Keeping Hot Water Hot

A designer explains the fundamentals to designing a hot water recirculation system.

by Harold Olsen

It is very frustrating to wait for hot water to arrive for your use. Perhaps you kick the wall, curse the lavatory, or, as I do, brush your teeth first and then shave when hot water is available. While this is a bothersome problem in a private residence, a lack of hot water in a public building or apartment house may be indicative of or cause more serious problems, such as

- an improperly sized water heater;
- unrealistic energy, water, and wastewater charges;
- problems with mixing valves; and
- loss of customers or tenants.

See Table 1 for some estimates of the amount of water lost in a typical home each year. You also can calculate the gallon losses for a project by utilizing the following calculation:

$$\text{Time delay (min)} = \frac{\text{Gallons/Foot} \times \text{Length (ft)}}{\text{Fixture flow rate (gal/min)}}$$

Some codes require a circulating line if the hot water supply is more than 100 feet, and others say 50 feet. Most experienced designers use a circulating line for any hot water supply more than 25 feet. Many designers use 10 seconds as a maximum, 11–30 seconds as acceptable for special situations, and more than 31 seconds as unacceptable anywhere.

Water heater selection is based on the maximum anticipated use in one hour; however, the water drawn is in gallons per minute (gpm). If the gpm flow rate exceeds the water heater delivery rate (in gpm), the water heater can no longer maintain the temperature. For example, if the water heater has a design delivery rate of 180 gallons per hour and you draw more than 3 gpm over an extended period, the water heater cannot keep up the aquastat design setting.

Table 1 Estimates of amount of water wasted in a typical home each year

Pipe Type	Hot Water Supply Length, ft	Pipe Volume, gal	Number of Times Water Used Daily	Daily Water Volume Wasted, gal	Annual Water Volume Wasted, gal
½-in. copper type L	100	2.7	10	27	9,855
½-in. copper type L	150	3.4	10	34	12,410
½-in. copper type L	200	4.5	10	45.3	16,534.5
½-in. copper type L	250	5.7	10	56.6	20,659
½-in. copper type L	300	6.8	10	67.9	24,783.5
¾-in. copper type L	100	5.0	10	50.3	18,359.5
¾-in. copper type L	150	7.5	10	75.4	27,521
¾-in. copper type L	200	10.5	10	105	38,325
¾-in. copper type L	250	12.6	10	126	45,990
¾-in. copper type L	300	15.1	10	151	55,115

Source: "Hot Water Recirculation Saves Water and Money," *Wisconsin Perspective,* January/February 2002

One means of sizing a tank-type water heater is selecting it on a 70 percent availability of the storage; however, this is with an approximately 30°F storage temperature drop.

You can calculate this for your situation. For example, assume a standard gas-fired water heater set at 140°F (burner off), 135°F (burner on), a 100-gallon storage tank, and 180-gallon-per-hour (gph) recovery 40°F to 140°F ($\Delta T = 100°F$). (Assumes cold water comes in at 40°F.) You are going to draw 70 gallons in seven minutes (10 gpm). The tank temperature calculation is as follows:

$$\frac{\text{Hot water in storage} + \text{Water heater recovery} + \text{Cold water}}{100}$$

Thus, 30 gallons at 140°F + 3 gpm × 7 minutes × 140°F + [70 - (3 × 7)] × 40/100 = 91°F tank water temperature.

See Table 2 for desired hot water temperatures, which may be modified as required by codes or specific cases. A properly designed and installed hot water system will provide hot water to all fixtures in a few seconds as well as provide additional hot water storage (see Tables 3, 4, and 5).

HOT WATER CIRCULATING SYSTEM ARRANGEMENTS

There are many types of system arrangements, but they all are alterations or combinations of the three arrangements depicted in Figures 1, 2, and 3.

Each arrangement is for one common hot water supply temperature. In some cases, the building may be zoned vertically (a group of floors per zone) or may have several wings with more than one hot water supply main and circulating system. The mixing valves usually require a separate pumped system (on the mixing valve discharge side also).

Alternatives exist in the form of self-regulating heat tapes or point-of-use water heaters (these might be of value for a remote location or odd-time use).

HOT WATER PIPING AND PIPE ACCESSORIES

The type of pipe used is usually the same type as is used for the hot water return line, which is probably steel, PVC, or copper,

Table 2 Typical delivered hot water temperatures for plumbing fixtures and equipment

Use	Temp. (°F)
Lavatory	105
Showers and tubs	110
Commercial and institutional laundry	140–180
Residential dishwashing and laundry	140
Commercial spray type dishwashing (as required by the NSF):	
Single or multiple tank hood or rack type: Wash	150
Final rinse	180–195
Single tank conveyor type: Wash	160
Final rinse	180–195
Single tank rack or door type:	
Single temperature wash and rinse	165
Chemical sanitizing glassware: Wash	140
Rinse	75

Note: Be aware that temperatures, as dictated by codes, owners, equipment manufacturers, or regulatory agencies, will occasionally differ from those shown.

