CHAPTER 5

DESIGNING A HOT WATER HEATING SYSTEM

Natural, or Gravity, Circulation Systems

The Cause of Natural Circulation. If we fill a water bucket designed to hold exactly 1 cu ft, using water of say 200 F temperature, and then weigh the bucket, we discover our cubic foot of water has a net weight of 60.13 lb. If we next allow the water to grow steadily cooler, we observe that it seems to shrink, so that when it reaches a temperature of 52 F we must add water to fill the bucket. By using the scales, we find our cubic foot of water weighs substantially more than did the hot water, having now a net weight of 62.42 lb.

This temperature of 52 F is an interesting one, for here the density of water stabilizes, no further shrinkage takes place, and at 32 F just before freezing it still weighs 62.42 lb to the cubic foot.

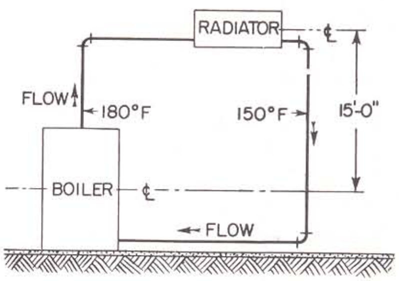


Fig. 5.1. Elementary circuit diagram, hot water system.

Natural circulation, or gravity circulation, to use the term we hear more often in heating problems, obtains its motive force from the difference in density that results from the differences in temperatures. Figure 5.1 illustrates what happens in a hot water heating circuit. The column of 150 F water in the return weighs 61.20 lb per cu ft, while the 180 F water leaving the boiler weighs only 60.57 lb per cu ft. Naturally the cooler water pushes the warmer water upward from the bottom of the boiler, being constrained to do this by its superior weight. All we need do is to supply heat to the boiler, and our water goes around and around, from boiler to radiator to boiler again, the loss of heat in the radiator supplying the difference in density.

Calculating the Motive Force for Natural Circulation. Being generated by a temperature difference that averages a mere 30 to 40 deg in everyday heating practice, our motive force is of slight power, at best.

For instance, refer to Fig. 5.1, the difference in weight between the 180 F supply and 150 F in the return is only 0.63 lb per cu ft. Expressed in pressure per square inch, this means 0.63/144 sq in. = 0.0044 psi.

Such a figure is awkward to work with; therefore we use another measure, the *milinch*. The milinch is 1/1,000 of an inch, or 1/12,000 of a foot. Since a pressure of 1 psi is developed by a column of water 2.3 ft high (27,600 milinches), we can discover easily the pressure of 1 ft (12,000 milinches) by 1 lb/2.3 ft = 0.434 lb.

Next, to convert our 0.0044 lb pressure into milinches, we solve the simple equation

$$\frac{0.0044 \times 12{,}000}{0.434} = 122 \text{ milinches}$$

This equation is based on common logic, for if 0.434 psi is exerted by a column of water 12,000 milinches high (1 ft), then our 0.0044 lb must be exerted by a column shorter in proportion. We need only set down the proportion, 0.0044 over 0.434, multiply by 12,000 milinches, and there is the answer.

Thus we see the difference in temperature between 180 F and 150 F can exert a circulating force of 122 milinches.

Relative Heights and Circulation. Fortunately for hot water heating systems, our radiators are usually well above the boiler, sometimes two or three stories. As a result the motive force is considerably increased. For example, our 122 milinches which developed from a column of water 1 ft high, grows to 2,440 milinches if the column extends to a radiator on the second floor, say 20 ft up. At the third-floor level, the pressure differential becomes 30 × 122, or 3,660 milinches.

