Effect of a Simulated Butterfly Valve on the Erosion-Corrosion Rate of Nickel Aluminum Bronze Alloys in Highly Turbulent Seawater

Ryan Taylor

Thesis submitted to the faculty of the Virginia Polytechnic Institute and State University in partial fulfillment of the requirements for the degree of

Master of Science in Materials Science and Engineering

Robert W. Hendricks (Chair)
William T. Reynolds
Sean G. Corcoran

May 3, 2018
Blacksburg, VA

Keywords:
Cavitation, corrosion loop, erosion-corrosion, nickel aluminum bronze, seawater corrosion, turbulence
Nickel aluminum bronze (NAB) alloys are used in naval and maritime applications for their excellent corrosion resistance under the influence of seawater. One application involves the use of a NAB butterfly valve within a NAB fluid line to control fluid flow of seawater. Due to the chaotic environment, the corrosion rate of the NAB tubing downstream from the valve increases significantly. The disc angle at which the valve alters fluid flow causes an increase in the fluid velocity and an increase in the turbulence produced on the downstream side of the valve. These fluid conditions contribute to the increase in the corrosion rate of the NAB piping downstream from the valve. This thesis aims to characterize how the change in the disc angle of the butterfly valve causes a change in the erosion-corrosion rate of NAB downstream from the valve. A butterfly valve is simulated using orifice plates of varying diameters to mimic flow conditions at different disc angles. An orifice plate is a simple device with a hole in its center that is designed to restrict fluid flow across a fluid line. Under the same hydrodynamic conditions, the orifice produces nearly the exact same flow coefficients as the valve. At a volumetric flowrate of 0.00757 \( m^3/s \) a total of eight locations found along the liquid/metal interface produced pitting sites. The average passivation layer thickness is also measured.
Nickel aluminum bronze alloys are used within the naval and maritime industries for many different types of applications. The main use of this material as studied within this project entailed the use of this alloy within a piping structure downstream from a type of butterfly valve. When seawater flows through this piping structure, the valve distortions within the fluid are believed to cause degradation of the piping material. This project aimed to look at how the change in the disc angle of the butterfly valve caused disruptions in the fluid and thereby changes in how nickel aluminum bronze degrades over time. It was found that as the disc angle inside of the butterfly valve decreased towards being completely closed, the greater the amount of degradation was produced upon the alloys surface. Micrographs within this paper aimed to characterize the amount of degradation upon the alloy surface and also report the overall thickness of oxide deposited onto the metal surface during testing.
Table of Contents

1.0 Problem Statement .................................................................................................................. 1

2.0 Introduction ............................................................................................................................ 1

   2.1 Butterfly Valves ................................................................................................................. 1

   2.2 Problems with Butterfly Valves ......................................................................................... 1

   2.3 The Virginia Tech High Turbulence Corrosion Loop ....................................................... 1

3.0 Background ............................................................................................................................. 1

   3.1 Properties of NAB ........................................................................................................... 1

   3.2 Flow - Enhanced Corrosion ............................................................................................... 3

   3.3 Erosion-Corrosion (EC) Downstream of Valves ................................................................. 4

   3.4 Cavitation .......................................................................................................................... 5

4.0 Modeling of a Butterfly Valve ............................................................................................... 6

   4.1 Fluid Flow Issues .............................................................................................................. 6

   4.2 Orifice Plate Model .......................................................................................................... 6

   4.3 Computations .................................................................................................................... 9

   4.4 Anticipated Performance ................................................................................................. 12

5.0 Experimental Studies ............................................................................................................. 15

   5.1 Tests of the model ............................................................................................................ 15

      5.1.1 Design/Construction of Pressure device .................................................................. 15

      5.1.2 Measurement of loss factors/flow factors ................................................................. 16

   5.2 Studies of Corrosion ......................................................................................................... 21

      5.2.1 Calibration ................................................................................................................. 21

      5.2.2 Experimental Setup of 32 mm Orifice Test 1 ............................................................ 23

      5.2.3 Experimental Results of 32 mm Orifice Test 1 ........................................................ 24

      5.2.4 Experimental Setup of 32 mm Orifice Test 2 ............................................................ 24

      5.2.5 Experimental Results of 32 mm Orifice Test 2 ........................................................ 25

      5.2.6 EC Calculations ......................................................................................................... 27

6.0 Characterization of Materials ............................................................................................... 27

   6.1 Metallography ................................................................................................................. 29

7.0 Discussion .............................................................................................................................. 31
8.0 Conclusions........................................................................................................................................33
9.0 Recommendations for Future Work...................................................................................................33
10.0 Acknowledgements..........................................................................................................................34
11.0 References........................................................................................................................................34
12.0 Appendix A.......................................................................................................................................38
1.0 Problem Statement
The purpose of this study is to determine the effect of a simulated butterfly valve on the erosion-corrosion rate of nickel aluminum bronze (NAB) alloys in highly turbulent seawater.

2.0 Introduction

2.1 Butterfly Valves
Butterfly valves are devices that control the rate of fluid flow across a body of water such as a pipeline. Unlike other types of valves, when the butterfly valve is completely open there is a disc directly in the fluid path that causes disturbances in the flow characteristics of the fluid. This is very different from ball or globe valves that provide a safe transition between the upstream and downstream sides of the valve. As the butterfly valve is turned the disc position will change causing different flow coefficients of fluid to move through the valve per unit time. The flow coefficient is defined as the amount of fluid that can move through a valve per unit time. These devices are currently used in many different applications including the naval and maritime industries. Butterfly valves have been constructed, for decades out of many different materials including duplex stainless steels and copper nickel alloys like NAB. This is mainly due to their resistance to seawater corrosion. Despite this, flow – accelerated corrosion still occurs for both materials at a certain rate when introduced to seawater [1].

2.2 Problems with Butterfly Valves
Such piping systems house seawater for days if not weeks on end, here restricting the flow inside condensers and heat exchangers. Depending on the disc angle, fluid inside of the piping system may react violently with the internal diameter of the pipe causing degradation to occur at some critical flowrate. The piping material in this example is also made up of NAB just like the valve itself. Because of the reaction with the seawater upon the oxide layer of the NAB, corrosion of this material can occur for even the static case in which no seawater is flowing. As the flowrate is increased in the fluid line the corrosion rate of the NAB increases. Experiments for this thesis will be performed to show the effect of flowrate on the corrosion rate of NAB as a function of time.

2.3 The Virginia Tech High Turbulence Corrosion Loop
In order to look at the effects of simulated butterfly valve on the erosion-corrosion rate of NAB in highly turbulent seawater, the Virginia Tech High Turbulence Corrosion Loop (VTHTCL) was used. The VTHTCL can create and control the environment in which corrosion testing may be performed. The temperature, volumetric flowrate, pressure, pH, electrical conductivity, and dissolved oxygen content of the fluid are monitored and controlled in this apparatus [2]. In these experiments, the tube wall thickness was measured using an array of ultrasonic transducers multiplexed to an ultrasonic thickness tester. All of the measurable quantities mentioned in this section were recorded and stored using a fully-functional data acquisition system programmed entirely in LABVIEW [3]. All data recorded during any given corrosion test is saved as a CSV file for ease of data management.

3.0 Background

3.1 Properties of NAB
Nickel aluminum bronze is a broad classification of materials that are particularly useful for naval applications due to their high mechanical strength (i.e. shock resistance, fracture toughness, and hardness).
and their strong corrosion resistance. NAB is a complex, multi-species alloy that contains copper, aluminum, nickel, cobalt, and several other small concentrations that develop a complex microstructure when worked. While these improved performance characteristics makes this class of alloy attractive, complex shapes are difficult to machine to high tolerances. As – cast NAB is used widely for the construction of valves that interact with seawater, however, this presents an aggressive tribocorrosive environment that significantly reduces the operational lifetime of these materials [1].

NAB is used to create many different naval products ranging from bearings, propulsion impellers, to valves [1] [4] [5]. NAB is implemented for these applications due to its high shock resistance, fracture toughness, and hardness compared to traditional materials [4]. The mechanical strength of NAB is greatly increased due to the aluminum and nickel concentrations. Nickel aids the overall yield strength of the material while aluminum, being a hard face-centered-cubic element, aids the overall hardness and fracture toughness of the material [4]. While attractive due to its improved mechanical properties, NAB experiences accelerated degradation in marine environments. Most notably, cavitation and erosion-corrosion present severe risks to their operational lifetime and function.

The specifications of C95510, the most common commercially available form of the alloy, have the composition ranges as shown in Table 1. The heat treatment of this nickel aluminum bronze is TQ50, which is manufactured by Busby Metals [6]. The TQ50 heat treatment involves the use of quench hardening and temper annealing. Although the material is continuously cast, the grain structure appears to be wrought-like in nature with fine grain sizes due to heat treatments [7]. This creates a cast material with a fine grain structure that provides enhanced corrosion and fatigue resistance. This material is available in the form of a tube with nearly the same dimensions as the 44.5-mm chlorinated polyvinyl chloride (CPVC) piping that is currently used in the Virginia Tech High Turbulence Corrosion Loop (VTHTCL) [2]. Minor machining of the tube surface was performed to reduce the surface roughness on both the internal and external surfaces.

**Table 1: Specification of C95510 nickel aluminum bronze [6]**

<table>
<thead>
<tr>
<th>Comp: (wt%)</th>
<th>Copper</th>
<th>Nickel + Cobalt</th>
<th>Antimony</th>
<th>Manganese</th>
<th>Zinc</th>
<th>Iron</th>
<th>Aluminum</th>
</tr>
</thead>
<tbody>
<tr>
<td>78.1 – 81.8</td>
<td>4.5 – 5.5</td>
<td>0.2</td>
<td>1.5</td>
<td>0.3</td>
<td>2.0 – 3.5</td>
<td>9.7 – 10.9</td>
<td></td>
</tr>
</tbody>
</table>

The heat treatment used to produce NAB has been shown to have a significant effect on the subsequent microstructure of the material [8] – [12]. The microstructure produced impacts the corresponding hardness of the final material and other corrosion related properties [8], [13] – [15]. Shot-peening can also impact the corrosion resistant properties of NAB [16]. The heat treatment, microstructure, and shot-peening produce a corrosion resistant material with high hardness and good strength. These factors influence the hardness and subsequent corrosion mechanisms like erosion-corrosion and pitting [17] - [21]. Figure 1 represents the generic microstructure of NAB [13]. Figure 2 shows the phase diagram of NAB [15].

