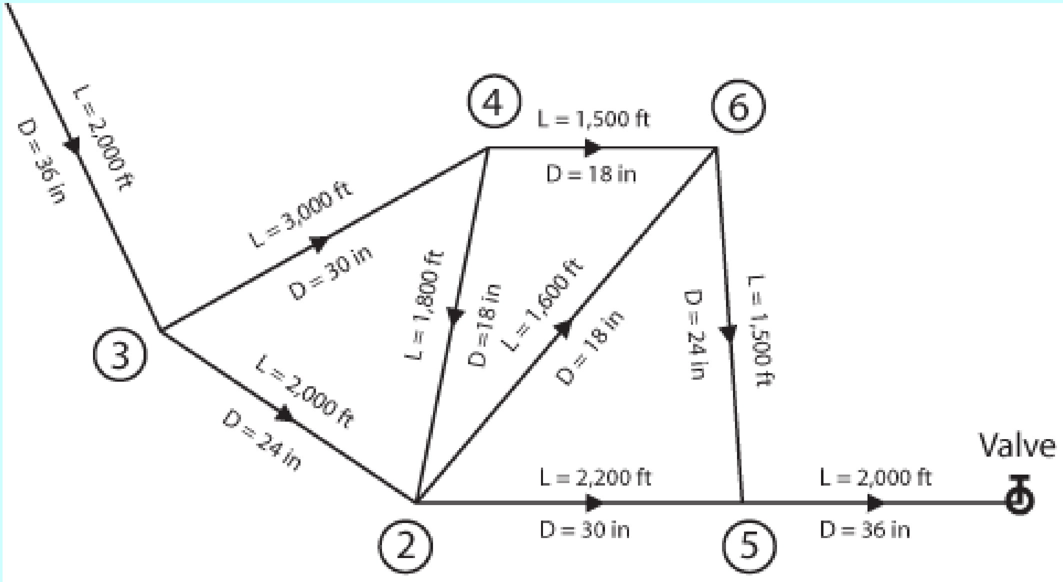
MEBS6008 Environmental Services II

http://www.mech.hku.hk/bse/MEBS6008/



Fluid Network Analysis II

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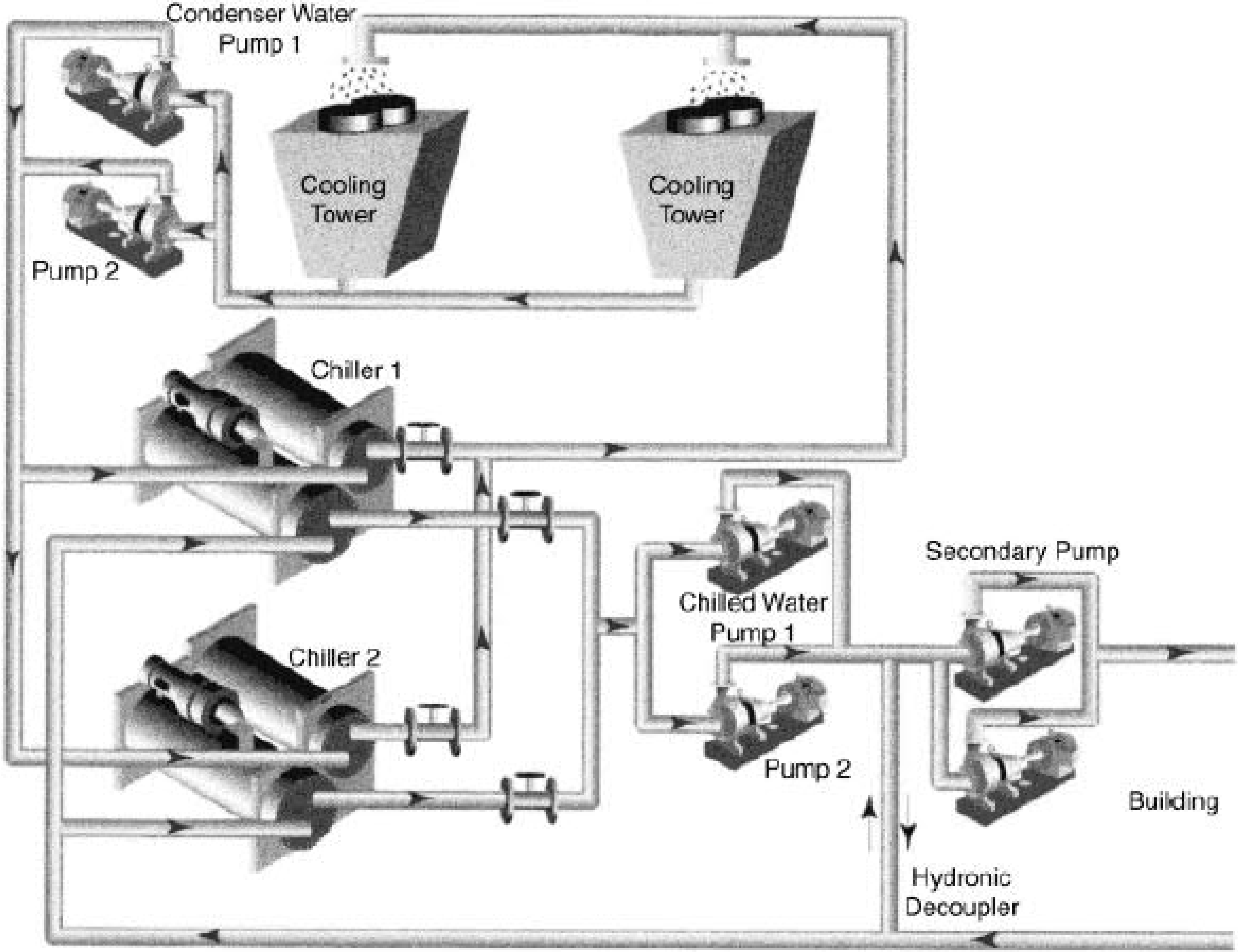
Contents

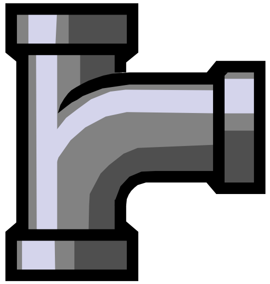
Pipe Systems and Design

- 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)



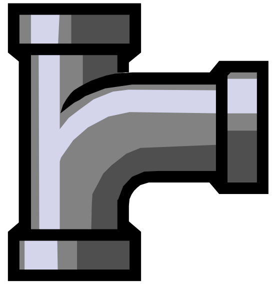
[Source: Kreider, K. F. (ed.), 2001. *Handbook of Heating, Ventilation, and Air Conditioning*, CRC Press, Boca Raton, FL.]

Pipe Systems and Design



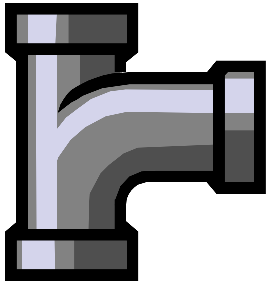
- Two major concerns:
  - Size the pipe (e.g. from charts & tables)
  - Determine the flow-pressure relationship
    - To analyse the system, e.g. to find out pump pressure
    - By using manual or computer-based methods
- Calculations for pipelines or pipe networks
  - Can be very complicated for branches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

Pipe Systems and Design



- 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 Systems and Design



- 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*.

