3.7: pH and Viscosity Sensors
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7.1 Introduction to pH

pH is a measure of concentration of $H^+$ ions ([H$^+$]) in solution, and can be defined as follows:

$$pH = \log \left( \left[ H^+ \right] \right)$$

Typically, pH values range between 0 (strongly acidic) and 14 (strongly basic, or alkaline). However, that is not to say that 0 and 14 are the limits of pH values. A solution that has a $H^+$ concentration of 10 M, such as very strong HCl, would have a pH of -1. Pure water, which has a pH of 7, is said to be neutral because its $H^+$ concentration is equal to its $OH^-$ concentration. An acid solution is said to have a greater $H^+$ concentration than its $OH^-$ concentration. Conversely, a base, or alkaline solution, is said to have a greater $OH^-$ concentration than its $H^+$ concentration. See for reference:

For weak acids and bases, the above equation is appropriate to use when calculating pH. However, many solutions are not weak acids and bases, which means that the other ions in solution play a large role in acidity and alkalinity, and thus a more accurate method is needed to calculate the pH. pH sensors are used to determine the acidity or alkalinity of a particular process solution. When dealing with a strong solutions, the sensors measure the effective concentration, or activity, of $H^+$ ions in solution, and do not measure the actual concentration. Hence, for the purposes of pH sensors, pH
is properly defined as:

\[ p\text{H} = -\log a_{H^{+}} \]

with

\[ a_{H^{+}} = \gamma_{H^{+}} [H^{+}] \]

where \( \gamma_{H^{+}} \) is the activity coefficient.

The activity coefficient accounts for the interactions between all the ions present. These interactions may prevent some of the H\(^+\) ions from contributing to the acidity of the solution, and thus decrease the effective concentration of H\(^+\) ions. This effective concentration is the concentration used when calculating pH.

### 7.2 Why is pH Relevant for Chemical Engineering?

pH sensors, while being relatively simple pieces of equipment, have numerous uses. Knowing the pH of a solution is valuable to an analytical chemist attempting to determine the contents of an unknown solution, as well as a farmer trying to determine the appropriate applications to his fields and many people in between. In industry pH sensors can be used as a simple way to monitor reactions involving acids or bases as either a reactant or product of a chemical process. They can also be used to monitor the conditions of a reactor to ensure optimal conditions. This is especially important in biological systems where very minor changes in pH can result in significantly lowered production levels or even a complete stoppage of production due to the death of the organisms on which the reaction is dependent.

An example of pH measurement's importance in industry is seen in food processing during the manufacture of fruit jelly. The gel formation brought about by pectin occurs over a small pH range, which is further complicated by the concentration of sugar. Too high of a pH value results in an unacceptably runny liquid. Too low of a pH causes the mixture to stiffen prematurely, resulting in a nearly-solid product. Continuous pH adjustment using edible acids such as citric acid yields the optimal gel consistency.

It is also important to keep in mind that application requirements should be carefully considered a pH sensor is chosen. In the case above, it is important that the pH sensor be made of a material that will not interfere with the quality of the product. For instance, the sensor should not be made of glass in order to avoid broken glass entering the product. Accurate pH measurement and the precise control that it allows for helps to optimize a process and can result in increased product quality and consistency. Continuous pH monitoring also controls chemical usage (such as the edible acids above), resulting in minimized system maintenance (i.e. less cleaning of hardened gel from containers, less corrosion of containers, etc.).

### 7.3 Typical pH Sensor Construction

Because it is difficult to directly measure the H\(^+\) concentration of a solution, pH is typically measured by comparing the potential of a solution with a known [H\(^+\)] (this is known as a reference solution) with the potential of a solution with an unknown [H\(^+\)]. The potentials of these solutions are measured using a reference half-cell and a sensing half-cell.
respectively.

### 7.3.1 Reference Half-Cell

The reference half-cell generally consists of a chamber with a conductor submerged in a reference electrolyte. The conductor, or external reference electrode wire, is typically silver coated with silver chloride (Ag/AgCl(s)) or mercury coated with mercurous chloride (Hg/Hg2Cl2(s)). The reference electrolyte is a standard solution such as KCl. The last component of the reference half-cell is a porous plug, which serves as a liquid-liquid interface between the standard solution and the process solution being analyzed. This plug allows standard solution to travel from the chamber out into the process solution, but does not allow process solution into the chamber. The purpose of this interface is to establish the electrical connection, which provides the reference potential.