One of the more corrosive environments to negatively impact the corrosion resistance of NAB is sulfide pollution of seawater, which has been shown to dramatically increase the corrosion rate of the alloy [1]. The corrosion rate of NAB due to sulfide seawater pollution is approximately 10 times higher than the
corrosion rate of NAB induced by pitting from seawater that was not polluted with sulfides [1]. In comparison, the corrosion rate for sulfide polluted seawater is eight times higher than that of cavitation and erosion-corrosion [1]. Some corrosion conditions that could be produced inside of the VTHTCL without hindering the further usage of the device were cavitation and erosion-corrosion. These corrosion mechanisms were the next most susceptible environments for nickel aluminum bronze alloys that could be studied using the VTHTCL. Because of the negative effects that cavitation has on the pump used within the VTHTCL, it was decided to study erosion-corrosion mechanisms of NAB in highly turbulent seawater. More data on NAB’s degradation behavior is needed for determining its performance and expected lifetime for these given applications. For these reasons an experimental design was created to study the effects of a simulated butterfly valve on the erosion-corrosion rate of nickel aluminum bronze alloys in highly turbulent seawater.

![Microstructure of Nickel Aluminum Bronze](image1.png)

![Phase Diagram of Nickel Aluminum Bronze](image2.png)

**Figure 1 (Left): Microstructure of Nickel Aluminum Bronze [13];**

**Figure 2 (Right): Phase Diagram of Nickel Aluminum Bronze [1]**

### 3.2 Flow-Enhanced Corrosion

Erosion-Corrosion (EC), also known as jet impingement attack, belongs to a family of degradation mechanisms known as flow-related materials degradation. Other corrosion mechanisms include oxidation, flow-accelerated corrosion, cavitation, pitting, intergranular, and galvanic corrosion [7]. Flow-accelerated corrosion involves the use of a high velocity fluid flowing over the surface of a metal to strip away the passivation (oxide) layer which protects the metal from degradation [22]. Oxidation involves the buildup of an oxide layer on the surface of a metal that creates either a protective or destructive surface film thus impeding or enhancing the rate of corrosion. Cavitation involves the creation of vapor bubbles arising from turbulence produced in low pressure regions that degrade chaotically in high pressure regions [23]. These bubbles cause surface degradation of the material. Pitting can occur in areas in which the protective surface film has been penetrated or removed by the corrosive environment [24]. An impression in the metal surface is formed in isolated locations due to the removal of this passivation layer. Intergranular corrosion occurs because of a break in the passivation layer of a metal. Cracks in the material form in
directions between the grain boundaries of the material. Galvanic corrosion occurs in areas where one metal encounters another metal of a different electrochemical potential that results from a different composition. When an electrolyte is added to this system the metal that has the higher corrosion potential will act as the cathode and the metal that has the lower corrosion potential will act as the anode [25]. The metal with a lower corrosion potential will act as a sacrificial anode and will reduce. The metal with the higher corrosion potential will become subject to oxidation reactions serving to protect the metal surface from further corrosion mechanisms [26]. Of these mechanisms erosion-corrosion/jet impingement and cavitation are of relevance here.

3.3 Erosion-Corrosion (EC) Downstream of Valves

When high velocity fluid moves over the surface of certain metals, shear stresses are produced that can remove the passivation layer on the surface of the metal in localized regions [8, 9]. Due to the localized removal of this protective oxide barrier, the high velocity fluid can attack the surface of the metal directly. The phenomena explained by this process involves the mechanical stripping away of the protective oxide layer and the electrochemical reactions that ensue between the electrolytic fluid and the bare metal [7]. This layer may be stripped away by the shear stresses developed by highly turbulent flow characterized by high Reynolds numbers. The resultant bare metal is then subject to electrochemical corrosion [27], [28]. The passivation layer produced on the NAB surface is composed of both aluminum and copper oxide and may be as small as 900 nanometers in thickness [4]. In our group, we are developing techniques to measure this wall shear stress directly [3]. Erosion-corrosion is quantitatively defined as the sum of the rate of mass loss produced solely by erosion, the rate of mass loss produced solely by electrochemical processes and the synergy in which one process can influence the other [9].

The electrochemical reactions involved within the erosion-corrosion process of NAB in aerated seawater involve both anodic and cathodic reactions [4]. The pH of seawater drives these reactions to occur within the NAB system. The cathodic reaction presented below is driven by the removal of the $K_{II}$ phase which only occurs for pH below 4.2 [29]. The anodic reaction on the other hand occurs for pH values above this limit and involves the selective attack of the alpha phase [29]. In Figure 2, $K$ is presented to be part of the NAB phase diagram. There are primarily 5 different phases of $K$ contained within this phase diagram, the most important phase from a corrosion perspective being $K_{II}$.

\begin{align*}
Cu - e^- + 2Cl^- & \rightarrow CuCl_2^2^- & \text{Anodic Reaction: (Equation 1)} \\
O_2 + 2H_2O + 4e^- & \rightarrow 4OH^- & \text{Cathodic Reaction: (Equation 2)}
\end{align*}

Depending on the environment in which erosion and corrosion mechanisms exist, the overall synergy term of this calculation will change dramatically. For instance, if the mechanical shearing away of the protective passivation layer occurs uniformly across the internal surface of a pipe then the rate at which electrochemical attack can occur will increase dramatically. Also, if the erosion process is unable to remove some of the passivation layer, then the overall corrosion rate will be significantly reduced. For these reasons synergy defines how erosion can influence corrosion or vice versa [28]. In either case, the overall erosion-corrosion rate is based upon the rate of passivation versus the rate of mechanical wear. If
the rate of mechanical wear is greater than the rate of passivation, the result would generally be an increase in the erosion-corrosion rate. If the passivation rate is greater than the rate of mechanical wear, the erosion-corrosion rate will be reduced [30]. For this series of experiments, we expect to see significant changes in the mechanism of corrosion as the flowrate changes.

Pitting has been defined as the preferential attack of less noble regions within the NAB microstructure [1]. When the passivation layer of NAB has been removed in a localized manner, small isolated regions that seawater encounters may corrode. These isolated corrosion sites are called pits and these locations have been known to provide detrimental problems to the marine and naval industries for years [24]. Due to the removal of the passivation layer in these regions, crack initiation sites may be formed as a result thus increasing the chances of material failure. However, it has been stated that for the family of NAB alloys, pitting can be almost entirely mitigated by controlling the aluminum and nickel content within the alloy [1]. If the alloy is less than 8.2 % aluminum and 0.5% nickel, then pitting brought about by the preferential phase attack may be stopped [1]. Unfortunately, the aluminum content within the NAB studied here is greater than these limits so the formation of pits is still possible, (See Table 1) [1].

Pitting is more prevalent in cast NAB as opposed to its wrought form due to differences in microstructure. Due to the wrought manufacturing processes of cold and hot working, the grain structure is very small and leads to very strong mechanical properties because of solid solution strengthening [1]. While wrought NAB is often desirable because of its strength and its increased corrosion resistance, cast NAB is often chosen due to the ease of manufacturing, cost, and the ability to form complex shapes without post-process machining. We selected cast NAB because it is available as a tube with roughly the same dimensions as schedule 80 pipe previously used within the VTHTCL.

The Copper Development Association [1] and Ault [31] have shown that the erosion-corrosion rate of NAB increases with increasing fluid velocity in seawater. The range of flowrates were between 4.3 to 30 m/s. However, the environment was not clearly stated and so we do not know the velocity gradient, or the shear stress produced during the experiments. NAB is only intended to operate at or below a fluid velocity of 4.3 m/s, so at this critical velocity the chances for erosion-corrosion to occur increases dramatically. Any fluid velocity above this point will provide increased corrosion rates as a function of time. At a fluid velocity of 7.6 m/s the nickel aluminum bronze alloy corroded through erosion-corrosion at a rate 19.7 mils/year [1], [31]. Also, at the highest fluid velocity for these experiments of 30 m/s, the corresponding erosion-corrosion rate was shown to be 29.9 mils/year [1], [31].

3.4 Cavitation

Cavitation of NAB alloys is a significant problem for marine applications. Cavitation is influenced by the level of turbulence seen within a fluid system. The higher the turbulence, the greater the chance a low-pressure region will allow the formation of vapor bubbles [1], [8]. As these vapor bubbles move from a high-pressure region to a low-pressure region, the bubbles expand causing degradation of the protective passivation layer and formation of microcracks in the material [26]. These bubbles expand as nucleation occurs at higher pressures and move toward the boundary between the fluid and the internal diameter of the pipe. Turbulence and thereby cavitation are impacted by sudden changes in the geometries of piping systems, the surface roughness of those piping systems, and changes is the fluid velocity. Predicting locations in which cavitation may occur proves to be a difficult task. Unlike other corrosion mechanisms, cavitation does not occur directly at the formation sites of these vapor bubbles [1], [8].
4.0 Modeling of a Butterfly Valve

Erosion-Corrosion of NAB tubing downstream from butterfly valves leads to premature failure of the tubing. The present investigation is designed to quantify the erosion-corrosion rate of tubing when subjected to the same hydrodynamic conditions as those of a butterfly valve. To reduce the complexity of this design, cylindrically symmetric orifice plates with carefully designed flow coefficients which mimic the flow coefficients of industrial butterfly valves currently used by the US Navy were implemented.