Pipe Systems and Design

- 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)

Pipe Systems and Design

- 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 Systems and Design

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

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

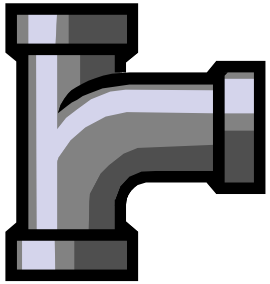
  - K_L = loss coefficient (K factor) of pipe fittings
    - Geometry and size dependent
    - May be expressed as equivalent lengths of straight pipe
  - Valve coefficient (A_v):
    - Volume flow rate $Q = A_v \sqrt{\Delta p / \rho}$

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

(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

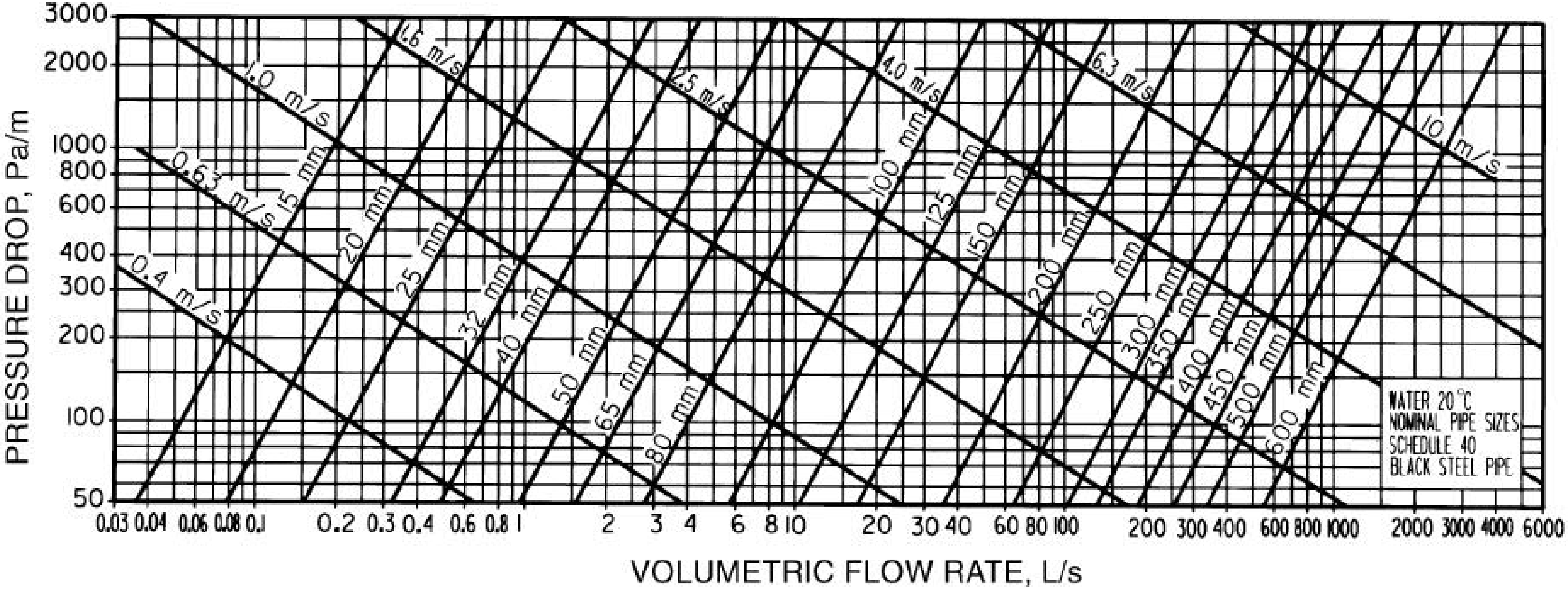


Fig. 4 Friction Loss for Water in Commercial Steel Pipe (Schedule 40)

(Source: ASHRAE Handbook Fundamentals 2005, Chp. 36)

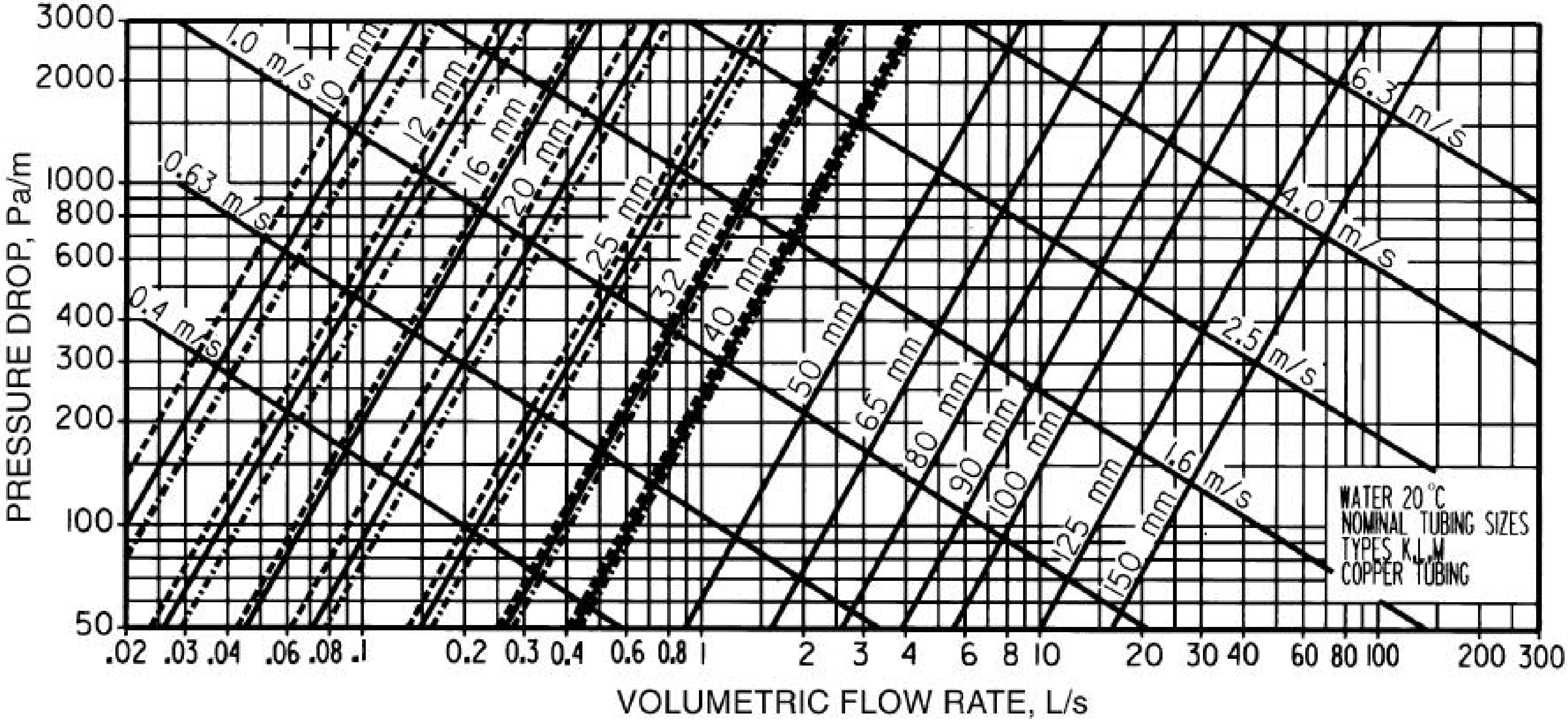
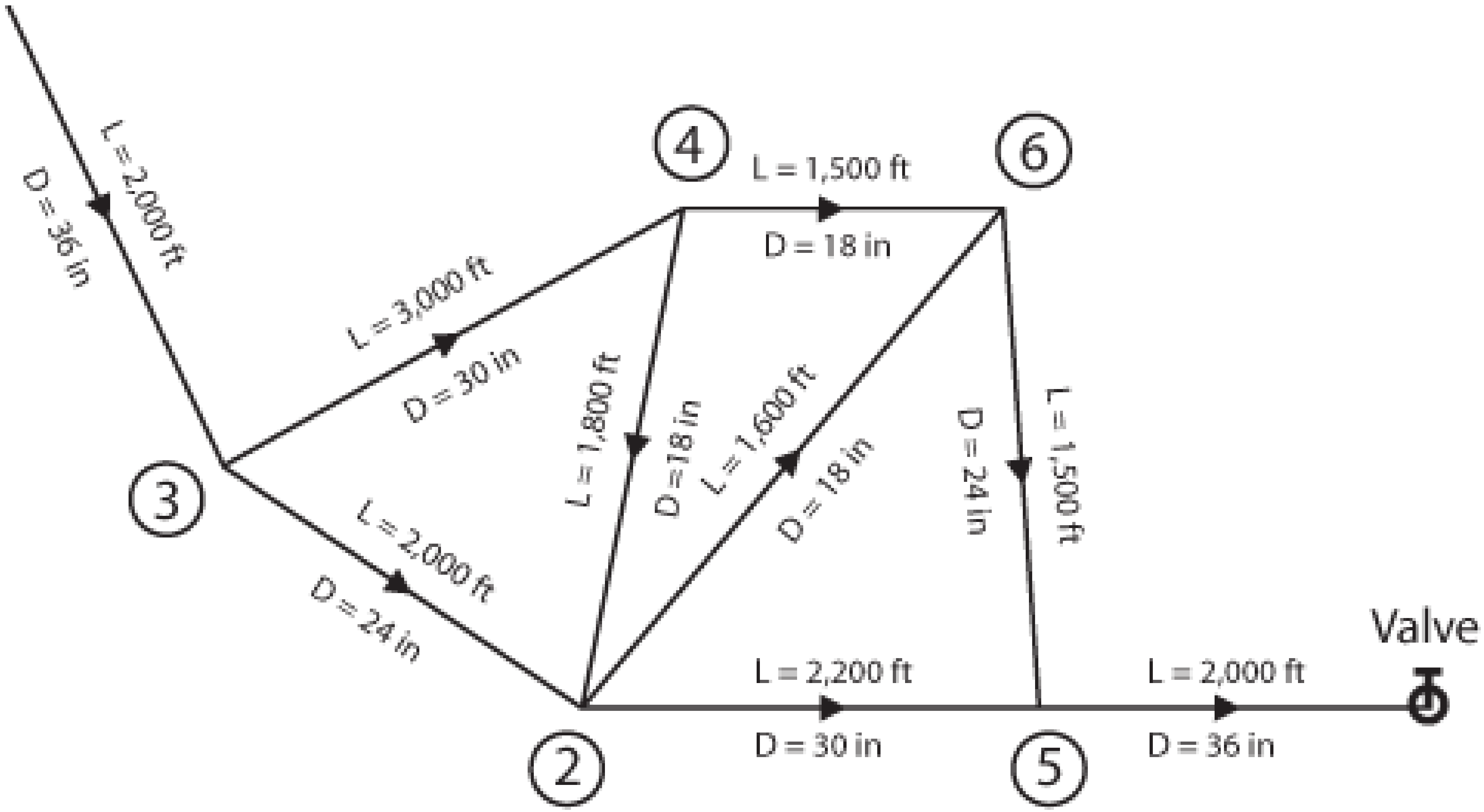


