

Sizing Pipe Using Life-Cycle Costs

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HVAC piping is typically sized using rules-of-thumb such as maximum friction rate or velocity, or a combination of the two. *Figure 1* shows a pipe sizing chart for Schedule 40 steel pipe¹ where friction rate is limited to 4 ft per 100 ft (1 m per 30 m) and velocity is limited to 10 fps (3 m/s) as indicated by the red line. Charts like these are generally based on tradition more than objective analysis; in fact, *Figure 1* was used for pipe sizing by one of the authors for many years and was passed to him from his boss who got it from his boss.

Once pipes are sized, designers must determine total pump head so that a pump can be selected. Head can be determined accurately using network piping software but inputting the required data can be time consuming and prone to errors. It is not uncommon for pump head to be determined using guesstimates based on

past experience or minimal calculations.

Fortunately, a free spreadsheet² has been developed as part of the Cool-Tools™ Chilled Water Plant Design Guide, funded by California utility customers through Energy Design Resources (www.energydesignresources.com). The spreadsheet provides these basic

functions:

- Pipe sizing based on a balance between first costs and future energy costs, with optional velocity limits for erosion and noise generation; and
- Pump head calculations including all fittings, valves, and devices.

The spreadsheet is fast and easy to use. Calculations for most systems can be done in a few hours.

This article discusses how the spreadsheet works and presents example system calculations.

Optimum Pipe Size Calculations

The optimum pipe size for a given

About the Author

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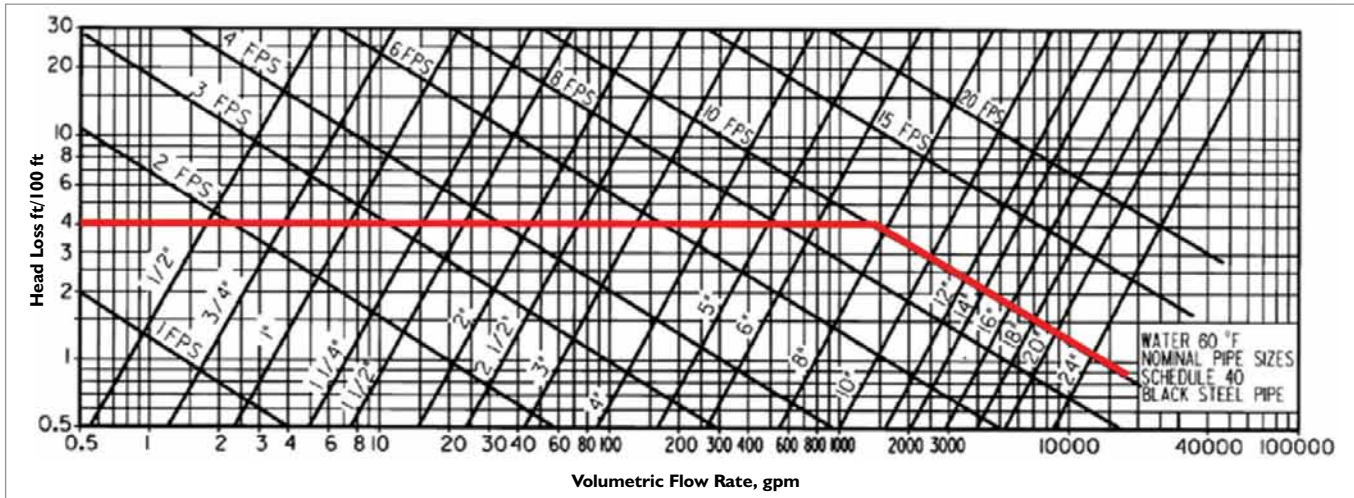


Figure 1: Typical friction rate/velocity limits for Schedule 40 steel pipe.

design flow rate is a function of:

- Location of pipe in the system (whether or not it is in the critical circuit*);
- First costs of installed system including piping, fittings, valves, pumps, pump motors, and variable speed drives;
- Pump energy costs, which depend on the pressure drop through the system at full load, pump and motor efficiency, hours of operation, energy rates, distribution system type (constant or variable flow), annual flow profile, type of pump control (variable speed or riding pump curve), etc.;
- Erosion considerations (high velocities can contribute to hastening of pipe wall deterioration);
- Noise considerations (high velocities and turbulence can cause noise problems in occupied areas);
- Physical constraints; and
- Budget constraints.