Source: *Domestic Water Heating Design Manual,* ASPE

Table 3 Approximate fixture and appliance water flow rates

Fittings	Maximum Flow Rates[a] GPM	Maximum Flow Rates[a] L/Sec
Lavatory faucet	2.0	1.3
Public non-metering	0.5	0.03
Public metering	0.25 gal/cycle	0.946 L/cycle
Sink faucet	2.5	0.16
Shower head	2.5	0.16
Bathtub faucets		
Single-handle	2.4 minimum	0.15 minimum
Two-handle	4.0 minimum	0.25 minimum
Service sink faucet	4.0 minimum	0.25 minimum
Laundry tray faucet	4.0 minimum	0.25 minimum
Residential dishwasher	1.87 aver	0.12 aver
Residential washing machine	7.5 aver	0.47 aver

[a] Unless otherwise noted.

Source: *Domestic Water Heating Design Manual,* ASPE

Table 4 Water contents and weight of tube or piping per linear foot

Nominal Diameter (in.)[a]	Copper Pipe Type L Water (gal/ft)	Copper Pipe Type L Wgt. (lb/ft)	Copper Pipe Type M Water (gal/ft)	Copper Pipe Type M Wgt. (lb/ft)	Steel Pipe Schedule 40 Water (gal/ft)	Steel Pipe Schedule 40 Wgt. (lb/ft)	CPVC Pipe Schedule 40 Water (gal/ft)	CPVC Pipe Schedule 40 Wgt. (lb/ft)
½	0.012	0.285	0.013	0.204	0.016	0.860	0.016	0.210
¾	0.025	0.445	0.027	0.328	0.028	1.140	0.028	0.290
1	0.043	0.655	0.045	0.465	0.045	1.680	0.045	0.420
1¼	0.065	0.884	0.068	0.682	0.077	2.280	0.078	0.590
1½	0.093	1.14	0.100	0.940	0.106	2.720	0.106	0.710

[a]Pipe sizes are indicated for mild steel pipe sizing.

Source: *Domestic Water Heating Design Manual,* ASPE

Table 5 Approximate time required to get hot water to a fixture

Fixture Flow Rate (gpm) / Piping Length (ft) Copper		0.5 / 10	0.5 / 25	1.5 / 10	1.5 / 25	2.5 / 10	2.5 / 25	4.0 / 10	4.0 / 25
Pipe	½ in.	25	63[a]	8	21	5	13	3	8
	¾ in.	48[a]	119[a]	16	40[a]	10	24	6	15
Steel Pipe Sched. 40	½ in.	63[a]	157[a]	21	52[a]	13	31[a]	8	20
	¾ in.	91[a]	228[a]	30	76[a]	18	46[a]	11	28
CPVC Pipe Sched. 40	½ in.	64[a]	159[a]	21	53[a]	13	32[a]	8	20
	¾ in.	95[a]	238[a]	32	79[a]	19	48[a]	12	30

(Delivery Time (sec))

Note: Table based on various fixture flow rates, piping materials, and dead-end branch lengths. Calculations are based on the amount of heat required to heat the piping, the water in the piping, and the heat loss from the piping. Based on water temperature of 140°F and an air temperture of 70°F.

[a] Delays longer than 30 sec are not acceptable.

Source: *Domestic Water Heating Design Manual,* ASPE

unless for a high-purity fluid, in which case it might be Kynar or stainless steel. The designer must be aware of the temperature and pressure limitations of the material.

One frequently overlooked item is the manufacturer's suggested maximum velocity for hot water piping. This can be confusing because many codes talk about a maximum velocity of 8 feet per second (fps) for water piping. This velocity can create noise and potential water hammer in many types of piping system. In some cases, such as copper, it can cause corrosion. The Copper Development Association recommends a maximum of 4–5 fps for hot water lines less than 140°F.