### 7.3.2 Sensing Half-Cell

The sensing half-cell is of similar construction to the reference half-cell. A glass chamber contains an electrode (Ag/AgCl(s)), known as the internal reference electrode, which is submerged in a standard solution of constant pH. However, instead of a porous plug acting as the liquid-liquid interface between the standard and process solutions, there exists a glass membrane. This membrane is coated on the inside and outside with a hydrated gel. When the sensing half-cell is placed in solution, metal ions (Na+) in the gel on the outside of the membrane diffuse out into the sample being analyzed and are replaced by H+ ions from the sample. The change in energy associated with this substitution creates the change in electric potential that is detected by the electrode. The combination of the hydrated gel and the glass membrane are what make the sensor specific only to H+ ions. The solution of constant pH ensures that the surface of the glass membrane and the electrode are at the same pH before the cell is exposed to the process solution being analyzed.

The electrode wires from the reference and sensing half-cells are each connected to the voltage measuring device.

The diagram below shows the setup of a typical pH measurement system:

While this figure shows the essential components of a pH sensor, it is not an accurate depiction of what pH sensors actually look like. The reference and sensing cells in most pH sensors are generally encased together in a sturdy housing (usually made of some sort of plastic). This does not affect the operation of the sensor, but allows for ease of
use, as there is only one major piece of equipment that the user needs to carry around.

pH sensors can be used both online and offline. If the sensor is being used to carefully control the pH of a system or to provide an accurate record of the pH of a solution it is often desirable to have an online pH sensor. In order to have an online pH sensor determine accurate readings it must be in a position to take a representative sample. This is most often done by diverting a side stream from the main process in which the pH sensor can be inserted. Often times continuous pH measurements are not necessary, but rather infrequent measurements to make sure that the system is running correctly are of interest. In these cases it is much more efficient to use an offline pH sensor.

### 7.4 How do pH sensors calculate pH?

pH is calculated using the potential drop between the reference and sensing electrodes. The potential across the overall pH measurement system can be expressed as:

\[
E = E_{\text{internal reference}} + E_{\text{membrane}} + E_{\text{porousplug}} - E_{\text{external reference}}
\]

The potential of the porous junction is usually negligible, and the potentials of the internal and external references can be lumped into a constant value, \(E_0\). Thus, we get:

\[
E = E_0 + E_{\text{membrane}}
\]

Using the Nernst equation, the potential of the membrane in a half-cell reaction can be expressed as:

\[
E = E_0 + \frac{RT}{nF} \ln(a)
\]

where

- \(R\) is the Universal Gas Constant
- \(F = 9.6490 \times 10^7\) coulombs/kmol is Faraday's Constant
- \(n\) is the net number of negative charges transferred in the reaction
- \(a\) is the activity of the ions involved in the reaction

This equation is the standard equation used in electrochemistry to find the potential with respect to a reference electrode. It can be viewed as a calculation of the change in free energy at an electrode, due to changing ion concentrations at that electrode. Assuming that the electrode is completely selective to \(H^+\) ions (\(a = 1\)) and that there is only one positive ion carrying one elementary charge in each half-cell reaction \((n = 1)\) the pH of the unknown solution can be expressed as:

\[
pH = \frac{F(E_0 - E)}{2.303RT}
\]

where \(T\) is the absolute temperature of solution being analyzed.
7.5 Temperature Compensation

As one can see from the Nernst equation, the pH as determined using the potential difference between the reference and sensing half-cells varies linearly with changes in temperature. That is, the voltage drop/pH unit across the cells increases with increasing temperature. Thus, pH measuring system needs to have some way to compensate for temperature changes in the process solution. Many pH control kits come equipped with automatic temperature compensation (ATC), which continuously measures and incorporates temperature changes into their pH calculations. Other older pH control kits require manual temperature compensation, meaning that the operator or user must manually input the process solution temperature into the control system.