Fig. 5 Friction Loss for Water in Copper Tubing (Types K, L, M)

(Source: ASHRAE Handbook Fundamentals 2005, Chp. 36)

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

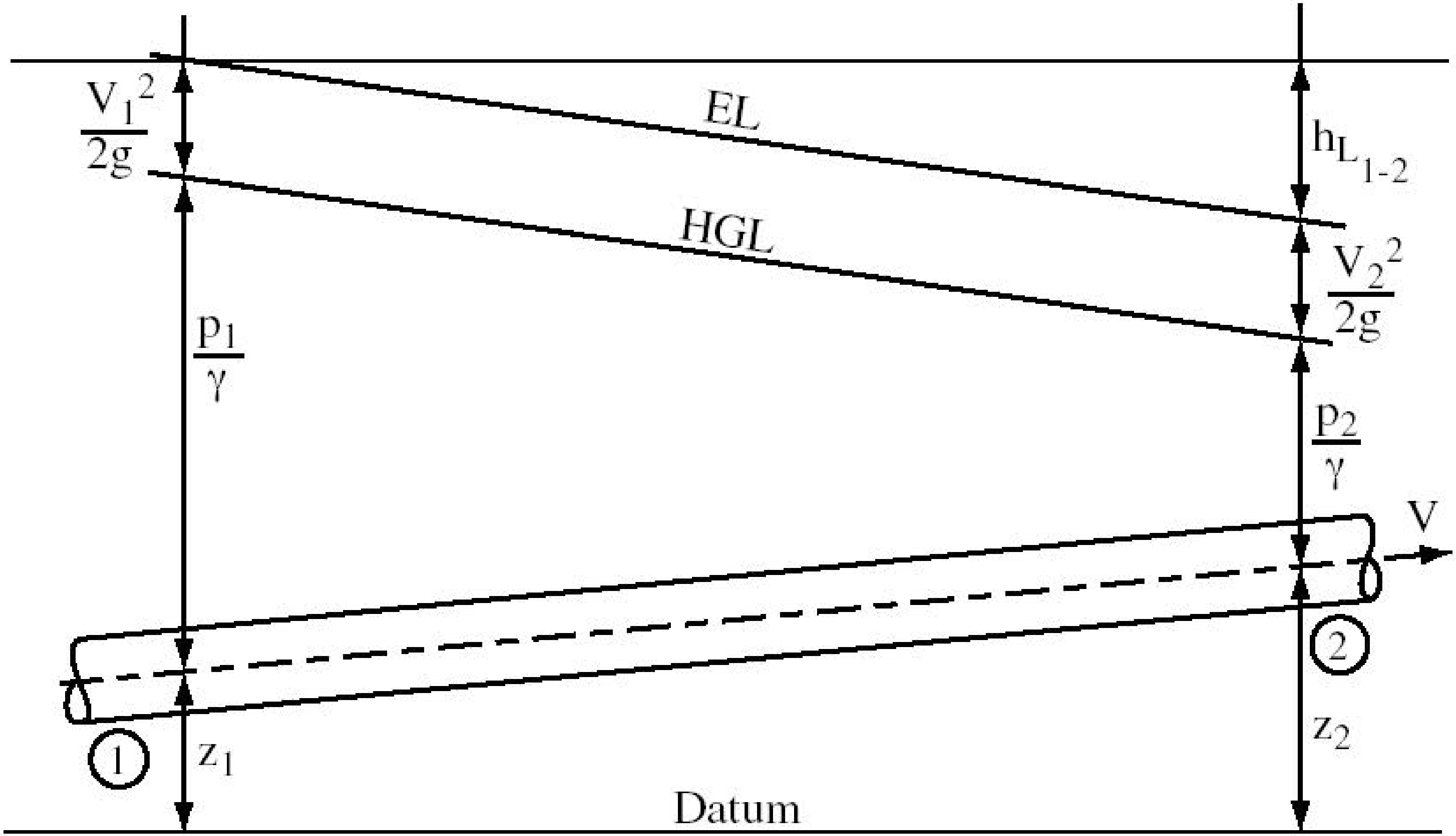


Pipe network analysis

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

Pipe Network Analysis

- 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)

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 "skeletonization"
    - 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