Figure 1 Upfeed low-rise hot water system with heater at bottom of system

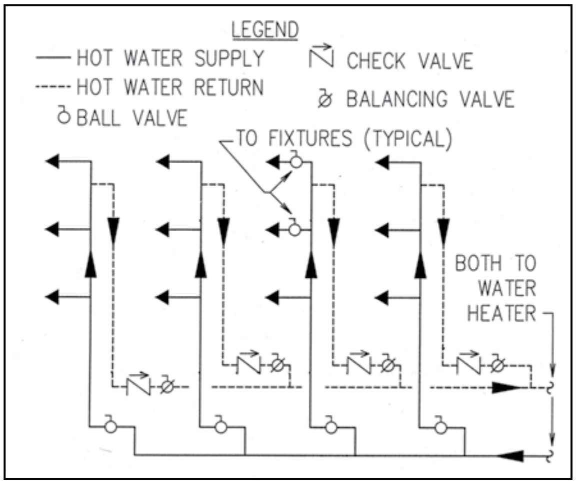


Figure 2 Upfeed hot water system with heater at bottom of system

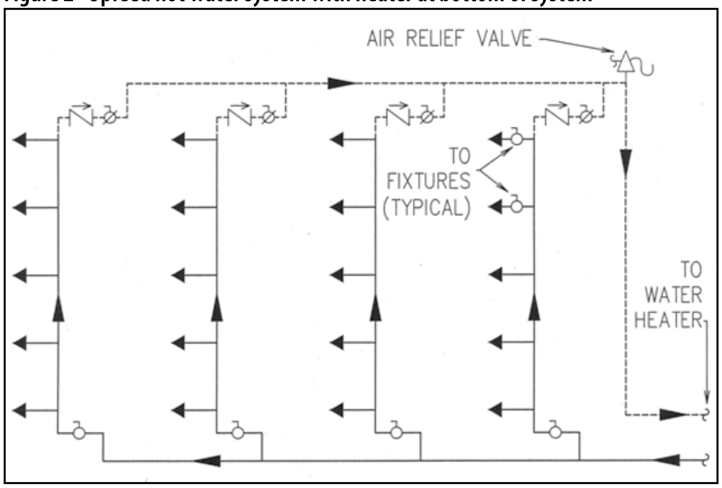
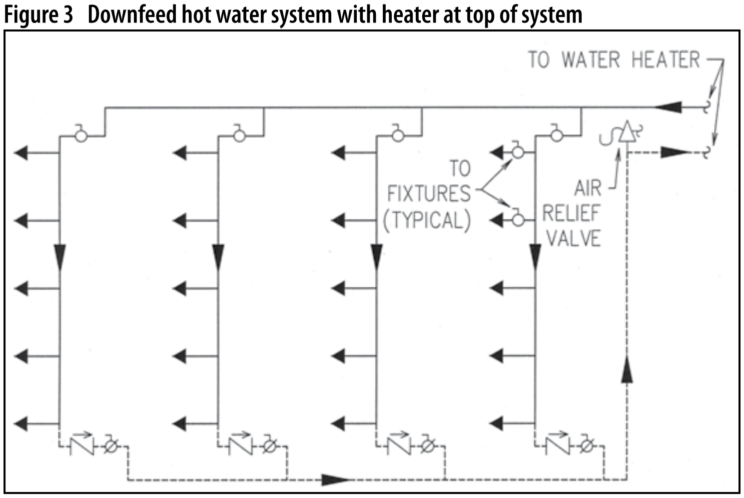


Figure 3 Downfeed hot water system with heater at top of system



Note the suggested valving in Figures 1, 2, and 3. Valves are generally bronze, stainless steel, or plastic.

Shutoff valves are desired on every riser for maintenance purposes and also on each branch to a toilet group (individual fixtures have their own shutoffs). Since most hot water piping is 2 inches or smaller, ball valves seem to be the preferred valve, although gate valves could be used since these are shutoff (open or closed) and not balancing valves. I prefer full-port ball valves, but it's the individual designer's decision.

Balancing valves are needed to ensure that approximately the desired flow is circulating in each circulating branch line, particularly since most system return lines are direct return (closest out is also the first back). You may in some cases have an opportunity to do a reverse return system (which is desirable), but you still should use balancing valves. The balancing valves that I use have a memory stop so that I can use the same valve as an isolation valve. Some designers may use a balancing valve and a separate shutoff valve. I like to have a minimum flow of 1 gpm through my balancing valve. This may sound wasteful because you don't need that much recirculation in some cases. However, I have a hard time finding a balancing valve that I can easily measure below 1 gpm. Also, I usually use a line-size balancing valve. Keep in mind that you should balance the system when no hot water, or very little, is flowing (being used). This gives you the maximum ΔP across the balancing valve. When water is flowing (being used) in the hot water piping, the ΔP across the valve and the gpm across the valve decrease. The pump head available increases, but this normally does not cause a problem.

Another component is the check valve. I have often thought about omitting this, but my friends in the field have told me too many war stories where portions of the circulating line were flowing backward. This could happen under certain situations such as incorrect valve operation, clogged lines, or incorrect pipe connection. Some designers like a swing check; others prefer a lift check. I favor the swing check because it has less pressure drop and requires less velocity to open. I am not concerned about water hammer due to the check valve in this situation because the check valve flapper position is generally fixed (may not be wide open) after pump startup. Some designers use 0.5–1.5 pounds per square inch (psi) to open the flapper on a swing check valve.