4.1 Fluid Flow Issues

Orifice plates that may have one or a number of holes are devices that are placed directly into a fluid line that change the flowrate of fluid and the differential pressure between the upstream and downstream face of the plate. In order to model the proposed valve, an orifice plate with a single hole of fixed diameter that expands at a 45-degree angle in the direction of fluid flow was designed. A series of 316 stainless steel orifice plates replace the butterfly valve for this set of experiments because they are inexpensive to produce, are easy and quick to manufacture, non-corrodible in a seawater environment, and most importantly, they produce cylindrically symmetric flow. We are not interested in the corrosion of the valve itself. Instead the focus of this study is to measure the corrosion of downstream piping. Orifice plates provide an alternative way to perform this research in a reasonable amount of time. Each orifice plate was designed to represent a specific disc angle of a butterfly valve through the change in the orifice diameter. At the same volumetric flowrate and pressure drop across this type of obstruction, the erosion-corrosion rate of nickel aluminum bronze downstream of the orifice should be the same as that of an actual butterfly valve when the same hydrodynamic conditions are subjected to both types of obstructions. The corrosion rate of the orifice plate can be controlled by making each plate out of 316 stainless steel which does not corrode easily in seawater. Type 316 stainless steel was chosen to create the orifice plates mentioned earlier. In the computation of orifice diameters section further aspects of how orifice plates compare to actual butterfly valves will be explained.

4.2 Orifice Plate Model

We wish to match the profile of the orifice to that of a butterfly valve at various degrees of openness. This relationship is upheld by matching the pressure drop produced between the upstream and downstream sides of the butterfly valve at a fixed flowrate with the pressure drop produced by an orifice plate of fixed diameter. The differential pressure across the valve, $\Delta P$, is given by

$$\Delta P = G \cdot \left(\frac{Q_v}{K_V}\right)^2$$

Equation 3

where, in industry standard units,

$\Delta P$ = pressure drop (bars),

$G$ = specific gravity of seawater (unitless),

$Q_v$ = volumetric flowrate of seawater in the valve $(\text{m}^3/\text{hr})$, and

$K_V$ = flow coefficient of the butterfly valve $(\text{m}^3/\text{hr} \sqrt{\text{bar}})$. 
The mass flowrate, \( q_m \), through an orifice is a function of the pressure drop across the orifice, the density of seawater, the diameter of the upstream pipe, the discharge coefficient, the viscosity of seawater, and the Reynolds number \([32]\).

\[
q_m = \frac{C_d}{\sqrt{1 - \beta^4}} \cdot \varepsilon \cdot \frac{\pi}{4} \cdot d^2 \cdot \sqrt{2 \cdot \Delta P \cdot \rho}
\]

Equation 4

where

\( q_m \) = mass flowrate \( (\text{kg/sec}) \),

\( C_d \) = discharge coefficient (dimensionless),

\( D \) = original diameter of pipe (m),

\( d \) = orifice diameter (m),

\( \beta \) = ratio of the orifice diameter to the original diameter of the pipe, \( \frac{d}{D} \), (dimensionless),

\( \varepsilon \) = expansibility factor (dimensionless), and

\( \Delta P \) = pressure drop across valve \( (\text{Pa}) \cdot 100,000 \),

\( \rho \) = density of fluid in system \( (\text{kg/m}^3) \).

The discharge coefficient of a butterfly valve, \( C_d \), is given by

\[
C_d = .5961 + .0261 \cdot \left( \frac{d}{D} \right)^2 - .216 \cdot \left( \frac{d}{D} \right)^8 + .000521 \cdot \left( \frac{10^6 \cdot \left( \frac{d}{D} \right)}{R_D} \right)^7 + (.0188 + .0063 \cdot \left( \frac{19000 \cdot \left( \frac{d}{D} \right)}{R_D} \right)) \cdot \left( \frac{10^6 \cdot \left( \frac{d}{D} \right)}{R_D} \right)^3 + (.043 + (.080 \cdot \text{Exp}[-5]) - (.123 \cdot \text{Exp}[-3.5])) \cdot (1 - .11 \cdot \left( \frac{19000 \cdot \left( \frac{d}{D} \right)}{R_D} \right)) \cdot \left( \frac{d}{D} \right)^{1.3}
\]

where

\( R_D \) = Reynolds number (dimensionless) = \( \frac{\rho \cdot v \cdot D}{\eta} \),

\( v \) = mean velocity of seawater in pipe \( (\text{m/s}) \), and

\( \eta \) = dynamic viscosity of seawater \( (\text{kg/m} \cdot \text{s}) \).

The expansibility factor of fluid moving through a butterfly valve is given by

\[
\varepsilon = \left[ \left( \frac{k T^2}{\kappa} \right) \left( \frac{1 - \beta^4}{1 - \beta^4 \tau^{2/k}} \right) \left( \frac{1 - \tau^{(\kappa-1)/\kappa}}{1 - \tau} \right) \right]^{5}
\]

Equation 5

where

\( \kappa \) = isentropic exponent of seawater (dimensionless) = 1.33, and
\( \tau = \text{ratio of pressure before and after valve (dimensionless)}. \)

In the present case, the dimensionless expansibility factor is equal to 1 since water is an incompressible fluid [33]. An expanded equation which compiles all these parameters together is

\[
q_m = \frac{C_d}{\sqrt{1 - \left( \frac{d}{D} \right)^4}} \sqrt{\frac{\pi}{4} d^2 * \sqrt{2 * G * \left( \frac{Q_v}{K_v} \right)^2 * 100,000 * \rho}} \tag{Equation 6}
\]

The above equation is valid for:

\begin{enumerate}
  \item a) 2" \( \leq \) D \( \leq \) 25"
  \item b) 10,000 \( \leq \) \( R_D \) \( \leq \) 10,000,000
  \item c) 0.2 \( \leq \) \( \beta \) \( \leq \) 0.8
  \item d) \( R_a \) / D (surface roughness profile) \( \leq \) 3.2 \( \times \) 10\(^{-4}\) in upstream pipe
\end{enumerate}

But \( q_m \) (\( kg \) / s) = \( Q_v \) (m\(^3\) / hr) \times \frac{1}{3600} (hr / s) \times \rho (kg / m\(^3\)).

For the orifice plate to perform as a butterfly valve we must solve for the diameter of the orifice as a function of the flow coefficient. This is performed by direct substitution of the above equation in equation 6.

Wolfram Mathematica has been used to calculate the orifice diameter for the proposed set of flow conditions. The equation of mass flowrate is constrained to only work for flow devices known as orifice plates. For this equation to be satisfied four conditions must be met. These conditions have been listed above.

The data plotted in Figure 3 represents the change in the flow coefficient as a function of the disc angle of the butterfly valve of four different types of commercial butterfly valves. The flow coefficient curve for each commercial valve was obtained directly from the valve manufacturer. Flow coefficients for each orifice diameter was picked based off their position on Figure 3 seen below for BX2001 Valve Big Max Butterfly Valves [34]. By picking flow coefficients of 58.8, 47.5, 34.6, and 28.1 (m\(^3\)/hr) / (bar), the flow characteristics of most of this curve can be represented by their corresponding orifice diameters. The other curves seen represent other commercial butterfly valves of the same size and these were added to show that this butterfly valve had the capability to produce nearly the same flow characteristics as do other commercial butterfly valves.

The operating point for the pump in the VTHTCL is approximately 200 kPa and this limits the maximum backpressure, which in turn limits the butterfly valve to close to no less than 32-degrees. Any degree of rotation lower than this will cause a build-up of pressure running back into the impeller pump causing the pump to stop rotating and shut off. The 90-degree opening represents the maximum flow coefficient at which a 50.8-mm valve can experience. The 50.4 degrees of rotation case was chosen because it corresponds to a flow coefficient of 47.6 as specified by the Navy standard [35]. The 38 degree of rotation case was chosen because it is almost directly half way between the 32 and 50.4-degree cases on the flow coefficient curve. Due to the dramatic shift in the flow coefficients between the 32 and 50.4-degree cases...
the 38-degree case was implemented. The amount of flow coefficient variability between the 50.4-degree case and the 90 degree is minimal and for this reason another design was not added [35], [36], [37].

![Flow coefficient vs. Butterfly Valve Disc Angle](image)

**Figure 3:** Flow coefficient vs. degree of rotation for four separate types of butterfly valves. Data taken from references [34], [35], [36], [37].

### 4.3 Computations

Using equation 6, and values for the specific gravity, the volumetric and mass flowrates, the velocity of seawater, the flow coefficients for each case, the pipe diameter, the density and viscosity of seawater at 25 degrees Celsius, the expansibility factor for water, and the pressure drop across the valve as function of the flow coefficient, the orifice diameter needed to represent each case was calculated. A temperature of 25 degrees was used because it is the operating point of the loop. The constants used in this equation for each case are shown in Using the parameters of these four cases, the orifice diameters needed to mimic the flow conditions seen inside of actual butterfly valves at various degrees of rotation were determined. The calculated orifice diameters for the four cases have been grouped in Table 3 below. For the 6.466 kg/s flowrate the orifice diameters the following orifice diameters were computed.

Table 2. The only parameters that change between each case is the flow coefficient and by conjunction the pressure drop across the valve. Cases 1 – 4 decrease the angle in which a butterfly valve would need to be open to produce the same flow coefficient as each designed orifice. Each column represents the constants used in the calculation of the orifice diameter for that particular case.
Using the parameters of these four cases, the orifice diameters needed to mimic the flow conditions seen inside of actual butterfly valves at various degrees of rotation were determined. The calculated orifice diameters for the four cases have been grouped in Table 3 below. For the 6.466 kg/s flowrate the orifice diameters the following orifice diameters were computed.

