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AG AND BIOSYSTEMS
ENGINEERING

# GREENHOUSE IRRIGATION

## *Pipe systems*

Greenhouse irrigation systems utilize white polyvinyl chloride (PVC) plastic pipe (Figure 1) for buried mainline and submains.  Surface drip laterals are black polyethylene pipe (Figure 8). The pump, filter and chemigation equipment are connected to steel pipe in above-ground pipe manifolds (Figure 2).

Figure 1. White PVC pipe in Ebb and Flood system. *Credit USDA NRCS*.

Greenhouses use many types of irrigation systems. This chapter focuses on hydroponic drip irrigation systems, such as those in the CEAC greenhouses.  Hydroponic drip irrigation systems have the same layout as field drip irrigation systems (Figure 3). Pumps, filters, and chemigation equipment supply water to a PVC mainline. Solenoid valves (Figure 10) on the mainline supply water to PVC submains, when activated by the controller. Submains supply water to polyethylene laterals..

Figure 2. Centrifugal pump mounted on steel pipe. *Credit USDA NRCS*.

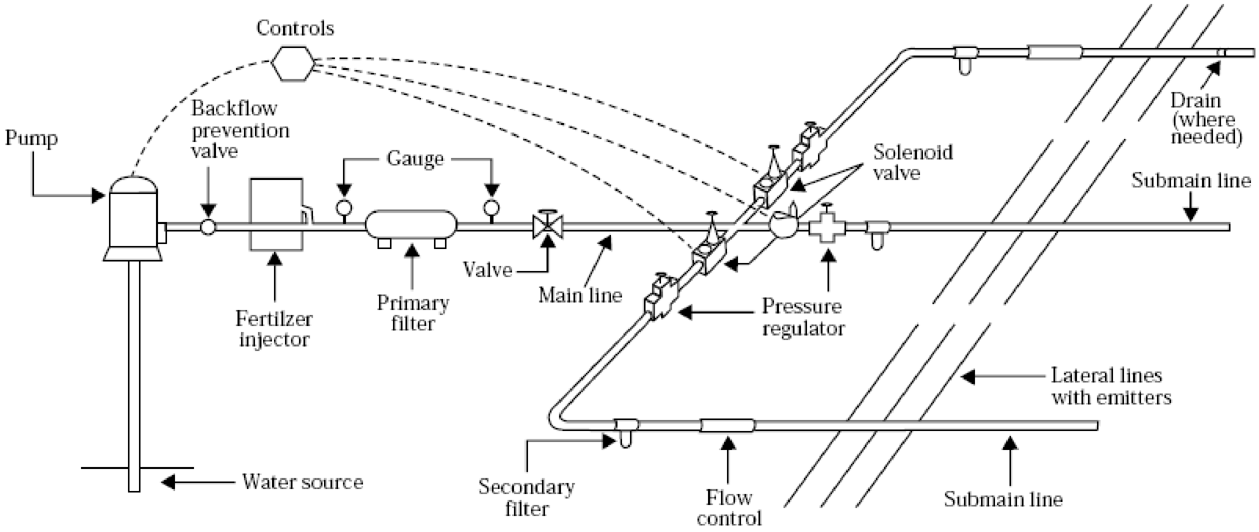

Figure 3. Drip irrigation system pipe network. *Credit USDA NRCS*.

There are three PVC pipe dimensional classification systems:

- Class (Standard dimension ratios)
- Schedule (based on steel pipe dimensions)
- PIP (Plastic Irrigation Pipe).

Greenhouse high-pressure systems use Class and Schedule classifications. The diameters correspond with the IPS (Iron Pipe Size) classification. Low-pressure flood irrigation systems use PIP pipe, which has its own outside diameter classification system. Thus, PIP pipe and IPS pipe are incompatible, and joining the two requires special transitional fittings. Class and Schedule pipes are compatible and use the same fittings.

Within each pipe classification system, wall thickness varies with pressure rating. All IPS pipes with the same nominal size have the same outside diameter, but they have different wall thicknesses and different inside diameters, based on pressure rating. Pressure ratings for the Class system are calculated based on the ratio of wall thickness to pipe diameter (standard dimension ratio). The Class system standard dimension ratios are 41, 32.5, 26, and 21 for Class 100, 125, 160, and 200, respectively. For example, the Class 200 pressure rating is 200 psi. The Schedule 40 and Schedule 80 classifications are not pressure ratings. Appendix A lists Class and Schedule diameters.

## Surge pressure and water hammer

Pressure surges and water hammer occur when pumps start or stop and when valves open or close. Small surges and water hammer can shake pipes and cause maintenance problems. Large surges cause disasters. If moving water suddenly stops, then Newton's second law states that the resultant force is equal to the rate of change of momentum, F = ma. Most people in the irrigation business have experienced pressure surge disasters (except this author). An old colleague at an irrigation business told this author a story. After installation of a long 250 mm (10″) diameter irrigation pipeline with a closed valve at the end, a worker suddenly opened the inlet valve, and the pipe blew a hundred feet out of the trench; opening the valve caused water to rush down the pipe at very high velocity until it reached the end. The resultant pressure wave traveled at extremely high velocity and blew the entire pipe out of the trench. One of the workers at the U of A farm told a similar story of a very long pipe that he blew out of the ground at Reid Park Golf Course.

Irrigation system operators should slowly fill a pipe with water. The valve should not be opened completely until the pipe is full. ASAE Standard 376.1 recommends a filling velocity of no more than 0.1 m/sec. This fill velocity results in a 10 minute filling time for a 300 m length pipe (ASAE 376.1). Centrifugal pumps should start with the discharge valve closed; then the valve should be cracked open until the pipe is full. Pumps should not run for an extended period against a completely closed valve because pumps are water cooled. Thus, the valve should be cracked open within several seconds after starting the pump.

Gate valves or gear operated butterfly valves are preferable on long, large diameter pipes because they open slowly, unlike ball valves or lever operated butterfly valves.

Most pressure surges in pipelines are caused by suddenly closing a valve. The surge may cause a banging sound, which is called water hammer. The banging sound is caused by pressure waves expanding and contracting the pipe as they move back and forth in the pipeline. Even if water hammer does not break the pipe, repeated water hammer events eventually lead to pipe or joint failure. Pressure relief valves allow water to escape if the pipe pressure exceeds a given threshold; they are placed just before the last valve on the mainline (Figure 4), and just after a check valve at the pump. The check valve prevents water hammer the next time the system is turned on because it prevents the mainline from draining when the system is shut down. Pressure relief valves should be set to release water at no more than 5 PSI (35 kPa) greater pressure than the design operating pressure of the system (ASAE S376.1). Air vents are also placed on irrigation mainlines; they allow air to escape from the pipe as the pipe is filling, or allow air to replace the water in the pipe when the pipe is draining. They have a small buoyant ball that is pressed against the upper vent hole when the pipe has water, but the ball drops down and allows air to escape when the pipe has air.

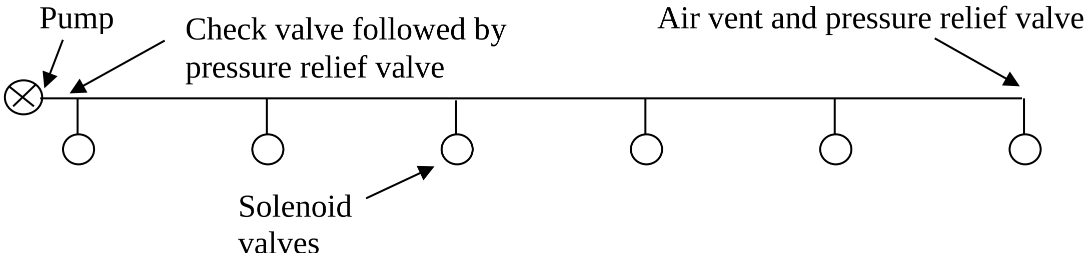

Figure 4. Irrigation main line with solenoids, air vents and pressure relief valves.

The irrigation system should also be designed with the criterion that the operating pressure plus possible surge pressure (as if the pressure relief valve were not there) should be no greater than 150% of the rated pipe pressure (Harvel Plastics Engineering Guide). This number, 150%, is based on an expected number of surges at which pipe failure will occur at a given surge pressure percentage over the rated pressure. The risk of surge pressure increases with design water velocity. The rule of thumb is that water velocity in closed end PVC pipes should be kept below 1.5 m/sec (5 ft/sec) in order to prevent excessive surge forces. The 1.5 m/sec rule does not apply to pipes that have an open discharge.

The highest flow velocity point in a system is most susceptible to water hammer. If water hammer is noticed (banging sound) in an irrigation pipe system, then troubleshooting the water hammer problem should be conducted as follows (Striker, 2007): (1) check for under-designed pipe diameters (> 1.5 m/sec velocity), (2) check for more than one zone turning on at a time resulting in double the design flow rate, (3) check for valves closing too quickly, which may be solved by installing valves that close slowly, (4) check for lack of pressure relief valves and air vents at the end of mainlines, (5) and check for pressure surges caused by abrupt changes in direction such as at 90 degree elbows..

The minimum acceptable pipe diameter based on the maximum 1.5 m/sec velocity is

$$D = \sqrt{\left(\frac{4Q}{\mathrm{v}_{\max}\pi}\right)} \tag{1}$$

where

Q = flow rate, $m^3$/sec,
$v_{max}$ = maximum allowable velocity, 1.5 m/sec for PVC pipe,
D = pipe diameter, m.

