>
<td>59.5</td>
<td>67.4</td>
<td>76.4</td>
</tr>
<tr>
<td>reading 4</td>
<td>8.6</td>
<td>16.9</td>
<td>29.0</td>
<td>39.9</td>
<td>50.3</td>
<td>59.4</td>
<td>67.5</td>
<td>76.5</td>
</tr>
<tr>
<td>reading 5</td>
<td>8.3</td>
<td>16.8</td>
<td>28.8</td>
<td>39.7</td>
<td>50.8</td>
<td>59.4</td>
<td>67.6</td>
<td>76.5</td>
</tr>
<tr>
<td>reading 6</td>
<td>8.3</td>
<td>16.7</td>
<td>28.8</td>
<td>39.6</td>
<td>50.8</td>
<td>59.4</td>
<td>67.6</td>
<td>76.8</td>
</tr>
<tr>
<td>average</td>
<td>8.65</td>
<td>17.37</td>
<td>28.97</td>
<td>39.88</td>
<td>50.78</td>
<td>59.45</td>
<td>67.48</td>
<td>76.55</td>
</tr>
<tr>
<td>GPM</td>
<td>0.99</td>
<td>1.83</td>
<td>2.82</td>
<td>3.75</td>
<td>4.65</td>
<td>5.22</td>
<td>5.88</td>
<td>6.51</td>
</tr>
</tbody>
</table>

The initial calibration of turbine flowmeter number one for the 0.8 to 8 GPM range was:

\[ GPM = 0.41945 + 0.08096 \times (Frequency \ Reading) \]  \hspace{1cm} (13)

with a standard error of estimation of 0.098652 and an R Squared value of 0.9979.

Final calibration of the turbine flowmeter gave the relationship:

\[ GPM = 0.49734 + 0.08054 \times (Frequency \ Reading) \]  \hspace{1cm} (14)

with a standard error of estimation of 0.078960 and an R squared value of 0.9990.
Table 4. Turbine Flowmeter Two Calibration Statistics
For 0.8-8 GPM Range

<table>
<thead>
<tr>
<th></th>
<th>run 1</th>
<th>run 2</th>
<th>run 3</th>
<th>run 4</th>
<th>run 5</th>
<th>run 6</th>
<th>run 7</th>
<th>run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>reading 1</td>
<td>9.3</td>
<td>18.6</td>
<td>28.9</td>
<td>36.9</td>
<td>46.2</td>
<td>58.0</td>
<td>66.6</td>
<td>74.9</td>
</tr>
<tr>
<td>reading 2</td>
<td>9.3</td>
<td>18.7</td>
<td>28.8</td>
<td>36.8</td>
<td>46.4</td>
<td>58.0</td>
<td>66.4</td>
<td>74.8</td>
</tr>
<tr>
<td>reading 3</td>
<td>9.3</td>
<td>18.7</td>
<td>28.9</td>
<td>37.0</td>
<td>46.5</td>
<td>57.9</td>
<td>66.7</td>
<td>74.7</td>
</tr>
<tr>
<td>reading 4</td>
<td>9.3</td>
<td>18.7</td>
<td>29.0</td>
<td>37.1</td>
<td>46.4</td>
<td>56.4</td>
<td>67.1</td>
<td>74.9</td>
</tr>
<tr>
<td>reading 5</td>
<td>9.3</td>
<td>18.7</td>
<td>28.9</td>
<td>36.9</td>
<td>46.4</td>
<td>56.5</td>
<td>67.2</td>
<td>74.8</td>
</tr>
<tr>
<td>reading 6</td>
<td>9.3</td>
<td>18.7</td>
<td>29.0</td>
<td>36.8</td>
<td>46.5</td>
<td>56.4</td>
<td>67.5</td>
<td>74.8</td>
</tr>
<tr>
<td>average</td>
<td>9.3</td>
<td>18.68</td>
<td>28.92</td>
<td>36.92</td>
<td>46.40</td>
<td>57.20</td>
<td>66.92</td>
<td>74.82</td>
</tr>
<tr>
<td>GPM</td>
<td>1.02</td>
<td>1.80</td>
<td>2.85</td>
<td>3.51</td>
<td>4.32</td>
<td>5.16</td>
<td>5.94</td>
<td>6.47</td>
</tr>
</tbody>
</table>

The initial calibration of turbine flowmeter number two for the 0.1 to 1 GPM range was:

\[ GPM = 0.31258 + 0.084354 \times (Freq\text{ency \ Reading}) \]  \hspace{1cm} (15)

with a standard error of estimation of 0.03887 and an R Squared value of 0.9992.