7.6 Alternative Methods for Determining pH

While glass membrane pH sensors are an effective method of measuring pH they are not always the best choice. Certain properties of the system of interest make using a glass membrane pH sensor impractical. Glass membrane pH sensors can become clogged by viscous solutions or solutions containing suspended solids. Harsh conditions can also scratch or break the glass membrane. There are also cases where a glass membrane pH sensor would work but using one would be an unnecessary cost. In these situations there are several alternatives that can be used to determine pH. One method is using pH paper. This paper changes color when submerged in a solution. The color of the paper can be compared to a standard scale included with the paper to determine an approximate pH. pH paper is an excellent choice when all that is needed is a “ballpark” pH value. Another method of determining pH is the use of indicators. These are substances that change color depending on the pH of the solution. They can be very useful if the primary interest is determining if the pH of the system is above or below a particular point. Numerous indicators exist that change colors at different pH values.

7.7 Other Ion-Specific Sensors

The same concepts that allow pH to be measured using a reference and measuring electrode can also be applied to measure the concentration of other ions. The differences between the pH sensors and ion specific sensors are the composition of the measuring electrode the membrane used in the measuring electrode. For some ions of interest glass membranes can still be used, however for other ions solid state membranes or liquid ion exchange may be necessary. The choice of membrane depends on both the size and the charge of the ion of interest.

While ion specific electrodes can be fairly accurate a number of problems can compromise their accuracy. Ion specific electrodes can suffer from interference. This can be especially problematic in complex solutions, especially those containing many other ions similar in charge and size to the ion of interest. The measurements reported by ion specific sensors are also functions of the ionic strength of the solution. This can also result in significantly decreased accuracy of the sensor if the effect of the ionic strength of the solution is not accounted for. As with pH the property that is actually being measured with an ion specific sensor is the activity of the ion, not its concentration. The activity can no longer be considered negligible in solutions with high ionic strength. In order to obtain proper readings the user must consider what effect the ionic strength of the solution has on the activity coefficient and adjust the measurement accordingly. Despite these limitations ion specific sensors can still provide accurate and valuable information, provided an appropriate measuring electrode membrane is used and the ionic strength of the solution is accounted for.
widely used.

### 7.8 Problems with pH Sensors

Several problems can occur with pH sensors that can negatively affect the accuracy of these devices. The majority of these problems involve the reference electrode. One such problem is a partial clogging of the porous plug. Another error associated with the plug is due to a junction potential which can vary depending on the electrode setup. This junction potential adds error to the pH measurement when the ionic composition of the solution being tested is significantly different than the ionic composition of the standard buffer used to calibrate the electrode. In general, a junction potential develops at the interface of two solutions with different ionic compositions because the various ions in each solution have different mobilities, and as oppositely charged ions diffuse at different rates a charge separation develops at the interface between the solutions. A different type of error can occur in measurements of solutions with very low hydrogen ion concentration and very high sodium ion concentration; pH electrodes can "mistake" the sodium for hydrogen, leading to a lower pH reading than the true value.

Other problems include the contamination of the electrolyte in the reference electrode or a complete depletion of the electrolyte. Any of these problems will result in an incorrect potential in the reference electrode and ultimately inaccurate pH measurements.

Problems can also occur with the measuring electrode. Any damage to the glass membrane including cracks, etching, or abrasion, as well as coating of the glass membrane will result in poor pH measurements. In addition, if the electrode is dry it will not measure pH correctly; it must be soaked in some aqueous solution for a few hours. Problems with pH sensors can be fairly easily detected. Any problems such as difficulty calibrating the sensor, unsteady pH readings, or significant drift in the readings usually indicate damage to the pH sensor. It is now possible to test some forms of pH sensors online to quickly and easily determine which electrode is the cause of the problems and potentially the source of these problems. In some cases these problems can be fixed by a careful cleaning of the sensor, however if problems persist it may be necessary to replace the pH sensor.

Example \(\text{PageIndex}\{1\})\): pH Sensor Application

Would it be wise to use a pH electrode in the following situations? If not what method would you use to determine the pH of the system of interest?

a. You are an engineer responsible for a wastewater treatment facility. It is important that you know the pH of the water at several points in the treatment process to detect any potential problems.

b. You work for a pharmaceutical company who uses bacteria to produce a desired protein. The bacteria are very sensitive to changes in pH and production falls off significantly if the pH varies from optimal conditions.

c. You work in a plant that uses hydrochloric acid as a catalyst. After the reaction has gone to completion and the product is extracted it is desirable to separate the acid from the remaining solution to be reused in the plant and allow for easy disposal of the remaining solution. The EPA requires accurate data on the pH (among other things) of all discharged solution.

d. You work in a plant that produces acetic acid. You want to ensure that the solution exiting the reactor contains at least 75 mol% acetic acid.

