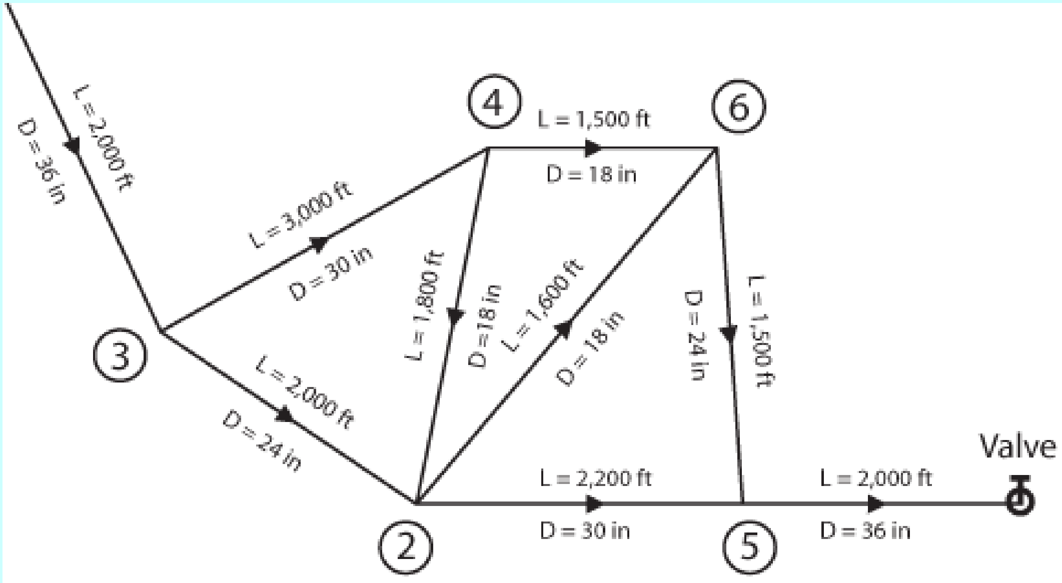

Fluid Network Analysis II

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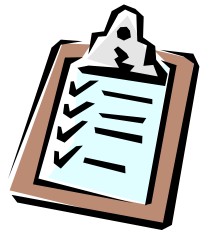
Jan 2021

Contents

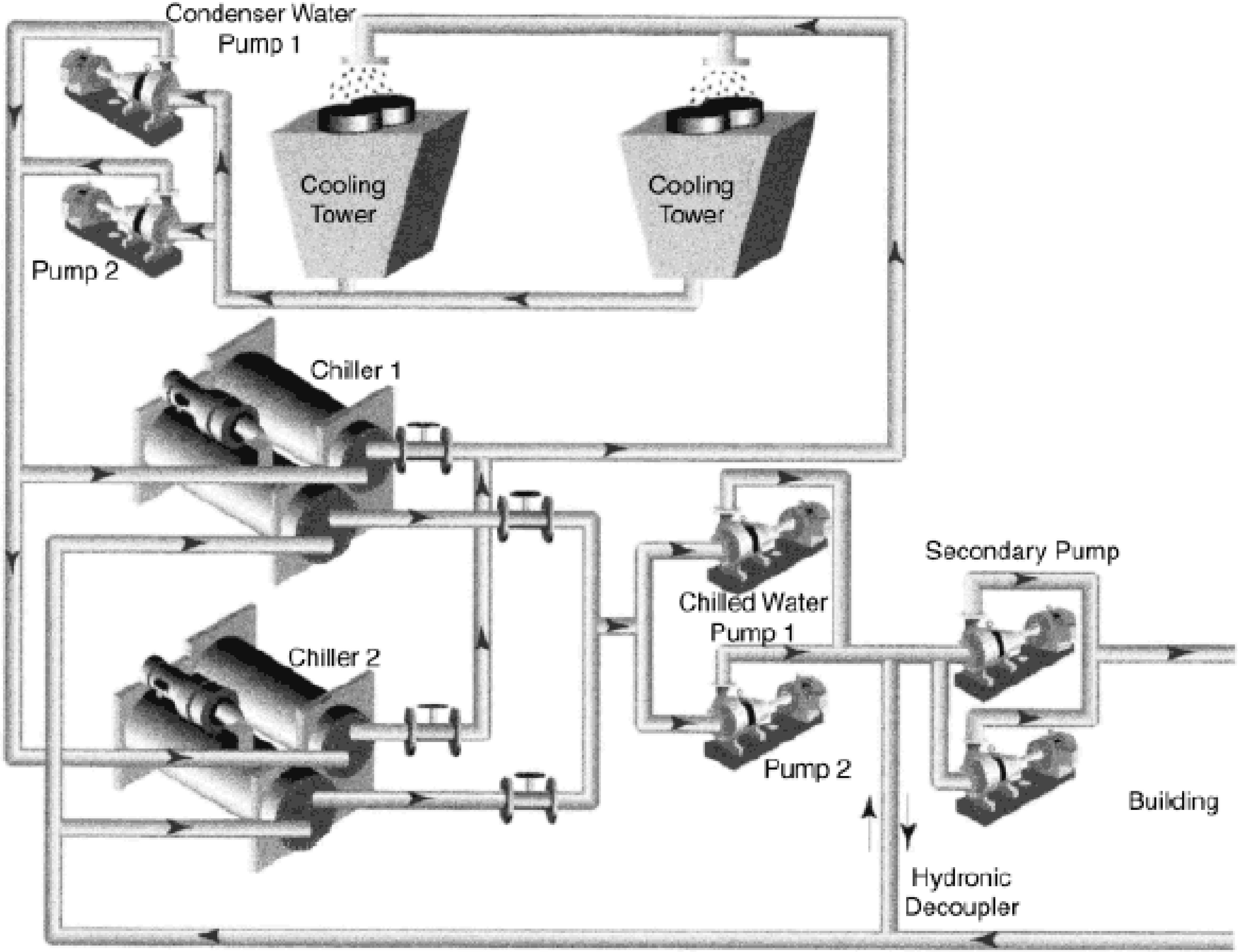


- Pipe Systems and Design
- HVAC Water Systems
- Practical Design Issues
- Pipe Network Analysis

Pipe Systems and Design

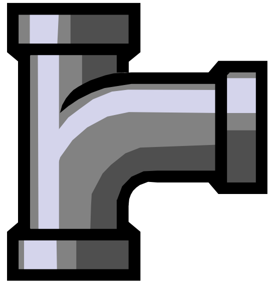
- Common types of HVAC piping systems
  - Chilled water (CHW) system
  - Condenser water (CW) system
  - Sea water system
  - Hot water supply system
  - Steam pipes, gas pipes
- Similar systems in other building services
  - Water supply & distribution (plumbing)

Typical HVAC piping systems



[Source: Kreider, K. F. (ed.), 2001. *Handbook of Heating, Ventilation, and Air Conditioning*, CRC Press, Boca Raton, FL.]

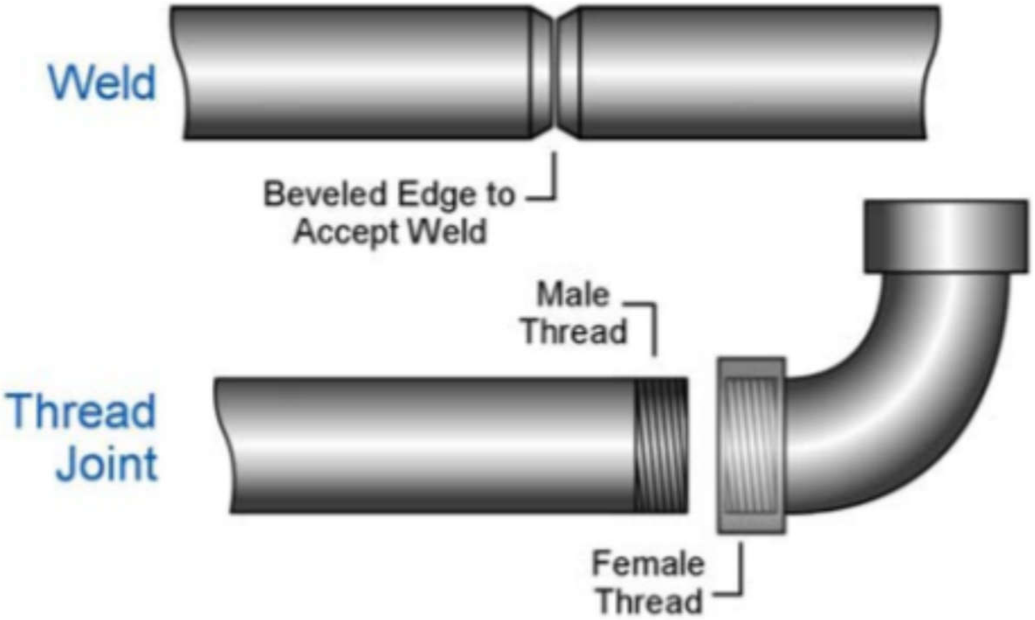
Pipe Systems and Design



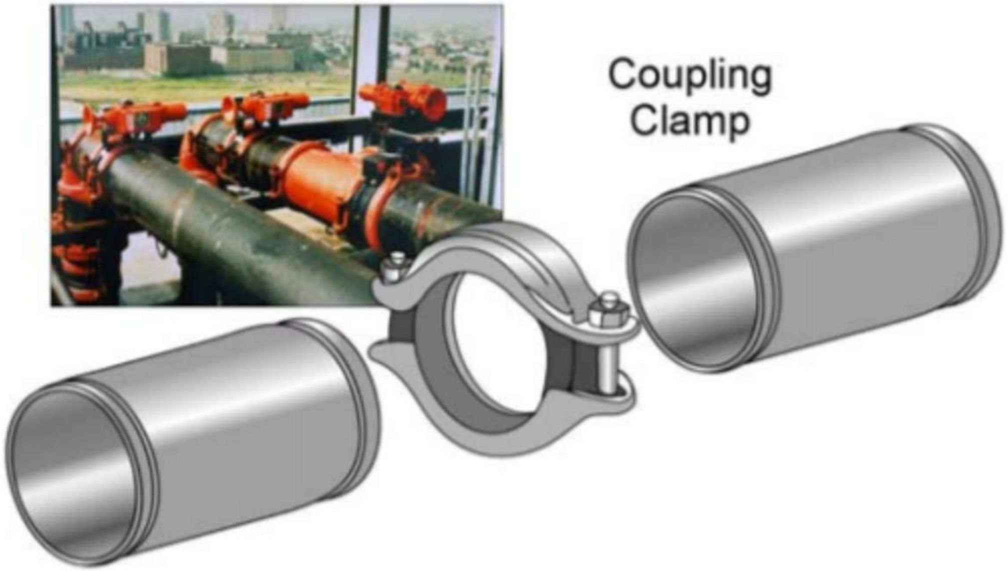
- Common piping materials & joints
  - Steel: Black or galvanized
    - More commonly used for larger piping sizes
    - May be joined by welding or thread/flanged fittings
  - Copper:
    - Typically for pipe sizes 75 mm and smaller
    - Joined with soldering, brazing or pressure seals
  - Plastic: PVC (polyvinyl chloride), CPVC (chlorinated PVC), or PE (polyethylene)
    - Widely used within waste & vent piping systems
    - Joined with socket-type fittings or solvent cements

(See also: https://www.csemag.com/articles/specifying-pipe-and-piping-materials/)

Common pipe jointing methods

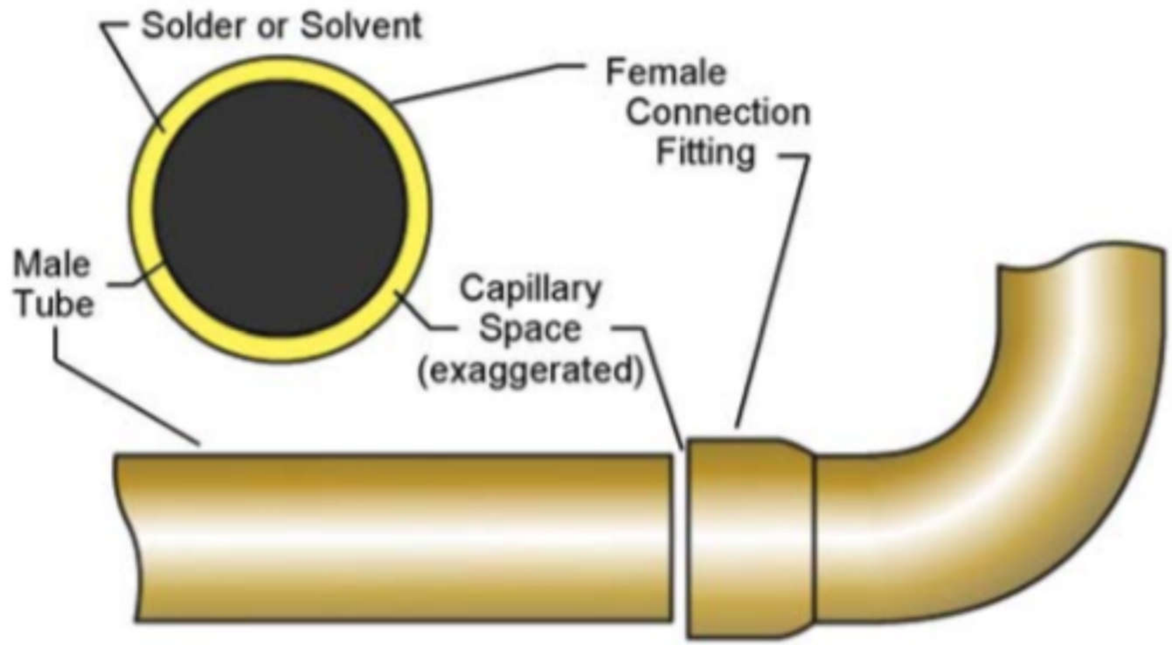


Weld and threaded joint



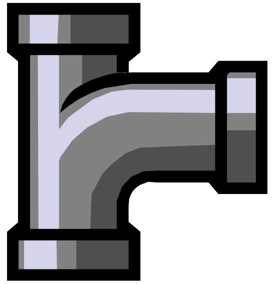
Mechanical (groove) joint

Sweat or solvent joint



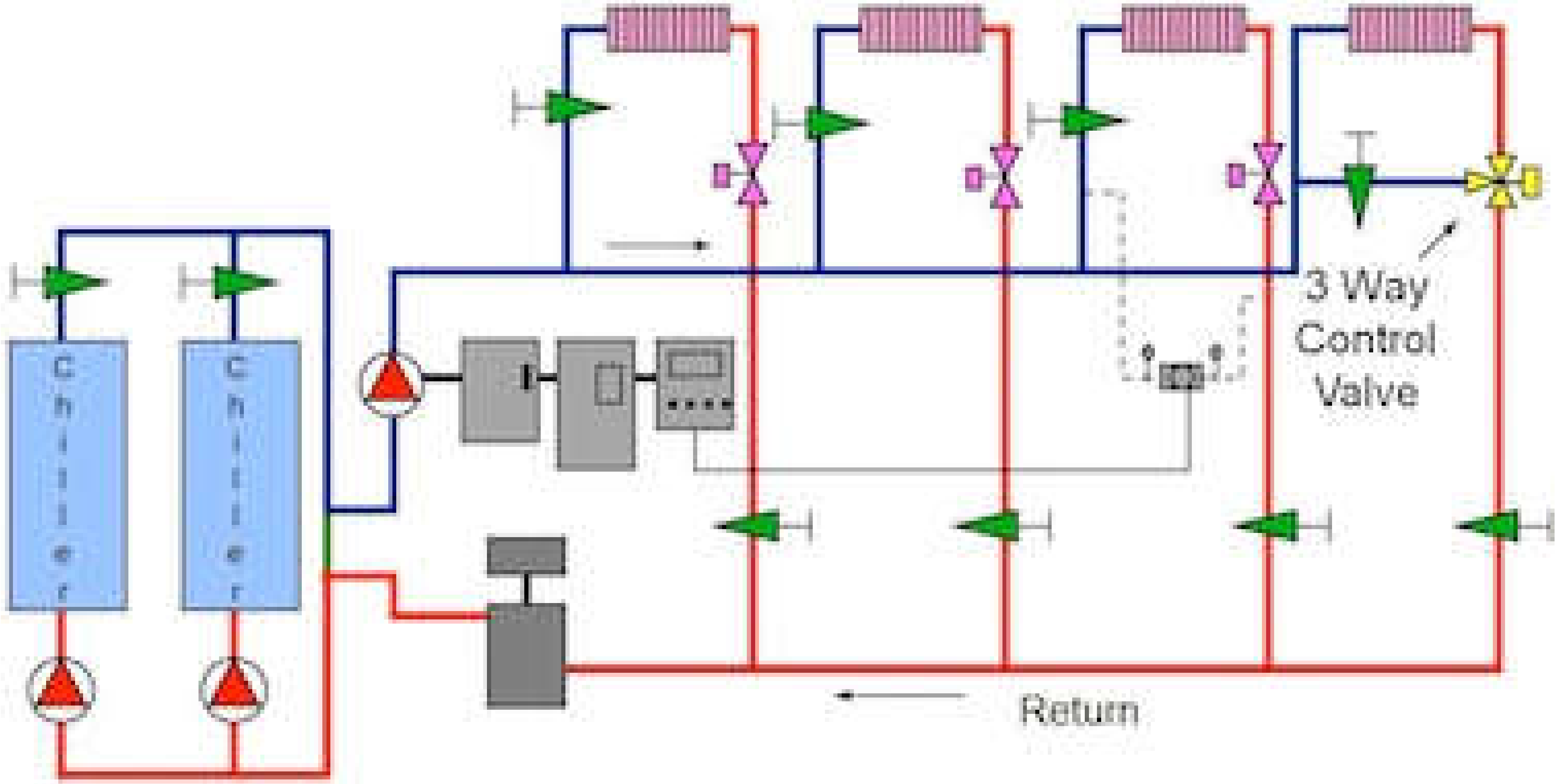
(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Pipe Systems and Design



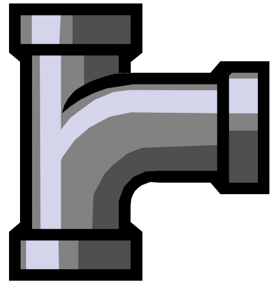
- Piping system consists of: (a) pipe sections, (b) pipe circuits, and (c) equipment components
- A piping system must be analyzed for:
  - Pressures
  - Temperatures
  - Critical circuits (for pressures & temperatures)
- Equipment in the piping system network must be analyzed and designed for:
  - Entering & leaving pressures, pressure loss, entering & leaving temperatures, temp. change

Example of HVAC piping system schematic



(Image source: https://jmpcoblog.com/hvac-blog/understanding-primary-secondary-pumping-part-6-5-ways-to-pump-an-hvac-system)

Pipe Systems and Design



- Two major concerns:
  - Size the pipe (e.g. from charts & tables)
  - Determine the flow-pressure relationship
    - To analyse the system, e.g. to find out pump pressure
    - By using manual or computer-based methods
- Calculations for pipelines or pipe networks
  - Can be very complicated for branches & loops
  - Basic parameters: pipe diameter, length, friction factor, roughness, velocity, pressure drop

Friction loss for water in commercial steel pipe (Schedule 40)