Final calibration of the turbine flowmeter gave the relationship:

\[ GPM = 0.27405 + 0.082040 \times (Freq\text{ency \ Reading}) \]  \hspace{1cm} (16)

with a standard error of estimation of 0.03666 and an R squared value of 0.9996.
Table 5. Turbine Flowmeter Three Calibration Statistics
For 0.1 to 1 GPM Range

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Run 7</th>
<th>Run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading 1</td>
<td>10.5</td>
<td>18.4</td>
<td>24.5</td>
<td>37.0</td>
<td>47.6</td>
<td>56.9</td>
<td>63.0</td>
<td>72.4</td>
</tr>
<tr>
<td>Reading 2</td>
<td>10.3</td>
<td>18.1</td>
<td>25.1</td>
<td>36.9</td>
<td>47.3</td>
<td>56.9</td>
<td>63.0</td>
<td>72.5</td>
</tr>
<tr>
<td>Reading 3</td>
<td>10.2</td>
<td>18.2</td>
<td>24.9</td>
<td>36.7</td>
<td>47.3</td>
<td>56.6</td>
<td>62.8</td>
<td>72.4</td>
</tr>
<tr>
<td>Reading 4</td>
<td>10.1</td>
<td>18.0</td>
<td>24.7</td>
<td>36.6</td>
<td>47.4</td>
<td>56.7</td>
<td>62.4</td>
<td>72.4</td>
</tr>
<tr>
<td>Reading 5</td>
<td>10.2</td>
<td>17.8</td>
<td>24.6</td>
<td>36.4</td>
<td>47.3</td>
<td>56.4</td>
<td>62.3</td>
<td>72.2</td>
</tr>
<tr>
<td>Reading 6</td>
<td>10.2</td>
<td>17.6</td>
<td>24.5</td>
<td>36.2</td>
<td>47.1</td>
<td>56.0</td>
<td>62.2</td>
<td>72.1</td>
</tr>
<tr>
<td>Average</td>
<td>10.25</td>
<td>18.02</td>
<td>24.72</td>
<td>36.63</td>
<td>47.33</td>
<td>56.58</td>
<td>62.62</td>
<td>72.33</td>
</tr>
<tr>
<td>GPM</td>
<td>0.21</td>
<td>0.31</td>
<td>0.42</td>
<td>0.60</td>
<td>0.75</td>
<td>0.87</td>
<td>0.96</td>
<td>1.11</td>
</tr>
</tbody>
</table>

The initial calibration of turbine flowmeter number three for the 0.1 to 1 GPM range was:

\[
GPM = 0.05917 + 0.014463*(\text{Frequency Reading})
\]  

(17)

with a standard error of estimation of 0.008196 and an R Squared value of 0.9994.

Final calibration of the turbine flowmeter gave the relationship:

\[
GPM = 0.07129 + 0.014400*(\text{Frequency Reading})
\]  

(18)

with a standard error of estimation of 0.01017 and an R squared value of 0.9992.
Table 6. Turbine Flowmeter Four Calibration Statistics  
For 0.1 to 1 GPM Range

<table>
<thead>
<tr>
<th></th>
<th>Run 1</th>
<th>Run 2</th>
<th>Run 3</th>
<th>Run 4</th>
<th>Run 5</th>
<th>Run 6</th>
<th>Run 7</th>
<th>Run 8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reading 1</td>
<td>7.1</td>
<td>18.8</td>
<td>26.9</td>
<td>37.1</td>
<td>46.0</td>
<td>54.2</td>
<td>64.9</td>
<td>73.6</td>
</tr>
<tr>
<td>Reading 2</td>
<td>7.0</td>
<td>18.5</td>
<td>26.8</td>
<td>37.0</td>
<td>46.0</td>
<td>54.3</td>
<td>64.6</td>
<td>73.6</td>
</tr>
<tr>
<td>Reading 3</td>
<td>6.9</td>
<td>18.5</td>
<td>26.5</td>
<td>36.9</td>
<td>45.8</td>
<td>54.3</td>
<td>64.7</td>
<td>73.7</td>
</tr>
<tr>
<td>Reading 4</td>
<td>5.6</td>
<td>18.5</td>
<td>26.2</td>
<td>37.0</td>
<td>45.7</td>
<td>54.5</td>
<td>64.6</td>
<td>73.5</td>
</tr>
<tr>
<td>Reading 5</td>
<td>6.4</td>
<td>18.5</td>
<td>26.1</td>
<td>36.9</td>
<td>45.6</td>
<td>54.3</td>
<td>64.3</td>
<td>73.5</td>
</tr>
<tr>
<td>Reading 6</td>
<td>5.3</td>
<td>18.4</td>
<td>26.0</td>
<td>36.7</td>
<td>45.4</td>
<td>54.1</td>
<td>64.1</td>
<td>73.4</td>
</tr>
<tr>
<td>Average</td>
<td>6.38</td>
<td>18.53</td>
<td>26.42</td>
<td>36.93</td>
<td>45.75</td>
<td>54.28</td>
<td>64.53</td>
<td>73.55</td>
</tr>
<tr>
<td>GPM</td>
<td>0.18</td>
<td>0.35</td>
<td>0.48</td>
<td>0.63</td>
<td>0.75</td>
<td>0.93</td>
<td>1.05</td>
<td>1.17</td>
</tr>
</tbody>
</table>

The initial calibration of turbine flowmeter number four for the 0.1 to 1 GPM range was:

\[ GPM = 0.08408 + 0.01493 \times (\text{Frequency Reading}) \tag{19} \]

with a standard error of estimation of 0.01701 and an \( R^2 \) squared value of 0.9979.