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**Example 1.** Find the minimum required PVC pipe inside diameter if flow rate is 95.3 L/sec.

$$D = \sqrt{\left(\frac{4Q}{\mathrm{v}_{\max}\pi}\right)} = \sqrt{\left(\frac{(4)(0.0953\, m^3/\sec)}{(1.5\, m/\sec)\pi}\right)} = 0.284\, m = 28.4\, cm$$

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Due to high tensile strength, PVC pipes can hold high positive pressure. However, vacuum can cause collapse, especially in thin wall pipes. In order to prevent development of a vacuum, all high points on pipelines (closed ends or middle) should have a vacuum relief valve to prevent the formation of a vacuum when the pipe is drained. Vacuum relief valves have a vent at the top of the valve that opens when a vacuum forms. Because air vents and vacuum relief valves are both needed at high points, combination air vent/vacuum relief valves are available.

ASAE Standard S376.1 specifies air vent dimensions (diameter of the threaded connection to the PVC pipe) for low-pressure and high-pressure pipelines (Appendix A). Air vents and vacuum relief valves on gravity flow pipelines are larger because prevention of vacuum and air locks is more important: air must be allowed to rush into or out of the pipe quickly.

## Installation

A typical irrigation system installation includes the following steps:

1. Lay out the locations of the trenches and possibly marking them with paint on the ground.
2. Verify the locations of existing utilities and irrigation pipes.
3. Trenching.
4. Glue the mainline pipe outside the trench.
5. Run water through the mainline in order to flush dirt from the pipe.
6. Install valves on the mainline.
7. Place solenoid valve wires into the trench.
8. Drop the mainline into the trench on top of the solenoid valve wires.
9. Glue submains and laterals outside the trench.
10. Attach submains and/or laterals to the mainline solenoid valves.
11. Drop the submains and laterals into trenches.
12. Run water through the submains and/or laterals in order to flush out dirt from the pipes.
13. Attach emitters, tubing, or sprinklers to the laterals.
14. Pressure check the entire system for leaks.
15. Backfill the trench.

## Trenching and pipe installation

Lay out trench locations carefully. Mark the locations with spray paint in order to guide the trencher operator. Urban installations should be “Blue Staked”. Utility companies mark the locations of all underground utilities. Neglecting this step can be hazardous and expensive. Many utilities have foil tape several cm above utility lines; find the exact location with a shovel before trenching. In agricultural fields, it is often necessary to find existing irrigation pipes. Some specially endowed individuals can walk through the field with L-shaped metal rods in each hand pointing straight ahead; when the person crosses a buried pipe, the metal rods cross over each other. It is thought that lines of magnetic or gravitational force cause the rods to change direction.

There are many types of trenchers, backhoes, and pipe pullers. Efficient installation of irrigation or pipe systems requires an adequately sized machine. Using an inadequately sized trencher could require a great deal of extra work and be dangerous. If preparing a commercial bid, take extensive soil core samples at the site. If not, the bid should assume the worst possible conditions (for example, rock) and include an appropriate trencher. Recommended trench widths and depths are specified in ASAE standard S376.1. In general, the minimum trench width is 12″ (30 cm) wider than the pipe diameter, and the maximum trench width is 30″ (75 cm) for pipes less than 15″ (37 cm).

Assemble solenoid valves, filters, and pressure regulators at the shop, and then bring the valve assemblies to the job site. Dirt should be flushed from the main line before solenoid valves are attached to the pipe. Even with great care, dirt and small rocks get into the pipe during gluing. If valves are attached before the pipe is flushed, then small particles or pebbles can lodge in the solenoid or under the valve diaphragm. If solenoid valves fail to turn off correctly, then this is a sign that debris has become lodged under the diaphragm or in the solenoid. Solenoid valves are designed for easy disassembly and cleaning; however, it is easier to flush the rocks and dirt out in the first place. After the pipe system is completely installed, the entire system should be pressure checked for leaks. Zones should be checked for proper system operation and pressure, and all solenoid valves should be activated before backfilling.

Low pressure, gravity flow drainage pipe may be needed to remove drainage water from the greenhouse area or in a recirculation and recycle system. The grade of the pipe and the trench bottom should be carefully surveyed or the pipe should be installed with a laser-guided machine in order to avoid high points that would develop air pockets that stop the flow of water. The shallower the slope of the pipe, the more likely it is that errors in grade will occur and result in air pockets that prevent flow. The minimum recommended grade for gravity-flow pipelines is 2 m per 1,000 m. This issue is not a concern for pressurized pipelines because high pressure forces air out of the system.

Pipe structural strength and stresses due to overload, sharp objects, and bends in pipe must be considered when selecting the correct backfill material. In general, small diameter, pressurized (Class 125 and heavier) irrigation pipes installed in shallow trenches with 18″ (45 cm) of backfill over the pipe are structurally stable. The soil removed from the trench can be placed back over the pipe. However, large rocks should not be placed back in the trench. Large pipes thin wall pipes, and deeper trenches are more susceptible to structural failure. These pipes should be “shaded” with sand backfill around the pipe. No rocks should be backfilled over the sand because the rocks will migrate downward in the trench over time. Rocks can be removed from backfill material at the site by screening.

Vehicular traffic can damage pipes. Tractors with large tires and uniform load distribution can be driven over lower SDR PVC pipes. However, trucks with small tires, if they are oriented in the same direction as the pipe, can collapse large diameter pipes buried in trenches.

Pressurized irrigation systems in greenhouses generally use Class 125 pipe or greater pressure rating; thus, pipe collapse in in the trench is not a concern.

Changes in flow direction exert force on the pipe and may cause fittings to come apart. For this reason, concrete is poured into the trench around large fittings. Required dimensions for thrust blocks are given in ASAE Standard S376.1. Thrust blocks are especially important for gasketed pipe that does not have a fixed connection.

Steel pipes are subject to corrosion. In order to prevent corrosion, the pipes are often coated with cement or epoxy on the inside and outside of pipes, and they should have cathodic protection to prevent electrons from being transferred from the pipe to the soil. Electrical cells that transfer electrons from pipe to the soil (iron is oxidized) can be microscopic in size or up to several miles long if the pipe is laid in different types of soils. A small investment in cathodic protection can essentially preserve steel pipe indefinitely, whereas ignoring cathodic protection may cause the pipe to degrade within several years. Consult an expert in cathodic protection if corrosion is possible.

In cold regions, the required depth of cover over pipes is based on the depth of soil freezing in winters. In cold areas where it is difficult to make deep trenches through bedrock, pipes may be installed at a shallower depth; however, they must be blown out with air before winter.

One of the concerns with thermoplastic pipeline installation is expansion due to changes in temperature. The coefficient of thermal expansion for PVC pipe is $2.9 * 10^{-5}$ ft/ft/$^0$F (5.2 m/m/$^0$C). The coefficient of thermal expansion for high density polyethylene pipe used in irrigation systems is $1.1 * 10^{-4}$ ft/ft/$^0$F ($1.8 * 10^{-4}$ m/m/$^0$C). Buried PVC pipes do not generally have large temperature fluctuations; however, black polyethylene pipe on the surface expands and contracts. Make sure to allow for expansion and contraction of polyethylene pipes.

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**Example 2.** Polyethylene drip irrigation laterals are laid in a greenhouse. The laterals are 200 m long. Calculate the change in length of the laterals if the minimum winter temperature is –10 $^0$C, and the maximum temperature of laterals exposed to the sun in summer during midday is 50 $^0$C.

$$(200 \text{ m}) (1.8 * 10^{-4} \text{ m/m/}^0\text{C}) (60\ ^0\text{C}) = 2.2 \text{ m.}$$

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White PVC pipe is susceptible to UV degradation. Thus, if the pipe is left in the sun for an extended period (a few months), then the pipe turns brown and is degraded because UV light breaks polymer bonds in the plastic. Although the color changes, UV degradation only occurs in the outer 0.001″, and results in only "slight degradation" of pipe strength (Harvel Plastics Engineering Manual). Painting the outside of pipe prevents UV degradation. Although it is standard practice to use steel pipe for all above ground pipe installations, some people paint PVC pipe with latex or acrylic paint. Installing PVC pipe above ground also exposes the pipe to temperature fluctuations, which weaken the pipe and joints due to expansion and contraction. Painting the pipe with a light colored paint can lower the maximum temperature of the pipe in sunlight and reduce the degree of swelling (Harvel Plastics Engineering Manual). Unlike PVC pipe, polyethylene pipe is not sensitive to UV degradation and is often used for above ground applications.

## Pipe connections

Large diameter polyethylene pipe is fused together by placing the ends together and melting the pipes. The joint is as strong as the pipe. Various types of barbed insert fittings and compression fittings are used to join drip irrigation tubes. These joints can be a source of minor leaks to large fountains in landscape drip irrigation systems; however, they are not generally a source of leaks on large agricultural systems.

PVC joints include glued, threaded, flanged, and gasketed/bell-ended connections. Glued PVC fittings and pipes are connected by softening the outer pipe surfaces with a primer or cement and then fusing the surfaces with cement. Primer is used to soften large diameter PVC prior to cement application while a more active cement (blue glue) can be used to both soften and cement small diameter pipes (< 2″). There are many solvent cement formulations. Higher viscosity and slower drying cements are used for large diameter pipe. Check the label in order to select the right cement for the given application.

