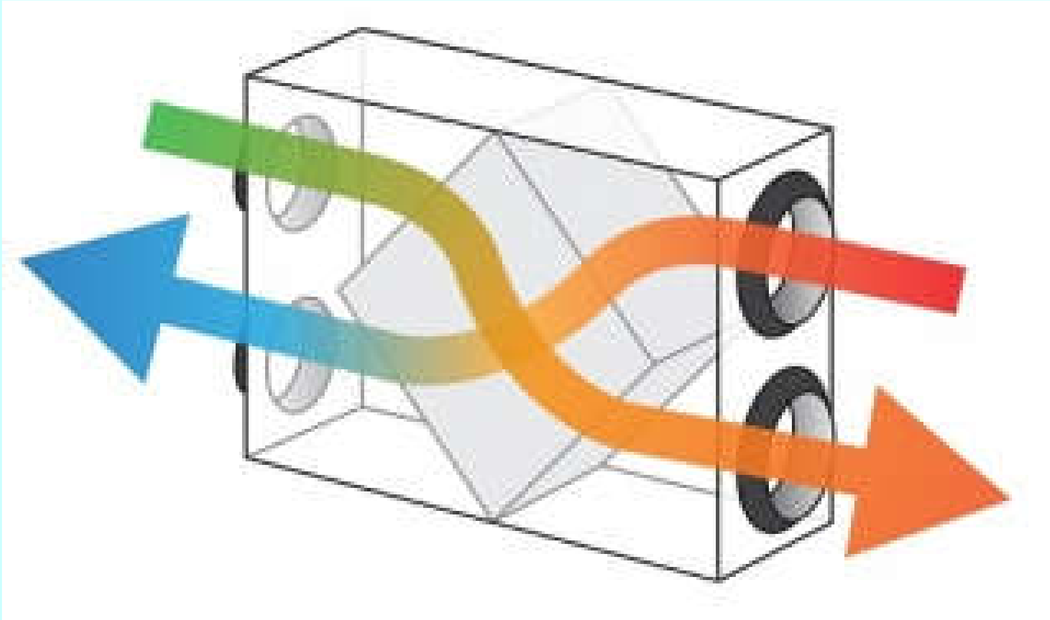
MEBS7014 Advanced HVAC applications

http://ibse.hk/MEBS7014/



Heat Recovery Systems I

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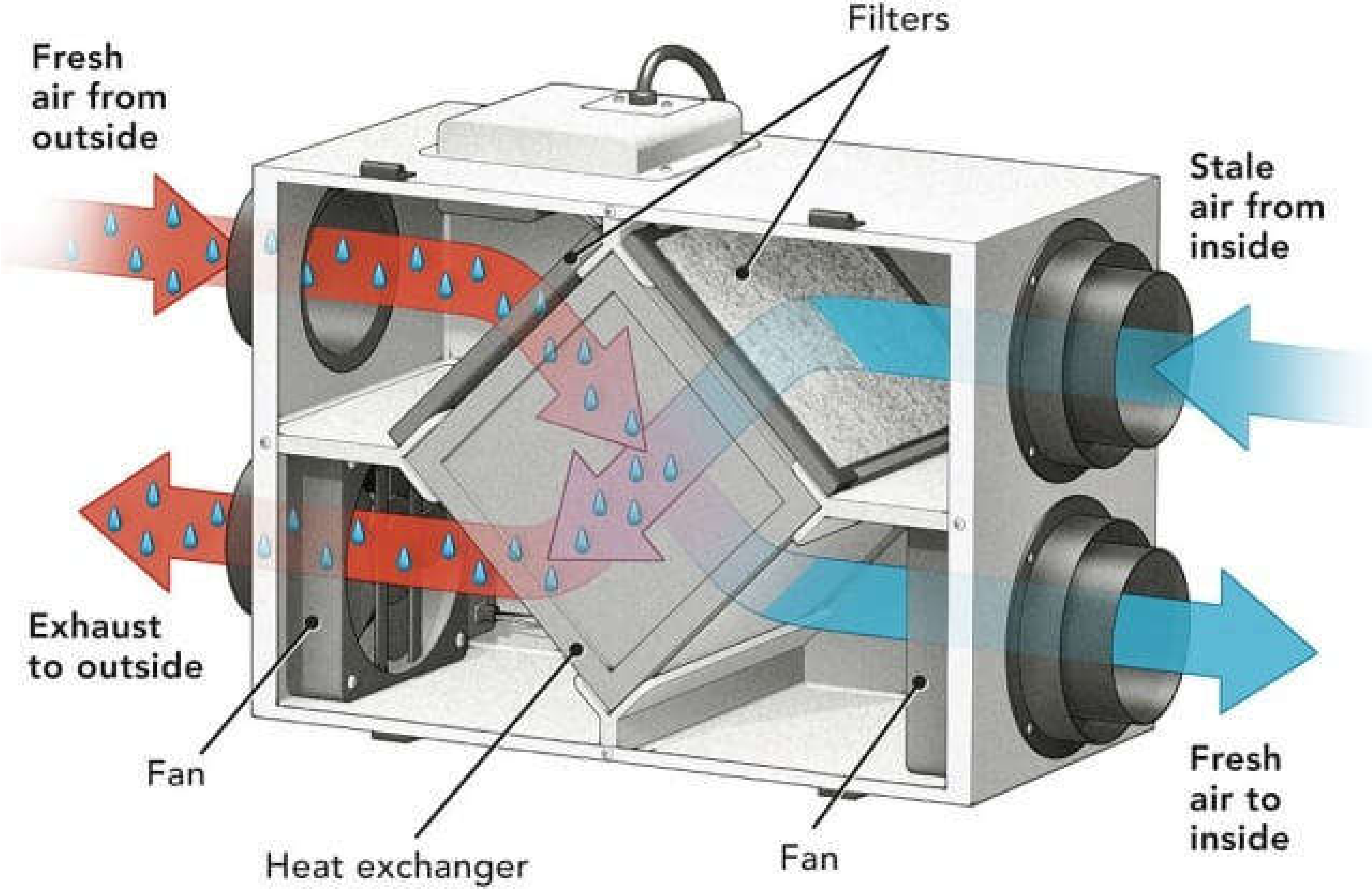
Basic concepts