Final calibration of the turbine flowmeter gave the relationship:

\[ GPM = 0.07259 + 0.014862 \times (\text{Frequency Reading}) \tag{20} \]

with a standard error of estimation of 0.01307 and an \( R^2 \) squared value of 0.9987.
The resolution of the data points for the turbine flowmeters was determined using the equation:

\[ \sigma = \sqrt{\frac{\sum (x_i - \bar{x})^2}{n-1}} \]

(21)

Where \( \sigma \) is the standard deviation of the data, \( x_i \) is the value of the data point, \( \bar{x} \) is the value of the data point predicted by the equation and \( n \) is the number of data points. The total uncertainty of the pressure transducer is then determined by the relationship:

\[ u_{\text{tpm}} = \sqrt{(u_{f.c.})^2 + (u_{\text{data}})^2} \]

(22)

where \( u_{\text{tpm}} \) is the uncertainty in the final output, \( u_{\text{data}} \) is the uncertainty in the test data and \( u_{f.c.} \) is the uncertainty in the frequency counter. The error calculated is the maximum error possible in the experimentation, and not a root mean square error.

Table 7. Resolution of Frequency Counters

<table>
<thead>
<tr>
<th>Equipment.</th>
<th>Initial Resolution (GPM)</th>
<th>Final Resolution GPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency Counter One (0.8-8)</td>
<td>± 0.00405</td>
<td>± 0.00403</td>
</tr>
<tr>
<td>Frequency Counter Two (0.8-8)</td>
<td>± 0.00422</td>
<td>± 0.00410</td>
</tr>
<tr>
<td>Frequency Counter Three (0.1-1)</td>
<td>± 0.00072</td>
<td>± 0.00072</td>
</tr>
<tr>
<td>Frequency Counter Four (0.1-1)</td>
<td>± 0.00075</td>
<td>± 0.00074</td>
</tr>
</tbody>
</table>
Table 8. Resolution and Accuracy of Turbine Flowmeters

<table>
<thead>
<tr>
<th></th>
<th>Initial Resolution</th>
<th>Final Resolution</th>
<th>Initial Accuracy</th>
<th>Final Accuracy</th>
</tr>
</thead>
<tbody>
<tr>
<td>TFM One (0.8-8)</td>
<td>± 0.0966</td>
<td>± 0.0791</td>
<td>± 5.06 %</td>
<td>± 4.14 %</td>
</tr>
<tr>
<td>TFM Two (0.8-8)</td>
<td>± 0.0889</td>
<td>± 0.0369</td>
<td>± 6.95 %</td>
<td>± 2.88 %</td>
</tr>
<tr>
<td>TFM Three (0.1-1)</td>
<td>± 0.0082</td>
<td>± 0.0102</td>
<td>± 2.48 %</td>
<td>± 3.09 %</td>
</tr>
<tr>
<td>TFM Four (0.1-1)</td>
<td>± 0.0170</td>
<td>± 0.0131</td>
<td>± 9.44 %</td>
<td>± 7.28 %</td>
</tr>
</tbody>
</table>
APPENDIX B

PRESSURE TRANSDUCERS CALIBRATION
PRESSURE TRANSDUCER CALIBRATION

The pressure transducers used in the experiment were calibrated at two different times. The first calibration was done during the initial design and building of the test apparatus. The final calibration was concluded after the last experimental run was completed. Tables 9 through 12 give the initial readings used in calibration of the pressure transducers. The resolution of the data points for the pressure transducers was determined using the equation:

$$
s = \sqrt{\frac{\sum(x_i - \bar{x})^2}{n-1}} \quad (23)
$$

Where $s$ is the standard deviation of the data, $x_i$ is the value of the data point, $\bar{x}$ is the value of the data point predicted by the equation and $n$ is the number of data points. The uncertainty of the data is then taken to be the 90% level, or $1.6449 \, s$. The total uncertainty of the pressure transducer is then determined by the relationship:

$$
u_{p.t.} = \sqrt{(u_w)^2 + (u_{data})^2 + (u_{p.t.})^2} \quad (24)
$$

where $u_{p.t.}$ is the uncertainty in the final output, $u_w$ is the uncertainty in the column of water, $u_{data}$ is the uncertainty in the data and $u_{p.t.}$ is the uncertainty in the pressure indicator. The error calculated is the worst possible error, and not the root mean square.
Table 9. Pressure Transducer One Calibration Statistics

<table>
<thead>
<tr>
<th>Indicator Reading</th>
<th>Elevation Difference (inches)</th>
<th>Ratio Reading/PSI</th>
<th>Pressure Difference PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>---</td>
<td>0.0000</td>
</tr>
<tr>
<td>12.7</td>
<td>2.5</td>
<td>140.64</td>
<td>0.0903</td>
</tr>
<tr>
<td>23.0</td>
<td>4.5</td>
<td>141.45</td>
<td>0.1626</td>
</tr>
<tr>
<td>48.8</td>
<td>9.625</td>
<td>140.35</td>
<td>0.3477</td>
</tr>
<tr>
<td>57.1</td>
<td>11.25</td>
<td>140.50</td>
<td>0.4064</td>
</tr>
<tr>
<td>81.8</td>
<td>16.125</td>
<td>140.41</td>
<td>0.5826</td>
</tr>
<tr>
<td>94.0</td>
<td>18.625</td>
<td>139.69</td>
<td>0.6729</td>
</tr>
</tbody>
</table>