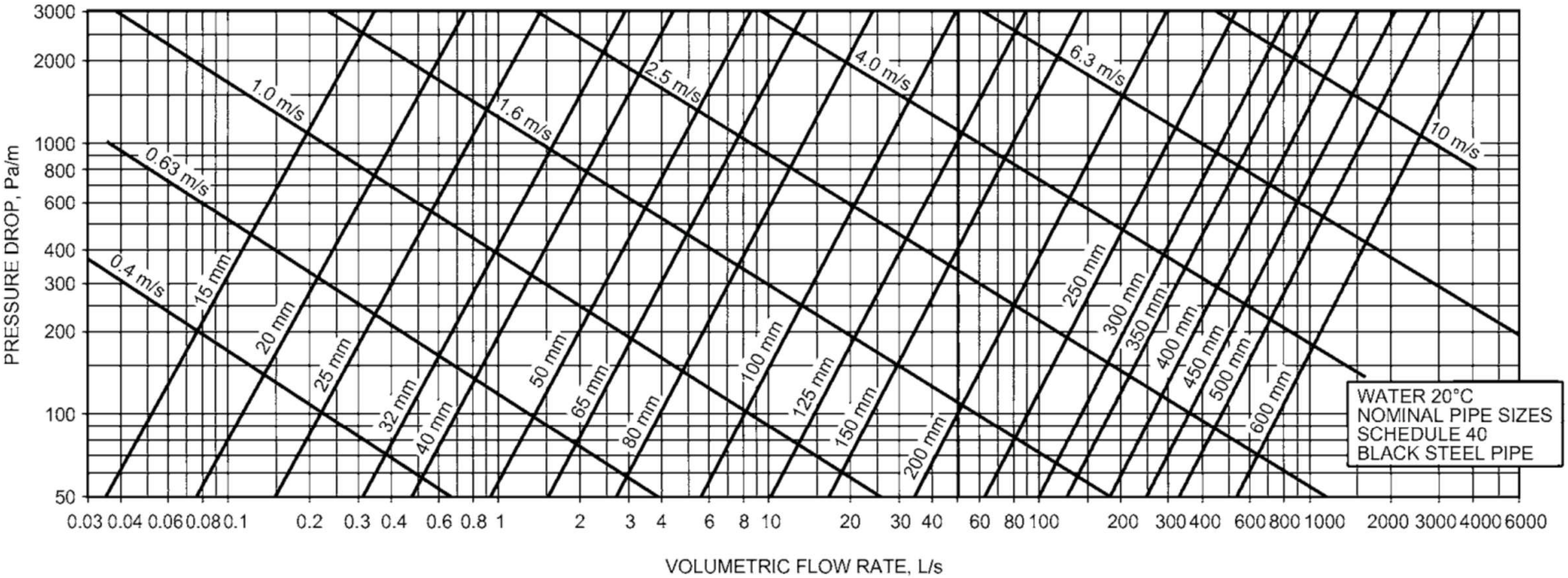


Fig. 14 Friction Loss for Water in Commercial Steel Pipe (Schedule 40)

(Source: ASHRAE Handbook Fundamentals 2017, Chp. 22)

Friction loss for water in copper tubing (Types K, L, M)

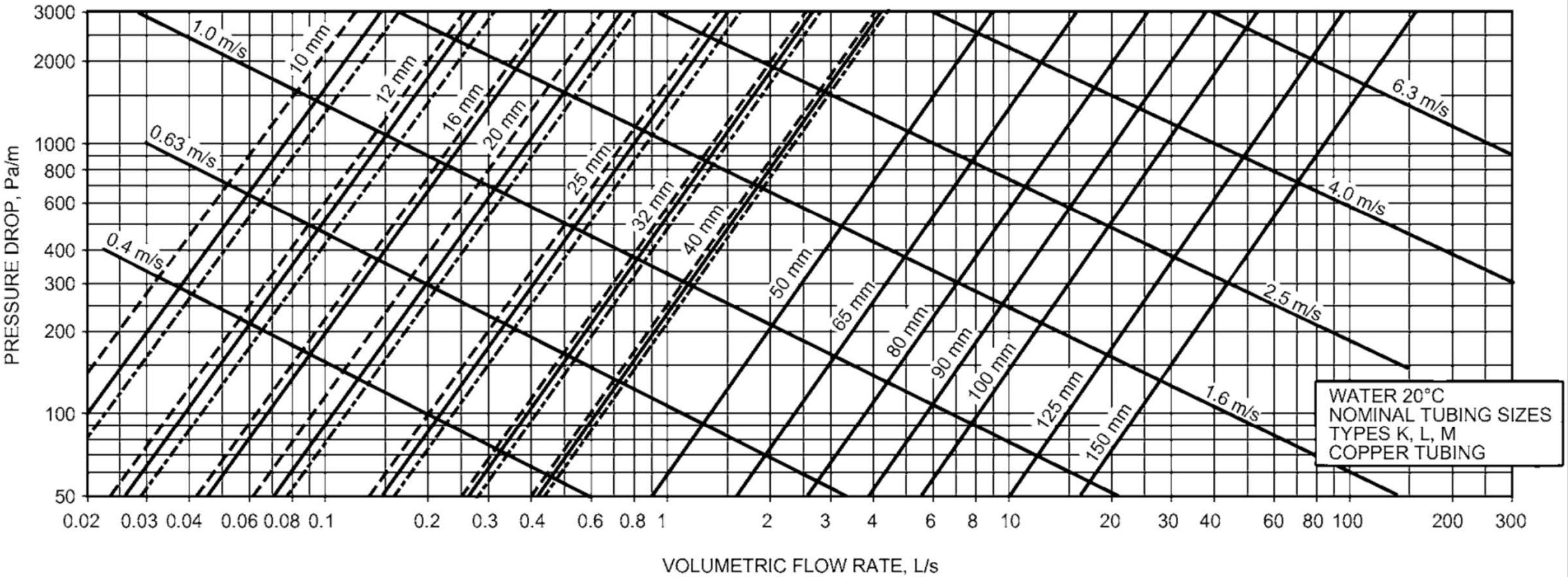


Fig. 15 Friction Loss for Water in Copper Tubing (Types K, L, M)

(Source: ASHRAE Handbook Fundamentals 2017, Chp. 22)

Friction loss for water in plastic pipe (Schedule 80)

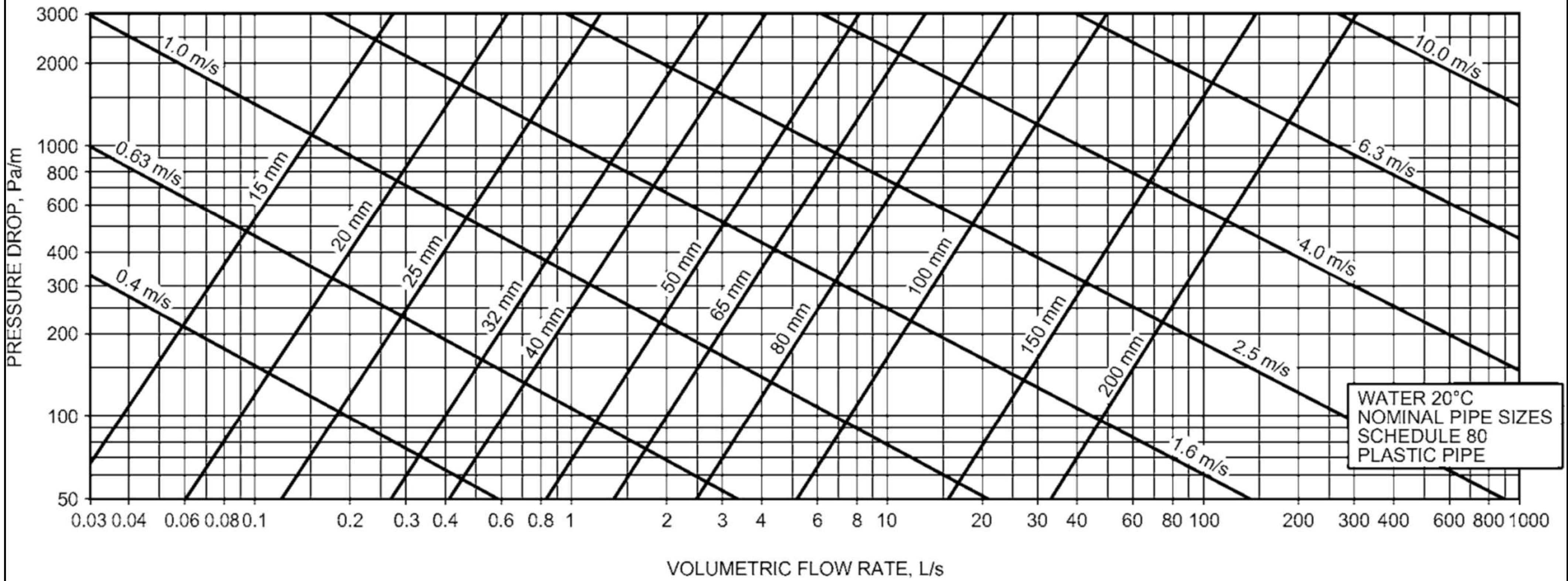


Fig. 16 Friction Loss for Water in Plastic Pipe (Schedule 80)

(Source: ASHRAE Handbook Fundamentals 2017, Chp. 22)

Pipe Systems and Design

- Valve and fitting losses
  - May be greater than pipe friction alone

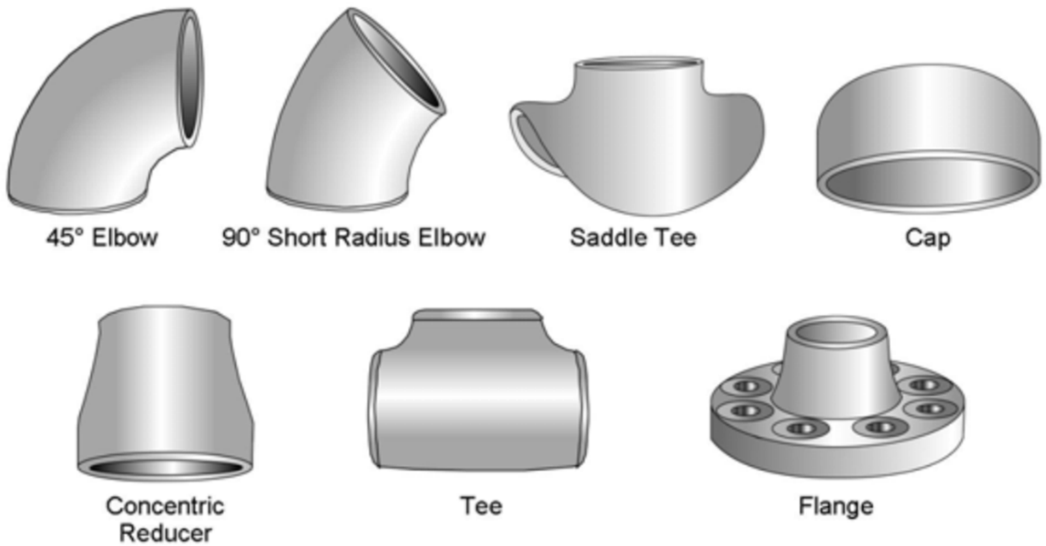
$$\Delta p = K_L \rho \left(\frac{V^2}{2} \right) \quad \text{or} \quad \Delta h = K_L \left(\frac{V^2}{2g} \right)$$

  - K_L = loss coefficient (K factor) of pipe fittings
    - Geometry and size dependent
    - May be expressed as equivalent lengths of straight pipe
  - Valve coefficient (A_v):
    - Volume flow rate $Q = A_v \sqrt{\Delta p / \rho}$

Table 2.5 Loss Coefficients for Fittings

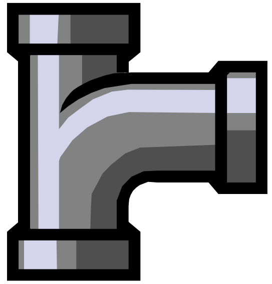
Fitting	K_L
Globe valve, fully open	10.0
Angle valve, fully open	5.0
Butterfly valve, fully open	0.4
Gate valve, fully open	0.2
3/4 open	1.0
1/2 open	5.6
1/4 open	17.0
Check valve, swing type, fully open	2.3
Check valve, lift type, fully open	12.0
Check valve, ball type, fully open	70.0
Foot valve, fully open	15.0
Elbow, 45°	0.4
Long radius elbow, 90°	0.6
Medium radius elbow, 90°	0.8
Short radius (standard) elbow , 90°	0.9
Close return bend, 180°	2.2
Pipe entrance, rounded, r/D < 0.16	0.1
Pipe entrance, square-edged	0.5
Pipe entrance, re-entrant	0.8

Types of Valves



(Source: Larock, Jeppson and Watters, 2000: *Hydraulics of Pipeline Systems*)

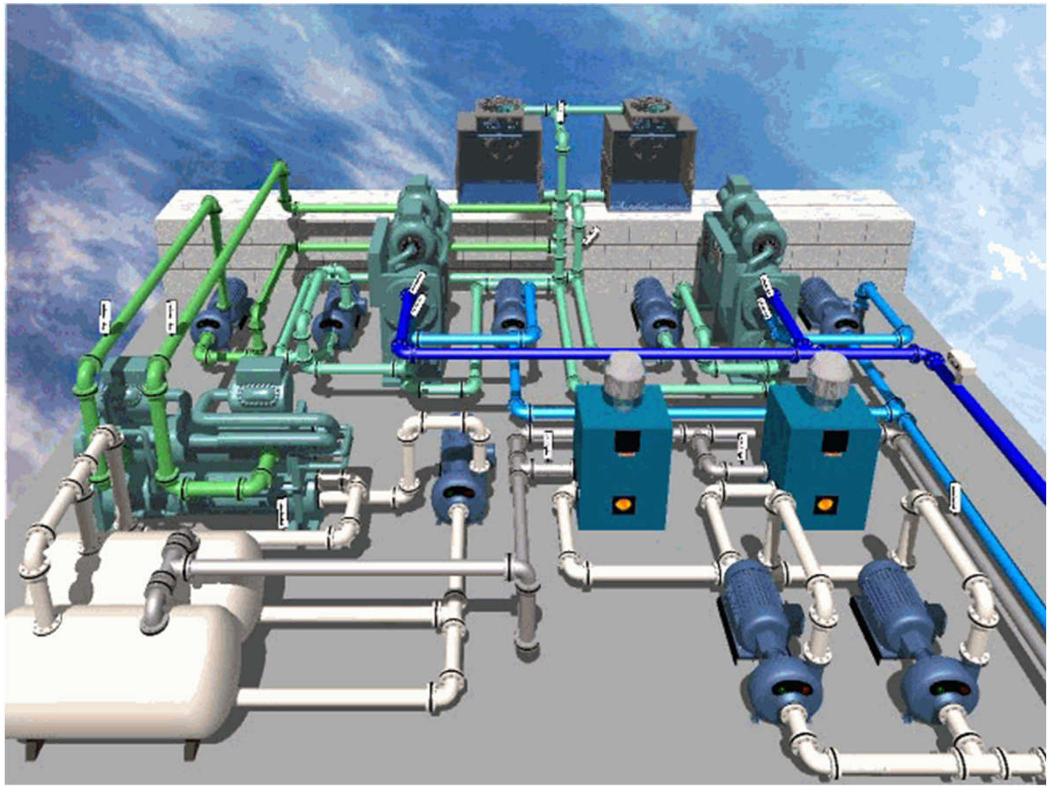
Pipe Systems and Design



- Practical design issues
  - Select a pipe size for desired total flow rate and available or allowable pressure drop, e.g.
    - Often assume 2.5 m / 100 m pipe length
    - Velocity limit 1.2 m/s for pipe < 50 mm dia., pressure drop limit 400 Pa/m for pipe > 50 mm dia.
  - Rule of thumb for practical design:
    - Assume design pipe length is 1.5 to 2.0 times actual to account for fitting losses; after pipe diameter is selected, then evaluate the influence of each fitting
  - Other considerations: e.g. noise & water hammer

HVAC Water Systems

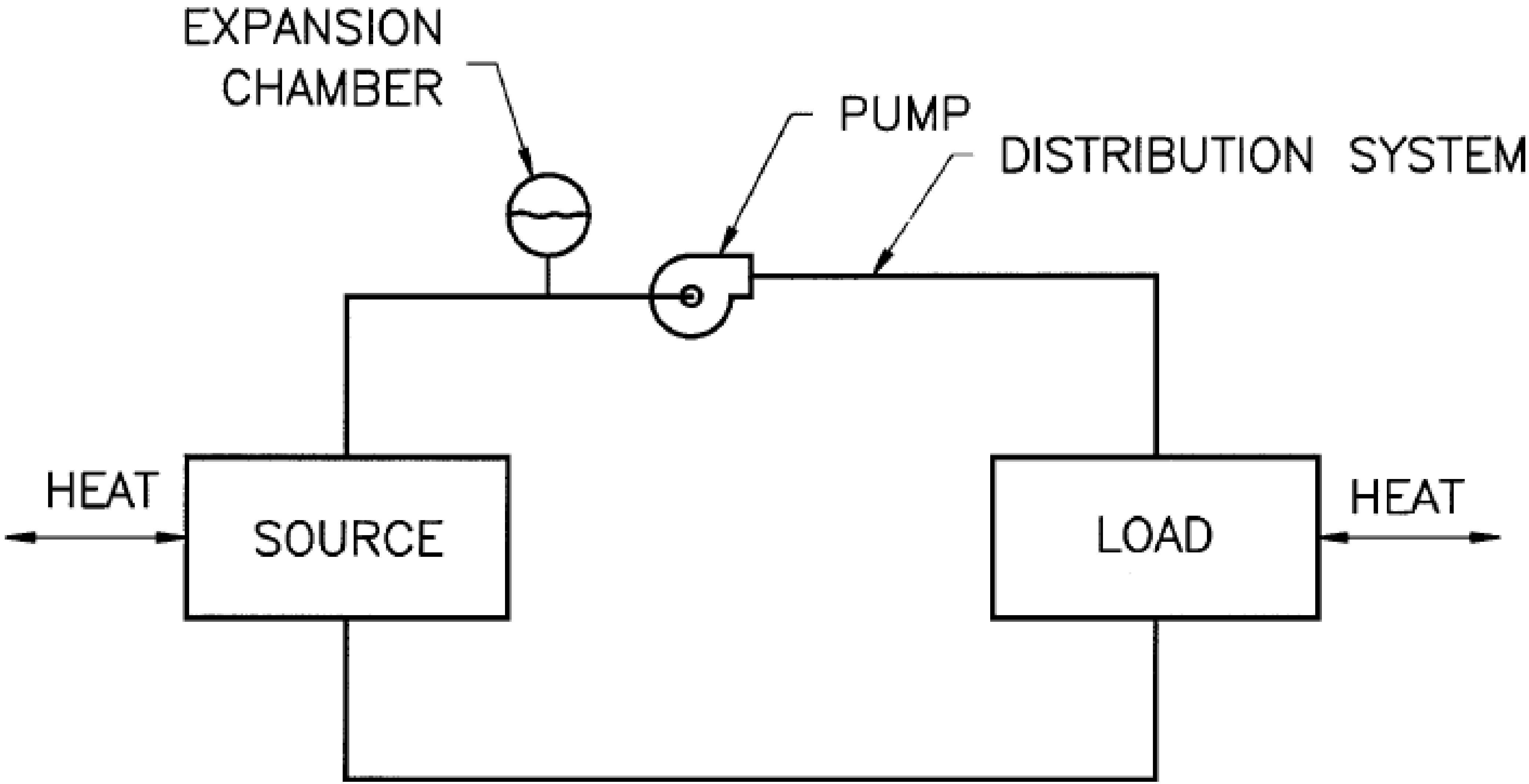
- HVAC water systems can be classified by
  - Operating temperature
  - Flow generation
  - Pressurization
  - Piping arrangement
  - Pumping arrangement