The entire fitting must be utilized in order to correctly join pipe. First, a primer is applied to both the fitting and the pipe end over the length of the connection surface (Figure 5). Next, solvent cement (glue) is applied to the same surfaces (Figure 5). The cement application thickness should be just enough so that a small ring of cement is formed just outside the joined fitting. The fitting should be rapidly inserted after gluing. Because fittings are tapered, they tend to push apart so they must be pressed together until the glue solidifies and the fitting remains fully inserted.

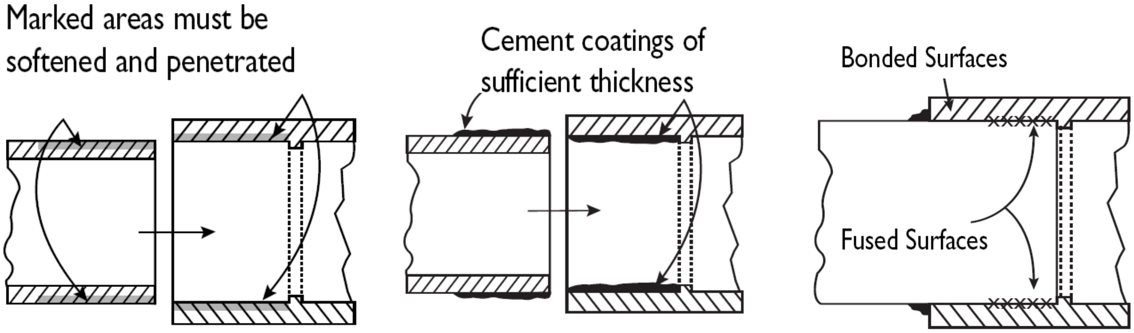

Figure 5. Primer (left) and cement (middle) application, and bonded pipe (right). *Credit Harvel Engineering Guide*.

Pipes should not be moved or pressure tested before the required drying time listed on the glue label. The strength of the connection increases gradually over time.

Gloves should be worn during gluing because pipe glue is a hazardous material. PVC pipe glue is a hallucinogenic: if large pipes are glued in deep trenches, then there is a danger of workers becoming high from the glue fumes. Unless workers are well trained and experienced, a supervisor should verify that workers are correctly gluing fittings and pipes together. Workers, especially those hired off the street, have been known to forget to glue pipe joints or inadequately glue pipe joints. A joint may not come apart during pressure testing but may come apart after the trenches are backfilled. This may result in a major leak that goes unnoticed for a long period and result in excessive water waste. Thus, it is very important to carefully monitor the installation of PVC pipe systems.

PVC pipe can be cut with wood saws or specialized pipe cutters. If pipe is cut with a saw, then the ends of the pipe should be deburred to prevent plastic particles from being a source of plugging over time.

## Pressure regulation

Pressure regulators (Figure 6) may be needed in order to prevent pressure from increasing beyond the rated pressure of the pipe or irrigation components.

Figure 6. Flanged pressure regulator. *Courtesy of Rain Bird Corp.*

A second reason to use a pressure regulator is to guarantee that pressure supplied to an irrigation system remains constant. This is necessary if pressure compensating emitters are not used. Flow rate in nonpressure compensating emitters varies with pressure so fluctuating pressure results in unknown water application rate.

## Hydraulics

One of the worst feelings is to glue a pipe network together, turn the water on, and then realize that the pipe system is too small to carry the required flow rate. The following video reviews this section. The exercise and table numbers correspond with the video.

http://www.youtube.com/watch?v=TtLaTkZ2Fn8&list=UUDVpBHOuUZusjhxyE0xTnoQ&index=3&feature=plcp

Pressure is a form of energy. Pressure is the amount of force per unit area exerted on the walls of a vessel or pipe. Other forms of energy that may be important in pressurized irrigation systems design are elevation and kinetic energy.

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**Exercise 1**. A one cubic foot container of water contains 62.4 pounds of water.

What is the pressure at the bottom of the container in pounds per square foot?

What is the pressure at the bottom of the container in pounds per square inch (PSI)?

What is the pressure in the container at a depth 0.5 ft below the top of the container (PSI)?

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Atmospheric pressure is 34 ft, which is the same as 14.7 PSI or 1 atm. The relationship between length and pressure is 2.31 ft = 1 PSI. Conversely, 1 ft = 0.433 PSI.

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**Exercise 2**. What is the ft of pressure when the pressure is 2 PSI?

What is the ft. of pressure when the pressure is 50 PSI?

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**Exercise 3.** Calculate the pressure in units of feet at the bottom of the container from exercise 1. Use pressure calculated in exercise 1 and convert to ft. with the unit conversion 2.31 ft. = 1 PSI.

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**Exercise 4.** Calculate the pressure (PSI and ft. of head) at the bottom of the swimming pool (at sea level) that is 9 ft. deep.

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There are two types of pressure in pipe systems: static pressure and dynamic pressure. Static pressure is the pressure in a pipe system when water is not flowing. Calculating static pressure is like calculating the pressure at the bottom of a swimming pool; it is just based on the depth below the surface.

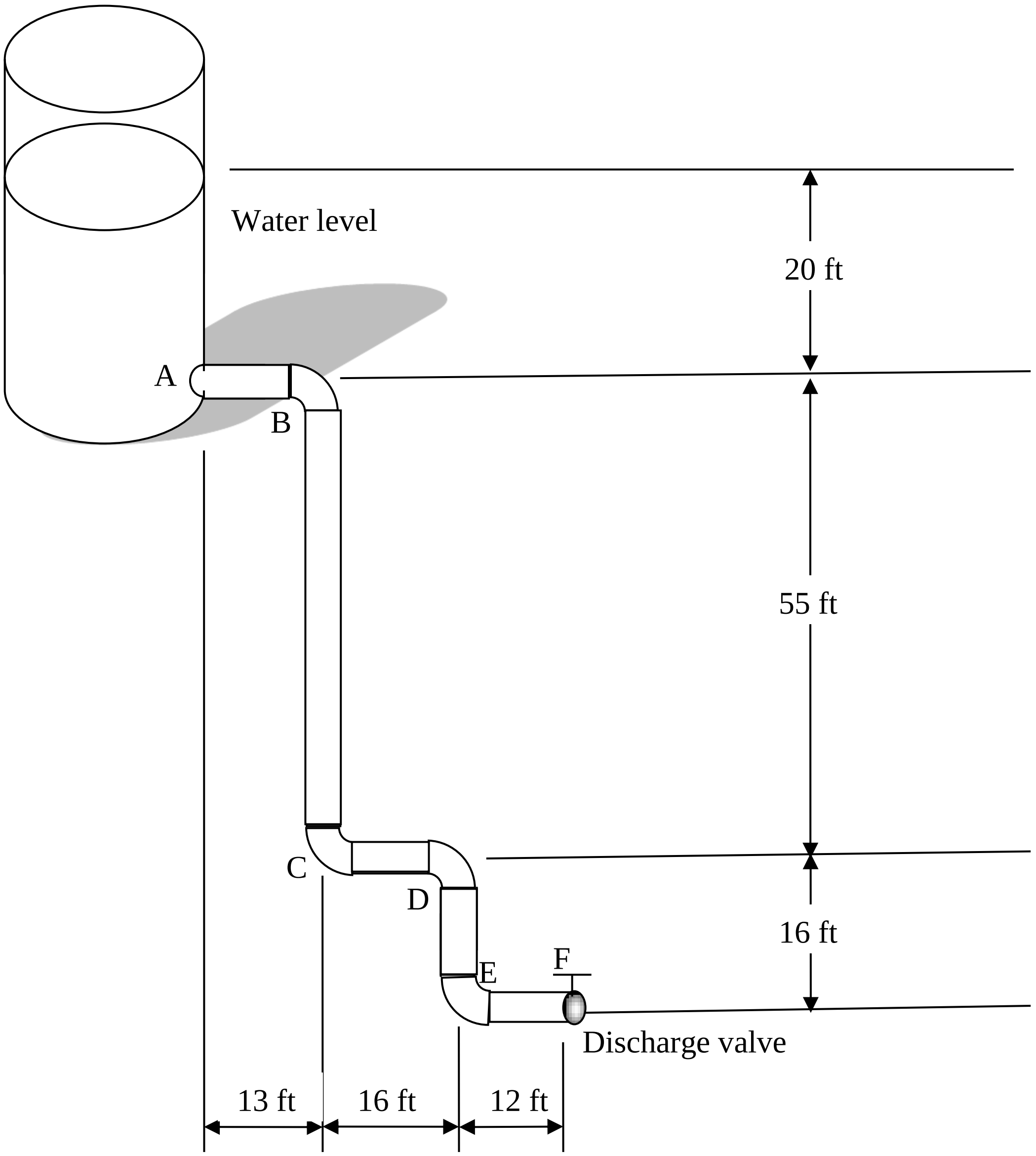


Figure 7. Pipe layout for examples and in-class exercises

Exercise 5. Write down the static pressure in PSI and ft of head at each of the fittings in the table below:

| | PSI | FT |
|---|---|---|
| A | | |
| B | | |
| C | | |
| D | | |
| E | | |
| F | | |

Dynamic pressure is the pressure that is measured when water is flowing in the pipe. It is different from static pressure because energy is lost due to turbulence in the pipe. Water molecules sliding past each other in the turbulent flow and past the pipe walls create friction, which gives off heat energy. The energy is then lost through the walls of the pipe. This energy loss results in loss of pressure.