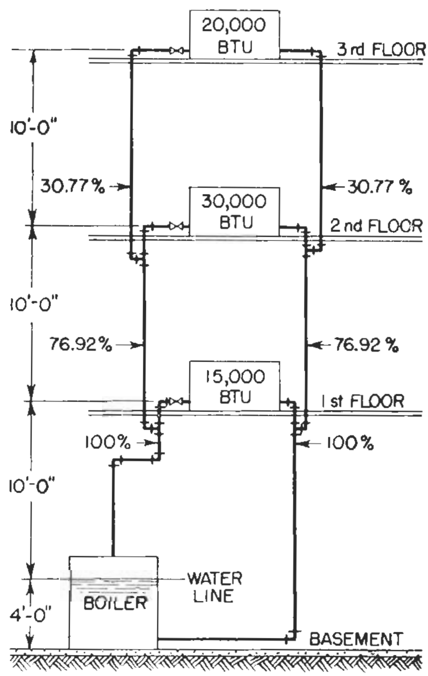


Fig. 5.2. Typical riser circuit.

At this point, we might stop to consider a natural phenomenon that affects our design of a gravity system. Figure 5.2 shows us three radiators, set one above the other on three different floors. On the first floor, we have a pressure differential based on 122 milinches multiplied by 10 ft, these 10 ft being assumed as the height of the radiator above the boiler. The total force available on the first floor is therefore 1,220 milinches.

Now we already have observed that the differential on the second floor is 2,440 milinches, and on the third floor, 3,660 milinches. The upper floors therefore, in consequence of having greater circulating forces to work with, will "hog" the heat unless we do something in our design to prevent it.

Several means are available for keeping all the heat from going to the top. The best is to design the piping and circuits so that greater resistances at the upper levels force the proper diversion of flow at the lower levels. A practical example of how this is accomplished appears in the following sections on sizing the piping.

Sizing the Gravity System Piping

General Considerations. Every foot of pipe, every fitting, every valve offers some more or less effective objection to the passage of water through it. The sum of these objections, expressed in our familiar milinches, must be kept below the available circulation-inspiring force. Thus, the maximum available force for the arrangement shown in Fig. 5.2 is 3,660 milinches, and all resistances must total less than this if we are to obtain circulation.

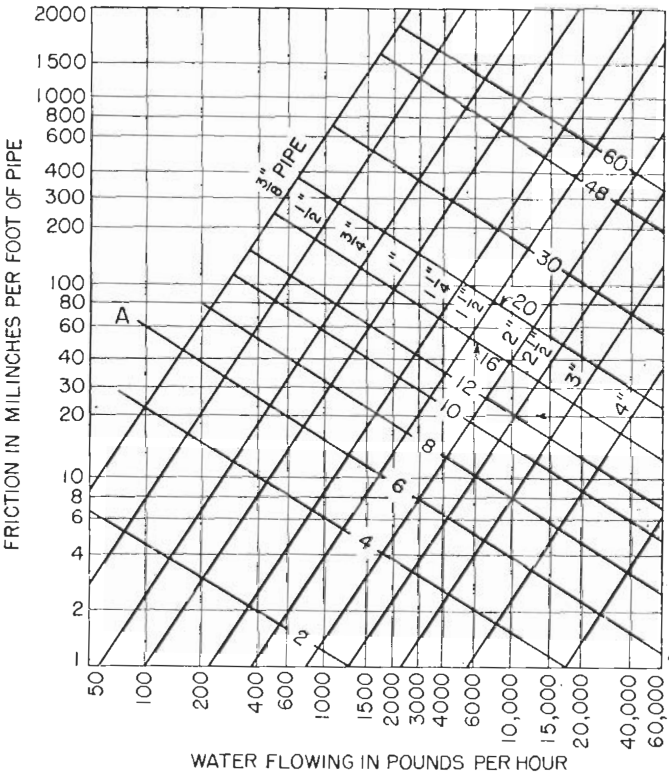
Referring to this figure, we have been wondering why our risers are not simply straight pipes, with radiator connections taken off through tees, and now we come to the explanation. We make the rising hot water pass through a couple of 90-deg turns to add resistance in the circuits to the upper radiators. In short, this is a means for making the circulation patronize the first-floor radiators in proper volume.