HVAC Water Systems

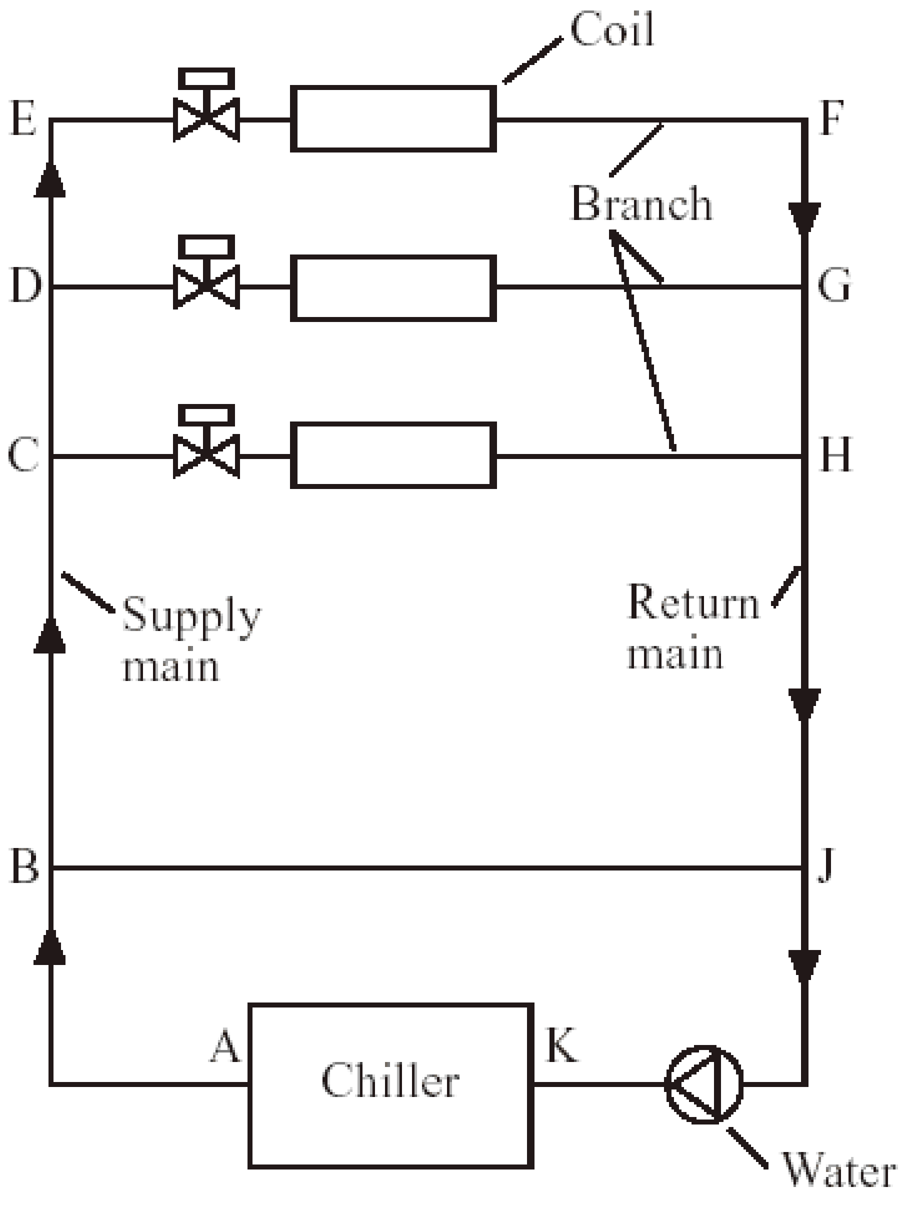
- Open water systems, e.g. using cooling tower
- Closed water systems
  - Chilled water (CHW) system [4-13 ^{o}C, 825 kPa]
  - Condenser water (CW) system
  - Dual temperature water system
  - Low temp. water (LTW) system [Max. 120 ^{o}C, < 1100 kPa]
  - Medium temp. water (MTW) system [120-125 ^{o}C, < 1100 kPa]
  - High temp. water (HTW) system [> 175 ^{o}C, > 2070 kPa]
- Once-through system, e.g. sea water system

Basic components of HVAC water (hydronic) system



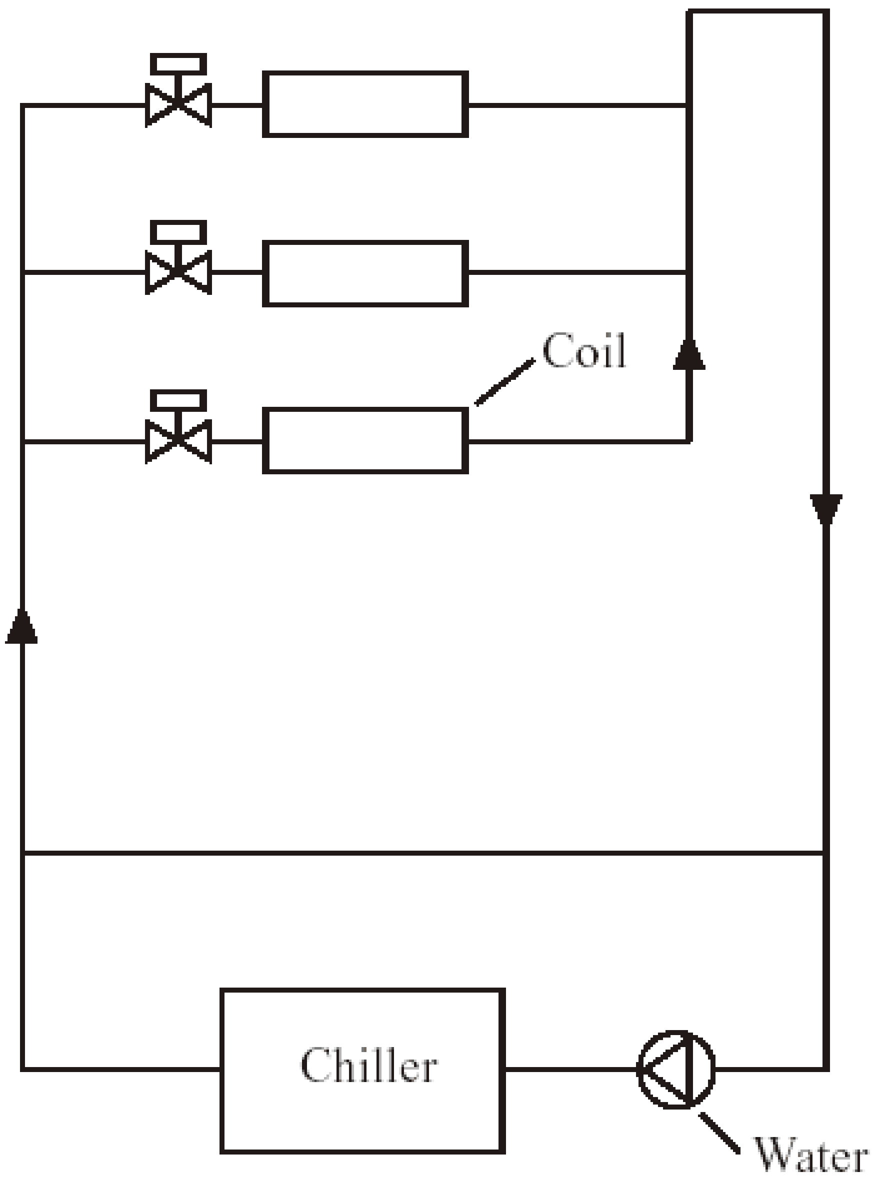
(Source: *ASHRAE HVAC Systems and Equipment Handbook 2004*)

2-pipe direct and reverse return systems



(a)

2-pipe direct return

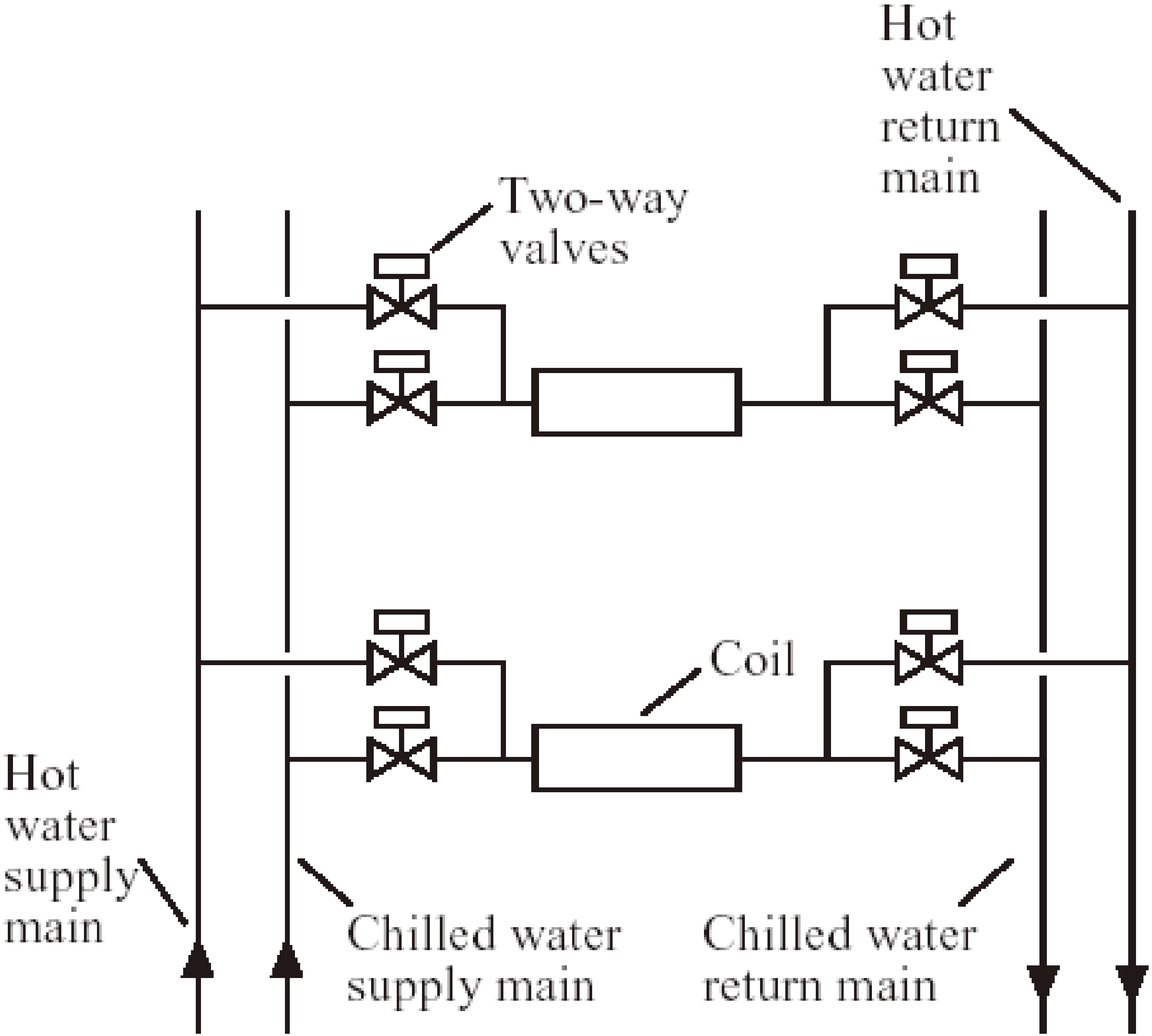


(b)

2-pipe reverse return

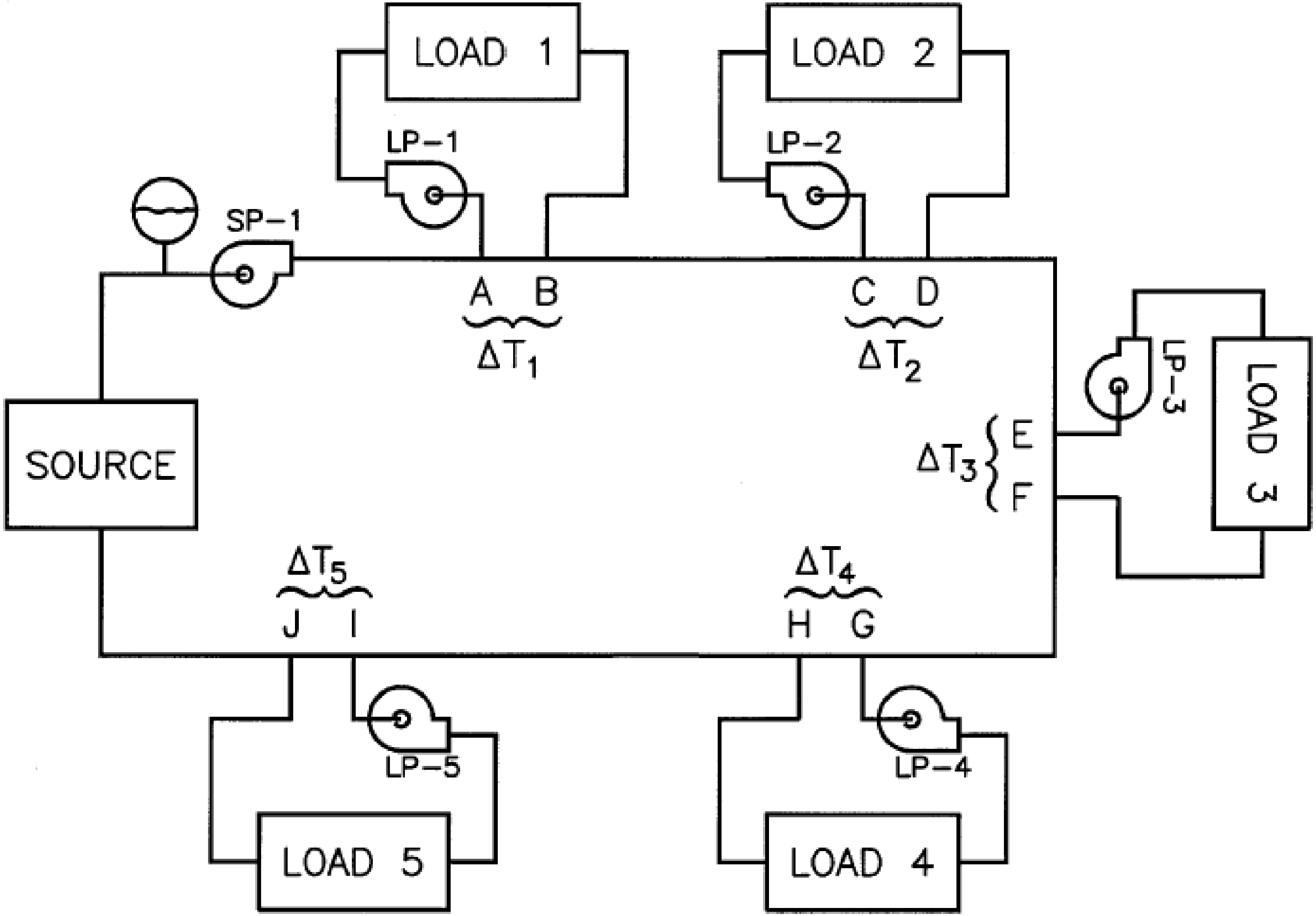
(Source: *ASHRAE HVAC Systems and Equipment Handbook 2004*)

4-pipe system (dual temperature)



(Source: *ASHRAE HVAC Systems and Equipment Handbook 2004*)

Series circuit with load pumps

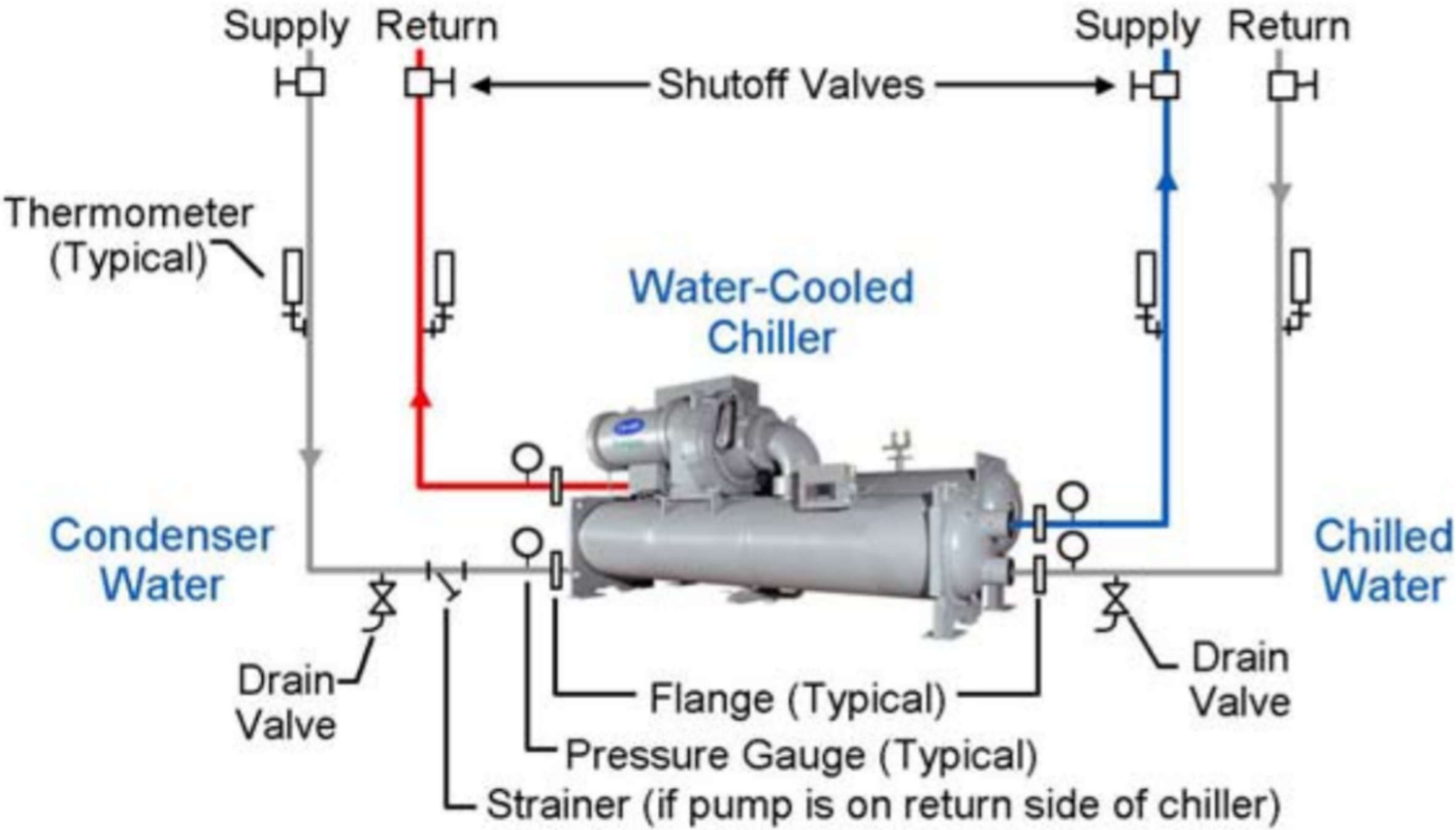


(Source: *ASHRAE HVAC Systems and Equipment Handbook 2004*)