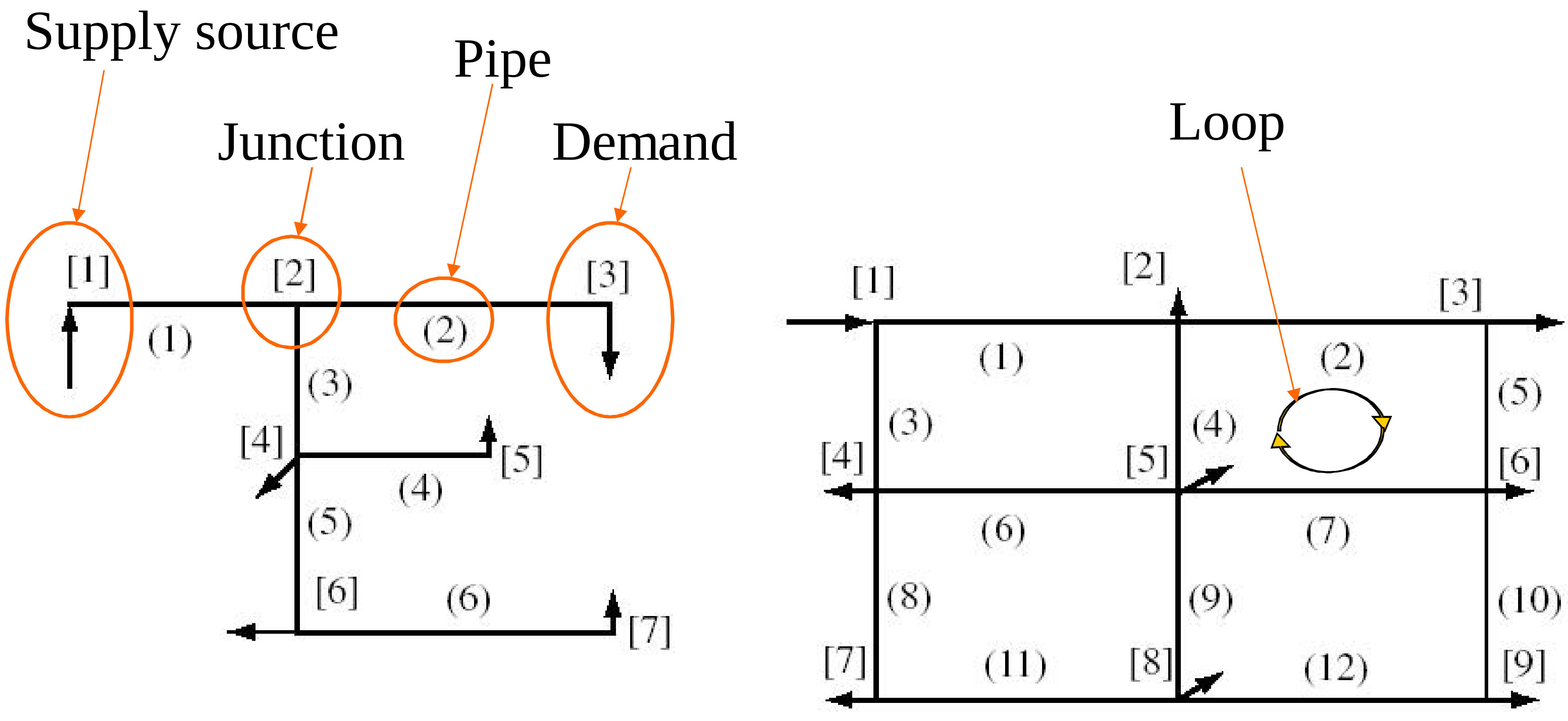


Figure 4.1 (a) A small branched system. 6 pipes, 7 nodes (b) A small looped system. 12 pipes, 9 nodes

(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
    - $$QJ_j - \sum Q_i = 0$$

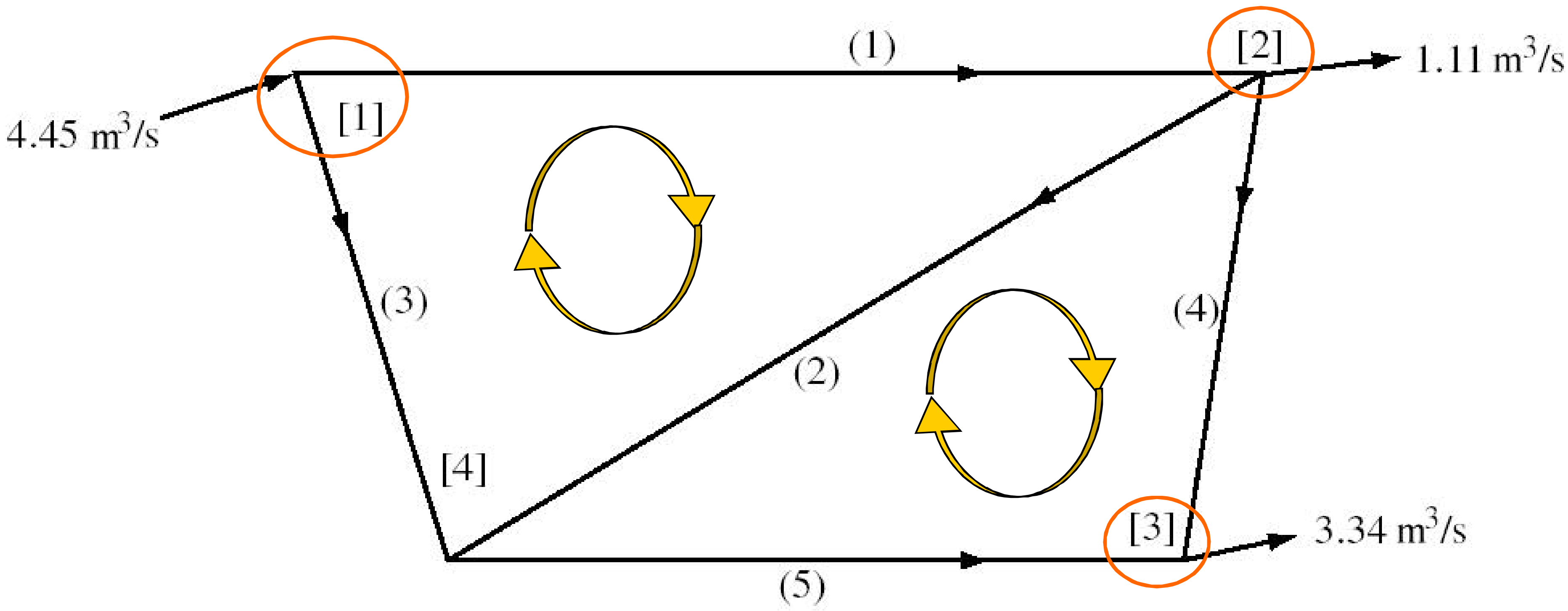
      QJ_j = flow out (demand)

      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: $K_1Q_1^n + K_2Q_2^n - K_3Q_3^n = 0$

Loop 4-5-2: $K_4Q_4^n - K_5Q_5^n - K_2Q_2^n = 0$

Pipe Network Analysis

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

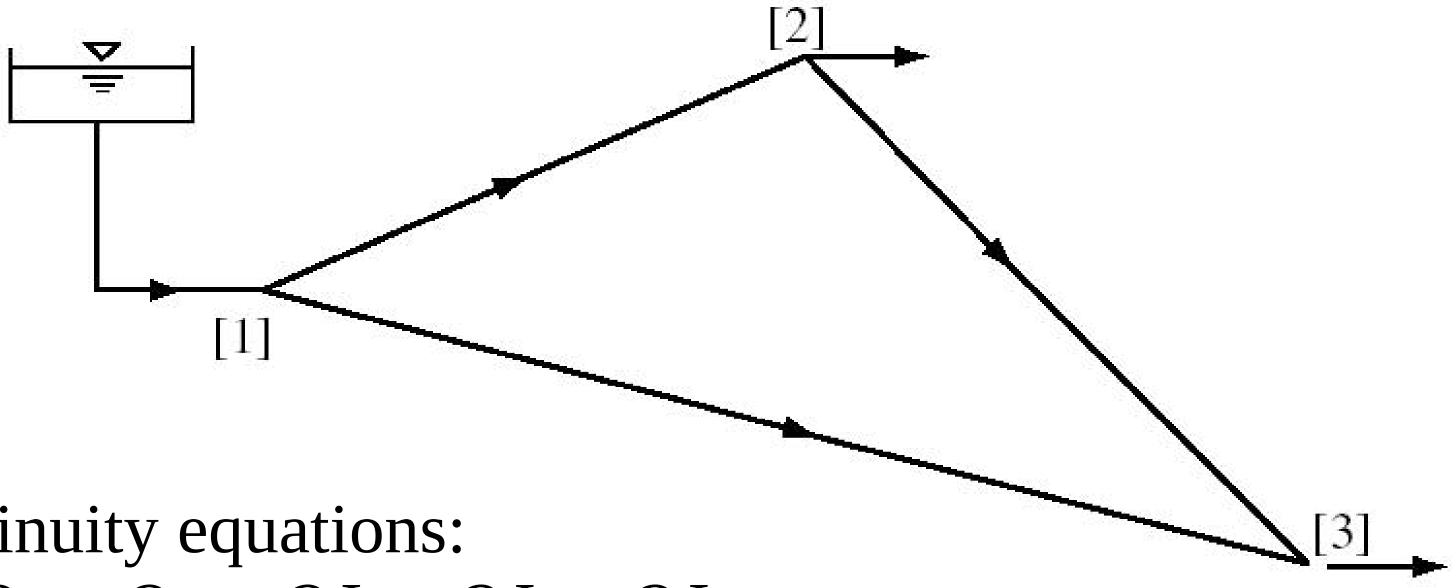
$$Q_{ij} = (h_{f\,ij} / K_{ij})^{1/n_{ij}} = [(H_i - H_j)/K_{ij})]^{1/n_{ij}}$$

    - 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:

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

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

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)