Table 2: Variables held constant for each case and predicted pressure drop across the valve as a function of valve position

<table>
<thead>
<tr>
<th>Variable</th>
<th>Units</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Specific Gravity, G</td>
<td>unitless</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
<td>1.03</td>
</tr>
<tr>
<td>Volumetric Flowrate, $Q_V$</td>
<td>$\frac{m^3}{hr}$</td>
<td>22.72</td>
<td>22.72</td>
<td>22.72</td>
<td>22.72</td>
</tr>
<tr>
<td>Flow coefficient, $K_V$ (From Figure 3)</td>
<td>$\left(\frac{m^3/hr}{\sqrt{\text{bar}}}\right)$</td>
<td>58.8</td>
<td>47.6</td>
<td>34.6</td>
<td>28.1</td>
</tr>
<tr>
<td>Tube diameter, D</td>
<td>mm</td>
<td>50.8</td>
<td>50.8</td>
<td>50.8</td>
<td>50.8</td>
</tr>
<tr>
<td>Density, $\rho(\text{seawater 25 C})$</td>
<td>$\frac{kg}{m^3}$</td>
<td>1025</td>
<td>1025</td>
<td>1025</td>
<td>1025</td>
</tr>
<tr>
<td>Viscosity, LIT Value: $\eta(\text{seawater 25C})$</td>
<td>$\frac{kg}{m \cdot s}$</td>
<td>0.00108</td>
<td>0.00108</td>
<td>0.00108</td>
<td>0.00108</td>
</tr>
<tr>
<td>Mass Flowrate, $q_m$</td>
<td>$\frac{kg}{sec}$</td>
<td>6.47</td>
<td>6.47</td>
<td>6.47</td>
<td>6.47</td>
</tr>
<tr>
<td>Expansibility Factor, $\varepsilon$</td>
<td>unitless</td>
<td>1</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Pressure drop across valve, $\Delta P$ (Calculated from Eq. 2)</td>
<td>$kPa$</td>
<td>15.4</td>
<td>23.5</td>
<td>44.4</td>
<td>67.4</td>
</tr>
</tbody>
</table>

Table 3: Orifice diameter calculations

<table>
<thead>
<tr>
<th>Case</th>
<th>Volumetric Flowrate, $\left(\frac{m^3}{s}\right)$</th>
<th>Degree of Openness, (degrees)</th>
<th>Flow Coefficient, $K_v$, $\left(\frac{m^3/hr}{\sqrt{\text{bar}}}\right)$</th>
<th>Orifice diameter, (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>0.00631</td>
<td>90.0</td>
<td>58.8</td>
<td>42</td>
</tr>
<tr>
<td>Case 2</td>
<td>0.00631</td>
<td>50.4</td>
<td>47.6</td>
<td>39</td>
</tr>
<tr>
<td>Case 3</td>
<td>0.00631</td>
<td>38.0</td>
<td>34.6</td>
<td>35</td>
</tr>
<tr>
<td>Case 4</td>
<td>0.00631</td>
<td>32.0</td>
<td>28.1</td>
<td>32</td>
</tr>
</tbody>
</table>
These four orifice plates have been analyzed to verify that they indeed satisfy the four conditions set forth in the ASME handbook as given below Equation 6 [32]. It was found that only criterion (d) is not satisfied by all four orifice plates. The orifice plate representing the 90-degree disc angle of a butterfly valve has a beta ratio greater than the 0.8 limit and therefore these set of equations used to find the orifice diameter become invalid. The beta ratio of the orifice plate representing the 90-degree disc angle is 0.826 a value that falls outside of the range reported for beta by only 0.026. Because, the change in flow coefficient between the 50.4-degree case and the 90-degree case was small it didn’t make sense to lower the degree of rotation in order to uphold the beta condition. This case was used to compare how a beta ratio that falls outside of the range specified by the standard compares with the other cases that satisfy all of the standards conditions.

Figure 4 shows the geometry of the orifice plate cross section for each reduction diameter. All other quantities are defined as a function of either the orifice diameter or the starting pipe diameter [32].

Figure 4: Geometry of Orifice Plate Cross-Section: (a) cross-section, (b) completed orifice, and (c) orifice dimensions.
4.4 Anticipated Performance

Figure 5 shows how increasing flow coefficient effects orifice diameter. As the flow coefficient increases, the orifice diameter increases in size as well. This increase in the flow coefficient and orifice diameter represents the opening of the butterfly valve until the valve has reached the 90-degree position. Using the line of best fit provided in the figure one can empirically solve for the orifice diameter as a function of the flow coefficient under the set of conditions explained earlier.

Figure 5: Relationship between flow coefficient and orifice diameter

The orifice diameters were picked with the backpressure created from these obstructions in mind. System limitations of the VTHTCL prevent the pressure in the corrosion loop from rising above 200 kPa. The orifice diameters picked do not exceed this requirement at the intended test conditions of this project. Cavitation is an important consideration for this problem. To estimate the probability of cavitation, we estimate the absolute pressure of the fluid at vena contracta. This may be done by calculating the absolute pressure on the up-stream side of the orifice and then subtracting the pressure drop from there to the vena contracta. The pressure at the upstream face is given by

\[ P_U = P_{atm} + \frac{1}{2} \rho \left( l K_L \frac{CPVC}{m} + K_{orif} L^0 \right) v^2 \]  

Equation 7

where

\[ P_{atm} = \text{atmospheric pressure (kPa)}, \]
v = mean fluid flow velocity \( \frac{m}{s} \),
\[ v = \text{mean fluid flow velocity} \quad \left( \frac{m}{s} \right) \]
\[ \rho = \text{density of fluid} \quad \left( \frac{kg}{m^3} \right) \]
\[ l = \text{length of pipe following the orifice} \]
\[ K_{\text{L}} \quad \text{loss factor per meter of PVC pipe, and} \]
\[ K_{\text{L, orif}} = \text{loss factor of orifice} \]

Substituting the pressure drop across the orifice from the upstream pressure given by Equation 7, the pressures at the vena contracta for the four orifices are shown in Figure 6.

![Figure 6: Pressure at the Vena Contracta vs. Flowrate](image)

**Figure 6: Pressure at the Vena Contracta vs. Mean Velocity**

At an operating temperature of 25 degrees Celsius for this series of experimentation, the vapor pressure of water is 3.17 kPa. Thus, it is seen that, under the operating conditions of the loop, cavitation is a significant problem. This is especially true for Case 4 in which the pressure at the vena contracta crosses the vapor pressure of water at room temperature. At a volumetric flowrate higher than 6.7 L/s cavitation is produced for this case. For these reasons, the smallest orifice was chosen to perform corrosion experimentation because, this case had the highest probability of forming pits due to cavitation.

The pressure drop from the upstream side of the orifice is given by the Bernoulli equation seen as Equation 8 and is shown in Figure 7.

\[ \Delta P = \frac{1}{2} \rho (v_1^2 - v_2^2) \times 10^{-3} \]  
\[ \text{Equation 8} \]

where, in SI units,
\[ \Delta P = \text{pressure drop across an orifice (kPa)} \]
\( v_1 = \text{mean velocity of fluid inside of the orifice (m/s)} = \frac{Q_v (m^3/s)}{\pi \left( \frac{d}{2} \right)^2} \)

\( v_2 = \text{velocity downstream of fluid downstream from orifice (m/s)} = \frac{Q_v (m^3/s)}{\pi \left( \frac{D}{2} \right)^2} \)

All other variables have been defined previously.

Figure 7: Relationship between Volumetric Flowrate and Pressure Drop created for Cases 1-4

Table 4: Least Squares Fit to Pressure Drop Calculations

<table>
<thead>
<tr>
<th>Case</th>
<th>Flow Coefficient</th>
<th>Least Square Fit</th>
<th>R^2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>58.8</td>
<td>( \Delta P = 1.476 \times 10^5 q_m^{2.00} )</td>
<td>1.0000</td>
</tr>
<tr>
<td>Case 2</td>
<td>47.6</td>
<td>( \Delta P = 2.249 \times 10^5 q_m^{2.00} )</td>
<td>1.0000</td>
</tr>
<tr>
<td>Case 3</td>
<td>34.6</td>
<td>( \Delta P = 4.222 \times 10^5 q_m^{2.00} )</td>
<td>1.0000</td>
</tr>
<tr>
<td>Case 4</td>
<td>28.1</td>
<td>( \Delta P = 6.354 \times 10^5 q_m^{2.00} )</td>
<td>1.0000</td>
</tr>
</tbody>
</table>

Using the equations for pressure for the VTHTCL given by Hendricks, et al [2] one can calculate how the pressure loss factor \( K_L \) of these orifice plates will affect the extent to which one can operate the apparatus\(^1\). The curves presented show how the system pressure changes when an orifice diameter is inserted into the VTHTCL. The VTHTCL as modified by the four orifices under consideration in this

\(^1\) The operating point of the VTHTCL was calculated using the dimensionless loss factor \( K_L \), while heretofore in the is document the dimensioned flow coefficient \( K_V \) has been used. The conversion from one to the other is given in Appendix A
paper are shown in Figure 8, while their operating points given by the intersection of the system curves and the pump curve, are shown in Table 5. The point at which the system pressure graph crosses the pump curve is the operating point of the system [38]. While this is the highest velocity fluid may travel as depicted by Figure 8, actual experimental tests should be at least 10% lower in flowrate to provide a safety factor for the pump.