HVAC Water Systems

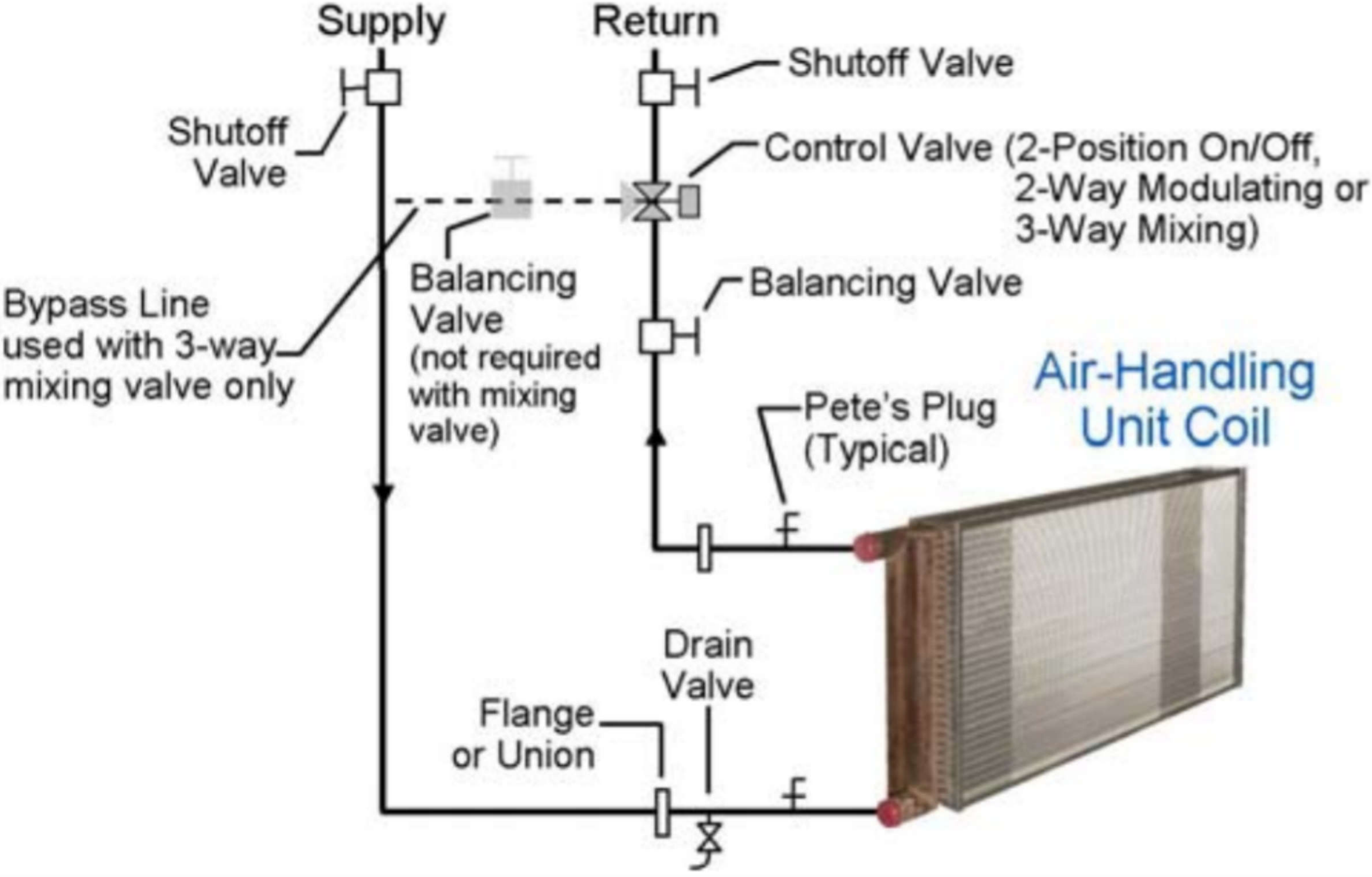
- Typical piping details at equipment
  - Chillers
    - Valves, thermometers, pressure gauges
  - Fan coil or AHU (air handling unit) coil
    - Balancing, control, shutoff & drain valves
  - Pumps
    - Balancing, shutoff, check & drain valves
    - Strainers, flexible connectors

Typical water-cooled chiller piping details



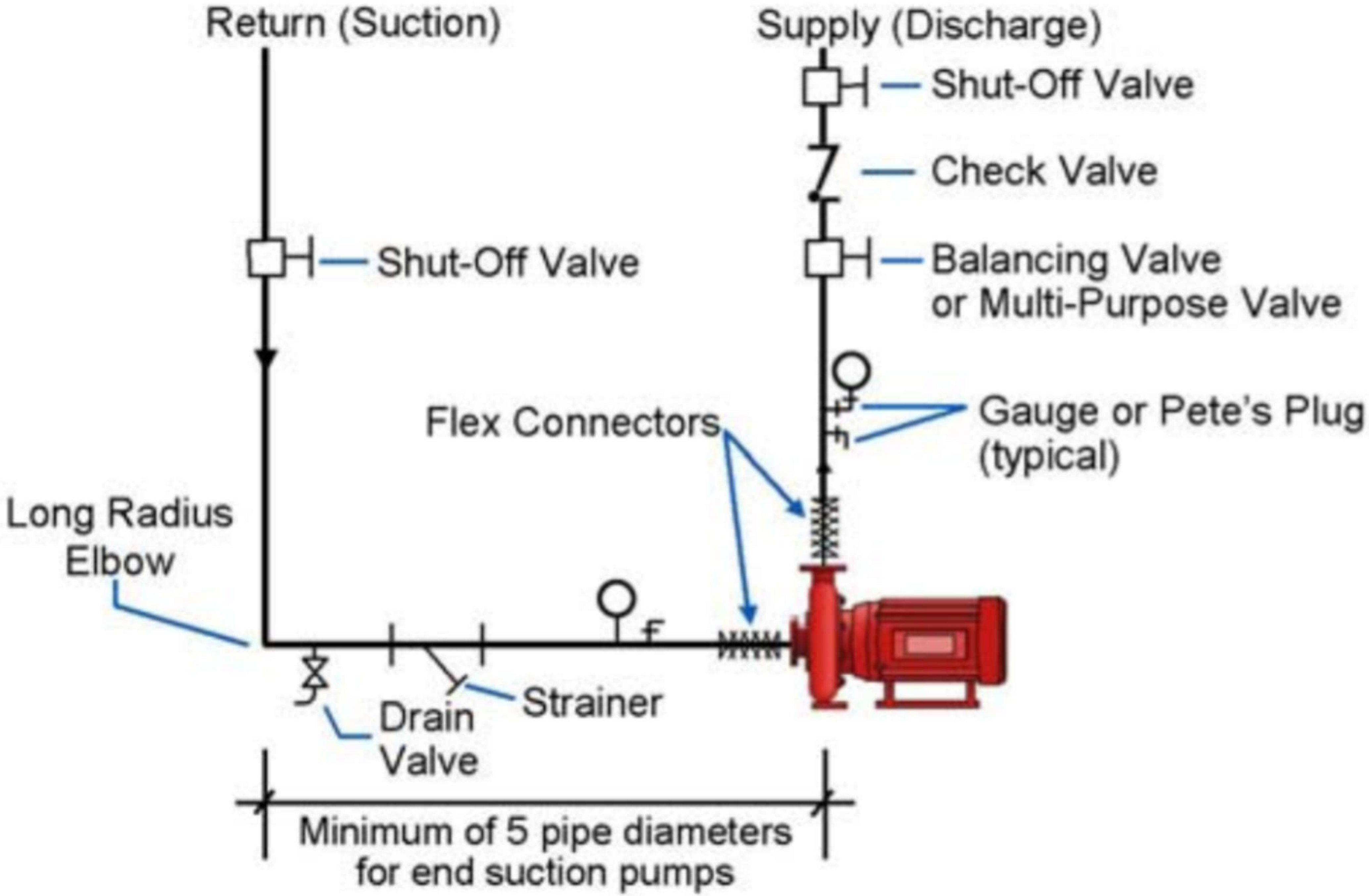
(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Typical chilled or hot water coil piping detail



(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Typical pump piping detail

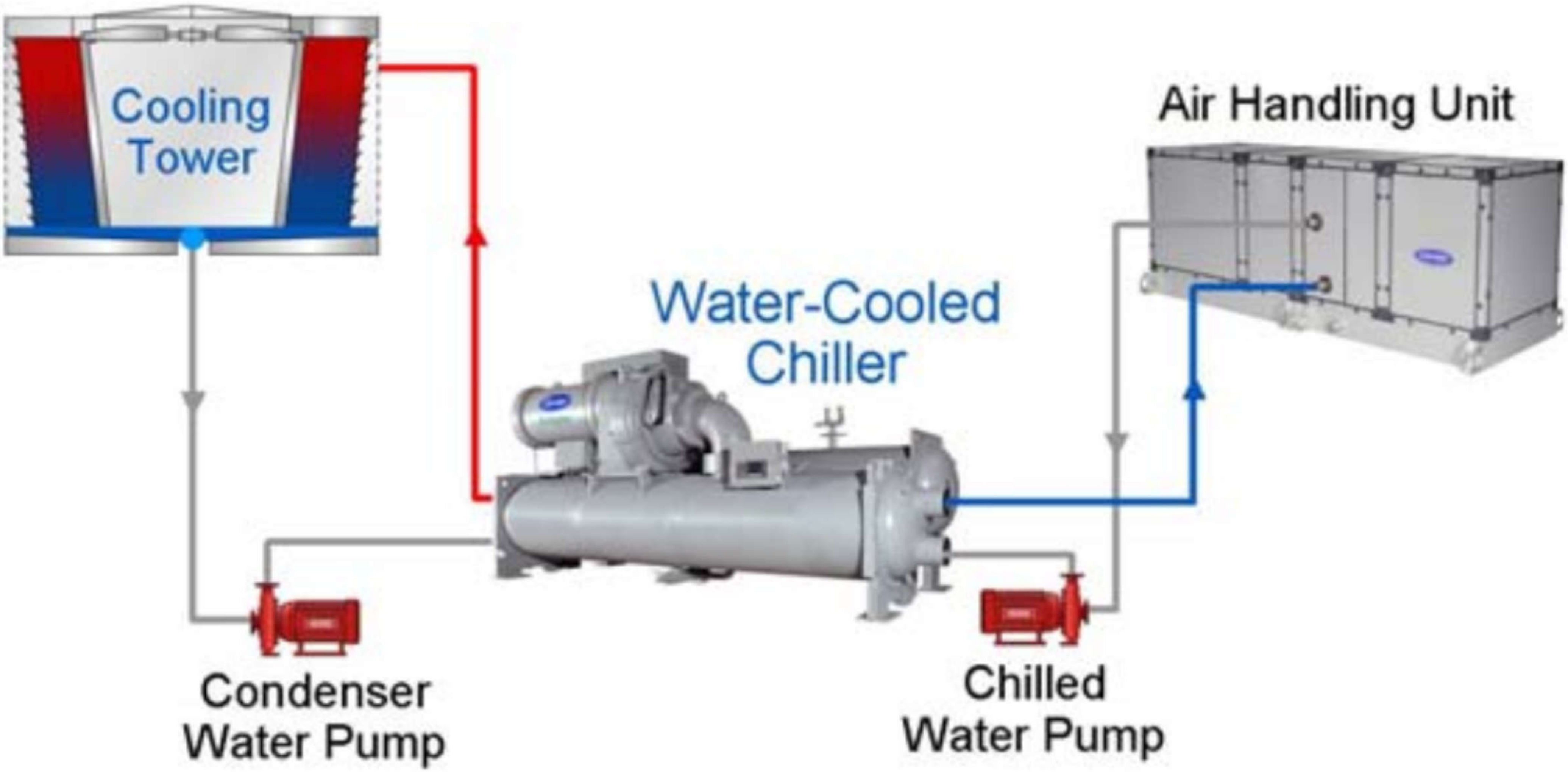


(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

HVAC Water Systems

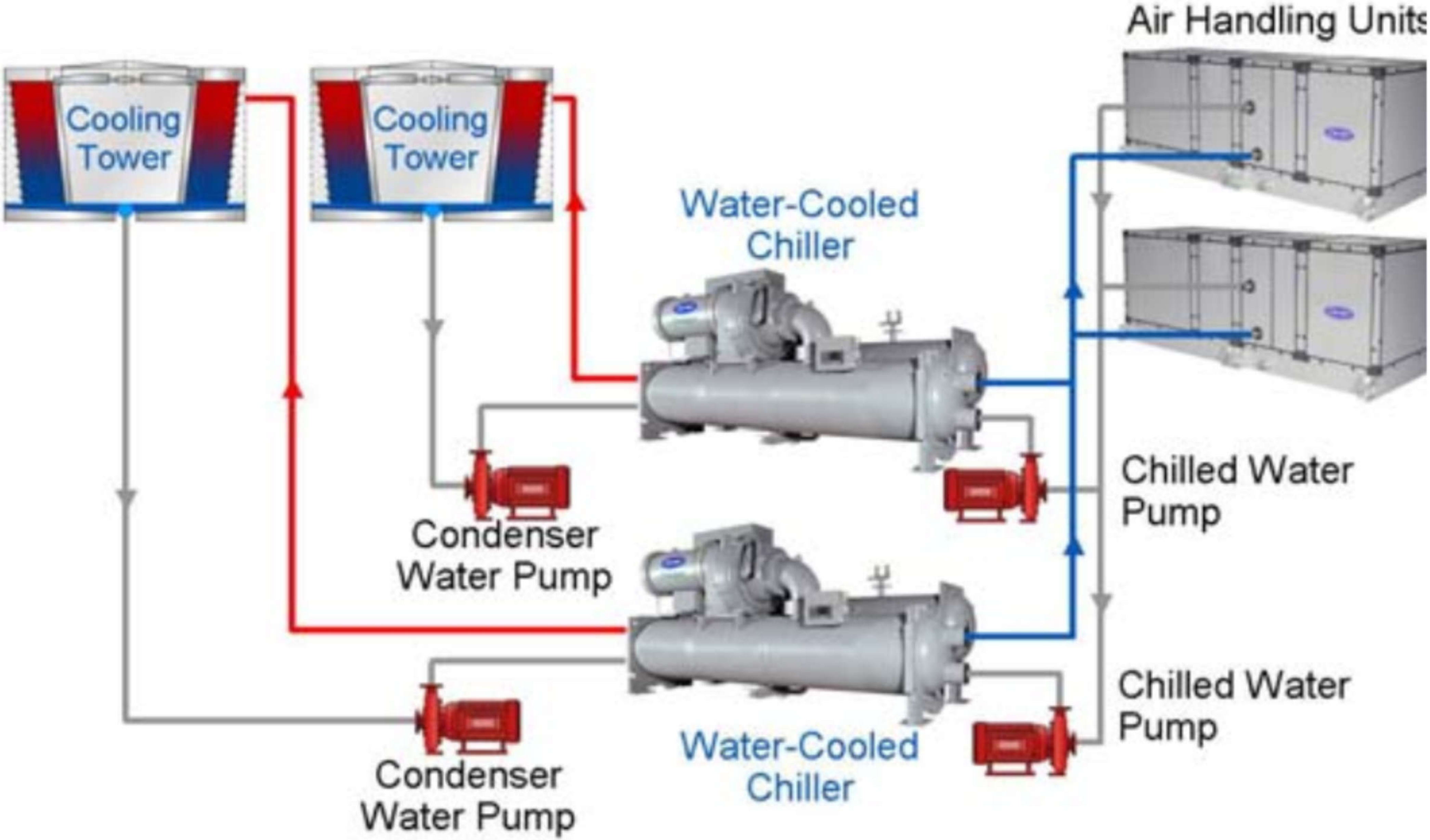
- System piping arrangements
  - Parallel and series chiller evaporators
  - Single water-cooled chiller loop
  - Multiple water-cooled chiller loop
    - With dedicated pumps
    - With manifold pumps
  - Primary-secondary chilled water system
  - Primary-only, variable-flow chilled water system

Single water-cooled chiller system piping



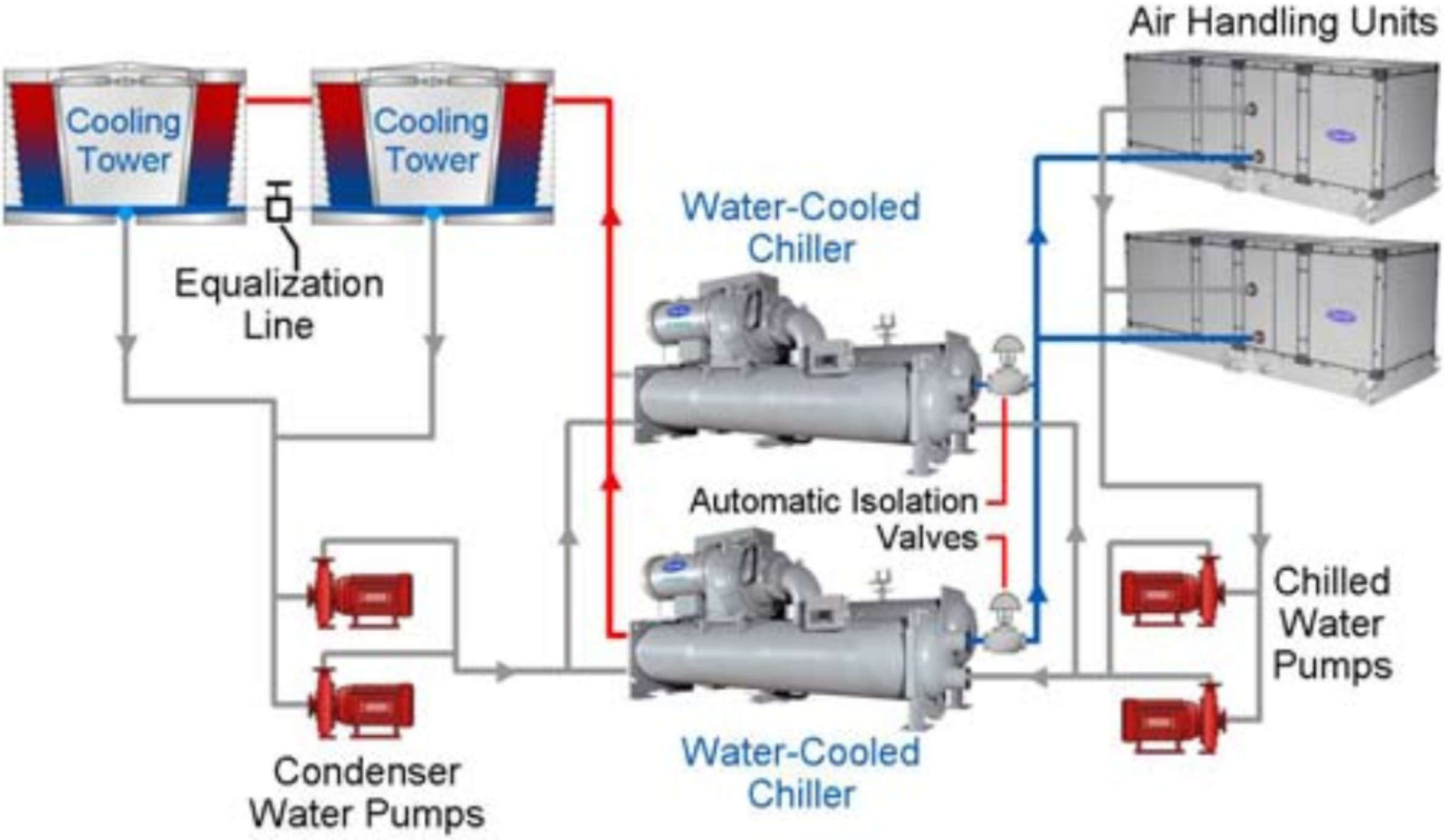
(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Multiple water-cooled chillers with dedicated pumps