According to *Engineered Plumbing Systems* by Alfred Steele, PE, the minimum velocity to cause a bronze swing check valve to open wide with no flutter is calculated as follows:

$$V = 35\,V_s^{1/2} \text{ for a swing check}$$
$$V = 40\,V_s^{1/2} \text{ for a lift check}$$

where

V = velocity of flow in ft/sec

V_s = fluid-specific volume in ft^3/lb

This gives a velocity of about 4.6 fps.

A frequently forgotten item is a means of venting the air that is trapped in the piping when you first fill or refill after a water piping system test. If the circulating line connection is below the fixture connections, the fixtures will vent the air. If it is not, the air must be vented manually or automatically or a combination thereof. I prefer a manual ball valve at a high point in the system.

You must provide for pipe expansion if the lines are long (more than 50 feet for copper). See Table 6 on pipe expansion. You can use pipe offsets or loops or bellows-type expansion compensators to compensate for pipe expansion. Whenever possible, I prefer using a loop or offset. See Figures 4, 5, and 6.

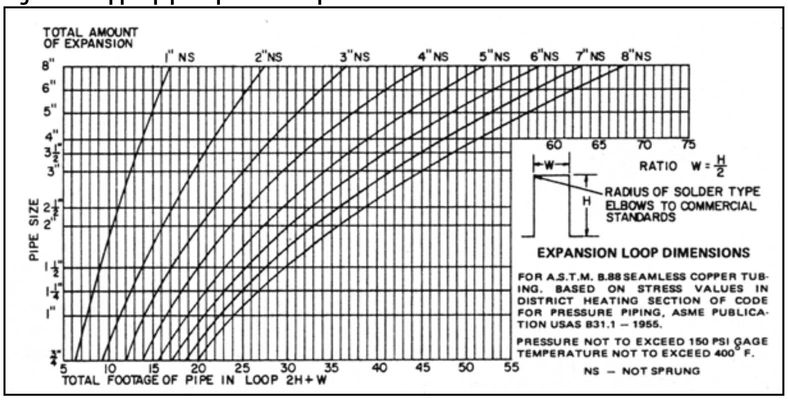
See the manufacturer's design literature for expansion amount and provision suggestions. Remember that PVC expands more than copper, which expands more than steel.

Table 6 Thermal linear expansion of copper tubing and steel pipe (inches per 100 feet)

Temperature Range (°F)	Copper Tubing	Steel Pipe
0	0	0
50	.56	.37
100	1.12	.76
150	1.69	1.15
200	2.27	1.55
250	2.85	1.96
300	3.45	2.38
350	4.05	2.81
400	4.65	3.25
450	5.27	3.70
500	5.89	4.15

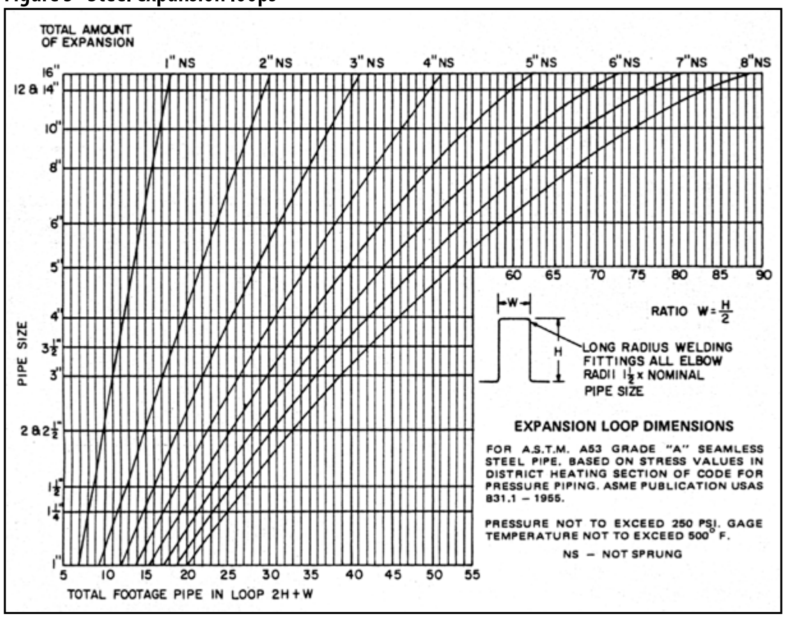
Note: Above data are based on expansion from 0°F but are sufficiently accurate for all other temperature ranges.
Source: "Carrier System Design Manual, Part 3," *Piping Design*