**Solution**

https://eng.libretexts.org/Bookshelves/Chemical_Engineering/Chemical_Process_Dynamics_and_Controls/03%3A_Sensors_...
a. NO. A pH electrode would not hold up well under the harsh conditions of a wastewater treatment plant. It is also not necessary in this case to have constant measurements or exact pH values as the pH is being used simply as an early problem detection system. Simple pH paper would be sufficient in this situation.

b. YES. The sensitivity of the bacteria, as well as the likely high value of the proteins being produced calls for the accuracy and frequent measurements afforded the engineer by a glass membrane pH sensor.

c. YES. Here not only constant measurements are required, but records of these measurements must be kept to prove that environmental standards are being met. The most cost effective way to measure and record this data would be with a pH sensor connected to a computer.

d. NO. While pH could be used as an effective way to monitor the progress of the reaction a sensor is not necessary. Here you are only interested in ensuring that a certain benchmark, in this case a reaction completion percentage measured using pH, is reached. Choosing an appropriate dye indicator would be a much simpler and more cost effective way to make sure this standard is met.

7.10 Introduction to Viscosity

Viscosity quantifies the systematic deformation of the surface of a fluid upon an applied shear stress. Fluid, while in motion, typically travels at varying velocities due to the geometry of contact surfaces. It may be characterized either as a Newtonian fluid or a Non-Newtonian fluid. A Newtonian fluid flows continuously in a uniform manner irrespective of the forces acting upon it (a common example, water). Conversely, the viscosity of a non-Newtonian fluid changes upon differing flow rates (common examples, table ketchup or mud).

Also, the effect of temperature on fluid viscosity is imperative. From a thermodynamic perspective, temperature measures the random movement of molecules of a given substance, and as movement increases internal energy increases, and temperature also increases. For most traditional substances, having higher internal energy/temperature also implies a lower viscosity, as the substance will be less resistant to movement (i.e. will deform sooner to an applied shear stress). For example, consider honey: at room temperature it oozes out of the squeeze bottle, but after a minute in the microwave it may be easily poured out, similar to a syrup.

Nearly all modern viscometers have built in controls to address temperature issues, and a competent operator or engineer may input temperature settings to that the appropriate calculations are carried out correctly.

Viscosity may be further subdivided into two distinct forms: dynamic viscosity and kinematic viscosity. Dynamic viscosity (μ), a figure representing shear stress as proportional to the strain rate, has the SI unit Pa*s. Kinematic viscosity, (v = μ/ρ), describes shifts in momentum and has SI units $m^2s^{-1}$, but is also commonly represented by the Stoke, $cm^2s^{-1}$ (content adapted from http://scienceworld.wolfram.com/physics/DynamicViscosity.html).
As noticed above, the typical Newtonian fluid experiences friction upon contacting a surface and resultantly develops a characteristic velocity profile. This profile may be described by examining the known properties of the fluid and the surrounding structure through which it travels, commonly piping for plant chemical engineering.

In the above diagram we notice a non-cylindrical surface featuring two boundary plates, one stationary to the observer, and one mobile. Fluid contained within the two boundaries may behave according to the constraining conditions of the boundary plates, and subsequently characterized by fluid mechanics:

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

Assuming $\mu$ as the coefficient of viscosity, the above equation describes the relationship between the shear (parallel) stress and velocity of fluid travel per unit height above the stationary boundary plate. Fluids having a relatively high viscosity resultantly also require greater force to induce motion—resulting in a larger shear stress.

7.11 Why is Viscosity Relevant for Chemical Engineering?

For engineers a thorough knowledge of the physical and chemical properties of products is essential to the successful implementation of any design. Viscosity, similar to volatility, density, or any other physical property, offers significant insight into the potential behavior of a substance, whether classified formally as a solid, liquid or gas. By taking viscosity into account, engineers may correctly select and place instrumentation in an environmentally friendly, sustainable method.