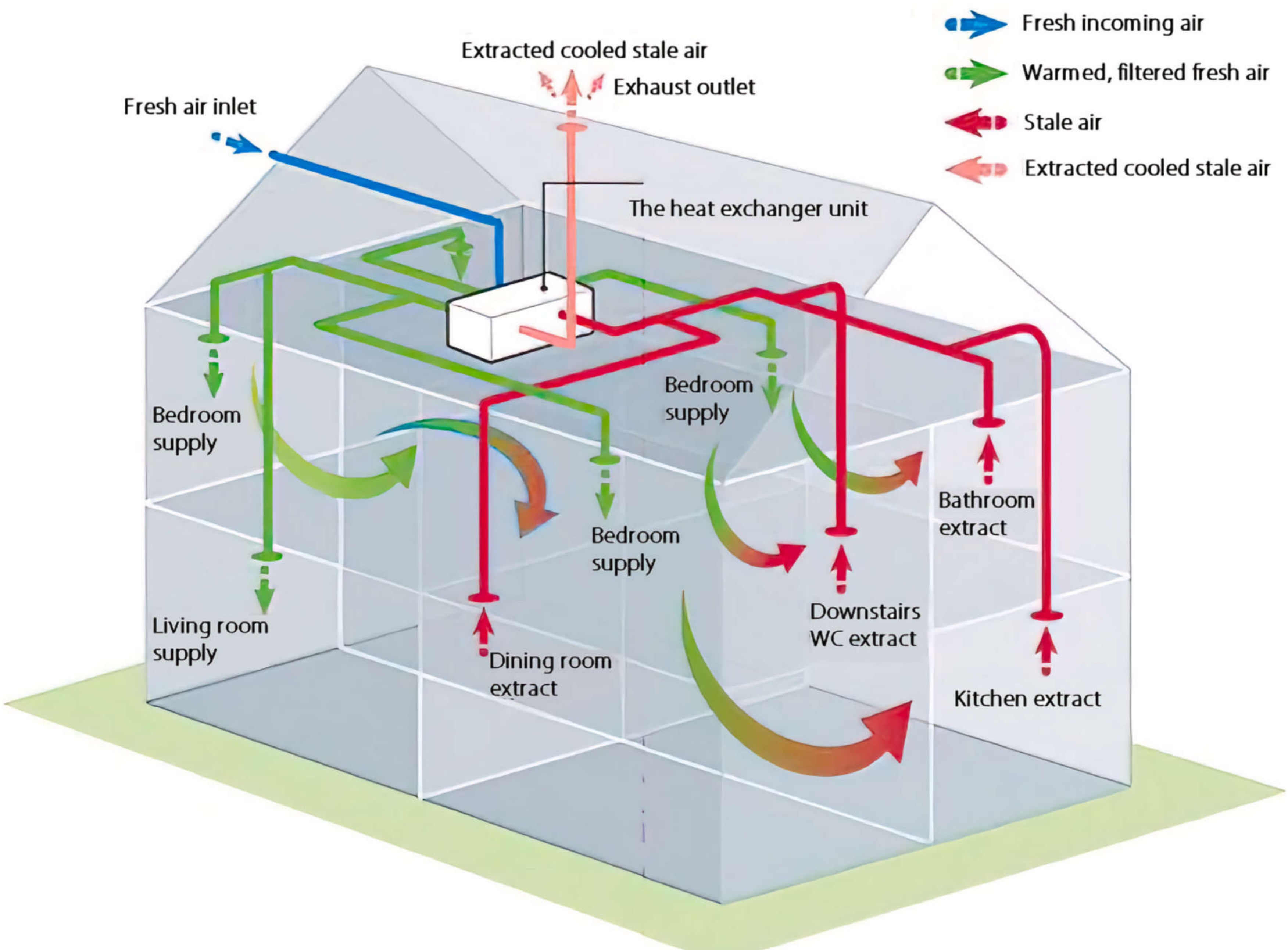
- Heat recovery is the process of collecting and re-using heat that is generated from any process where the heat would otherwise be lost
  - Can help reduce the energy consumption of the process or the heat can be used elsewhere, reducing running costs and carbon emissions
  - Heat recovery devices can be used in most buildings since the majority use energy for HVAC or some may house industrial processes that generate heat

An example of heat recovery ventilation system



(Source: https://energywiseireland.ie/hrv-overview/)

Schematic of a typical heat recovery ventilation system (HRV) in a residential building



(Source: Bai H. Y., Liu P., Alonso M. J. & Mathisen H. M., 2022. A review of heat recovery technologies and their frost control for residential building ventilation in cold climate regions, *Renewable and Sustainable Energy Reviews*, 162: 112417. https://doi.org/10.1016/j.rser.2022.112417)

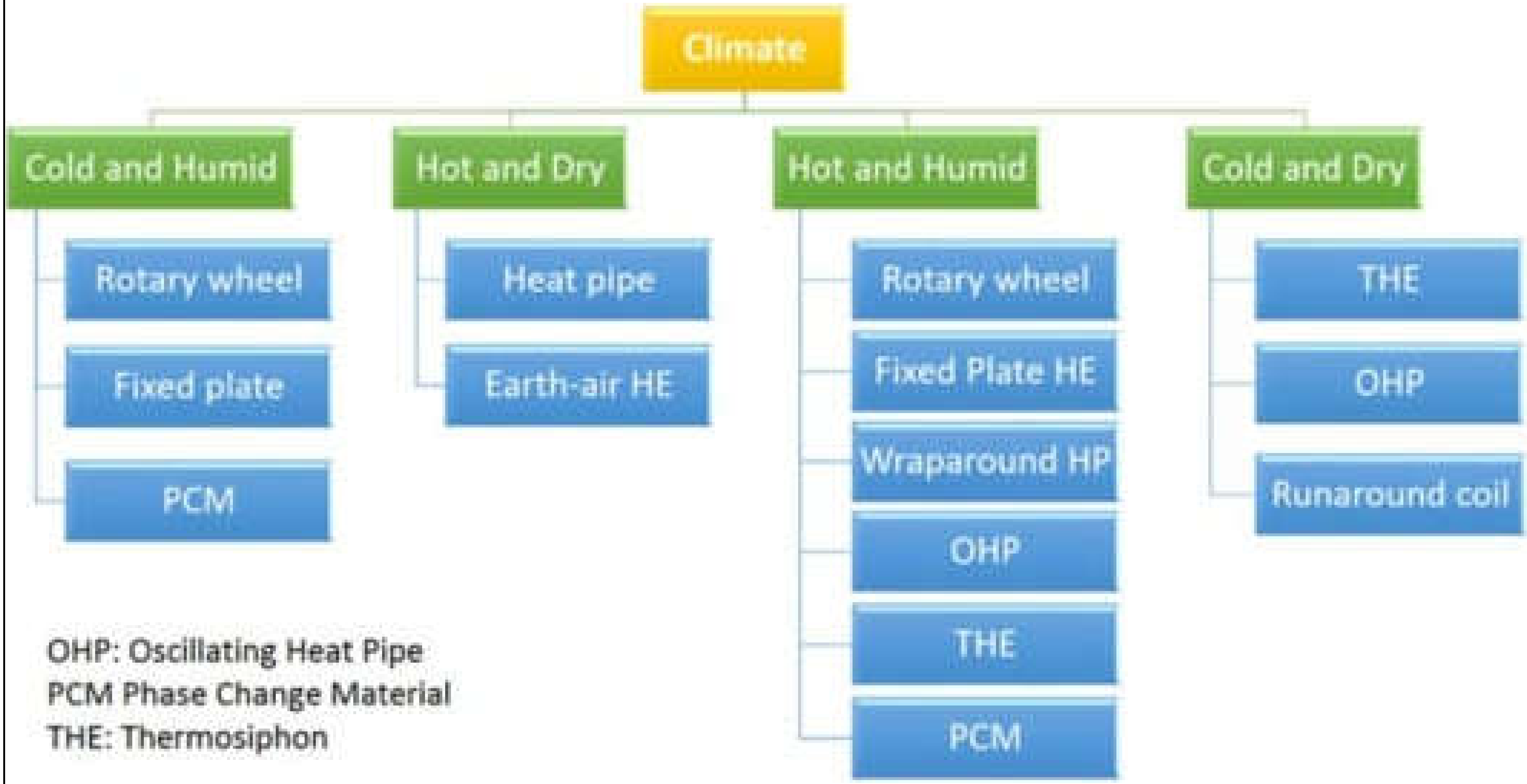
Basic concepts

- Sources of waste heat that might provide opportunities for heat recovery include:
  - Ventilation systems (air side)
  - Refrigeration units and chiller units (water side)
  - Boilers (e.g. flue economiser)
  - Power generation plant
  - Plant cooling systems
  - Hot liquid effluents and high-temperature exhaust gasses

Basic concepts

- Heat/Energy recovery in HVAC systems
  - Can improve energy efficiency and system effectiveness
  - Common methods of energy recovery:
    - Air-to-air energy recovery (using ventilators)
    - Applied heat pumps and water-side heat recovery
  - Can be applied to residential, commercial and industrial HVAC and process systems
  - The effectiveness depends on seasons, climate, control and operation conditions

Heat recovery devices according to the climate



Why some heat recovery devices can/cannot work well in that climate?