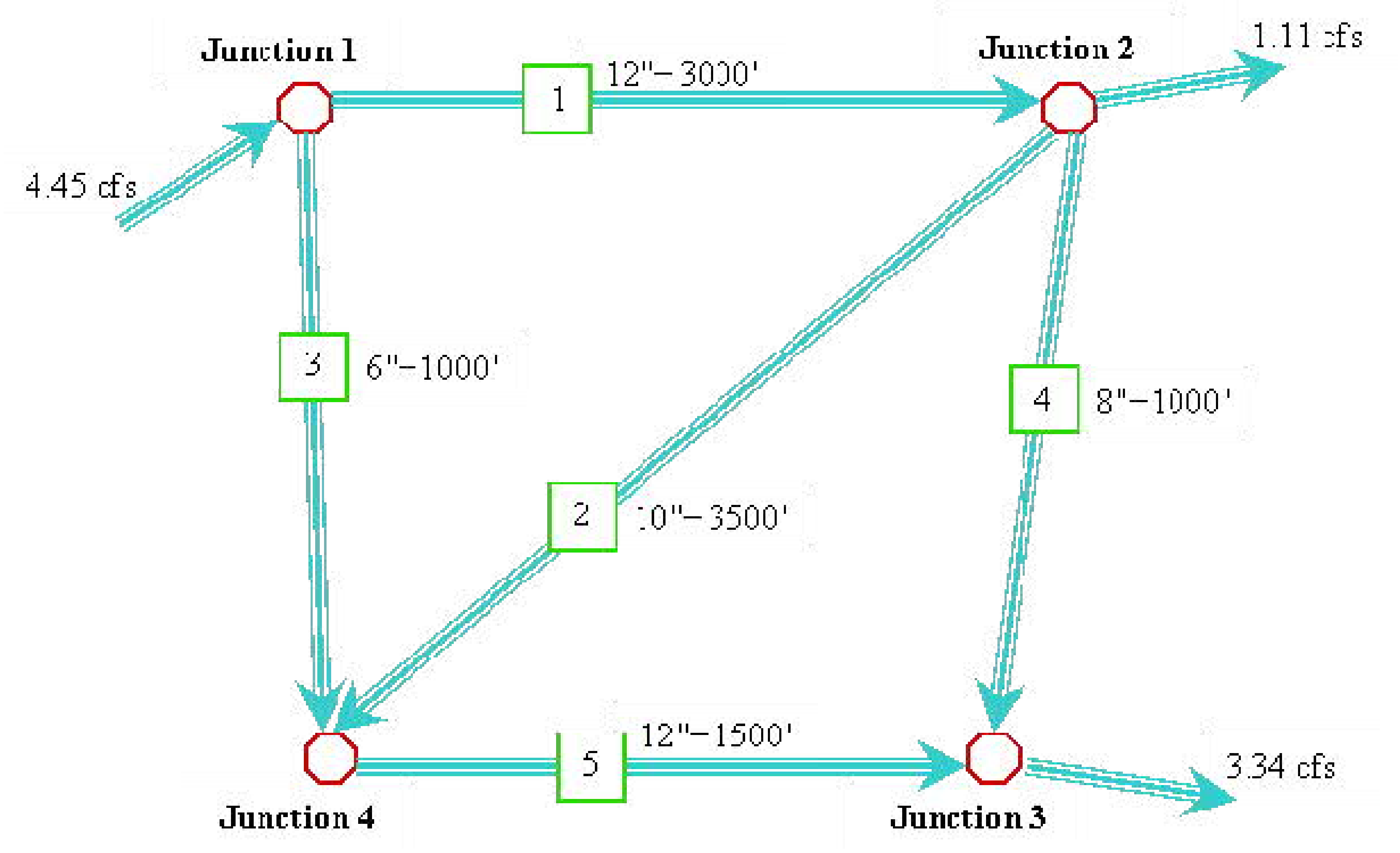
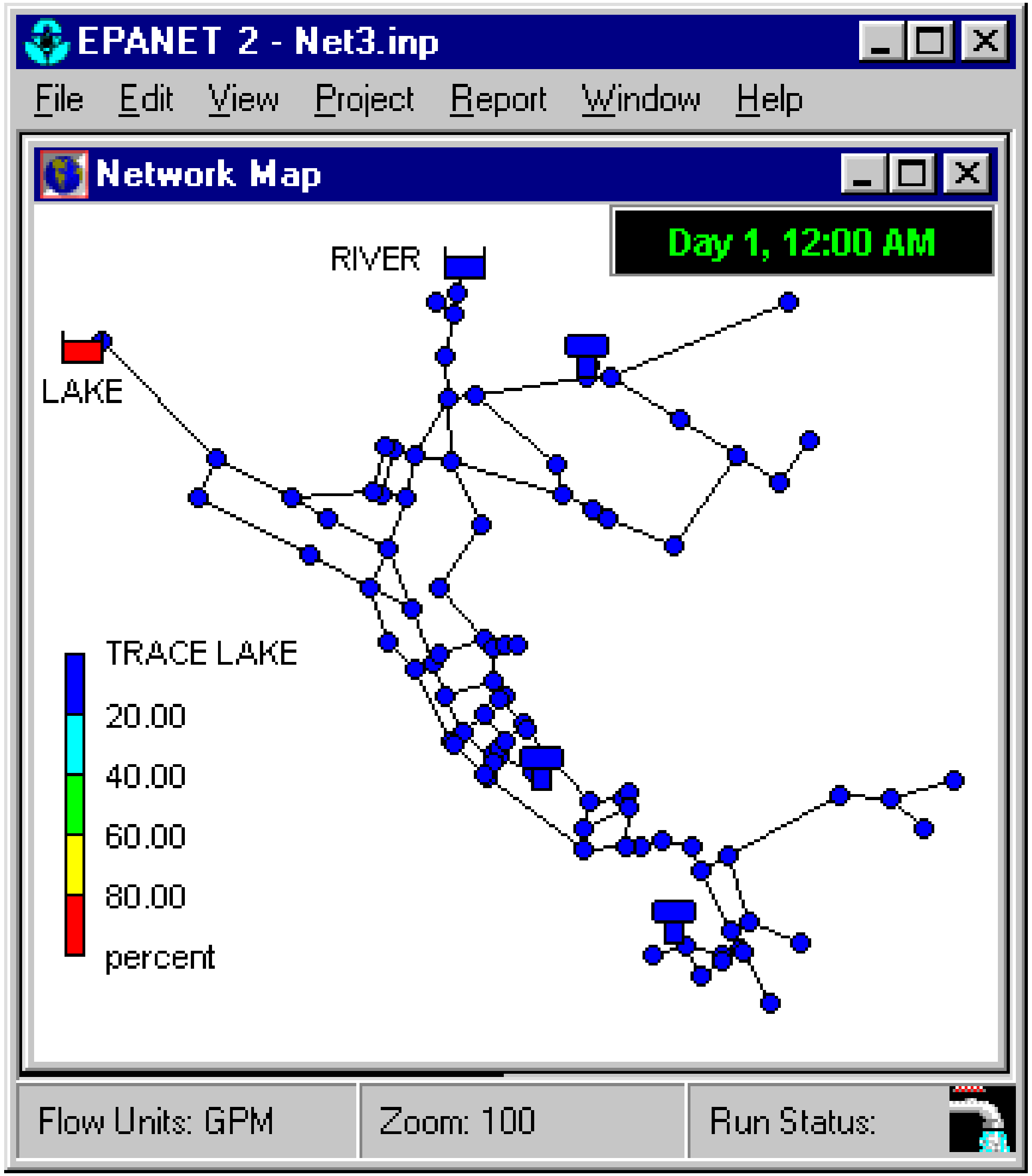


Figure 1: A Small Pipe Network

Pipe Network Analysis

- Computer solutions to networks
  - Implement using equation solver package e.g. MathCAD, or computer programs e.g. FORTRAN
  - Other pipe analysis software are available, e.g. EPANet (for water supply & distribution)
    - http://www.epa.gov/nrmrl/wswrd/dw/epanet.html
  - Simple demon. of piping simulation software:
    - http://www.vcity.ou.edu/demoModules/piping/home.htm



