Ion-Exchange Resins

Introduction

Water is an excellent solvent and therefore often contains many impurities. These impurities can be either beneficial, such as giving drinking water its good taste, or undesirable, such as making water hard.

There are six main types of contaminants found in water:

- Dissolved ionized solids
- Dissolved gases
- Dissolved organics
- Particulates
- Microbials
- Pyrogens

Distillation and deionization (ion exchange) are the most common methods of removing impurities from water. The chart in Figure 1 compares the effectiveness of these two methods at removing the various impurities.

Contaminants	**Distillation**	**(Ion Exchange) Deionization**
Dissolved Ionized Solids	E/G	E
Dissolved Ionized Gases	P	E
Dissolved Organics	G	P
Particulates	E	P
Microbials	E	P
Pyrogens	E	P

E = Excellent G = Good P = Poor

Figure 1.

The focus of this article will be the removal of dissolved ionized solids and gases by a filtration process called ion exchange. Ion-exchange resins (IER) will also be discussed, since they are the principal material used in the process.

You can remove undesirable ions in water by running the water through an ion-exchange resin. The resin will swap or exchange its "chemically pure" ions with the "impure" (undesirable) ions originally found in the water. After the ion-exchange process is complete, the water will be of higher quality with few, if any, "impure" ions remaining. However, the ion-exchange resin used will have lost some of its effectiveness since it now contains the impurities that were originally in the water and fewer of its original "pure" ions.

An example of the ion-exchange process is the softening of water. Common tap water contains chemical impurities such as magnesium ions (Mg^{2+}) and calcium ions (Ca^{2+}). These ions that are present in water are what make water hard. Hard water is undesirable mainly because of the mineral deposits it leaves behind and its resistance to the lathering of soap, with its resultant soap scum. These properties are so undesirable that most homes contain a water softener.

Most home water softeners are really ion-exchange columns. The ion-exchange resin is a form of sodium chloride (rock salt) which contains sodium ions (Na^+). By running hard water through a water softener, the "impure" magnesium ions and "impure" calcium will swap or exchange places with the "pure" sodium ions. The end result is soft water that is high in sodium ions but free of the hard water ions, magnesium and calcium. The sodium ions do not affect the hardness of the water. The magnesium and calcium ions are now trapped in the ion-exchange resin in the water softener. When all the sodium ions originally in the water softener are used up, they must be replenished. This is done by reversing the process; that is by pouring a saturated sodium chloride solution through the ion-exchange resin. Most of us are quite familiar with lugging home heavy salt blocks or bags of salt pellets from the store for our water softeners. Because of the high concentration of sodium ions present in soft water, people watching their sodium intake should limit the amount of soft water they drink.

Concepts

- Chemistry in the environment
- Chemical bonding
- Ion-exchange

Background

Chemical Bonding

Understanding the types of chemical bonds is important to understanding the use of ion- exchange resins. There are two main types of chemical bonds—ionic and covalent.

Ionic bonds are found between a metal and a non-metal. The metal loses an electron or electrons to the non-metal. This gives the metal a positive charge (since it lost a negatively charged electron) and the non-metal gets a negative charge (since it gained a negatively charged electron). Positively charged ions are called cations, and negatively charged ions are called anions. Sodium chloride (NaCl) is an ionic compound, meaning it contains an ionic bond. Sodium (a metal) loses an electron becoming a positive ion or cation (Na^+). Chlorine (a non-metal) gains the electron that sodium gave up and becomes a negative ion or anion (Cl^-). Sodium chloride is a crystal made up of a countless number of these two ions in a three-dimensional lattice. When salt (NaCl) is placed in water, it dissolves, separating the ions so they can move freely in the water.

In contrast, a covalent bond does not involve the transfer of an electron or electrons between a metal and a non-metal, but the sharing of an electron or electrons between two non-metals. Silicon dioxide (SiO_2) or quartz is a covalent compound, meaning it contains covalent bonds between the silicon atom and each oxygen atom; therefore, no ions are present. Electrons are shared between the silicon atom and each oxygen atom. A very large (macromolecule) three-dimensional network of silicon atoms and oxygen atoms forms quartz. Each grain of sand (sand is mostly quartz) is really one huge molecule of silicon atoms and oxygen atoms with twice as many oxygen atoms as silicon atoms. These atoms are bonded so tightly in this covalently bonded substance that a solvent like water cannot split the network into small parts that will dissolve; therefore, sand does not dissolve in water.

Some substances contain both ionic bonds and covalent bonds. Silver nitrate ($AgNO_3$) is a crystalline solid that consists of positive silver ions (Ag^+) and negative nitrate ions (NO_3^-). The silver ion and the nitrate ion are bonded together ionically. A nitrate ion, however, consists of one nitrogen atom covalently bonded to three oxygen atoms. That means that the nitrogen atom shares electrons with each oxygen atom. When silver nitrate is placed in water, the solid dissolves into monatomic (one atom) silver ions and polyatomic (many atoms) nitrate ions. The covalent bonds between the nitrogen atom and oxygen atoms remain intact.