Table 5: Operating Points for Orifice Plates

<table>
<thead>
<tr>
<th>Operating Point</th>
<th>(K_v), ((m^3/hr)\sqrt{bar})</th>
<th>(K_L)</th>
<th>Volumetric Flowrate at the Calculated Operating Point, (L/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Case 1</td>
<td>58.8</td>
<td>3.14</td>
<td>9.43</td>
</tr>
<tr>
<td>Case 2</td>
<td>47.6</td>
<td>4.79</td>
<td>9.13</td>
</tr>
<tr>
<td>Case 3</td>
<td>34.6</td>
<td>9.06</td>
<td>8.48</td>
</tr>
<tr>
<td>Case 4</td>
<td>28.1</td>
<td>13.73</td>
<td>7.90</td>
</tr>
</tbody>
</table>

Figure 8: Pressure constraints added to system pressure from Cases 1-4

5.0 Experimental Studies

5.1 Tests of the model

5.1.1 Design/Construction of Pressure device
A differential pressure chamber was designed to determine the pressure drop across an orifice plate under the same conditions as an experimental corrosion test. This chamber was designed to ASME MFC-3M using the D to D/2 procedure. A differential pressure gauge was acquired to measure the pressure drop between two pressure taps located along the differential pressure chamber. This pressure gauge has the ability to measure a decrease in pressure from the upstream pressure tap location to the downstream pressure tap location up to 207 kPa. Clear PVC tubing was implemented to attach the differential pressure gauge to the differential pressure chamber\(^2\). The pressure chamber was machined from CPVC in four parts. An exploded view of the design is shown in Figure 9. Part 1 is the main chamber that houses all other pieces of the assembly. The right portion of the main chamber was threaded to attach to a 50.8-mm CPVC threaded union. The holes located on top of the main chamber are the pressure tap locations. These are 6.35-mm threaded connections. Part 2 is a spacer ring used to establish the same origin for every device that our group uses\(^3\). Part 3 is the orifice plate to be tested. Part 4 is the end tube which is also threaded onto a 50.8-mm CPVC threaded union. O-rings are implemented on this portion of the assembly to assure a water-tight seal when it is compressed between the two unions. The tap located on the top side of part 1 is designed to line up with the hole on the top of part 4 when fully compressed. The pressure tap on the upstream side is located D/2 distance away from the origin. The pressure tap on the downstream side is located D distance away from the origin. The complete device assembly is shown in Figure 9.

![Exploded View of Differential Pressure Chamber](image)

**Figure 9: Exploded View of Differential Pressure Chamber; Main Chamber (1); Spacer (2); Orifice Plate (3); Capping Tube (4)**

### 5.1.2 Measurement of loss factors/flow factors

The apparatus described in 5.1.1 was used to determine the pressure drop across each orifice plate as a function of the volumetric flowrate and is shown in Figure 10. Results are shown in Figure 11. The least squares fit to these data are given in Table 6. In fitting the least square function, \( y = ax^b \) to the data of Figure 11, it was found that the best fit was very sensitive to the lowest pressure values. A small constant offset pressure of 0.5 to 1.5 kPa (0.01% of one atmosphere) was subtracted from each curve. The least square data of Table 6 have been so corrected. It is seen from the data that Equation 3 is satisfied, and \( K_p \)

---

\(^2\) Omega Engineering, Model # DPG409-030DWU Differential Pressure Gauge

\(^3\) The origin for the distance of downstream components is defined to be the downstream face of the orifice or other device under consideration
can be computed from the coefficients. The various values for each case are also shown in Table 6. A plot of the designed $K_v$ versus the measured $K_v$ values is shown in Figure 12, where it is seen that the observed values are about 50% higher than the predicted values. This discrepancy is not yet understood but appears to be a result of the extreme sensitivity of the fit of a quadratic function to the data. Table 7 also shows the difference between the calculated and designed flow coefficients plotted in Figure 12.

Table 6: Least Squares Fit of Pressure Drop Data for Orifice Plates

<table>
<thead>
<tr>
<th>Case</th>
<th>Orifice, mm</th>
<th>Least Squares Fit (bar)</th>
<th>$R^2$</th>
<th>$K_v \left( \frac{m^3}{hr} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>$\Delta P = 8.507 \times 10^{-5} \times Q_v^{2.059}$</td>
<td>0.9912</td>
<td>110</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
<td>$\Delta P = 2.830 \times 10^{-4} \times Q_v^{1.981}$</td>
<td>0.9969</td>
<td>60.3</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>$\Delta P = 5.114 \times 10^{-4} \times Q_v^{2.063}$</td>
<td>0.9987</td>
<td>44.9</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>$\Delta P = 8.971 \times 10^{-4} \times Q_v^{2.083}$</td>
<td>0.9965</td>
<td>33.9</td>
</tr>
</tbody>
</table>

Figure 10: Pressure Chamber Experimental Setup (Left)
Figure 11: Pressure Chamber Experimental Data

Figure 12: Measured Flow Coefficient vs. Designed Flow Coefficient
Table 7: Difference in Actual vs. Designed Flow Coefficients of Orifice Plates

<table>
<thead>
<tr>
<th>Case</th>
<th>Orifice diameter, mm</th>
<th>Designed Kv, ( \text{m}^3/\text{hr} \sqrt{\text{bar}} )</th>
<th>Actual Kv, ( \text{m}^3/\text{hr} \sqrt{\text{bar}} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>58.8</td>
<td>111.3</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
<td>47.6</td>
<td>61.0</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>34.6</td>
<td>45.4</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>28.1</td>
<td>34.3</td>
</tr>
</tbody>
</table>

The pressure drop across an actual butterfly valve at various degrees of rotation was determined and compared to the pressure values produced by the orifice plates which aimed to create the same flow conditions. The experimental set-up is shown in Figure 13 while the resulting data from this experiment is seen in Figure 14. The least squares fits of the data of Figure 15 are given in Table 8. Following the same procedure as for the orifice plates, the flow coefficients for the various opening angles were determined. This experiment aims to compare the flow characteristics of the orifice plate with those of a butterfly valve under the same set of conditions. Assuming that the characteristics produced by the orifice plates match the rotation of the butterfly valve, then the corrosion rate of nickel aluminum bronze downstream would be expected to be the same for both cases under the same set of flow conditions.

**Figure 13: Butterfly Valve Experimental Setup (Right)**

We note that the butterfly valve used to model each orifice plate was hydraulically actuated while the commercial valve was mechanically actuated. While both types of butterfly valves are 50.8-mm in size, their exact geometries are not the same. The surface roughness of the hydraulic butterfly valve is much higher than that of the CPVC commercial valve used in this experiment because the hydraulic valve is
made up of an as-cast metal and the CPVC commercial valve is made up of a smooth extruded polymer. For these reasons, the commercial valve purchased does not have a one-to-one relationship with the butterfly valve that each orifice plate was modeled after, and therefore a different disc angle had to be used to produce the same flow coefficients. For example, the orifice plate used to create a flow coefficient of 28.1 is modelled after a butterfly valve that is 32 degrees open. To produce the same flow coefficient at the same volumetric flowrate, the commercial BYV butterfly valve must be open 40-degrees. The other three cases follow similar logic.

**Table 8: Least Squares Fit for BYV Butterfly Valve**

<table>
<thead>
<tr>
<th>Case</th>
<th>Corresponding Orifice (mm)</th>
<th>Degree of Rotation</th>
<th>Least Squares Fit</th>
<th>$R^2$</th>
<th>$K_v \left( \frac{m^3/hr}{\sqrt{bar}} \right)$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>42</td>
<td>60</td>
<td>$\Delta P = 3.421 \times 10^{-4} \times Q_v^{2.030}$</td>
<td>0.9803</td>
<td>55.5</td>
</tr>
<tr>
<td>2</td>
<td>39</td>
<td>55</td>
<td>$\Delta P = 4.595 \times 10^{-4} \times Q_v^{2.030}$</td>
<td>0.9996</td>
<td>47.9</td>
</tr>
<tr>
<td>3</td>
<td>35</td>
<td>45</td>
<td>$\Delta P = 1.058 \times 10^{-3} \times Q_v^{2.004}$</td>
<td>0.9996</td>
<td>31.5</td>
</tr>
<tr>
<td>4</td>
<td>32</td>
<td>40</td>
<td>$\Delta P = 1.190 \times 10^{-3} \times Q_v^{2.002}$</td>
<td>0.9998</td>
<td>29.7</td>
</tr>
</tbody>
</table>

A graph of the measured pressure drop across the commercial butterfly valve is shown in Figure 14. Also, a graph of the measured flow coefficient versus the design flow coefficient is shown in Figure 15. The slope of the curve is $K_v^{meas} = 0.9K_v$. This is considered to be in excellent agreement.

**Figure 14: Pressure drop across Commercial Butterfly Valve**
5.2 Studies of Corrosion

Precision ultrasonic wall thickness gauging was used to study erosion-corrosion in NAB downstream from the orifices designed in section 5.3. For precision measurements, it is essential to know the velocity of sound at the transducer operating frequency of the alloy microstructure of the tubes under investigation. To account for parallax effects involved with measuring tubes, we have built a special structure designed to minimize these effects as discussed in section 6.2.1.

5.2.1 Calibration

The velocity of sound of C95510 grade nickel aluminum bronze was found in the following manner. A calibration block made from C95510 was fabricated with two known internal diameters (thick and thin) separated by a single step. The calibration block measured 203-mm in length and 63.4-mm in external diameter can be seen in Figure . This procedure has been defined by Todoroff [3]. To start, the inner diameter of both the thick and thin sides of the calibration block were measured at four different axial positions in 19-mm increments. This internal diameter was found using a bore gauge with a resolution up to 25.4 μm. At each axial position the bore gauge was rotated in increments of 120-degrees for a total of three measurements. A total of 12 internal diameter measurements were determined in this fashion for
both the thin and thick sides of the calibration block. The mean and standard deviations of these measurements were calculated. Next, the outer diameter of the thick and thin sides of the calibration block were found using the same measurement procedure as for the internal diameter with a digital micrometer to find the average thickness as a function of axial position. The standard deviation was calculated for both the thick and thin sides. The overall thickness for each side of the calibration tube as a function of axial position were calculated using Equation 9.

Figure 16: Calibration block design for velocity of sound measurement in NAB

\[ t = \frac{OD - ID}{2} \]  
Equation 9

where

\( t \) = wall thickness, \( m \)

\( OD \) = Outer Diameter measured with digital micrometer, \( m \),

\( ID \) = Inner Diameter measured with bore gauge, \( m \).

From these measurements, the thickness of the thin and thick sections were determined to be 3.05 and 9.44 mm respectively. Using the built-in velocity of sound calibration routine of the Olympus Model DLP – 38S ultrasonic wall thickness gauge, the velocity of sound for the model M208 ultrasonic single transducers were found to be 0.20133 \( \frac{in}{\mu - sec} \). The advantages of this procedure are the parallax errors associated with mounting a ¼” diameter transducer onto a 2.5” outer diameter tube are minimized, and the effects of alloy microstructure on the velocity of sound are eliminated.