This information was entered into a curvefit program to determine the equation of the data. The program determined that this data followed a linear relationship with a standard error of estimation of 0.001227, and a R squared value of 0.9999. Therefore, the equation for pressure transducer one was calculated to be:

\[ P(lbf/\text{inch}^2) = -0.001559 + 0.0071 \times \text{Indicator Reading} \]  \hspace{1cm} (25)

The equation determined by the curvefit program for the final calibration of pressure transducer one gave the following relationship:

\[ P(lbf/\text{inch}^2) = -0.00073461 + 0.007225 \times \text{Indicator Reading} \]  \hspace{1cm} (26)

with a standard error of estimation of 0.001145 and an R squared value of 0.9999.
Table 10. Pressure Transducer Two Calibration Statistics

<table>
<thead>
<tr>
<th>Indicator Reading</th>
<th>Elevation Difference (inches)</th>
<th>Ratio Reading/PSI</th>
<th>Pressure Difference PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>16.7</td>
<td>2.1</td>
<td>217.17</td>
<td>0.0769</td>
</tr>
<tr>
<td>36.1</td>
<td>4.5</td>
<td>222.02</td>
<td>0.1626</td>
</tr>
<tr>
<td>56.7</td>
<td>7.04</td>
<td>222.96</td>
<td>0.2543</td>
</tr>
<tr>
<td>81.2</td>
<td>10.1</td>
<td>223.45</td>
<td>0.3634</td>
</tr>
<tr>
<td>107.4</td>
<td>13.3</td>
<td>223.33</td>
<td>0.4809</td>
</tr>
<tr>
<td>141.9</td>
<td>17.6</td>
<td>222.87</td>
<td>0.6367</td>
</tr>
<tr>
<td>0.0</td>
<td>0.0</td>
<td>------</td>
<td>0.0000</td>
</tr>
</tbody>
</table>

This information was entered into the curvefit program and the equation best represented by this data was a linear equation. The equation had a standard error of estimation of 0.0008929 and a R squared value of 0.9999. The equation determined by the program was:

\[ P(lbf/inch^2) = 0.0012725 + 0.0044708 \times (Indicator \ Reading) \]  \hspace{1cm} (27)

The equation determined by the curvefit program for the final calibration for pressure transducer two gave the relationship:

\[ P(lbf/inch^2) = 0.0028943 + 0.0044059 \times (Indicator \ Reading) \]  \hspace{1cm} (28)

with a standard error of estimation of 0.001339 and an R squared value of 0.9999.
Table 11. Pressure Transducer Three Calibration Statistics

<table>
<thead>
<tr>
<th>Indicator Reading</th>
<th>Elevation Difference (inches)</th>
<th>Ratio Reading/Inches</th>
<th>Pressure Difference PSI</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.3</td>
<td>3.2</td>
<td>124.13</td>
<td>0.1152</td>
</tr>
<tr>
<td>23.2</td>
<td>5.1</td>
<td>125.27</td>
<td>0.1852</td>
</tr>
<tr>
<td>32.2</td>
<td>7.1</td>
<td>126.26</td>
<td>0.2551</td>
</tr>
<tr>
<td>47.2</td>
<td>10.4</td>
<td>125.93</td>
<td>0.3748</td>
</tr>
<tr>
<td>59.2</td>
<td>12.9</td>
<td>126.66</td>
<td>0.4674</td>
</tr>
<tr>
<td>75.0</td>
<td>16.3</td>
<td>127.30</td>
<td>0.5893</td>
</tr>
<tr>
<td>00.0</td>
<td>00.0</td>
<td>0.0000</td>
<td></td>
</tr>
</tbody>
</table>

This information was entered into the curvefit program and the equation best represented by the data was a linear equation. The equation had a standard error of estimation of 0.001435 and a R squared value of 0.9999. The equation determined by the program was:

\[
P(lbf/inch^2) = 0.003091 + 0.0089447 \times (Indicator \ Reading) \quad (29)
\]

The equation determined by the curvefit program for the final calibration of pressure transducer number three was:

\[
P(lbf/inch^2) = -0.00057 + 0.009151 \times (Indicator \ Reading) \quad (30)
\]

with a standard error of estimation of 0.001732 and an R squared value of 0.9997.
Table 12. Pressure Transducer Four Calibration Statistics

<table>
<thead>
<tr>
<th>Indicator-Reading</th>
<th>Elevation Difference (inches)</th>
<th>Ratio Reading/PSI</th>
<th>Pressure Difference</th>
</tr>
</thead>
<tbody>
<tr>
<td>11.8</td>
<td>2.5</td>
<td>130.67</td>
<td>0.0903</td>
</tr>
<tr>
<td>22.3</td>
<td>4.7</td>
<td>131.71</td>
<td>0.1693</td>
</tr>
<tr>
<td>29.0</td>
<td>6.1</td>
<td>131.04</td>
<td>0.2213</td>
</tr>
<tr>
<td>43.2</td>
<td>9.1</td>
<td>131.95</td>
<td>0.3274</td>
</tr>
<tr>
<td>54.8</td>
<td>11.5</td>
<td>131.89</td>
<td>0.4967</td>
</tr>
<tr>
<td>65.9</td>
<td>13.8</td>
<td>132.68</td>
<td>0.4967</td>
</tr>
<tr>
<td>00.0</td>
<td>00.0</td>
<td></td>
<td>0.0000</td>
</tr>
</tbody>
</table>