As you will see later, the nature of the chemical bond will have a direct influence on the use of ion-exchange resins for particular applications.

Structure of Ion-Exchange Resins

Ion-exchange resins are often thought to be confusing because of the technical names given to them like “Dowex 50 WX-8” or “Amberlite IRA-400.” Do not let these names intimidate you. Ion-exchange resins bear a strong resemblance to a substance like silver nitrate. The atoms in an ion-exchange resin are held together with the same two types of bonds—ionic and covalent.

The first part of an ion-exchange resin is a three-dimensional structure of covalently bonded atoms that carry a charge. Instead of nitrogen and oxygen, as in our silver nitrate example, the atoms that make up the ion-exchange resin are organic atoms like carbon, hydrogen, some oxygen and possibly sulfur and nitrogen.

Our silver nitrate example contained a four atom nitrate ion (one nitrogen and three oxygen). An ion-exchange resin, in contrast, contains tens of thousands of atoms in a huge network. Such huge networks are called macromolecules or polymers (polymer = many units). Most organic polymers are electrically neutral. This macromolecule of an ion-exchange resin, however, is not electrically neutral and carries a charge. Depending on the ion-exchange resin, the macromolecule may have either an excess or deficiency of electrons in its structure. Remember, excess electrons would yield a negative charge while a deficiency would yield a positive charge.

So, the first part of an ion-exchange resin is an ion because of its electrical charge and also a macromolecule because of the large number of atoms. This part of the ion-exchange resin is called a *polymer-ion*.

The second part of the ion-exchange structure consists of numerous, individual, small ions. The electrical charge of these small ions is the opposite of the polymer ions, the first part of our ion-exchange resin. There are enough of these counter-ions in the second structure to balance the charge on the first part of the structure. The result is that the ion-exchange resin is electrically neutral.

To summarize: An ion-exchange resin contains multi-atom polymer-ions. The polymer-ions contain a very large number of atoms with a very large electrical charge. The ion-exchange resin also contains a large number of counterbalancing individual ions to render an ionically neutral substance. Ion-exchange resins are usually in the form of tiny, amber colored beads.

Ion-Exchange Resins In Water

Polymers usually do not dissolve in water, and the big polymer-ions, the beads of the ion-exchange resin, are not an exception. The individual counter-ions do not move away from the polymer ions because of the attraction of opposite charges. The beads of the ion-exchange resin are similar to a sponge in that they will absorb water into the spaces between the polymer chains, and thus swell up and gain weight.

If the ion-exchange resin is put in water that contains dissolved ions, then something important does happen. The beads still do not dissolve, but if, for example, the counter-ion is sodium and the water contains calcium ions, these ions will exchange places. Sodium ions from the ion-exchange resin will go into solution and the calcium ions will attach themselves to the ion-exchange resin. Ion exchange takes place. Most ion-exchange resins attract some ions preferentially over others. Heavier ions and larger charged ions will exchange before lighter ions and smaller charged ions. So, for example, a magnesium ion (Mg^{2+}) will be attracted more than a sodium ion (Na^+), and a barium ion (Ba^{2+}) with an atomic weight of 137 will be exchanged preferentially over a magnesium ion (Mg^{2+}) with an atomic weight of 24. These preferences, however, may not apply at high concentrations and may, in fact, reverse. Reversal happens with sodium ions and calcium ions, and this reversal characteristic is the basis of water softening.

Types of Ion-Exchange Resins

There are different kinds of ionizable groups that may be found in ion-exchange resins. The type of ionizable group determines which of the four major classes of ion-exchange resin results:

A. Strong Acid

B. Weak Acid

C. Strong Base

D. Weak Base

The exchangeable ions for the acid type are the hydrogen ions (H^+) and for the base type are the hydroxide ions (OH^-).

Commercial Ion-Exchange Resins

Two major manufacturers, Rohm & Haas and Dow Chemical Company, make ion-exchange resins. Amberlites is the trade name Rohm & Haas uses for their ion-exchange resins and Dow Chemical Company uses the name Dowex. These firms and others have created a series of trade names to identify different classes and characteristics of products they make. A few of the more common ion-exchange resins are shown in Figure 2.

Trade Name	Class
Amberlite IR-120	Strong-acid, cation (SAC)
Dowex 50W-X8	Strong-acid, cation (SAC)
Amberlite IRA-400	Strong-base, anion (SBA)
Dowex 2	Strong-base, anion (SBA)
Amberlite IRC-50	Weak-acid, cation (WAC)
Amberlite IR-45	Weak-base, anion (WBA)
Dowex 3	Weak-base, anion (WBA)

Figure 2.

In the past, natural materials, like zeolite minerals, were used as ion-exchange resins. Today almost all ion-exchange resins are man-made, synthetic materials.

