MEBS7014 Advanced HVAC applications

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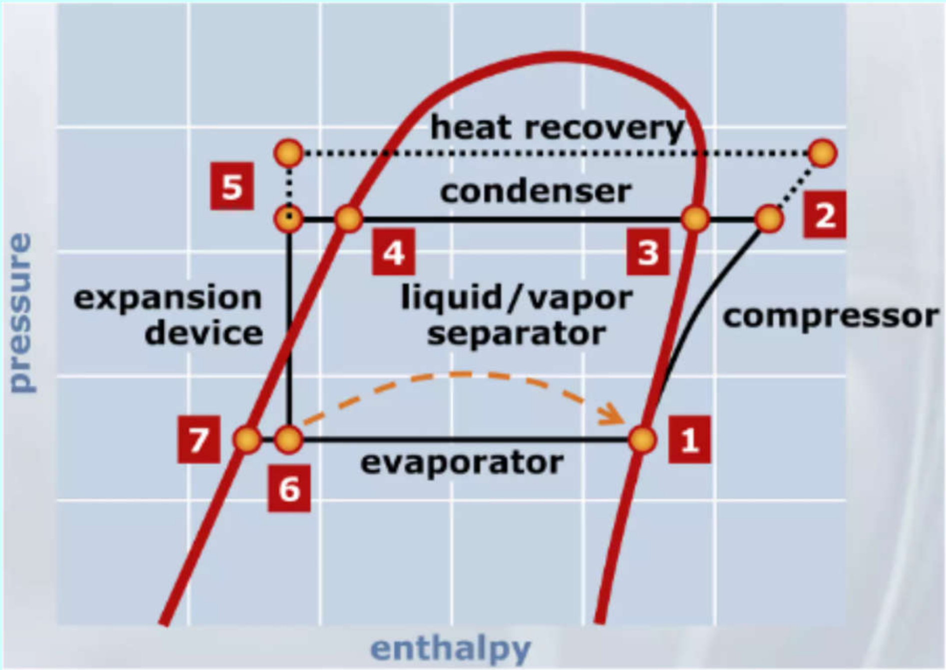

Heat Recovery Systems II

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Contents

- Basic principles
- Applied heat pumps
- Heat recovery chillers
- Wastewater heat recovery

Basic principles

- Balanced heat recovery:
  - Occurs when internal heat gain equals recovered heat and no external heat is introduced to the conditioned space
  - Maintaining balance may require raising the temperature of recovered heat
  - Many, if not most, systems do not have balanced heat recovery over time (e.g., during unoccupied periods or extreme cold) and require supplemental heat to overcome heat losses

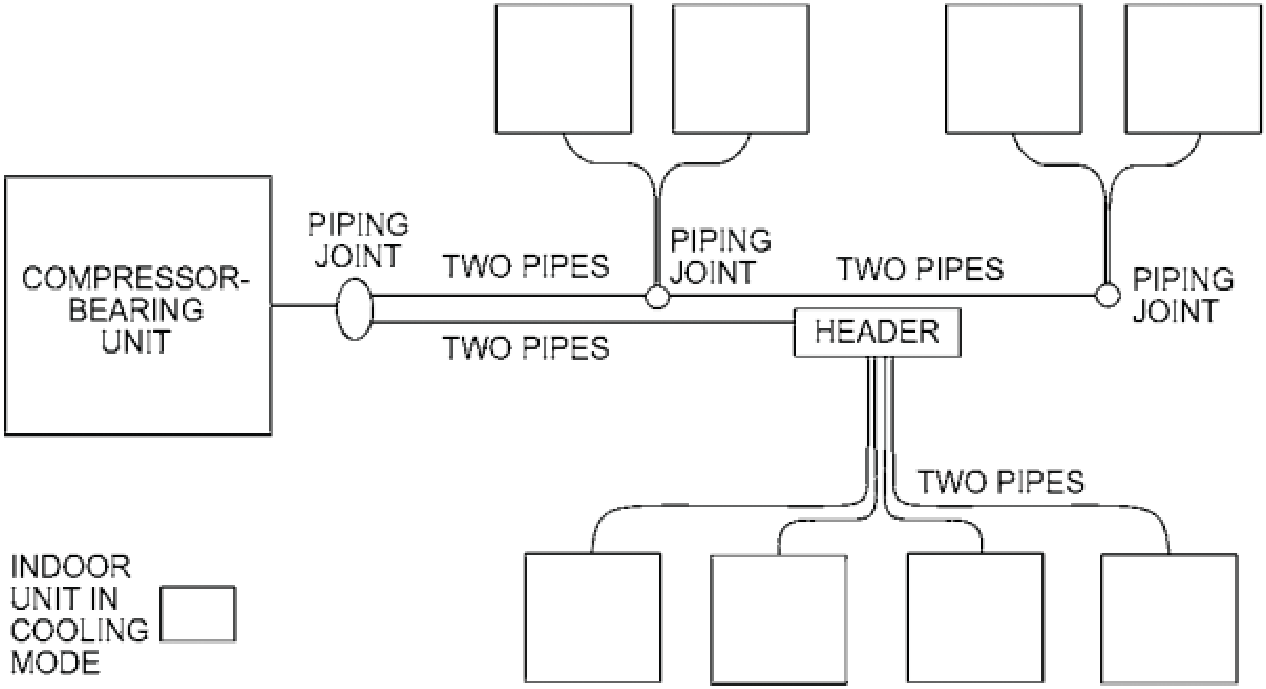
Basic principles

- HVAC heat recovery systems
  - Can be assembled by combining a number of systems to enable heat recovery functionality, e.g.
    - Variable refrigerant flow (VRF) systems that enable recovery of energy between cooling and heating
    - Reverse cycle water-to-air heat pumps on a common water loop that allows recovery of energy between units rejecting heat and those requiring heat
    - Heat recovery/reclaim chillers that simultaneously provide heating and cooling (with single or double bundle/condenser)

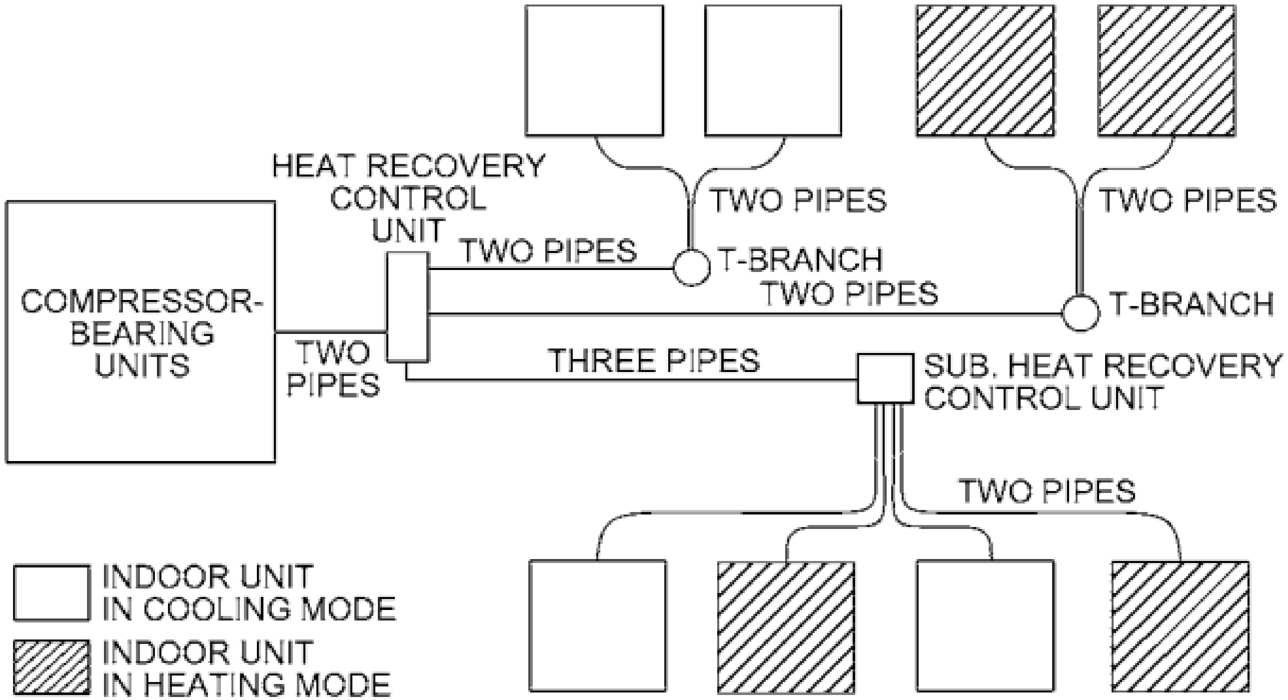
Basic principles

- Variable refrigerant flow (VRF) systems*
  - Direct expansion (DX), similar to multi-split systems; widely used in Japan and Europe
  - Able to control the amount of refrigerant flowing to the multiple evaporators (indoor units), enabling the use of many evaporators of differing capacities and configurations connected to a single condensing unit
  - Provides an individualized comfort control, and simultaneous cooling & heating in different zones

(*See also: Variable refrigerant flow - Wikipedia http://en.wikipedia.org/wiki/Variable_refrigerant_flow)



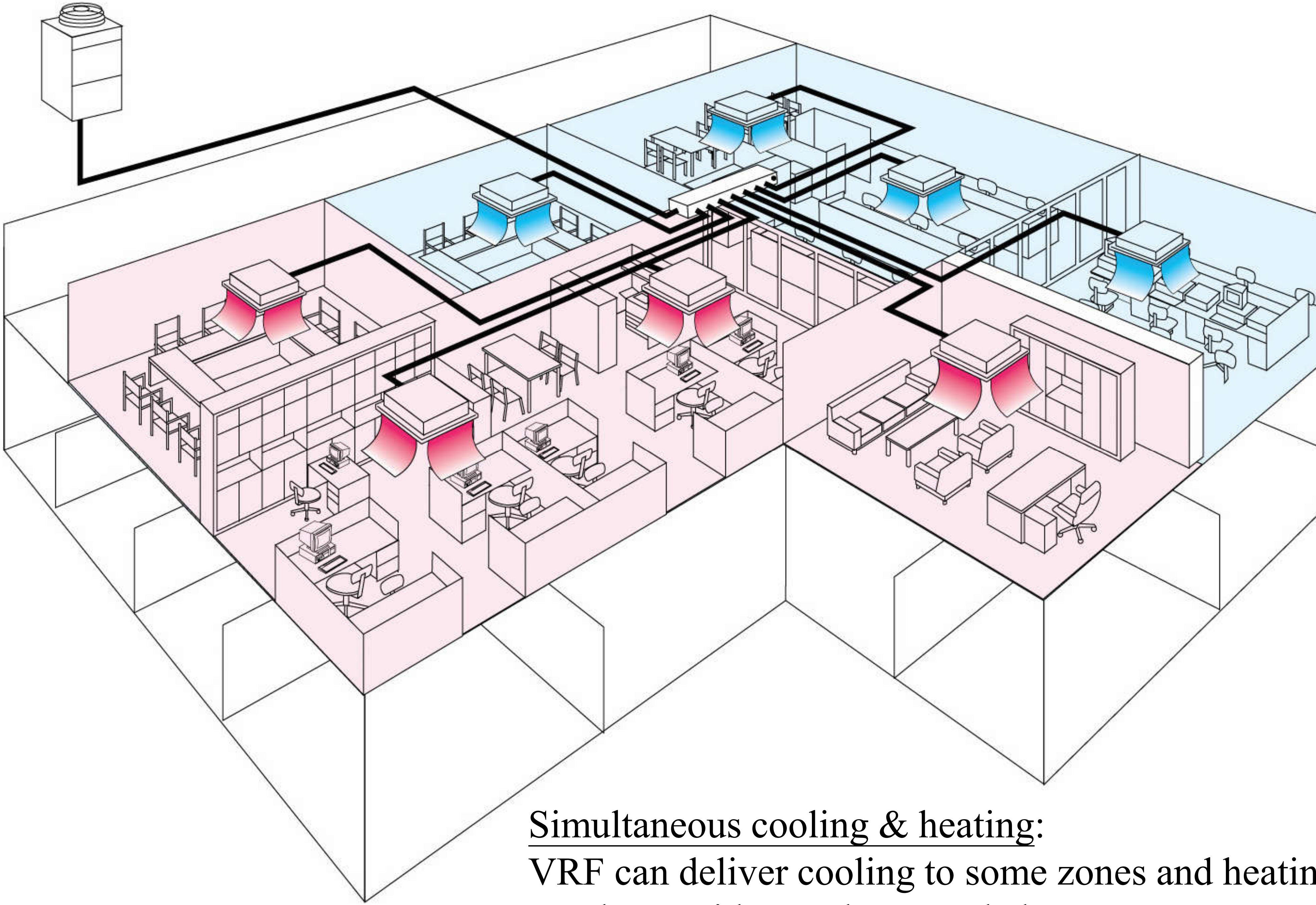
Cooling-only and heat pump VRF system



Two-pipe heat recovery VRF system

(Source: ASHRAE Handbook 2020 HVAC Systems and Equipment, Chapter 18 – Variable Refrigerant Flow)

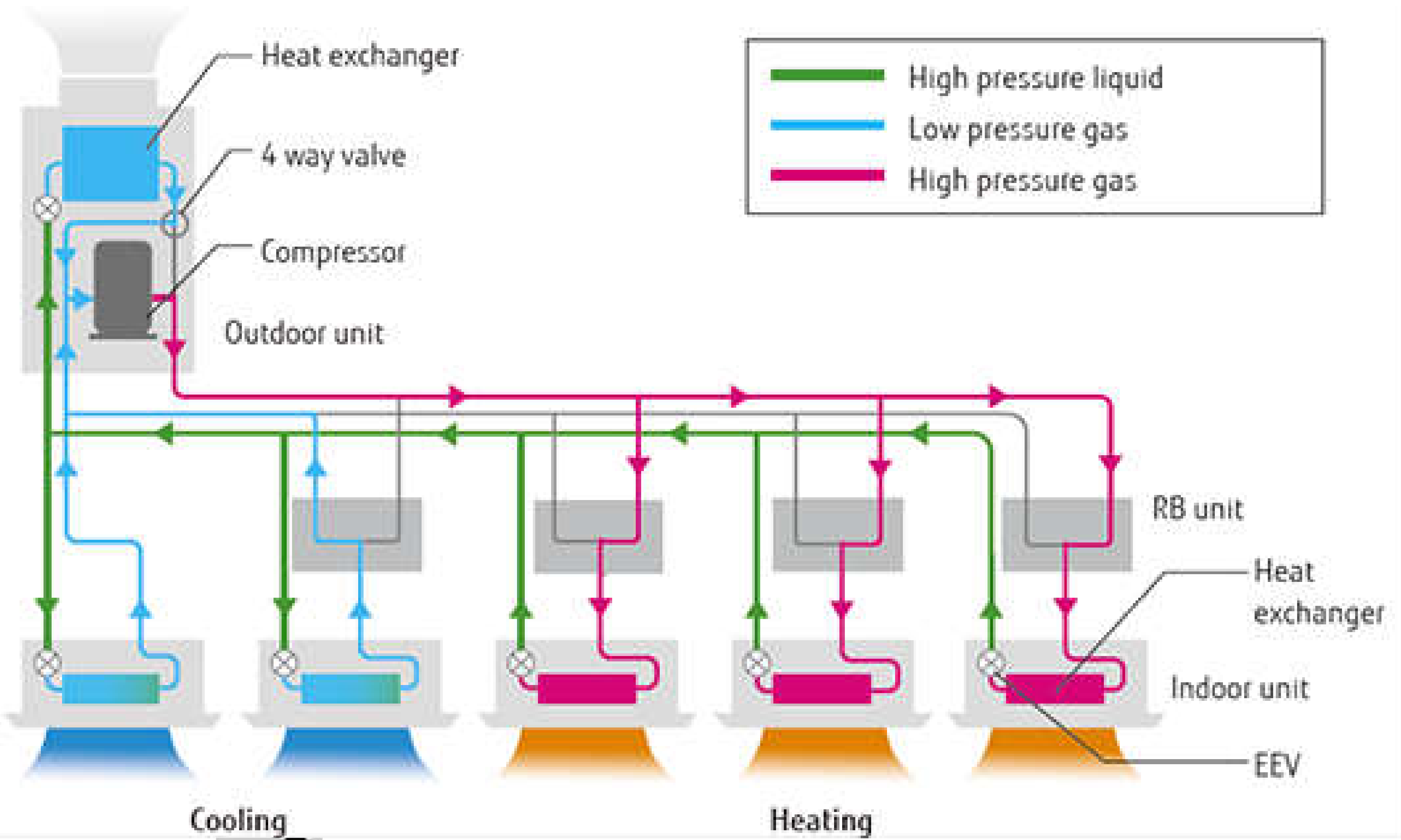
Variable refrigerant flow (VRF) system with heat recovery

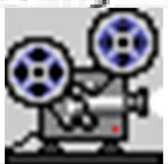


Simultaneous cooling & heating:
VRF can deliver cooling to some zones and heating to others, with no reheat needed.

(Source: Mitsubishi Electric)

Variable refrigerant flow (VRF) system with simultaneous cooling & heating (by heat recovery)

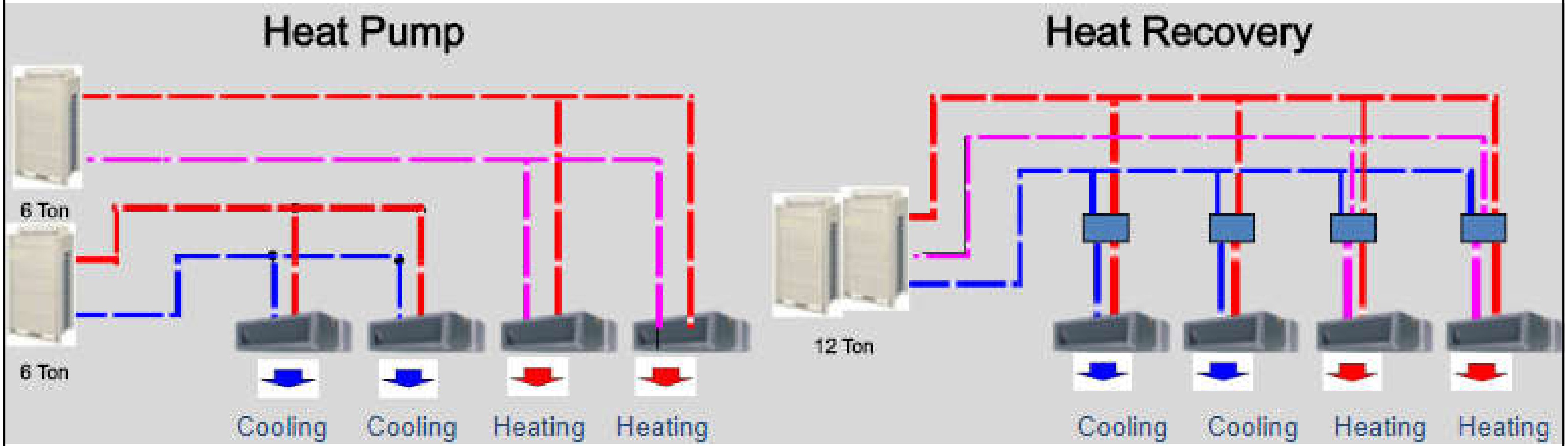




Video: Heat Recovery VRF System - How it Works (3:26) https://youtu.be/r-NQEoPidX8

(Source: Fujitsu)

Heat pump and heat recovery VRF systems

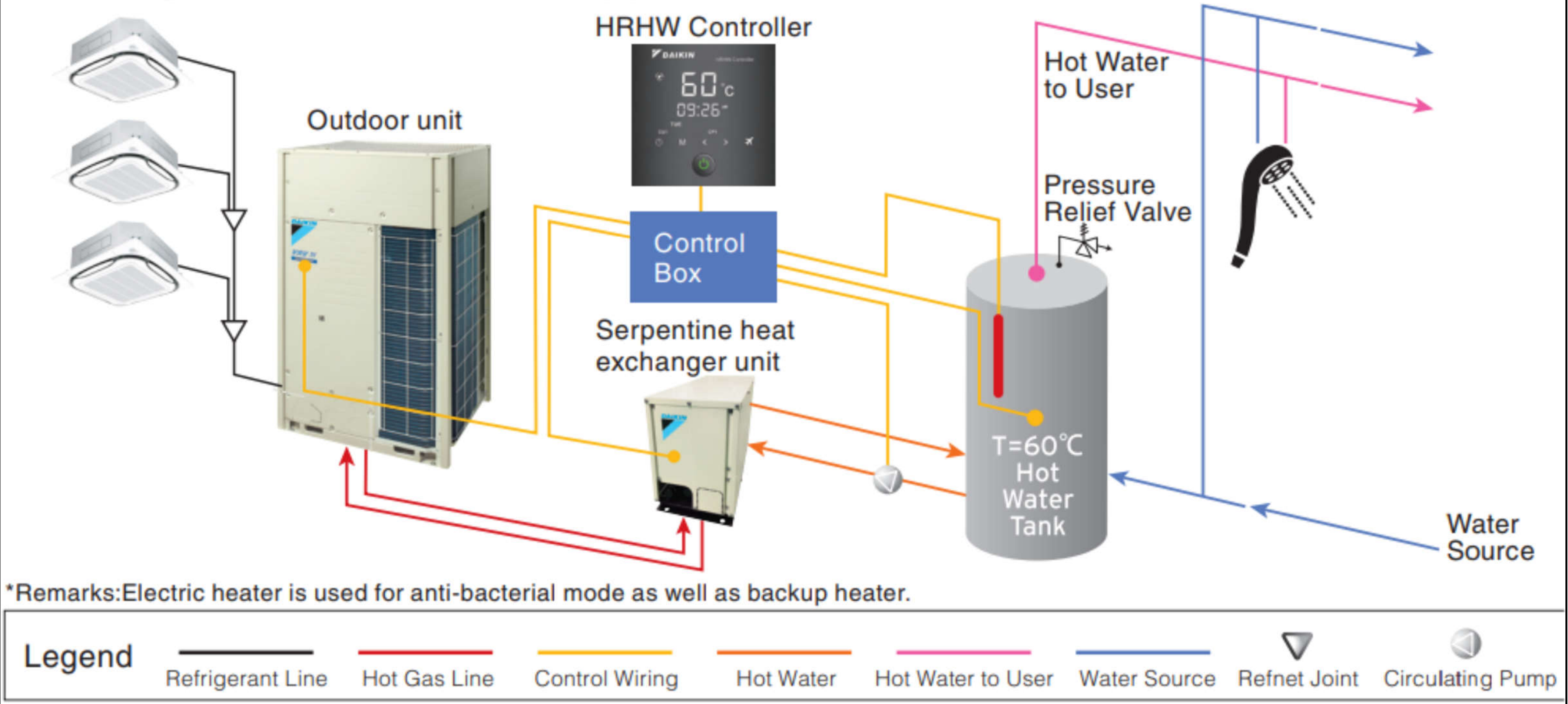


<u>Heat pump VRF</u>:
- 2-pipe system
- heat/cool changeover

<u>Heat recovery VRF</u>:
- 3-pipe system
- Can provide simultaneous cooling & heating
- Extra heat exchangers in distribution boxes are used to transfer some reject heat from superheated refrigerant existing the cooling zone to the refrigerant going to the heating zone

(Source: Allen Anaya, W M Carroll LLC)

Variable refrigerant flow (VRF) heat recovery hot water system for residential application



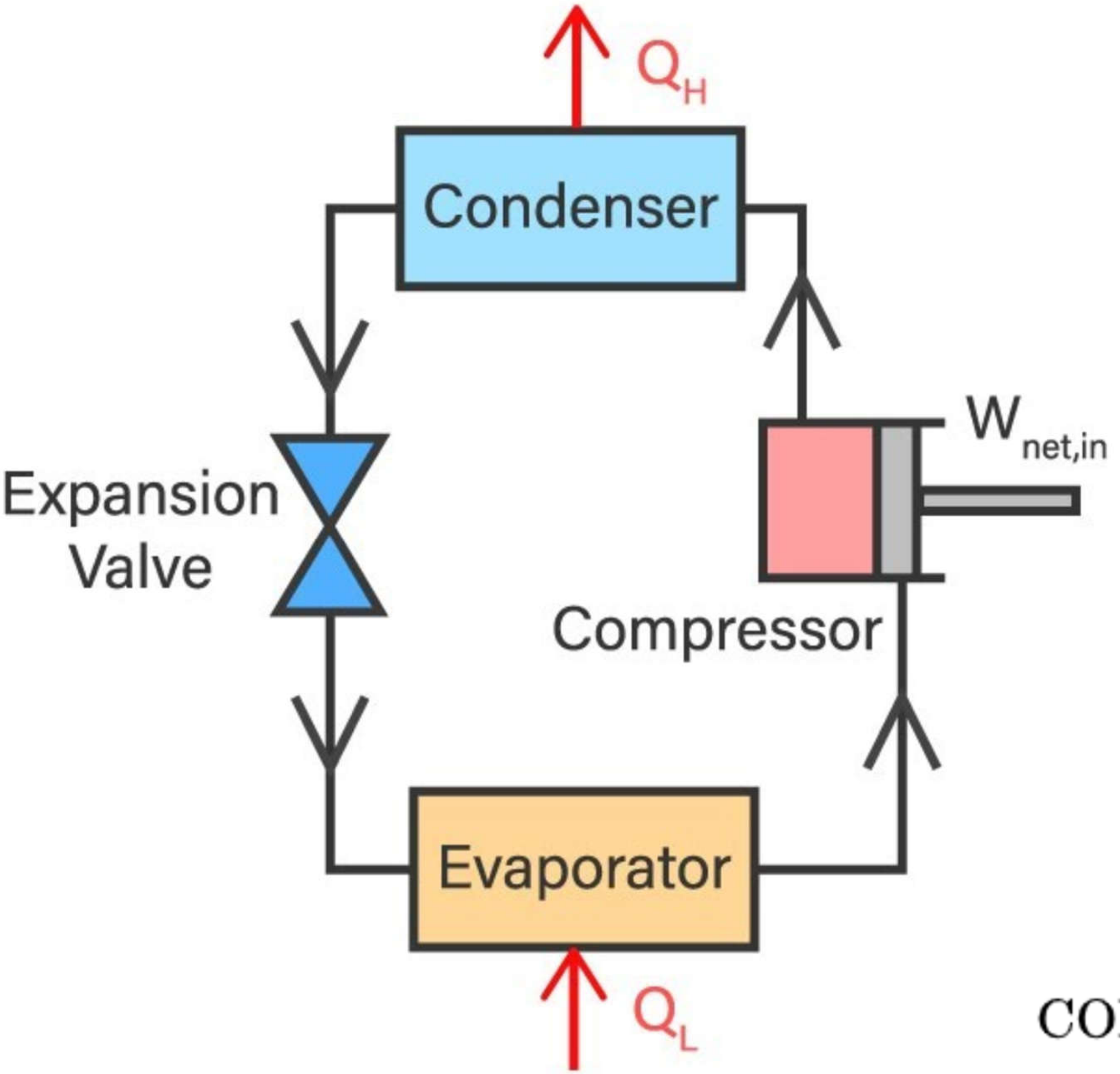
(Source: Daikin)