Figure 4 Copper pipe expansion loops



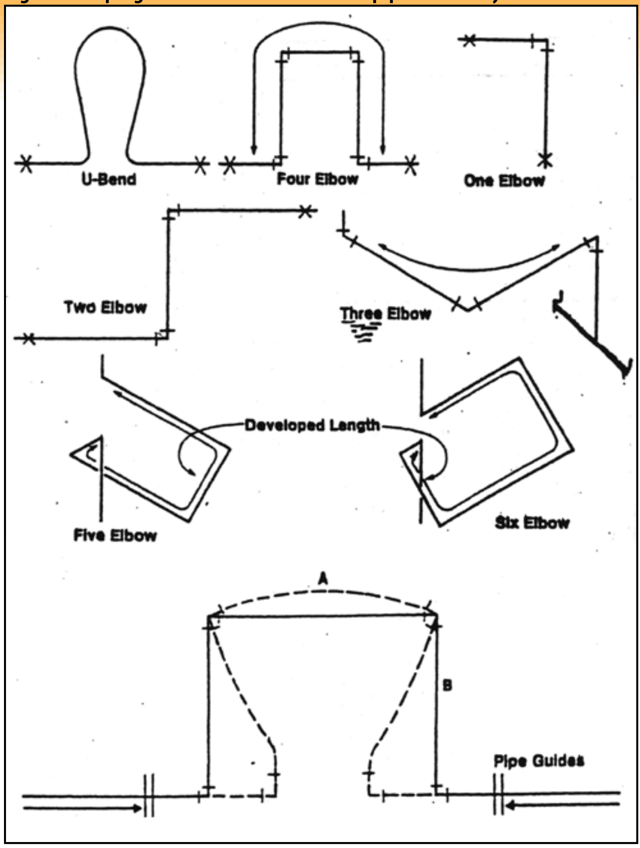
Source: "Carrier System Design Manual, Part 3," *Piping Design*

Figure 5 Steel expansion loops



Source: "Carrier System Design Manual, Part 3," *Piping Design*

Figure 6 Piping to absorb movement and pipe deformity



Source: "Carrier System Design Manual, Part 3," *Piping Design*

SIZING THE HOT WATER RETURN GPM

The calculations to determine the required gallons and temperature drop to maintain the desired water temperature at the fixtures are simple, and I prefer to use them rather than rules of thumb.

If there is no hot water circulating system and the hot water use is inactive or little used for long periods, the hot water temperature would gradually decrease, possibly even to room temperature whether insulated or not. Insulation only slows the heat loss; it does not eliminate it.

To prevent deterioration of the hot water temperature, you must continuously circulate some amount of hot water and allow its temperature to drop to make up for the heat loss of the hot water piping. Therefore, you need to allow some temperature drop in the hot water supply system when it is relatively inactive. Most designers use a temperature drop of 5°F or 10°F depending on the final temperature desired.

Next you must determine the heat loss from the hot water supply piping system. The piping has already been sized and the amount of insulation determined (see Table 7). You can use the heat loss data shown in Table 8 or use the free software developed by the North American Insulation Manufacturers Association (NAIMA) found at www.pipeinsulation.org. When using such tables, ensure that you have the correct pipe material, insulation type and thickness, wind speed, and ambient temperature.

Most tables show the heat loss for bare steel pipe and copper separately. For insulated piping or tubing, they show one heat loss for both. This is accurate enough for our domestic hot water calculations.

So now you know the heat loss, the desired temperature drop, the actual pipe length, the maximum desired velocity, and the water heater set temperature. Next you must calculate the gpm required using the following formula, which is good for any water heating or cooling problem.

$$q = r\,w\,c\,\Delta T$$

where

- q = Time rate of heat transfer, Btu/h
- r = Flow rate, gph
- w = Weight of heated water, lb/gal
- c = Specific heat of water, Btu/lb/°F
- ΔT = Change in heated water temperature (temperature of leaving water minus temperature of incoming water, represented as $T_h - T_c$, °F)

For purposes of this discussion, the specific heat of water is constant, c = 1 Btu/lb/°F, and the weight of water is constant at 8.33 lb/gal. Generally, this is simplified for using gpm.

$$q = \text{gal/min} \times 60\ \text{min/hr} \times 1\ \text{BTU/lb/°F} \times 8.33\ \text{lb/gal} \times \Delta T(\text{°F})$$
$$q = \text{gpm} \times 500 \times \Delta T, \text{ yielding}$$
$$\text{gpm} = q/500 \times \Delta T$$

PUMP SELECTION AND CONTROL

To select a pump, you need the gpm and pump head, but first you need to size the pipe to get the head. Which comes first: the pump or the pipe? You decide.