Equations and tables have been developed to calculate the amount of energy loss in a pipe due to friction as a function of pipe diameter and flow rate. Friction loss expressed as feet of pressure loss per hundred feet of pipe are tabulated in Tables 4- 6 for Class 160, Class 200, and Schedule 40 pipe, respectively. The friction loss at corresponding positions in the tables are different because the wall thickness and inside diameters vary with different classes of pipe.

Table 4. Friction loss in PVC Class 160 pipe (ft/100 ft). C = 150. 73.4 $^{0}$C.

| Flow rate | Nominal pipe diameter (inches) | | | | | | |
|---|---|---|---|---|---|---|---|
| GPM | 1 | 1 1/4 | 1 1/2 | 2 | 2 1/2 | 3 | 4 |
| 1 | 0.0408 | 0.0122 | 0.0063 | 0.0021 | 0.0008 | 0.0003 | 0.0001 |
| 2 | 0.1473 | 0.0439 | 0.0227 | 0.0077 | 0.003 | 0.0012 | 0.0003 |
| 3 | 0.312 | 0.0931 | 0.0481 | 0.0162 | 0.0064 | 0.0025 | 0.0007 |
| 4 | 0.5316 | 0.1585 | 0.082 | 0.0276 | 0.0109 | 0.0042 | 0.0012 |
| 5 | 0.8036 | 0.2397 | 0.124 | 0.0418 | 0.0165 | 0.0063 | 0.0019 |
| 6 | 1.1264 | 0.3359 | 0.1738 | 0.0585 | 0.0231 | 0.0089 | 0.0026 |
| 7 | 1.4985 | 0.4469 | 0.2312 | 0.0779 | 0.0307 | 0.0118 | 0.0035 |
| 8 | 1.9189 | 0.5722 | 0.296 | 0.0997 | 0.0393 | 0.0151 | 0.0044 |
| 9 | 2.3866 | 0.7117 | 0.3682 | 0.1241 | 0.0489 | 0.0188 | 0.0055 |
| 10 | 2.9008 | 0.8651 | 0.4475 | 0.1508 | 0.0594 | 0.0229 | 0.0067 |
| 11 | 3.4607 | 1.0321 | 0.5339 | 0.1799 | 0.0709 | 0.0273 | 0.008 |
| 12 | 4.0658 | 1.2125 | 0.6273 | 0.2113 | 0.0833 | 0.0321 | 0.0094 |
| 13 | 4.7154 | 1.4062 | 0.7275 | 0.2451 | 0.0966 | 0.0372 | 0.0109 |
| 14 | 5.4091 | 1.6131 | 0.8345 | 0.2812 | 0.1108 | 0.0427 | 0.0125 |
| 15 | 6.1463 | 1.8329 | 0.9482 | 0.3195 | 0.1259 | 0.0485 | 0.0142 |
| 16 | 6.9265 | 2.0656 | 1.0686 | 0.36 | 0.1419 | 0.0546 | 0.016 |
| 17 | 7.7495 | 2.311 | 1.1956 | 0.4028 | 0.1588 | 0.0611 | 0.0179 |
| 18 | | 2.5691 | 1.329 | 0.4478 | 0.1765 | 0.0679 | 0.0199 |
| 19 | | 2.8396 | 1.469 | 0.4949 | 0.1951 | 0.0751 | 0.022 |
| 20 | | 3.1226 | 1.6154 | 0.5443 | 0.2145 | 0.0826 | 0.0242 |
| 21 | | 3.4178 | 1.7681 | 0.5957 | 0.2348 | 0.0904 | 0.0265 |
| 22 | | 3.7253 | 1.9272 | 0.6493 | 0.2559 | 0.0985 | 0.0289 |
| 23 | | 4.045 | 2.0926 | 0.705 | 0.2779 | 0.107 | 0.0314 |
| 24 | | 4.3767 | 2.2642 | 0.7628 | 0.3007 | 0.1157 | 0.034 |
| 25 | | 4.7203 | 2.442 | 0.8227 | 0.3243 | 0.1248 | 0.0367 |

**Example 3.** Find the pressure loss in 200 ft of 1 ½ inch Class 160 pipe at a flow rate of 25 GPM.

The friction loss is 2.442 ft/100 ft.

Because the pipe is 200 ft long, the total friction loss in the entire length of pipe is

(2.442 ft/100 ft)( 200 ft) =( 2.442 ft )( 2 ) = 4.884 ft.

Table 5. Friction loss in PVC Class 200 pipe (ft/100 ft). C = 150. 73.4 $^0$C.

| Flow rate | Nominal pipe diameter (inches) | | | | | | |
|---|---|---|---|---|---|---|---|
| GPM | 1 | 1 1/4 | 1 1/2 | 2 | 2 1/2 | 3 | 4 |
| 1 | 0.0403 | 0.0134 | 0.0069 | 0.0023 | 0.0009 | 0.0004 | 0.0001 |
| 2 | 0.1455 | 0.0484 | 0.025 | 0.0084 | 0.0033 | 0.0013 | 0.0004 |
| 3 | 0.3083 | 0.1025 | 0.053 | 0.0179 | 0.0071 | 0.0027 | 0.0008 |
| 4 | 0.5252 | 0.1746 | 0.0902 | 0.0305 | 0.012 | 0.0046 | 0.0014 |
| 5 | 0.7939 | 0.2639 | 0.1364 | 0.0461 | 0.0182 | 0.007 | 0.0021 |
| 6 | 1.1127 | 0.3699 | 0.1912 | 0.0646 | 0.0255 | 0.0098 | 0.0029 |
| 7 | 1.4803 | 0.4921 | 0.2543 | 0.086 | 0.0339 | 0.013 | 0.0038 |
| 8 | 1.8956 | 0.6301 | 0.3257 | 0.1101 | 0.0434 | 0.0167 | 0.0049 |
| 9 | 2.3576 | 0.7837 | 0.405 | 0.1369 | 0.054 | 0.0207 | 0.0061 |
| 10 | 2.8656 | 0.9525 | 0.4923 | 0.1664 | 0.0657 | 0.0252 | 0.0074 |
| 11 | 3.4187 | 1.1364 | 0.5873 | 0.1985 | 0.0784 | 0.0301 | 0.0088 |
| 12 | 4.0165 | 1.3351 | 0.69 | 0.2333 | 0.0921 | 0.0353 | 0.0104 |
| 13 | 4.6582 | 1.5484 | 0.8002 | 0.2705 | 0.1068 | 0.041 | 0.012 |
| 14 | 5.3434 | 1.7762 | 0.918 | 0.3103 | 0.1225 | 0.047 | 0.0138 |
| 15 | 6.0717 | 2.0182 | 1.0431 | 0.3526 | 0.1392 | 0.0534 | 0.0157 |
| 16 | 6.8425 | 2.2745 | 1.1755 | 0.3974 | 0.1568 | 0.0602 | 0.0177 |
| 17 | 7.6554 | 2.5447 | 1.3151 | 0.4446 | 0.1755 | 0.0674 | 0.0198 |
| 18 | | 2.8288 | 1.462 | 0.4942 | 0.1951 | 0.0749 | 0.022 |
| 19 | | 3.1267 | 1.6159 | 0.5463 | 0.2156 | 0.0828 | 0.0243 |
| 20 | | 3.4383 | 1.777 | 0.6007 | 0.2371 | 0.091 | 0.0267 |
| 21 | | 3.7634 | 1.945 | 0.6575 | 0.2595 | 0.0996 | 0.0292 |
| 22 | | 4.102 | 2.12 | 0.7167 | 0.2828 | 0.1086 | 0.0319 |
| 23 | | 4.4539 | 2.3019 | 0.7782 | 0.3071 | 0.1179 | 0.0346 |
| 24 | | 4.8192 | 2.4906 | 0.842 | 0.3323 | 0.1276 | 0.0374 |
| 25 | | 5.1976 | 2.6862 | 0.9081 | 0.3584 | 0.1376 | 0.0404 |

Notice in Table 6 that friction loss is higher than in Tables 4 and 5 at the same flow rate and pipe diameter because Schedule 40 pipe has thicker walls and a smaller pipe diameter.