Basic principles

- Heat pump – designed to heat water
  - Provides 100% of heat as hot water
  - Capacity controlled by leaving condenser water temp.
  - Evaporator fluid temperatures uncontrolled
- Heat recovery chiller – designed to chill water
  - Provides a percentage of heat as warm water
  - Capacity controlled by leaving chilled water temp.
  - Condensing temperature is uncontrolled
  - Additional condenser bundle used to capture cooling tower heat rejection typically at temperatures 35-46 °C

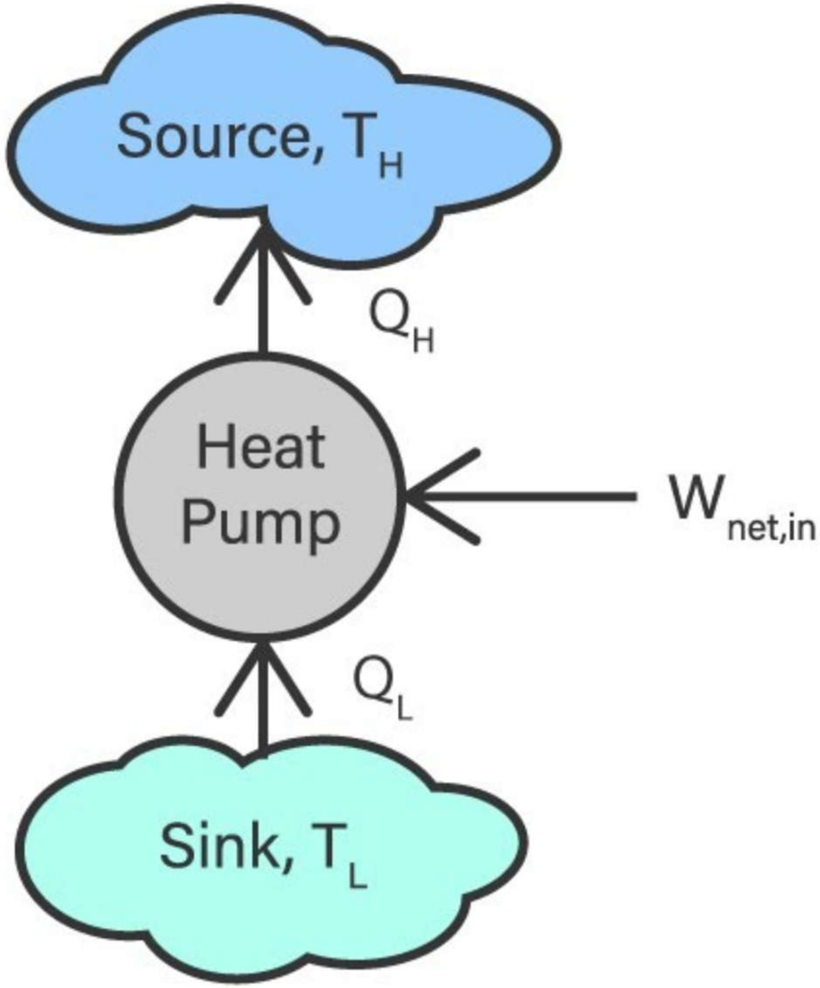
Basic concepts of refrigeration and heat pump cycles

Refrigeration cycle



$$\mathrm{COP_R} = \frac{\text{Cooling Effect}}{\text{Work Input}} = \frac{Q_L}{W_{\text{net,in}}}$$

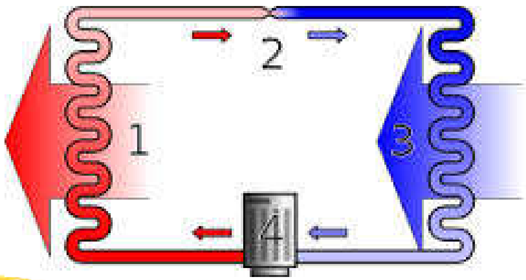
Heat pump cycle



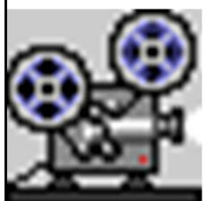
$$\mathrm{COP_{HP}} = \frac{\text{Heating Effect}}{\text{Work Input}} = \frac{|Q_H|}{W_{\text{net,in}}} = \frac{W_{net,in} + Q_L}{W_{\text{net,in}}} = 1 + \frac{Q_L}{W_{\text{net,in}}}$$

(See also: Heat pump and refrigeration cycle - Wikipedia https://en.wikipedia.org/wiki/Heat_pump_and_refrigeration_cycle)

Applied heat pumps

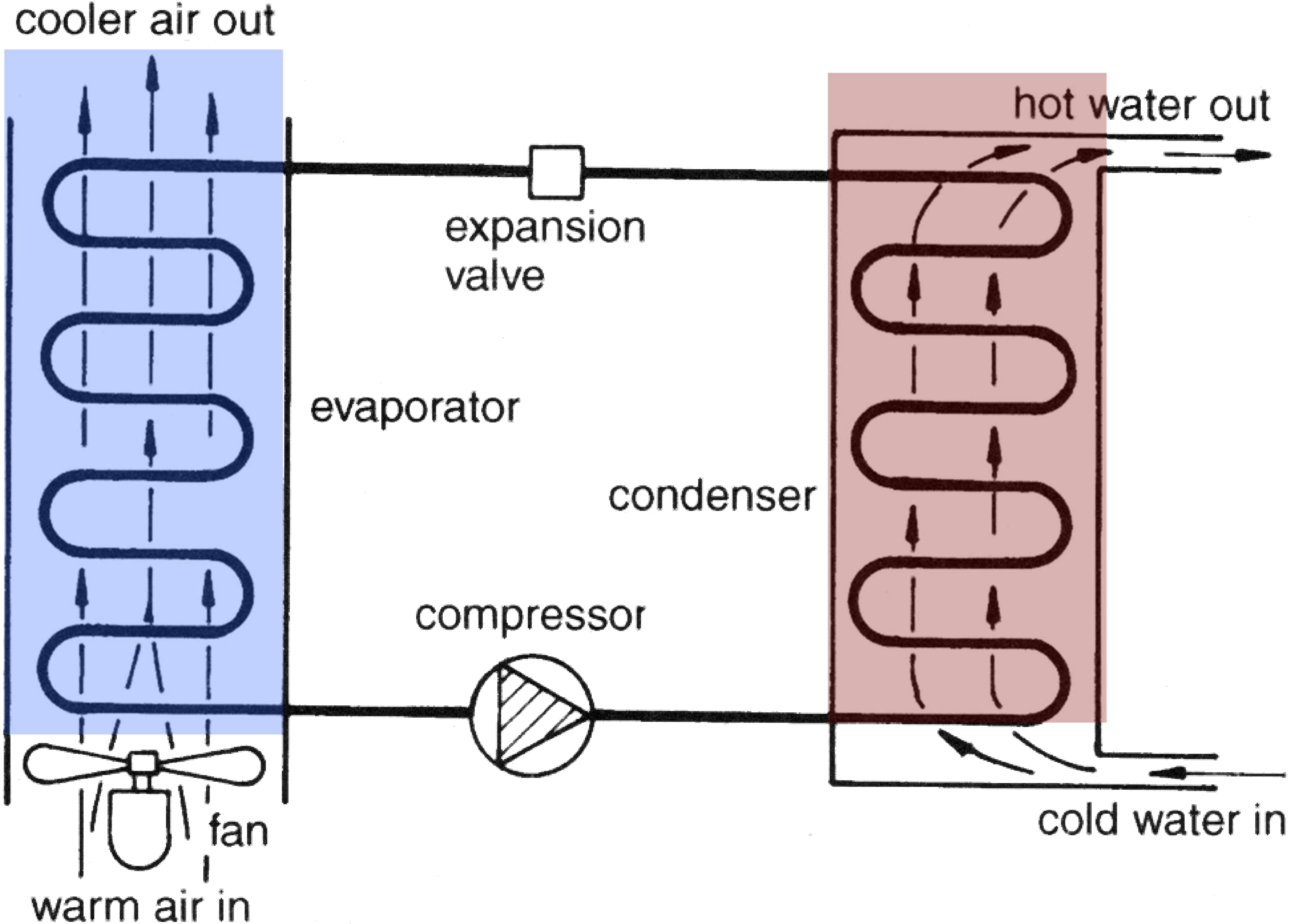


- A heat pump extracts heat from a source and transfers it to a sink at a higher temperature
- Heat pump sources and sinks
  - Air (outdoor ambient, exhaust)
  - Water (well, surface, tap, condensing, closed loops, waste)
  - Ground (ground-coupled, direct expansion)
  - Solar energy (direct or heated water)
  - Industrial process (process heat or exhaust)



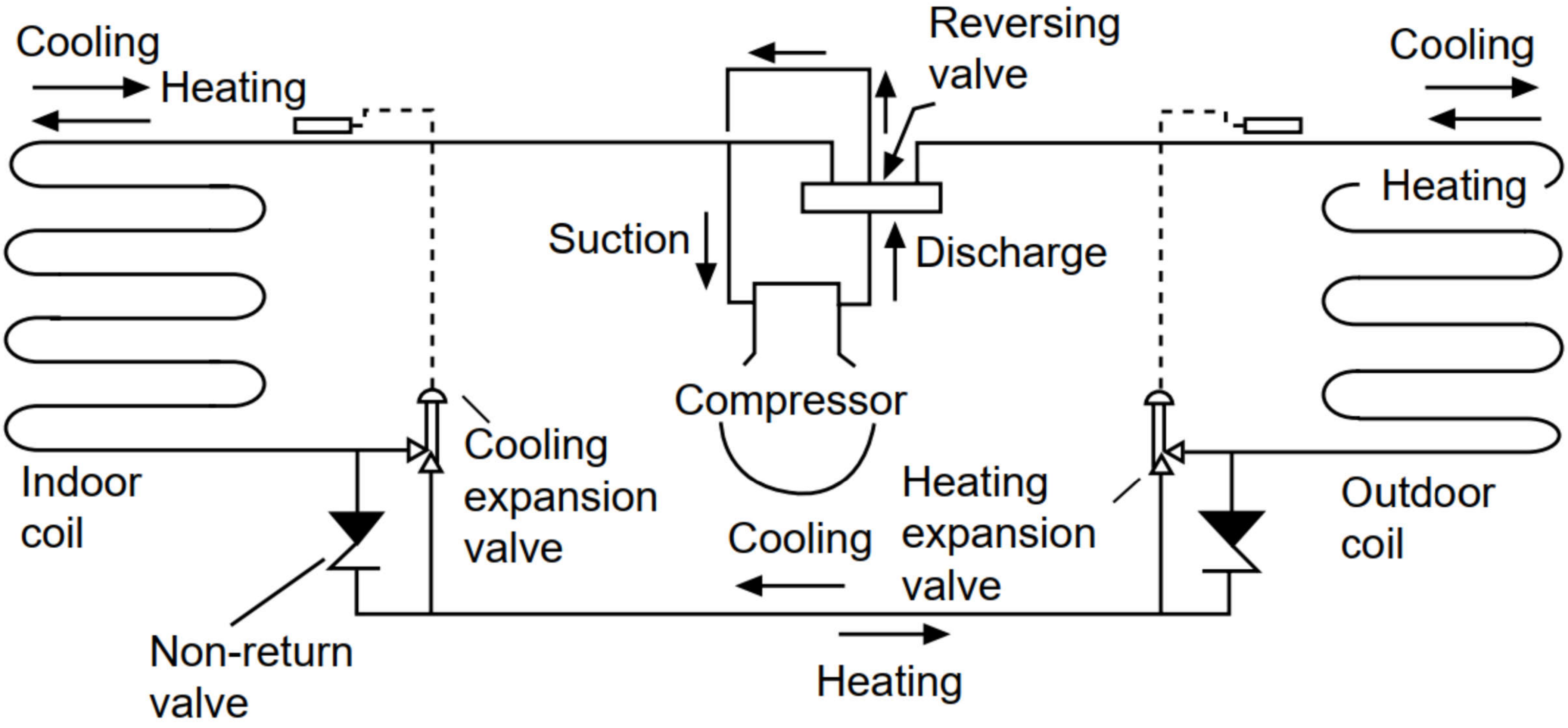
(Video: How A Heat Pump Works (11:32) http://youtu.be/G53tTKoakcY)

Basic principles of heat pump

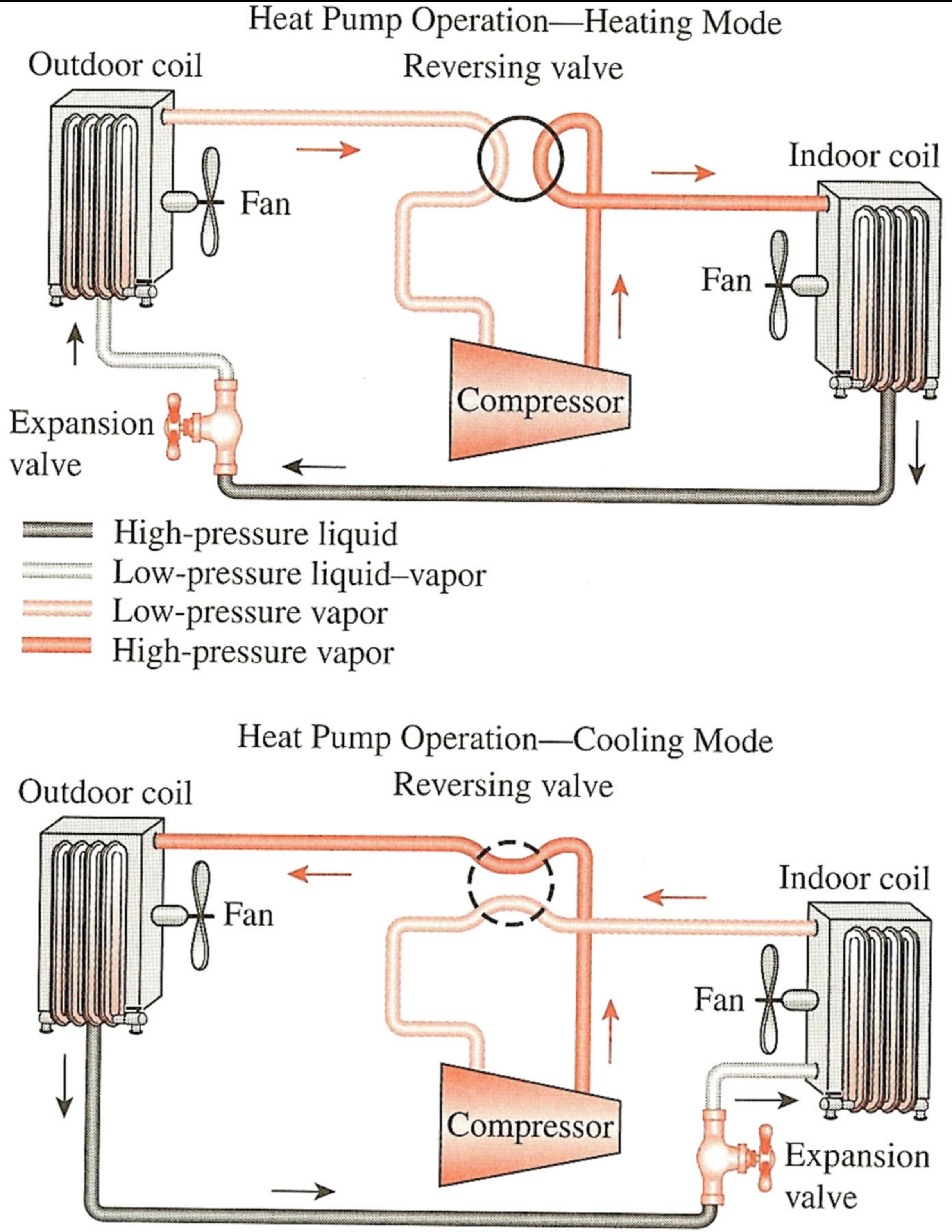


(Source: Garrett, R. H., 2008. *Hot and Cold Water Supply*)

Piping arrangement for reversible flow circuit of heat pump air conditioner

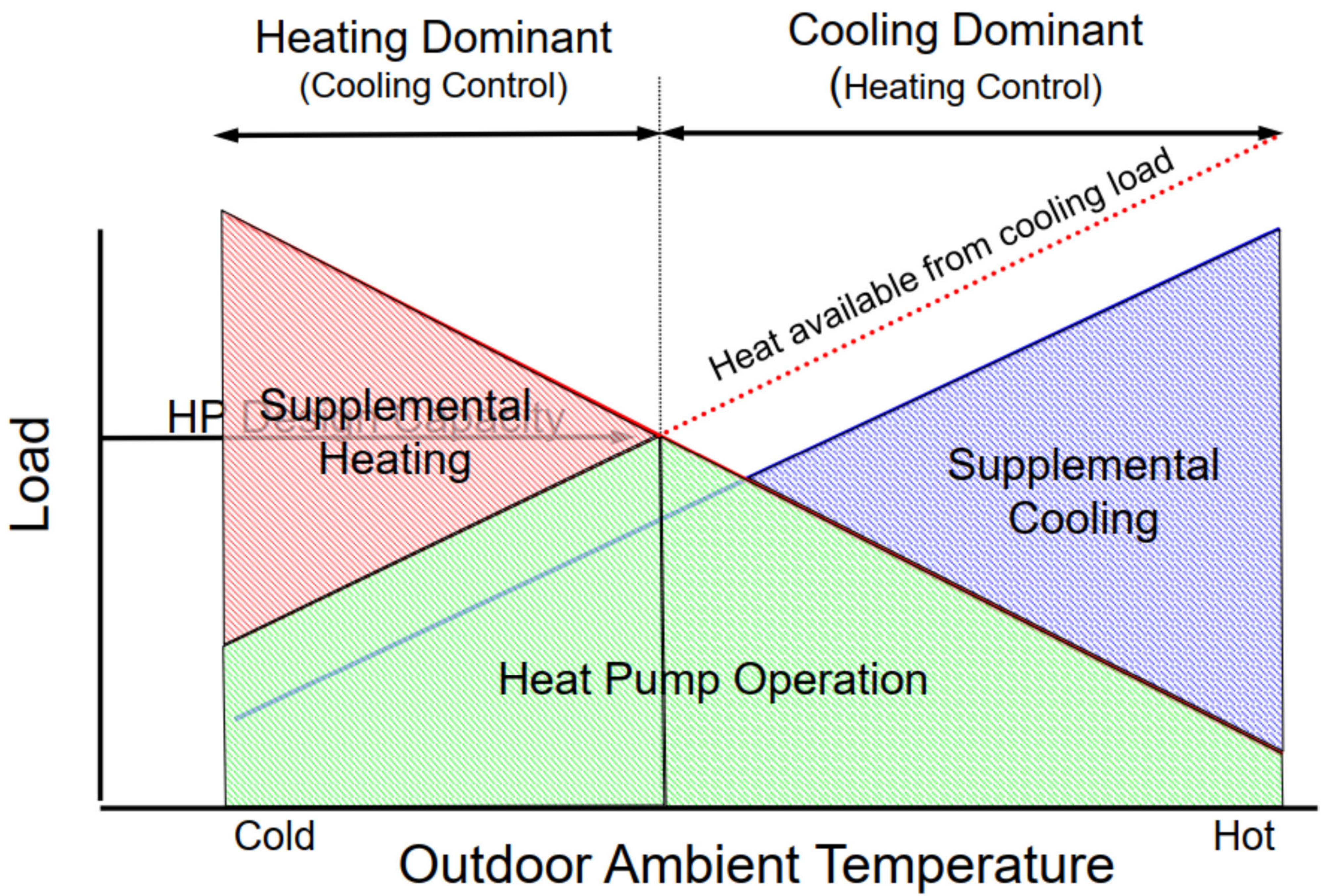


(Source: Hundy G. F., Trott A. R. & Welch T. C., 2008. *Refrigeration and Air-conditioning*, Fourth Edition, Butterworth-Heinemann.)



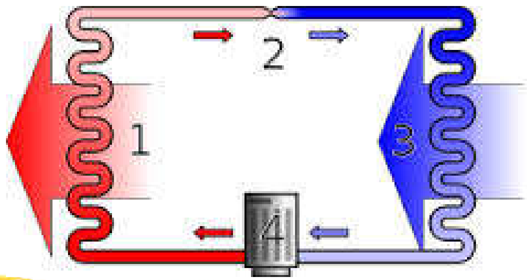
Heat Pump Operation—Heating Mode
Outdoor coil
Reversing valve
Indoor coil
Fan
Fan
Compressor
Expansion
valve
High-pressure liquid
Low-pressure liquid–vapor
Low-pressure vapor
High-pressure vapor
Heat Pump Operation—Cooling Mode
Outdoor coil
Reversing valve
Indoor coil
Fan
Fan
Compressor
Expansion
valve

Heat pump sizing and control



(Source: Johnson Controls, Inc.)

Applied heat pumps



- Common types of heat pumps
  - Air-to-air heat pump
  - Water-to-air heat pump
    - Ground water, surface water, internal-source, solar-assisted, wastewater-source
  - Water-to-water heat pump
  - Ground-coupled heat pump
  - Air-to-water heat pump
    - Also called heat pump water heater

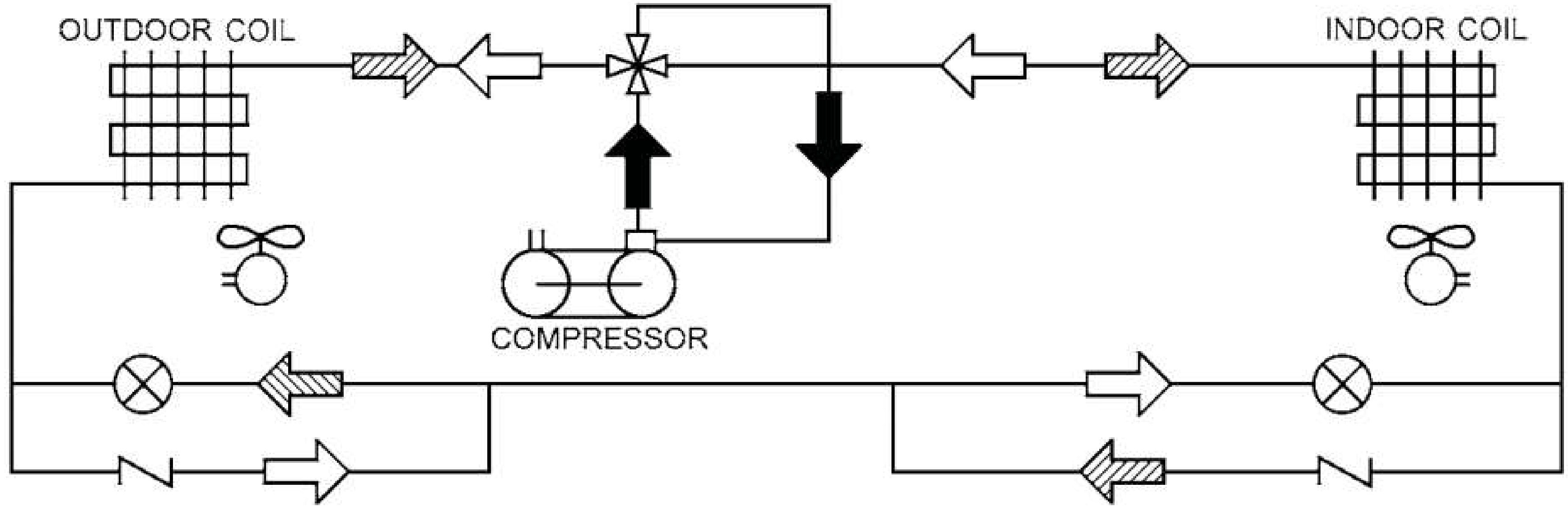
(See also: Heat pump - Wikipedia http://en.wikipedia.org/wiki/Heat_pump)