If the pump turns out to be too large, then increase the pipe size and select a smaller pump. For a large building, consider using ¾-inch pipe on the multiple riser main return. I don't recommend going over 4–5-fps velocity for copper and over a 4-foot-per-100-foot pressure drop. I don't like to use less than ½ inch—it's too fragile. (Knowing the gpm helps you estimate the pipe size.) The hot water return pipe is frequently one-half the size of the hot water supply line.

See the pump connection diagram shown in Figure 7. Note that for piping pressure drop, we are using equivalent length, which allows for pipe and fittings. I would normally not add more than 30 percent to the actual length to get the equivalent length because there are relatively few fittings. When the pipe and valve sizing are completed, you can, if you wish, calculate the actual system pressure drop using C_v factors for the valves and fittings. These are available from valve manufacturers, the Hydronic Institute, and ASHRAE.

Figure 8 shows a typical piping pressure drop chart. Whenever flow occurs, there is a continuous loss of pressure along the piping in the direction of flow. The amount of this head loss because of friction is affected by the density and temperature of the fluid, roughness of the pipe, length of run, and velocity of the fluid. Experiments have demonstrated that the friction head loss is inversely proportional to the diameter of the pipe and proportional to the roughness and length of the pipe, and varies approximately with the square of the velocity. This relationship can be expressed as

Table 7 Minimum pipe insulation thickness for domestic and service hot water systems

Fluid Design Operating Temp. Range (°F)	Insulation Conductivity		Nominal Pipe Diameter (inches)				
	Conductivity Btu•in./(h•ft2•°F)	Mean Rating Temperature °F	<1	1–1¼	1½–3½	4–6	≥8
105 and greater	0.22–0.28	100	0.5	0.5	1.0	1.0	1.0

Source: ASHRAE 90.1 (2001)

Table 8 Heat loss in Btu/h/ft length of fiberglass insulation, ASJ cover 150°F temperature of pipe

Horizontal

NPS	½		¾		1		1¼		1½		2		2½		3		4		5		6		8	
THK	HL																							
BARE	36		44		54		67		75		92		110		131		165		200		235		299	
½″	10	92	10	90	13	93	20	98	18	94	20	93	23	94	30	95	36	95	43	95	53	97	68	97
1″	7	86	8	87	9	86	11	88	11	87	13	87	15	88	18	88	22	88	27	89	32	89	38	89
1½″	5	84	6	84	7	84	8	84	9	85	10	85	10	84	14	85	17	86	20	86	23	86	28	8
2″	5	82	5	83	6	83	7	83	7	83	9	83	9	83	11	84	14	84	16	84	18	84	23	85

Vertical

NPS	½		¾		1		1¼		1½		2		2½		3		4		5		6		8	
THK	HL																							
BARE	32		40		49		61		69		84		100		120		152		185		217		277	
½″	9	92	10	90	13	93	19	99	18	95	20	94	23	94	30	96	35	96	43	96	52	97	67	98
1″	7	86	8	87	9	86	11	88	11	87	13	88	15	88	18	89	22	89	26	89	31	90	38	89
1½″	5	84	6	84	7	84	8	84	9	85	10	85	10	84	14	86	16	86	20	86	23	87	28	8
2″	5	83	5	83	6	83	7	83	7	83	9	83	9	83	11	84	14	84	16	85	18	85	23	85

Source: Courtesy of Owens/Corning. Notes:
80°ambient temperature, 0 wind velocity,
0.85 bare surface emittance,
0.90 surface emittance

HL = heat loss (BTU/h/ft length)
ST = surface temperature (°F)
Bare = bare pipe, iron pipe size
THK = thickness

Source: *ASPE Data Book, Volume 4: Piping Insulation*

$$h = \frac{fLV^2}{D \times 2g_c}$$

where

h = friction head loss, ft (1 ft of water = 0.43 psi)
f = coefficient of friction, dimensionless
L = length of pipe, ft
D = diameter of pipe, ft
V = velocity of flow, ft/sec
g_c = gravitational constant, 32.2 lbm ft/lbf sec^2

Don't forget to subtract all the equipment pressure drops from the pump head (such as softeners, water heaters, backflow preventers, etc.) to get the head allowable for the piping.

Pump Control. I recommend using a 24-hour, seven-day timer set up for the schedule of use, when temperature mixing valves are not used on the timed system. (Note that some codes may require the use of a time clock.) In buildings where the amount of hot water use varies greatly, consider using separate circulating systems or a separate local water heater.

In some cases, such as an office building or school, you might want to add an aquastat to shut off the pump if the water usage is such that the circulating system is sometimes not needed. Make the aquastat setting realistic. It won't be the setting of the water heater aquastat. Don't forget to allow for the return line temperature drop, water heater control differential, and hot water supply line temperature drop. (For example: 140°F—5° differential, 5°F hot water line temperature drop, 2°F return line temperature drop, use 125°F.)