Table 6. Friction loss in PVC Schedule 40 pipe (ft/ 100 ft). C = 150. 73.4 $^0$C.

| Flow rate | Nominal pipe diameter (inches) | | | | | | |
|---|---|---|---|---|---|---|---|
| GPM | 1 | 1 1/4 | 1 1/2 | 2 | 2 1/2 | 3 | 4 |
| 1 | 0.077 | 0.0202 | 0.0096 | 0.0028 | 0.0012 | 0.0004 | 0.0001 |
| 2 | 0.2778 | 0.0731 | 0.0345 | 0.0102 | 0.0043 | 0.0015 | 0.0004 |
| 3 | 0.5886 | 0.1548 | 0.0731 | 0.0216 | 0.0091 | 0.0032 | 0.0008 |
| 4 | 1.0028 | 0.2637 | 0.1245 | 0.0369 | 0.0155 | 0.0054 | 0.0014 |
| 5 | 1.5159 | 0.3987 | 0.1882 | 0.0557 | 0.0234 | 0.0081 | 0.0022 |
| 6 | 2.1248 | 0.5588 | 0.2637 | 0.0781 | 0.0329 | 0.0114 | 0.003 |
| 7 | 2.8267 | 0.7434 | 0.3509 | 0.1039 | 0.0437 | 0.0152 | 0.004 |
| 8 | 3.6198 | 0.9519 | 0.4493 | 0.1331 | 0.056 | 0.0194 | 0.0052 |
| 9 | 4.502 | 1.1839 | 0.5588 | 0.1655 | 0.0696 | 0.0242 | 0.0064 |
| 10 | 5.472 | 1.439 | 0.6792 | 0.2011 | 0.0846 | 0.0294 | 0.0078 |
| 11 | 6.5282 | 1.7168 | 0.8103 | 0.24 | 0.101 | 0.0351 | 0.0093 |
| 12 | 7.6696 | 2.017 | 0.952 | 0.2819 | 0.1186 | 0.0412 | 0.011 |
| 13 | 8.895 | 2.3392 | 1.1041 | 0.327 | 0.1376 | 0.0478 | 0.0127 |
| 14 | | 2.6833 | 1.2665 | 0.3751 | 0.1578 | 0.0548 | 0.0146 |
| 15 | | 3.049 | 1.4391 | 0.4262 | 0.1793 | 0.0623 | 0.0166 |
| 16 | | 3.4361 | 1.6218 | 0.4803 | 0.2021 | 0.0702 | 0.0187 |
| 17 | | 3.8443 | 1.8145 | 0.5374 | 0.2261 | 0.0785 | 0.0209 |
| 18 | | 4.2736 | 2.0171 | 0.5973 | 0.2514 | 0.0873 | 0.0232 |
| 19 | | 4.7236 | 2.2296 | 0.6603 | 0.2779 | 0.0965 | 0.0257 |
| 20 | | 5.1943 | 2.4517 | 0.726 | 0.3055 | 0.1061 | 0.0282 |
| 21 | | 5.6855 | 2.6836 | 0.7947 | 0.3344 | 0.1161 | 0.0309 |
| 22 | | 6.197 | 2.925 | 0.8662 | 0.3645 | 0.1266 | 0.0337 |
| 23 | | 6.7287 | 3.176 | 0.9405 | 0.3958 | 0.1374 | 0.0366 |
| 24 | | | 3.4364 | 1.0176 | 0.4283 | 0.1487 | 0.0396 |
| 25 | | | 3.7062 | 1.0976 | 0.4619 | 0.1604 | 0.0427 |

Dynamic pressure must be calculated in sequence beginning from a point in the pipe system with known pressure. Dynamic pressure can be calculated from one point to the next in a pipe network as follows:

$$\text{Pressure}_2 = \text{Pressure}_1 + \text{elevation gain} - \text{friction loss}. \qquad (2)$$

where

Pressure$_2$ = downstream pressure, ft,
Pressure$_1$ = upstream (known) pressure, ft,
Elevation gain = Elevation of point 1 over point 2
Friction loss = Friction loss in the pipe between point 1 and point 1

**Example 4.** Calculate the pressure at points, A, B and C in Figure 7 if the flow rate in the pipe is 25 GPM and the pipe is 1 ½ inch Class160 pipe.

From example 3, the friction loss in the pipe is 2.44 ft/100 ft.

The pressure at A is 20 ft since there is no pressure loss in the pipe.

The length of pipe from A to B is 13 ft. Thus, the friction loss in that pipe section is

$$(13 \text{ ft}) (2.44 \text{ ft} / 100 \text{ ft}) = 0.32 \text{ ft}.$$

There is no elevation gain between A and B; thus, the pressure at B is calculated as follows:

$$\text{Pressure}_B = \text{Pressure}_A + \text{elevation gain} - \text{friction loss}.$$

$$\text{Pressure}_B = 20 + 0 - 0.32 = 19.68 \text{ ft}$$

The length of pipe between B and C is 55 ft. Thus, the friction loss between B and C is

$$(55 \text{ ft}) (2.44 \text{ ft} / 100 \text{ ft}) = 1.34 \text{ ft}.$$

The elevation gain is 55 ft; thus, the pressure at C is calculated as follows:

$$\text{Pressure}_C = \text{Pressure}_B + \text{elevation gain} - \text{friction loss}.$$

$$\text{Pressure}_C = 19.68 + 55 - 1.34 = 73.34 \text{ ft}$$

---

**Exercise 6.** The pipe in Figure 7 is 2 inch Class 160 pipe and the flow rate is 22 GPM. Calculate the pressure at all locations in the pipe. Report the pressure in ft.

A

B

C

D

E

F

---

Pipe friction loss in straight pipes, $h_f$, can be calculated with the Hazen-Williams equation rather than tables. The Hazen-Williams equation is valid within the normal ranges of flow velocity and temperature found in irrigation pipelines. You will not use the Hazen-Williams equation in this class. Instead, you will use a spreadsheet that includes the Hazen-Williams equation.

$$h_f = k_1 L \frac{\left(\frac{Q}{C}\right)^{1.85}}{D^{4.87}} \tag{3}$$

where

$k_1$ = conversion factor (Table 7), $1.22 * 10^{10}$,
L = length of the pipe, m of ft,
Q = pipe flow rate, various units,
C = roughness coefficient,
D = diameter, mm,

Table 7. Conversion constants for the Hazen-Williams equation given different combinations of units (from Cuenca, 1989).

| $h_f$ | L | Q | D | $k_1$ |
|---|---|---|---|---|
| m | m | L/sec | mm | $1.22*10^{10}$ |
| m | m | L/hr | mm | 3163 |
| m | m | $m^3$/day | mm | $3.162*10^6$ |
| ft | ft | $ft^3$/sec | ft | 4.73 |
| ft | ft | gpm | in | 10.46 |

The *Pipe Calculator* Excel Workbook includes a spreadsheet labeled *Pipe pressure loss U.S. units* that calculates friction loss based on the Hazen-Williams equation. The C value in the equation is based on pipe wall roughness. In general, the Hazen-Williams equation uses a C value of 140 to 150 for new PVC and polyethylene pipe used in irrigation systems although it decreases for older pipe. Thus, let C = 150 in the third row for calculations in this text.

---

**Example 5.** Calculate the pressure loss in 50 ft of 1 ¼ inch Schedule 40 pipe at a flow rate of 25 GPM with the Pipe *Pressure loss U.S. units* Worksheet. Repeat the calculation for 1 ½ inch pipe. Pressure at the beginning of the pipe is 20 ft and there is a 1 ft elevation gain.

The inside diameter of Schedule 40 1 ¼ inch pipe is 1.38 inches. This can be found in Table MM in the Pipe Calculator program or in the second to the last row in Table 1 in the appendix. Hazen-Williams C = 150.

Numbers are input in the pipe calculator program in the white boxes. Your spreadsheet shows that the friction loss in the pipe is 3.96 ft and the final pressure at the end of the pipe is 17.04 ft.

Note that the velocity in the pipe is 5.96 ft, which is unacceptable because of the threat of water pressure. Thus, you should use a larger diameter pipe. This would also result in a lower pressure loss. The next larger size would be 1.5 inch.

| Hazen-Williams calculation of pressure loss | | |
|---|---|---|
| **Minor + vel. losses Km** | 0 | **Dimensionless** |
| **Flow rate** | 25 | **GPM** |
| **C** | 150 | |
| **Pipe length** | 50 | **ft** |
| **Inside pipe diameter** | 1.38 | **in** |
| **Cross-sectional area** | 0.0104 | **ft2** |
| **Velocity** | 5.36 | **ft/sec** |
| **Pressure loss** | 3.96 | **ft** |
| **starting pressure** | **20** | **ft** |
| **elevation gain** | **1** | **ft** |
| **Final pressure** | **17.04** | **ft** |

## *Hydroponic irrigation systems*

Greenhouses commonly use a hydroponic irrigation system that includes a drip irrigation system with plants grown in rock wool media. Electronic solenoid valves (Figure 1) control flow to drip laterals. Emitters are typically 2 LPH. Spaghetti tubing brings water from drip emitters to plant containers, and plastic stakes fix the tubing to plant containers. Plant containers sit on bags of rock wool. Before placing the plant container on the rock wool bag, the rock wool is wetted in order to prevent the rock wool from sucking the water out of the plant container and killing the plant (Figure 8).

Figure 8. Components of hydroponic irrigation system.

## Greenhouse lateral friction loss

Drip irrigation laterals have a decreasing flow rate along the lateral. Thus, the total friction loss in the pipe is less than if the full flow rate traveled the entire length of the pipe. The rule of thumb is to multiply the friction loss that is calculated for a pipe with no outlets by 0.34 to calculate the friction loss in a drip irrigation lateral. This number is called the Christiansen's F factor

There is addition friction loss caused by the barbed fittings inserted into the drip lateral. There are very complex equations that consider the length of the barbs, etc., but it is easiest to check with the manufacturer regarding the additional friction loss caused by specific fittings.

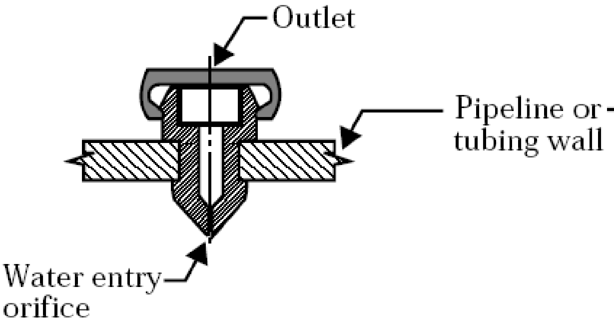
Because of the multiple outlets along a greenhouse drip lateral or submain, you can generally multiply the calculated friction loss with the Hazen-Williams equation by 0.34. Thus, friction loss is only 1/3 of the calculated value.