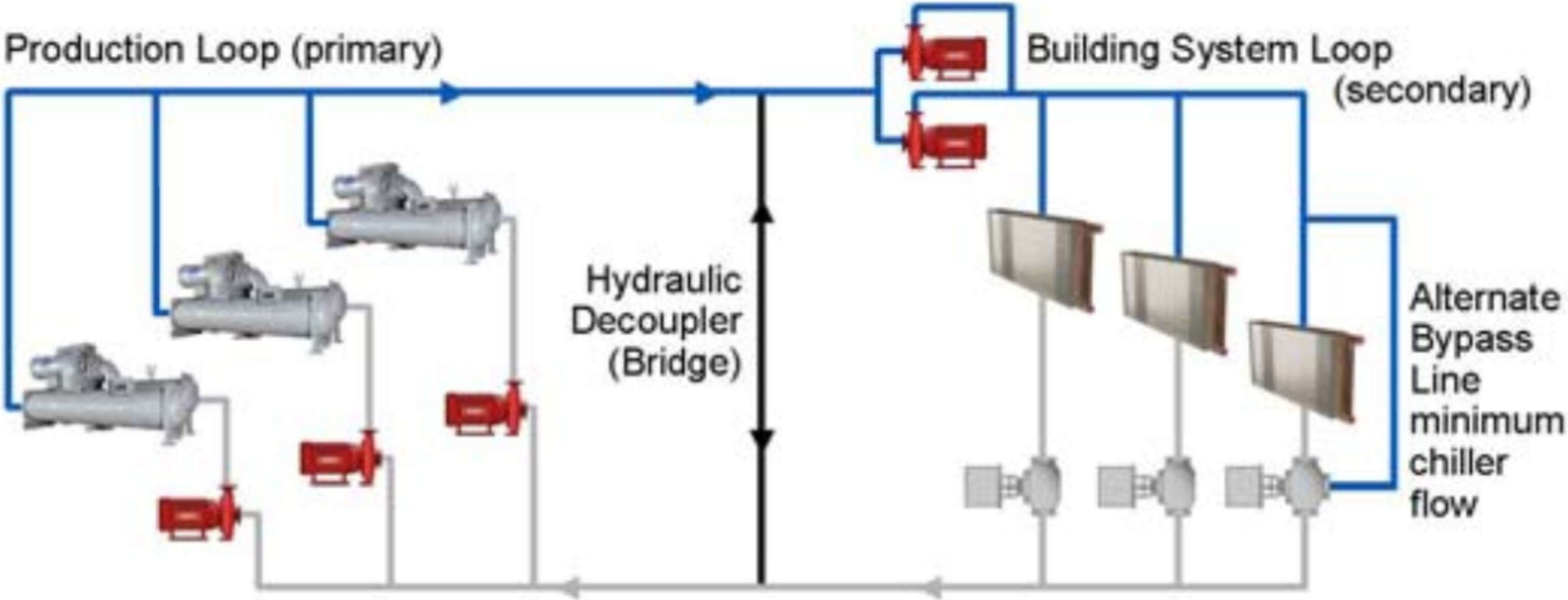
(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Multiple water-cooled chillers with manifold pumps



(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

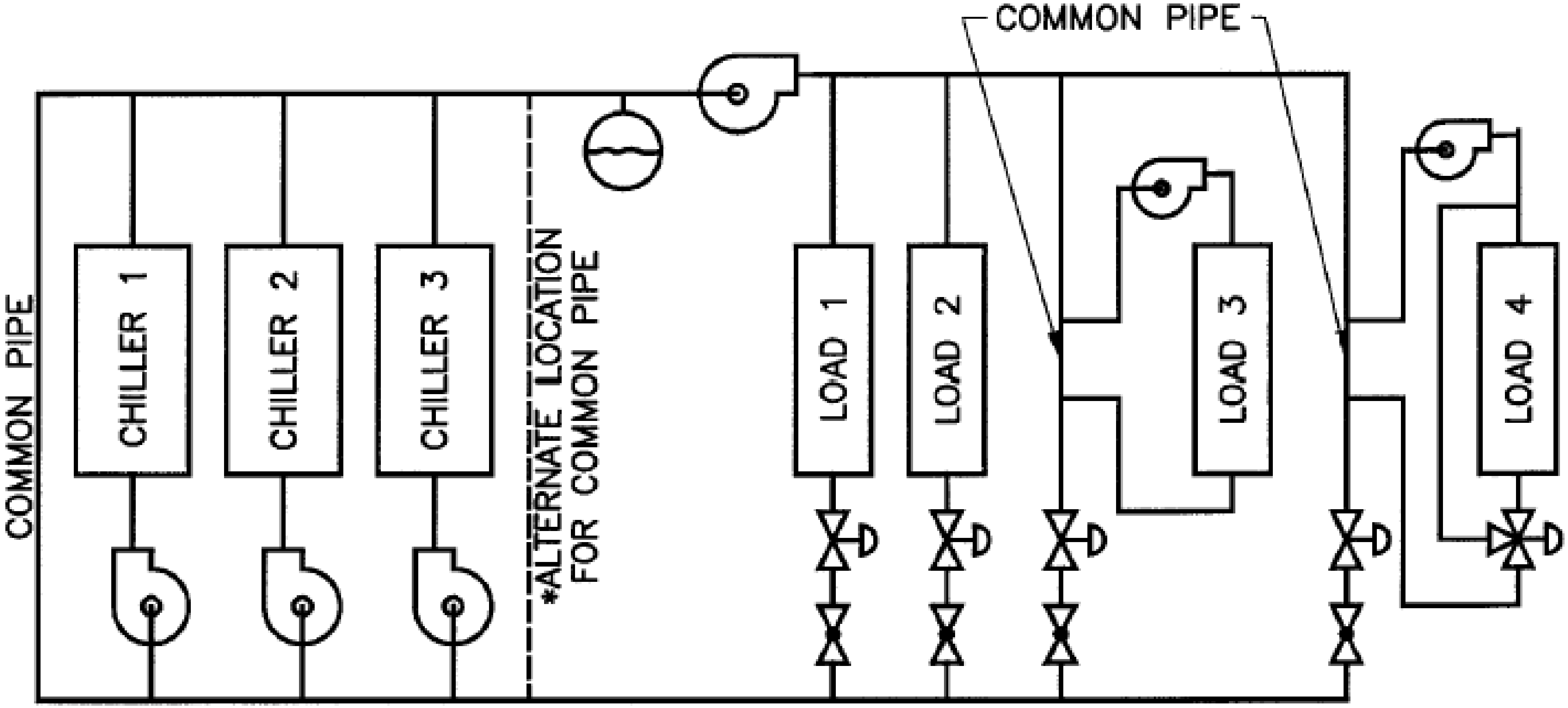
Primary-secondary piping system



- Secondary pumping station
  - One pump active, the other standby (lead-lag)
  - Pumps are VFD-equipped if all coils are 2-way
  - Matches secondary flow to coil loads
- Hydraulic decoupler maintains constant primary flow

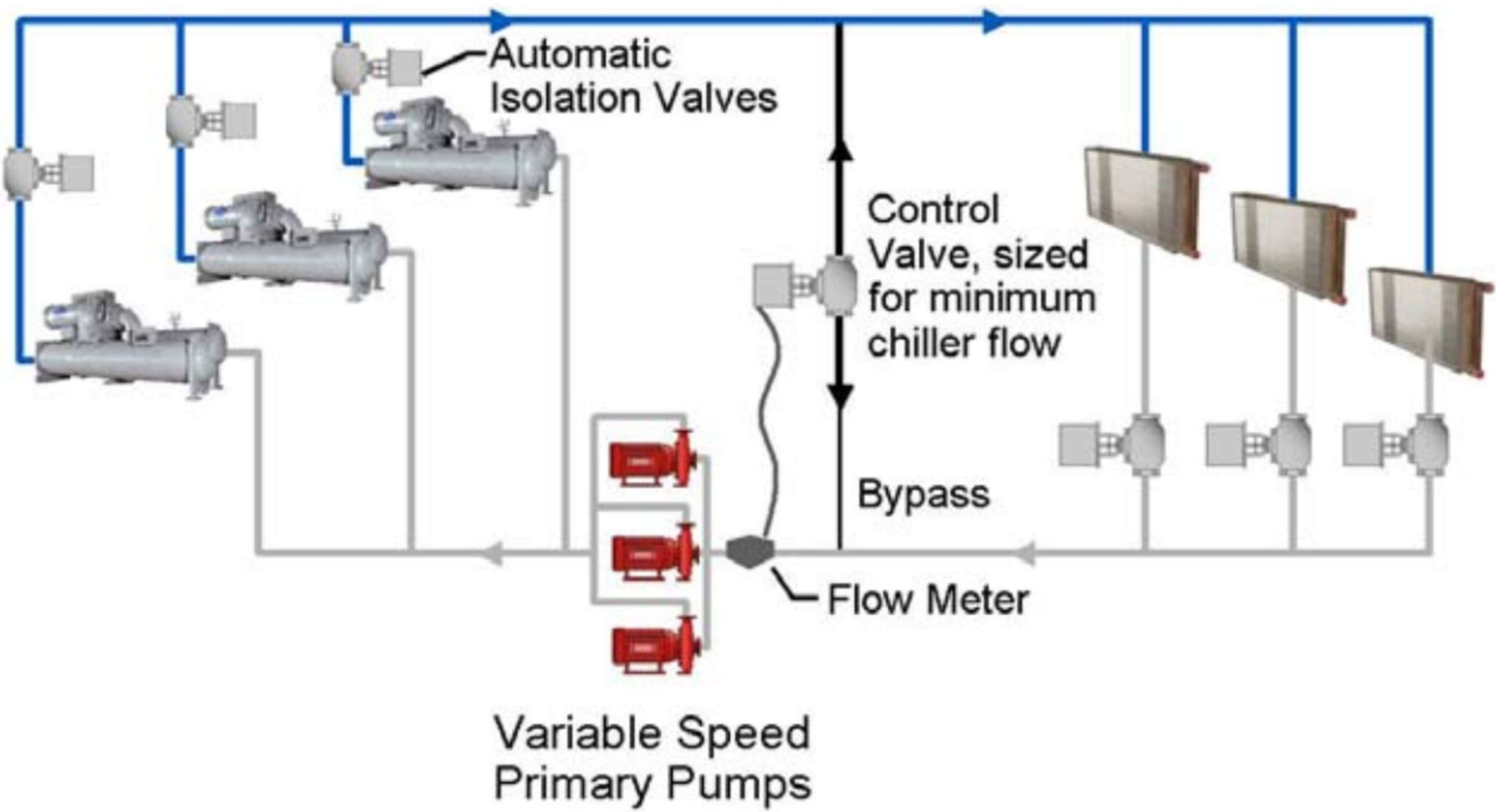
(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Multiple chiller variable flow chilled water system (primary-secondary)



(Source: *ASHRAE HVAC Systems and Equipment Handbook 2004*)

Primary-only variable-flow system



(Source: Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program.)

Practical Design Issues

- Heat transfer in water systems
  - Terminal units/devices that convey heat from/to water for heating/cooling
  - Common heat exchangers
    - Water-to-air finned coil
    - Water-to-water
  - Heating load devices, e.g. radiators
  - Cooling load devices, e.g. fan coil units (FCU)

Calculate Heat Transferred to or from Water:

$$q_w = 1000\dot{m}c_p\Delta t$$

where

q_w = heat transfer rate to or from water, W
$\dot{m}$ = mass flow rate of water, kg/s
c_p = specific heat of water, kJ/(kg·K)
Δt = water temperature increase or decrease across unit, K
1000 = constant to change kJ in c_p to J

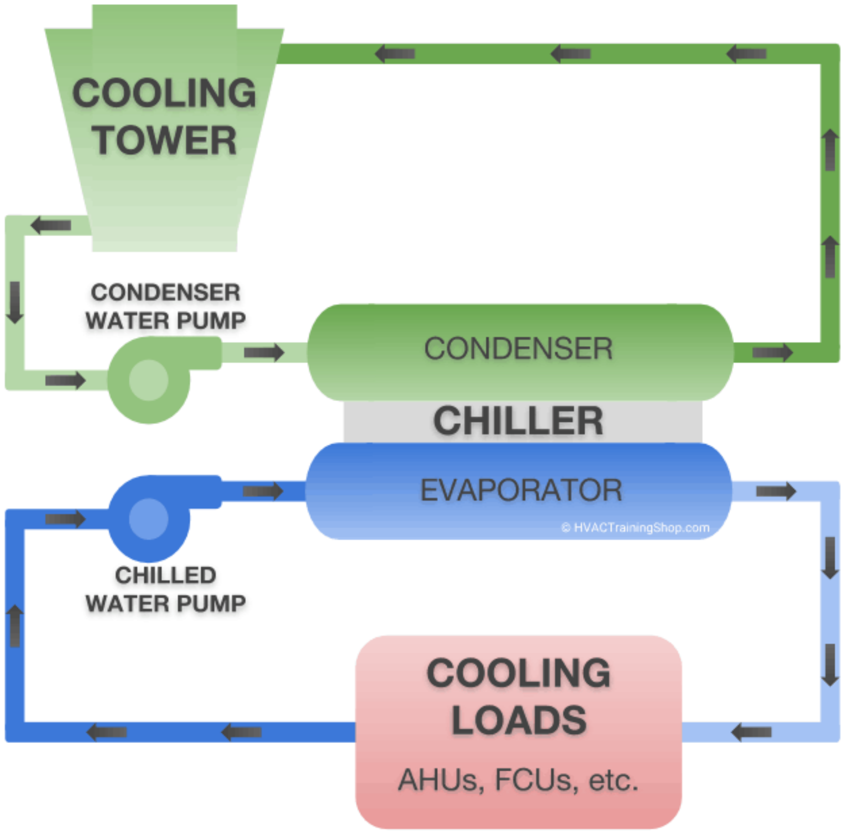
$$q_w = \rho_w c_p Q_w \Delta t$$

where

Q_w = water flow rate, L/s
ρ_w = density of water, kg/m^3

Practical Design Issues

- Design issues
  - Design water temperature
  - Flow rate
  - Piping layout
  - Pump selection
  - Terminal unit selection
  - Control method



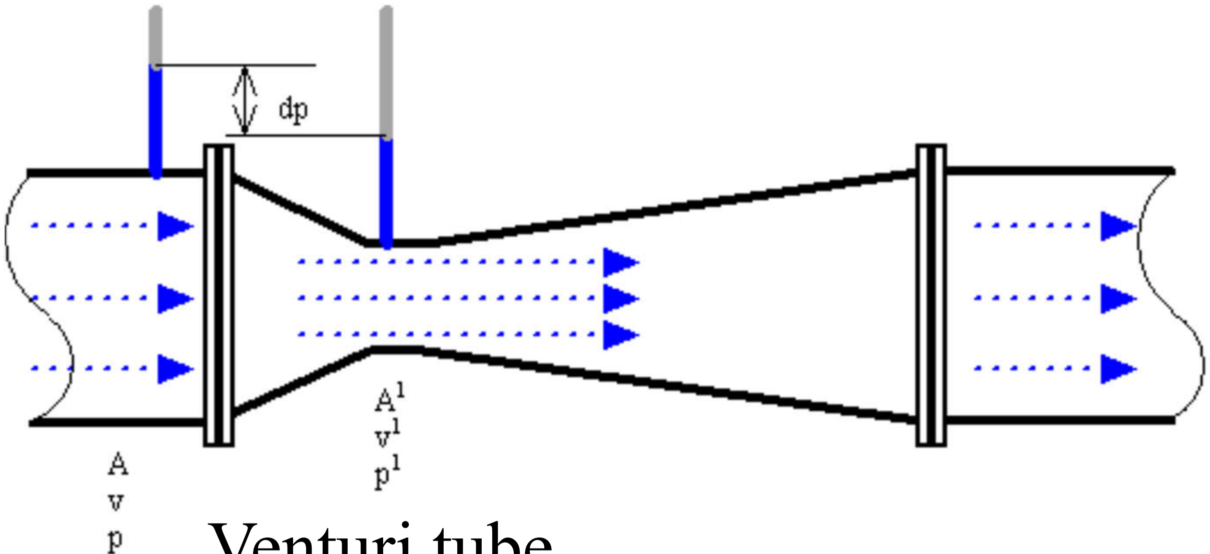
Practical Design Issues

- Design principles
  - Constant flow? Variable flow? Intermittent flow?
  - Direct return piping or reverse return piping
  - Direct return riser & reverse zone piping
- Design factors
  - Pump speed controls
  - Pressure distribution
  - System balancing
  - Thermal expansion & joints (or loops)

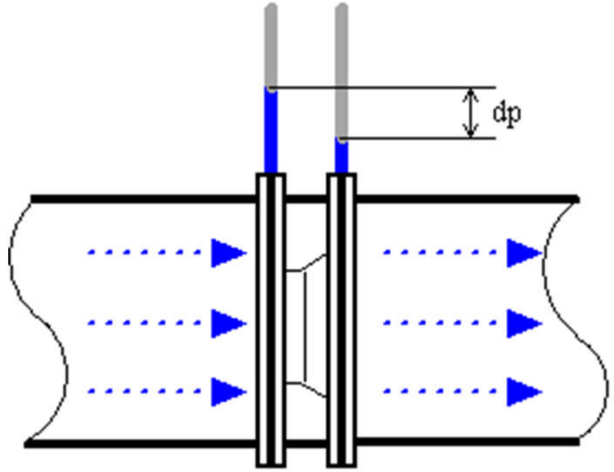
Practical Design Issues

- Piping materials
  - Chilled water: black & galvanized steel
  - Hot water: black steel, hard copper
  - Condenser water: black steel, galvanized ductile iron, PVC
- Flow rate measurements
  - Venturi, nozzle & orifice flowmeters
  - Variable area flowmeters (rotameters)
  - Turbine flowmeters

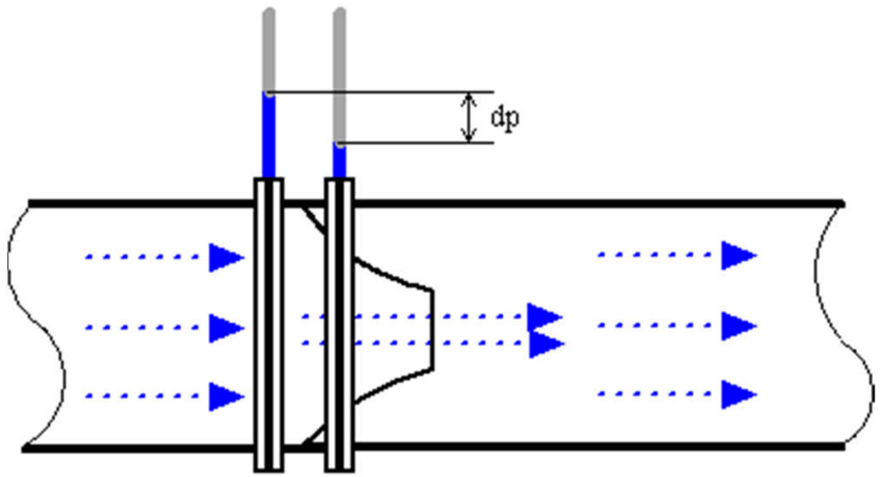
Flow measurements methods



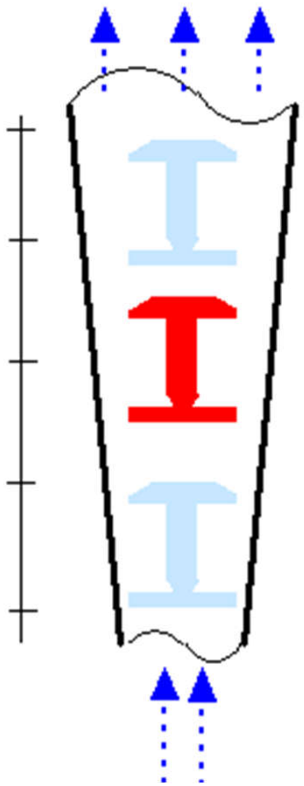
Venturi tube



Orifice plate



Flow nozzle



Variable area flowmeter or rotameter

(Source: Types of Fluid Flow Meters https://www.engineeringtoolbox.com/flow-meters-d_493.html)

Practical Design Issues

- Other design considerations
  - Makeup water (from city water or wells)
  - Safety relief valves (for pressurised systems)
  - Air elimination (e.g. by air separator/vent)
  - Drain (at low points) & shutoff (for isolation)
  - Balance fittings (allow balancing of sub-circuits)
  - Strainers (remove dirt)
  - Insulation (reduce heat loss & condensation)
  - Condensate drains (to drainage system or recover)

Practical Design Issues

- System design process
  - "*A Guide to HVAC Building Services Calculations*" - water flow distribution systems
    - W1 Pipe sizing – general
    - W2 Pipe sizing – straight length
    - W3 Pipe sizing – pressure drop across fittings
    - W4 System resistance for pipework – index run
    - W5 Pump sizing
    - W6 Water system pressurisation

(Ref: Pennycook, K., Churcher, D. and Bleicher, D., 2007. *A Guide to HVAC Building Services Calculations*, 2nd ed., Building Services Research and Information Association, Bracknell, Berkshire, England.)