Heat pump types

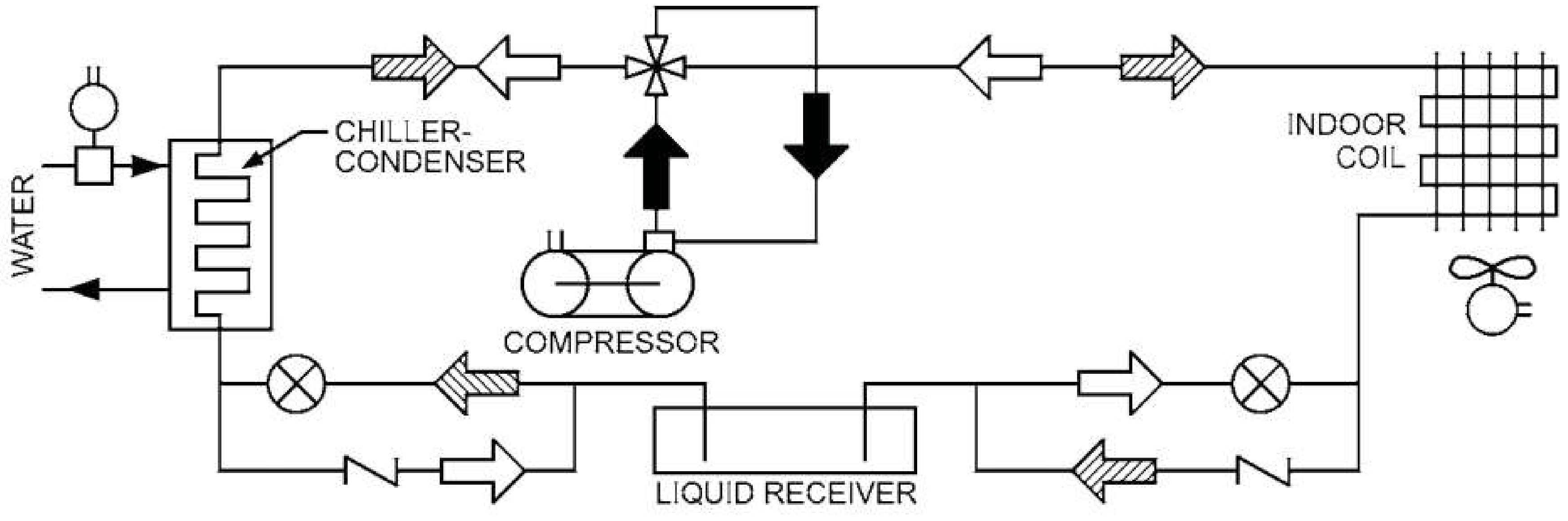
Diagram

Heating **Cooling** **Heating and Cooling**

Air-to-air heat pump



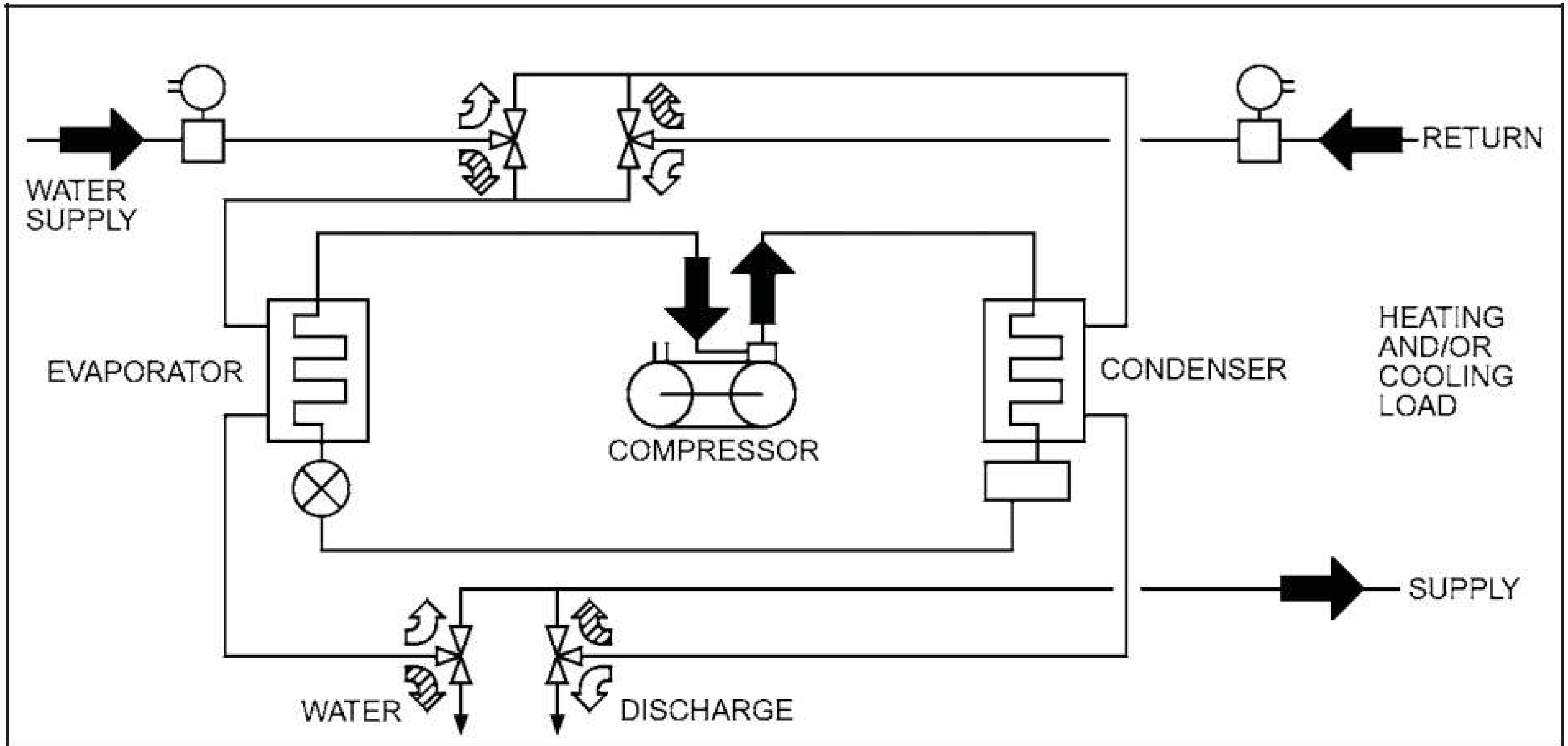
Water-to-air heat pump



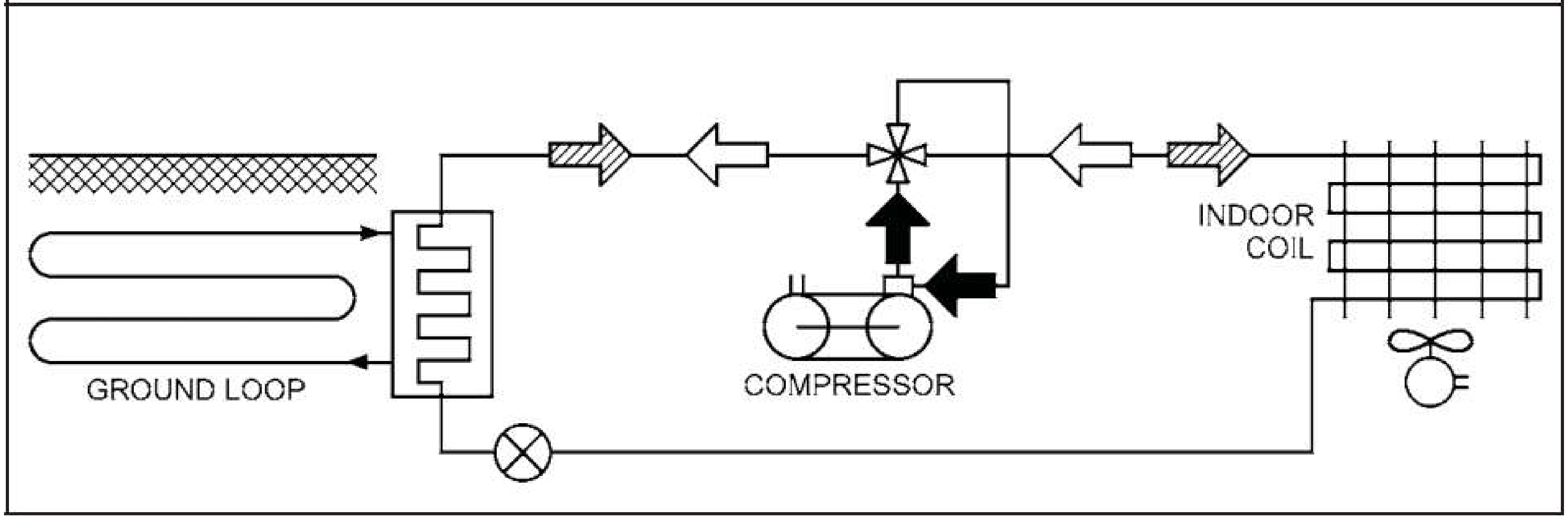
(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 9 – Applied Heat Pump and Heat Recovery Systems)

Heat pump types

Water-to-water heat pump

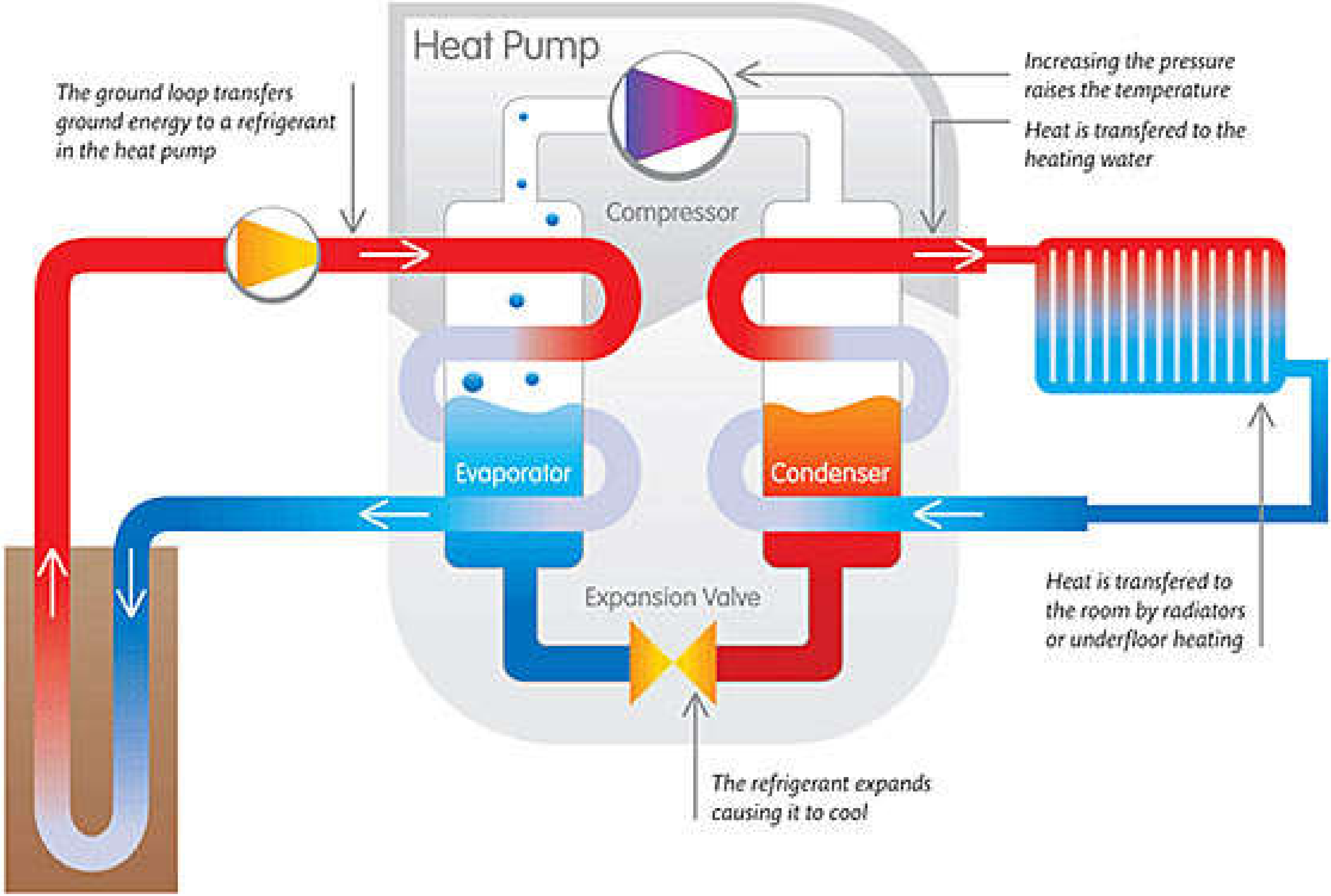


Ground-coupled heat pump



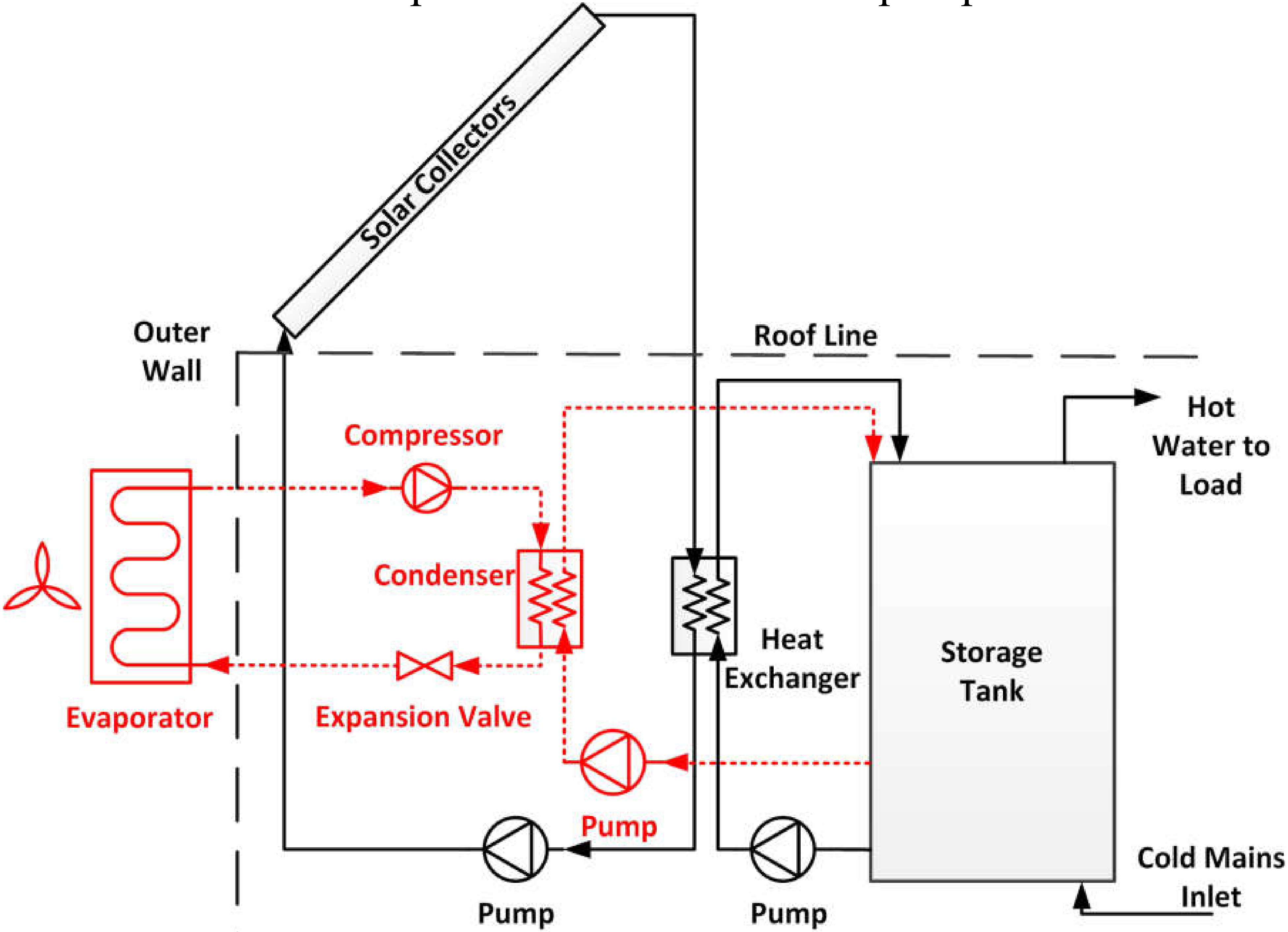
(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 9 – Applied Heat Pump and Heat Recovery Systems)

Principles of ground source heat pump



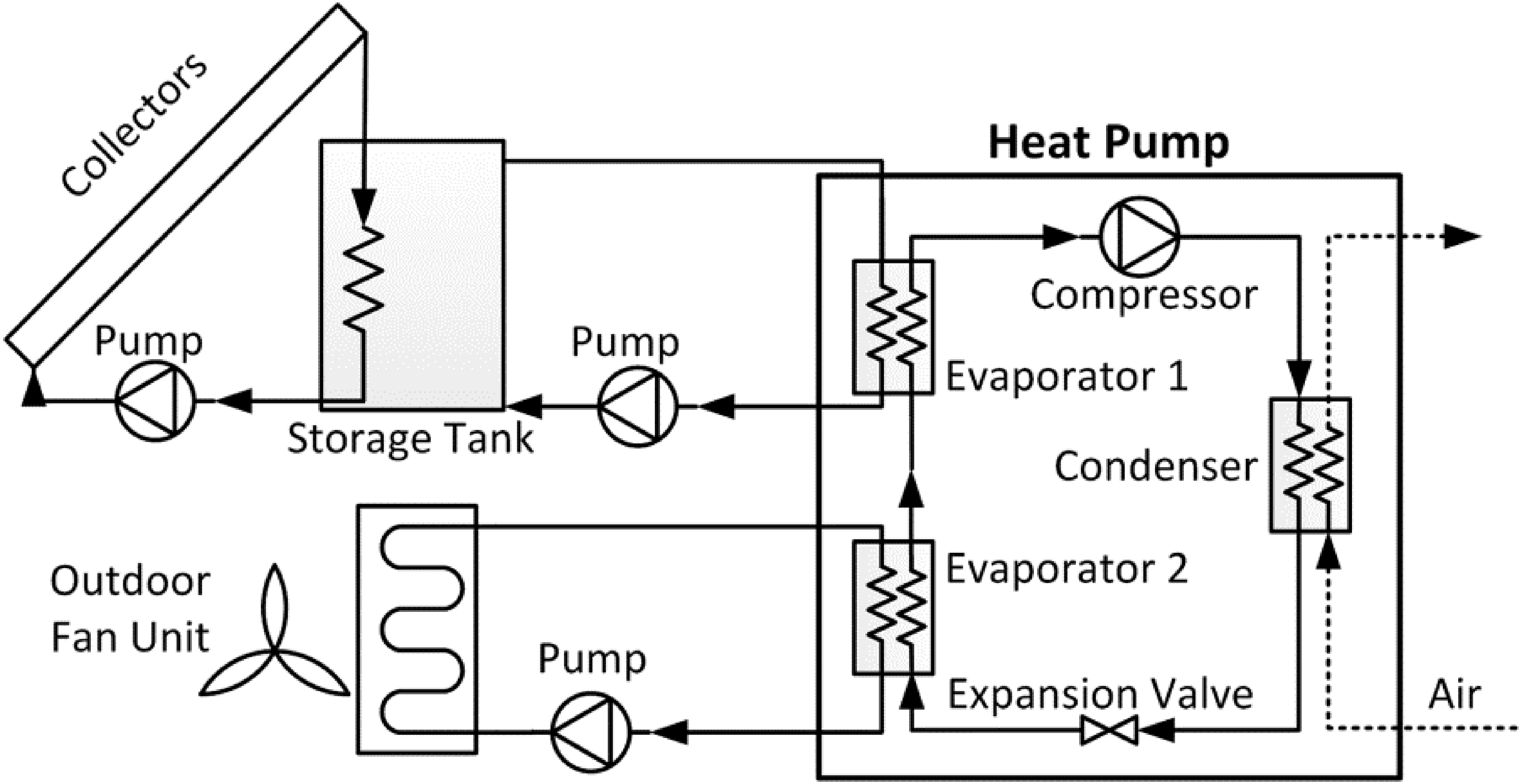
(Source: http://www.energygroove.net/technologies/heat-pumps/)

Example of solar-assisted heat pump



(Source: Chu J. & Cruickshank C. A., 2014. Solar-assisted heat pump systems: a review of existing studies and their applicability to the Canadian residential sector, *Journal of Solar Energy Engineering*, 136 (4) 041013. https://doi.org/10.1115/1.4027735)

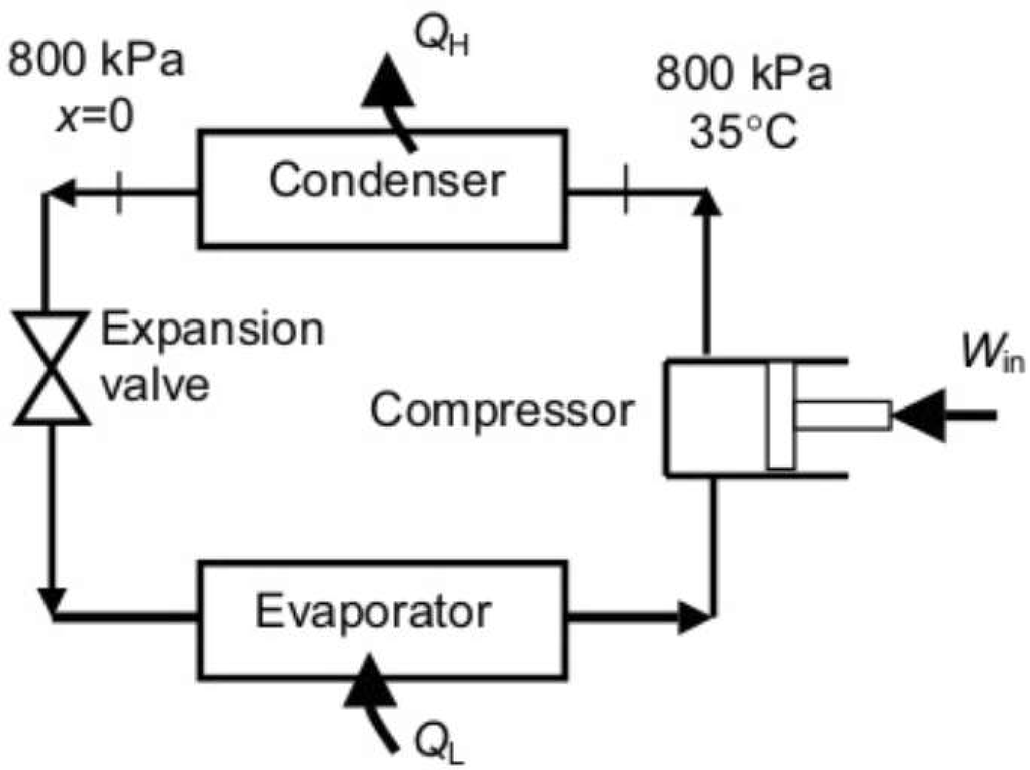
Example of solar-assisted heat pump (cont'd)



(Source: Chu J. & Cruickshank C. A., 2014. Solar-assisted heat pump systems: a review of existing studies and their applicability to the Canadian residential sector, *Journal of Solar Energy Engineering*, 136 (4) 041013. https://doi.org/10.1115/1.4027735)

Worked example of heat pump calculations

6-54 Refrigerant-134a flows through the condenser of a residential heat pump unit. For a given compressor power consumption the COP of the heat pump and the rate of heat absorbed from the outside air are to be determined.



Assumptions **1** The heat pump operates steadily. **2** The kinetic and potential energy changes are zero.

Properties The enthalpies of R-134a at the condenser inlet and exit are

$$\left.\begin{array}{l} P_1 = 800\,\text{kPa} \\ T_1 = 35°\text{C} \end{array}\right\} h_1 = 271.22\ \text{kJ/kg}$$

$$\left.\begin{array}{l} P_2 = 800\,\text{kPa} \\ x_2 = 0 \end{array}\right\} h_2 = 95.47\ \text{kJ/kg}$$

Analysis (*a*) An energy balance on the condenser gives the heat rejected in the condenser

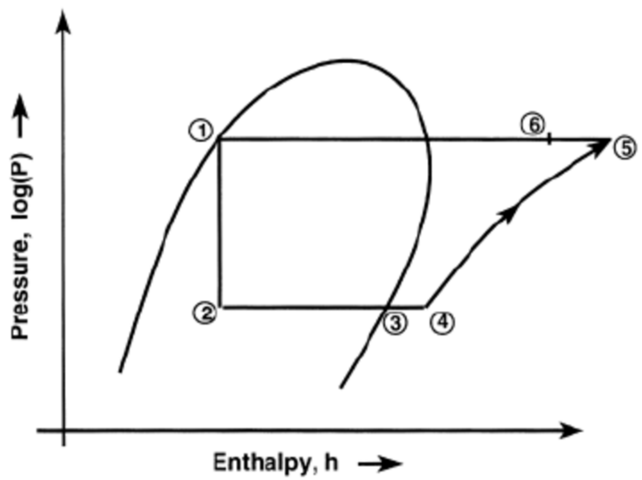
$$\dot{Q}_H = \dot{m}(h_1 - h_2) = (0.018\ \text{kg/s})(271.22 - 95.47)\ \text{kJ/kg} = 3.164\ \text{kW}$$

The COP of the heat pump is

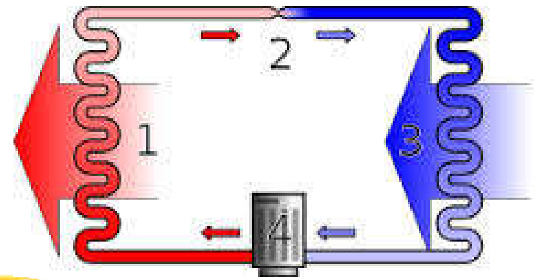
$$\text{COP} = \frac{\dot{Q}_H}{\dot{W}_{in}} = \frac{3.164\ \text{kW}}{1.2\ \text{kW}} = \mathbf{2.64}$$

(*b*) The rate of heat absorbed from the outside air

$$\dot{Q}_L = \dot{Q}_H - \dot{W}_{in} = 3.164 - 1.2 = \mathbf{1.96\ kW}$$

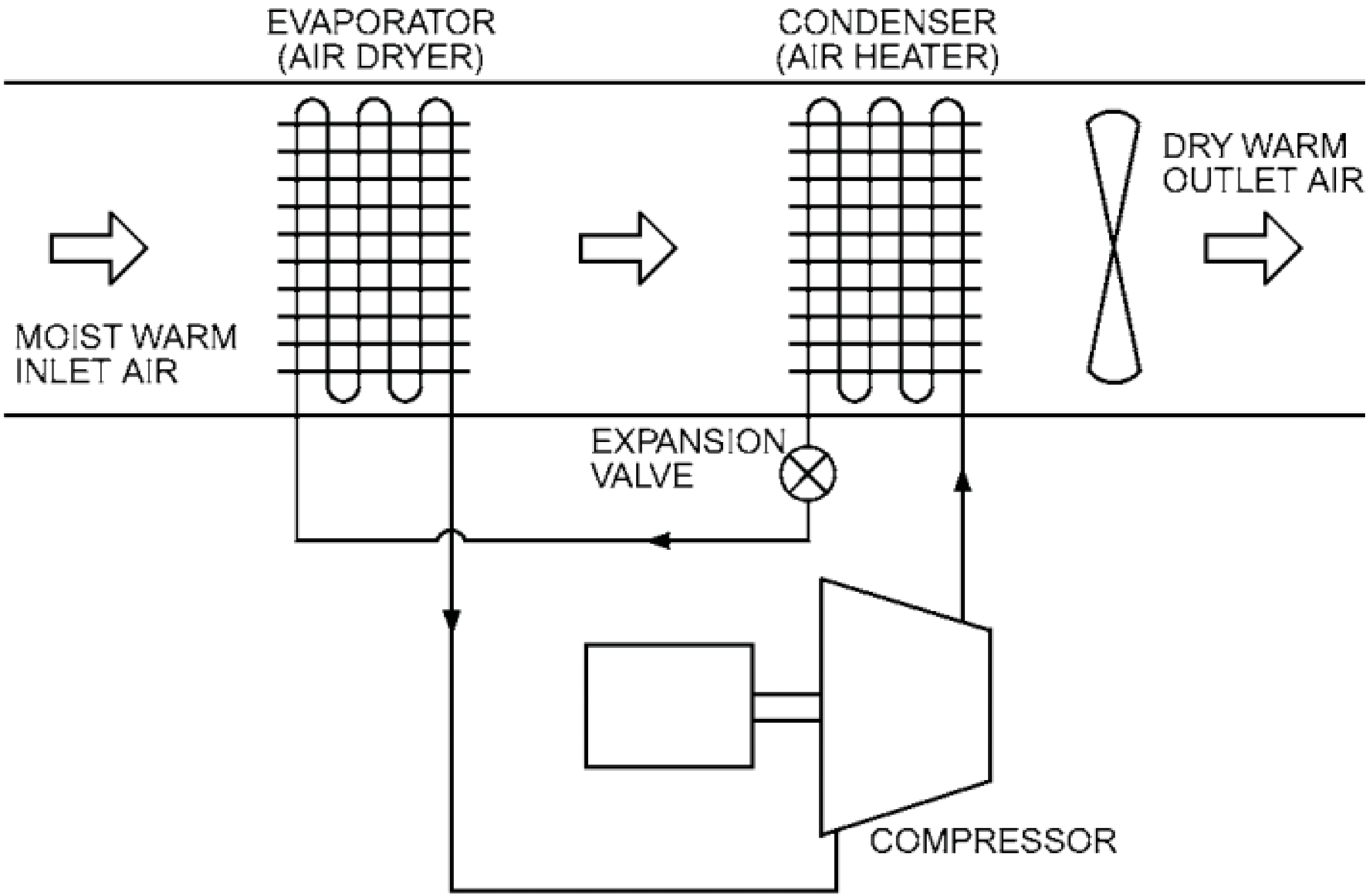


Applied heat pumps



- Heat recovery heat pump (HRHP) systems
  - Such as industrial heat pump systems
  - Translate low grade (low temperature) rejected heat to usable heat in a process
  - Two major types:
    - Closed-cycle systems
      - Use a suitable working fluid, usually a refrigerant in a sealed system; can use either absorption or vapour compression
    - Open-cycle (and semi-open-cycle) systems
      - Use process fluid to raise the temperature of available heat energy by vapour compression (to produce steam)

Air-to-air or dehumidification heat pumps (closed-cycle)

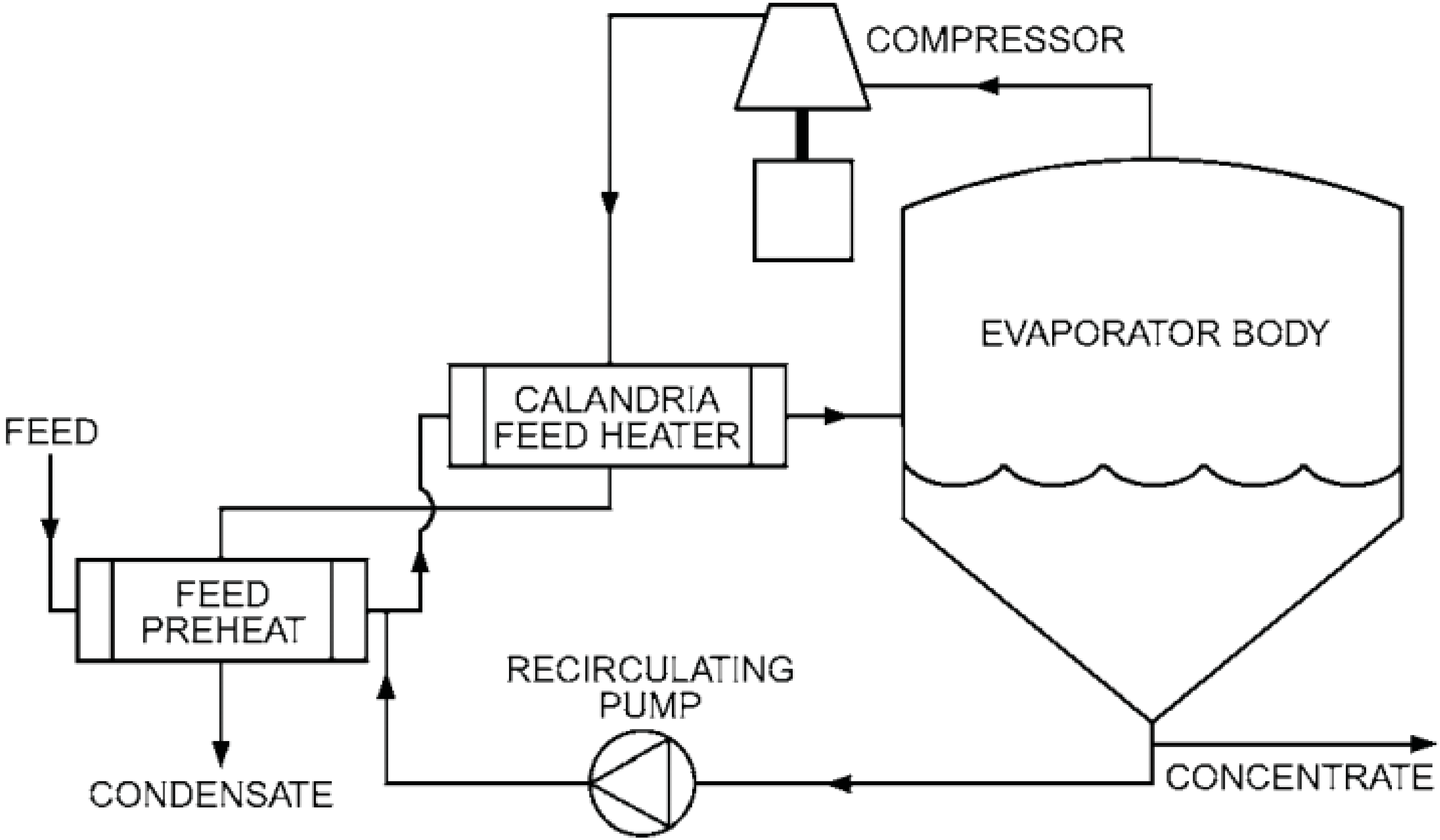


Most frequently used in industrial operations to dry or cure products. For example, dehumidification kilns are used to dry lumber to improve its value (lumber can be dried at a lower temperature, which reduces warping, cracking, checking, and discoloration). Can also be used to dry agricultural products; poultry, fish, and meat; textiles; and other products.