Many professional assignments necessitate a genuine understanding of viscosity and its effects on process engineering. For a more detailed and insightful glance into the daily upkeep and activities associated with plant maintenance, please consult Michael Pearce at www.reynolds mixers.com/whitepapers/030910_hotmelt.doc. He speaks at length regarding the cost-effective selection of specific types of blades used in mixing processes.

As an example, a key parameter in food process monitoring is viscosity. The viscosity is directly related to the flow characteristics of the product, which impact pumpability, pourability, and spreadability. In the food-processing environment there are a number of challenges to viscosity measurement, such as harsh process conditions and the
complex rheological properties (relationships between deformations and stresses of materials). Offline measurements are often cumbersome, labor-intensive, and prone to operator error. Online viscometers must be able to deliver continuous measurement day after day with minimal maintenance. Therefore, considerations when choosing viscosity sensors for food processing should include ease of cleaning, minimal risk of fouling, and whether or not they meet sanitary requirements.

### 7.12 Off-line Instruments

For the measurement of viscosity in controlled settings (typically laboratory) where the majority of variables are maintained as constant, engineers and scientists use off-line viscometers. Typical examples include: Capillary, Couette, Falling Ball, Cone and Plate and Oscillating Cylinder. It is very important to keep these instruments in a regulated environment with a stable temperature (such as in a water bath) because of viscosity's sensitivity to changes in temperature.

#### 7.12.1 Capillary

The Ostwald U- Tube viscometer functions by measuring the amount of time a specified quantity of fluid takes to move from its initial position to a final position.

Typically, a suction device holds the bottom of the fluid meniscus at the start position (indicated by the solid horizontal red line), and upon its release the fluid drops an approximate distance of 5 mm (to reach the solid horizontal green line). The time for this drop is recorded so that the acquired data may then be used in Poiseuille’s Law to determine the outcome of kinematic viscosity.

Both the dynamic and kinematic viscosities may be found by applying these formulae (where $K_0$ is the non-dimensionless viscometer constant):

- Dynamic Viscosity: $\mu = K_0 t$
- Kinematic Viscosity: $v = K_0 t$
7.12.2 Couette

This device may be used in both off-line and on-line applications with appropriate modifications in the output settings. A couette type viscometer measures viscosity by spinning a cylinder encapsulated in fluid. This is accomplished through the synchronization (identical frequency, no phase difference) of a motor with magnetic coupling to rotate a magnet which in turns forces the inner cylinder to revolve within the fluid.

The torque reaction of the motor is resultant of the viscous drag on the rotating cylinder. This torque on the motor is effectively counteracted by the torsion bar (a thin rod connecting the control/ measuring band to the linear variable displacement transformer). The deflection of the torsion bar, a function of the fluid viscosity, is then subsequently converted into local signal available for laboratory analysis.

Engineers use viscometers of the couette type in in-line or in-tank applications. Also, the meters are appropriate for both Newtonian and non-Newtonian fluids. The acceptable range of viscosity spans from $10^{-3}$ to $5 \times 10^3 \text{Ns/m}^2$.

Information for this device has been adapted from Richardson's Chemical Engineering.
7.12.3 Falling Ball

A substantially more direct approach to viscosity measurement, testers allow a ball to fall through a column containing liquid of unknown viscosity and then measure the amount of time necessary for the ball to reach the bottom of the column.

A commonly used method involves a stainless steel ball which sinks through the liquid under scrutiny; researchers measure the time necessary for the ball to drop from one preselected level to another. To attain the terminal velocity of the ball in the liquid, \( u_0 \), timers write the initial timing mark a minimum of six ball diameters below the ball release point.

Also important to note, the ratio of ball diameter to column tube diameter should not exceed 1:10 to account for the drag effects of the column tube walls on the terminal velocity of the falling steel ball. A simple viscosity derivation from buoyancy principles is presented in Richardson's text, and is shown again here:

\[
v = \frac{K_v (\rho_s - \rho)}{\rho} t
\]

where

- \( (K_v) \) is the dimensional viscometer constant
- \( (\rho_s) \) is the density of the ball
- \( (\rho) \) is the density of the liquid
• \((t)\) is the time required for the ball to sink the measured distance

7.12.4 Cone and Plate

Another popular method used employs a cone placed in a manner so that the tip touches the center of a stationary plate. Fluid encapsulates the cone and researchers take a measurement of the amount of torque required to keep the plate stationary.