The orifice plates were designed so that they would fit in the VTHTCL universal sample chamber as shown in Figure [2]. Straight 44.5-mm diameter by 304.8-mm long C95510 tubing was threaded into the chambers of the VTHTCL downstream from an orifice plate. The setup of this corrosion chamber can be seen in Figure . The area marked with a red box in Figure 17 identifies the location of the orifice plate. The fluid was a 3.5% NaCl commercial grade ASTM seawater held at a controlled temperature of 25°C.
5.2.2 Experimental Setup of 32 mm Orifice Test 1

The first experiment was a preliminary one in which the rate of removal of NAB was analyzed over a period of 120 hours using the 32-mm orifice plate. This cell was placed directly upstream of a 305-mm NPSM threaded NAB tube with an internal diameter of approximately 44.5-mm. Figure 18 shows the setup of the first experimental run.

Saltwater solution created using 32.471 g/L reagent grade salt and distilled water flowed through the orifice plate at a volumetric flowrate of 0.00631 $\frac{m^3}{s}$ over a 120-hour period. This salt concentration produces a 3.5% NaCl solution with the same salinity as commercial grade ASTM seawater. The Reynolds number produced for this experiment is 330,630. The wall thickness was measured at 28 points across the surface of the NAB sample section every 24 hours. Ultrasonic thickness measurement locations were picked as function of longitudinal and azimuthal position. Seven longitudinal positions were measured, each being 38.1-mm apart. Four azimuthal positions were measured in 90-degree increments at the seven longitudinal positions. Figure shows the locations at which ultrasonic thickness data were recorded. The longitudinal distances are stated as a function of the tube diameter, D. The origin is located at the downstream face of the orifice.
Figure 19: Ultrasonic Thickness measurement locations

Thickness measurements of the NAB wall in each specified location were determined manually using a dual element transducer in conjunction with an Olympus 38DL – Plus ultrasonic thickness gauge per the ASTM E213 standard for ultrasonic inspection [39], [40]. The resolution of the measurements made using this transducer was 25.4 μm.

5.2.3 Experimental Results of 32 mm Orifice Test 1

A distribution was created by subtracting the thickness measured on day one of testing from the data recorded at each respective location on each day after the first day of testing. ANOVA of the data indicated that there was no statistically significant reduction in the wall thickness at the resolution of the dual element transducer. Therefore, the erosion-corrosion rate at any location measured must be lower than 0.208 μm/hr. This corrosion rate is calculated by dividing the resolution of the dual element transducer by the length of the test in hours. This equates to 25.4 μm/120 hours. This high minimum is due to systematic errors associated with the angle the users hand places the transducer to the surface of the pipe the overall thickness of NAB in that location will change. Because each location of the pipe examined during testing was performed manually by hand with a lower resolution transducer the data created is statistically insignificant in nature. This states that there wasn’t a dramatic change in the overall thickness of the pipe that occurred for the conditions of the experiment during the 120-hour test.

5.2.4 Experimental Setup of 32 mm Orifice Test 2

On completion of the analysis performed during the first experiment a second experiment was devised. This experiment implemented the use of 15 single element transducers (Olympus Model M208) as compared to the dual element transducer used in the first experiment. Instead of placing each transducer on the surface of the pipe by hand and measuring the thickness at each chosen location, a series of ultrasonic transducer adapters were placed in various longitudinal locations along the length of NAB pipe. The adapters came equipped with delay lines and threaded connections to mount each sensor onto the surface of the pipe. Each transducer was attached to a 15-channel multiplexor that allowed the user to switch between the thickness at each respective location with ease. This multiplexor was wired to the 38DL – P ultrasonic thickness gauge and a data acquisition system was developed using LABVIEW coding technologies. This code controlled the rate at which thickness measurements were taken and then exported each measurement with a time stamp to an Excel file which was e-mailed the user [3]. This code also recorded the pH, electrical conductivity, and the dissolved oxygen content of the water as well as, the
absolute pressure readings at various positions in the fluid line, the volumetric flowrate of the fluid, and the temperature of fluid at various positions. The volumetric flowrate was increased to $0.00757 \frac{m^3}{s}$ and the 32-mm orifice plate was used. These conditions had the highest probability of creating turbulence and thereby causing erosion. All other conditions were the same as in the first run. This experiment ran for a total of 328.5 hours. The setup of this experiment is shown in Figure 20.

![Figure 20: Setup of Experimental section for experiment 2](image)

5.2.5 Experimental Results of 32 mm Orifice Test 2

The orifice plate is located in the stainless-steel chamber on the right. Fluid flow moves from the right to the left in this figure. The difference between the starting thickness of the pipe and the thickness at time $n$ was found for every time interval and every sensor. No significant change in the wall thickness was seen for the majority of locations measured. At sensor location F over the course of the 328.5 hour test the thickness of the pipe increased by 18 $\mu m$ as shown in Figure 21. This sensor was located at a distance 4D downstream from the orifice at the 270-degree azimuthal position. With the exception of the measurements made for sensor F, no statistical evidence was found to show a significant change in the wall thickness at the resolution of the single transducers used for this experiment. The resolution of these sensors was 2.5 $\mu m$. 

Figure 21 employs the idea that the growth of an oxide layer at sensor location F follows the mechanism of diffusion between an oxide and a bare metal. This diffusion mechanism follows the equation $Y = a * t^{0.5}$, where $Y$ is the change in thickness due to an oxide growth and $t$ represents time. This process involves the diffusion of oxygen through the oxide formed on the liquid/metal interface which attacks the bare metal preferentially. For these reasons a new ANOVA technique was implemented to accurately represent this set of data. In most locations the thickness difference between any two, time intervals are less than 7.6 $\mu m$. This thickness difference is very close to the resolution at which the ultrasonic system can read a change in the thickness of the pipe over time. The resolution of the ultrasonic thickness gauge is between 2-3 microns. To account for this, the difference between the starting thickness and the final thickness was calculated for each of the 15 single transducers. Since the 3-way ANOVA showed no dependence on time, a 2-way ANOVA test was implemented looking only at the effect of the azimuthal position and longitudinal position on the thickness difference between the starting thickness and the end thickness. This analysis found that there was no significant change in the thickness of the NAB pipe over the course of experimentation. From this we conclude that the corrosion rate is less than that of 500 $\mu m/yr$. This value of the corrosion rate as a function of the flow velocity is converted from mils/year found within the literature [31].

The total erosion-corrosion rate of NAB is the average of the EC rates for each location. The total erosion-corrosion rate of NAB was found to be -37.33 mils per year indicating that the ability of this material to create an oxide layer was much greater than its ability to allow degradation at least for the duration of this experiment. In other studies, it has been shown that the erosion-corrosion rate of nickel aluminum bronze alloys in turbulent seawater was around 29.8 mils per year at a flow velocity of 30.48 m/s [31]. This study was performed over 42 days under conditions more turbulent than possible in the VTHTCL.
5.2.6 EC Calculations

Using the thickness change of the NAB tube between the beginning and ending of each experiment the erosion-corrosion rate at any given point can be determined. The total corrosion rate of the entire tube is just the summation of the corrosion rate at any given point along the internal surface of the tube, as given by

\[
EC \text{ Rate}(\text{mpy}) = \frac{PT_o - PT_n}{t}
\]

Equation 11

where

- \(PT_o\) = pipe thickness before testing (mils),
- \(PT_n\) = new pipe thickness after testing (mils),
- \(t\) = length of test (years).

6.0 Characterization of Materials

Each NAB tube was analyzed using optical microscopy. An abrasive cut-off saw was used to cut a small section of the tube from each set of experiments 6.35-mm^2 and corresponded to areas in which the ultrasonic thickness data fluctuated at specific sensor locations during corrosion testing. Figure displays the samples both before and after sectioning. Each sample was mounted horizontally into 25 mL of diethyl phthalate polymer mounting powder at a pressure of 20.7-MPa for 12 minutes while applying heat. The samples were ground and polished using the procedure given in Table 9.
Figure 22: NAB prior to cutting (a); NAB pipe cut 1.40D away from upstream edge (b); NAB pipe cut 2D away from upstream edge (c); NAB pipe cut 3D away from upstream edge (d); NAB pipe cut 4D away from upstream edge (e)

Table 9: Grinding and Polishing Procedure

<table>
<thead>
<tr>
<th>Grinding and Polishing procedure</th>
<th>Step number</th>
</tr>
</thead>
<tbody>
<tr>
<td>Swipe sample 30 times over 240-grit SiC paper</td>
<td>1</td>
</tr>
<tr>
<td>Rotate sample 90-degrees</td>
<td>2</td>
</tr>
<tr>
<td>Swipe sample 60 times over 320-grit SiC paper</td>
<td>3</td>
</tr>
<tr>
<td>Rotate sample 90-degrees</td>
<td>4</td>
</tr>
<tr>
<td>Swipe sample 120 times over 400-grit SiC paper</td>
<td>5</td>
</tr>
<tr>
<td>Rotate sample 90-degrees</td>
<td>6</td>
</tr>
<tr>
<td>Swipe sample 240 times over 600-grit SiC paper</td>
<td>7</td>
</tr>
<tr>
<td>Implement use of Minimet Auto-polisher</td>
<td>8</td>
</tr>
<tr>
<td>Polish sample for 5 minutes in 9.5-micron alumina suspension using nylon circles</td>
<td>9</td>
</tr>
<tr>
<td>Rinse and dry sample</td>
<td>10</td>
</tr>
<tr>
<td>Polish sample for 5 minutes in 3-micron alumina suspension using nylon circles</td>
<td>11</td>
</tr>
<tr>
<td>Rinse and dry sample</td>
<td>12</td>
</tr>
<tr>
<td>Polish sample for 3 minutes in 1-micron alumina suspension using suede circles</td>
<td>13</td>
</tr>
<tr>
<td>Rinse and dry sample</td>
<td>14</td>
</tr>
<tr>
<td>Polish sample for 3 minutes in 0.05-micron alumina suspension using suede circles</td>
<td>15</td>
</tr>
<tr>
<td>Use ultrasonic cleaner to remove contaminants</td>
<td>16</td>
</tr>
</tbody>
</table>

The oxide layer thickness, the size of NAB grains, and the overall density of pitting sites were determined using optical microscopy. Pitting size and overall evaluation of pits located within each sample were analyzed following ASTM G46-94 [41].
6.1 Metallography

On completion of the grinding and polishing, the NAB samples were optically examined at 100X magnification, as shown in Figure. Pits are seen in these micrographs for the 2D and 4D cases. The passivation layer could be determined at distances 1.40D, 2D, and 3D downstream from the 32-mm orifice plate. However, there was no passivation layer seen across the liquid-metal surface for the 4D sample. From these micrographs the average passivation layer thickness was determined as a function of longitudinal position and then the average passivation thickness across the entire pipe was determined. The average depth of pits was also calculated in this fashion. The results of these calculations are shown in Table 10. At the 2D location downstream from the upstream end of the tube, the formation of pits has allowed the deposition of a passivation layer to build upon the liquid/metal interface. The first thickness measurement of the oxide layer found using optical microscopy is seen as T1. Also, the first pit depth is listed as P1. The notation used for all other thickness measurements and pit depths follow this logic. This information is reported for each of the four longitudinal positions examined.