Practical Design Issues

- Basic equations
  - Darcy-Weisbach Equation (for fully developed flows of all Newtonian fluids)

$$\Delta p = f\left(\frac{L}{D}\right)\left(\frac{\rho V^2}{2g}\right) \quad \text{or} \quad \Delta h = f\left(\frac{L}{D}\right)\left(\frac{V^2}{2g}\right)$$

  - Colebrook-White Equation (for transition region):

$$\frac{1}{\sqrt{f}} = 1.14 + 2\log(D/\varepsilon) - 2\log\left[1 + \frac{9.3}{\mathrm{Re}(\varepsilon/D)\sqrt{f}}\right]$$

    - * The equation is implicit in f (appears on both sides), so iterations are required to solve for f.

Practical Design Issues

- Basic equations (cont'd)
  - Hazen-Williams Equation (alternative to Darcy-Weisbach formula; empirical)

$$\Delta p = 6.819 L \left(\frac{V}{C}\right)^{1.852} \left(\frac{1}{D}\right)^{1.167} (\rho g)$$

    - C = roughness factor (typically, C = 150 for plastic or copper pipe, C = 140 for new steel pipe, C < 100 for badly corroded or very rough pipe)

(See also: Darcy-Weisbach equation - Wikipedia http://en.wikipedia.org/wiki/Darcy%E2%80%93Weisbach_equation
Hazen-Williams equation - Wikipedia http://en.wikipedia.org/wiki/Hazen%E2%80%93Williams_equation)

Practical Design Issues

- Basic equations (cont'd)
  - Exponential formula:
    - The previous equations (Darcy-Weisbach or Hazen-Williams) can be expressed by an exponential form to generalise the theory

$$\Delta h = KQ^n$$

    - Q = volume flow rate; K, n = coefficient & exponential
    - Values for the coefficient and n change, depending on which equation is used

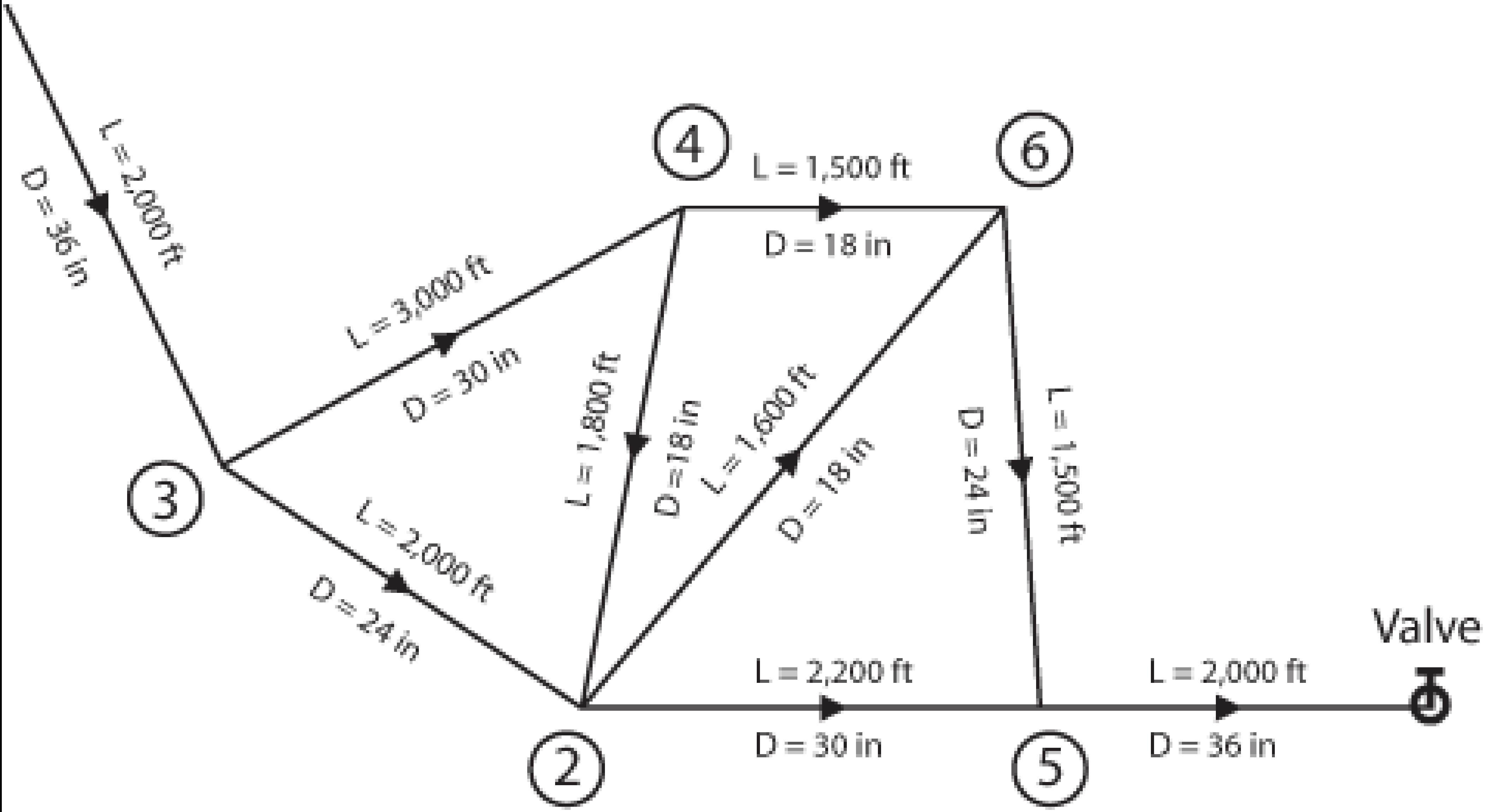
Pipe Network Analysis

- Pipe network analysis
  - Physical features are known
  - Solution process try to determine flow & pressure at every node
- Pipe network design
  - Variables are unknown
  - Try to solve & select pipe diameters, pumps, valves, etc.

Pipe Network Analysis

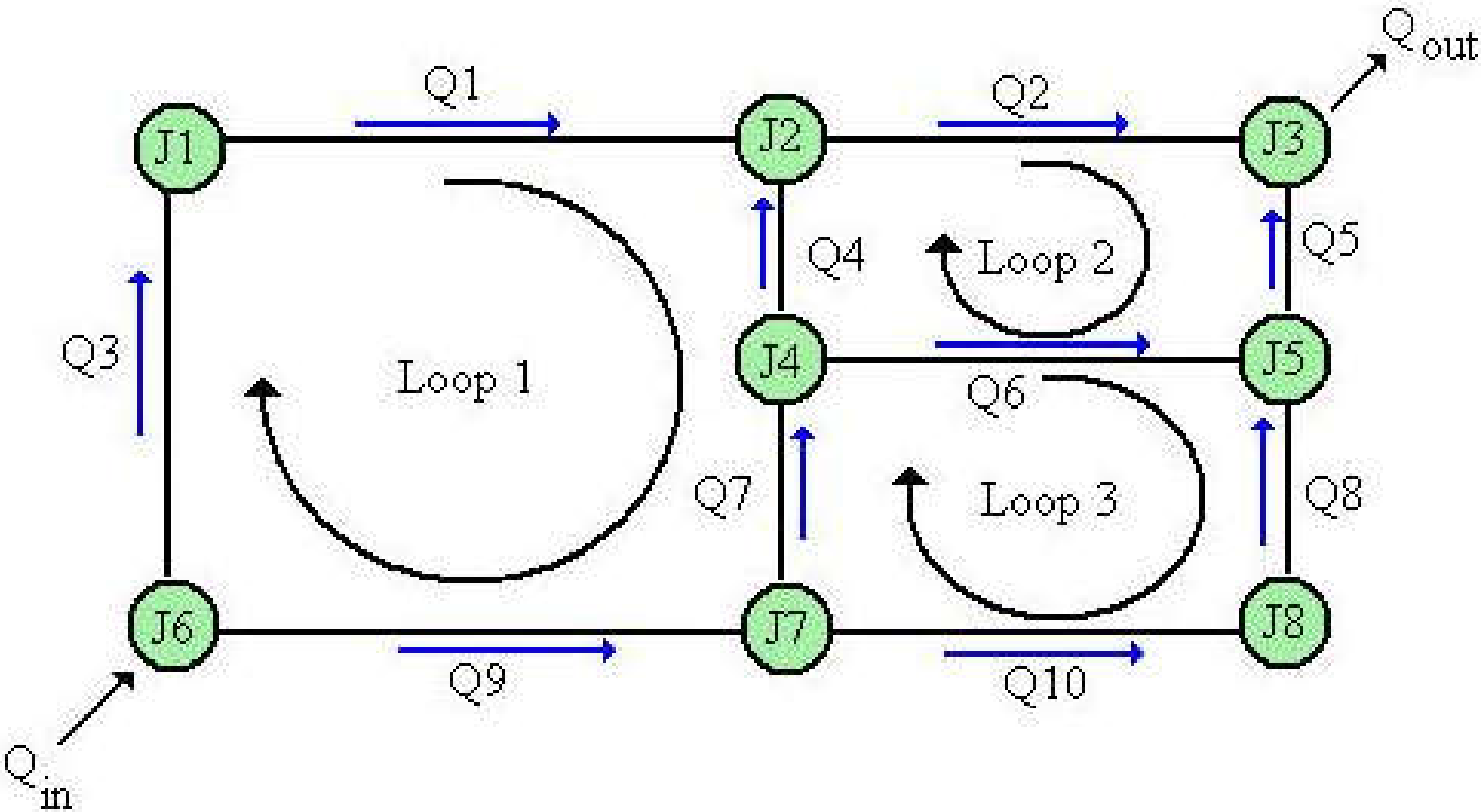
- Often a complex mathematical problem
  - Solving entire set of non-linear equations
  - Large networks are usually analysed by computers
- Basis of the computer solutions
  - Basic principles of fluid mechanics
  - Suitable equations that embody them
  - Interrelate the pipe discharge & pressure at each node of the network

Pipe network analysis



(Source: Larock, Jeppson and Watters, 2000: *Hydraulics of Pipeline Systems*)

Pipe network analysis (deterministic)

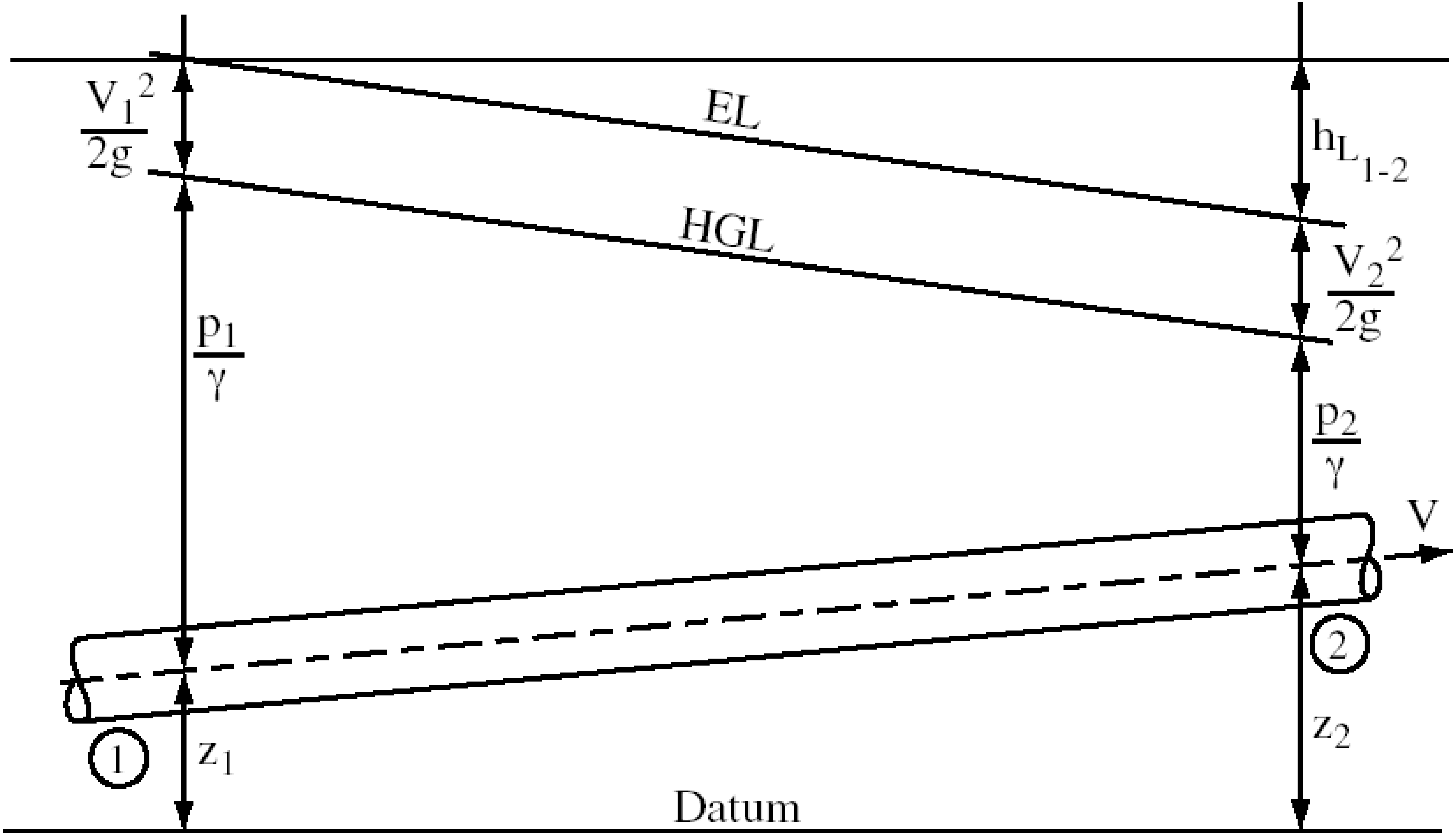


(Source: https://en.wikipedia.org/wiki/Pipe_network_analysis)

Pipe Network Analysis

- Basic principles of fluid mechanics
  - 1) Conservation of mass (continuity principle)
  - 2) Work-energy principle (Darcy-Weisbach or Hazen-Williams)
  - 3) Fluid friction & energy dissipation
- The task is to
  - Describe the hydraulic system accurately and efficiently by means of equations
  - Solve these simultaneous equations effectively

Energy Line (EL) and Hydraulic Grade Line (HGL)



(Source: Larock, Jeppson and Watters, 2000: *Hydraulics of Pipeline Systems*)

Pipe Network Analysis

- Methods to solve steady flow problem in a pipe network
  - Hardy Cross method
    - Adapted from structural engg.
    - Oldest systematic method; suited for hand computations
    - Convergence problems for large systems
  - Newton method
    - Linear algebra matrix operations
    - Perform iterative set of calculations (using computers)

(See also: Hardy Cross method - Wikipedia http://en.wikipedia.org/wiki/Hardy_Cross_method)

Pipe Network Analysis

- Define an appropriate pipe system
  - Decide what features are important & to retain
    - No hard rules; requires much insight & judgment
  - Determine which demands should be specified
    - Analysis for a range of system demands
  - For large systems, require some "<u>skeletonization</u>"
    - Not all pipes or nodes are included in the analysis
    - Some may be lumped at a single node
  - After studying the entire system, more detailed analysis may be done within a building or area

Pipe Network Analysis

- Basic relations between network elements
  - Junction Continuity Equations
    - Summing volume flows at each junction (or node)
  - Energy Loop Equations
    - Summing initial energy within a network loop with the friction losses within that loop
  - Basic parameters:
    - NP = number of pipes
    - NJ = number of junctions
    - NL = number of loops
  - Branched system and looped system

Branched system and looped system

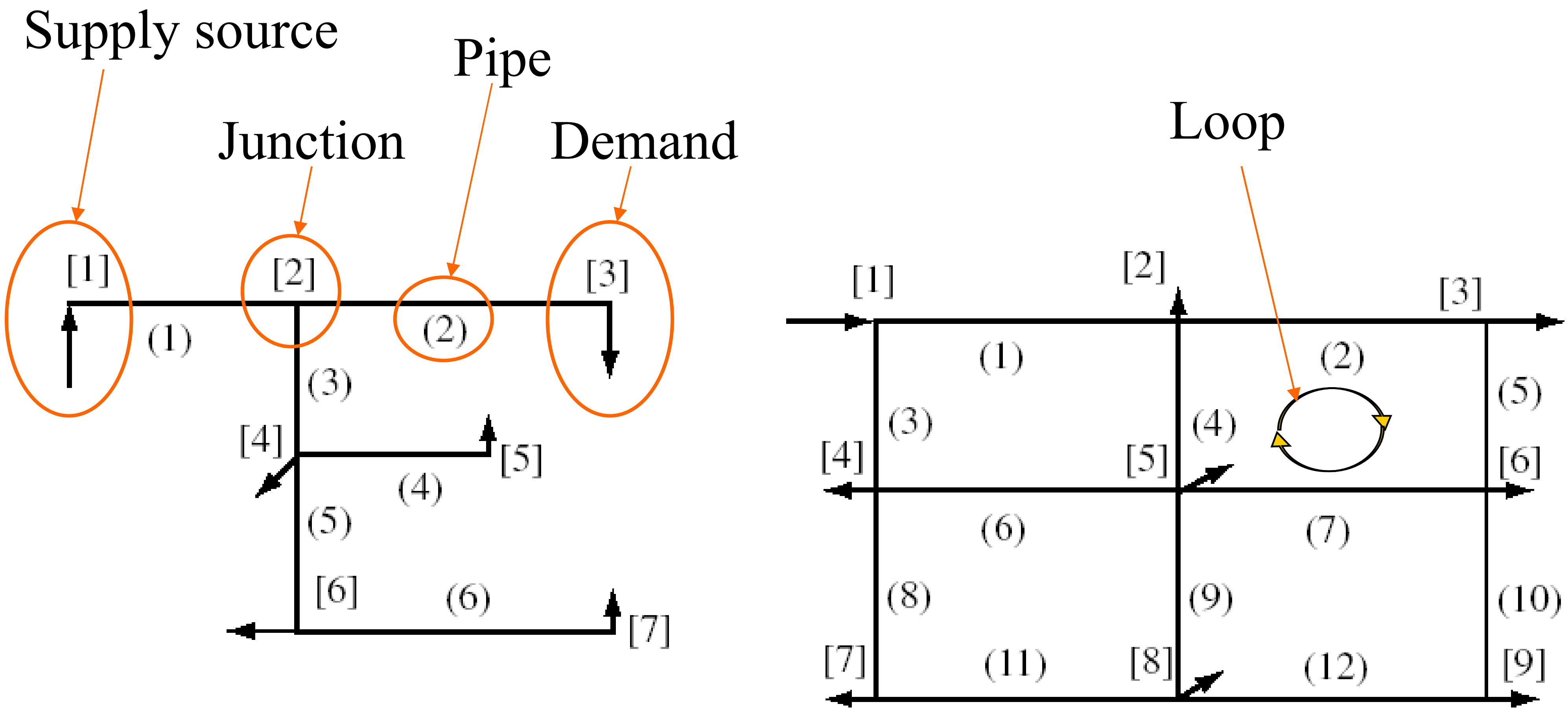


Figure 4.1 (a) A small branched system.
6 pipes, 7 nodes

(b) A small looped system.
12 pipes, 9 nodes

(Source: Larock, Jeppson and Watters, 2000: *Hydraulics of Pipeline Systems*)