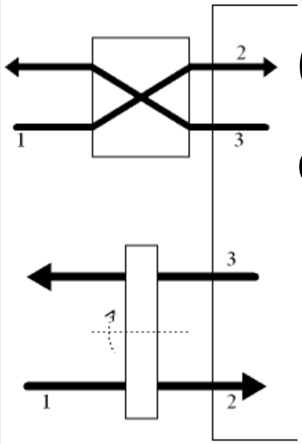
(Source: Energy Recovery in Air Conditioning Systems https://encyclopedia.pub/entry/18026)

Basic concepts

- Heat sources and sinks:
  - Air (outdoor ambient air, exhaust from ventilation)
  - Water (well, surface, tap, condensing, waste)
  - Ground (ground-coupled, direct expansion)
  - Solar energy (direct or indirect heated water/air)
  - Industrial process (process heat or exhaust)
- Use the waste heat to support domestic water heating, terminal reheat, outdoor air heat, dehumidification, space or process heating

Air-to-air energy recovery

- Air-to-air energy recovery
  - Recover heat and/or moisture between two air streams
  - Important for maintaining acceptable indoor air quality (IAQ) while reducing energy costs
  - Energy can be recovered either in its sensible (temperature only) or latent (moisture) form, or combination of both
    - Sensible only: Heat Recovery Ventilator (HRV)
    - Energy/enthalpy: Energy Recovery Ventilator (ERV)

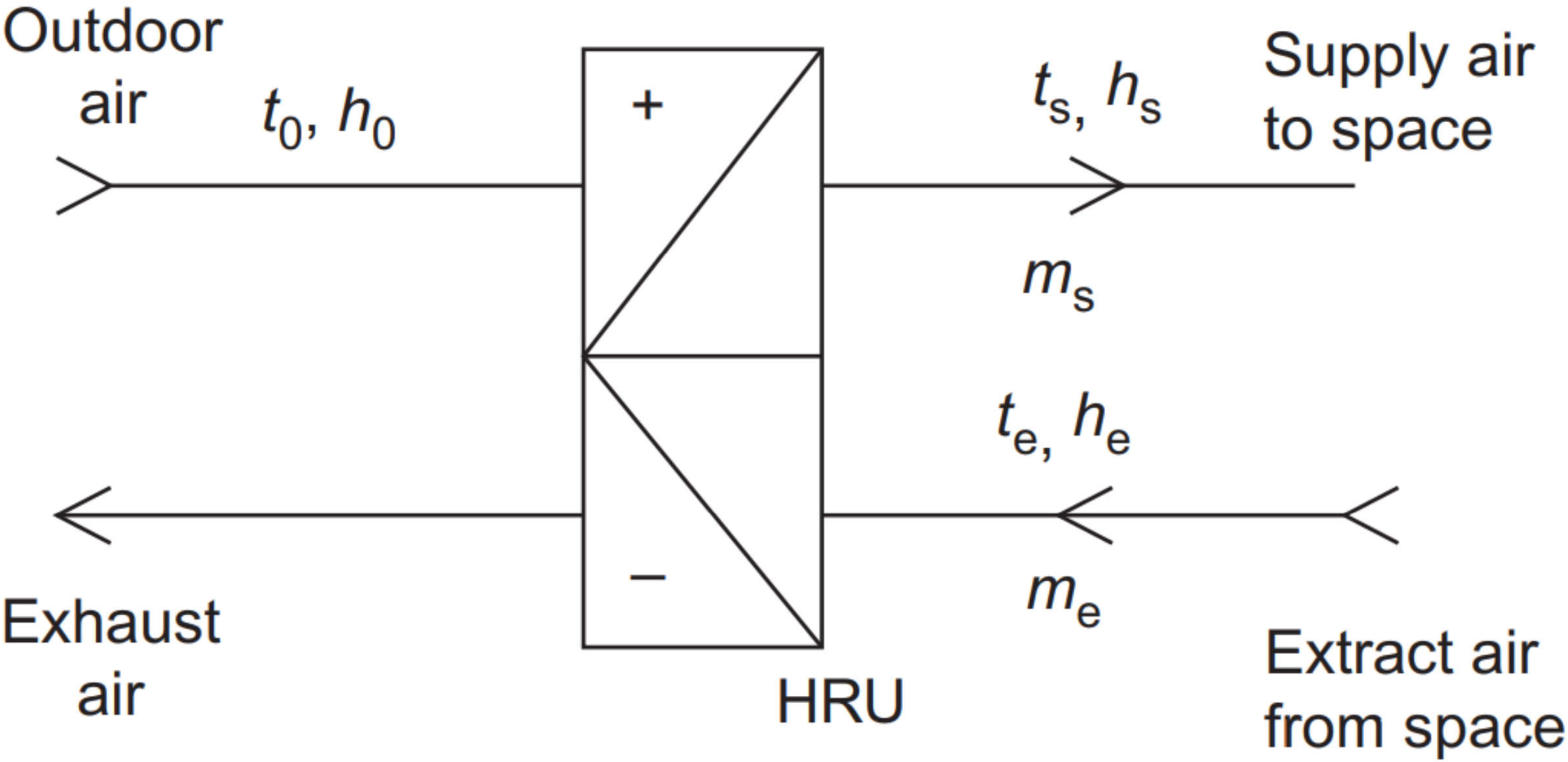


Typical applications for air-to-air energy recovery

Method	**Application**
Comfort-to-comfort (the energy recovery device lowers the enthalpy of the building supply air during warm weather and raises it during cold weather by transferring energy between the ventilation air supply and exhaust airstreams)	Residences Offices Classrooms Retail Bars and restaurants Swimming pools Locker rooms Operating rooms Nursing homes Animal ventilation Plant ventilation Smoking exhaust
Process-to-process (heat is captured from the process exhaust stream and transferred to the process supply airstream) and Process-to-comfort (waste heat captured from process exhaust heats building makeup air during winter)	Dryers Ovens Flue stacks Burners Furnaces Incinerators Paint exhaust Welding exhaust

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

Schematic of an air-to-air heat recovery unit (HRU)

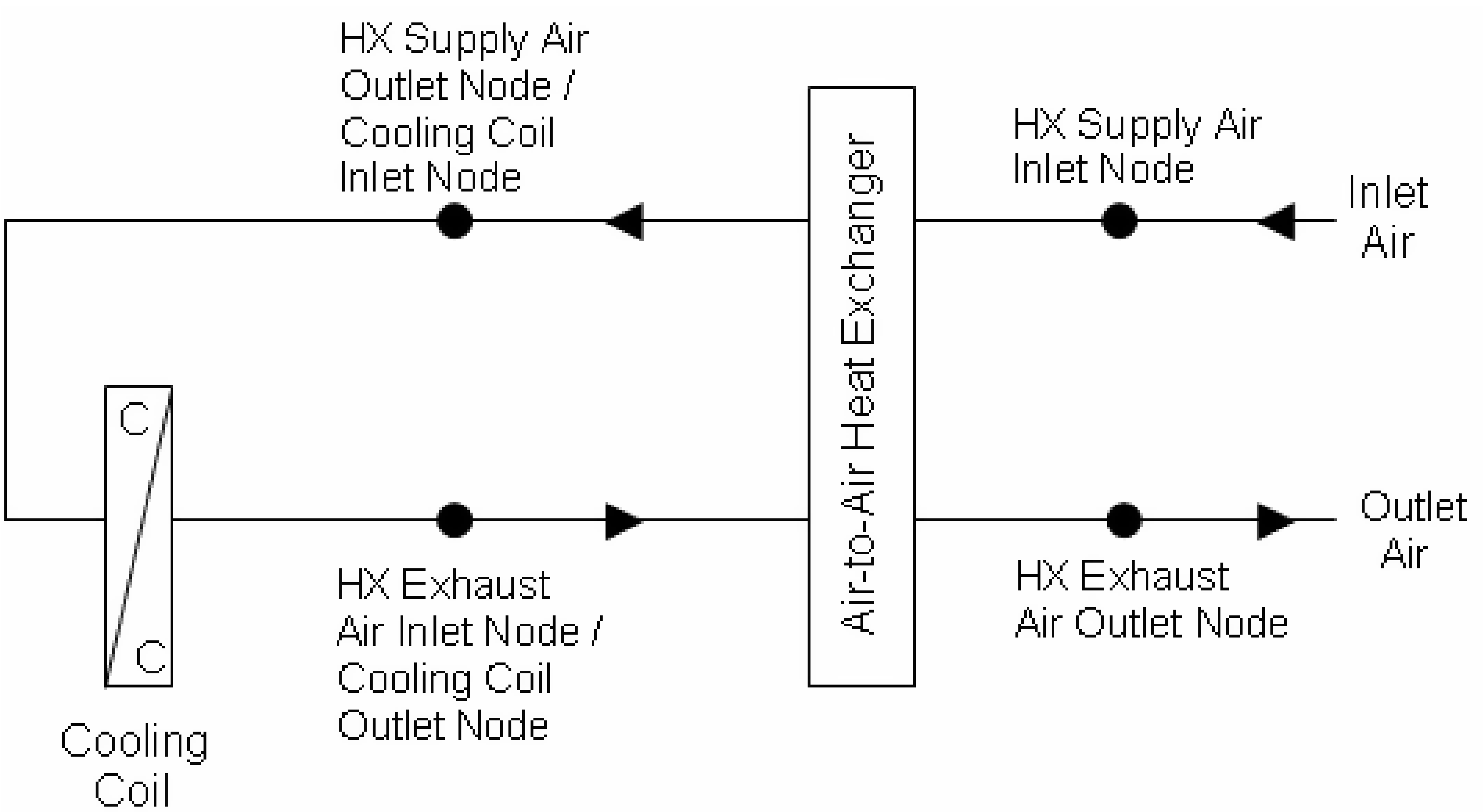


Symbols:
t = temperature (°C)
h = enthalpy (kJ/kg)
m = air mass flow rate (kg/s)