EPANET 2.0 interface

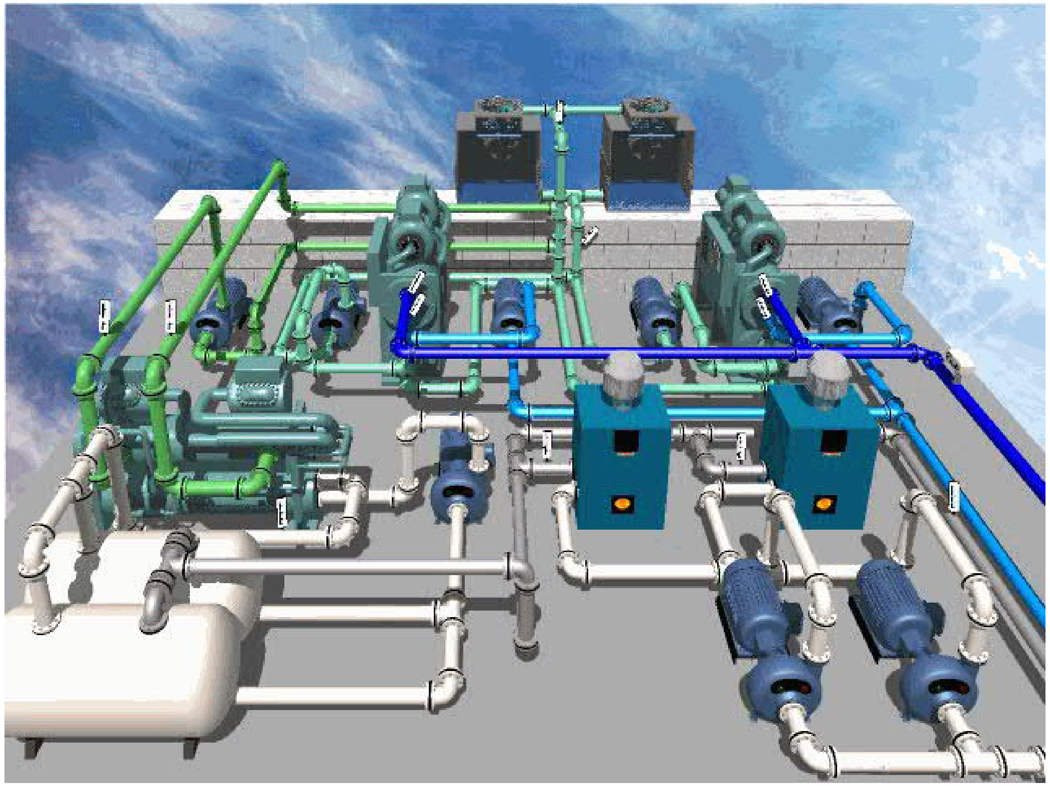
(Source: http://www.epa.gov/nrmrl/wswrd/dw/epanet.html)