(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 9 – Applied Heat Pump and Heat Recovery Systems)

Single-effect heat pump evaporator (open-cycle)

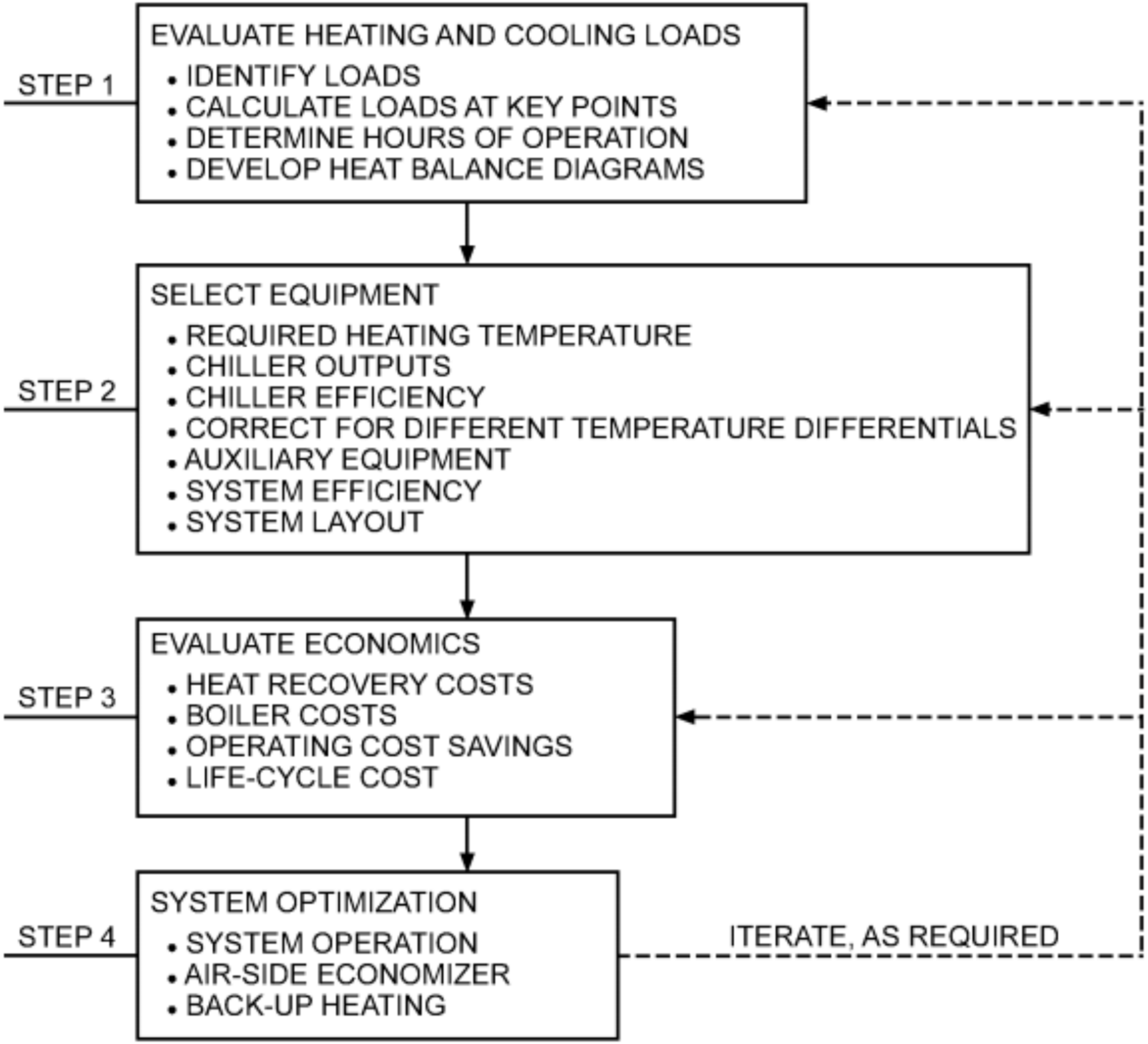
(For separating small volumes of water and solid, e.g. in food and dairy industries)



The overhead vapours of the evaporator are compressed, and thus heated, and piped to the system heater (i.e. calandria). The heat is transferred to the dilute solution, which is then piped to the evaporator body. Flashing occurs upon entry to the evaporator body, sending concentrate to the bottom and vapours to the top.

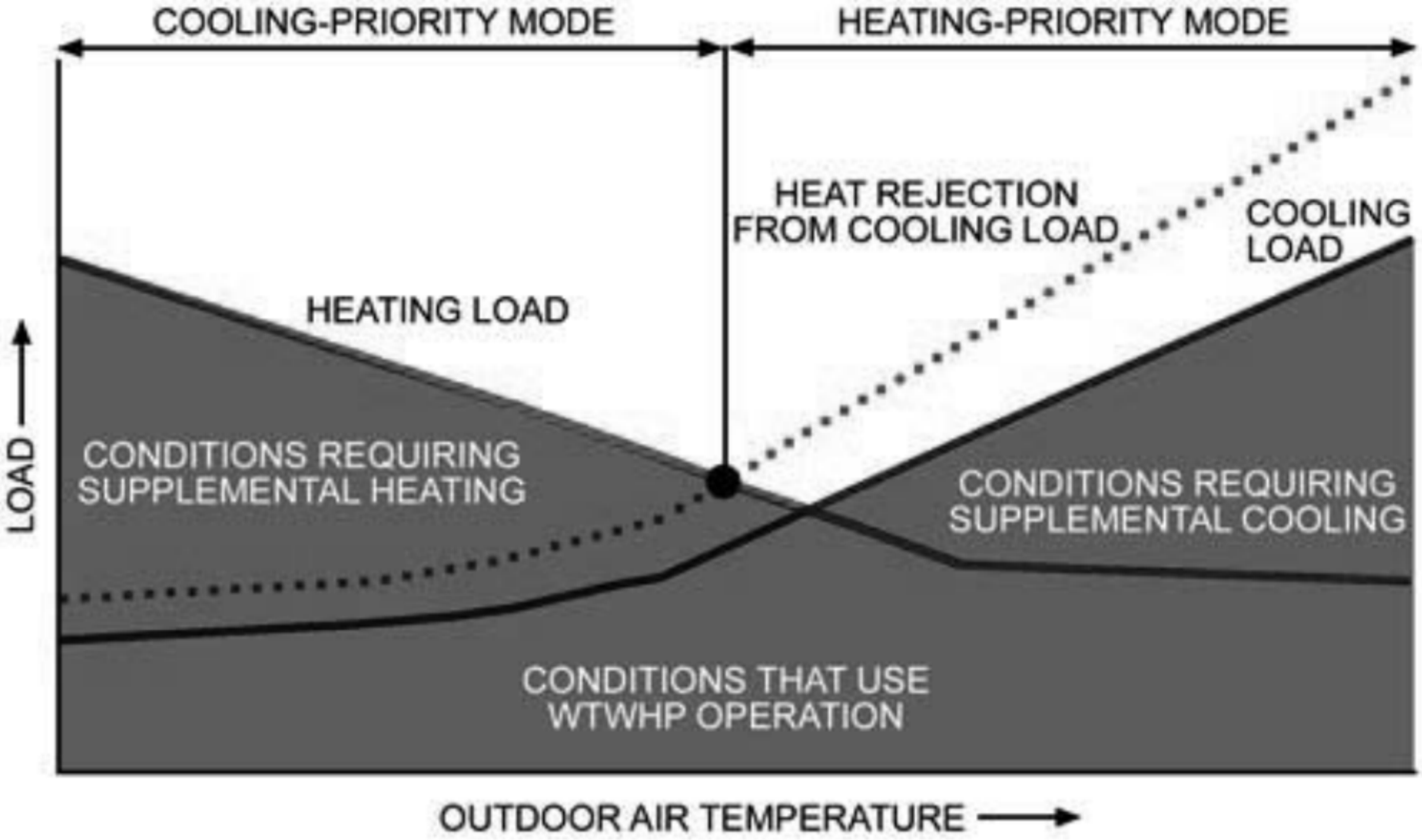
(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 9 – Applied Heat Pump and Heat Recovery Systems)

Heat recovery heat pump (HRHP) application flowchart



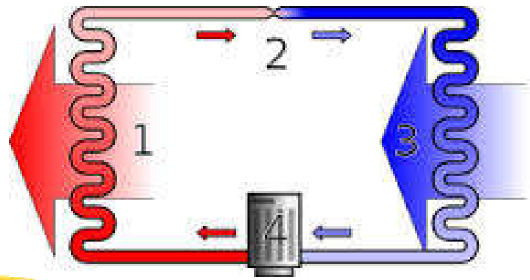
(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 9 Applied Heat Pump and Heat Recovery Systems)

Operating areas for simultaneous heat recovery heat pump (HRHP)



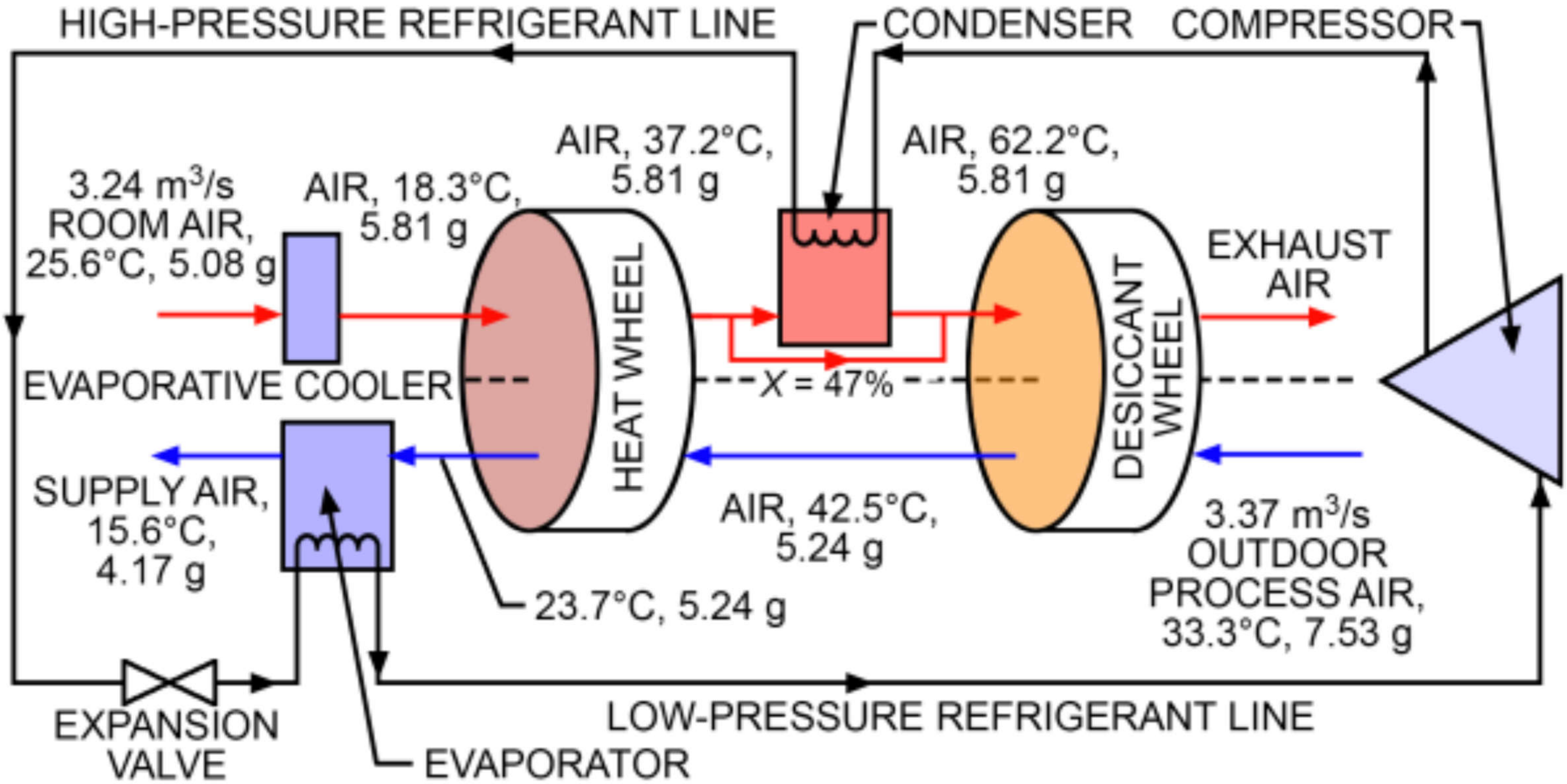
(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 9 Applied Heat Pump and Heat Recovery Systems)

Applied heat pumps



- Systems with multiple energy recovery exchangers, e.g. desiccant wheel + heat wheel
  - The first exchanger reduces the cooling capacity by recovery exhaust energy
  - The second exchanger improves latent cooling and reduces sensible cooling delivered by the system
- The heat dissipated in the condenser of a heat pump can be used to regenerate the desiccant wheel

Heat pump augmented by heat and desiccant wheels (multiple energy recovery exchangers in series mode)

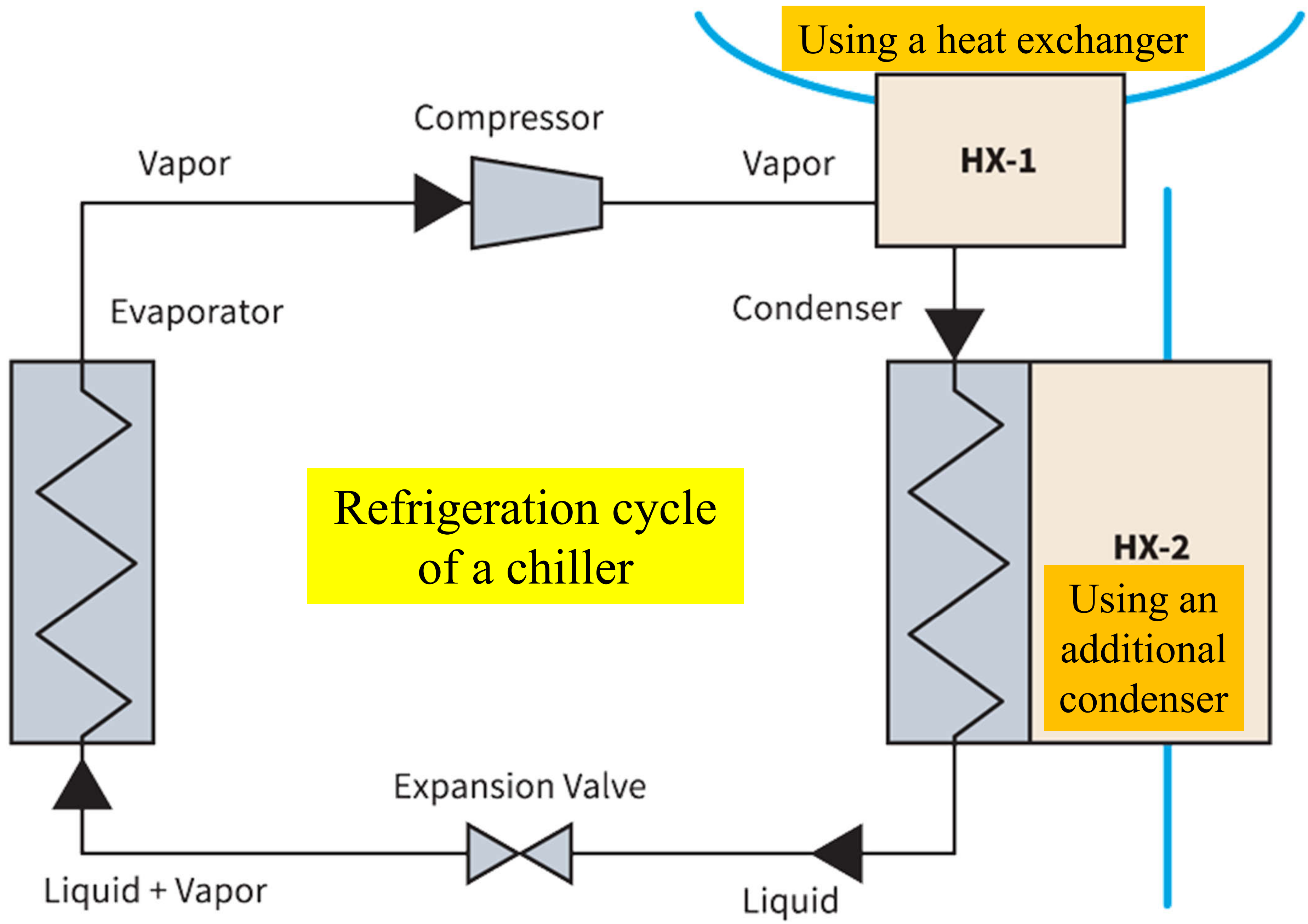


(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, Chapter 26. Air-to-Air Energy Recovery Equipment)

Heat recovery chillers

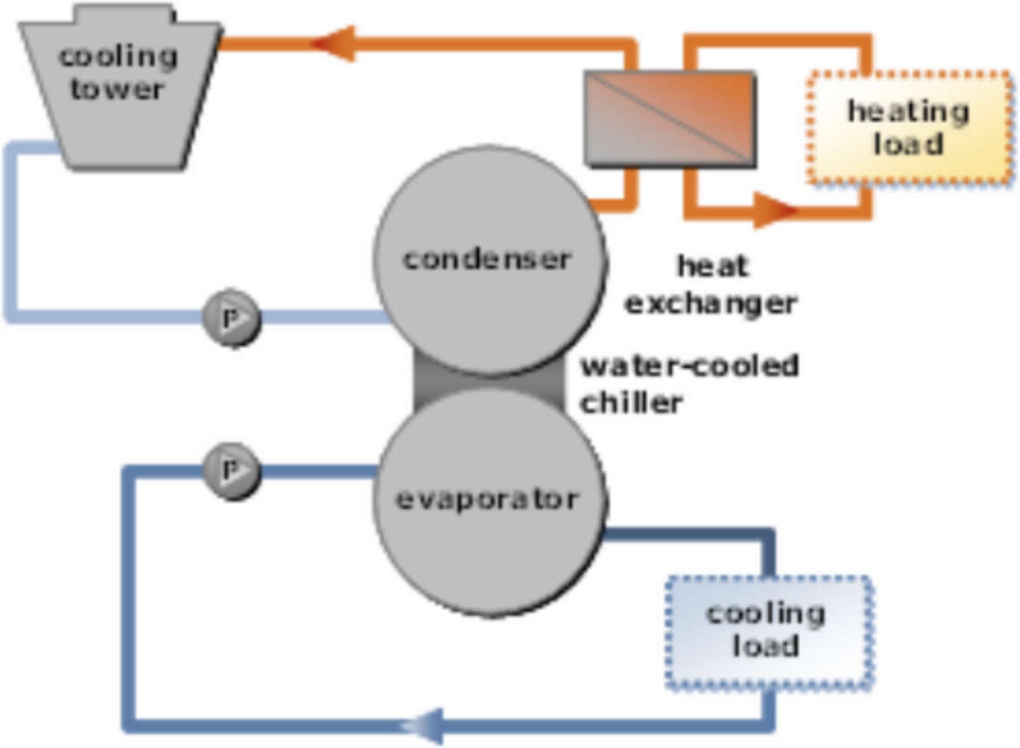
- How It Works: (for water or air-cooled chillers)
  - When there is a simultaneous need for chilled water and hot water, these chillers have the capability to operate in heat recovery mode
  - The recovered heat can be redirected for various heating applications, which saves energy while maintaining conditions
    - Building space heating
    - Service water pre-heating (e.g. laundry, dish washing)
    - Process hot water (e.g. swimming pool heating)

Basic principles of a heat recovery chiller

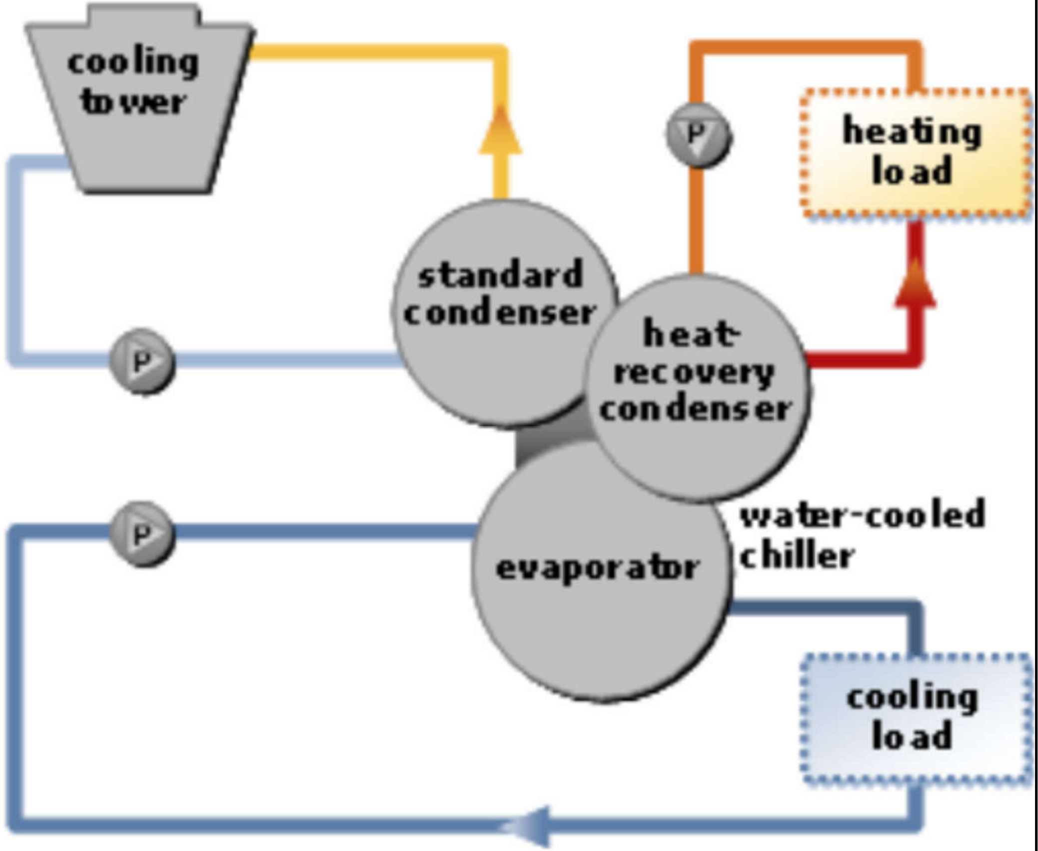


(Adapted from: https://www.hpac.com/facility-management/article/20929701/using-heat-recovery-to-improve-chiller-efficiency)