PRESSURE-REDUCING VALVES

Figure 9 shows a typical pressure drop curve for a pressure-reducing valve (PRV). Let's say that we use an 18-pound fall-off pressure at 25 gpm (this could occur when we are drawing maximum hot water and circulating water). Next, let's assume that, at a particular time, we are drawing a total of 5 gpm of hot water through the PRV and the fall of pressure is then 3 psi. We cannot easily balance any system where the pressure varies other than by the square of the velocity (to develop a system curve). Therefore, we cannot balance this circulating system with the PRV.

You might say that the check valve and ball valve have the same problem. That's partially true, but we assume that the check valve and ball valve are open at a fixed position, in which case the pressure drop change is approximately proportional to the square of the flow (gpm = $C_v \times \Delta P^{1/2}$ and $\Delta P \propto V^2$).

I have not had that much experience with PRVs. Most of my projects have had 80 psi or less at the meter, and the high rises I have worked on were zoned vertically, seven to 10 floors per zone. Dan Brusewitz, an application engineer for Bell & Gossett, indicated that when PRVs cannot be eliminated, he does one or more of the following:

- circulates the hot water line only up to the PRV;
- circulates the hot water line after each PRV by itself;
- provides a heat tape on the main line from the PRV; or
- provides a booster heater on the discharge side of the PRV.

MIXING VALVES

Another area that the designer needs to be concerned with is mixing valves.

First of all, you cannot get a higher temperature than the maximum hot water temperature available at the mixing valve. If the water heater shuts off at 140°F, you will never see that tem-

Figure 7 Typical pump connections

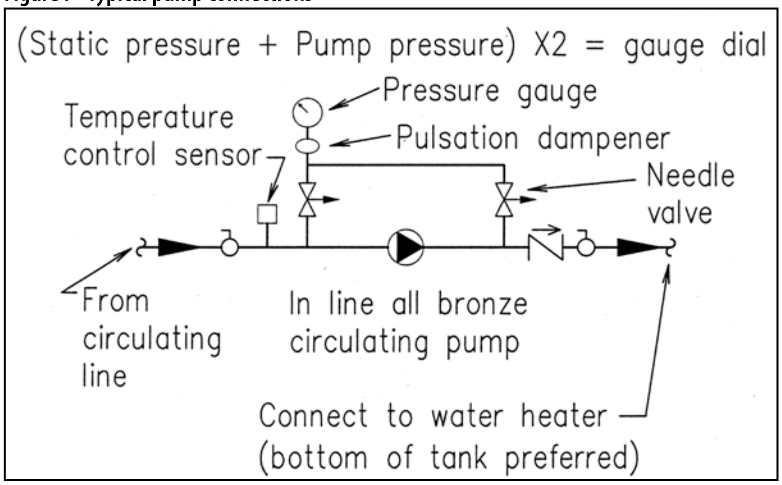
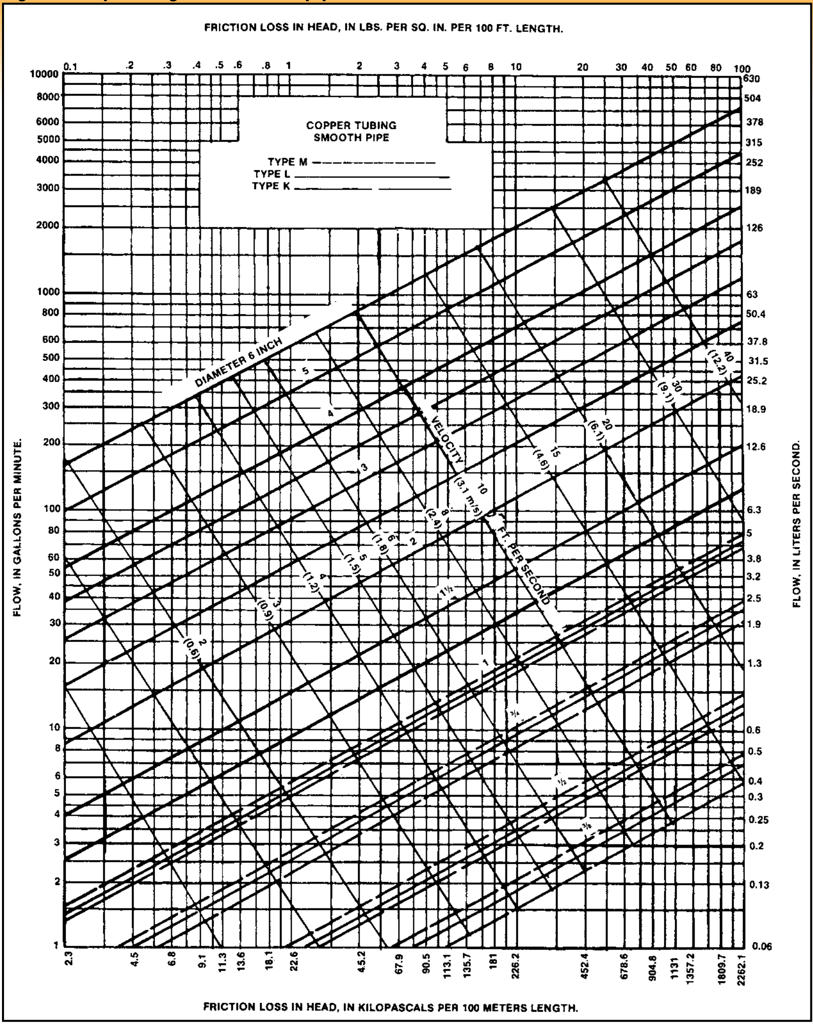
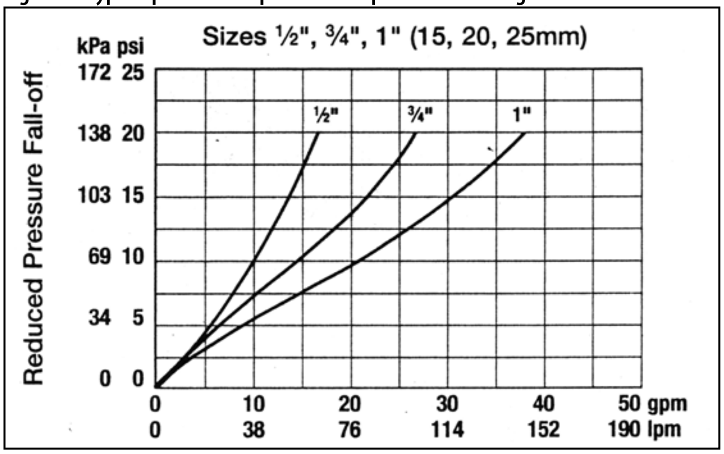