## Drip emitters and tubing

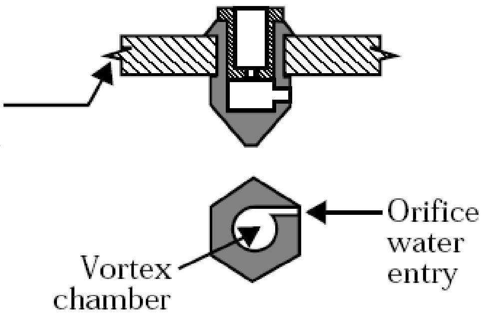
Emitters (Figure 5) are classified as laminar, turbulent, orifice, vortex, partially pressure compensating, or pressure compensating. Turbulent emitters dissipate energy in turbulent eddies that form in tortuous paths within the emitter. Orifice emitters dissipate energy in a single orifice; thus, the opening is extremely small and these emitters are very prone to plugging. The flow varies with the square root of pressure. Vortex emitters are similar to orifice emitters except that the water passes through one turbulent eddy before exiting the orifice. As with orifice emitters, vortex emitters have a very small orifice and are prone to plugging. Laminar flow emitters (long path) have a long straight flow path and energy is dissipated in the laminar flow. Flow rate varies directly with pressure. The flow path diameter is larger than the orifice emitters, but is still small and prone to plugging. The flow path may be narrow "spaghetti tubing" or the path may be a spiral flow path around a cylindrical emitter. One of the new designs that resists plugging in organic greenhouse systems is large diameter spaghetti tubing. It is so large that particulates can be blown out of the tube by mouth.

Turbulent flow emitters are designed so that vortices are set up in the corners as the flow direction changes in the tortuous path (Figure 9, lower left). One advantage of turbulent flow emitters is that they have a larger diameter flow path because energy is dissipated in turbulent eddies rather than in small diameter paths or orifices. Thus, they are less likely to plug than laminar flow or orifice emitters.

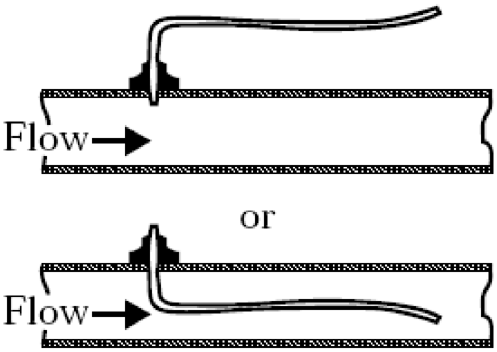
Pressure compensating emitters are normally used in greenhouse hydroponic systems. They have no change in flow rate over a wide range of pressures. Pressure compensating emitters are even less likely to plug than turbulent emitters. Pressure compensating emitters are normally used in greenhouses and are shown in Figure 8. Pressure compensating emitters are normally used in greenhouse hydroponic systems. The reason they are used is that greenhouses have very high value crops and paying a little extra for the pressure compensation (uniform flow) is justified by the value of the crop and the precision of the irrigation application.



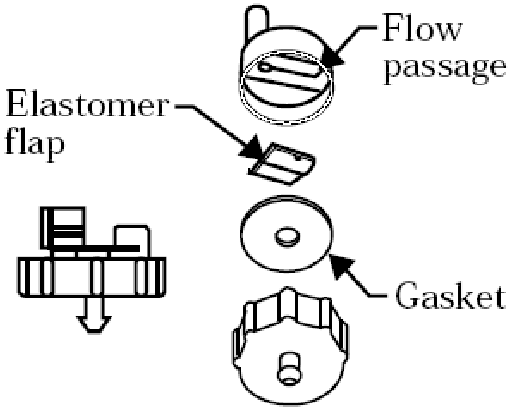
**Orifice emitter**



**Orifice-vortex emitter**



**Long path emitter small tube**



Pseudo “pressure compensating”

**Groove and flap short path emitter**

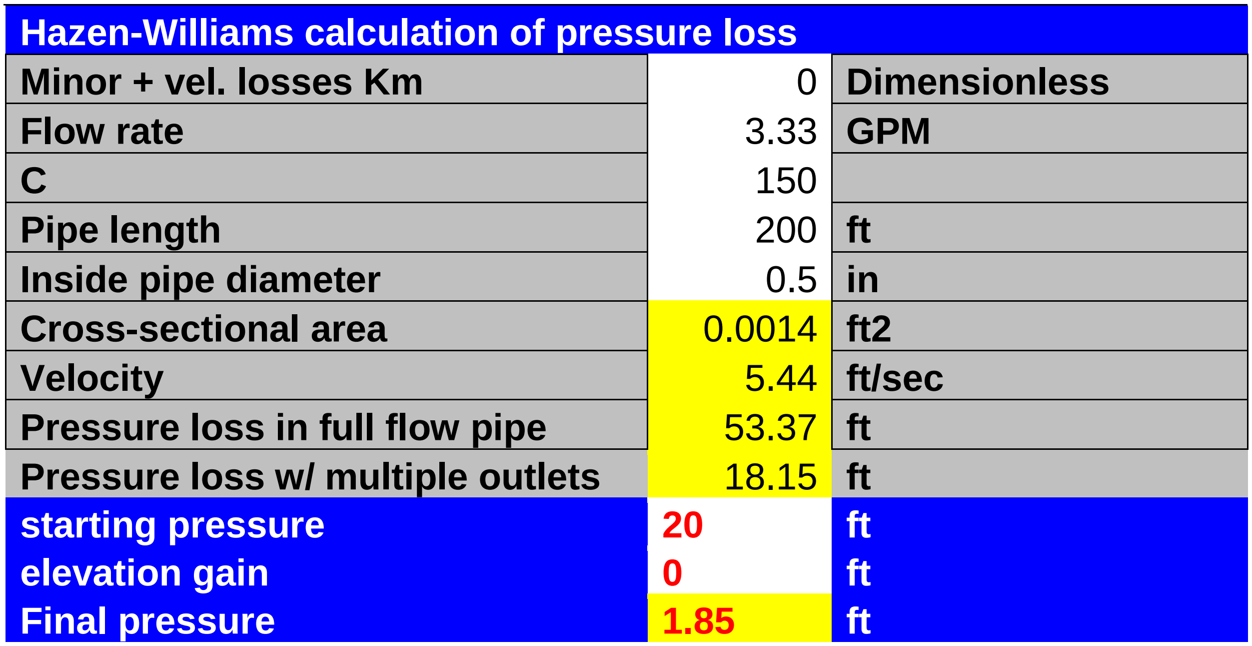
**Turbulent flow path with flushing diaphragm**

*Roberts Irrigation.*

Figure 9. Drip irrigation emitters. *Credit Natural Resource Conservation Service, NEH.*

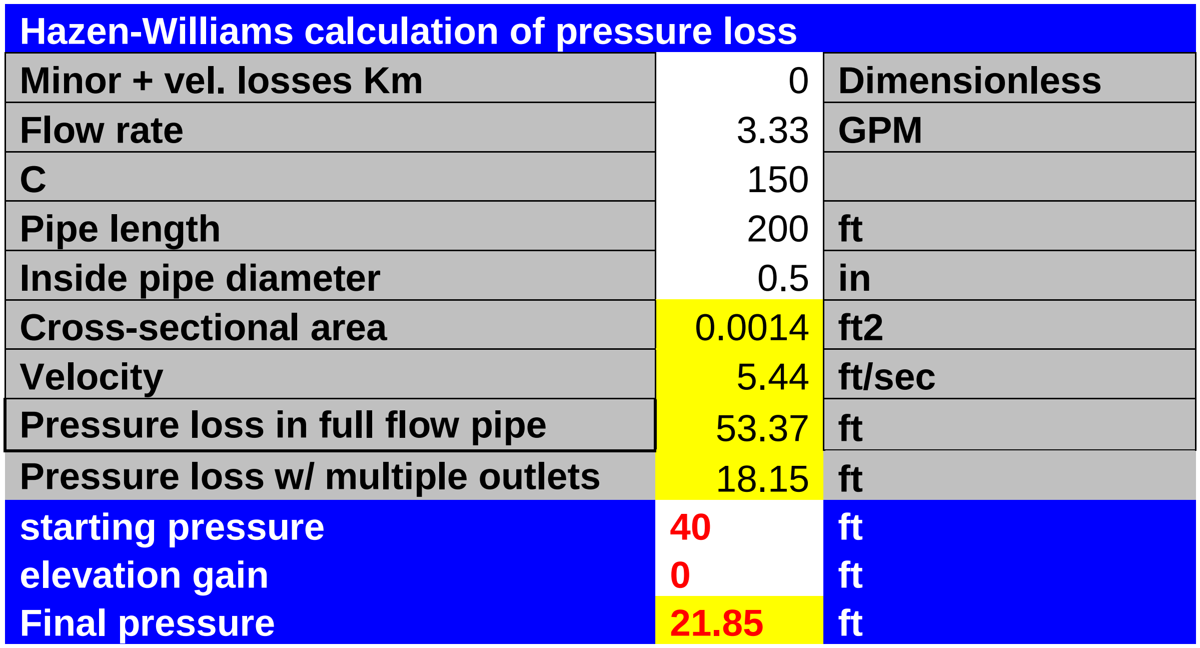
**Example 6.** Calculate head loss and flow variation in a 200 ft length of 12 mm ID drip tubing (0.5 inch). There is one emitter per foot and each emitter has a flow rate of 1 GPH (gallons per hour). The minimum acceptable dripper pressure is 20 ft. The inlet pressure is 30 ft. Make sure the final pressure is acceptable.