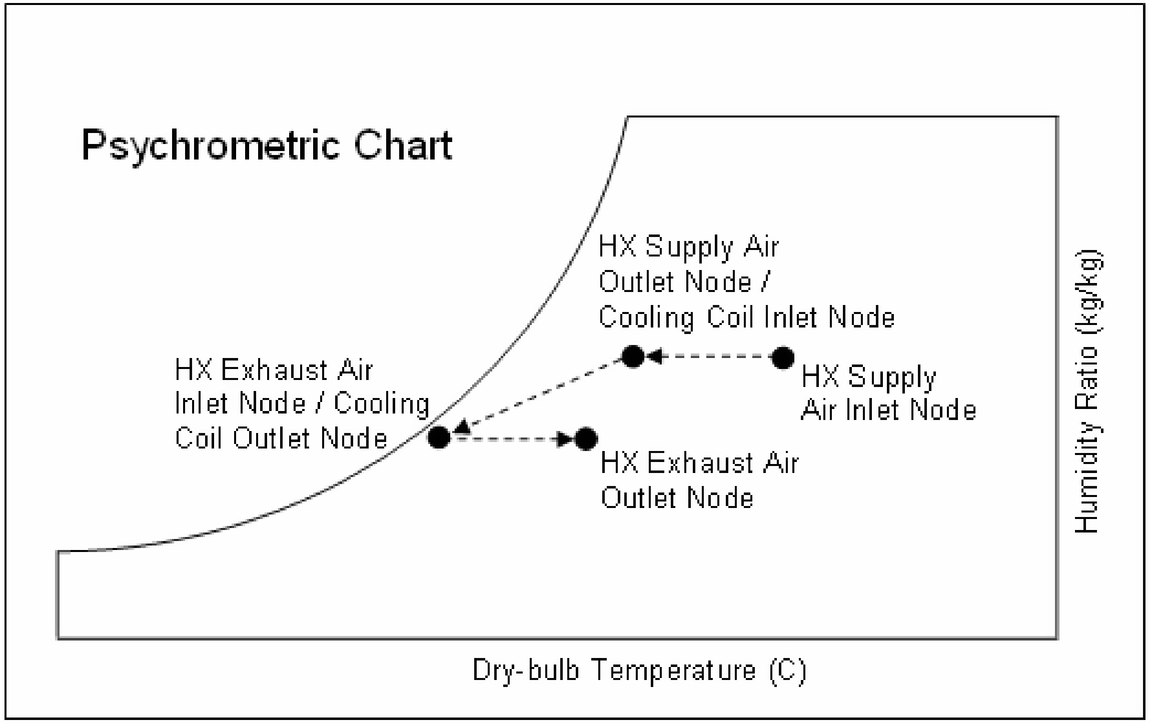
Subscripts:
0 = outdoor air
s = supply air
e = exhaust air

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

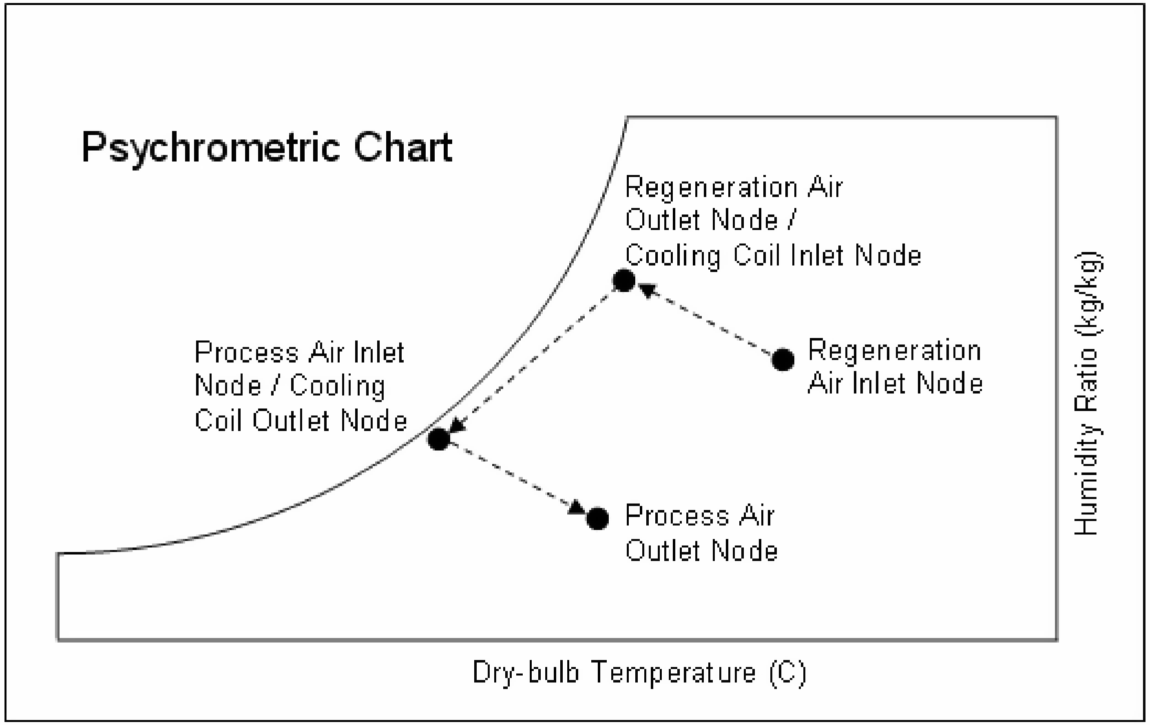
Schematic of a heat exchanger (HX) assisted cooling coil



(Source: http://www.energyplus.net/sites/default/files/docs/site_v8.3.0/EngineeringReference/13b-EncyclopaedicRefs/index.html#heat-exchanger-assisted-air-cooling-coil-systems)



Psychrometric process for heat exchanger assisted cooling coil (sensible heat exchange only) - HRV



Psychrometric process for heat exchanger assisted cooling coil (sensible + latent heat exchange) - ERV

(Source: http://www.energyplus.net/sites/default/files/docs/site_v8.3.0/EngineeringReference/13b-EncyclopaedicRefs/index.html#heat-exchanger-assisted-air-cooling-coil-systems)