![Micrographs of passivation layer](image)

Figure 23: (a) 1.40D downstream from upstream face, 90-degrees, 100X; (b) 2D downstream from upstream face, 270-degrees, 100X; (c) 2D downstream from upstream face, 270-degrees, 100X; (d) 2D downstream from upstream face, 90-degrees, 100X;
Figure 23 (cont.): (e) 3D downstream from upstream face, 180-degrees, 100X; (f) 3D downstream from upstream face, 270-degrees, 100X; (g) 3D downstream from upstream face, 90-degrees, 100X; (h) 4D downstream from upstream face, 180-degrees, 100X; (i) 4D downstream from upstream face, 270-degrees, 100X; (j) 4D downstream from upstream face, 90-degrees, 100X;
Table 10: Passivation Layer Thicknesses and Pit Depths across NAB surface

<table>
<thead>
<tr>
<th>Position</th>
<th>T1</th>
<th>T2</th>
<th>T3</th>
<th>T4</th>
<th>T5</th>
<th>T6</th>
<th>T7</th>
<th>T8</th>
<th>AVG</th>
<th>STD DEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.40D</td>
<td>10.4</td>
<td>10.6</td>
<td>9.2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>10.0</td>
<td>0.62</td>
</tr>
<tr>
<td>2D</td>
<td>16.2</td>
<td>13.1</td>
<td>11.9</td>
<td>6.2</td>
<td>5.8</td>
<td>5.8</td>
<td>12.4</td>
<td></td>
<td>10.2</td>
<td>3.9</td>
</tr>
<tr>
<td>3D</td>
<td>6.4</td>
<td>7.4</td>
<td>6.4</td>
<td>6.8</td>
<td>6.0</td>
<td>10.1</td>
<td>19</td>
<td>8.9</td>
<td>8.9</td>
<td>4.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Position</th>
<th>P1</th>
<th>P2</th>
<th>P3</th>
<th>P4</th>
<th>AVG</th>
<th>STD DEV</th>
</tr>
</thead>
<tbody>
<tr>
<td>2D</td>
<td>15.5</td>
<td>17.5</td>
<td>12.8</td>
<td>18.0</td>
<td>15.9</td>
<td>2.1</td>
</tr>
<tr>
<td>4D</td>
<td>9.1</td>
<td>13.3</td>
<td>7.4</td>
<td>6.4</td>
<td>9.1</td>
<td>2.6</td>
</tr>
</tbody>
</table>

7.0 Discussion
The data presented in Sections 6 and 7 may be qualitatively explained by a model, presented in Figure 24, in which cavitation occurred closest to the orifice and lead to pitting, and which, further from the orifice, lead to a possible diffusion-controlled growth of an oxide layer. Each of these is discussed in the following paragraphs.

At the flowrate of experiment 2, (7.57 L/s), it is shown in Figure 6 that cavitation began at a flowrate of approximately 6.7 L/s for the case 4, 32 mm diameter orifice with the fluid held at 25°C. The nature of the cavitation induced pitting is seen in Figure 23 for several distances in the range of approximately 2D to 4D downstream from the upstream pipe end (Figure 23, b-c, h-j).

On the other hand, at distances of approximately 4D downstream from the orifice, an oxide buildup was observed which follows a $t^{0.5}$ growth law as shown in Figure 21. Such a growth law is reminiscent of the oxide layer growth rate observed in numerous systems, notably the growth of silicon dioxide layers in wet gas [42].

The model presented in Figure 24 suggests that the high velocity flow at the orifice boils, causing intense turbulence. At the location where the fluid reattaches to the tube surface (2D-4D) the water vapor bubbles expand and cause severe localized degradation of the surface (e.g. pits form). However, once the fluid returns to its normal turbulent flow ($v = 3.71$ m/s) and the normal turbulence is established, the erosion of the surface film decreases, and an oxide film grows. From the data of Figure 21 the oxide growth rate is given by $(x - x_0)^2 = 0.8022 \times t$. In this expression $x_0$, represents the starting oxide thickness of the metal which is 2.5 $\mu$m. The variable $t$ represents the time of the experiment which was 328.5 hours. So, the overall growth of oxide as defined by the $t^{0.5}$ growth law is calculated to be 18.73 $\mu$m within the time frame of the second experiment. Also, the overall growth rate of oxide per year as defined by this growth law is 86.73 $\mu$m. Location 1.40D shows how the fluid moves down the length of the pipe after exiting the orifice. Also, location 2D on this figure shows the formation of eddy currents which cause degradation of the metal layer and location 3D shows the possible area in which degradation of the bare metal has occurred. At location 3D the idea of an increased amount of cavitation comes into play. Due to the
reduction of the pressure calculated at the vena contracta falling below the vapor pressure of water at 25°C, cavitation is prevalent, and it is believed to cause the formation of pits. It was the hope of the experimenter that the corrosion rate would change concentrically around all azimuthal positions. Based off the data received at sensor location F this is proved to be incorrect. Sensor F is located 4D downstream from the upstream face in the 270-degree position. It is believed that at a longitudinal location upstream from this oxide buildup material was mechanically sheared off the internal diameter of the NAB tube and an oxide formed downstream from this zone non-concentrically. Upon inspection of the NAB tube after testing, the formation of a black surface film occurred at a distance halfway down the length of the pipe away from the upstream threaded end. This corresponded directly with the data of sensor location F in which the thickness growth would indicate the buildup of an oxide layer. Also, this black buildup extends further past this location in other areas along the length of the pipe. It is important to note that if this data were to be replicated it would greatly help in understanding how mass transport of metal from one location to another occurs for the family of nickel aluminum bronze. Perhaps if this test had run for a longer run time other sensors would have shown further evidence of what the experimenter has theorized. At a distance 4D downstream from the orifice, the total amount of oxide growth seen over the 328.5-hour corrosion test is 17.8 microns, as found through UT measurements. It has been calculated that this oxide growth was produced at or near a flow velocity of 9.3 m/s produced within the vena contracta. This flow velocity is well above the critical velocity value of 7.6 m/s needed to produce a corrosion rate close to that of the literature [1], [31]. When this thickness change is then converted into a corrosion rate, the calculated value becomes 475 microns/year indicating that there was a thickness buildup in this location. In the upstream regions the erosion-corrosion rate of NAB in highly turbulent seawater is stated to be 0.5 mm/year at flow velocity of 7.6 m/s. However, ultrasonic thickness measurements showed no statistical evidence that wall thinning of the NAB occurred during experimentation. The thickness data at 4D downstream from the orifice saw an increase in the overall thickness of NAB and because of the way the 38DL-P ultrasonic thickness gauge measures thickness we assume that the change in thickness is due to the buildup of an oxide. Because of the index of refraction difference between the metal and the oxide the change in thickness is attributed to the buildup of an oxide layer.

Figure 24: Experiment 2 Corrosion Model of NAB
8.0 Conclusions

The model presented in Figure 24 is one of many different ways in which the experimental results of experiment 2 can be explained. The main idea is that pit formation occurs at some distance downstream from the orifice. This occurs because of cavitation created within the fluid line as a result of the pressure at the vena contracta dropping below the vapor pressure of water at room temperature. This causes water to boil which causes enhanced degradation at the liquid/metal interface. At a distance further down the length of the pipe from these isolated areas of pit formation, the growth of an oxide has been shown through UT measurements made at a distance 4D downstream from the upstream edge of the pipe. Also, one can state that the overall rate of this cavitation induced corrosion is greater than the rate of oxide buildup leading up to this 4D location. At this location, the oxide buildup can be explained by the $t^{0.5}$ law, which states that for most metals the growth of an oxide layer is essentially equal to the square root of the time in which the experiment ran multiplied by a constant. It is concluded that the rate of mechanical wear is greater than the rate at which an oxide can form. This is confirmed by the data received from Figure 23.

In this experiment a series of corrosion tests were performed on the surfaces of NAB to determine its erosion-corrosion rate directly downstream from an orifice plate. Each orifice plate was designed to produce the same flow coefficient as a butterfly valve at a specific disc angle. After implementation of the case 4 orifice, corrosion experiments were formulated to statically look at the thickness change in select areas through the use of a 38DL – P ultrasonic thickness gauge. The ultrasonic thickness data of experiment 2 shows that at a distance 4D downstream from the orifice an oxide layer was formed. The thickness of this oxide layer was 17.8 microns. These tests created pits and a passivation layer upon certain areas of the pipe. The average depth of these pits were 12.5-microns and the average passivation layer thickness was 9.7-microns. These pits were likely the cause of cavitation produced by the 32-mm orifice during experimentation. It can be determined that the overall erosion-corrosion rate of NAB for the duration of the 328.5 is less than 500 micron/year. Overall, the design of orifice plates to produce cavitation and pitting which create nearly exact flow coefficients as a butterfly valve at a specific disc angles was a success.