The spreadsheet addresses all but the last two bullets, which are project specific.

The spreadsheet models a single circuit in a system. Typically only the critical circuit is analyzed, selected by the user by inspection or by testing multiple circuits in the spreadsheet to see which requires the highest pump head. For each segment of the circuit, the user inputs pipe lengths and properties, valves and fittings, pressure drop of coils and other equipment, and optionally applies noise and erosion constraints. If the modeled circuit is indicated to be the critical circuit, the spreadsheet (within noise and erosion constraints) sizes the pipe for each segment to minimize first costs plus life-cycle energy costs.

The spreadsheet includes a cost database of the following hydronic system components:

- Piping; †

* The critical circuit is the circuit within the system with the highest pressure loss. This is often the longest run in the system, but not always. The pressure loss in this circuit, and only this circuit, determines the required pump head and drives annual energy consumption.

† At this time only Type L copper and standard weight black steel piping are included since they are the most commonly used for HVAC applications. The spreadsheet allows the user to enter data for any piping materials.

- Fittings such as 90° elbows, 45° elbows, and tees;
- Valves and accessories including calibrated balancing valves, check valves, ball valves, butterfly valves, wye-strainers, suction diffusers, and flow limiting valves;
- Piping insulation (for hot and chilled water); and
- Pumps, pump motors, and variable speed drives.

Costs are based on RS Means Mechanical Cost Data,³ or local suppliers when items were not covered in Means. Adjustments for inflation can be entered to keep the cost data up-to-date. Adjustments for labor costs are included for various California cities or can be manually entered. Component costs can also be entered manually by the user.

Energy Calculations

Pressure drop through piping is calculated from the Darcy-Weisbach Equation with the friction factor determined from the Moody chart⁴ as a function of Reynolds Number (including fluid temperature effects) and pipe roughness. Pressure drops through valves, fittings, and accessories are determined from manufacturer's data (K-value or Cv) for representative products. Pressure drops for control valves, heat exchangers, etc. are entered by the user.

Pump efficiency is assumed to vary with flow from a minimum of 55% to a maximum of 80% (user adjustable). The values were determined from typical centrifugal pump selections. Motor size for cost calculations is assumed to be the next size above the calculated brake horsepower. Motor efficiency corresponds to the minimum required for NEMA Premium Efficiency designation. All values may be overridden by the user.

Flow control system types included are:

- Constant flow and speed;
- Variable flow, constant speed (ride pump curve); (assumed to be ~one-third of design head); and
- Variable flow, variable speed with differential setpoint reset by valve position.

Annual hours of operation are input by the user. Part-load performance assumed for the variable flow systems is shown in Figure 2. The spreadsheet assumes the annual average flow rate is

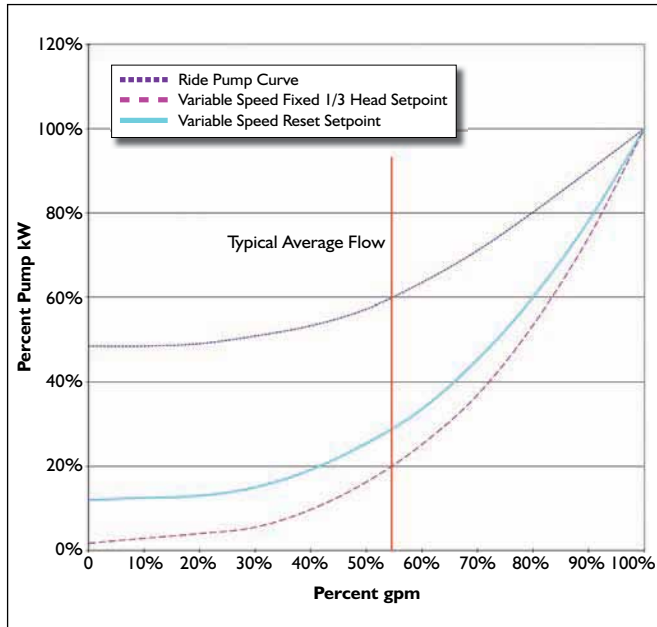


Figure 2: Typical pump power versus flow

55%, which was developed from generic DOE-2 models of several California office buildings. The resulting average percent power value for each system type can be overridden by the user.