Heat recovery chiller and water system design



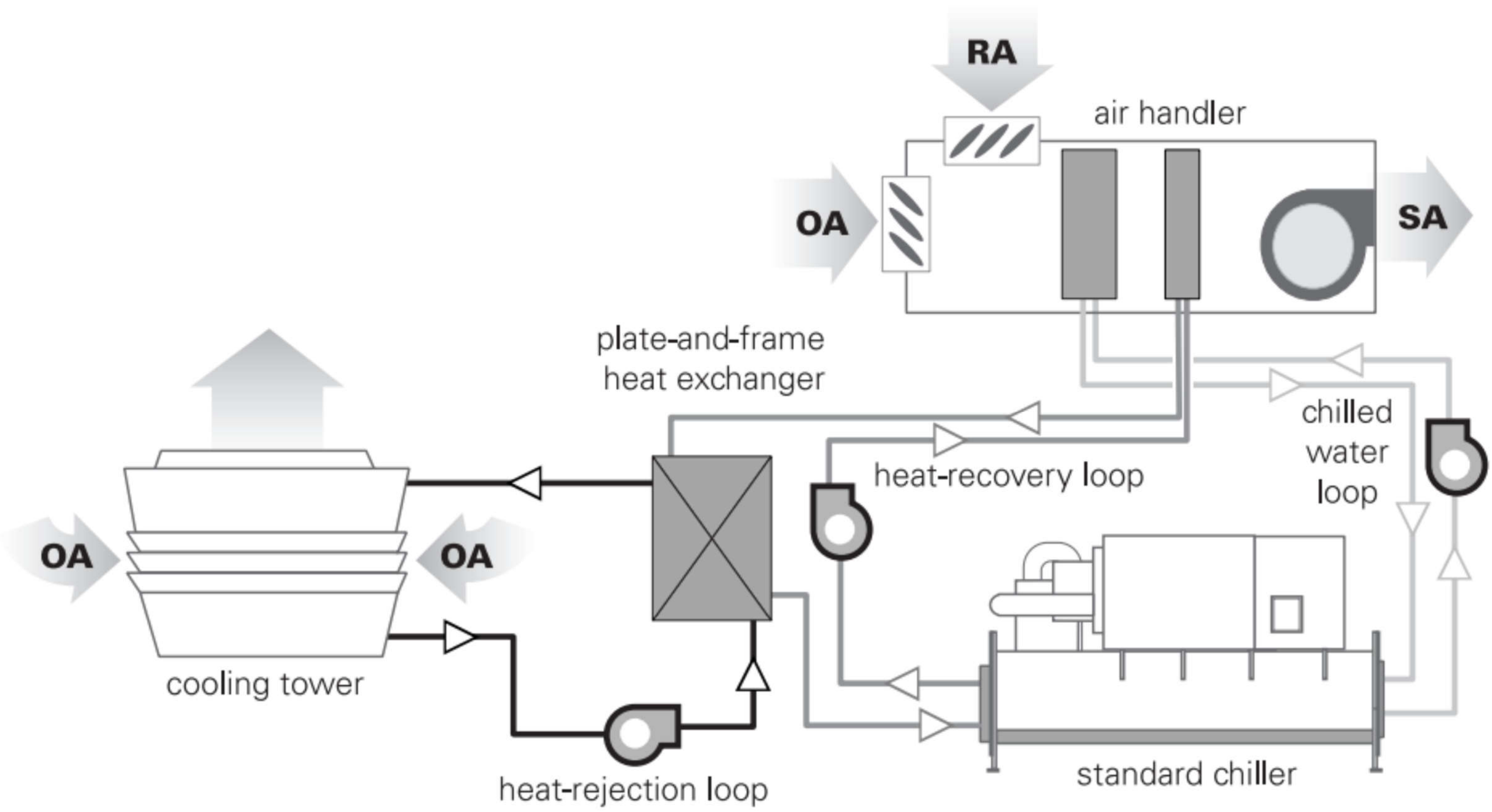
Heat recovery using a heat exchanger



Heat recovery using an additional condenser

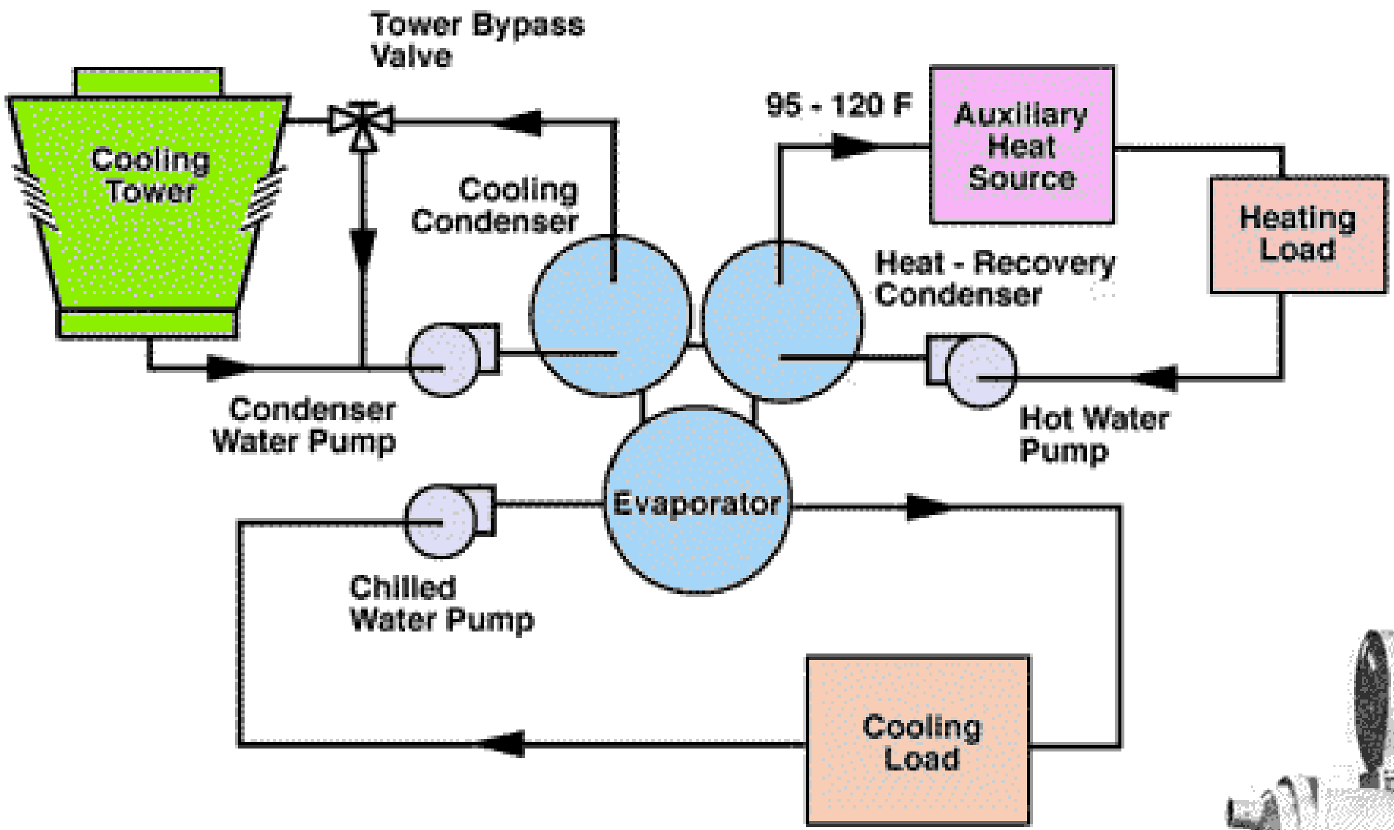
(Source: Trane Air Conditioning)

Condenser-water heat recovery using a plate-and-frame heat exchanger



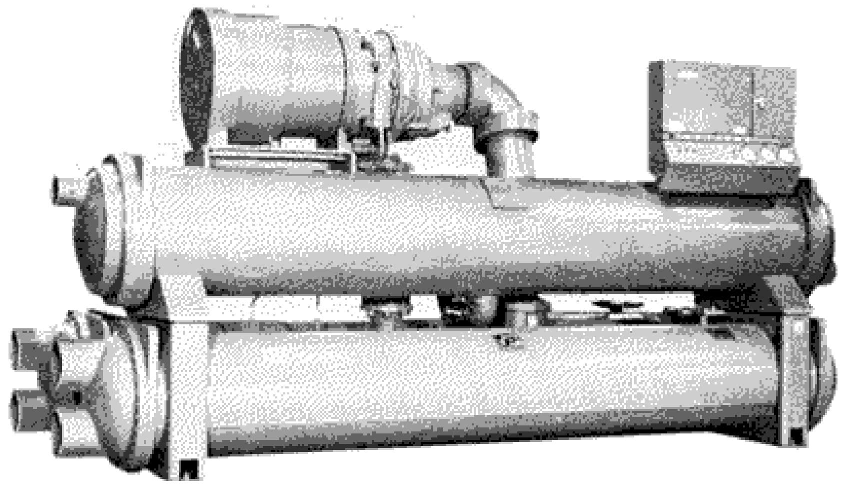
(Source: Trane Air Conditioning)

Waste heat recovery – e.g. double bundle heat recovery chiller



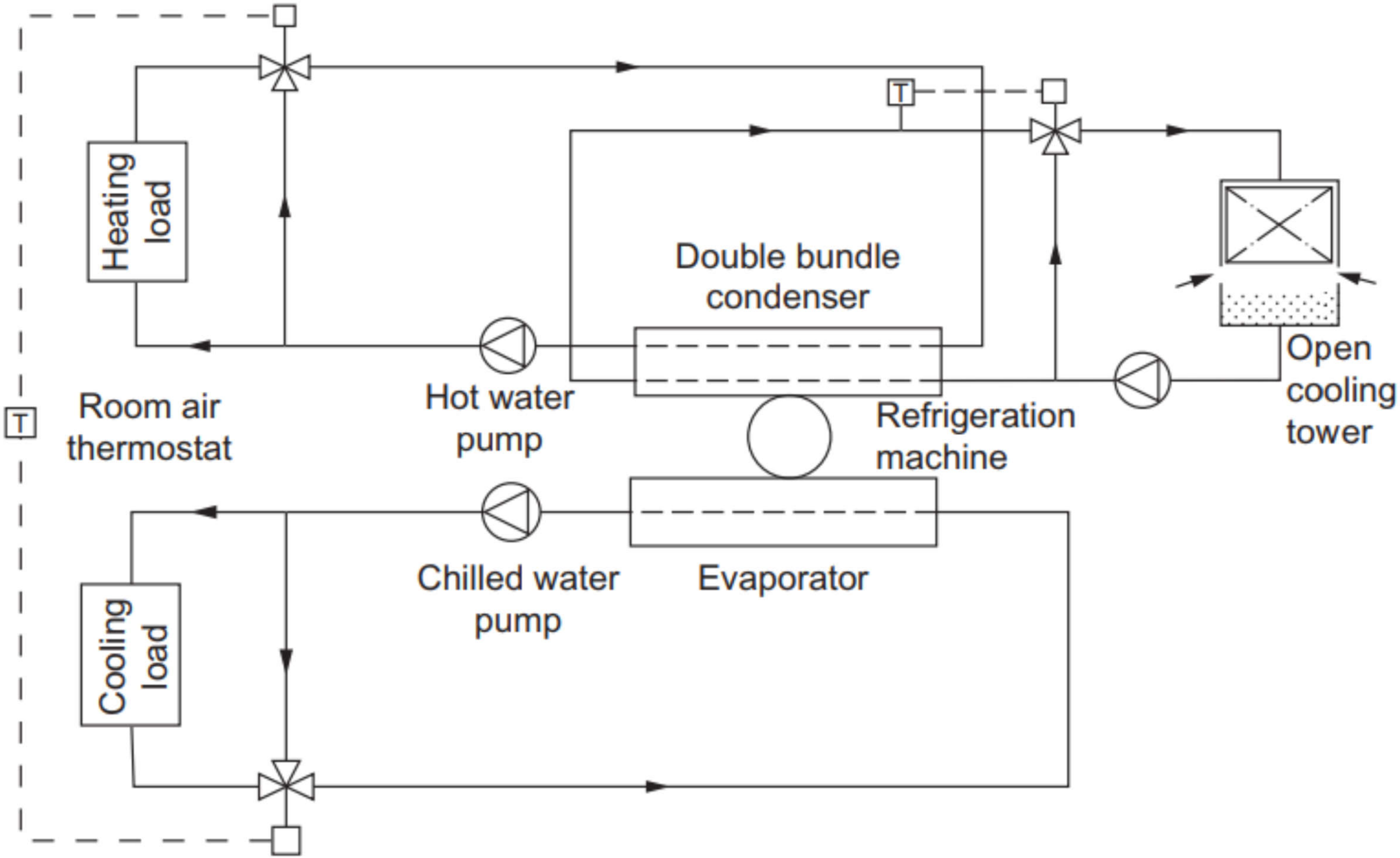
Make use of waste heat from condenser to produce warm/hot water or for heating the space.

- Waste heat = "dumped" heat that can still be reused
- Waste heat recovery saves fuel



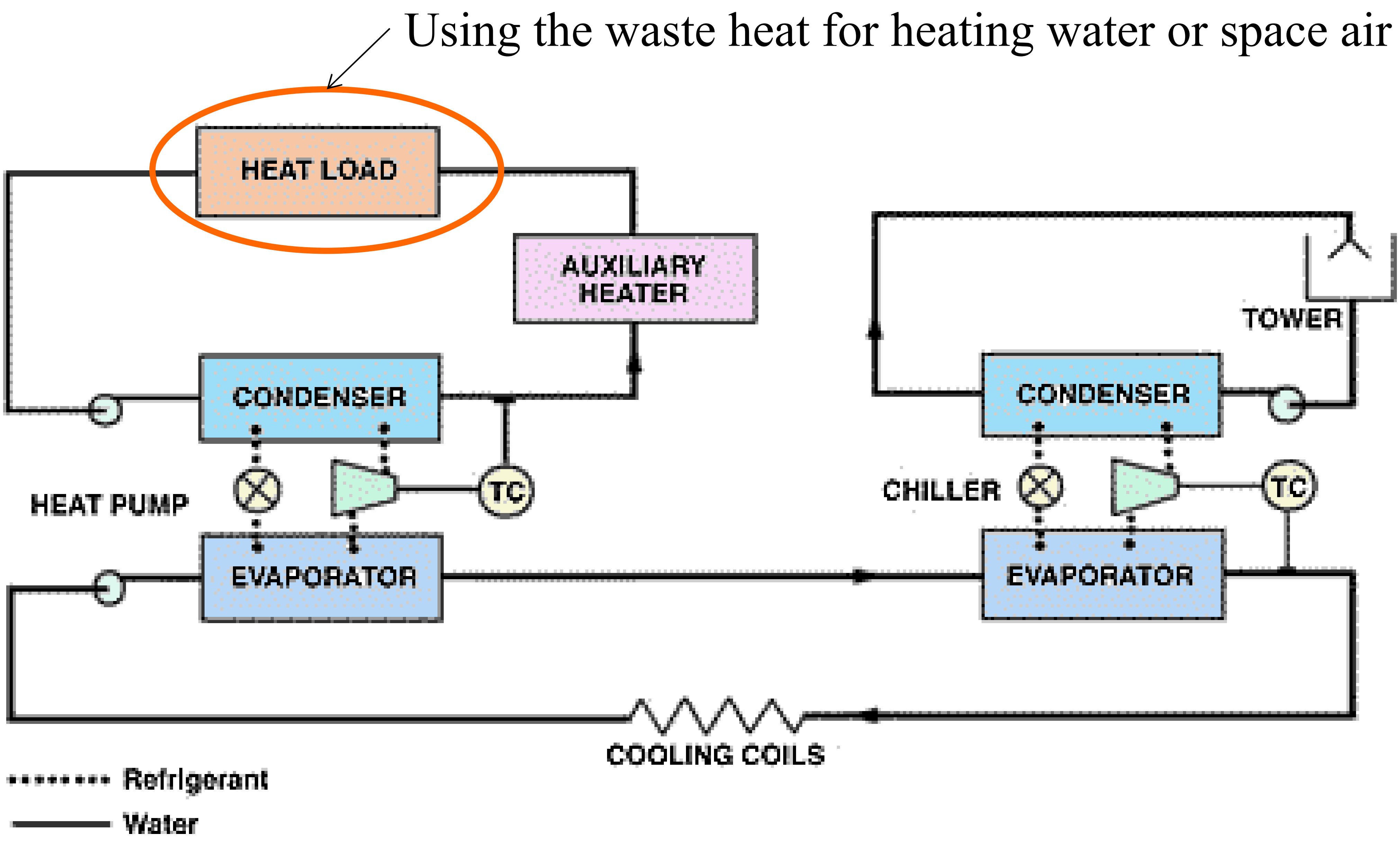
Double bundle heat recovery chiller

Heat recovery system with double-bundle condenser

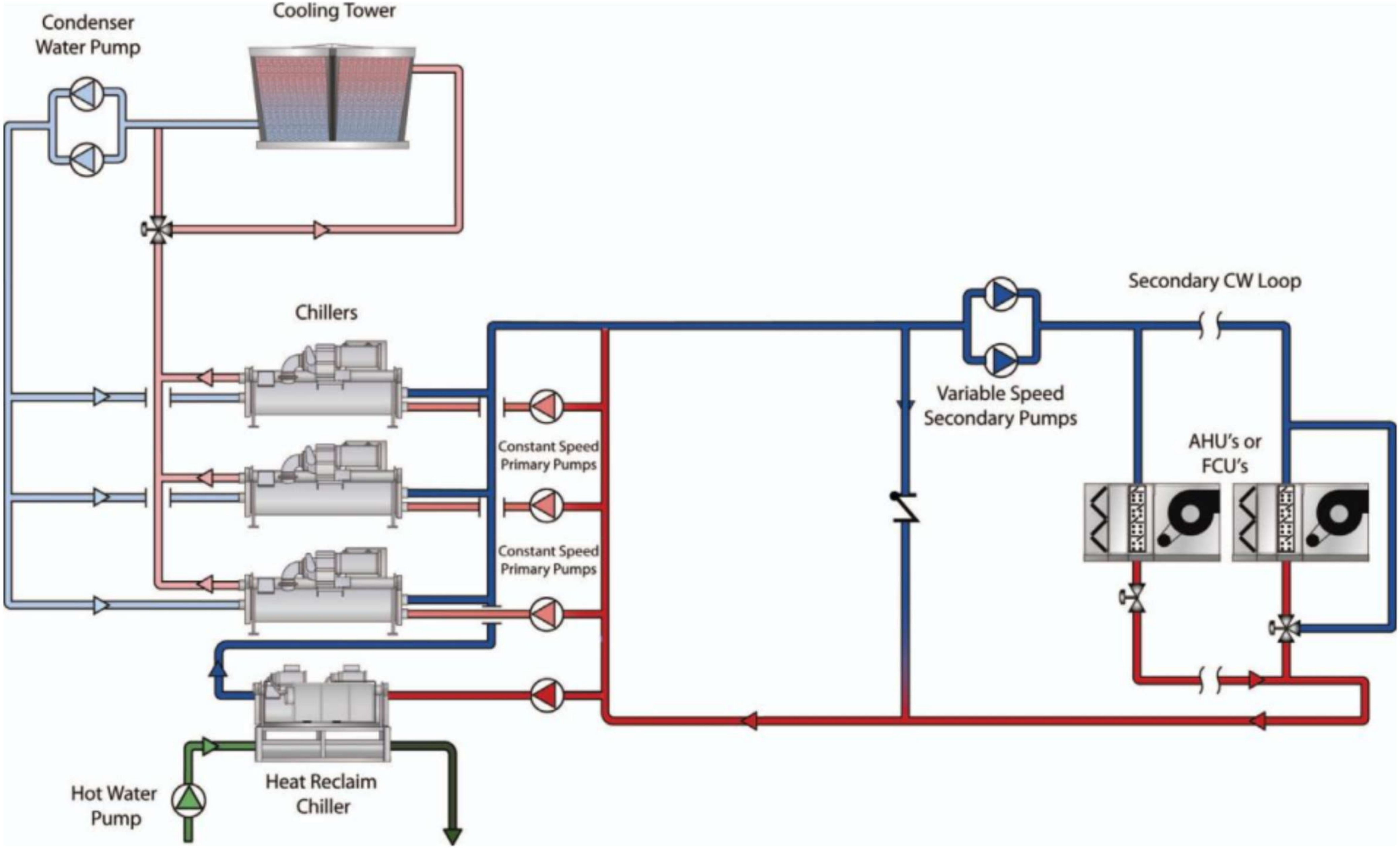


(Source: Legg R., 2017. *Air Conditioning System Design*, Elsevier Science & Technology, Oxford.)

Schematic diagram of waste heat recovery - heat pump + chiller

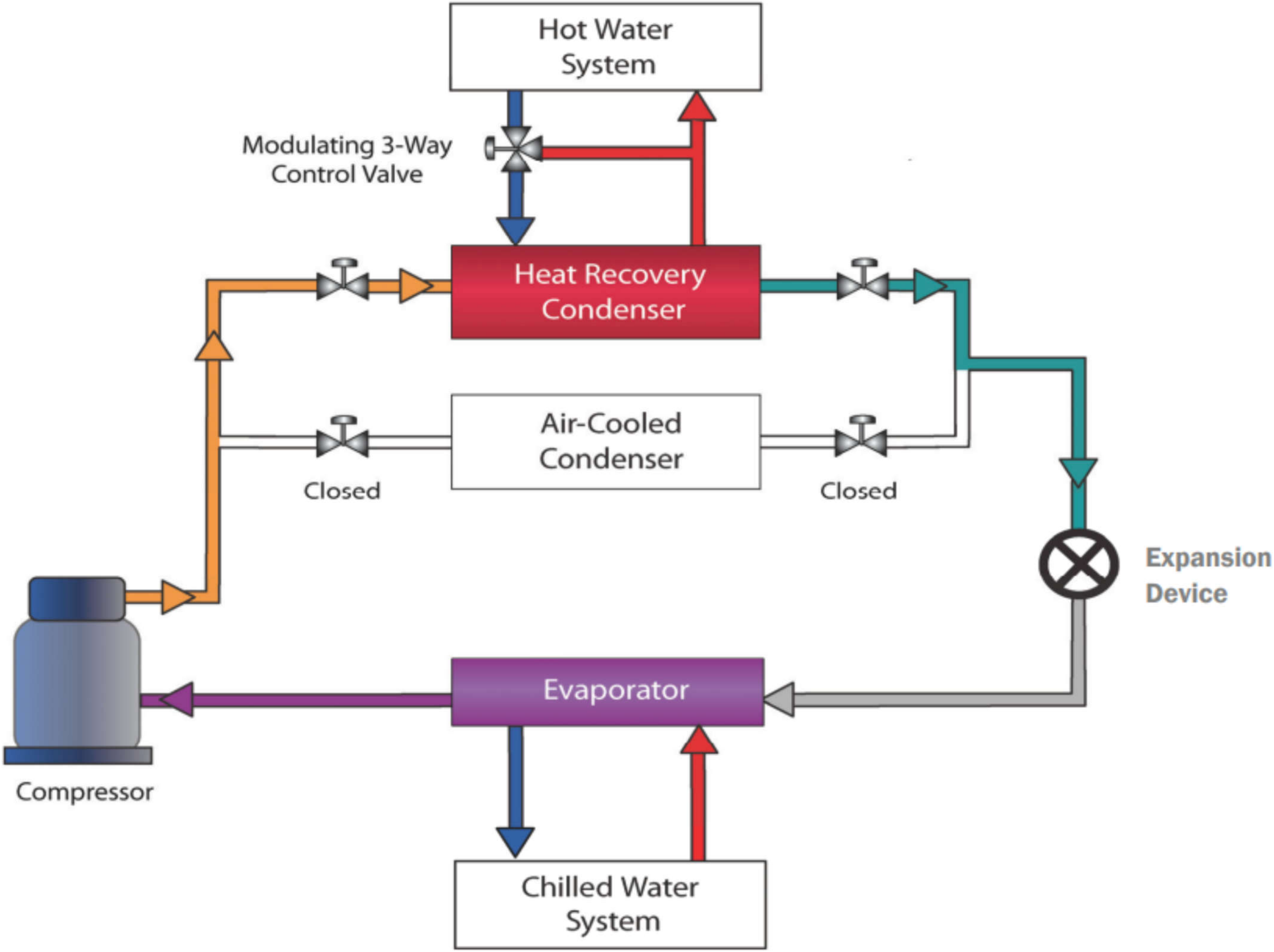


Primary/Secondary chilled water system with heat recovery chiller



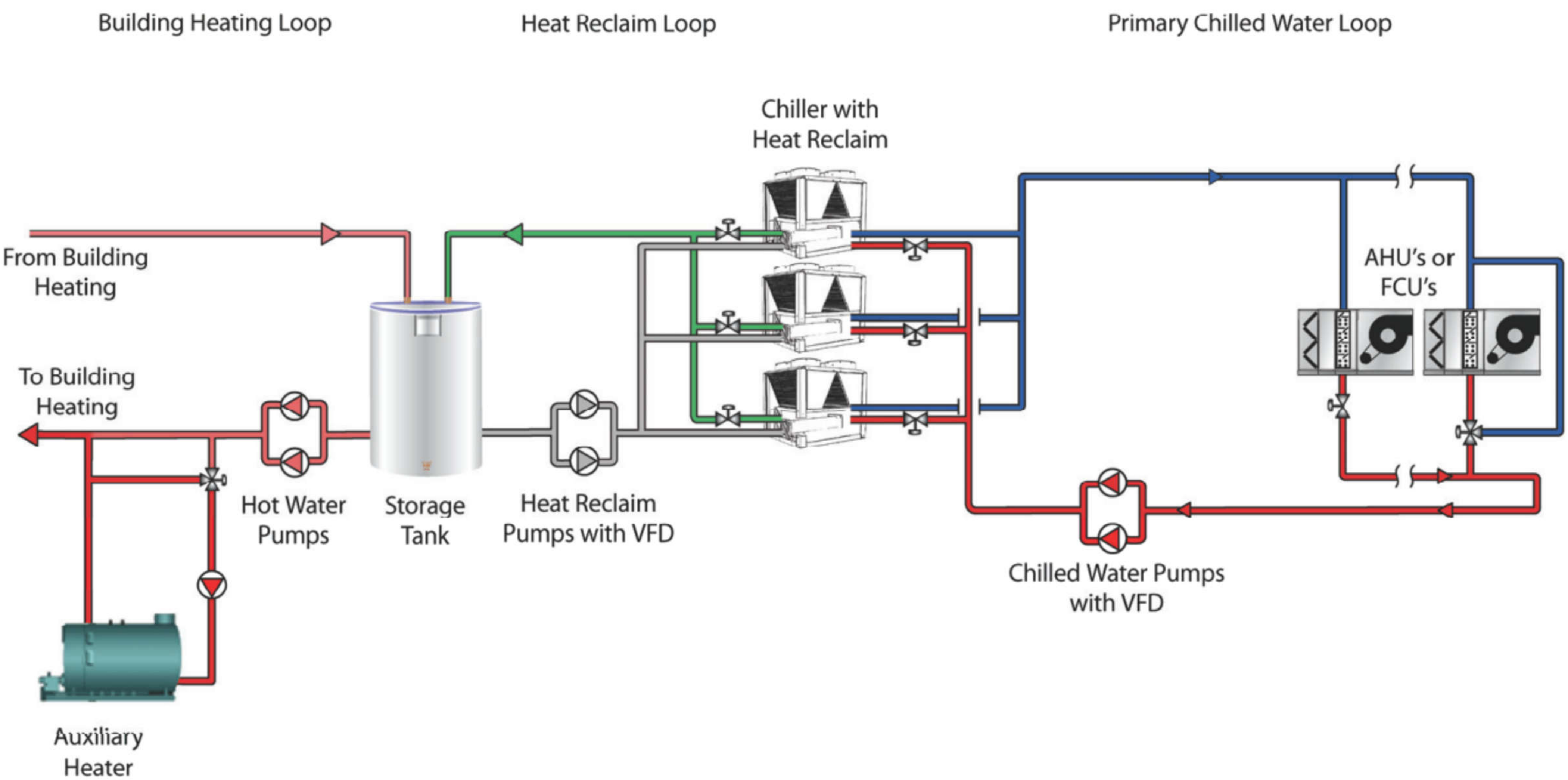
(Source: Carrier Corporation)