Our first step in sizing the piping is to find out how much water we need for each radiator. This is easy, for if 1 Btu will lift the temperature of 1 pound of water 1 degree Fahrenheit, then every pound which enters a radiator at 180 F and leaves at 150 F will drop 30 Btu during the passage. Consequently our three radiators will require water as follows:

Third floor	20,000 Btu ÷ 30 =	667 lb/hr
Second floor	30,000 Btu ÷ 30 =	1,000
First floor	15,000 Btu ÷ 30 =	500
Total		2,167 lb/hr

Water Velocities. Our next problem is to decide how fast the water shall move. Experience warns against designing for high velocities, because with gravity circulation high velocities are likely to be beyond us.

Suppose that we assume a velocity of 10 inches per second and see how this works out. Figure 5.3 which represents graphically the friction in iron pipes shows us that our total load of 65,000 Btu moving at 10 ips stirs up a resistance of 30 milinches per ft. Since we have 122 milinches available, we will run up the load line in Fig. 5.3 until we reach the 100-milinch level, as there is not any profit in selecting pipe larger than neces-



NOTE: SLANT LINES A-A SHOW VELOCITY, INCHES PER SECOND

Fig. 5.3. Friction graph for pipe sizing. *(Abstracted by permission from the 1948 ASHVE Guide, Chap. 24.)*

sary. The velocity at this 100-milinch point is 16 fps and the pipe size is $1\frac{1}{4}$ in. We will accept these values until we check the pipe lengths and fittings and will tentatively figure on $1\frac{1}{4}$-in. piping.

The Effect of the Fittings. Table 5.1 gives the equivalent length of straight pipe for each of the commonly met fittings and valves. For various kinds of specialties, we must obtain the friction loss direct from the manufacturer. Thus, a cast-iron convector will produce a loss of one value, a copper convector of another shape a different value.

A look at Table 5.1 informs us immediately that we must calculate the

TABLE 5.1. FRICTION OF FITTINGS IN PIPE DIAMETERS

Fitting	Equivalent Length of Straight Pipe
90-deg elbow	25.0 × pipe diameter
45-deg elbow	17.5 × pipe diameter
90-deg long radius ell	12.5 × pipe diameter
Return bend	25.0 × pipe diameter
Open gate valve	12.5 × pipe diameter
Open globe valve	300.0 × pipe diameter
Angle radiator valve	50.0 × pipe diameter
Flow-control valve	500.0 × pipe diameter
Open stopcock	25.0 × pipe diameter
Tee:	
With 25% diversion to branch	400.0 × pipe diameter
With ⅓ diversion to branch	225.0 × pipe diameter
With 50% diversion to branch	100.0 × pipe diameter
With 100% diversion to branch	45.0 × pipe diameter

flow through each of the four tees in the system we are sizing, as the friction loss through a tee varies with the volume passing through the branch. The percentages through each tee may be determined by the following:

Third floor	20,000/65,000 = 30.77%
Second floor	30,000/65,000 = 46.15%
First floor	15,000/65,000 = 23.08%

While this method uses the loads in Btu per hour, the same percentages will result if we use pounds per hour or gallons per hour.

Looking at Fig. 5.2, we see that the first tee in the supply riser passes water for the two upper radiators, or a total of 76.92 per cent. The second-floor tee supplies the third floor only, and 30.77 per cent is the value at this point. Going across the radiators to the return piping, we find the same percentages to exist; thus for our friction calculations we have two tees rated at 76.92 per cent and two at 30.77 per cent. As the first two fall about halfway between the 50 and 100 per cent values in Table 5.1, we will assign them an appropriate friction value of 73 pipe diameters. The latter two are close enough to the 33 per cent line in the table to be given the loss of 225 diameters.

Since we have determined the value of the tees, we can now tabulate the whole line-up of fittings (see Table 5.2).

Final Sizing. Our next step is to multiply the total equivalent length by the friction loss per foot of the 1¼-in pipe as shown on the graph (Fig. 5.3), and the answer appears to be about 19,000 milinches. Therefore we cannot use 1¼-in. pipe. It creates too great a friction loss.

As we have an equivalent length of approximately 193 ft and a total head of 3,660 milinches, apparently a friction loss of 18 milinches per ft is permissible. On the graph (Fig. 5.3) an 18-milinch loss at 65,000 Btu per hr requires the use of a 2-in. pipe with a velocity of a little more than 8 inches per second. Perhaps our original assumption of a 10-in. velocity was not so far wrong at that.