The addition of heat to the central plant load due to pump energy is taken into account since it significantly affects overall energy and life-cycle costs. For instance, chilled water pump energy is added to the chiller load. Hot water pump energy, on the other hand, reduces boiler load. Chiller annual average efficiency is assumed to be 0.6 kW/ton (0.17 kW) while boiler annual average efficiency is assumed to be 75%; both values are user adjustable.

Velocity Limits

Erosion velocity limits are based on the rules-of-thumb shown in Table 1.⁵ These limits can be enabled and disabled for each piping section and manually changed by the user.

Noise from piping results from turbulence, cavitation, entrained air, and water hammer. Of these, only turbulence associated with velocity can be addressed in the spreadsheet, but there are few studies showing a consistent relationship.⁶ The spreadsheet includes rule-of-thumb velocity limits developed by a local acoustical consultant.⁷ Figure 3 shows the corresponding maximum allowable velocity for a given pipe size. As with erosion, these velocity limits can be enabled and disabled for each piping section and manually changed by the user.

Economic Variables

Economic variables include:

- Inflation rate;
- Energy escalation rate (above inflation);
- Electricity cost (effective cost per kWh including demand);
- Natural gas cost (for estimating pump energy impact on hot boiler cost);
- Discount rate; and
- System lifetime.

Normal Operation, h/yr	Water Velocity, fps
1,500	15
2,000	14
3,000	13
4,000	12
6,000	10

Table 1: Maximum velocity to limit erosion.⁵

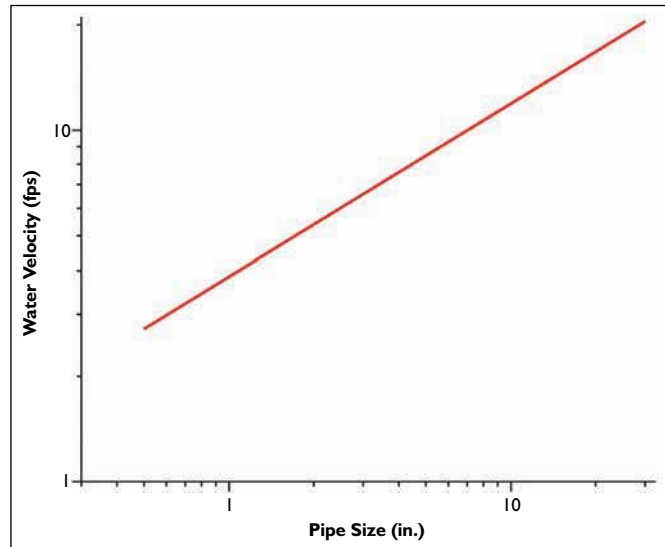


Figure 3: Maximum velocity for piping adjacent to noise sensitive spaces.⁷

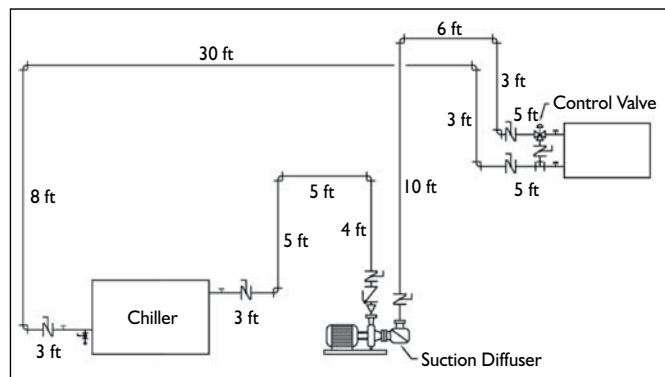


Figure 4: Example chilled water plant schematic

Calculated annual energy costs are adjusted for inflation and escalation then discounted over the system lifetime.