There is one emitter per foot and there are 200 emitters. Thus, the total flow rate is 200 GPH. This is the same as 200 GPH / 60 = 3.33 GPM (gallons per minute)



| Hazen-Williams calculation of pressure loss | | |
|---|---|---|
| Minor + vel. losses Km | 0 | Dimensionless |
| Flow rate | 3.33 | GPM |
| C | 150 | |
| Pipe length | 200 | ft |
| Inside pipe diameter | 0.5 | in |
| Cross-sectional area | 0.0014 | ft2 |
| Velocity | 5.44 | ft/sec |
| Pressure loss in full flow pipe | 53.37 | ft |
| Pressure loss w/ multiple outlets | 18.15 | ft |
| starting pressure | 20 | ft |
| elevation gain | 0 | ft |
| Final pressure | 1.85 | ft |

The final pressure is 1.85, which is below the minimum acceptable pressure. Increase the inlet pressure to 40 ft in order to have the minimum acceptable pressure of 20 ft at the end.



| Hazen-Williams calculation of pressure loss | | |
|---|---|---|
| Minor + vel. losses Km | 0 | Dimensionless |
| Flow rate | 3.33 | GPM |
| C | 150 | |
| Pipe length | 200 | ft |
| Inside pipe diameter | 0.5 | in |
| Cross-sectional area | 0.0014 | ft2 |
| Velocity | 5.44 | ft/sec |
| Pressure loss in full flow pipe | 53.37 | ft |
| Pressure loss w/ multiple outlets | 18.15 | ft |
| starting pressure | 40 | ft |
| elevation gain | 0 | ft |
| Final pressure | 21.85 | ft |

## *Irrigation system maintenance*

Reliability of the irrigation system important in hydroponic systems because water-holding capacity of the soil or rock wool media is very low: plant death occurs quickly. Perform regular maintenance to ensure reliable operation of the irrigation system. The following procedures prevent degradation of drip irrigation systems:

1. Injection of biocides
2. Injection of acids to prevent precipitation of salts
3. Flushing drip laterals on a regular basis
4. Filtration
5. Checking pump station and drip laterals for correct pressure
6. Checking uniformity and flow rates of drip emitters

Bacteria can grow within drip emitters and the bacteria or the slime produced by the bacteria can plug up the small openings in drip emitters. Hydroponic drip irrigation systems are especially susceptible to bacterial growth because of high nutrient concentrations in irrigation water. Biocides such as chlorine kill bacteria. However, greenhouse growers do not inject chlorine because chlorine harms plants; in addition, chlorine gas (toxic) escapes into the greenhouse air. Other disinfection methods include hydrogen peroxide (a weak biocide), UV light, and ozonation. The best solution in the greenhouse is to use water that does not require a biocide.

Water quality determines the need for a biocide. Water from wells that are deeper than 200 ft will probably not have appreciable amounts of bacteria or organic carbon, and chlorination is not necessary. The well water must not contact the atmosphere; holding well water in an open tank between the well and the irrigation system introduces light and bacteria into the water. Water from a municipal source is normally chlorinated and has low organic matter and bacterial concentrations. However, water from an open water system such as a river or canal requires disinfection.

Because greenhouse growers normally lower pH to the range of 5.5 to 6.5 in order to make nutrients more available to the plant, calcium carbonate deposition is normally not a problem. The most common acid in greenhouses is phosphoric acid, but nitric acid and sulfuric acid are also used. Nitric acid is most expensive, but is appropriate for nitrogen tolerant tomato varieties. Phosphoric acid has the added benefit of increasing the phosphorous – potassium ratio.

Filtration prevents particulate clogging of emitters. For water that is high in organic matter or particulate matter, sand filters are required. Otherwise, screen filters are acceptable. Sand filters are expensive and add an additional 10 PSI pressure (energy) to the pump requirement. Organic growers should use sand filters due to the higher possibility of microbial growth in irrigation lines.

It may be necessary to flush drip laterals regularly (weekly or monthly) in order to remove sediment that builds up in laterals.

## *Irrigation scheduling*

Many growers schedule irrigations based on total energy accumulation measured by a pyranometer placed outside the greenhouse. A typical (inexpensive) pyranometer measures total electromagnetic radiation energy between 400 and 1,100 nanometers, approximately 90 % of total solar radiation. A typical guideline for growers would be one irrigation per 80 J/cm$^2$ of energy that reaches the outside of the greenhouse. Growers often decrease the frequency of irrigation in order to increase salinity in the growing media, increase plant stress, increase fruit sugar content, or increase reproductive growth. However, avoid causing excess stress to the plant. Increase frequency of irrigation in midday because higher evapotranspiration leads to greater plant stress, and plants need more water and oxygen. There is normally no irrigation for the first 1 ½ to 2 hours after sunrise and the last 1 ½ to 2 hours before sunset. When heat pipes are used during the night, then 2 irrigations during the night are also recommended.

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**Example 7.** Develop an irrigation schedule based on the solar radiation data shown in Figure 10, a typical winter day in Tucson.

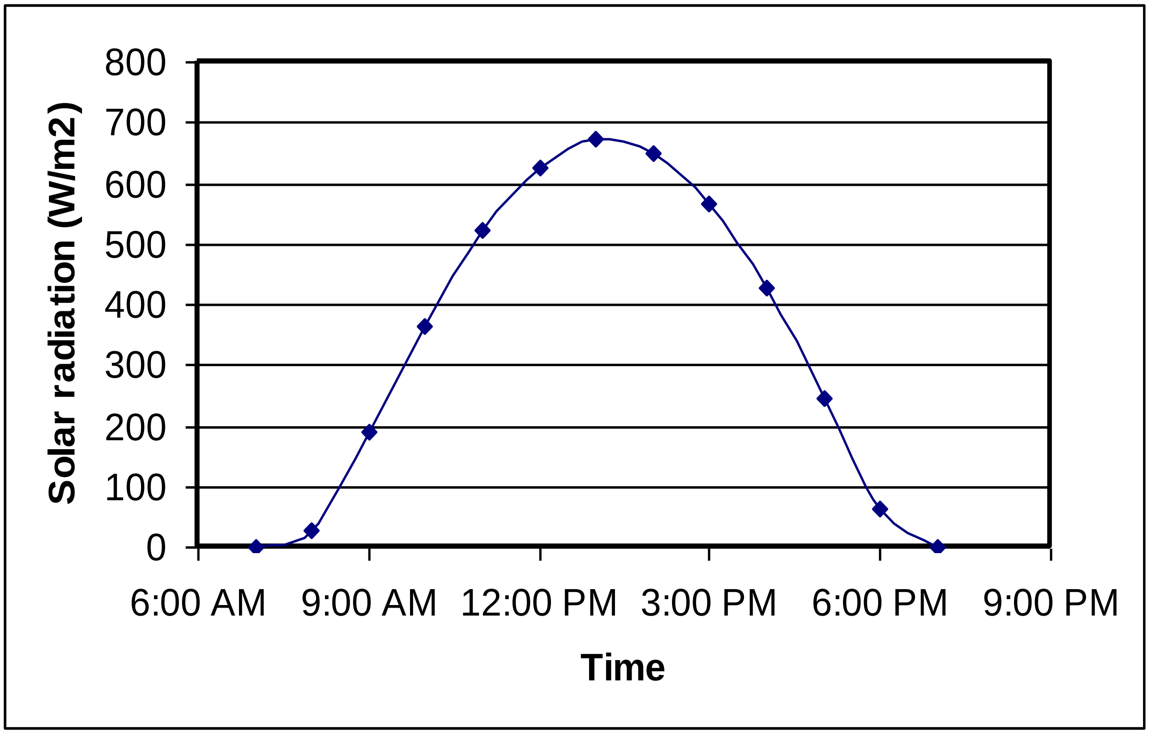

Figure 10. Solar radiation intensity during winter day in Tucson, Arizona.

Energy (J/m$^2$) that reaches the greenhouse during each one hour period is the product of power (W/m$^2$) and time (3,600 seconds). Calculate the number of irrigations per hour by dividing the energy that reaches the greenhouse by 80 J/cm$^2$. Results are shown in Table 8.

Table 8. Solar energy and irrigation schedule during winter in Tucson.

| Time | Average power ($W/m^2$) reaching greenhouse | Energy ($J/cm^2$) reaching greenhouse | Number of irrigations |
|---|---|---|---|
| 6:00 -7:00 AM | 0 | 0 | |
| 8:00 AM | 29 | 10.4 | |
| 9:00 AM | 190 | 68.4 | 1 |
| 10:00 AM | 365 | 132 | 2 |
| 11:00 AM | 521 | 188 | 3 |
| 12:00 PM | 626 | 225 | 3 |
| 1:00 PM | 671 | 242 | 3 |
| 2:00 PM | 650 | 234 | 3 |
| 3:00 PM | 568 | 204 | 3 |
| 4:00 PM | 427 | 154 | 2 |
| 5:00 PM | 247 | 88.9 | |
| 6:00 PM | 62 | 22.2 | |
| 10:00 PM | | | 1 |
| 2:00 PM | | | 1 |

The plant requires adequate oxygen in the growing media. Application of 100 ml per emitter per irrigation maximizes the intake of oxygen from the air into the growing media. In addition, dissolved oxygen is contained in the irrigation water. The minimum acceptable level of dissolved oxygen in irrigation water is 6 mg/L. Recycled water and warm water often has less oxygen than water from wells, and oxygenation or cooling of the water may be necessary.