This process allows the dynamic viscosity to be quantitatively described as:

\[
v = \frac{3}{\pi \gamma r^3} T
\]

• \(T\) = Torque required to keep the top plate in place
• \(\gamma\) = Rate of shear

The rate of shear is the ratio of the angular velocity of the cone to angle between the cone and the plate (note: this angle must be small enough so that the sin of the angle approximately equals the angle itself).

Important Additional Notes:

Edge effects of the cone or plate are neglected. The equation may also be used for Non-Newtonian fluids provided that \(\gamma\) is relatively constant.

7.12.5 Parallel Plates

Parallel plates or discs viscometer is similar to the cone and plate method. The cone in the case is replaced with another plate. In this viscometer, the fluid flows in a gap between two parallel discs. One of the discs rotates with an angular velocity \(\omega\) which creates the shear. Torque is applied to the other plate so it stays stationary. A normal force, \(F\), is created by fluid elasticity and acts as to separate the two plates. No slip at boundaries is assumed.
Parallel Plates viscometer

\( \omega, T \) and \( F \) are all experimental parameters. Shear rate is given by:

\[
\dot{\gamma} = \frac{\omega r}{d}
\]

- \( \dot{\gamma} \) = Shear rate
- \( r \) = The radius of the disc
- \( d \) = The distance between the two plates

Shear stress, \( \tau \), is given by:

\[
\tau = \frac{T}{2\pi r^2 \left(3 + \frac{d \ln T}{d \ln \dot{\gamma}}\right)}
\]

Viscosity is, therefore, the ratio of shear stress to shear rate. Some limitations associated with parallel plates include:

1. Sufficient data of \( T \) vs \( \omega \) and \( F \) vs \( \omega \) must be available
2. Uniform temperature at different points in the gap between the two plates is required
3. Error might be caused from edge fracture, wall slip, misalignment of the plates and viscous heating.

### 7.12.6 Oscillating Cylinder

This instrument involves an arrangement requiring a rotating cylinder placed in a quantity of a viscous fluid. The level of disturbance noticed in the fluid resulting from the rotation of the cylinder is then noted, and may be used if the following equation to determine viscosity:

\[
v = \frac{\left(r_2^2 - r_1^2\right)}{4\pi \omega v r_2^2 r_1^2} T'
\]

- \( r_2 \) = Outer cylinder radius
- \( r_1 \) = Inner cylinder radius
• \( \omega_v \) = Angular velocity

The outer cylinder of radius \( r_2 \) rotates with an angular velocity of \( \omega_v \) while the inner cylinder of \( r_1 \) remains stationary thus allowing for the torque (alternatively referred to as 'viscous drag'), \( T' \), to be measured at predetermined values of \( \omega_v \).

### 7.13 On-line Instruments

On-line instruments are those that are capable of giving a precise measurement of viscosity under plant conditions. This means that they will be able to withstand the wide range of viscosities and the variable temperature, pressure, and flow rate that occur within a process plant while still obtaining the accuracy that is required. In all on-line instruments automatic temperature compensation is always required because of viscosity's temperature dependence.

#### 7.13.1 Capillary

This type of viscometer is derived from Poiseuille’s law:

\[
\frac{d v}{d t} = v_s \cdot \pi \cdot r^2
\]

- \( v_s \) = Fluid velocity
- \( r \) = Internal radius

The instrument has many temperature and pressure sensors in the intricate system because there must be a precisely controlled pressure drop and temperature in the stream. Response time is minimized by adding a fast loop sampling system. A capillary viscometer would be useful when using Newtonian fluids such as lubricating oils or fuel oils. It can endure viscosities ranging from \( 2 \times 10^{-3} \) to \( 4 \text{ Ns/m}^2 \).

#### 7.13.2 Couette

Identical to the description provided earlier, except now with a change in the output data processing. The deflection of the torsion bar, a function of the fluid viscosity, is now converted into a 4-20 mA output signal and is readily available for additional plant data management/processing.

Information for this device has been adapted from Richardson's Chemical Engineering.