Examples

Two examples are described in the following sections. The first example is a simple chilled water plant. The example also examines the same basic system but assuming the plant produces hot water rather than chilled water to demonstrate the impacts on pipe size. The second example describes a recently approved addendum to ANSI/ASHRAE/IESNA Standard 90.1-20078 that establishes maximum flow rates for chilled and condenser water system piping based on the life-cycle calculations performed by the piping spreadsheet. Similar pipe sizing limitations have been put forward in proposed ASHRAE Standard 189.1P9

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A		B		D	F	H	J	K	P	Q	AF	AG	AH	AI	AJ	AK	AL	AM	AP	AS	AV	AZ	BC	BF	BI	BK	BN	BO	BP	BQ	
Clear and Apply User Settings		Auto-select Optimized Pipe Size		Inputs																											
		Total system flow		500 GPM																											
Add a Row		Delete a Row		Add or delete a row above current cursor position		Segment Grouping	Flow rate	Select Pipe Size or "AUTO"	Pipe Size	Flow Speed Limit to Prevent Noise?	Flow Speed Limit to Prevent Erosion?	Desired Insulation Wall Thickness	Insulation Thickness	Straight Pipe Length	Number of Elbows	Tees with flow through:	Number of Valves										Control Valve ΔP	Other: Chiller/Boiler/Coil/HV etc.	Segment Head	Velocity	Friction Rate
Pipe Segment Description		Auto Group	GPM	Inches	Too fast?	Too fast?	Inches	Feet	90°	45°	Straight	Branch	Circuit Saver	Silent Check	Swamp Check	Ball or Butterfly	Wye-Strainer	Wye-Valve	Suction Diffuser	Limiting	Flow	Psi	Feet	Feet	psi	Feet/ sec	Feet/ 100 ft				
7 Main circuit		1	500	AUTO	6	OFF	N/A	OFF	N/A	Title 24	1	90	10	1	1	1	6	1	1	1	1	2,366.9	12	7.92	3.4	5.6	1.7				
8 Coil and control valve		1	500	AUTO	6	OFF	N/A	OFF	N/A	Title 24	1													17.47	7.6	5.6	1.7				
9 chiller		1	500	AUTO	6	OFF	N/A	OFF	N/A	Title 24	1													10.00	4.3	5.6	1.7				
																						Totals		35.38	15.32						
																								5		Safety factor					
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Output Summary:																															
14 Total Head (Feet)																															
15 Total Head w S.F. (Feet)																															
16 Total Cost																															
17 Lifecycle Energy Cost																															
18 First Cost																															

A		B		D	F	H	J	K	P	Q	AF	AG	AH	AI	AJ	AK	AL	AM	AP	AS	AV	AZ	BC	BF	BI	BK	BN	BO	BP	BQ	
Clear and Apply User Settings		Auto-select Optimized Pipe Size		Inputs																											
		Total system flow		500 GPM																											
Add a Row		Delete a Row		Add or delete a row above current cursor position		Segment Grouping	Flow rate	Select Pipe Size or "AUTO"	Pipe Size	Flow Speed Limit to Prevent Noise?	Flow Speed Limit to Prevent Erosion?	Desired Insulation Wall Thickness	Insulation Thickness	Straight Pipe Length	Number of Elbows	Tees with flow through:	Number of Valves										Control Valve ΔP	Other: Chiller/Boiler/Coil/HV etc.	Segment Head	Velocity	Friction Rate
Pipe Segment Description		Auto Group	GPM	Inches	Too fast?	Too fast?	Inches	Feet	90°	45°	Straight	Branch	Circuit Saver	Silent Check	Swamp Check	Ball or Butterfly	Wye-Strainer	Wye-Valve	Suction Diffuser	Limiting	Flow	Psi	Feet	Feet	psi	Feet/ sec	Feet/ 100 ft				
7 Main circuit		1	500	AUTO	5	OFF	N/A	OFF	N/A	Title 24	1 1/2	90	10	1	1	1	6	1	1	1	1	2,366.9	12	17.44	7.6	8.0	3.9				
8 Coil and control valve		1	500	AUTO	5	OFF	N/A	OFF	N/A	Title 24	1 1/2														17.47	7.6	8.0	3.9			
9 chiller		1	500	AUTO	5	OFF	N/A	OFF	N/A	Title 24	1 1/2														10.00	4.3	8.0	3.9			
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18 First Cost																															