Air-cooled chiller with heat reclaim capabilities: heat recovery mode



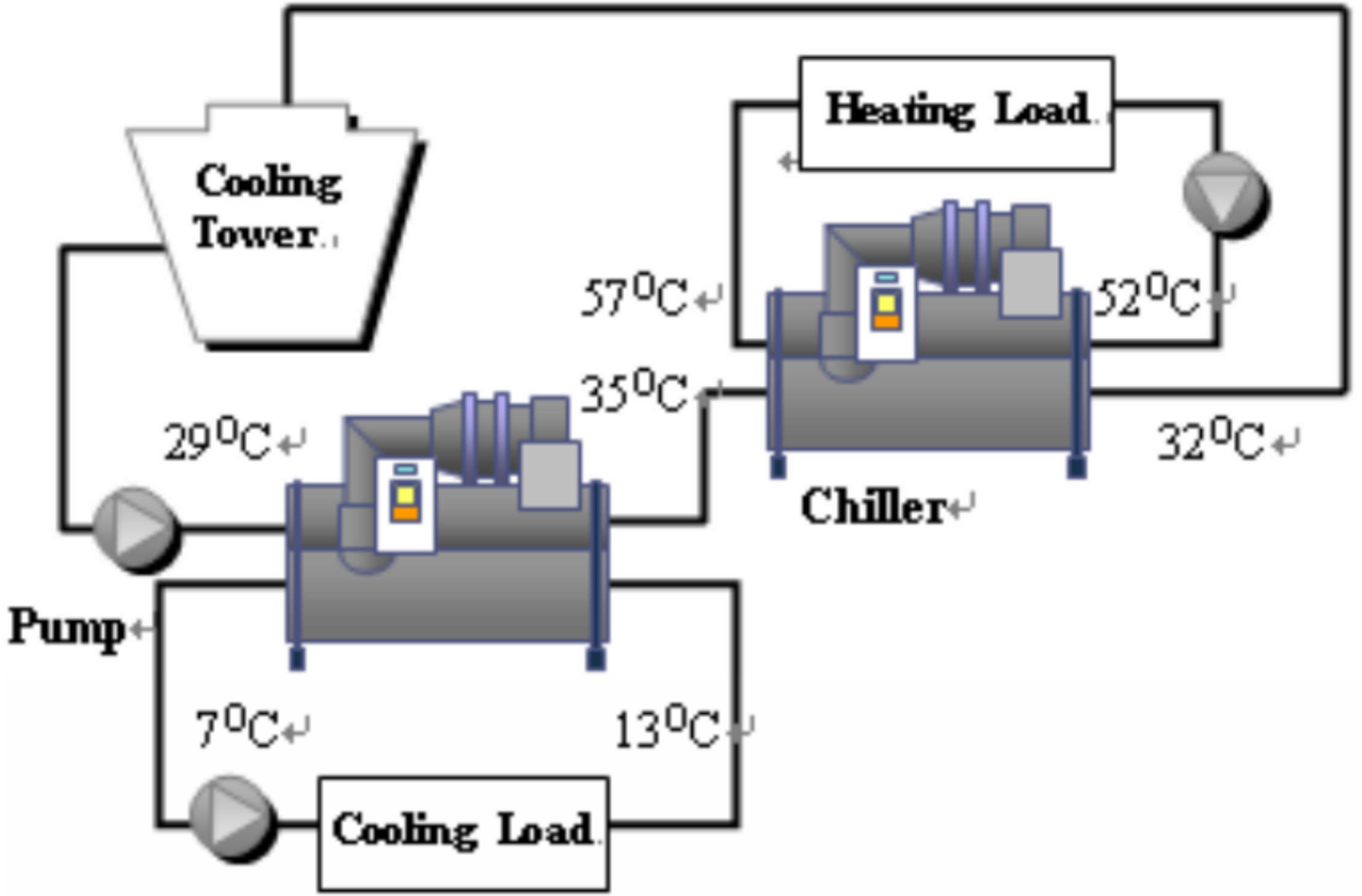
(Source: Carrier Corporation)

Multiple air-cooled chiller system with heat reclaim for building heating



(Source: Carrier Corporation)

Configuration of heat recovery chiller for higher water temperature



(Source: Trane Air Conditioning)

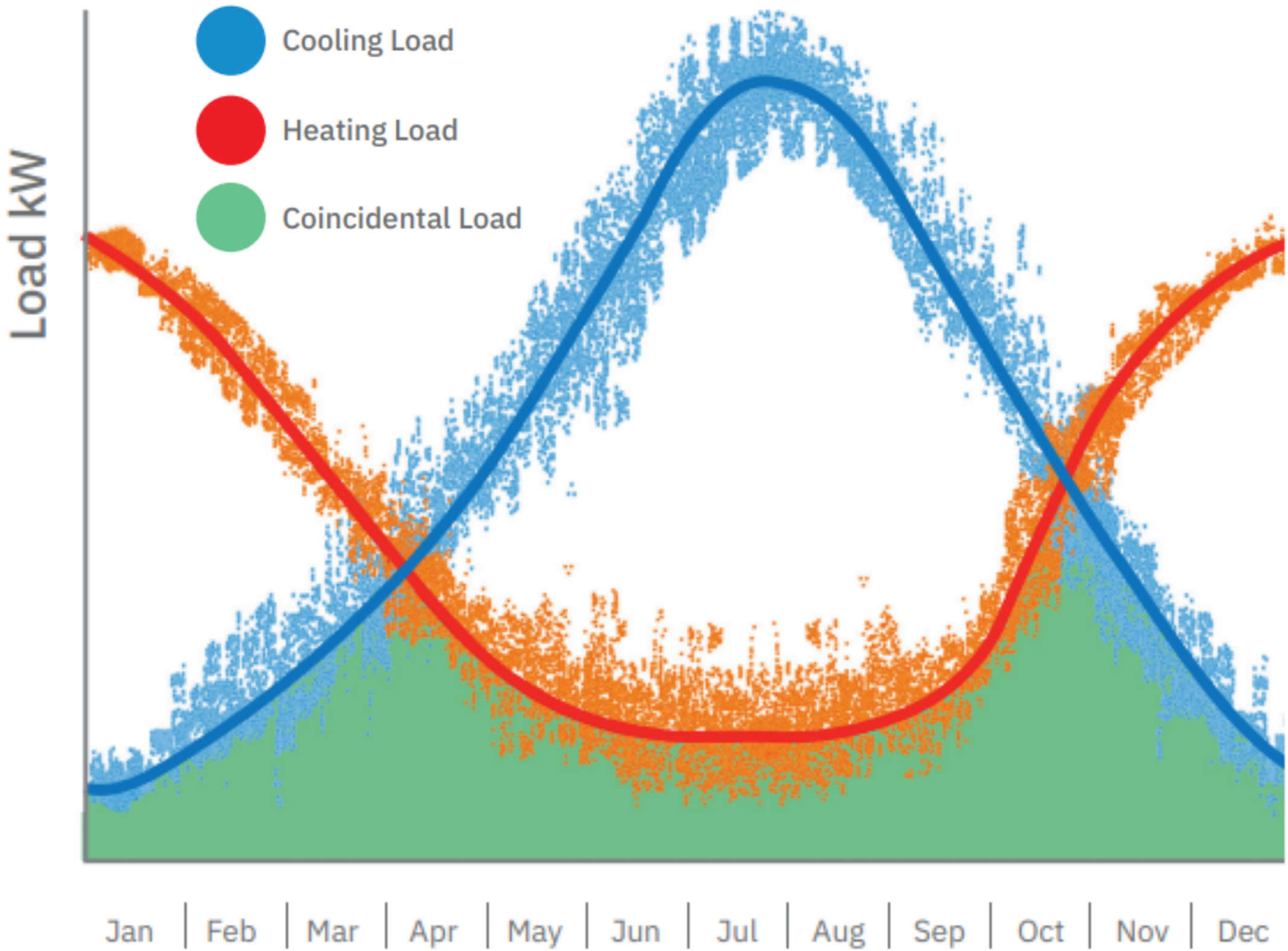
Heat recovery chillers

- Design considerations
  - Building must have simultaneous cooling and heating to operate in heat-recovery mode
  - A backup source of heat is required if the heat recovered from the cooling load and compressor is not sufficient to satisfy the entire heating load
  - Recovery mode consumes more chiller energy than cooling-only mode (because the chiller operates at an elevated condensing pressure and temperature)

Heat recovery chillers

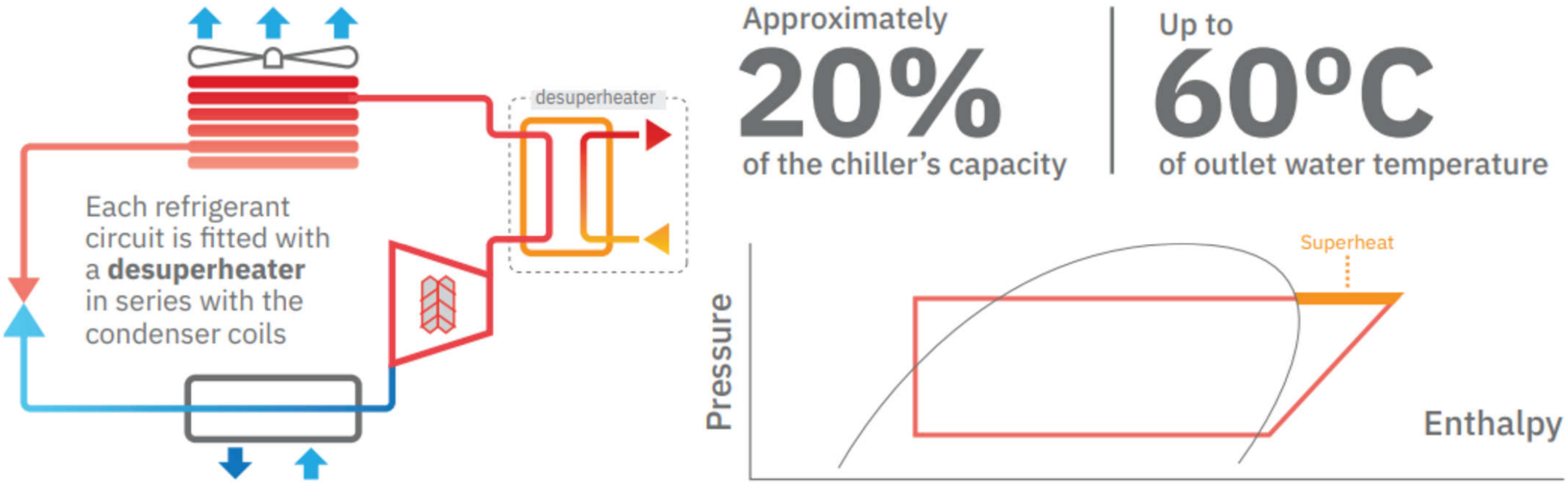
- Water-side energy recovery steps:
  - Simultaneous cooling and heating loads
  - Chiller heat recovery capacity = design HR load
  - Select lowest temperature that meets requirements
  - Select the proper chiller type
  - Analyse the system
  - Place the chiller in an appropriate location
  - Design system with proper connections/controls
  - Train the building operator for proper operation

Year-round cooling and heating load profile of a building

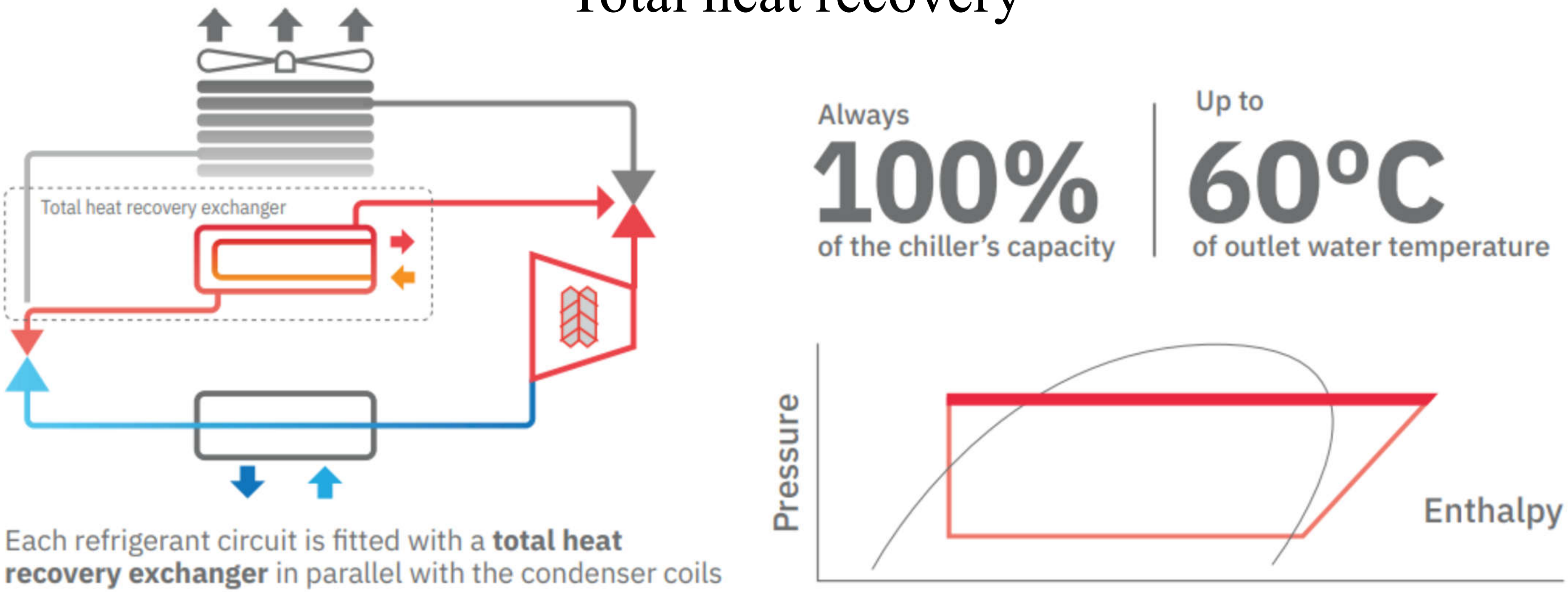


(Source: Mitsubishi Electric Guide to Heat Recovery Chillers https://library.mitsubishielectric.co.uk/pdf/book/67_HEAT_RECOVERY_CHILLERS)

Partial heat recovery (desuperheater)

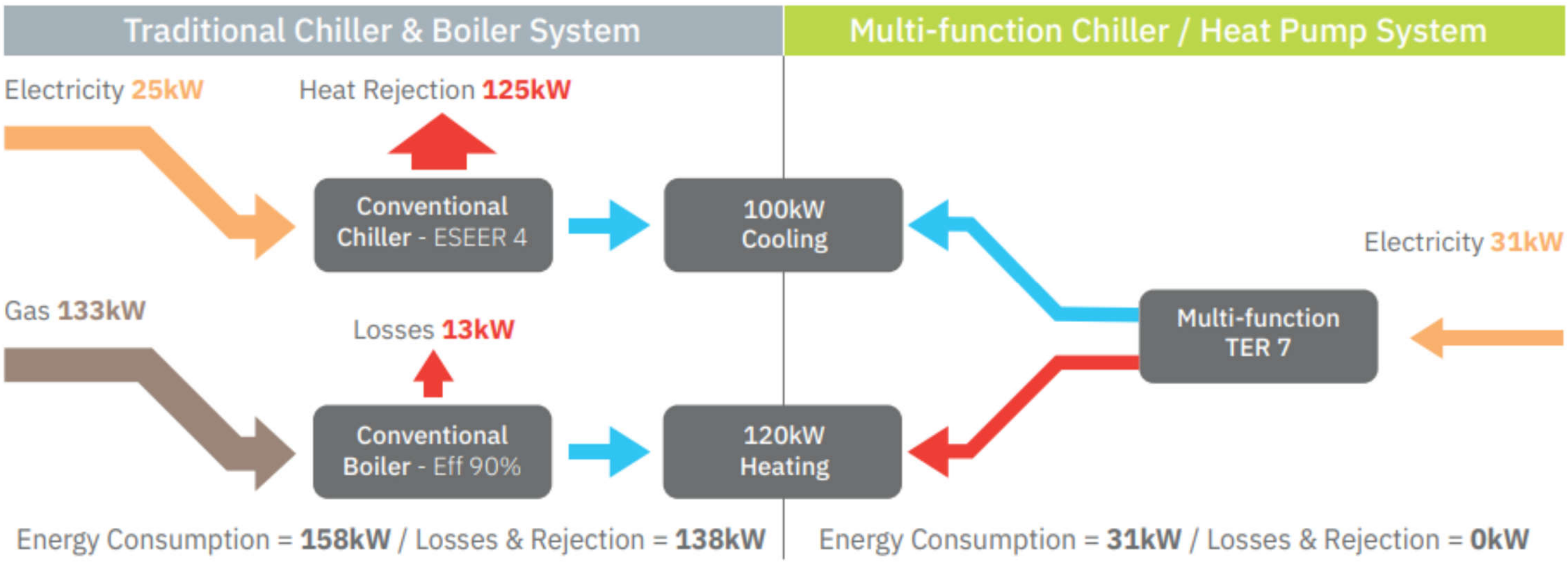


Total heat recovery

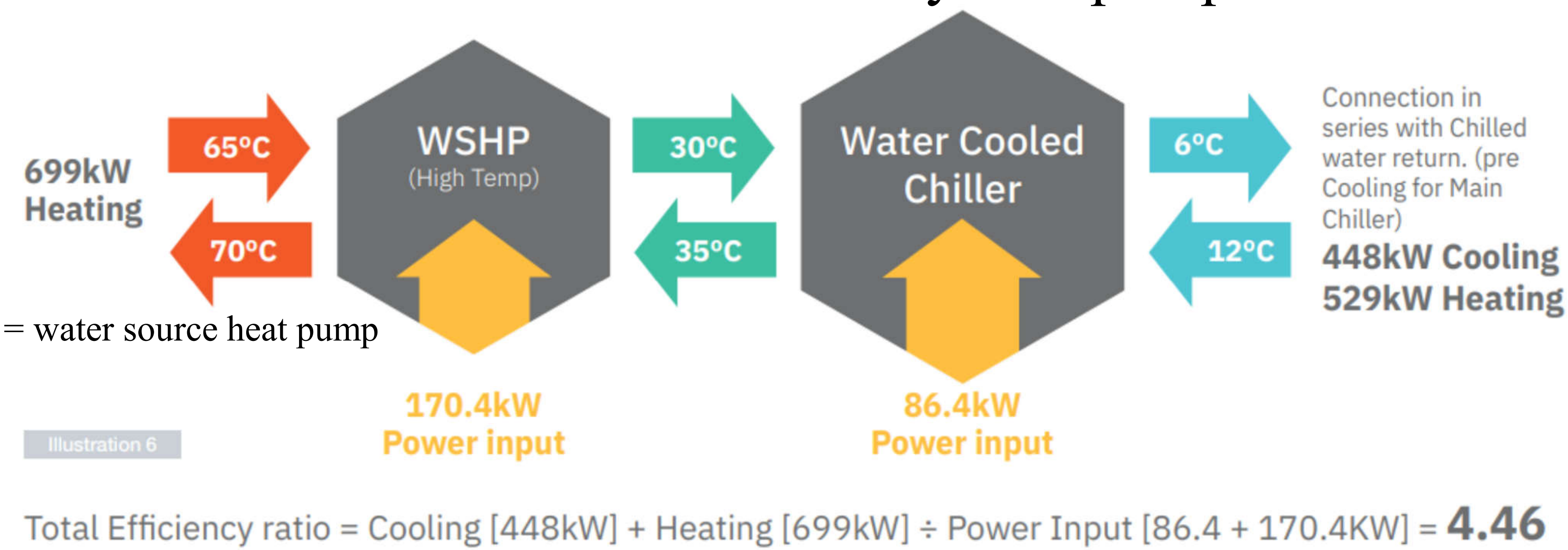


(Source: Mitsubishi Electric Guide to Heat Recovery Chillers https://library.mitsubishielectric.co.uk/pdf/book/67_HEAT_RECOVERY_CHILLERS)

Comparison of traditional chiller & boiler with heat recovery systems



Dedicated heat recovery heat pump



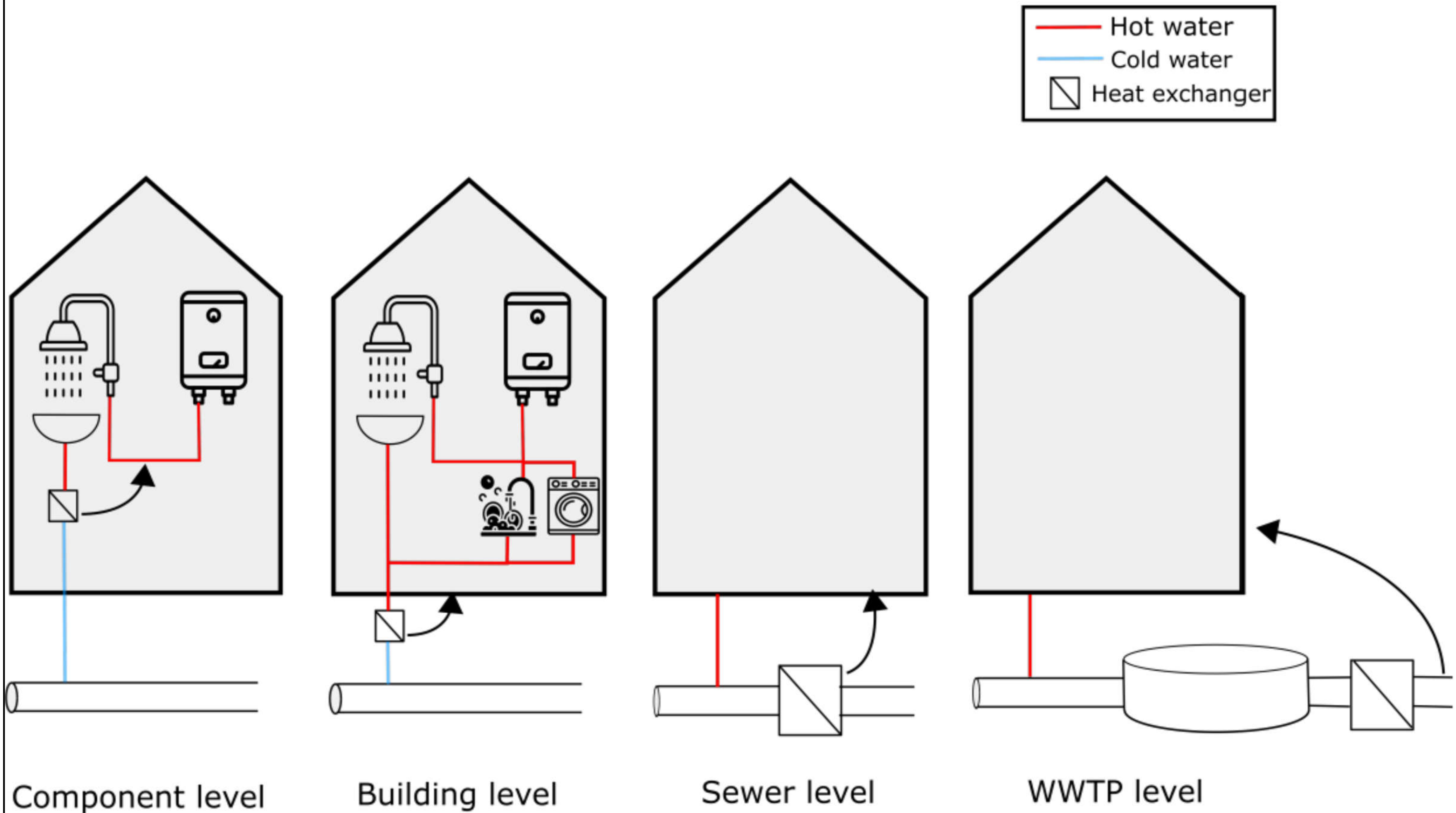
WSHP = water source heat pump

(Source: Mitsubishi Electric Guide to Heat Recovery Chillers https://library.mitsubishielectric.co.uk/pdf/book/67_HEAT_RECOVERY_CHILLERS)

Wastewater heat recovery

- Wastewater heat recovery (WWHR) system
  - Captures the heat from a wastewater discharge pipe and is used to preheat incoming water for the domestic hot water tanks or for space heating, e.g.
    - Drain wastewater (residential)(say, 10 to 25 $^{\circ}$C)
    - Medium building wastewater (residential/commercial)
    - Trunk sewers (urban areas, sewage flow > 100 L/s)
      - Using external or in-sewer heat exchanger
    - Discharge effluent from the wastewater treatment plants
      - Recover heat in winter; reject heat in summer

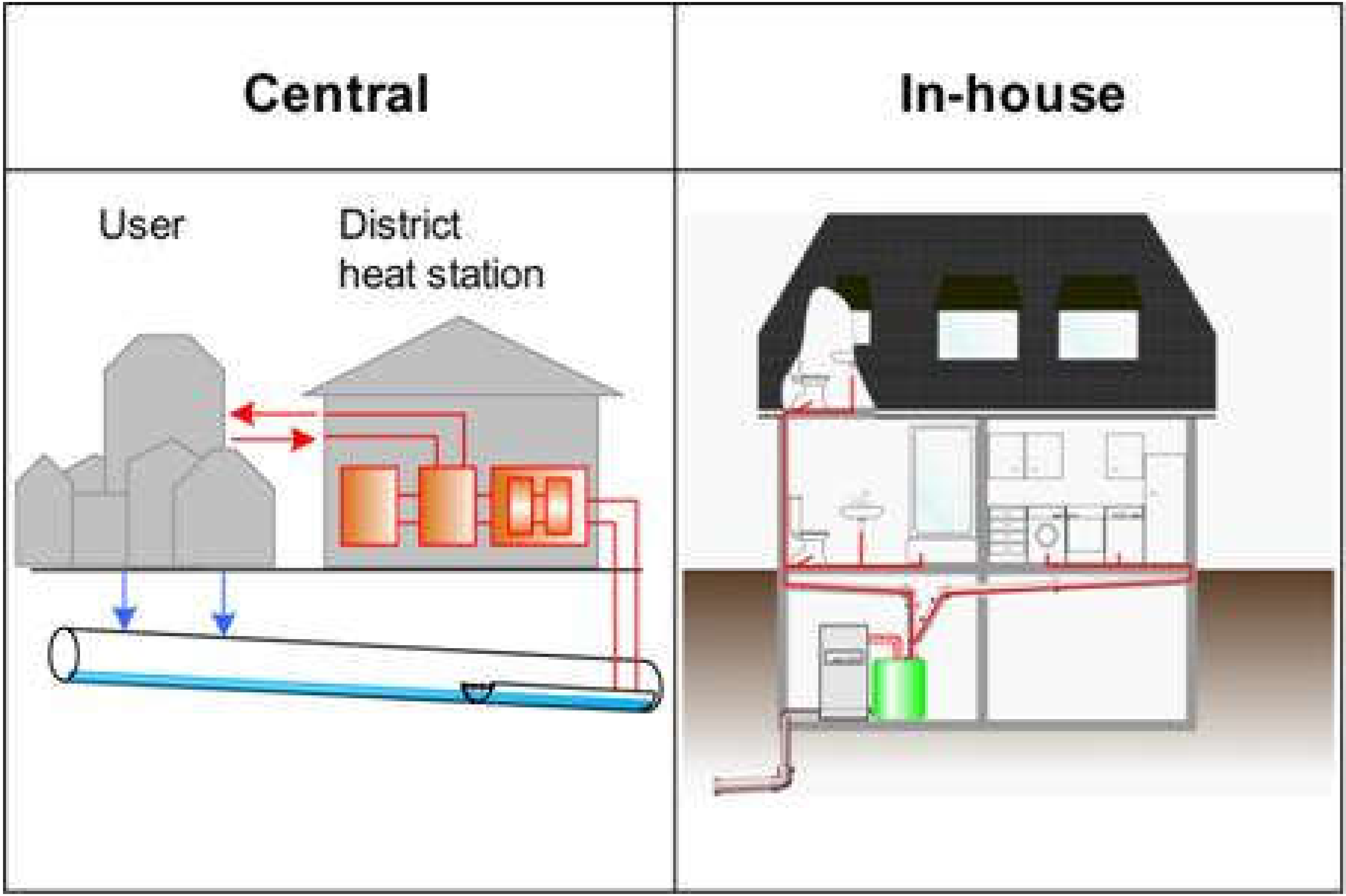
Possible options of heat recovery from wastewater