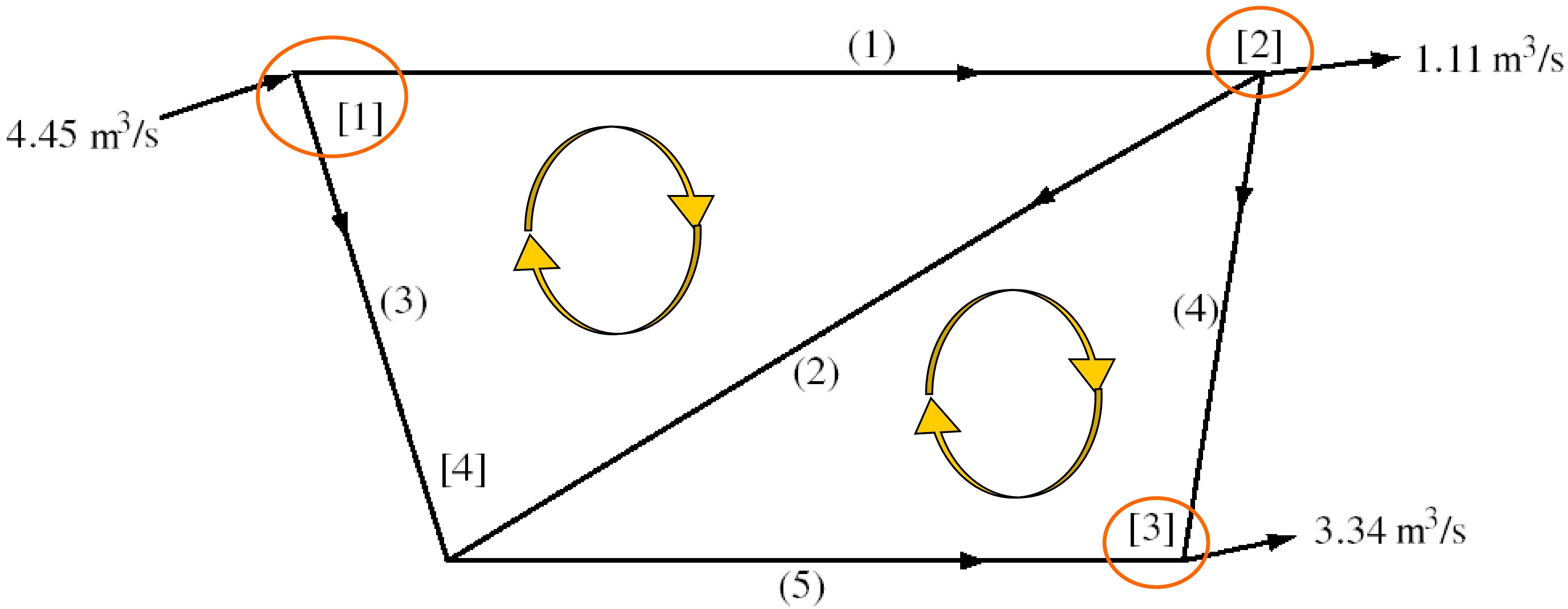
Pipe Network Analysis

- Equations for steady flow in networks
  - ***Q-equations*** (pipe charges are the unknowns)
  - ***H-equations*** (heads are the unknowns)
  - ***ΔQ-equations*** (corrective discharges are the unknowns)
  - When the equations are established, may use Newton method to solve them
    - Linear algebra matrix operations
    - Determine Jacobian matrix
    - Iterative procedure to calculate desired discharges

Pipe Network Analysis

- *Q*-equations (assume flow as unknowns)
  - Based on continuity
    - Flow into a junction = Flow out of the junction
    - $$QJ_j - \sum Q_i = 0$$ QJ_j = flow out (demand); Q_i = flow in from pipe i
  - Based on work-energy principles
    - Sum of the head loss around each loop is zero
    - $$\sum h_{fi} = \sum K_i Q_i^n = 0$$ h_{fi} = head loss; K_i, n = coefficients

Example of Q-equations for a simple network



Node [1]: $Q_1 + Q_3 - 4.45 = 0$

Node [2]: $-Q_1 + Q_2 + Q_4 + 1.11 = 0$

Node [3]: $-Q_4 - Q_5 + 3.34 = 0$

Loop 1-2-3: $K_1 Q_1^n + K_2 Q_2^n - K_3 Q_3^n = 0$

Loop 4-5-2: $K_4 Q_4^n - K_5 Q_5^n - K_2 Q_2^n = 0$

Pipe Network Analysis

- *H*-equations (assume head as unknowns)
  - Solve the exponential equation for the flow

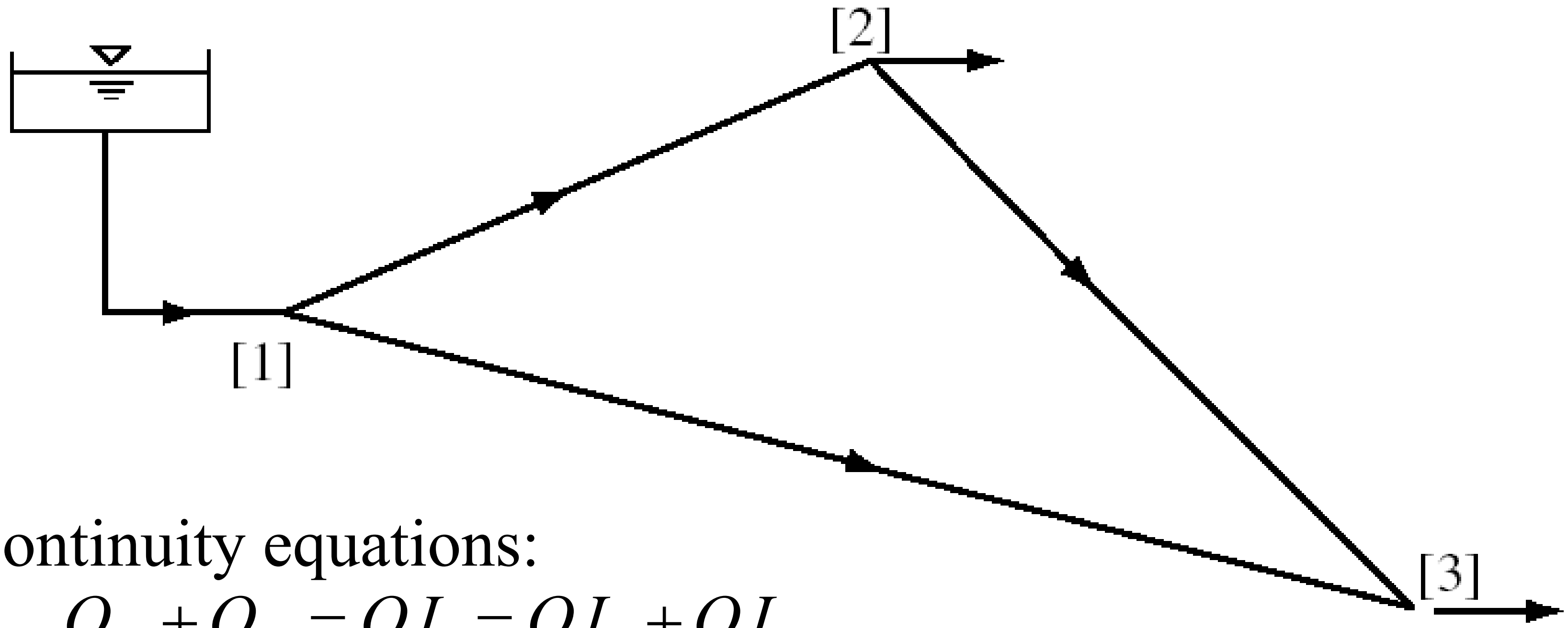
$$Q_{ij} = (h_{f\,ij} / K_{ij})^{1/n_{ij}} = [(H_i - H_j)/K_{ij})]^{1/n_{ij}}$$

    - Subscript ij = for the pipe from node i to node j
  - Substitute the above into junction continuity equ.

$$QJ_j - \sum \{[(H_i - H_j)/K_{ij})]^{1/n_{ij}}\}_{in}$$

$$+\sum \{[(H_i - H_j)/K_{ij})]^{1/n_{ij}}\}_{out} = 0$$

Example of *H*-equations for a simple network



Continuity equations:

$$Q_{12} + Q_{13} = QJ_1 = QJ_2 + QJ_3$$

$$Q_{21} + Q_{23} = -QJ_2 \quad (\text{or} \quad -Q_{12} + Q_{23} = -QJ_2)$$

H-equations (by substituting the *Q* above):

$$\left[\frac{H_1 - H_2}{K_{12}}\right]^{1/n_{12}} + \left[\frac{H_1 - H_3}{K_{13}}\right]^{1/n_{13}} = QJ_2 + QJ_3$$

$$-\left[\frac{H_1 - H_2}{K_{12}}\right]^{1/n_{12}} + \left[\frac{H_2 - H_3}{K_{23}}\right]^{1/n_{23}} = -QJ_2$$

Pipe Network Analysis

- ΔQ-equations (corrective flows as unknowns)
  - To obtain these equations, replace the flow in energy loop equations by an initial Q_{0i}, plus the sum of all initially unknown corrective flow

$$Q_i = Q_{0i} + \sum \Delta Q_k$$

  - Energy equation becomes

$$\sum K_i \{Q_{0i} + \sum \Delta Q_k\}^{n_i} = 0$$

  - Nos. of equations can be reduced, but the equations are nonlinear & contain many terms

Pipe Network Analysis

- Solving the network equations
  - Newton iterative formula:

$$\{x\}^{(m+1)} = \{x\}^{(m)} - [D]^{-1}\{F\}^{(m)}$$

    - $\{x\}$ = entire column vector of unknowns
    - $\{F\}$ = entire column vector of equations
    - $[D]^{-1}$ = inverse of matrix $[D]$, the Jacobian

$$\{x\} = \begin{Bmatrix} x_1 \\ x_2 \\ \cdot \\ \cdot \\ x_n \end{Bmatrix} \qquad \{F\} = \begin{Bmatrix} F_1 \\ F_2 \\ \cdot \\ \cdot \\ F_n \end{Bmatrix} \qquad [D] = \begin{bmatrix} \frac{\partial F_1}{\partial x_1} & \frac{\partial F_1}{\partial x_2} & \cdot & \cdot & \frac{\partial F_1}{\partial x_n} \\ \frac{\partial F_2}{\partial x_1} & \frac{\partial F_2}{\partial x_2} & \cdot & \cdot & \frac{\partial F_2}{\partial x_n} \\ \cdot & \cdot & \cdot & & \cdot \\ \cdot & \cdot & & \cdot & \cdot \\ \frac{\partial F_n}{\partial x_1} & \frac{\partial F_n}{\partial x_2} & \cdot & \cdot & \frac{\partial F_n}{\partial x_n} \end{bmatrix}$$

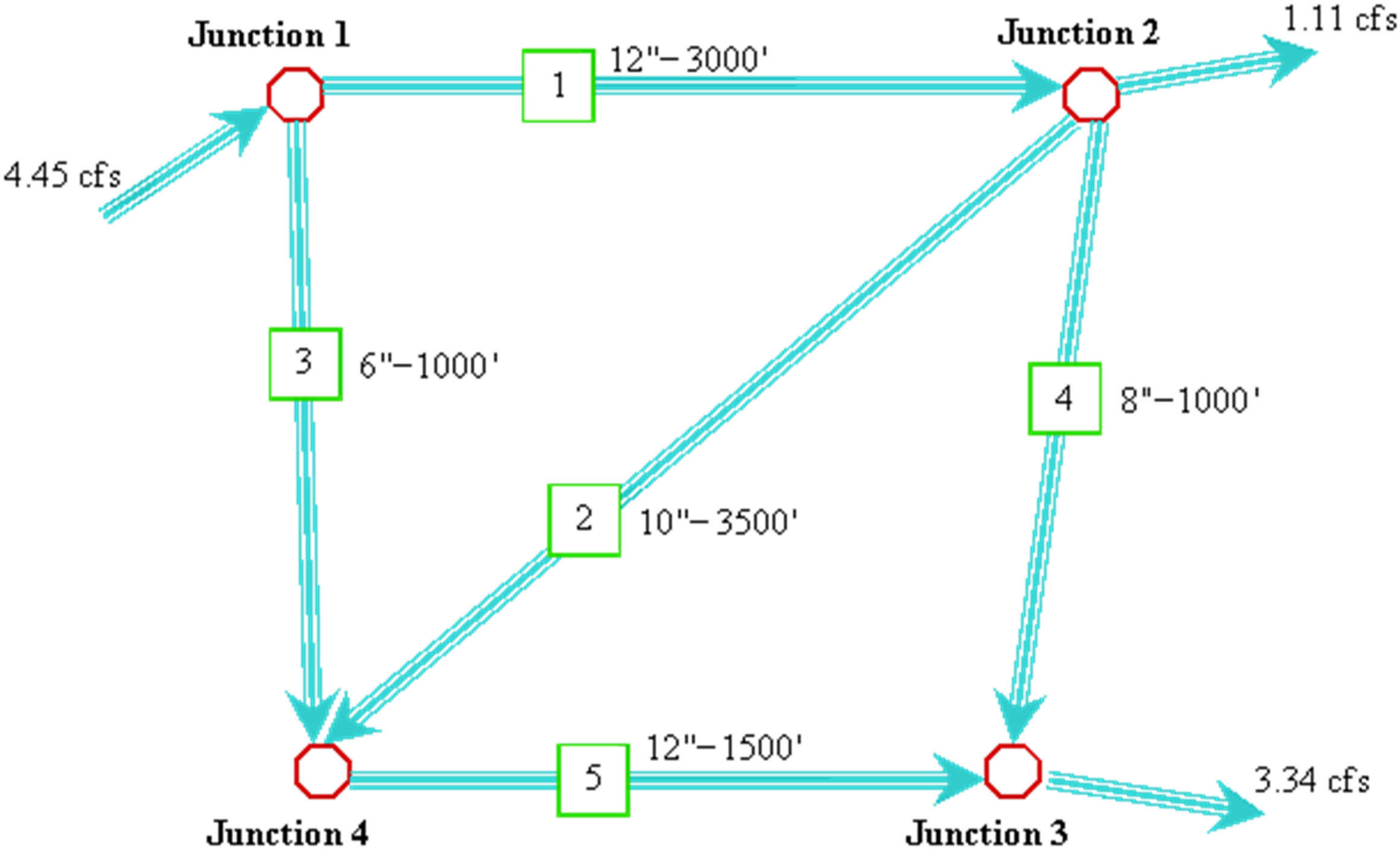
Pipe Network Analysis

- Solving the network equations (cont'd)
  - Newton method solves a system of nonlinear equations by iteratively solving a system of linear equations. The iterative formula is:

$$\{x\}^{(m+1)} = \{x\}^{(m)} - \{z\}$$

  - $\{z\}$ = solution vector, solved by $[D]\{z\} = \{F\}$
  - The solution is developed by using a multi-dimensional Taylor series expansion to evaluate the individual equation

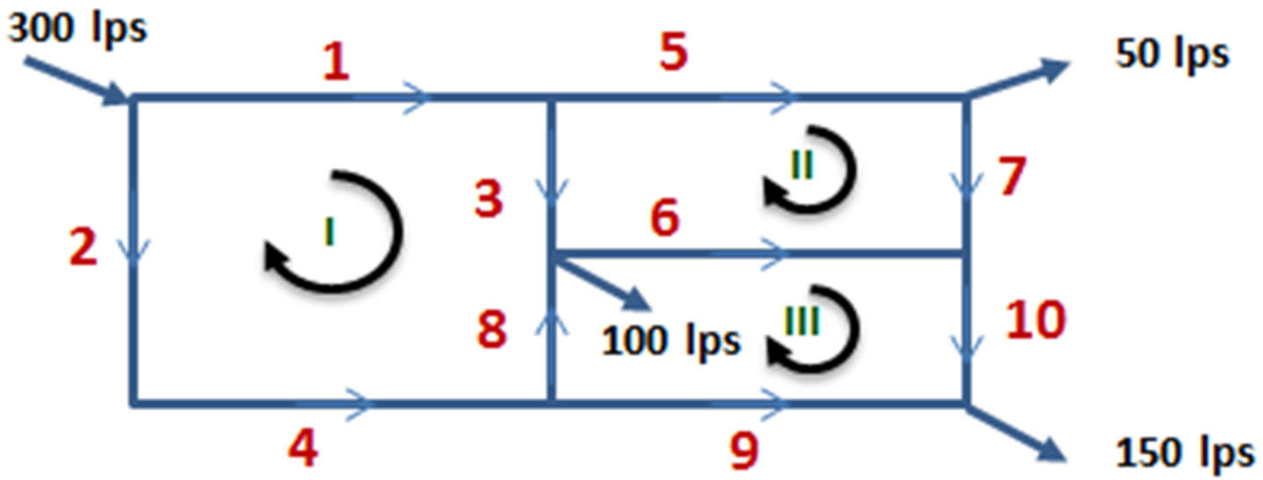
An example of simple pipe network analysis (using MathCAD)



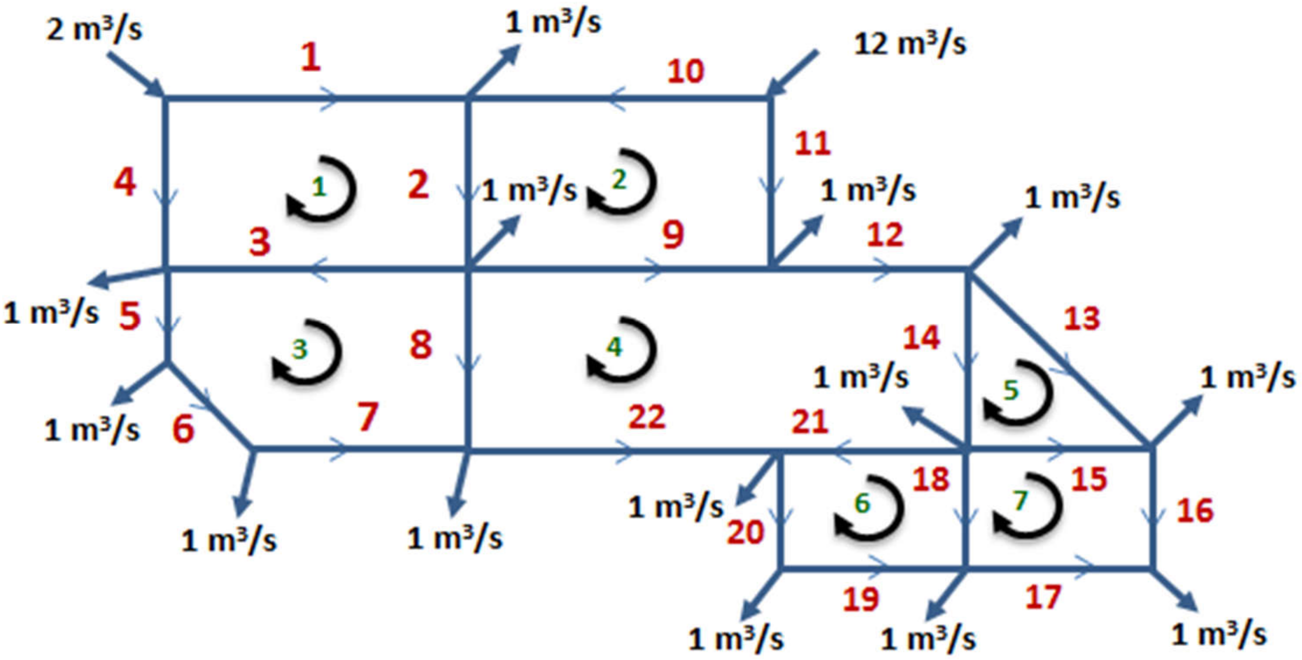
Pipe Network Analysis

- Computer solutions to networks
  - Implement using equation solver package e.g. MathCAD, or computer programs e.g. FORTRAN
  - Spreadsheet for Pipe Network Analysis https://cheguide.com/pipe_network.html
  - Other pipe analysis software are available, e.g. EPANet (for water supply & distribution)
    - https://www.epa.gov/water-research/epanet