Figure 6: Example hot water plant spreadsheet results

Example 1: Simple Chilled Water System

Figure 4 shows a simple 500 gpm (32 L/s) chilled water system. The user must enter the lengths of each pipe and the quantity of each type of fitting into the spreadsheet. On a real project, pipe lengths are measured from drawings (typically directly from CAD files) while piping accessories are tabulated from piping schematics. Each section of pipe that has a different flow rate must be entered as a separate row in the spreadsheet. In this case, there is only one flow rate, so all data could be entered on a single row. However, for clarity it is often convenient to enter data on multiple rows, as was done in this example. When piping sections with the same or similar flow rate are entered on separate rows, they can be grouped into a common segment (identified in the spreadsheet by segment group number) to ensure all piping of similar flow rate will have the same pipe size. Once the piping data are entered, the "Auto-select Optimum Pipe Size" button is pressed and piping is automatically sized to minimize life-cycle costs.

The resulting pump head and system first costs and energy costs are instantly calculated (Figure 5). In this example, life-cycle costs were based on piping costs for Oakland, Calif., \$0.15 per kWh electricity costs, 2% energy escalation, 10% discount rate, 2,000 hours per year operation, and a 30-year lifetime. The optimum pipe size was determined to be 6 in. (152 mm) for this constant flow chilled water plant.

Now imagine the plant was a gas-fired hot water plant with all else the same. The optimum pipe size would then be 5 in. (127 mm) (Figure 6) rather than 6 in. (152 mm). The pipe size is smaller because pump energy is not "lost" in a hot water plant; it goes into the water and is simply a form of electric resistance heat which decreases the load on the boiler. Conversely, in a chilled water plant the pump energy must be removed by the chiller and so adds to the overall energy consumption of the system. This is why the proposed pipe sizing limitations in Standards 90.1 and 189.1P only apply to chilled and condenser water systems.

Example 2: Standard 90.1 Addendum

Addendum af to 90.1-2007 limits the maximum design flow rates through chilled and condenser water piping systems. The limits were determined using the piping spreadsheet along with the following inputs:

The piping system includes the following:

- 100 ft (30 m) of straight pipe;
- Ten 90° elbows;
- Six straight flow-through tees;
- Four ball (≤2 in. [51 mm]) or butterfly valves (>2 in. [51 mm]);
- One wye strainer;
- One silent check valve;
- Average water temperature of 50°F (10°C);
- No limits for noise or erosion; and