An Ion-Exchange Resin In Use

For our example, let's use a strong-acid, cation ion-exchange resin. We can do this on a laboratory scale, using a buret. A student grade buret, like Flinn Catalog Nos. AP1200 and AP1201, would work best. Put a piece of glass wool, as a plug, loosely in the bottom of the buret. Fill the buret with the beads of the ion-exchange resin. Now, plug the other end with glass wool. The glass wool will keep the beads in the buret and will also allow liquid to flow through the tube. Put the stopcock on the end of the buret so you can control the flow of liquid through the buret. A large funnel or reservoir is needed at the top of the column to contain the solution you wish to run through the column. In our example, let's fill the reservoir with a saturated sodium chloride solution (brine). Allow the sodium chloride solution to flow from the reservoir through the ion-exchange resin in the buret and out into some collection vessel, like an Erlenmeyer flask.

The concentration of sodium ions in the brine is very high. The concentration of hydrogen ions in the ion-exchange resin is high. What will happen? The sodium ions and the hydrogen ions will exchange places on a one-to-one basis. For every one sodium ion that leaves the brine and attaches itself to the ion-exchange resin, one hydrogen ion will detach itself and be flushed out of the buret. The water in the collection vessel will slowly become more acidic as the hydrogen ion concentration increases. If you would like to confirm the process, check the pH of the brine before passing it through the ion-exchange resin and after the exchange has occurred. The strong-acid cation ion-exchange resin, after use, has little or no acid remaining since sodium ions (Na^+) have replaced hydrogen ions (H^+). In principle, the process works for any cation exchange.

Demineralizing

Consider that we mix a strong-acid cation-exchange resin (of the H^+ type) with a strong-base anion-exchange resin (of the OH^- type). Now pass tap water through this mixture of ion-exchange resins. Any dissolved cations (magnesium, calcium, etc.) will exchange places with hydrogen ions while the dissolved anions (carbonate, chloride, etc.) will exchange places with the hydroxide ions. The displaced hydrogen ions and hydroxide ions will pass out of the demineralizer and combine, just as you might expect, producing more water molecules. Thus, we have demineralized the water and made it pure.

Creating very high purity water with a demineralizer is more practical than the standard energy- consuming method of heating, distilling, condensing, and cooling—such as is done with a water still. Remember, however, demineralizers remove only ionized contaminants (see Figure 1). Non-ionic contaminants, such as a wide range of organic substances, bacteria, etc., can only be removed by heat distillation or ultra filtration.

The two ion-exchange resins mixed together are considered expendable. Separating them into their components is not practical, and therefore, the mixed resin is discarded after it is exhausted.

To determine when the mixed resin is exhausted, a simple electrical bridge (meter) is needed to monitor the output of the mixed bed demineralizer. As water is purified, its electrical resistance increases, and the meter will show that change.

Other Interesting Applications of Ion-Exchange Resins

Remember the near melt down at the Three Mile Island Nuclear Power Plant in Pennsylvania? A huge amount of contained cooling water was contaminated with low concentrations of radioactive salts: e.g., thorium, polonium, bismuth, lead, and, of course, uranium. These radioactive salts were removed by the use of sodium ion-exchange. The process was relatively efficient since the contaminants contained both a high charge and high mass. The ion-exchange resins, of course, became radioactive, but the volume or size of the radioactive problem was enormously reduced and concentrated into the ion-exchange resin instead of millions of gallons of water.

Weak acid and weak base ion-exchange resins are often found useful in biological separations. Ion-exchange resins are much less likely to affect or degrade complex bio-molecules because the ion-exchange resins will operate at very nearly normal pH values. The very common antibiotic streptomycin is concentrated and purified by use of a weak acid ion-exchange resin. Dilute solutions of the impure substance are passed through an ion-exchange resin specifically developed for this application. The streptomycin molecules are selectively exchanged onto the resin. The impurities pass through. Next, the column is rinsed with distilled water. Now, a concentrated weak acid solution is passed through the resin and yet another exchange occurs liberating a very pure solution of the antibiotic.

Summary

Ion-exchange materials originally consisted of naturally available materials like zeolite. Selectively exchanging and reversing ion-exchange became practical and economically feasible as science allowed the synthesis of a wide array of very selective, man-made ion-exchange resins. Now, most every aspect of our lives includes the use of ion-exchange materials from our home water softener to the preparation of pure water for the laboratory and many other applications. Some examples of industries heavily dependent on ion-exchange resins are:

Cosmetics
Environmental Clean-Up
Farming
Food Processing
Medicine
Metals Manufacturing
Petroleum
Pharmaceutical
Plastics
Space Exploration

Ion-Exchange Resins are available from Flinn Scientific, Inc.

Catalog No.	Description
I0033	Ion Exchange Resin, SBA, 100 g
I0034	Ion Exchange Resin, SBA, 500 g
I0043	Ion Exchange Resin, SAC, 100 g
Z0001	Ion Exchange Resin, SAC-Na, 500 g

Consult your *Flinn Scientific Catalog/Reference Manual* for current prices.