Schematic and psychrometric analysis of air-to-air heat exchanger

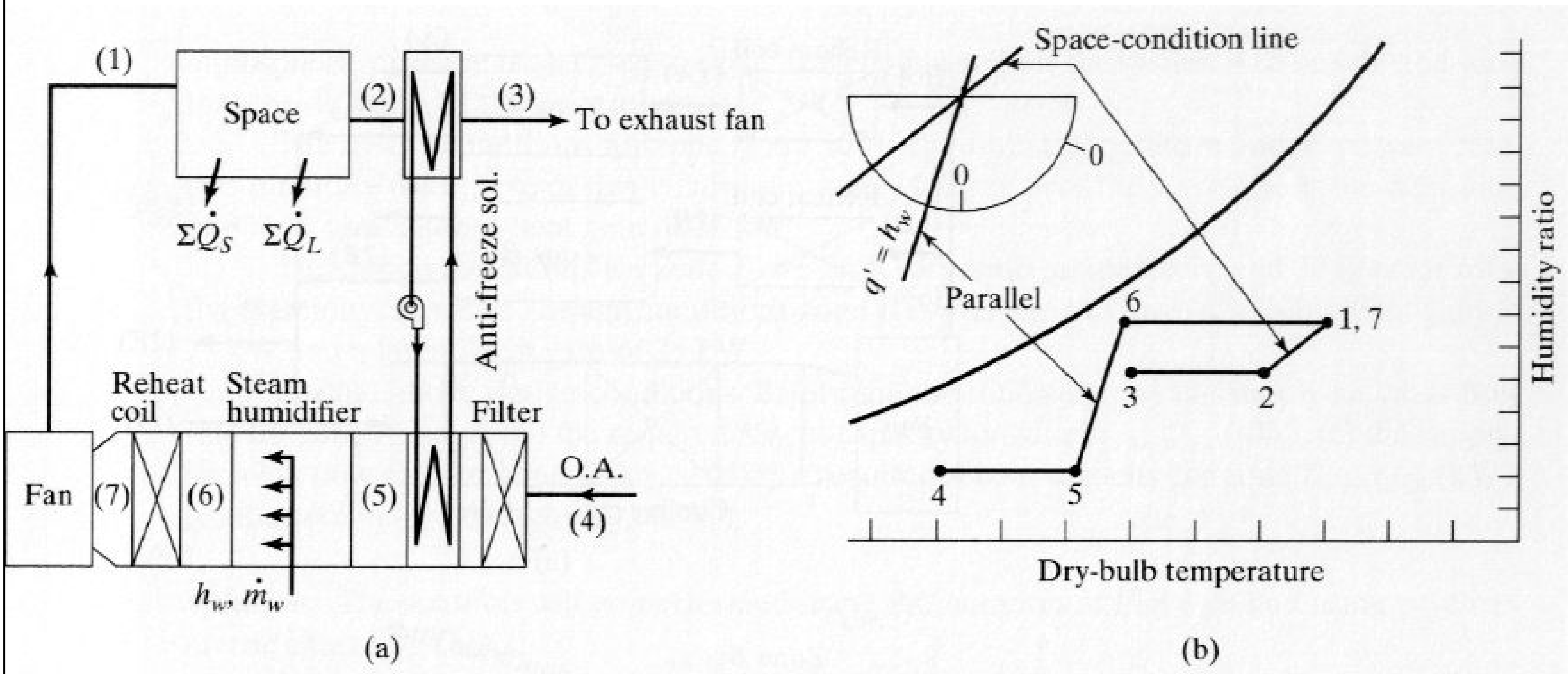
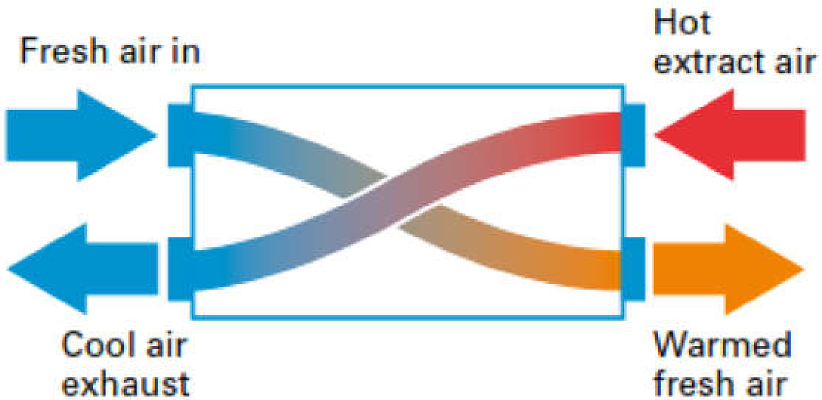


Figure 8.19 Schematic winter air conditioning system using 100 percent outdoor air with preheating by waste heat from the exhaust air.



Air-to-air energy recovery

- Air-to-air energy recovery (cont'd)
  - Air conditioners use much energy to dehumidify moist airstreams (excessive moisture can result in mold, allergies, and bacterial growth)
  - ERV can enhance dehumidification and introduce more outdoor ventilation air to achieve acceptable indoor air quality (IAQ)
  - Recovery efficiency = ratio of output to its input
    - For HRV or ERV, effectiveness is defined as:

$$\varepsilon = \frac{\text{Actual transfer of moisture or energy}}{\text{Maximum possible transfer between airstreams}}$$

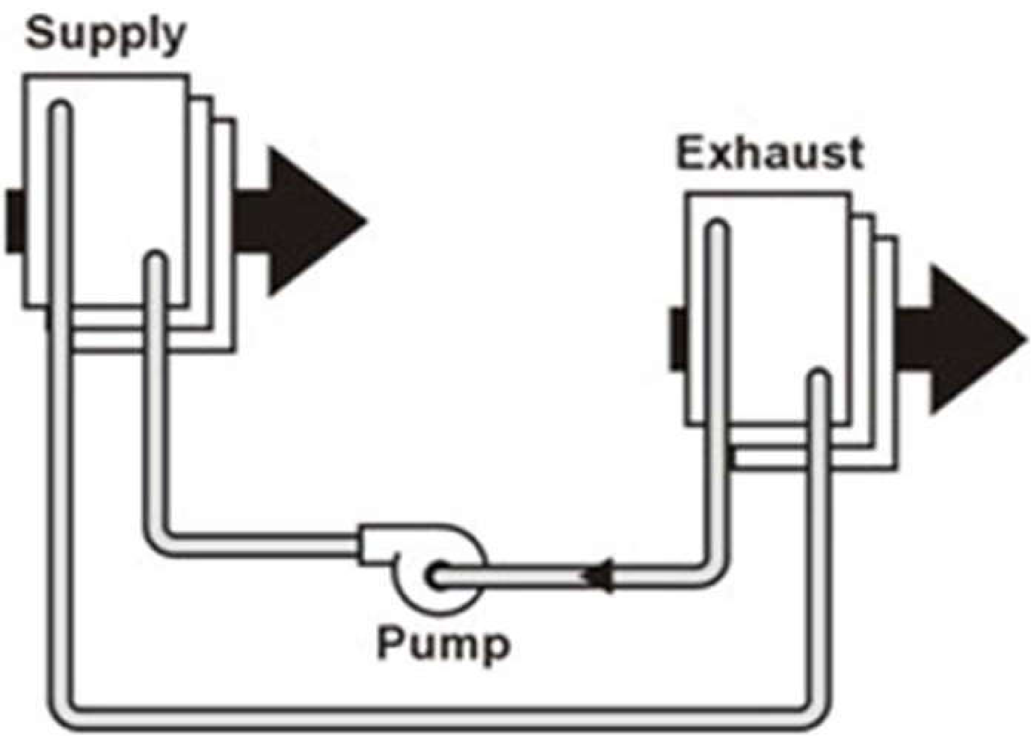
Air-to-air energy recovery

- In winter, exhaust air to heat the outdoor air
- In summer, exhaust air to absorb the heat and humidity from the outdoor air
- Examples of air-to-air energy recovery devices:
  - Run-around coil
  - Heat pipe
  - Two-phase thermosiphon heat exchanger
  - Plate heat exchanger
  - Energy transfer wheel

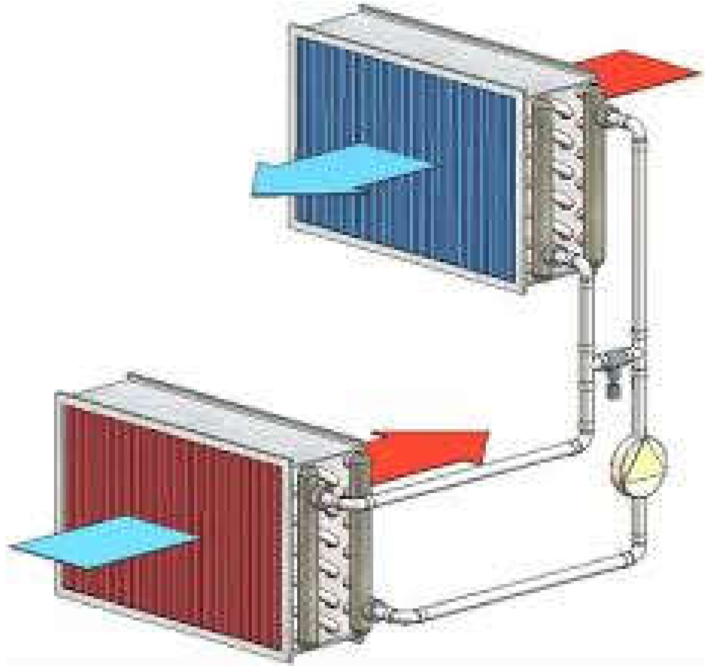
Air-to-air energy recovery

- Run-around coil (sensible heat)
  - Finned-tube copper coils placed in supply and exhaust airstreams
  - A pump circulates water, glycol or other thermal fluid solution
  - The system utilizes the energy from the exhaust air stream to pre-condition the outdoor air
  - Can increase overall HVAC system effectiveness from 50% to 70%

Run-around coil (sensible heat)



Run-around coil system



In summer, the exhaust air from the air-conditioned space cools the circulating fluid in the coil. The cooled fluid is then pre-cool the outdoor air. In winter, the process is reversed; heat is extracted from the exhaust air and then transferred to the make-up air.