This information was entered into a curvefit program and the equation best represented by this information was a linear equation. The equation had a standard error of estimation of 0.0008718 and a $R^2$ squared value of 0.9999. The equation determined by the program was:

$$P(\text{lb}f/\text{inch}^2) = 0.002118 + 0.007523*(\text{Indicator Reading})$$  \hspace{1cm} (31)

The equation determined by the curvefit program for the final calibration of pressure transducer four was:

$$P(\text{lb}f/\text{inch}^2) = -0.001276 + 0.007477*(\text{Indicator Reading})$$  \hspace{1cm} (32)

with a standard error of estimation of 0.001105 and an $R^2$ squared value of 0.9999.
Table 13. Resolution of Pressure Calibration Equipment

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Initial Resolution (PSI)</th>
<th>Final Resolution (PSI)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water Column</td>
<td>± 0.00113</td>
<td>± 0.00113</td>
</tr>
<tr>
<td>Pressure Transducer 1</td>
<td>± 0.00101</td>
<td>± 0.00115</td>
</tr>
<tr>
<td>Pressure Transducer 2</td>
<td>± 0.00073</td>
<td>± 0.00134</td>
</tr>
<tr>
<td>Pressure Transducer 3</td>
<td>± 0.00108</td>
<td>± 0.00173</td>
</tr>
<tr>
<td>Pressure Transducer 4</td>
<td>± 0.00059</td>
<td>± 0.00110</td>
</tr>
<tr>
<td>Pressure Indicator 1</td>
<td>± 0.00036</td>
<td>± 0.00036</td>
</tr>
<tr>
<td>Pressure Indicator 2</td>
<td>± 0.00025</td>
<td>± 0.00022</td>
</tr>
<tr>
<td>Pressure Indicator 3</td>
<td>± 0.00045</td>
<td>± 0.00046</td>
</tr>
<tr>
<td>Pressure Indicator 4</td>
<td>± 0.00038</td>
<td>± 0.00037</td>
</tr>
</tbody>
</table>

Table 14. Resolution and Accuracy of Pressure Transducers

<table>
<thead>
<tr>
<th></th>
<th>Pressure Readout One</th>
<th>Pressure Readout Two</th>
<th>Pressure Readout Three</th>
<th>Pressure Readout Four</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Resolution (PSI)</td>
<td>± 0.00156</td>
<td>± 0.00137</td>
<td>± 0.00163</td>
<td>± 0.00133</td>
</tr>
<tr>
<td>Final Resolution (PSI)</td>
<td>± 0.00165</td>
<td>± 0.00177</td>
<td>± 0.00212</td>
<td>± 0.00162</td>
</tr>
<tr>
<td>Initial Accuracy (%)</td>
<td>± 14.7</td>
<td>± 8.8</td>
<td>± 3.9</td>
<td>± 2.91</td>
</tr>
<tr>
<td>Final Accuracy (%)</td>
<td>± 15.6</td>
<td>± 10.4</td>
<td>± 5.5</td>
<td>± 3.8</td>
</tr>
</tbody>
</table>
DATA REDUCTION PROGRAM

The data reduction program was used to determine several parameters related to the basic measurements. The program called information from a data file named bio.dat which contained the time the data was taken, the temperature of the fluid, the pressure drop across the test section, the biofilm thickness, the oxygen content of the fluid and the frequency counter reading for all four flow loops. The program first calculated the kinematic viscosity using the relationship:

\[ \nu = (A + B^*T + C^*T^2 + D^*T^3) \times 10^{-5} \text{ft/}s^2 \]  

(33)

Where \( T \) is the fluid temperature and the variables \( A, B, C, \) and \( D \) are:

\[ A = 3.11187\times10^{-00} \]
\[ B = -4.78969\times10^{-02} \]
\[ C = 3.21462\times10^{-04} \]
\[ D = -7.99526\times10^{-07} \]

This relationship was determined using a curvefit program and accurately represented the values of the kinematic viscosity for temperatures between 0°F and 140°F.
The loss of head pressure was then determined using Bernoulli's equation:

\[
\frac{p_1}{\gamma} + \frac{v_1^2}{2} + gz_1 = \frac{p_2}{\gamma} + \frac{v_2^2}{2} + gz_2 + h_f
\]  

(34)

Where the specific weight, \( \gamma \) was derived from the relationship:

\[
\gamma = \rho g
\]  

(35)

where \( g \) is the acceleration due to gravity. Since the elevation and velocity remained constant throughout the experimentation, Bernoulli's equation reduced to:

\[
h_f = \frac{p_1 - p_2}{\gamma}
\]  

(36)