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

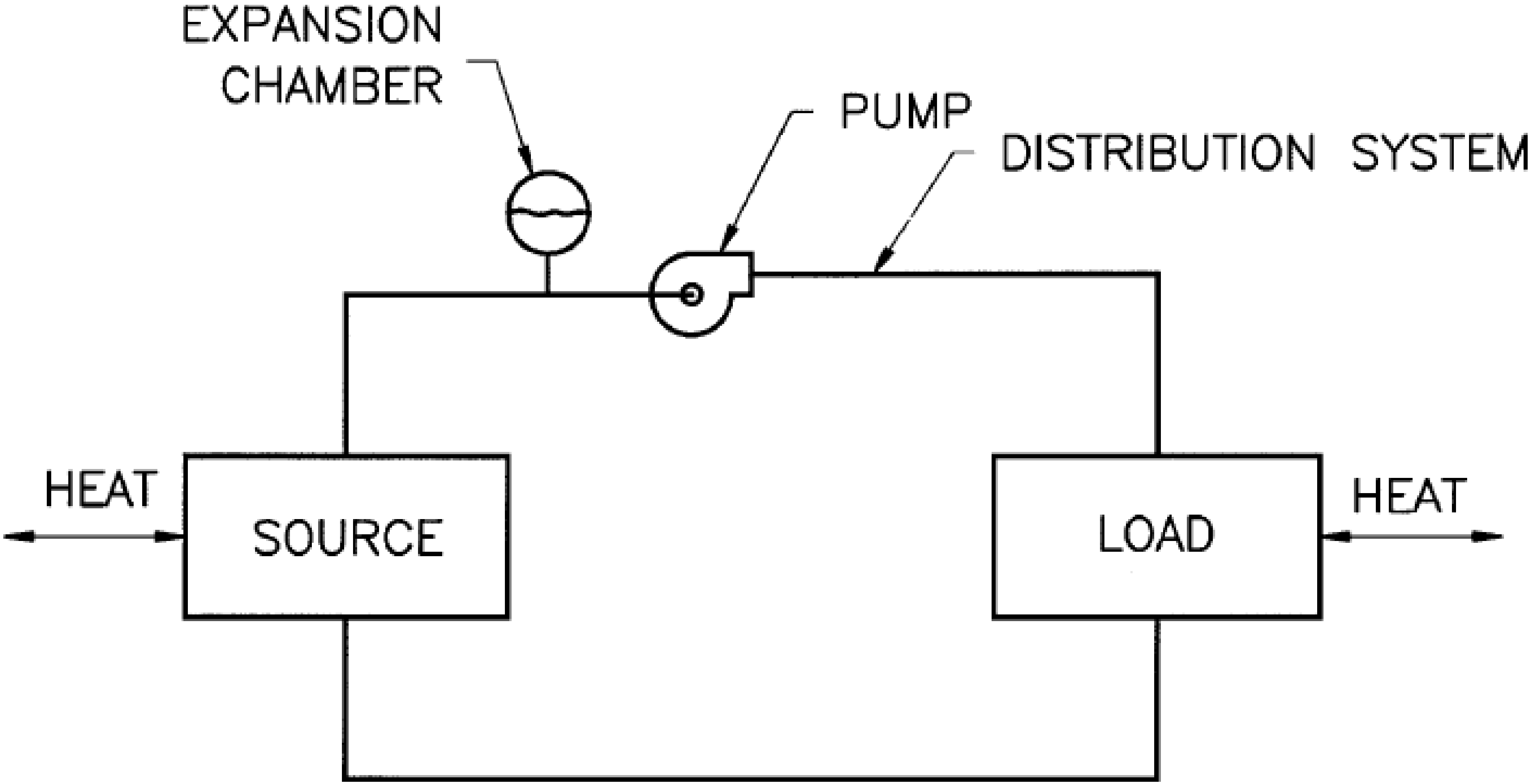
Water Systems in HVAC

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



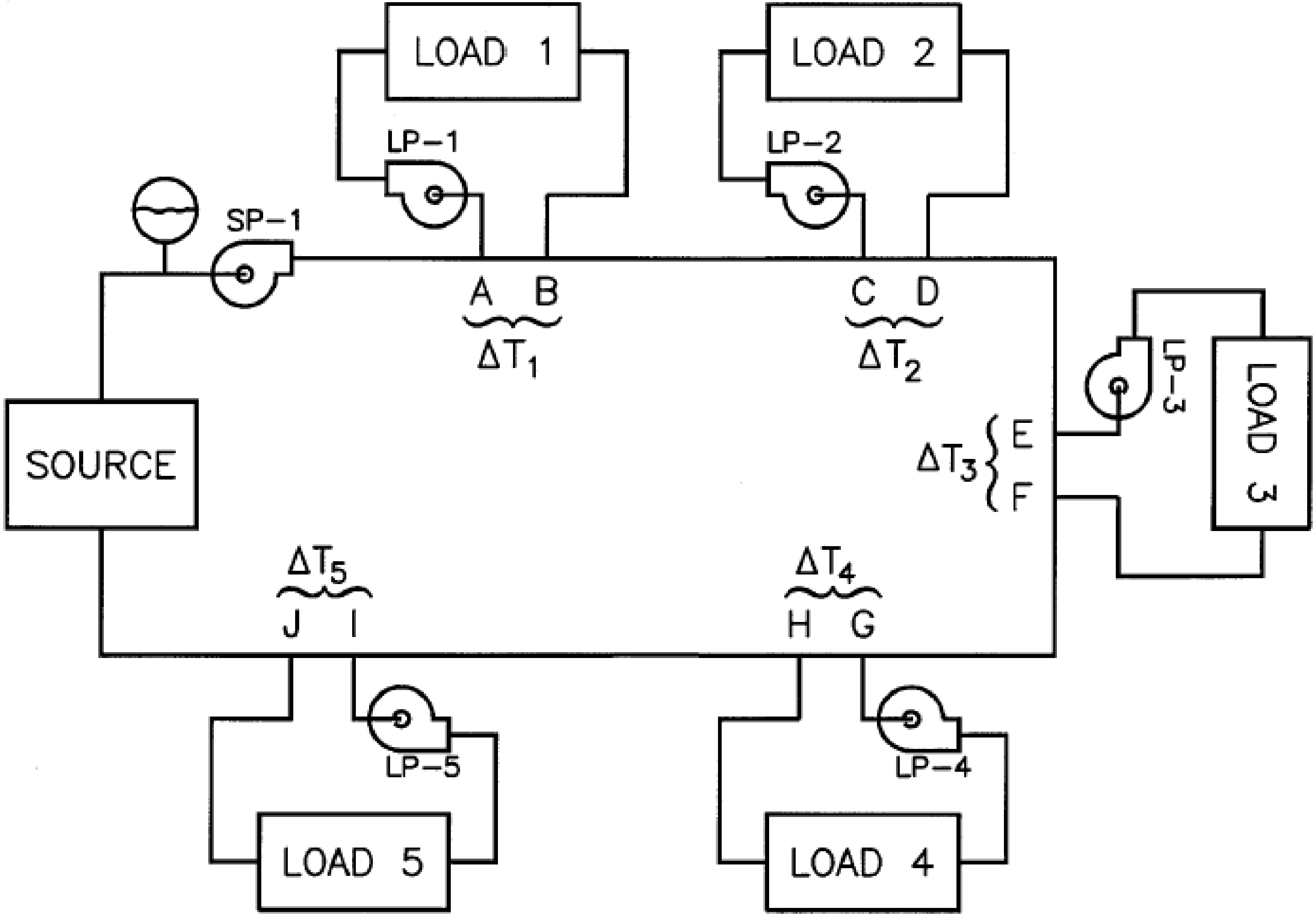
Water Systems in HVAC

- 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



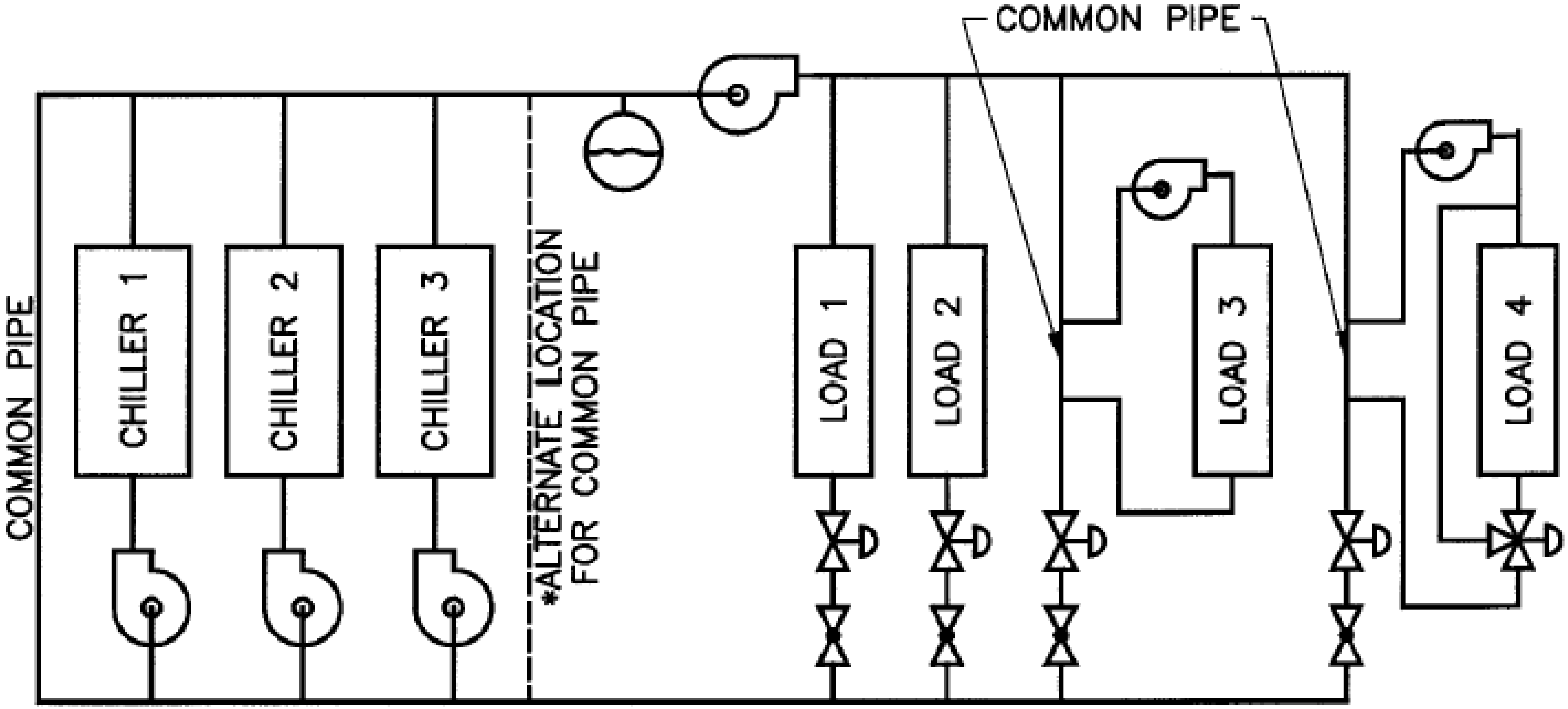
Basic components of water (hydronic) system