TABLE 5.2

No.	Item	Equivalent pipe diameters	1¼-in. pipe, total equivalent length, ft (approx.)
11	90-deg elbows	275	29
1	Angle radiator valve	50	5
1	Radiator	75	8
1	Boiler	75	8
	Tees:		
2	76.92%	146	15
2	30.77%	450	49
	Total	...	114
	Total straight piping, from Fig. 5.2	...	79
	Total equivalent length	...	193

Now we must recheck our fitting evaluation for the larger size pipe, for as losses in fittings are expressed in pipe diameters, we can expect our equivalent over-all length to increase. The new picture is shown by the data in Table 5.3.

TABLE 5.3

Item	Equivalent pipe diameters	2-in. pipe, total equivalent length, ft
Ells	275	46
Radiator valve	50	8
Radiator	75	13
Boiler	75	13
Tees:		
76.92%	146	24
30.77%	450	75
Total	...	179
Total straight piping	...	79
Total equivalent length	...	258

At a rate of 18 milinches per ft, 258 ft total 4,644 milinches, which still exceeds our available head by 984 mil. The situation is now clear, and we shall be required to use 2½-in. pipe between the first-floor radiators and the boiler, on both the supply and return sides.

Right here we might note that the large piping required by natural circulation systems is one of the important reasons behind the development of the forced circulation layouts. Large piping is both expensive and space filling.

Just to complete the record, we observe that with 2½-in. piping our resistance per foot is a trifle more than 5 milinches and the velocity is 5 ips.

Sizing the risers to the radiators on the upper floors follows the same general plan, but the problem is much shortened and simplified by our knowledge of resistances and velocities. Starting at the first floor, we have a total load of 50,000 Btu per hr and a velocity of 5 ips. Referring to the graph, we observe that we must still use a 2½-in. pipe to the second-floor radiators, but the drop in load to the third floor is enough to permit us the use of a 1½-in. pipe for this last leg.

Valve-area Sizing Method Compared. There are other ways of sizing gravity system piping, generally much simpler, and generally less accurate. One of these, called the valve-area method, we will apply to Fig. 5.2 and compare the results with the outcome of our more lengthy procedure.

The principle of this method is to add together the areas of all the radiator valves on the main at any given point, and then make the main area at this point at least equal to their sum.

Our first step is to convert the output of each radiator into square feet of heating surface, then take the standard tapping for radiators of the sizes so determined, and add together their areas. Thus, with our design for 180 F water entering a radiator and 150 F leaving, we have an average 165 F in the radiator. According to Table 4.1 the heat emission per square foot of radiator surface will be about 140 Btu per hr.

Our 20,000 Btu load on the third floor, therefore, will need 143 sq ft of radiator surface; 214 must be provided for the 30,000 Btu load of the second floor, and the first floor has the modest requirement of 107 sq ft. From any catalogue of radiators we can find physical data, including tapping sizes approximately as shown in Table 5.4.

TABLE 5.4. SIZE AND AREA OF INLET

Inlet Size	*Area of Inlet, Sq In.*
143 sq ft, 1¼ in.	1.50
214 sq ft, 1½ in.	2.04
107 sq ft, 1 in.	0.86
Total area	4.40

By referring this area to Table 5.5 which shows us the dimensions of standard wrought-iron and steel pipe, we discover that the valve-area method also calls for a 2½-in. pipe to carry the whole load. For the first leg of the riser above the first floor, the radiator inlet areas total 3.54 sq in.; therefore we must again use a 2½-in. pipe. As for the third floor, a 1¼-in. pipe seems satisfactory and reasonable, but our more elaborate approach to the sizing problem indicates that a 1½-in. pipe is needed to keep velocities and friction within our available head.