If 100 ml is applied per emitter (per plant) each time the irrigation system is turned on, then A 2 LPH emitter is left on for (100 ml) / (2,000 ml/hr) = 3 minutes. With high solar radiation in the summer in Arizona, the irrigation system may run as often as once every 10 minutes. With a 1-2 minute solenoid valve opening time, a maximum of two separate zones are possible without risk of plant stress: (3) (2 minutes) watering for each zone = 6 minutes.+ valve cycle time.

Salt accumulation in the growing media stresses the plant. Leaching (overdrain) removes salts from the growing medium. Drip irrigated vegetable crops should have approximately 1/3 overdrain percentage. Overdrain depths vary based on plant type, plant maturity, time of day, and season of the year. Outflow/inflow is the overdrain percentage.

Measure outflow (overdrain) by placing a container below a small trough (Figure 11). Measure inflow by inserting the outlet of one extra emitter into a container. The overdrain percentage is the drainage percent divided by the inflow. Thus, if the inflow is 1 gallons per day, and overflow is 1/3 gallons per day, then the overdrain fraction is 1/3 (0.33 = 33%).

Irrigation to field agriculture crops is often expressed as an average depth of water applied per day over the field area. This can also be done in greenhouse irrigation by dividing the volume applied by each emitter per day by the area watered by each emitter or applied to each plant.

Typical tomato plant spacing is 0.2 m along the row and 1.5 m between rows. Thus, area per plant is approximately (0.2 m) (1.5 m) = 0.3 $m^2$/plant.

---

**Example 8.** Calculate depth applied per day in the greenhouse. The volume applied per plant is 2 Liters, which is the same as 0.002 $m^3$. The plant spacing is 0.3 $m^2$

$$\text{Volume / Area} = 0.002\ m^3/\text{day} / 0.3\ m^2 = 0.006\ m/\text{day} = 6\ mm/\text{day}$$

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Figure 11. Measuring overdrain.

# Appendix A

Table A-1. Nominal diameters, wall thickness, and inside diameters for PVC irrigation pipe (United States units: inches); the Schedule 40 dimensions are Schedule 40 steel pipe dimensions.

| | Spec | ¾″ | 1″ | 1¼″ | 1½″ | 2″ | 2½″ | 3″ | 4″ | 6″ | 8″ | 10″ | 12″ |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Type | OD (in) | 1.050 | 1.315 | 1.660 | 1.90 | 2.375 | 2.875 | 3.500 | 4.500 | 6.625 | 8.625 | 10.75 | 12.75 |
| Cl 100 | Wall (in) | | | | | | | 0.085 | 0.110 | 0.162 | 0.210 | 0.262 | 0.311 |
| Cl 125 | | | | 0.051 | 0.058 | 0.073 | 0.088 | 0.108 | 0.138 | 0.204 | 0.265 | 0.331 | 0.392 |
| Cl 160 | | | | 0.064 | 0.073 | 0.091 | 0.110 | 0.135 | 0.173 | 0.255 | 0.332 | 0.413 | 0.490 |
| Cl 200 | | 0.060 | 0.063 | 0.079 | 0.090 | 0.113 | 0.137 | 0.167 | 0.214 | 0.316 | 0.410 | 0.511 | 0.606 |
| SC 40 | | 0.113 | 0.133 | 0.140 | 0.145 | 0.154 | 0.203 | 0.216 | 0.237 | 0.280 | 0.322 | 0.365 | 0.406 |
| Cl 100 | ID (in) | | | | | | | 3.33 | 4.28 | 6.301 | 8.205 | 10.226 | 12.128 |
| Cl 125 | | | | 1.56 | 1.78 | 2.23 | 2.70 | 3.284 | 4.224 | 6.217 | 8.095 | 10.088 | 11.966 |
| Cl 160 | | | | 1.53 | 1.75 | 2.193 | 2.655 | 3.23 | 4.154 | 6.115 | 7.961 | 9.924 | 11.77 |
| Cl 200 | | 0.93 | 1.189 | 1.50 | 1.72 | 2.149 | 2.601 | 3.166 | 4.072 | 5.993 | 7.805 | 9.728 | 11.538 |
| SC 40 | | 0.824 | 1.049 | 1.38 | 1.61 | 2.067 | 2.469 | 3.068 | 4.026 | 6.065 | 7.981 | 10.02 | 11.938 |
| SC 40 | PSI | 480 | 450 | 370 | 330 | 280 | 300 | 260 | 220 | 180 | 160 | 140 | 130 |

Table A-2. Nominal diameters, wall thickness, and inside diameters for PVC pipe (metric: mm); Schedule 40 dimensions are Schedule 40 steel pipe dimensions.

| | Spec | 18 | 25 | 31 | 37 | 50 | 62 | 75 | 100 | 150 | 200 | 250 | 300 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| kPa rating | OD (mm) | 26.7 | 33.4 | 42.2 | 48.3 | 60.3 | 73.0 | 88.9 | 114.3 | 168.3 | 219.1 | 273.1 | 323.9 |
| 689 | Wall (mm) | | | | | | | 2.16 | 2.79 | 4.11 | 5.33 | 6.65 | 7.90 |
| 862 | | | | 1.30 | 1.49 | 1.86 | 2.25 | 2.74 | 3.51 | 5.18 | 6.73 | 8.41 | 9.96 |
| 1103 | | | | 1.63 | 1.85 | 2.31 | 2.79 | 3.43 | 4.39 | 6.48 | 8.43 | 10.49 | 12.45 |
| 1379 | | 1.52 | 1.60 | 2.01 | 2.29 | 2.87 | 3.48 | 4.24 | 5.44 | 8.03 | 10.41 | 12.98 | 15.39 |
| SCH40 | | 2.87 | 3.38 | 3.56 | 3.68 | 3.91 | 5.16 | 5.49 | 6.02 | 7.11 | 8.18 | 9.27 | 10.31 |
| 689 | ID (mm) | | | | | | | 84.6 | 108.7 | 160.0 | 208.4 | 259.7 | 308.1 |
| 862 | | | | 39.6 | 45.3 | 56.6 | 68.5 | 83.4 | 107.3 | 157.9 | 205.6 | 256.2 | 303.9 |
| 1103 | | | | 38.9 | 44.6 | 55.7 | 67.4 | 82.0 | 105.5 | 155.3 | 202.2 | 252.1 | 299.0 |
| 1379 | | 23.6 | 30.2 | 38.2 | 43.7 | 54.6 | 66.1 | 80.4 | 103.4 | 152.2 | 198.2 | 247.1 | 293.1 |
| SCH40 | | 20.9 | 26.6 | 35.1 | 40.9 | 52.5 | 62.7 | 77.9 | 102.3 | 154.1 | 202.7 | 254.5 | 303.2 |
| SCH40 | kPa | 3360 | 3150 | 2590 | 2310 | 1960 | 2100 | 1820 | 1540 | 1260 | 1120 | 980 | 900 |

Table A-3. Large diameter PVC and steel Schedule 40 pipe dimensions.

| United States units | | | | | | Metric units | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Nominal diameter (in) | OD (in) | Wall thickness (in) | ID (in) | Rating (PSI) | DR | Nominal diameter (mm) | OD (mm) | Wall thickness (mm) | ID (mm) | rating (kPa) |
| 14 | 14 | 0.437 | 13.126 | 130 | 32 | 350 | 356 | 11.1 | 333 | 900 |
| 15 | 15 | 0.469 | 14.062 | 130 | 32 | 375 | 381 | 11.9 | 357 | 900 |
| 16 | 16 | 0.5 | 15 | 130 | 32 | 400 | 406 | 12.7 | 381 | 900 |
| 18 | 18 | 0.562 | 16.876 | 130 | 32 | 450 | 457 | 14.3 | 429 | 900 |
| 20 | 20 | 0.593 | 18.814 | 120 | 34 | 500 | 508 | 15.1 | 478 | 830 |
| 21 | 21 | 0.617 | 19.766 | 120 | 34 | 525 | 533 | 15.7 | 502 | 830 |
| 24 | 24 | 0.687 | 22.626 | 120 | 35 | 600 | 610 | 17.4 | 575 | 830 |

Table A-4. Air vent and vacuum relief valve standards (after Cuenca, 1989).

| High pressure systems<br>Pipe diameter | | Valve threaded connection diameter | |
|---|---|---|---|
| ≤ 102 mm | ( ≤ 4″) | 13 mm | (0.5″) |
| 125 - 200 mm | ( 5 - 8″) | 25 mm | (1″) |
| 250 - 500 mm | ( 10 - 20″) | 51 mm | (2″) |
| ≥ 525 mm | ( ≥ 21″) | 0.1 * pipe diameter | |
| **Low pressure systems<br>Pipe diameter** | | **Valve threaded connection diameter** | |
| ≤ 150 mm | ( ≤ 6″) | 51 mm | (2″) |
| 200 - 250 mm | ( 8 - 10″) | 76 mm | (3″) |
| ≥ 300 mm | ( ≥ 12″) | 102 mm | (4″) |