Merits:

- This system does not require that the two air streams be adjacent to each other, several air streams can be used.
- It has relatively few moving parts - a small pump and control valve.
- There is no cross-contamination between air streams.

Run-around coil (sensible heat)

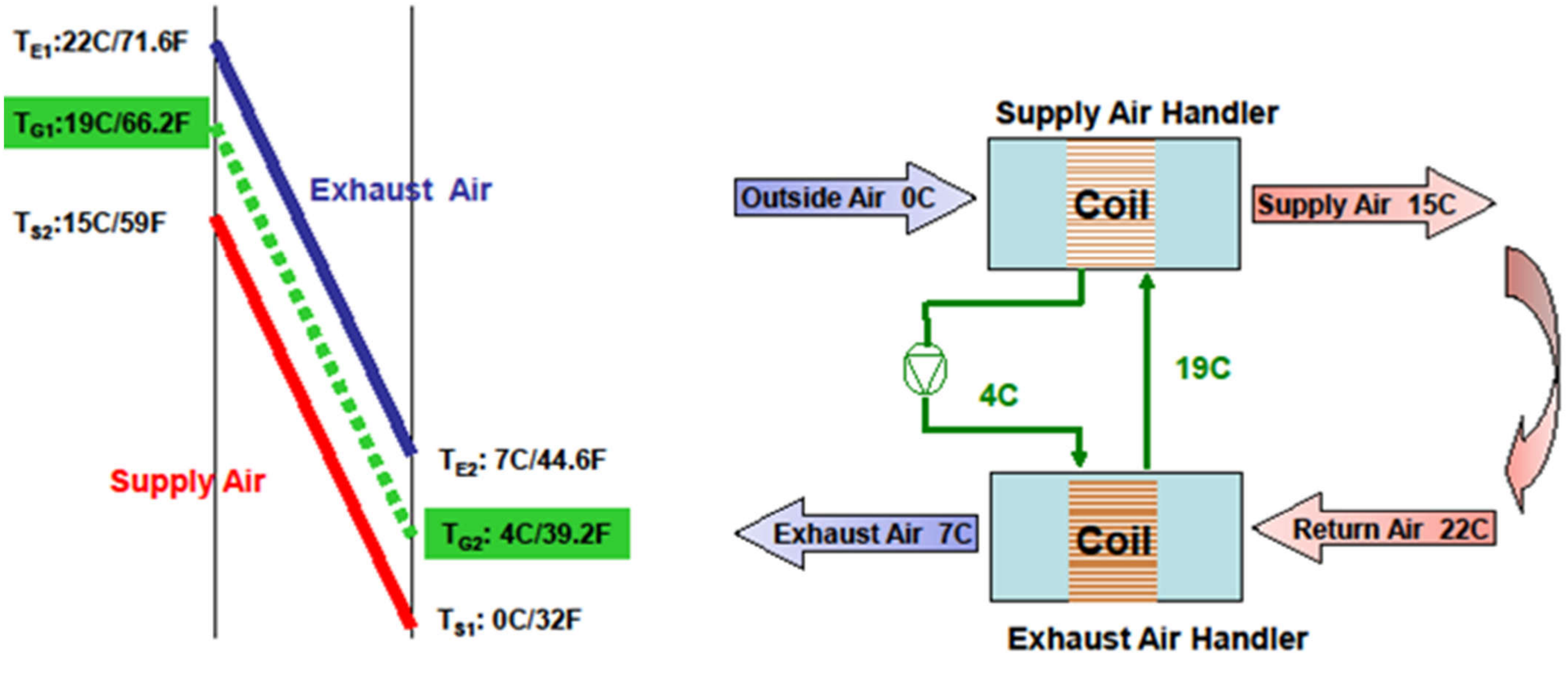
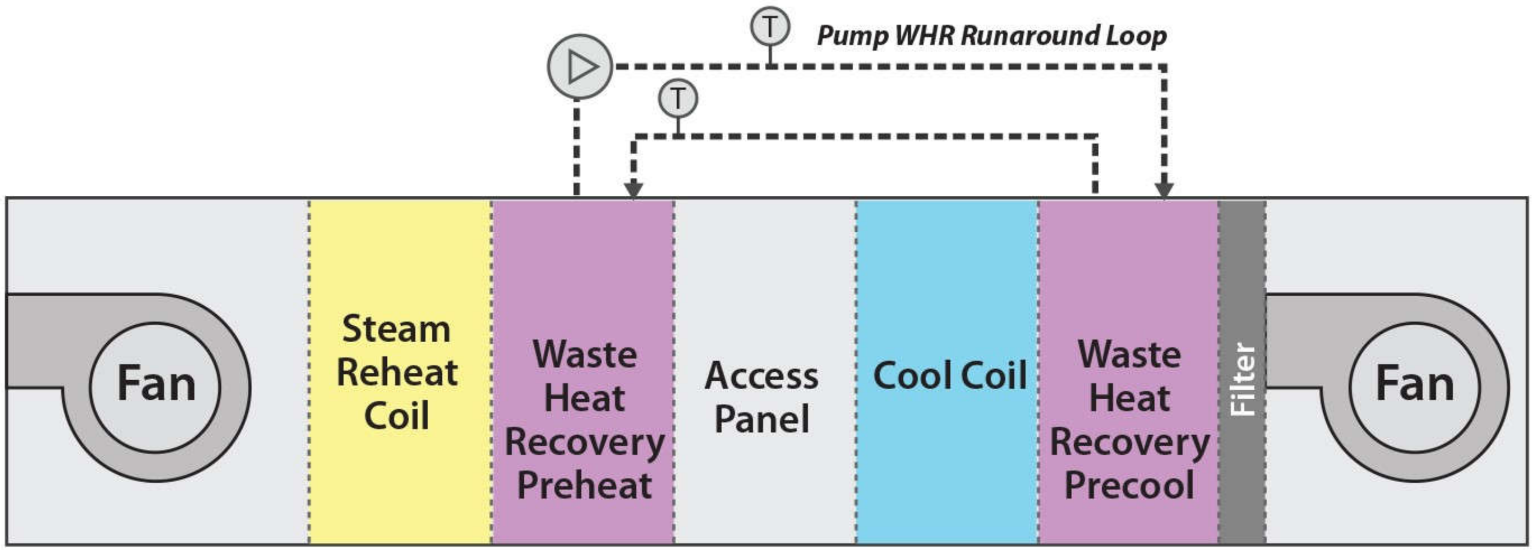


Figure 1: Temperature diagram and components of a basic run-around energy recovery system



Air-to-air energy recovery

- Run-around coil (cont'd)
  - Advantages:
    - Suitable for existing ductwork systems as it does not require adjacent fresh and exhaust ducts
    - Relatively low capital cost compared to other systems
    - Coils are standard items of proven equipment
    - No possibility of cross-contamination of air streams
    - The number of rows and fin spacing can be selected to suit the required heat transfer rate, permissible air pressure drop and exhaust air contaminants