Some designers feel that use of the valve-area system of sizing produces piping somewhat larger than is necessary. No doubt with some installations this belief may be substantiated; on the other hand, every system presents problems and characteristics that are peculiarly its own, and experience will oftimes guide us in our decisions. For example, a generally sound rule of thumb allows us to add 50 per cent to our straight pipe lengths for fittings and valves, but in the design just studied, fittings and valves actually added 153 ft of equivalent length to the 79 ft of straight pipe. On the basis of the 50 per cent rule, our conclusions would have been in serious error. Almost certainly we should have chosen piping too small for the job.

TABLE 5.5. DIMENSIONS OF STANDARD WEIGHT IRON PIPE

Pipe size, in.	Inside diameter, in.	Inside area, sq in.
½	0.622	0.304
¾	0.824	0.533
1	1.049	0.864
1¼	1.380	1.495
1½	1.610	2.036
2	2.067	3.355
2½	2.469	4.788
3	3.068	7.393
4	4.026	12.730
6	6.065	28.891
8	7.981	50.027
10	10.02	78.855
12	12.00	113.097

Sizing Horizontal Piping. We must exercise special judgment in sizing horizontal piping. Here we have no static head to aid the flow of water, and we must depend entirely on the pressure differential developed by temperature to move our water through the pipe. If the horizontal run is long, say over 10 ft, choosing a pipe one size larger than theory calls for will reduce friction and perhaps prove essential for satisfactory operation.

If there is one rule above all others that we should observe in designing a gravity system, it is this: Design with the utmost care, and then evaluate the design with the most exacting judgment.

Forms of Gravity Systems

All hot water systems are subject to classification according to (1) the sort of circulation employed, whether gravity or forced; (2) whether one-pipe or two-pipe; (3) whether direct return or reversed return.

One-pipe Systems. Since we are now examining the gravity systems, suppose that we consider the one-pipe layout, shown in Fig. 5.4. Here we see a system incorporated in one circuit, with the hot supply water being constantly cooled by admixture with the returns. The farther we travel from the boiler, the cooler becomes the water delivered to the radiators; consequently somewhere along the line we must provide more radiator surface to compensate for the cooler water.

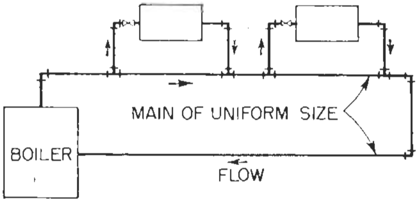


Fig. 5.4. Diagram of a one-pipe system.

This system is a simple one, but not wholeheartedly recommended except for the smaller applications.

We size the mains for a one-pipe system exactly as we did for the elementary system previously examined and sized. The radiator connections, however, introduce a complication in the form of progressively changing water temperatures and reducing differentials.

For example, we assume that a system is composed of five radiators with a total load of 50,000 Btu. We shall assume that the water leaving the boiler is at 180 F and that the return temperature is 150 F.

Now the first radiator will have 180 F water at the inlet, and since the outlet will be 150 F, the motive force in the radiator circuit will be realized from this 30-deg differential, or 122 milinches. We therefore size the piping to the first radiator on this basis.

The second radiator, however, is going to receive cooler water, as the result of dilution in the main from the 150 F discharge from the first radiator. This reduced temperature is calculated on the premise that each radiator in the circuit will contribute its share of the total 30 F drop in proportion to its own load. Thus, if we assume that radiator 1 emits 15,000 Btu per hr, the drop in temperature for radiator 2 will be $(15{,}000/50{,}000) \times 30 = 9$ deg. The second radiator therefore can expect to receive water at $180 - 9 = 171$ F.

The motive force to this second radiator is calculated on a difference of 171 F and 150 F, or 21 deg. Since water at 150 F weighs 61.2 lb per cu ft, and at 171 F, 60.78 lb approximately, our circulating head drops to 83 milinches. We must size the piping to the second radiator accordingly.

By the time the water reaches the third radiator, a further reduction of temperature has occurred. This time, on the assumption that the load in radiator 2 is 5000 Btu per hr, it will be

$$\frac{15{,}000 + 5{,}000}{50{,}000} \times 30 = 12 \text{ deg}$$

Radiator 3 therefore will receive water at 180 − 12 = 168 F. With a weight differential between 168 F and 150 F of only 0.37 lb, the circulating head for this circuit goes down to about 72 milinches.