Figure 8 Pipe sizing data, smooth pipe



Source: *ASPE DataBook Volume 2*

Figure 9 Typical pressure drop curve for a pressure reducing valve



Source: Bell & Gossett

perature. If the water heater can't keep up with the hot water demand, you might be able to get 70 percent of the tank volume, but it won't be at 140°F. It may be 30 degrees or more lower, as previously mentioned.

When you know the maximum temperature available and how much it will vary, you need to make sure that it is available at all times when the mixing valve might be used. Otherwise, you have no way of determining how many gpm of hot water you need. The lower the supply hot water temperature, the more hot water is needed. If you don't circulate the hot water line to the valve, the temperature could reach room temperature over a long period. Then the valve could go into a hunting situation.

$$p = (T_m - T_c)/(T_h - T_c)$$

where

p = % of total flow required for hot water
T_h = Supply hot water temperature
T_c = Inlet cold water temperature
T_m = Desired mixed water temperature

The master mixing valve requires a small but constant flow across the control element to control the mixture temperature and avoid hunting. Manufacturers provide the minimum flow rates in their installation manuals. Therefore, the circulating line must somehow in the piping scheme feed each side of the valve (both hot and cold water side on a separate inlet port) so that continuous flow can occur when no water is being drawn.

Each mixing valve should have its own circulating line and pump (however, in some cases, manufacturers may deviate from the one pump, one valve requirement). A timer on the pump is not desired. If the valve hunts and sends a scalding temperature surge to the user, a severe burn may result. Table 9 shows how quickly skin damage can occur due to hot water. Consult the various codes and design guides such as for hospitals for help in determining the desired mixed temperature. It is unlikely that the cold water will be ground temperature, unless the use is very high. With very low use, the cold water could approach room temperature minus 5–10 degrees. For safety sake, however, we usually use the building inlet water temperature. This causes us to use more hot water (gives us a safety factor).

Remember: People expect hot water to be available at all times of use (this means almost immediately, not 30 seconds later). For some practical examples and practice calculations, visit www.psdmagazine.org. You'll also find some commonly used conversions and hydronic equations to help in designing your hot water circulation systems. PSD

Table 9 Time/water temperature combinations producing skin damage

Water Temperature		
°F	°C	Time (sec)
Over 140	Over 60	Less than 1
140	60	2.6
135	58	5.5
130	54	15
125	52	50
120	49	290

Source: *Domestic Water Heating Design Manual*, ASPE

Note: The above data indicate conditions producing the first evidence of skin damage in adult males.

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