WWTP = waterwater treatment plant

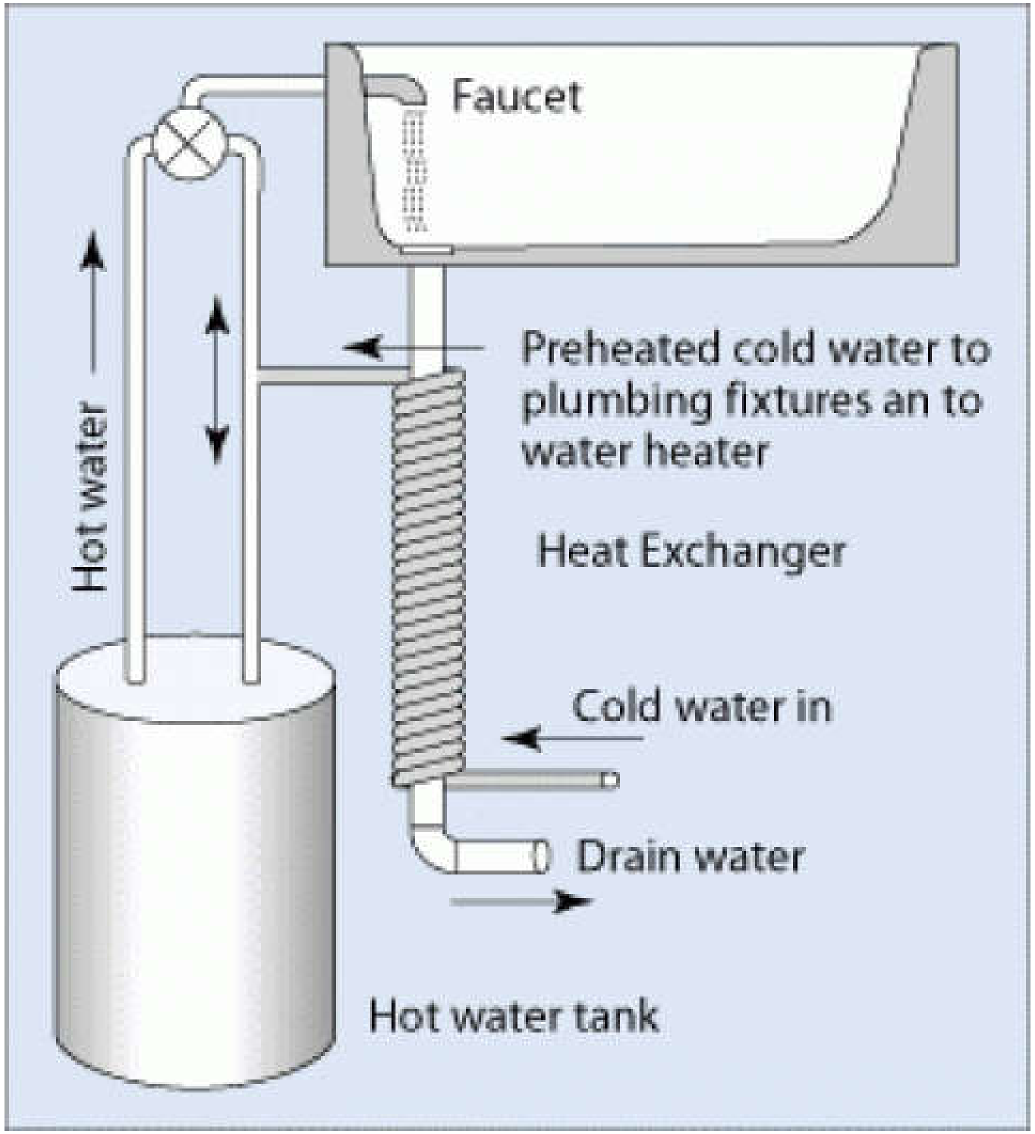
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274)

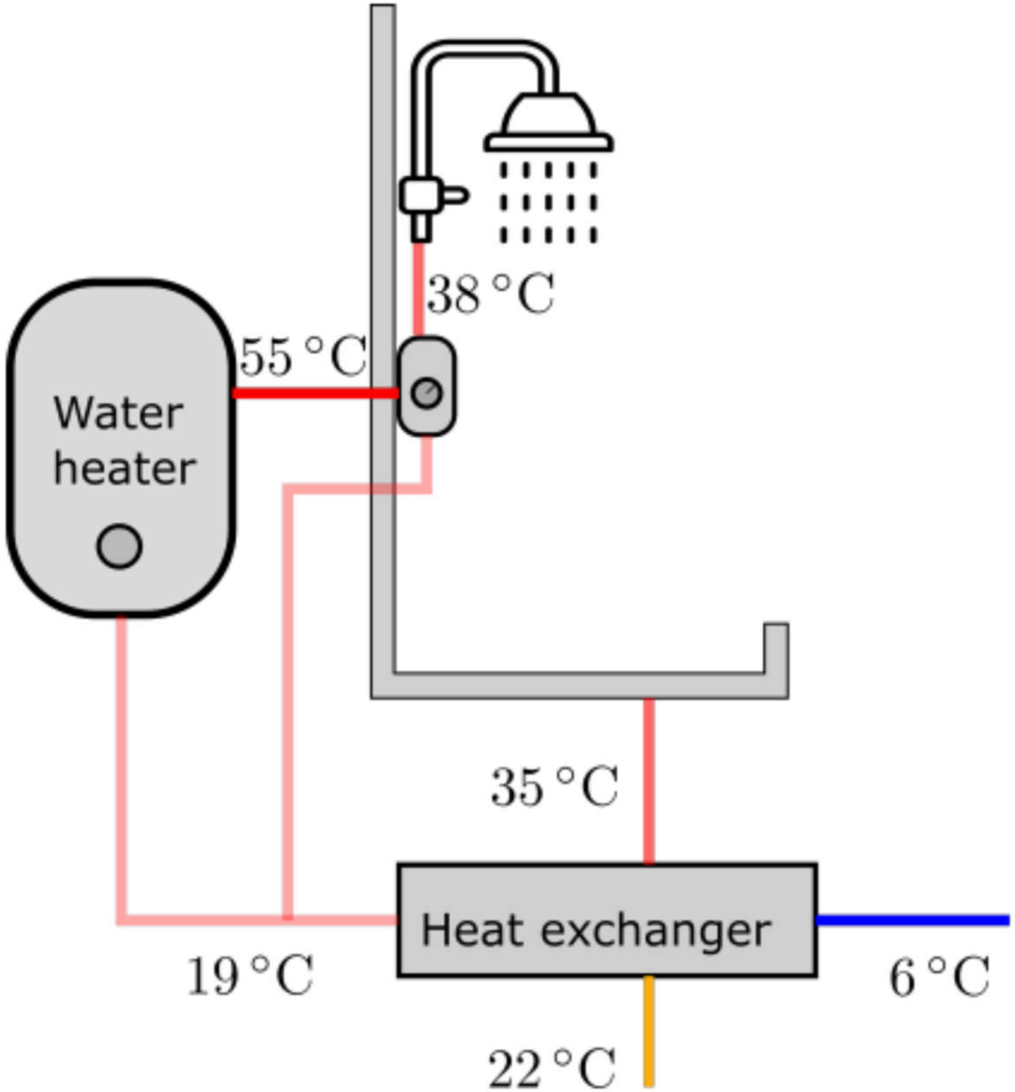
Concepts of central and in-house wastewater heat recovery



(Source: In-house Waste Water Heat Recovery https://www.rehva.eu/rehva-journal/chapter/in-house-waste-water-heat-recovery)

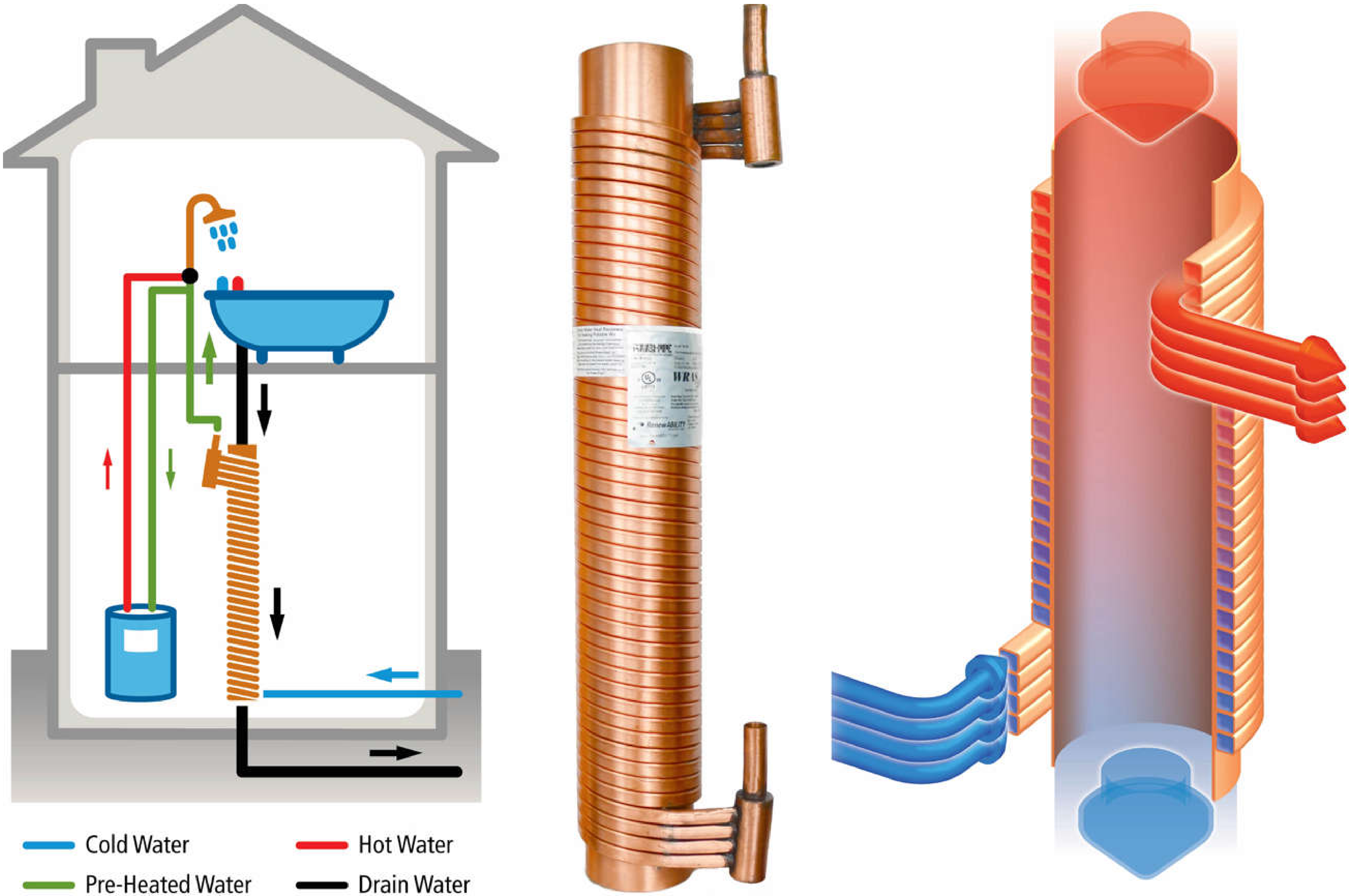
Drain-water heat recovery (at component level)





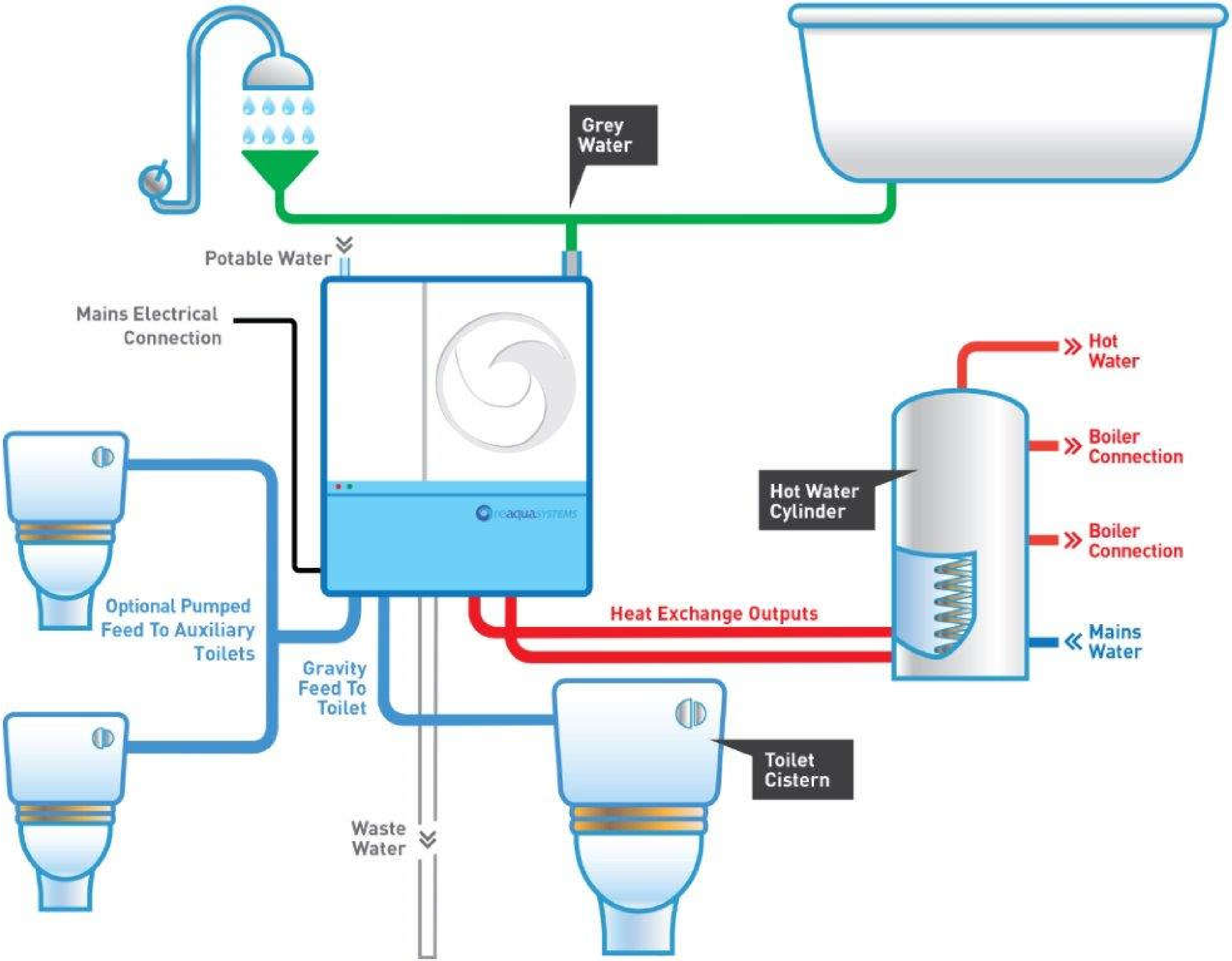
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274 & Drain-Water Heat Recovery https://www.energy.gov/energysaver/drain-water-heat-recovery)

An example of wastewater heat recovery device for residential building



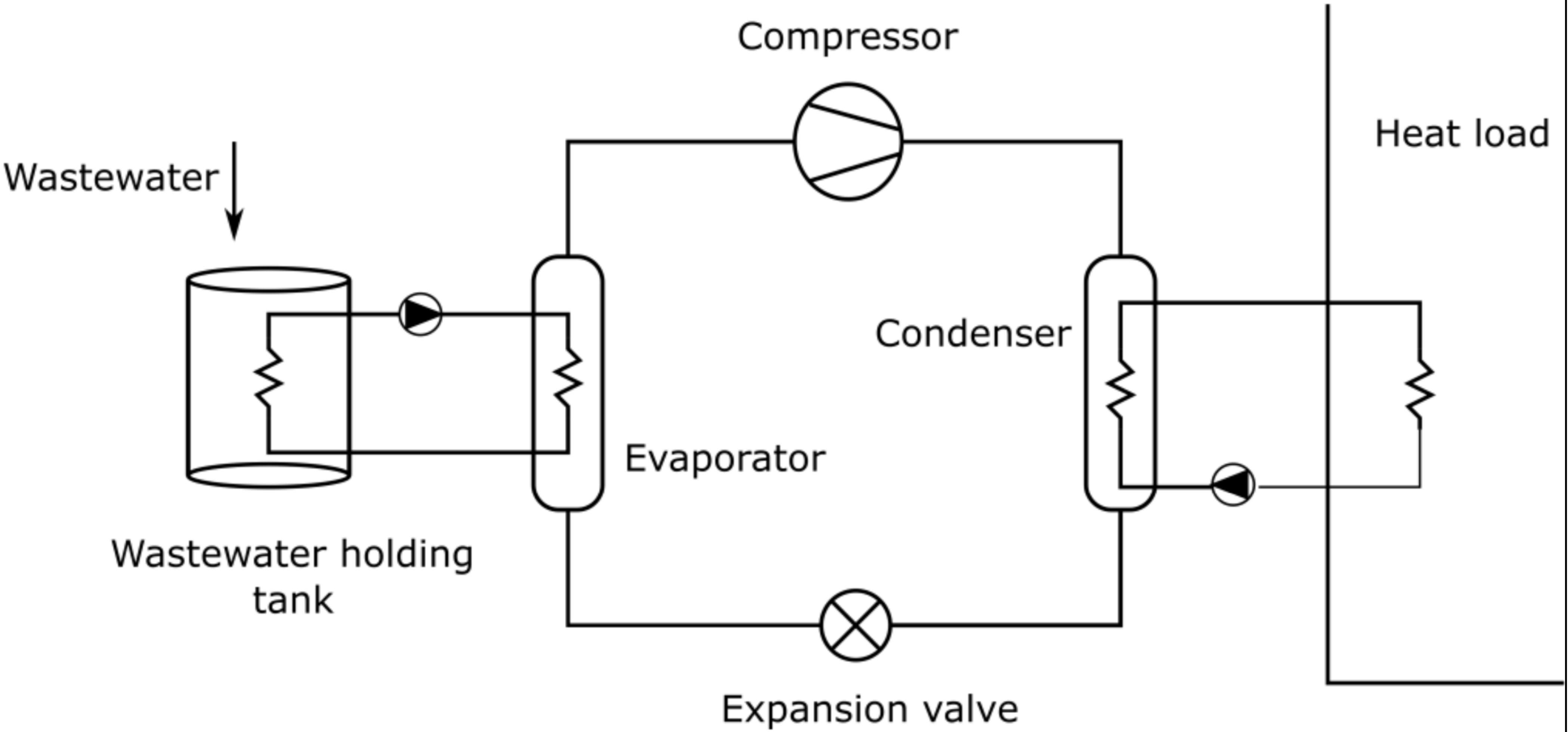
(Source: https://www.phamnews.co.uk/wise-up-to-water-waste-heat-recovery/)

Heat recovery system incorporated within a greywater recycling system



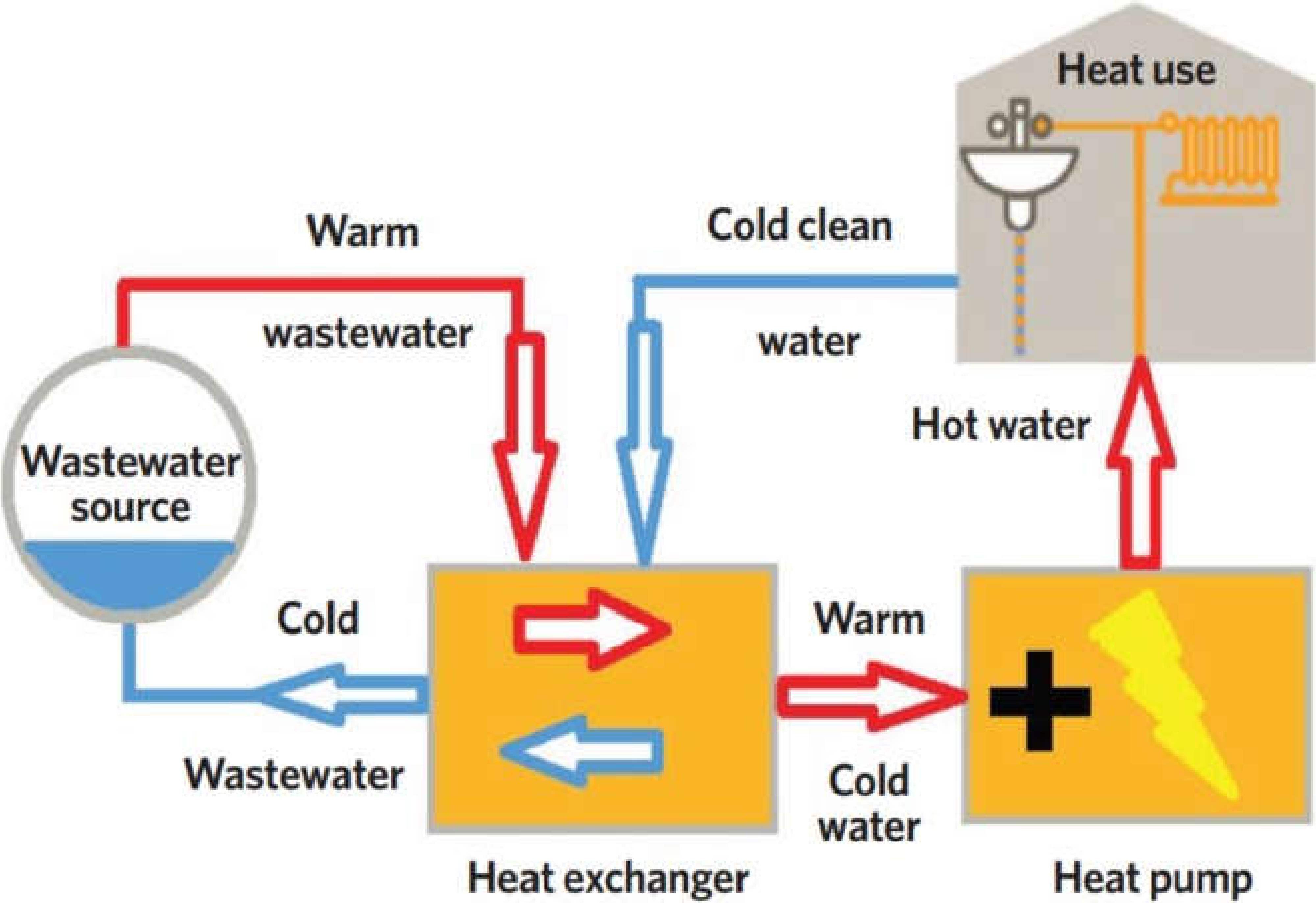
(Source: https://en.wikipedia.org/wiki/Water_heat_recycling)

Wastewater heat recovery with heat pump (at building level)



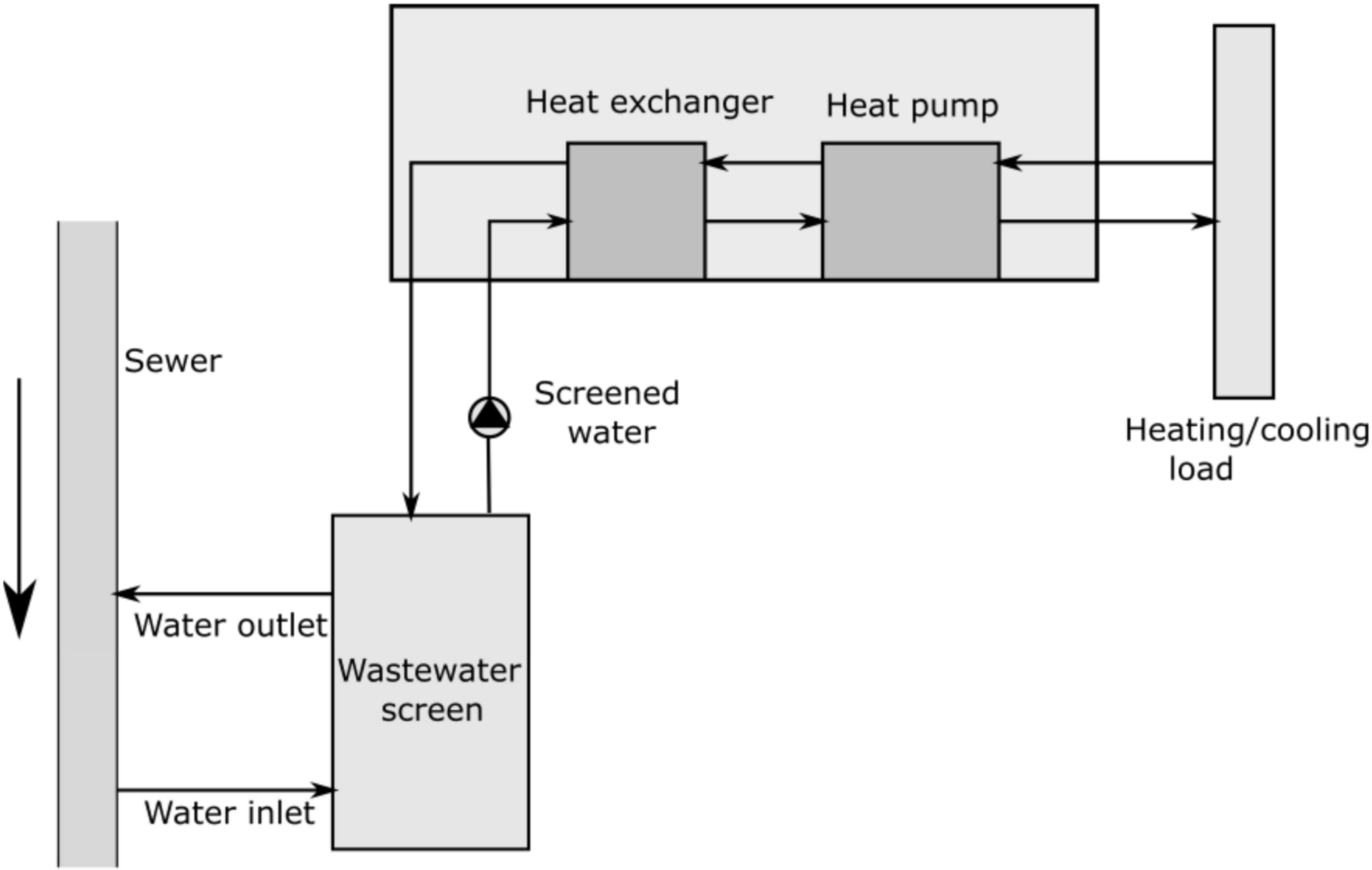
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274)