#### 7.13.3 Vibrating Rod or Cylinder

This type of viscometer can also be used in-line or in-tank. It is suitable for Newtonian, non-Newtonian fluids, and mineral slurries. The vibrating rod or cylinder works by using an electromechanical system as the driving force, or by a pulse of current through a specific alloy. The lowest viscosity that it can handle is \( 10^{-4} \text{ Ns/m}^2 \) and it can extend to \( 2 \times 10^3 \text{ Ns/m}^2 \). Normally on lower viscosity ranges the cylinder is used, while with higher ranges the rod is used. Given a plant’s natural vibration care must be taken when deciding on the location of an oscillation viscometer because of their sensitivity.
7.14 Table of Viscometer Uses

This table found in Richardson's text offers some guidance on the device selection process.

<table>
<thead>
<tr>
<th>Viscometer Type</th>
<th>Lower Viscosity Range</th>
<th>Upper Viscosity Range</th>
<th>Lower Flow Rate Range</th>
<th>Upper Flow Rate Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Capillary</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Plate &amp; Bulb</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Cone and Plate</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Tapered Capillary</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Unified Flowmeters</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
<tr>
<td>Sputtering</td>
<td>10^{-14}</td>
<td>100</td>
<td>10^{-15}</td>
<td>10^{-4}</td>
</tr>
</tbody>
</table>

One may notice that the viscosity ranges of some of the viscometers overlap. In a situation where this occurs and it is necessary to choose between multiple viscometers, one needs to take into account process conditions such as changes in temperature, pressure, and solution flow rate. The appropriate viscometer should be able to handle these conditions without disrupting the process.

7.15 Problem Solving Schematic

The following schematic may be employed to select an appropriate viscometer. Additional considerations must also take place, as the usable viscometer ranges occasionally overlap. This requires the competent operator or engineer to base his or her selection from a host of other valuable criteria, including but not limited to: cost-effectiveness, difficulty of implementation, heat generation, availability of qualified local maintenance personnel, environmental impact, and long term sustainability.
Example Question:

How should an engineer correctly begin the viscometer selection process?

Solution:

Mentally develop a systematic decision schematic as indicated below:

1. Is the viscometer to be used for an on-line (plant implementation) or an off-line (lab use)?

   Yes → Ns
   No → What is the expected viscosity range of the test fluid? (Visc.)

   2 to 1000 Ns/m²
   1 to 100
   10 to 1000
   10⁴ to 10⁷
   10⁷ to 10⁴

   Match to appropriate instrument (Visc. range):

   Capillary, vibrating rod or cylinder

   Consider type of meter as an option, and proceed to specifically check other parameters:

   Ultrasonic, falling ball, Couette, cone and plate, oscillating cylinder

   What are the expected applications?

   Newtonian fluids
   In-Line or In-Task
   Used for both Newtonian and non-Newtonian fluids

   Solution:

After looking at the summary table given above, we can immediately narrow down our search to just the on-line instruments from the information given in the problem statement. For the hot glycol stream we find which instruments have a viscosity range which allows for a viscosity of 0.002 Ns/m². We find that the following viscometers would be acceptable: Capillary, vibrating rod or cylinder.

The cool glycol stream involves the same process, but it must have a different range of viscosity which includes 5 Ns/m². Viscometers which are acceptable for this stream include: Couette, vibrating rod or cylinder.

7.17 pH/Viscosity Sensor Key Learnings

As is apparent after reading this article, pH and viscosity measurements do not have much in common with each other. However, there is a common thread between these two types of sensors that needs to be acknowledged, and that is the
method that needs to be taken when deciding what type of sensor to use. While there is only one single type of pH sensor available, before it is to be used the user needs to evaluate whether there is an easier and cheaper way (eg. using pH paper or a pH activated dye) to accomplish the task at hand. With viscometers, there are multiple types of viscometers to use over various ranges of viscosity. The user needs to evaluate process conditions such as temperature, pressure, and flow rate, in order to decide which type of viscometer is optimal for the application.

The math associated with both types of sensors is good to know for background purposes and to gain a fundamental understanding of how a sensor produces a measurement, however it is not information that greatly helps the user decided what type of pH indicator or viscometer to use. Hence, this article has tried to give the background theory behind the measurements, but a thorough analysis of this theory is not included and not necessary for the purposes of Process Control.

### References

- Cole-Palmer Catalog, 2005/2006