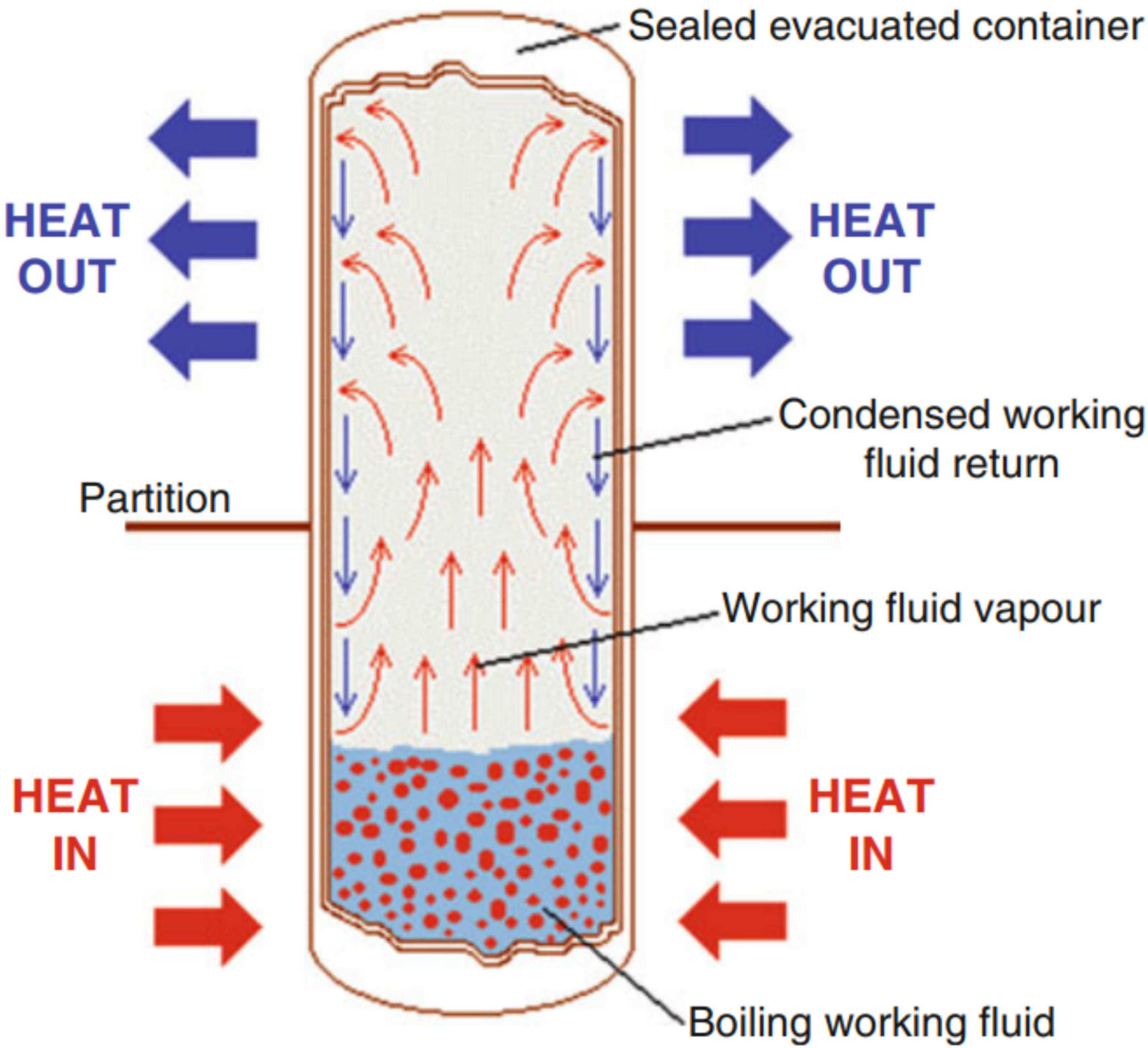
Air-to-air energy recovery

- Run-around coil (cont'd)
  - Disadvantages:
    - Sensible heat transfer only (except when condensation occurs on the coil in warmer airstream)
    - Relatively low heat transfer efficiency, typically 45% for a high quality unit
    - Circulating pump and additional fan energy consumptions (or running costs) must be offset against heat recovery savings

Air-to-air energy recovery

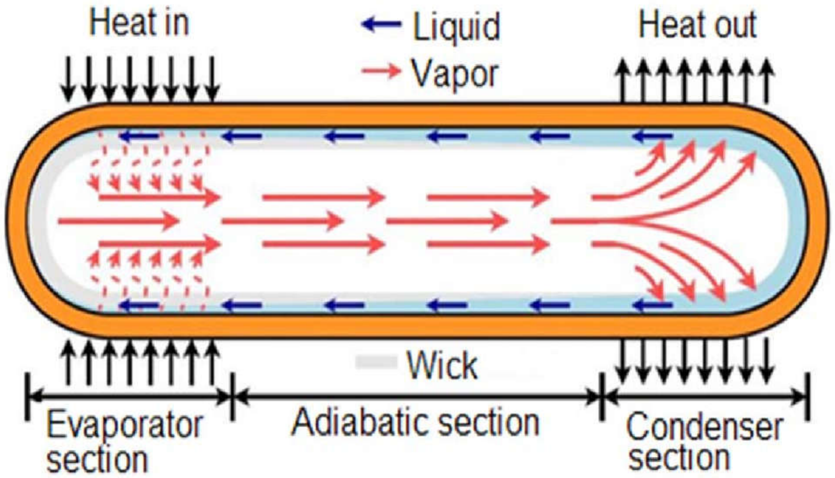
- Heat pipe (sensible heat)
  - A sealed self-contained, liquid evaporating and condensing system
  - Hot air passes through the evaporator section and the cold air passes through the condenser side in a counter-flow arrangement
  - Made of a material with high thermal conductivity e.g. copper or aluminum at both hot and cold ends
  - Working fluid (or coolant) is normally Class I refrigerant (CFC)

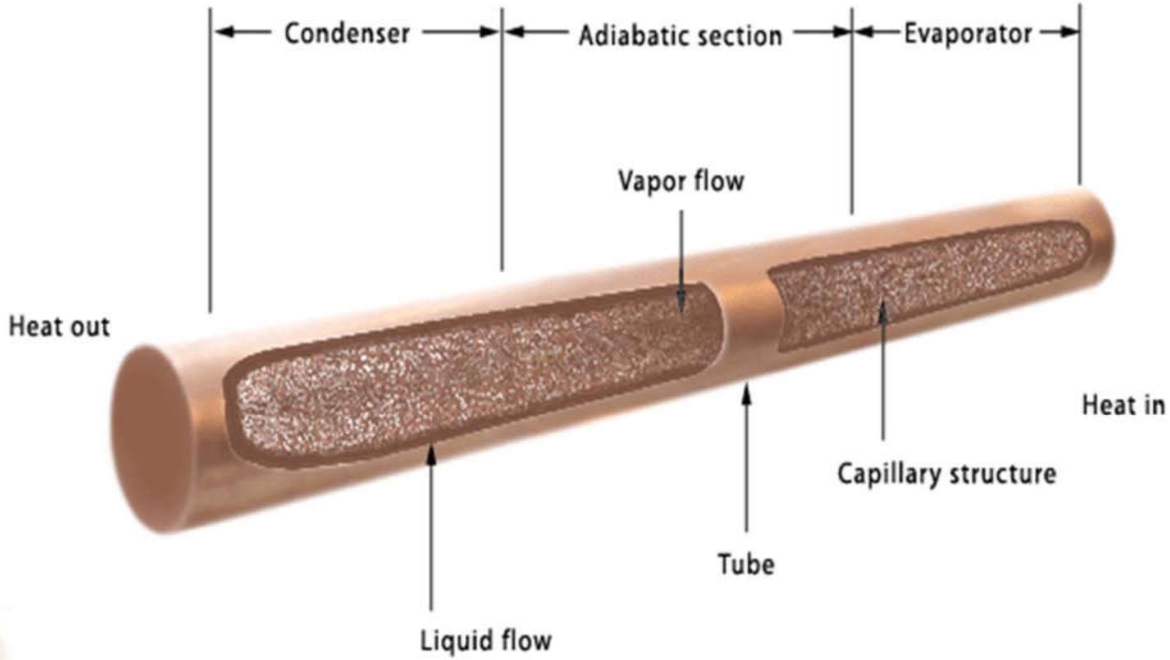
Schematic representation of the heat pipe

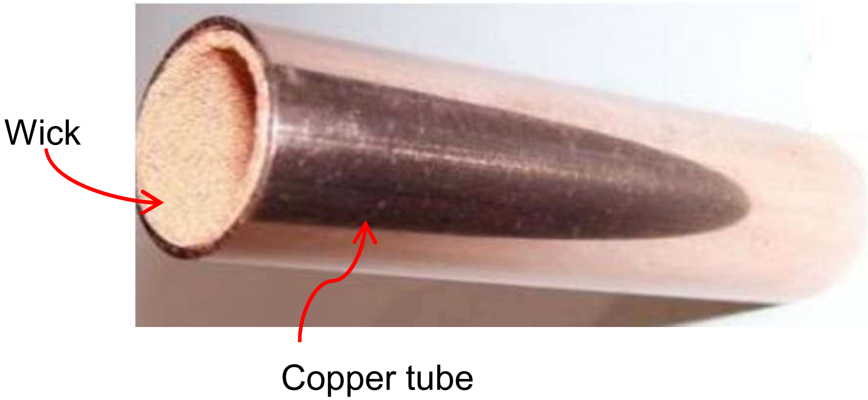


(Source: Basic Principles of Heat Pipes and History, In book: Heat Pipe Design and Technology (pp.1-41) http://dx.doi.org/10.1007/978-3-319-29841-2_1)