The friction factor was then determined using the relationship:

\[
f = h_f \frac{d}{L} \frac{\rho v^2}{2}
\]  

(37)

The friction factor was then used to determine the coefficient of friction using the relationship:

\[
c_f = \frac{f}{4}
\]  

(38)

The wall shear stress was then solved for using the relationship:

\[
\tau_w = \frac{c_f \rho v^2}{2}
\]  

(39)

The Reynolds number and relative roughness were found using the equations:

\[
Re = \frac{\nu D}{\nu}
\]  

(40)
The dynamic pressure was then found using the relationship:

$$ p_{\text{dyn}} = \frac{\rho v^2}{2g} $$  \hspace{1cm} (42)  

To help in comparison of data, the friction factor and wall shear stress were then determined for a Reynolds number of 10,000 using the relationships:

$$ f_{10,000} = \frac{0.25}{(\log \left( \frac{d/\delta}{3.7 + \frac{2.51}{Re_{10,000} [f_{10,000}]} \right))^2} $$  \hspace{1cm} (43)  

$$ \tau_{10,000} = \frac{f_{10,000} \rho v^2}{8g} $$  \hspace{1cm} (44)  

The solutions to this information was stored in a data file or sent to a printer for later reference. A listing of the program follows.
Figure 27. Data Reduction Program Used to Determine Flow Parameters

************ NOMENCLATURE USED ************

1 C
2 C
3 C DOUGLAS W. HEAL
4 C FEBRUARY 4, 1989
5 C
6 C THIS IS THE PROGRAM USED TO DETERMINE THE WALL
7 C SHEAR STRESS ON THE BIOFILM IN THE TEST SECTION.
8 C THE PROGRAM READS THE PRESSURE DROP, THE FREQUENCY
9 C COUNTER READING, THE TEMPERATURE, AND THE TIME THE
10 C DATA WAS TAKEN FROM A DATA FILE CALLED BIO.DAT.
11 C THE PROGRAM THEN USES THIS INFORMATION TO CALCULATE
12 C THE DESIRED RESULTS.
13 C ************ NOMENCLATURE USED ************
14 C
15 C
16 C
17 C DP = PRESSURE DROP
18 C D = DIAMETER OF PIPE
19 C L = LENGTH OF TEST SECTION
20 C RHO = MASS DENSITY OF FLUID
21 C F = FRICTION FACTOR
22 C CF = COEFFICIENT OF FRICTION
23 C V = FLUID VELOCITY
24 C T = FLUID TEMPERATURE
25 C KV = KINEMATIC VISCOSITY
26 C TAU = WALL SHEAR STRESS
27 C RE = REYNOLDS NUMBER
28 C E = RELATIVE ROUGHNESS
29 C MON = MONTH
30 C DAY = DAY
31 C H = HOUR
32 C N = COUNTER
33 C FC = FREQUENCY COUNTER RESULT
34 C GPM = GALLONS PER MINUTE
35 C GAM = SPECIFIC WEIGHT OF FLUID
36 C HF = HEAD LOSS DUE TO FRICTION
37 C G = ACCELERATION FROM GRAVITY
38 C O = OXYGEN CONTENT OF WATER
39 C DYN = DYNAMIC PRESSURE
40 C FNEW = CORRECTED FRICTION FACTOR
41 C VNEW = CORRECTED VELOCITY
42 C TNEW = CORRECTED WALL SHEAR STRESS
43 C
44 C
FIRST, INITIALIZE ALL VARIABLES TO BE USED IN CALCULATING
THE RESULTS. THESE ARE THE SAME VALUES LISTED IN THE TEST
SECTION SPECIFICATIONS.

D(I)
D(2)
D(3)
D(4)
L(I)
L(2)
L(3)
L(4)
G
RHO
GAM

NOW, OPEN THE DATA FILE TO BE USED.

NOW, DETERMINE THE KINEMATIC VISCOSITY FOR THE KNOWN
TEMPERATURE.

DO 30, N = 1, 4 1

NOW, CALCULATE THE GALLONS PER MINUTE OF FLUID PASSING
THROUGH THE TURBINE FLOWMETER.
Figure 27—Continued

86

GPM(3) = 0.075626 + (0.014003 * FC(3))
GPM(4) = 0.067479 + (0.013770 * FC(4))

91 C

NOW, CALCULATE THE VELOCITY OF THE FLUID IN THE TEST SECTIONS.

93 C

V(1) = ((GPM(1)/60)*0.13368)/(3.14*((D(1)/2)**2))
V(2) = ((GPM(2)/60)*0.13368)/(3.14*((D(2)/2)**2))
V(3) = ((GPM(3)/60)*0.13368)/(3.14*((D(3)/2)**2))
V(4) = ((GPM(4)/60)*0.13368)/(3.14*((D(4)/2)**2))

98 C

NOW, CALCULATE THE PRESSURE DROP IN PSI.

100 C

DP(1) = (-0.001559 + 0.007157*DP(1)) * 144
DP(2) = (0.000213 + 0.004441*DP(2)) * 144
DP(3) = (-0.009023 + 0.009337*DP(3)) * 144
DP(4) = (0.002118 + 0.007523*DP(4)) * 144

105 C

NOW, ENTER A DO-LOOP TO DETERMINE THE RESULTS.