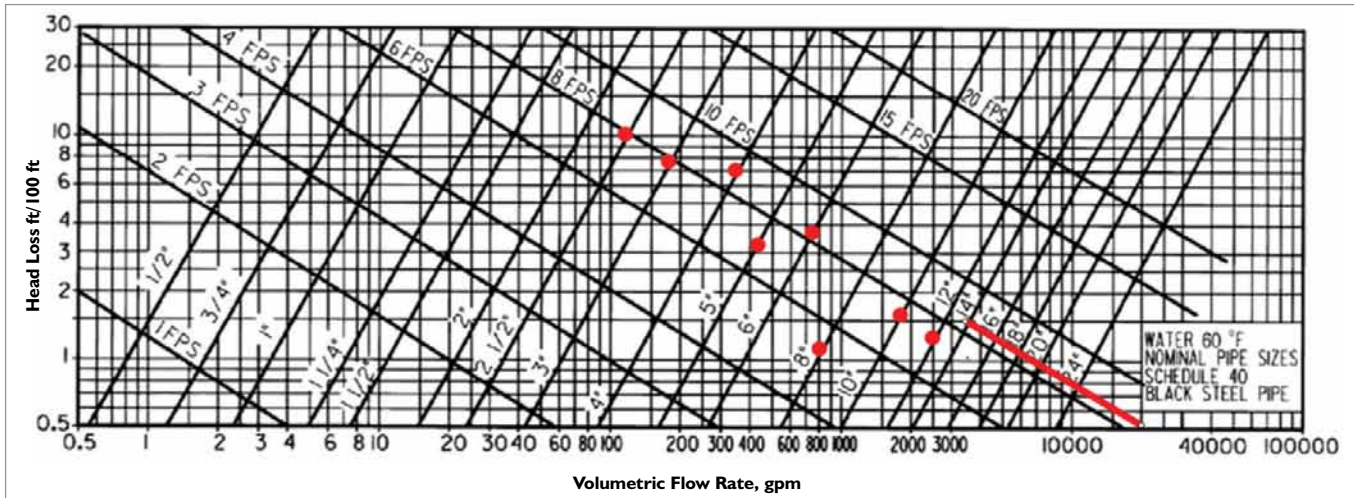


Figure 7: Proposed Standard 90.1 flow limits for 2,000 hr/year constant flow CHW systems

- First costs are based on national average from 2008 RS Means Mechanical Cost Data.

Economic assumptions are those agreed to by the committee responsible for the development of Standard 90.1 for life-cycle cost calculations performed in the development of new requirements in the standard:

- Electricity costs: 0.0939 \$/kWh;
- Electricity escalation rate: 3.7%;
- Discount rate: 7%; and
- System lifetime: 30 years.

The result of the analysis is the flow limits in Table 2 (Table 6.5.4.5 from Standard 90.1-2007). The limits vary as a function of estimated operating hours and whether or not the system is variable flow/variable speed. Figure 7 shows the requirements for constant flow systems operating for less than 2,000 hours per year plotted on a friction chart. Compared to Figure 1, the requirements result in higher friction rates for smaller piping and lower friction rates for piping 5 in. (127

mm) and larger. Limitations for variable flow systems are generally less stringent but stringency increases as operating hours increase.

Conclusions

HVAC system piping is typically sized using rule-of-thumb limits for velocity and friction rates. A spreadsheet has been developed to allow piping to be easily and quickly sized based on life-cycle costs with optional noise and erosion velocity limits. The spreadsheet has been used to establish pipe sizing limits in an addendum to ASHRAE Standard 90.1 and in proposed Standard 189.1P. The spreadsheet also can be used to quickly but accurately calculate pump head, which should result in pump first cost and energy cost savings versus conservative pump head guesstimates. The spreadsheet is free and can be downloaded from www.taylor-engineering.com/publications/design_guides.shtml.

References

Based on 1. ASHRAE Handbook—Fundamentals, Chapter 36, Figure 4.

Operating hr/yr	<=2,000 hr/year		>2,000 and <=4,400 hr/year		>4,400 and <=8,760 hr/year	
	Nominal Pipe Size (in.)	Other	Variable Flow/Variable Speed	Other	Variable Flow/Variable Speed	Other
2 1/2	120	180	85	130	68	110
3	180	270	140	210	110	170
4	350	530	260	400	210	320
5	410	620	310	470	250	370
6	740	1,100	570	860	440	680
8	840	1,300	650	970	510	770
10	1,800	2,700	1,300	2,000	1,000	1,600
12	2,500	3,800	1,900	2,900	1,500	2,300
Maximum Velocity for Pipes Over 12 in. Size	8.5 fps	13.0 fps	6.5 fps	9.5 fps	5.0 fps	7.5 fps

Table 2: From Standard 90.1-2007, Table 6.5.4.5 “Piping System Design Maximum Flow Rate in Gallons Per Minute.”

2. “EDR Cool-Tools Pipe Size Optimization Spreadsheet.” Free download available from the developer’s Web site at www.taylor-engineering.com/publications/design_guides.shtml.

3. 2008 RS Means Mechanical Cost Data. Kingston, Mass.: RSMeans.

4. ASHRAE Handbook—Fundamentals, Chapter 2, Figure 13.

5. Carrier. 1960. “System Design Manual, Piping Design.” Syracuse, N.Y.: Carrier Air Conditioning Company.

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7. HVAC Noise Design Guide. Unpublished. Oakland, Calif.: Wilson Ihrig Associates.

8. ANSI/ASHRAE/IESNA Standard 90.1-2007, Energy Standard for Buildings Except Low-Rise Residential Buildings.

9. ASHRAE/IESNA/USGBC Standard 189.1P, Standard for the Design of High-Performance Green Buildings Except Low-Rise Residential Buildings. Proposed standard, not yet published. ❖