Each of the radiators subsequently on the circuit must be considered similarly, and obviously the tendency of the water to circulate through the radiator weakens as the supply cools.

The Two-pipe Direct Return System. Figure 5.5 shows us an arrangement of piping that avoids mixing the returns with the supply water.

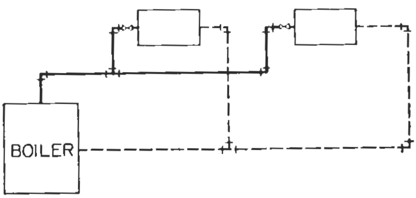


Fig. 5.5. Diagram of two-pipe, direct return system.

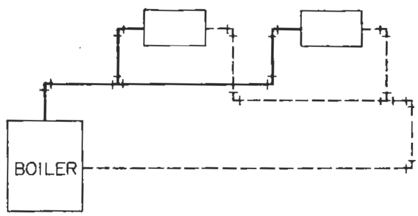


Fig. 5.6. Diagram of two-pipe, reversed return system.

However, this scheme takes little note of the inequalities of length which characterize the individual radiator circuits. In consequence, there is a tendency to short circuit, and radiators nearest the boiler when in the same plane may overheat while more distant ones underheat.

We calculate pipe sizes in accordance with the basic plan for this sort of system, which means we make no allowances for either the short circuiting or the probable inequalities of temperature. We just close our minds to facts, so to speak, and hope that nature somehow will correct the balance.

The direct return system does not enjoy very wide approval and should not be adopted if any other system can be made to apply.

The Two-pipe Reversed Return System. Here is undoubtedly the best design for a hot water installation. Figure 5.6 illustrates how a reversed return system is laid out. Basically, each radiator is part of a circuit which is approximately equal in length to all the other circuits. Thus, if the supply piping is of short run, the return is correspondingly long.

The reversed return is generally preferred by engineers for the medium and large installations, since balancing these larger jobs for the correct flow in all their parts becomes easier with this system.

However, the reversed return tends to add to the cost, and this additional expense is not always justified. Economics are important in heating just as they are important everywhere, and the designer must evaluate every job before he makes a final decision on the type of layout that will go in.

Occasionally it is possible to install a reversed return system without any additional cost, or perhaps a very slight additional cost.

Forced Circulation Systems

Benefits of Forced Circulation. By using a pump to circulate our hot water in place of the thermal head, we obtain several definite benefits.

First, we can reduce substantially the size of the piping, thereby saving money. Second, if we design properly, every radiator will get heat. Third, the use of a pump permits us to use hot water for panel and baseboard types of heating. Fourth, by using water almost at steam temperature, we can whittle down radiator sizes.

All these glowing benefits make us wonder just why anybody would choose gravity systems of hot water heating. Nothing, however, is perfect. A forced circulation system needs a pump which costs good dollars and is subject to the usual measure of casualties that befall operating machinery. If we must divide the system into zones or circuits, a common necessity for medium-to-large jobs, we may need a pump for every zone.

Pump failure can have serious results. As circulation stops, chilling starts, and if this unhappy condition occurs during the night or within a week end, frozen and ruptured pipes may produce for us a cold greeting at the first subsequent meeting.

The electricity that pumps use must be paid for, and while this is a small item, small items are of considerable importance to many persons.

All in all, we can think up numerous dangers and gloomy shortcomings of the forced circulation system, but the fact remains that a properly designed system provides excellent and dependable heating, and its popularity is increasing all the time.

First Considerations for Forced Circulation. In Figs. 3.3 and 3.4, we studied a steam heating layout for a two-story house. Now we shall design a forced circulation hot water heating system for this same house, and thereby enjoy the profitable thoughts that come from making comparisons.

Figures 5.7 and 5.8 therefore recall to us the room arrangement, dimensions, elevation, and other necessary data on which to base a heating design. Also, we must make some assumptions. First, there is the assumption of 20 deg for the temperature drop, and second, we shall set