9.0 Recommendations for Future Work

Corrosion testing needs to be performed on this alloy for longer periods of time in order to fully understand the corrosion mechanisms involved. The longest experiment that was performed during the course of this research was 14 days. If another experiment were to run longer using the same conditions as set in the 0.00757 $\frac{m^3}{s}$ experiment a more developed model of how the erosion-corrosion rate of C95510 NAB changes as function of time when in the presence of seawater. In order to test the model explained by Figure 24 further, dissolved oxygen tests and temperature measurements need to be performed to determine their effects on cavitation induced pitting. Scanning electron microscopy could also be performed on the metal obtained from the latest experiment in order to obtain information like the oxide composition as well some surface morphologies that would help explain the corrosion mechanisms involved. The surface roughness of the NAB surface both before and after needs to be measured in order to relate how the shear stress causes degradation of the oxide layer inside of the pipe. Another test that needs to be performed is that of a static corrosion test in order to have some sort of control to compare experimental values to. It would be interesting to measure the effect that a small addition of Sulphur to
the seawater used in this static test would have on the corrosion rate of the alloy. Sulphide pollution is
detrimental to the NAB alloy.

10.0 Acknowledgements

I would like to thank my advisor, Dr. Robert Hendricks, for the inspiration to complete a master’s degree,
his guidance in multiple aspects of life and professionalism, and the numerous meetings that guided me
through my graduate studies. Also, I would like to thank Dr. Sean Corcoran and Dr. William Reynolds for
serving on my graduate committee. Thank you to Peter Todoroff and Erik Cothron for the significant
amount of time spent working with me on the VTHTCL and for numerous talks about corrosion
mechanisms as well as other concepts related to our research. I would like to thank Dr. Thomas Staley for
allowing our team to use the departmental teaching labs to build the VTHTCL. I would also like to thank
the Department of Materials Science and Engineering at Virginia Tech for supporting this project. Thank
you to NAVSEA in Carderock, Maryland for the inspiration to perform this research and the Department
of Energy for funding our corrosion studies.

11.0 References


of Corrosion and Tribocorrosion of Metals Induced by the Flow of Highly Turbulent Aqueous
Solutions," The Journal of Corrosion Science and Engineering, vol. 21, no. 18, p. (under review),
2018.

[3] P. Todoroff, "Investigation of Turbulence on the Passivation Film Growth and Associated
Durability of Aluminum Alloys in Simulated Seawater Naval Heat Exchangers (Master thesis),"
Department of Materials Science and Engineering, Virginia Tech, p. All, 2018.


September 2017].


The relationship between the flow coefficient, $K_v$, and the loss coefficient, $K_L$, may be determined as follows: The flow factor of a section of pipe, or a device, is defined by the relationship

$$\Delta P = G \cdot \left(\frac{Q_v}{K_v}\right)^2$$

Equation 1

where

$\Delta P =$ pressure drop (bars)

$G =$ specific gravity of the fluid (dimensionless)

$Q_v =$ volumetric flowrate ($m^3/\text{hr}$)

$K_v =$ flow coefficient ($m^3/hr/\sqrt{\text{bar}}$).

On the other hand, the loss coefficient is for the same section of pipe, or device, is defined by the relationship

$$\Delta P = \frac{1}{2} \cdot K_{L\text{ orif}} \cdot \rho \cdot v^2$$

Equation 2

where

$\Delta P =$ pressure drop (Pa)

$K_{L\text{ orif}} =$ loss coefficient (dimensionless)

$\rho =$ density of the fluid ($\text{kg/m}^3$)

$v =$ mean velocity of the fluid entering and leaving the device ($m/s$)

It is assumed that the pipe is the same diameter both entering and leaving the device. Note that the units commonly used in the literature to define $K_v$ and $K_L$ are different and that $K_v$ is a dimensioned quantity while $K_L$ is dimensionless. Since the pressure drop across the section of pipe or device must be the same for both representations, we may equate Equations 1 and 2, provided that correct units are used. By converting the pressure drop in Equation 1 to Pa, we find

$$G \cdot \left(\frac{Q_v}{K_v}\right)^2 \cdot 10^5 = \frac{1}{2} \cdot K_{L\text{ orif}} \cdot \rho \cdot v^2$$

Equation 3

By conservation of mass

$$v = \frac{Q_v}{\frac{\pi}{4} \cdot D^2 \cdot 3600}$$

Equation 4
By substitution of Equation 4 in Equation 3, and rearranging terms, we find

\[ K_L^{orif} = \frac{2G \left( \frac{Q_v}{K_V} \right)^2 \times 10^5}{\rho \left( \frac{Q_v}{\pi D^2 \times 3600} \right)} \]

Equation 5a

or

\[ K_L^{orif} = 1.598 \times 10^{12} \frac{D^4}{\rho_w K_V^2} \]

Equation 5b

where

\[ Q_v = 22.72 \text{ (m}^3\text{hr)} \]
\[ \rho = G \times \rho_w \text{, and} \]

\[ \rho_w = \text{density of water (kg/m}^3\text{).} \]

In the present case

\[ D = 0.051 \text{ m} \]

\[ \rho_w = 997 \text{ (kg/m}^3\text{)} \]

And

\[ K_L^{orif} = \frac{10,843}{K_V^2} \]

Equation 6

From Equation 6 the loss coefficients for each of the four orifice plates are then calculated as a function of the flow coefficient, \( K_V \).

\[ K_L^{orif} (58.8) = \frac{10,843}{58.8^2} = 3.14 \]

\[ K_L^{orif} (47.6) = \frac{10,843}{47.6} = 4.79 \]

\[ K_L^{orif} (34.6) = \frac{10,843}{34.6^2} = 9.06 \]

\[ K_L^{orif} (28.1) = \frac{10,843}{28.1^2} = 13.73 \]

From these results, the total pressure drop around the loop using Equation 7
\[
\Delta P_{\text{loop}} = \frac{1}{2} * \left( 11.43 K_L^{\text{CPVC/m}} + 4 K_L^{\text{elb}} + K_L^{f_{\text{m}}} + K_L^{h_{\text{e}}} + K_L^{\text{orif}} \right) * \rho * v^2 \tag{Equation 7}
\]

where

\[
K_L^{f_{\text{m}}} = 1.725 \pm 0.003
\]
\[
K_L^{\text{CPVC/m}} = 0.38 \pm 0.06 \text{ m}^{-1}
\]
\[
K_L^{\text{elb}} = 0.55 \pm 0.08
\]
\[
K_L^{h_{\text{e}}} = 0.134 V^2 - 2.544 V + 18.319
\]
\[
\Delta P_{\text{pump}} = -0.458 V^2 - 4.657 V + 292.3
\]

In these equation, the volumetric flowrate, \( V \), is given in L/s. The values are those determined for the VTHTCL [2].

\[
V = \text{Volumetric flowrate} \left( \frac{L}{s} \right)
\]

Thus, the expected pressure drop in the loop is expected to be

\[
K_{\text{sys}} = \left( 11.43 K_L^{\text{CPVC/m}} + 4 K_L^{\text{elb}} + K_L^{f_{\text{m}}} + K_L^{h_{\text{e}}} + K_L^{\text{orif}} \right) \tag{Equation 8}
\]

Substituting the various values of \( K_L \), the effective system loss factors are

\[
K_{\text{sys}(58.8)} = (11.43 \times 0.38 + 4 \times 0.55 + 1.725 + 0.134 \times 6.31^2 - 2.544 \times 6.31 + 18.319 + 3.14) = 19.01
\]
\[
K_{\text{sys}(47.6)} = (11.43 \times 0.38 + 4 \times 0.55 + 1.725 + 0.134 \times 6.31^2 - 2.544 \times 6.31 + 18.319 + 4.79) = 20.66
\]
\[
K_{\text{sys}(34.6)} = (11.43 \times 0.38 + 4 \times 0.55 + 1.725 + 0.134 \times 6.31^2 - 2.544 \times 6.31 + 18.319 + 9.06) = 24.93
\]
\[
K_{\text{sys}(28.1)} = (11.43 \times 0.38 + 4 \times 0.55 + 1.725 + 0.134 \times 6.31^2 - 2.544 \times 6.31 + 18.319 + 13.73) = 29.60
\]

At the operating point

\[
\Delta P_{\text{loop}} = \Delta P_{\text{pump}} \quad \tag{Equation 9a}
\]

or

\[
\frac{1}{2} * K_{\text{sys}} \rho v^2 = -0.458 V^2 - 4.657 V + 292.3 \quad \tag{Equation 9b}
\]
Substituting the various loss values $K_{sys}$, one must solve the quadratic equation for $V$, for each of the four cases.

$$\frac{1}{2} \times 19.01 \times 1025 \times \frac{1}{1000} \left( \frac{V}{1000 \times \frac{\pi}{4} \times 0.051} \right)^2 = -0.458V^2 - 4.657V + 292.3$$

$$V = 9.43 \frac{L}{S}$$

$$\frac{1}{2} \times 20.66 \times 1025 \times \frac{1}{1000} \left( \frac{V}{1000 \times \frac{\pi}{4} \times 0.051} \right)^2 = -0.458V^2 - 4.657V + 292.3$$

$$V = 9.13 \frac{L}{S}$$

$$\frac{1}{2} \times 24.93 \times 1025 \times \frac{1}{1000} \left( \frac{V}{1000 \times \frac{\pi}{4} \times 0.051} \right)^2 = -0.458V^2 - 4.657V + 292.3$$

$$V = 8.48 \frac{L}{S}$$

$$\frac{1}{2} \times 29.60 \times 1025 \times \frac{1}{1000} \left( \frac{V}{1000 \times \frac{\pi}{4} \times 0.051} \right)^2 = -0.458V^2 - 4.657V + 292.3$$

$$V = 7.90 \frac{L}{S}$$