Wastewater heat recovery process



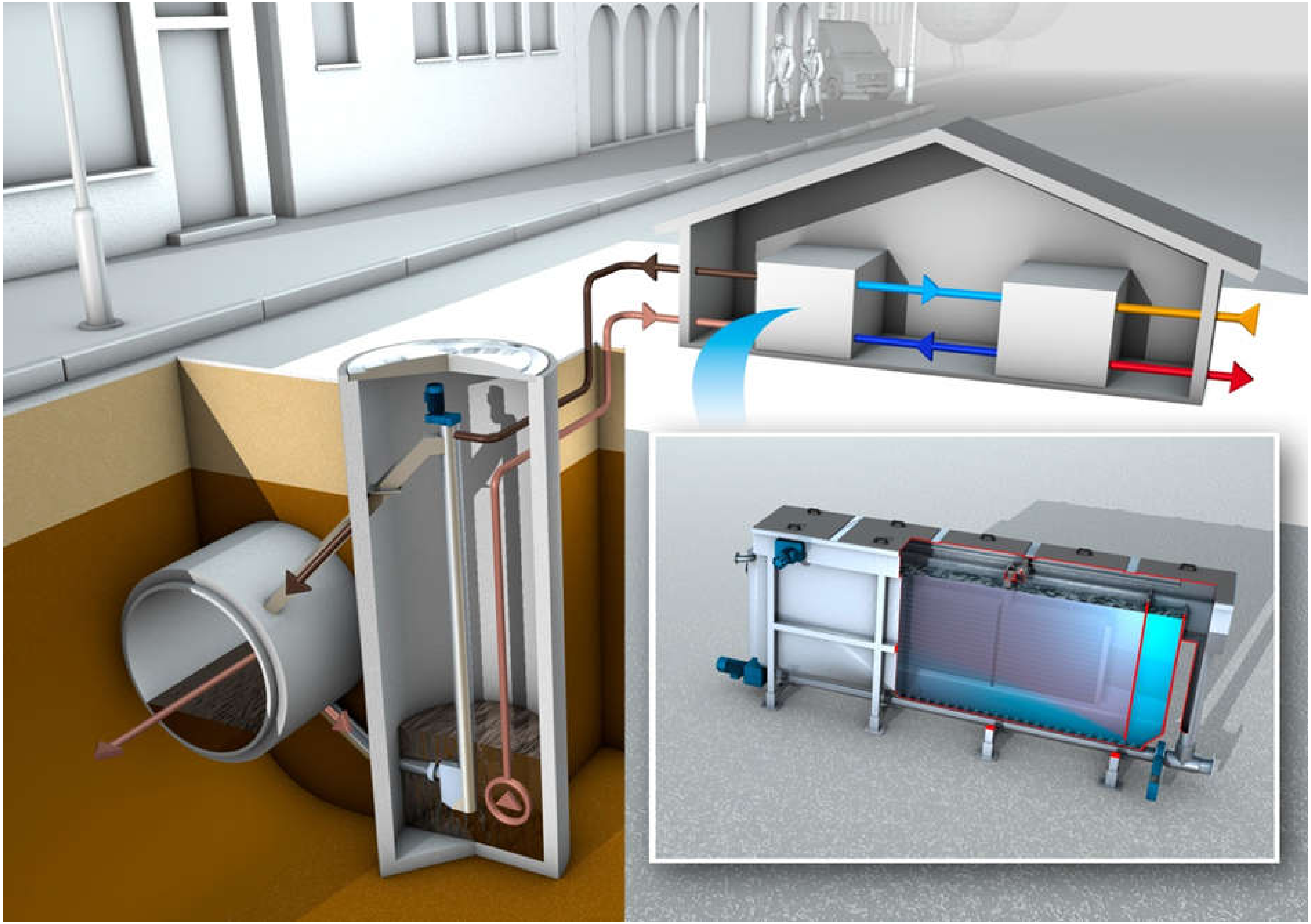
(Source: https://www.cibsejournal.com/general/londons-hidden-energy-source-recovering-heat-from-sewage/)

Wastewater heat recovery with an external heat exchanger with upstream filtration (at sewer pipe network level)



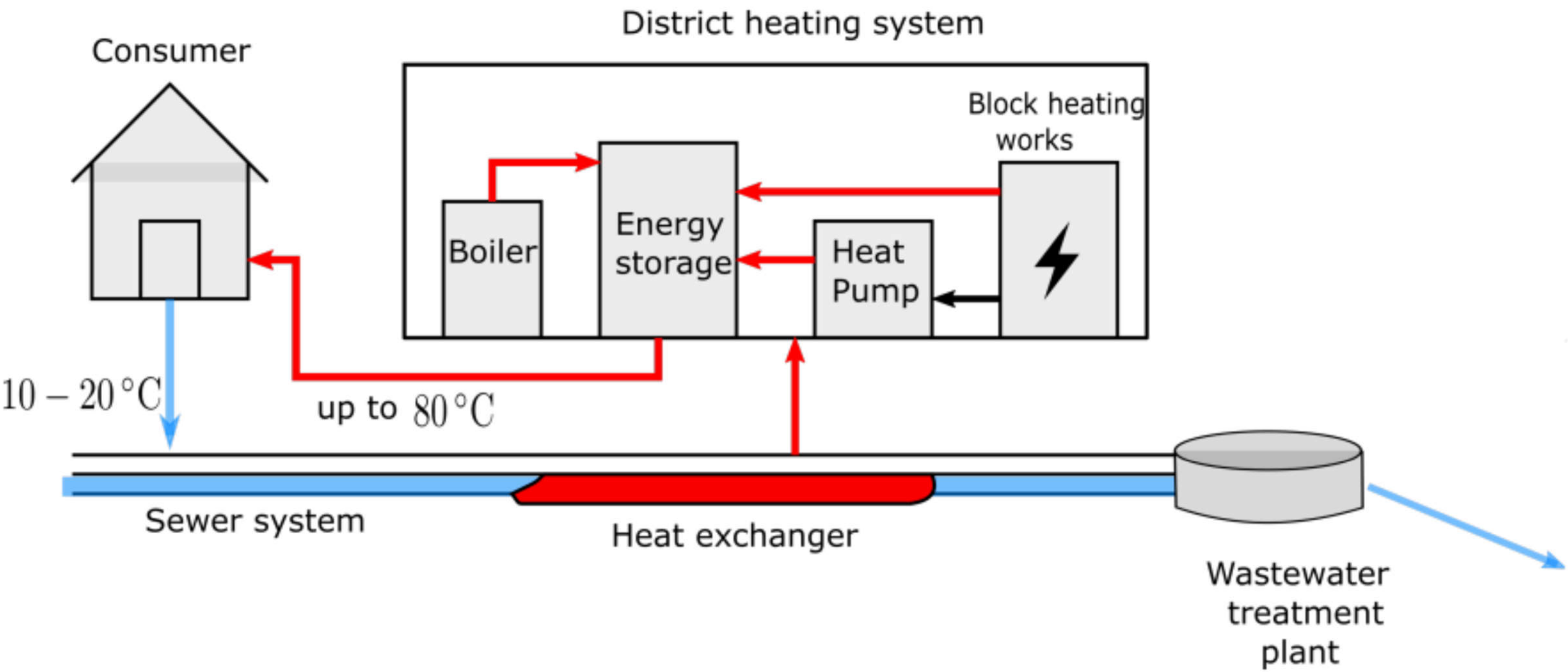
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274)

An example of sewer heat recovery system (external heat exchanger)



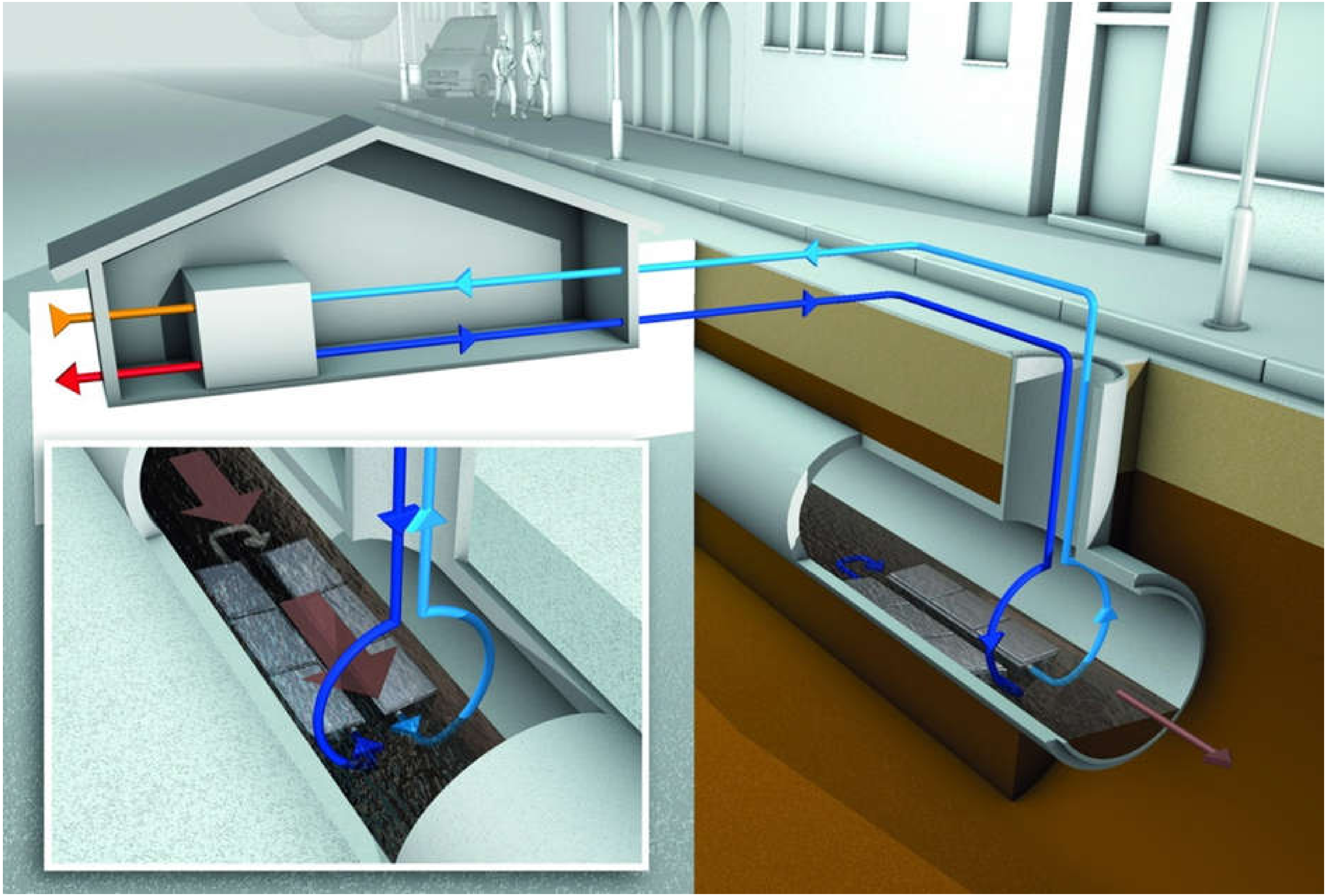
(Source: https://celsiuscity.eu/clean-energy-from-sewage/)

Wastewater heat recovery with an integrated heat exchanger in sewer bed (at sewer pipe network level)



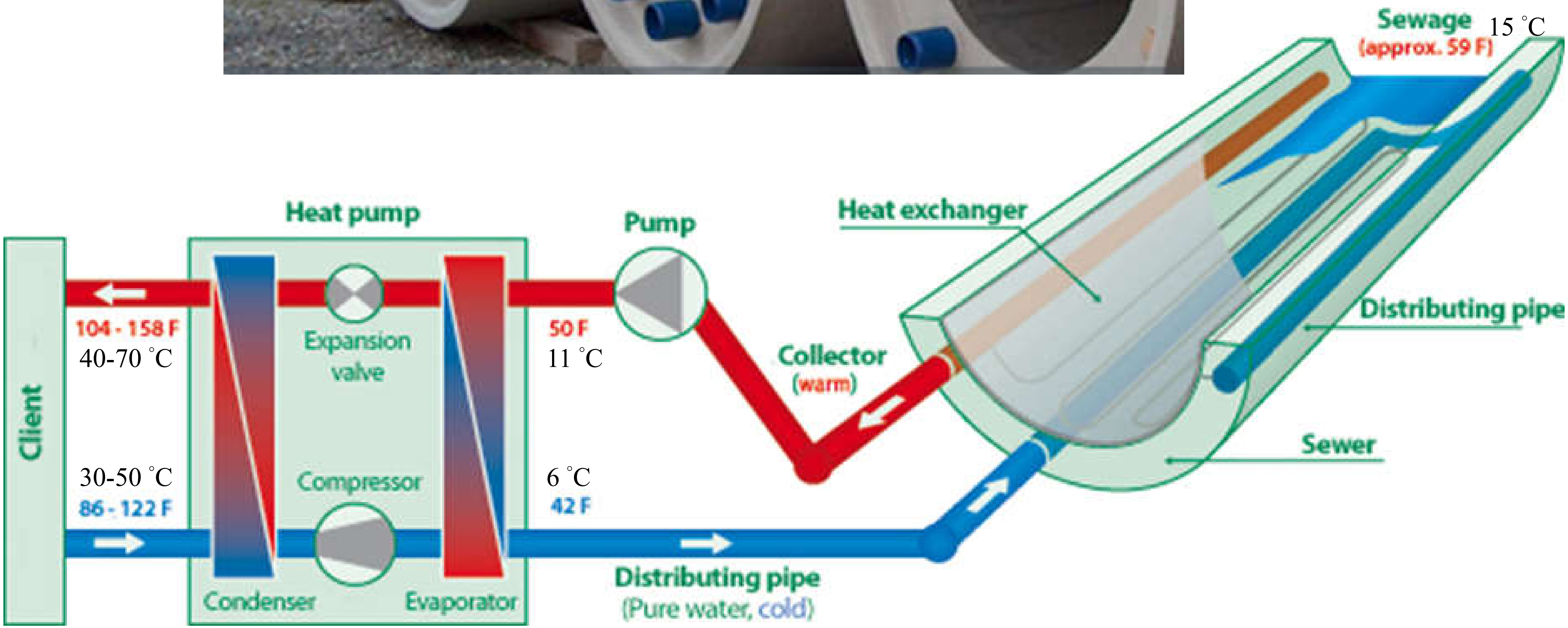
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274)

An example of sewer heat recovery system (in-sewer heat exchanger)



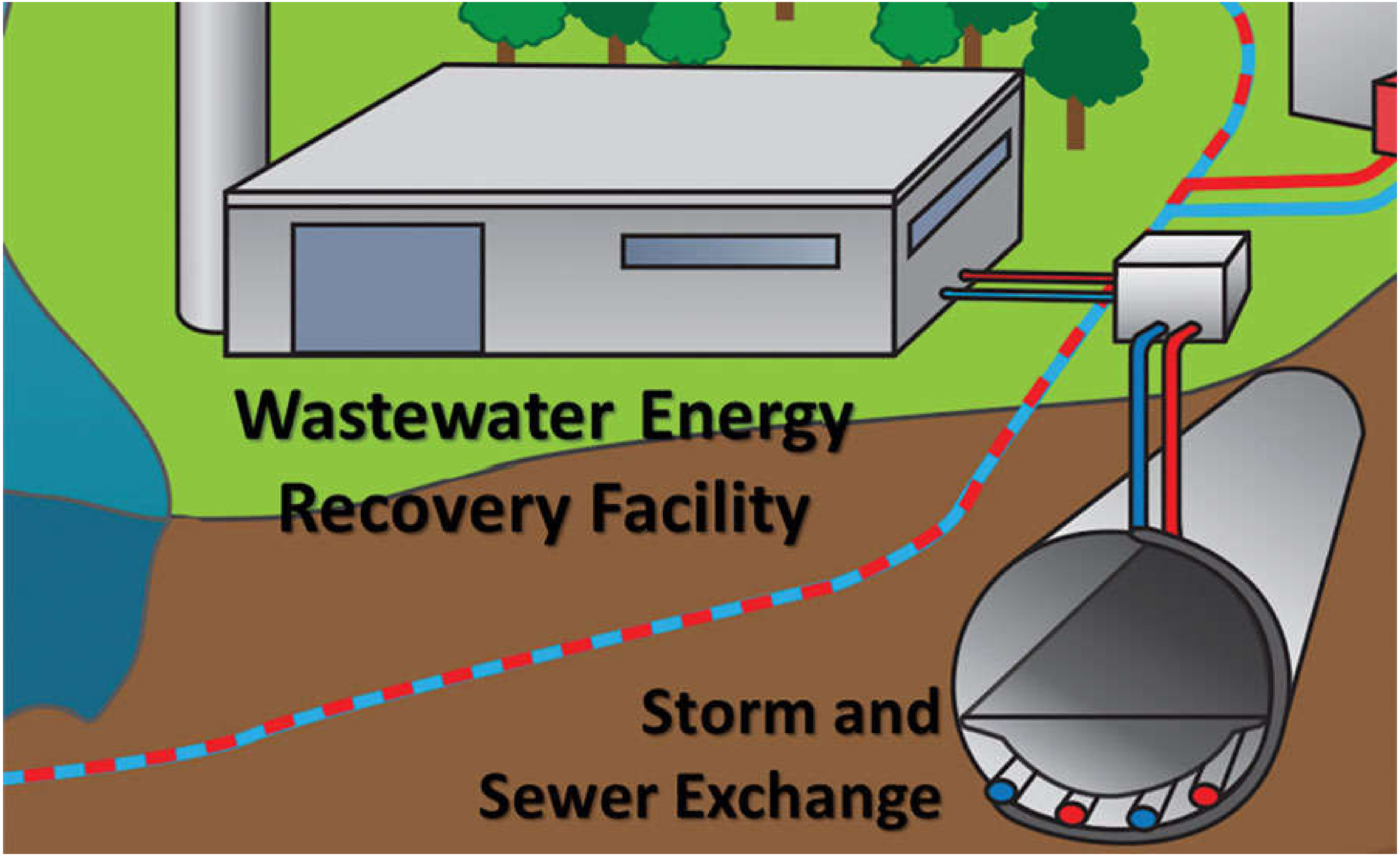
(Source: https://celsiuscity.eu/clean-energy-from-sewage/)

Sewer heat recovery system in new sewers (in-sewer heat exchanger)



(Source: https://celsiuscity.eu/clean-energy-from-sewage/)

Wastewater thermal extraction technology for energy recovery



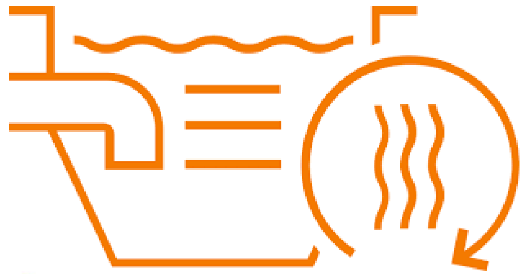
(Source: http://www.achrnews.com/articles/133785-lets-get-hvac-out-of-the-sewer)

Summary for wastewater heat recovery technologies

Technology	Scale	Characteristics
Vertical wastewater heat exchanger	Component	• Can be used for preheating shower water • Higher space requirements • Higher efficiency due to the higher contact surface area
Horizontal wastewater heat exchanger	Component	• Suitable for preheating shower water • Low space requirements • Less efficient due to the lower contact surface area
Heat exchanger with wastewater storage tank	Building	• Hot water is stored in the storage tank • Higher cost of the device due to the additional storage tank • More feasible with a heat pump
Heat pump with heat exchanger	Building	• Higher energy recovery • Less economic feasibility for individual dwellings
Integrated heat exchanger in sewer pipes with heat pumps	Sewer	• Heat exchanger in the sewer pipe bed • Need to meet technical specifications based upon sewer pipe parameters • No additional space requirements • More prone to fouling and demand regular maintenance
External heat exchanger with heat pumps	Sewer	• Sewage is pumped out of the sewer pipe • Less prone to fouling due to pre-screening of wastwater • Independent of the sewer pipe and easy maintenance • Additional space requirements

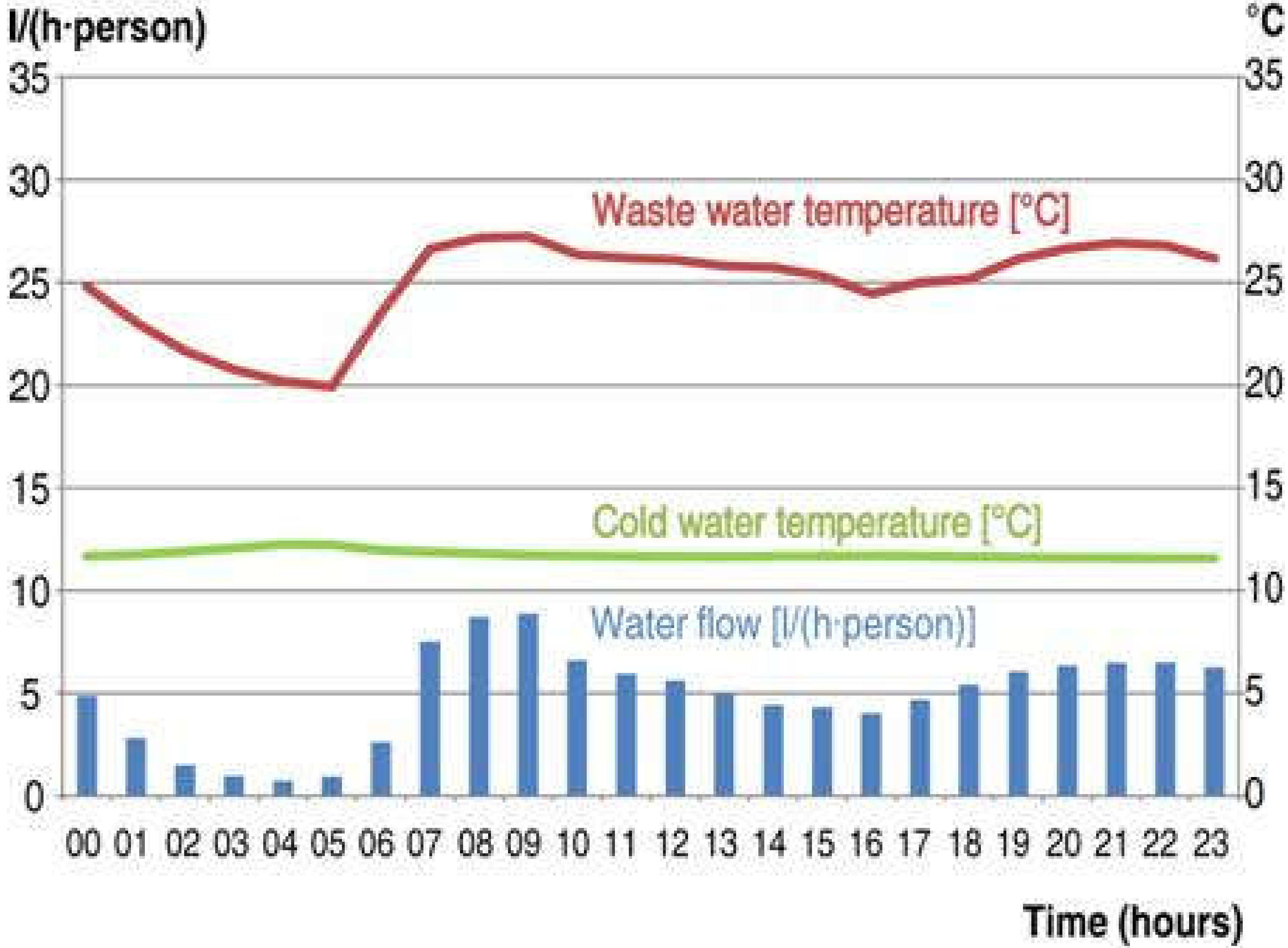
(Source: Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274)

Wastewater heat recovery



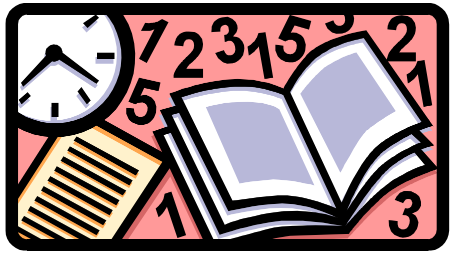
- Factors determining the efficiency of waste heat recovery from wastewater
  - Temperature difference (ΔT) between pre-heat water and cold tap water
  - The amount of pollutants (fouling) in wastewater
  - Design and type of heat exchanger used
  - Diameter of sewer pipes
  - Technical condition of the network and devices associated with it

Wastewater temperature and flow rate in a student residence



(Source: In-house Waste Water Heat Recovery https://www.rehva.eu/rehva-journal/chapter/in-house-waste-water-heat-recovery)

Further Reading



- Heat Pump and Heat Recovery Technologies
  - http://www.environment.gov.au/system/files/energy/files/hvac-factsheet-heat-pump-tech.pdf
- Mitsubishi Electric Guide to Heat Recovery Chillers https://library.mitsubishielectric.co.uk/pdf/book/67_HEAT_RECOVERY_CHILLERS
- Don’t waste the waste water: Clean energy from sewage https://celsiuscity.eu/clean-energy-from-sewage/
- Heat Recovery from Wastewater https://encyclopedia.pub/entry/11457

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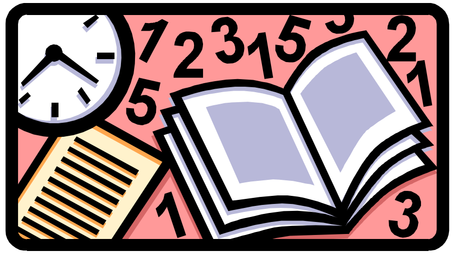

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  - Chapter 9. Applied Heat Pump and Heat Recovery Systems
  - Chapter 18. Variable Refrigerant Flow
- Chu J. & Cruickshank C. A., 2014. Solar-assisted heat pump systems: a review of existing studies and their applicability to the Canadian residential sector, *Journal of Solar Energy Engineering*, 136 (4) 041013. https://doi.org/10.1115/1.4027735
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- Nagpal H., Spriet J., Murali M. K. & McNabola A., 2021. Heat recovery from wastewater—a review of available resource, *Water*, 13 (9) 1274. https://doi.org/10.3390/w13091274