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



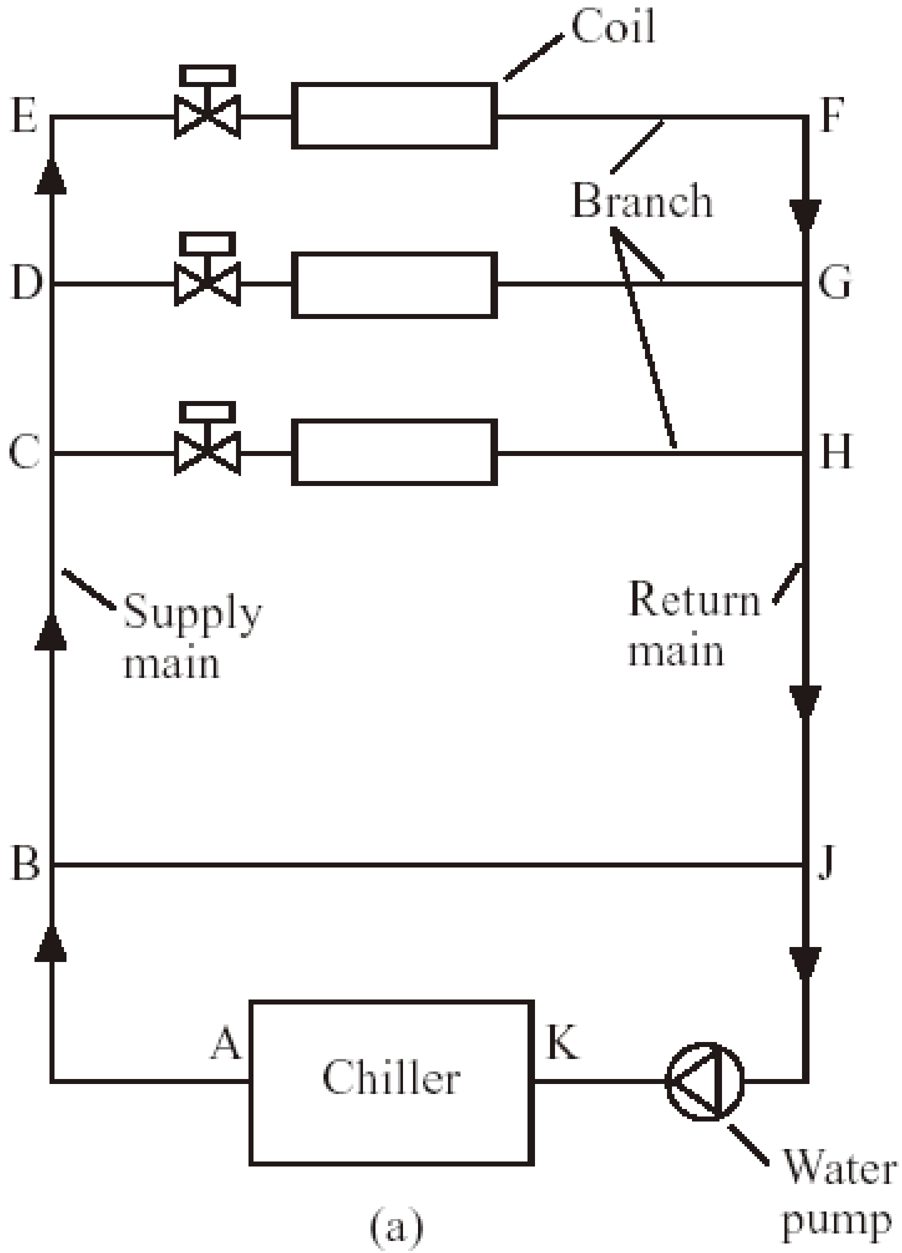
Series circuit with load pumps

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

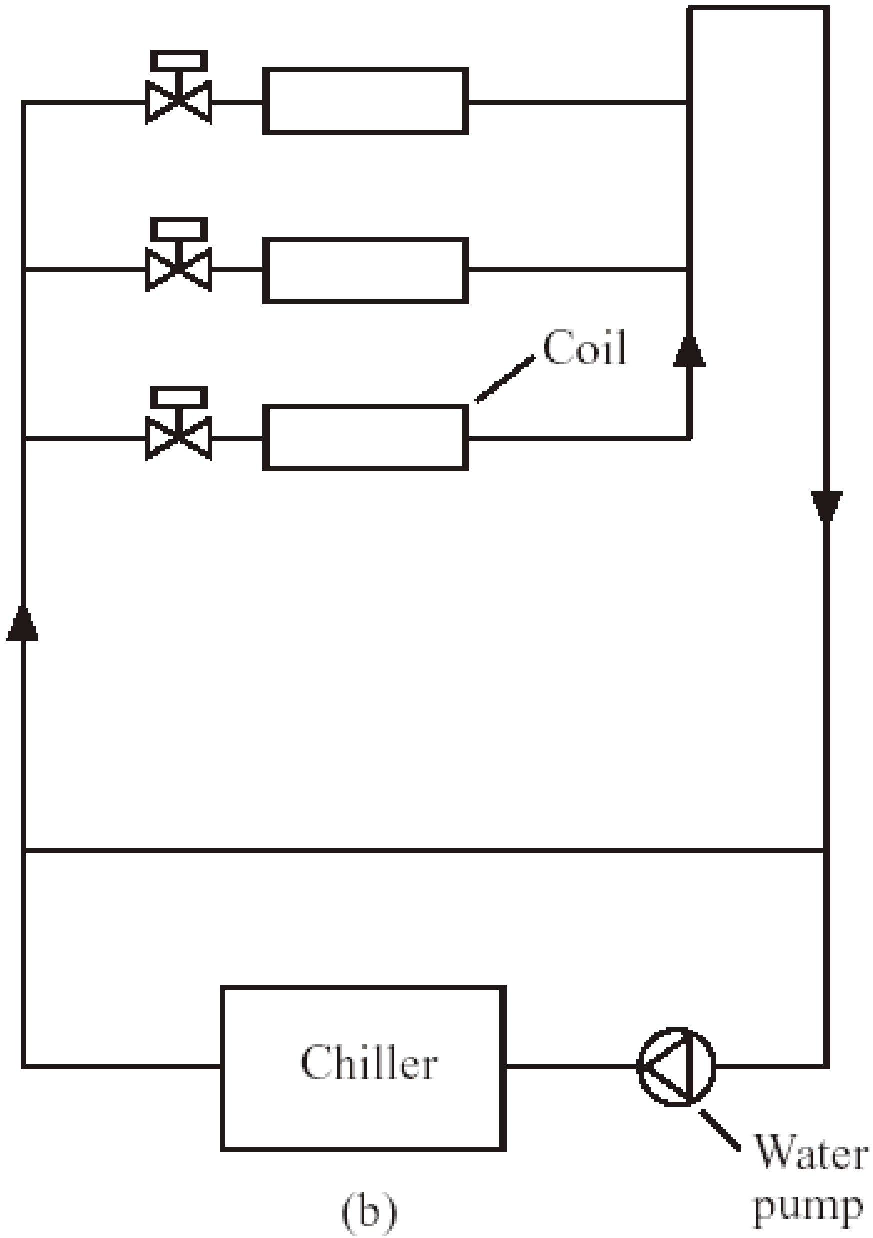


Multiple chiller variable flow chilled water system

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

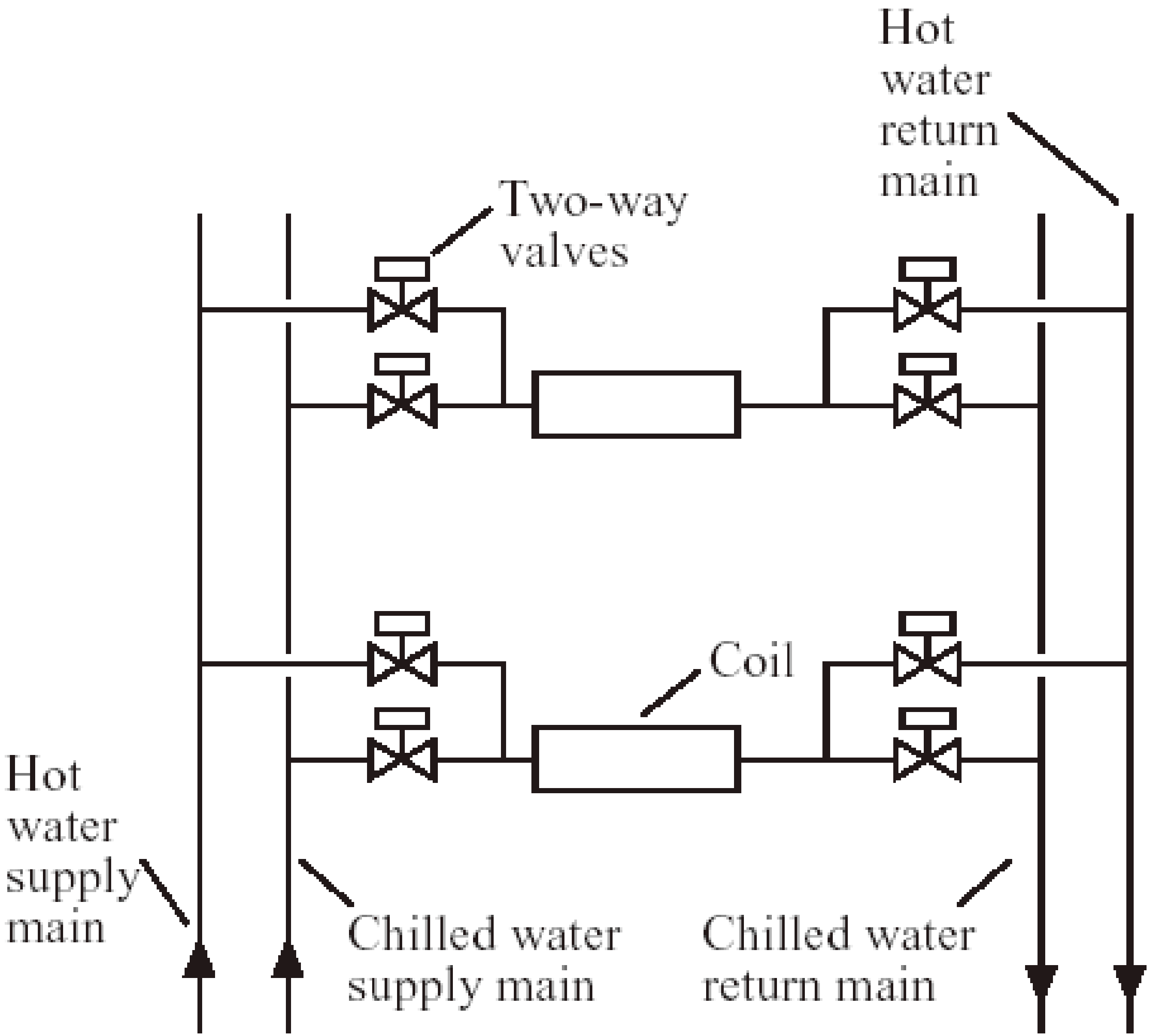


2-pipe direct return



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*)

Water Systems in HVAC

- 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

Water Systems in HVAC

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

Water Systems in HVAC

- 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)

Water Systems in HVAC

- 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

Water Systems in HVAC

- 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)

Water Systems in HVAC

- Practical design process (see reference)
  - See "*Practical Guide to HVAC Building Services Calculations*" - water flow distribution systems: overview of system design process
    - 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