Spreadsheet for Pipe Network Analysis



Pipe	Length m	Diameter m	e/D
1	300	0.30	0.00087
2	250	0.25	0.00104
5	350	0.20	0.00130
3	125	0.20	0.00130
6	350	0.20	0.00130
7	125	0.20	0.00130
4	300	0.20	0.00130
8	125	0.15	0.00173
9	350	0.20	0.00130
10	125	0.15	0.00173



$$J_L = \begin{bmatrix} \frac{\partial F_I}{\partial(\Delta Q_I)} & \frac{\partial F_I}{\partial(\Delta Q_{II})} & \frac{\partial F_I}{\partial(\Delta Q_{III})} \\ \frac{\partial F_{II}}{\partial(\Delta Q_I)} & \frac{\partial F_{II}}{\partial(\Delta Q_{II})} & \frac{\partial F_{II}}{\partial(\Delta Q_{III})} \\ \frac{\partial F_{III}}{\partial(\Delta Q_I)} & \frac{\partial F_{III}}{\partial(\Delta Q_{II})} & \frac{\partial F_{III}}{\partial(\Delta Q_{III})} \end{bmatrix}$$

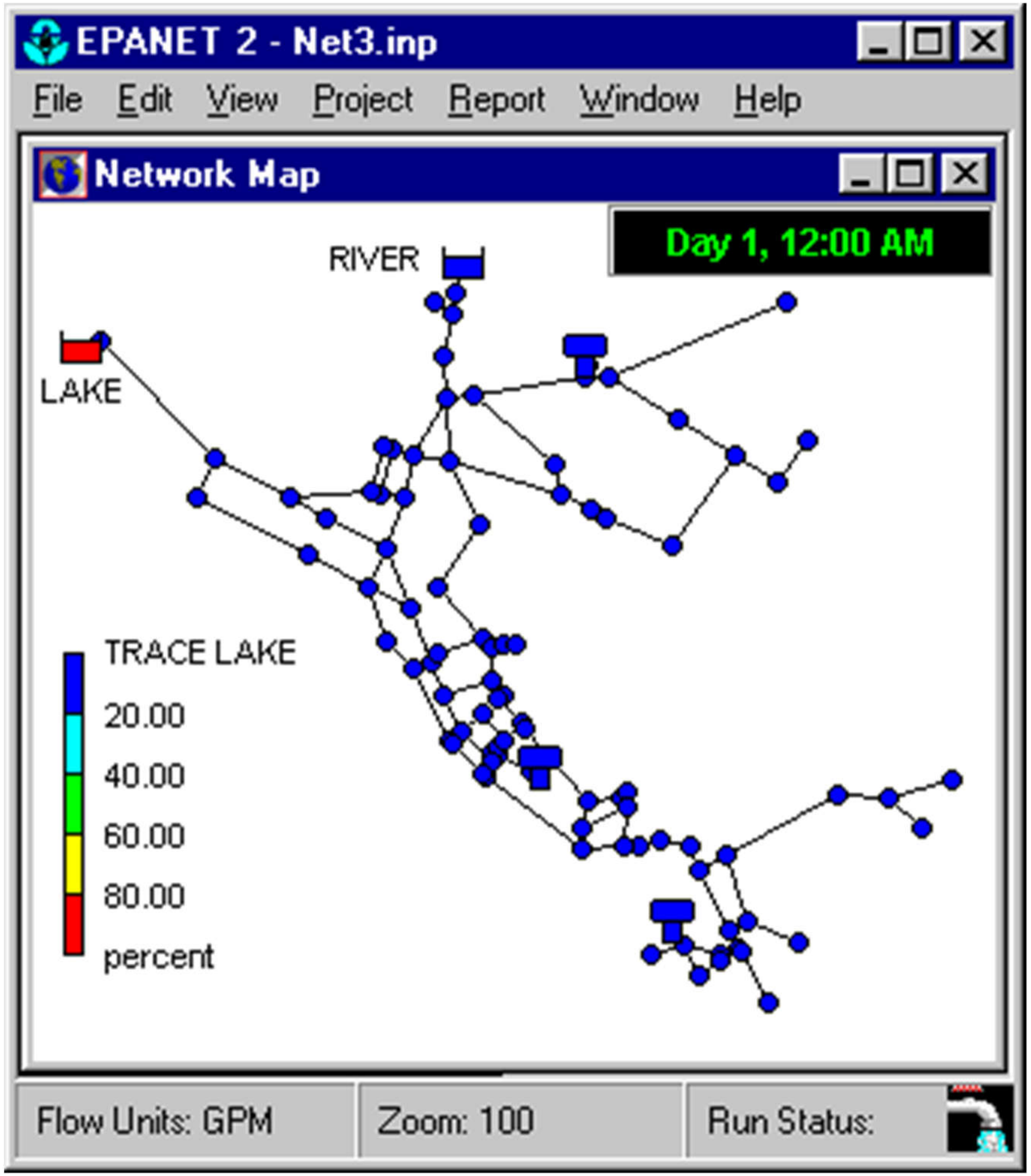
(Source: https://cheguide.com/pipe_network.html)

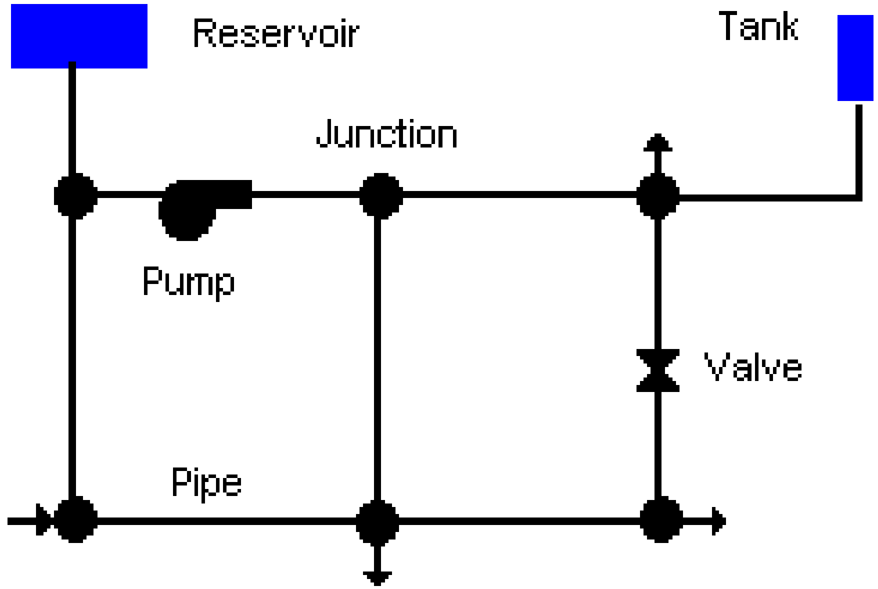
Spreadsheet for Pipe Network Analysis

	A	B	C	D	E	F	G	H	I	J	K	L
93	**Iteration**											
94	**5**	Pipe	Flow	Length	Diameter	e/D	Velocity	Reynold's	Friction			
95			m3/s	m	m		m/s	Number	Factor, f	K	hL	nHL/Q
96		1	0.205	300	0.30	0.00087	2.90	869910	0.019	199	8.34	81.42
97		2	0.095	250	0.25	0.00104	1.94	483995	0.021	435	3.93	82.61
98		5	0.080	350	0.20	0.00130	2.54	507484	0.022	1949	12.38	310.66
99		3	0.125	125	0.20	0.00130	3.99	797381	0.021	689	10.82	172.72
100		6	0.033	350	0.20	0.00130	1.05	210734	0.022	2010	2.20	133.09
101		7	0.030	125	0.20	0.00130	0.95	189174	0.022	722	0.64	42.90
102		4	0.095	300	0.20	0.00130	3.02	604994	0.021	1663	15.02	316.17
103		8	0.008	125	0.15	0.00173	0.44	66630	0.025	3455	0.21	54.24
104		9	0.087	350	0.20	0.00130	2.78	555021	0.022	1944	14.78	339.04
105		10	0.063	125	0.15	0.00173	3.55	533211	0.023	3133	12.36	393.64
106												
107		Coefficient Matrix					Inverse				F	DQ
108			707.16	-172.72	-54.24		1.53E-03	4.32E-04	1.53E-04		0.00	0.00000
109			-172.72	659.37	-133.09		4.32E-04	1.68E-03	2.69E-04		0.00	0.00000
110			-54.24	-133.09	920.01		1.53E-04	2.69E-04	1.13E-03		0.00	0.00000

(Source: https://cheguide.com/pipe_network.html)

EPANET software for modelling water distribution systems



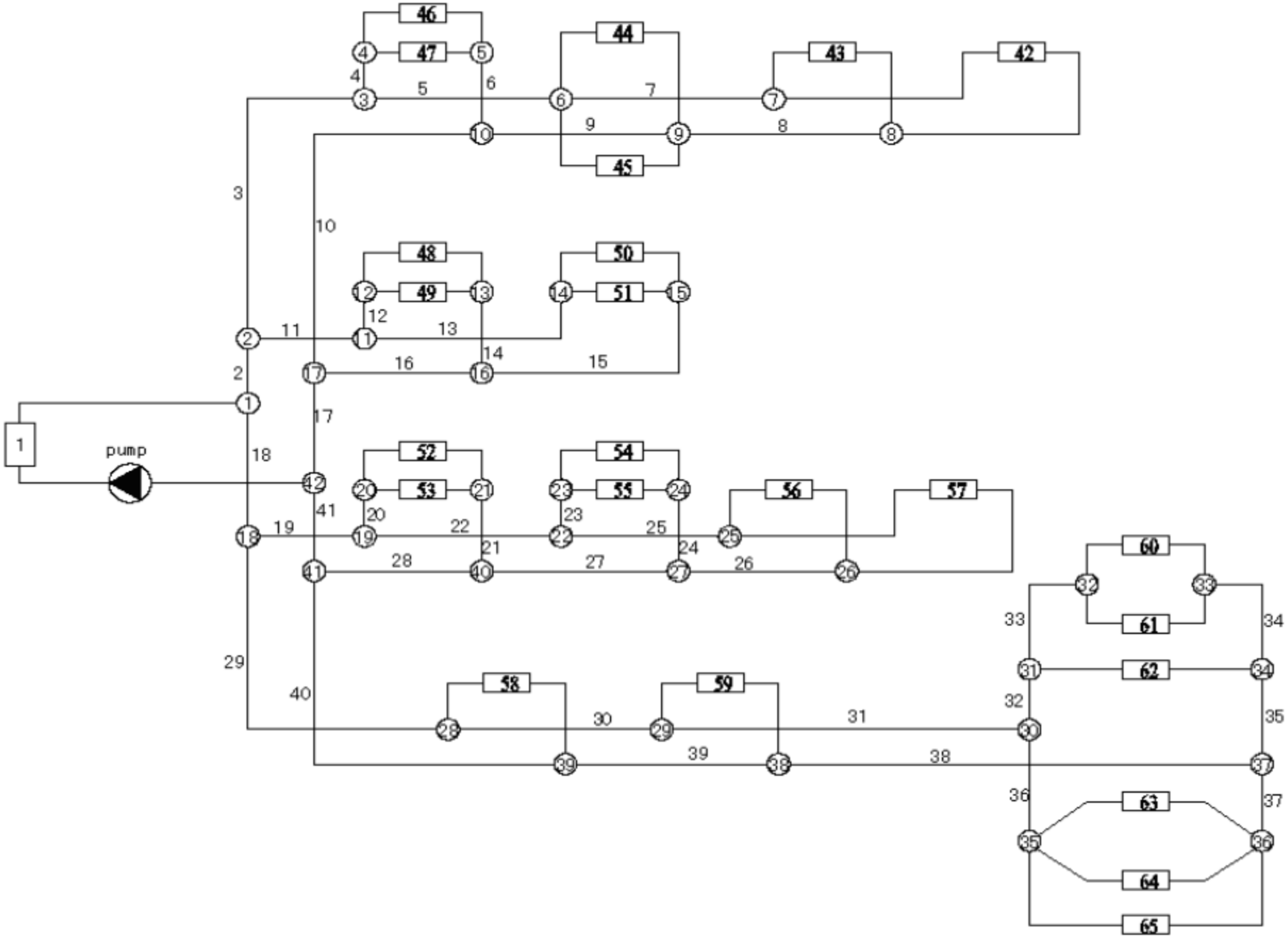


(Source: https://www.epa.gov/water-research/epanet)

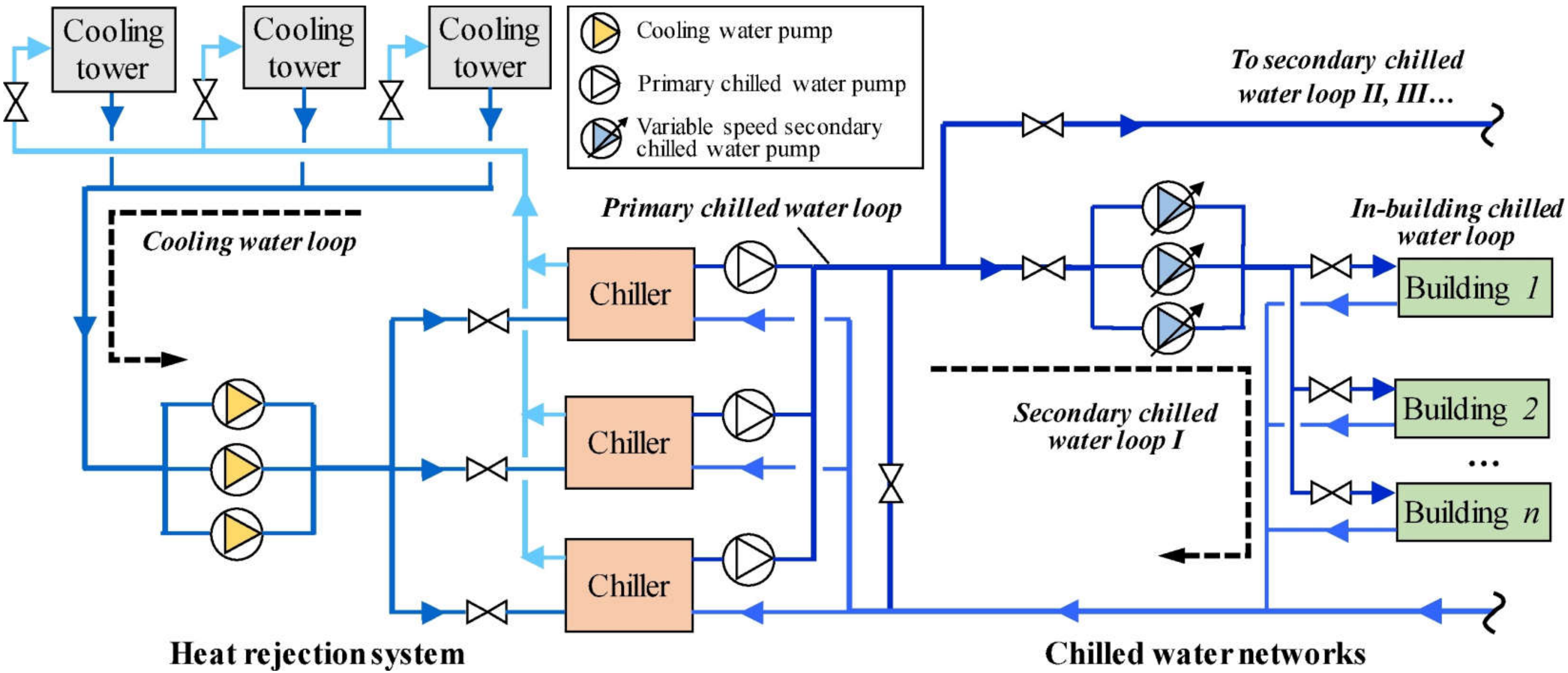
Pipe Network Analysis

- After the analysis is done, the next step is to verify by measurements in actual system (network verification) & identify deficiencies
  - Such as for designing water supply systems
- Application to HVAC systems
  - At present, large network analysis is not common in HVAC, except district cooling system (DCS)
  - But the technique can be applied to studies of water systems, air systems and building infiltration

Pipe network of a district cooling system (DCS)



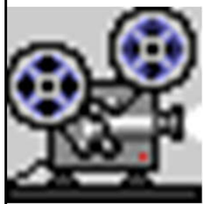
Heat rejection and chilled water networks of a district cooling system



(Source: DOI: 10.1016/j.renene.2018.07.052)

Pipe Network Analysis

- Videos for illustration:

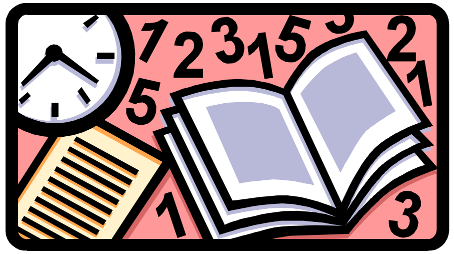


  - CE234--Lecture9--Pipe Networks (23:50) https://youtu.be/UEiOw1tWmJw
  - Hardy Cross Method (7:32) https://youtu.be/pxCWxGHKo2M
  - Hardy Cross Method for Pipe Networks - CE 331 - Class 12 (10 Feb 2020) (35:30) https://youtu.be/1G8ckwcL3jg
  - Pipe network analysis in Excel using Hardy cross method (English) (19:21) https://youtu.be/M8f1FNgeq7o

Further Reading

- ASHRAE, 2017. *ASHRAE Handbook Fundamentals 2017*, Chp. 22 - Pipe Design, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA.
- Example: Analysis of Complex Pipe Networks with Multiple Loops and Inlets and Outlets http://ibse.hk/MEBS7014/Abbreviated_Hardy-Cross.pdf
- Spreadsheet for Pipe Network Analysis https://cheguide.com/pipe_network.html

References



- Carrier Corporation, 2005. *Distribution Systems: Water Piping and Pumps*, Technical Development Program, Carrier Corporation, Syracuse, NY. http://siglercommercial.com/wp-content/uploads/2017/10/02-Chilled-Water-Piping-Pumps.pdf
- Hegberg, R. A., 1999. *Fundamentals of Water System Design*, Chp. 1 & 2, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA. [697 H46]
- Larock, B. E., Jeppson, R. W. and Watters, G. Z., 2000. *Hydraulics of Pipeline Systems*, Chp. 4, CRC Press, Boca Raton, FL. [621.8672 L328 h]
- Pennycook, K., Churcher, D. and Bleicher, D., 2007. *A Guide to HVAC Building Services Calculations*, 2nd ed., Building Services Research and Information Association, Bracknell, Berkshire, England, pp. 81-95.