107 C

DO 1, N = 1,4 1
   HF(N) = DP(N)/RHO 1
   F(N) = (HF(N)*D(N)**2*G)/(L(N)*(V(N)**2)) 1
   CF(N) = F(N)/4 1
   TAU(N) = (CF(N)*RHO*(V(N)**2))/(2*G)
   RE(N) = V(N)*D(N)/KV(N) 1
   E(N) = 3.7*((10**(-0.5/(F(N)**.5)))
& -(2.51/(RE(N)*(F(N)**0.5)))) 1
   DYN(N) = (RHO*(V(N)**2))/(2*G) 1
117 1 CONTINUE

119 C

NOW, DETERMINE THE FRICTION FACTOR FOR A REYNOLDS NUMBER OF 10,000.

121 C

DO 70, N = 1,4 1
   FNEW(N) = F(N) 1
   DO 80, I= 1,4 2
      FNEW(N)= 0.25/((ALOG10(E(N)/3.7)+(2.51/(10000* 2
& (FNEW(N)**0.5))))**2) 2
  80 CONTINUE 1
128 70 CONTINUE

130 C

NOW, CALCULATE THE CORRECTED WALL SHEAR STRESS FOR A REYNOLDS NUMBER OF 10,000.
Figure 27—Continued

133  DO 110, N = 1, 4
134     VNEW(N) = 10000*KV(N)/D(N)
135     TNEW(N) = (FNEW(N)*RHO*(VNEW(N)**2)/(8*G))
136 110 CONTINUE
137 C NOW, PRINT THE RESULTS
138 C
139 C
140 WRITE(*,2) H
141 2 FORMAT( ',THE DATA WAS TAKEN AT ',I2,'00' )
142 WRITE(*,20) MON,DAY
143 20 FORMAT( ',ON ',I2,'-',I2,'-',I2,'-99' )
144 WRITE(*,*)
145 WRITE(*,9) GAM
146 WRITE(*,90) O
147 90 FORMAT( ',THE OXYGEN CONTENT WAS ',F7.2, 'PPM' )
148 WRITE(*,60) $\rho$
149 60 FORMAT( ',THE SPECIFIC WEIGHT OF THE FLUID WAS ',F7.1, 
150 & ',LB/FT^2' )
151 WRITE(*,*)
152 WRITE(*,*) 'FLOW FRICTION COEFF. SHEAR REYNOLDS'
153 WRITE(*,*) 'LOOP FACTOR OF STRESS NUMBER'
154 WRITE(*,9) F
155 WRITE(*,*) 'FRICTION LBF/FT^2'
156 DO 5, N=1,4
157 5 WRITE(*,6) N,F(N),CF(N),TAU(N),RE(N)
158 6 FORMAT( ', ',I1, ', ',F7.4, ', ',F8.5, ', ',F7.4, ', ',F10.1 )
159 CONTINUE
160 WRITE(*,*)
161 WRITE(*,*) 'FLOW RELATIVE VELOCITY GPM'
162 WRITE(*,*) 'LOOP ROUGHNESS FT/S'
163 WRITE(*,*) '--------------------------'
164 DO 7, N=1,4
165 7 WRITE(*,8) N,E(N),V(N),GPM(N)
166 8 FORMAT( ', ',I1, ', ',F8.5, ', ',F7.2, ', ',F6.4 )
167 CONTINUE
168 WRITE(*,*)
169 WRITE(*,*)
170 WRITE(*,*) 'FLOW HEAD LOSS PRESSURE BIOFILM'
171 WRITE(*,*) 'LOOP FROM FRICTION DROP THICKNESS'
172 WRITE(*,*) 'FT LBF/FT^2 METERS'
173 WRITE(*,*) '-----------------------------'
174 DO 10, N = 1, 4
175 10 WRITE(*,11) N,HF(N),DP(N),BT(N)
176 11 FORMAT( ', ',I1, ', ',F7.5, ', ',F7.2, ', ',F9.6 )
Figure 27—Continued

177 10 CONTINUE
178 WRITE(*,*)
179 WRITE(*,*)
180 WRITE(*,*) 'FLOW TEMPERATURE DYNAMIC KINEMATIC'
181 WRITE(*,*) 'LOOP DEGREES F. PRESSURE VISCOSITY'
182 WRITE(*,*) 'LB/FT^2  FT/S^2'
183 WRITE(*,*) '-------------------------------------------'
184 DO 50, N = 1, 4, 1
185 WRITE(*,40) N, T(N), DYN(N), KV(N)
186 40 FORMAT(' ', I1, 10X, F7.3, 5X, F10.8)
187 WRITE(*,100) N, FNEW(N), TNEW(N)
188 100 FORMAT(' ', I1,10X, F7.5,5X, F8.6)
189 50 CONTINUE
190 WRITE(*,*)
191 WRITE(*,*) 'FLOW CORRECTED CORRECTED'
192 WRITE(*,*) 'LOOP FRICTION SHEAR'
193 WRITE(*,*) 'FACTOR STRESS'
194 WRITE(*,*) '-------------------------------------------'
195 DO 90, N = 1, 4, 1
196 WRITE(*,100) N, FNEW(N), TNEW(N)
197 100 FORMAT(' ', I1,10X, F7.5,5X, F8.6)
198 90 CONTINUE
199 C
200 C NOW, CLOSE THE DATA FILE
201 C
202 C CLOSE (1)
203 C
204 END
APPENDIX D

OXYGEN LEVEL MEASUREMENTS
OXYGEN LEVEL MEASUREMENTS

Oxygen Level Measurements

The level of oxygen in the fluid was determined using a Dissolved Oxygen Meter, or DO meter. This instrument was capable of determining the percentage of dissolved oxygen in a sample of the test fluid. The DO Meter was used to take readings once a day throughout the test runs. The readings were taken by placing the DO Meter tip in the lower tank at the exit of the flow loop drain hoses. The meter was placed in this position for approximately five minutes to allow the meter to stabilize its reading. The oxygen content was then read from the meter in parts per million of dissolved oxygen per sample of test fluid.

Oxygen Level Results

The results of the DO meter for oxygen are shown in Figure 28. As can be seen, the oxygen level varies with the temperature of the fluid throughout the experiment. The DO meter determined that the water remained near the saturation point of oxygen throughout the entire investigation. This was caused by the design of the test apparatus. The fluid dropped approximately thirty feet in circulating through the flow loop. This continually reintroduced water into the test fluid throughout the experimentation.
Figure 28. Oxygen Level in Test Fluid
APPENDIX E

FLUID NUTRIENT MEASUREMENT
FLUID NUTRIENT MEASUREMENT

Nutrient Measurements

At the beginning of each test run, nutrients were added to the test fluid to increase the growth rate of the biofilm in the test section. This consisted of mixing 11.35 gm of glucose, $C_6H_{12}O_6$, 1.42 gm of potassium nitrate, $KNO_3$, and a trace of yeast extract into the fluid in the lower tank. This combination of glucose, potassium nitrate and yeast extract provided a carbon to nitrogen ratio in the tank of 8, with a carbon content at 40 parts per million and a nitrogen content at 5 parts per million, which was ideal for microbial growth. Yeast extract added the trace elements to speed the growth process. The trace element and carbon to nitrogen ratio were maintained throughout the experiment by adding 3.78 gm of glucose, 0.47 gm of potassium nitrate and a trace of yeast extract to the fluid in the tank once a day.

Nutrient measurements were taken at the beginning of each of the four test runs. This measurement consisted of taking a sample of the fluid leaving the test section of flow loop number one and storing it in a glass container. The glass container was then frozen to stop biological processes within the container. At the end of the test runs, all of the frozen glass containers were taken to the Industrial and Process Analysis Laboratory on the second floor of Cobleigh Hall to be analyzed for organic carbon. To determine the carbon
content, ultraviolet light was passed through the test sample and the amount of absorbed light recorded. Since carbon absorbs ultraviolet, the amount of carbon in a test sample could then be determined.

**Nutrient Results**

Table 15 shows the organic carbon content of the fluid for test runs number one through four. As can be seen from the figure, the carbon content varied slightly throughout the experiment, with a maximum of 145 ppm and a minimum of 212 ppm. This variation is relatively insignificant, with similar growth rates occurring for carbon contents between 20 ppm and 10,000 ppm.

Table 15. Nutrient Content of Test Fluid:

<table>
<thead>
<tr>
<th>Test Run</th>
<th>Carbon Content One (PPM)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test Run One</td>
<td>145</td>
</tr>
<tr>
<td>Test Run Two</td>
<td>183</td>
</tr>
<tr>
<td>Test Run Three</td>
<td>212</td>
</tr>
<tr>
<td>Test Run Four</td>
<td>165</td>
</tr>
</tbody>
</table>
APPENDIX F

TEMPERATURE VARIATION MEASUREMENTS
TEMPERATURE VARIATION MEASUREMENTS

Temperature Measurements

Throughout the investigation, the major factors affecting the fluid temperature were the pump located in the lower tank and the surrounding room temperature. Any fluctuation in the room temperature resulted in a corresponding fluctuation in the fluid temperature. The lower pump influenced the fluid temperature by heating the fluid during circulation.

Temperature Results

Figures 29 through 32 show the temperature of the test fluid and room temperature in flow loop number one for test runs one through four respectively. Only the temperature in flow loop one was plotted because the temperatures in all four flow loops remained within $\pm 1^\circ F$ of each other. As can be seen from the figures, the fluid temperature varied throughout the investigation with a maximum variation of twenty degrees $F$ for test run one over a nine day period, with a maximum temperature of $98^\circ F$ and a minimum temperature of $72^\circ F$. 
Figure 29. Variation in Fluid and Room Temperature v. Time for a Fluid Velocity of 1 ft/sec
Figure 30. Variation in Fluid and Room Temperature v. Time for a Fluid velocity of 1.25 ft/sec
Figure 31. Variation in Fluid and Room Temperature v. Time for a Fluid Velocity of 1.50 ft/sec
Figure 32. Variation in Fluid and Room Temperature v. Time for a Fluid Velocity of 1.75 ft/sec