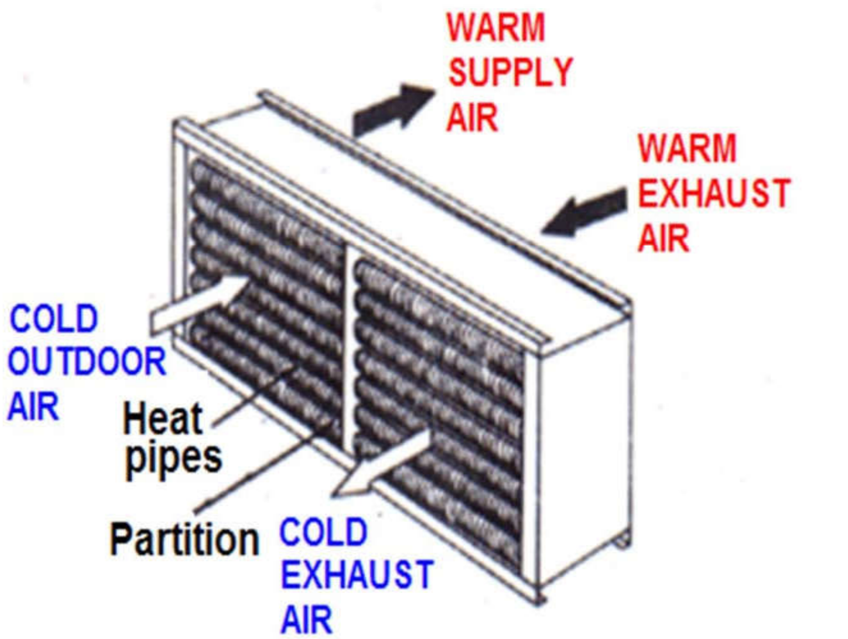
Heat pipe (sensible heat)





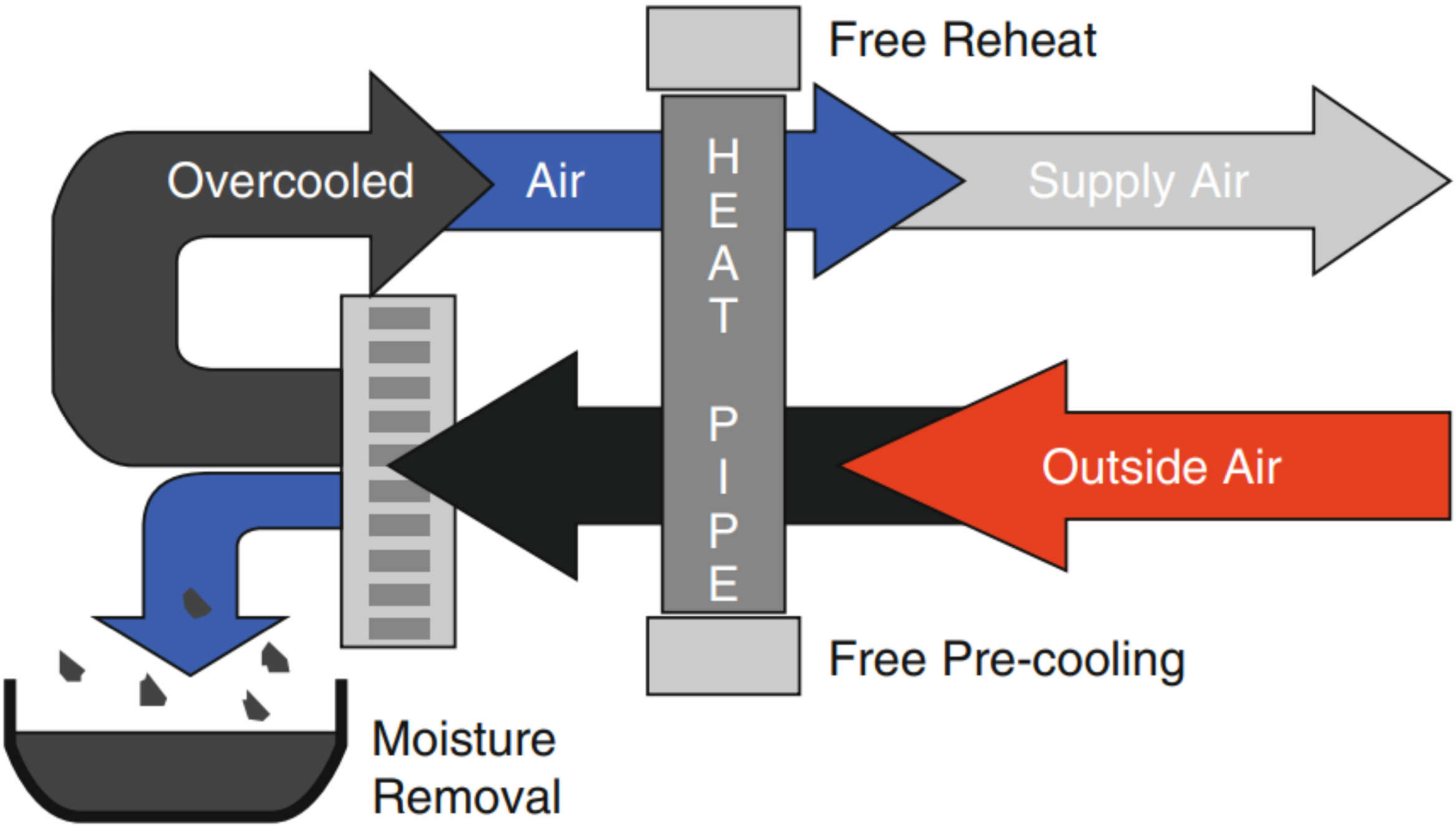


Heat is transferred from the hot incoming gas to the evaporator section of the heat pipe. The local vapour pressure of the evaporator section increases and evaporated fluid moves along the pipe to the condenser section. As the condenser section's temperature is low due to the cold air passing around it, the migrated vapour condenses and the heat is released to the cold air. The liquid then returns to the evaporator section by a combination of capillary action and gravity.



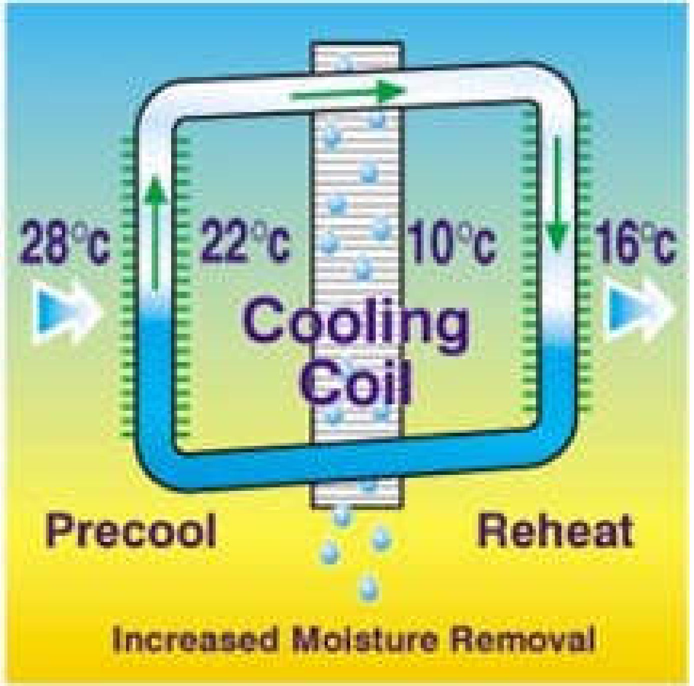
Heat pipe array intalled between two airstreams

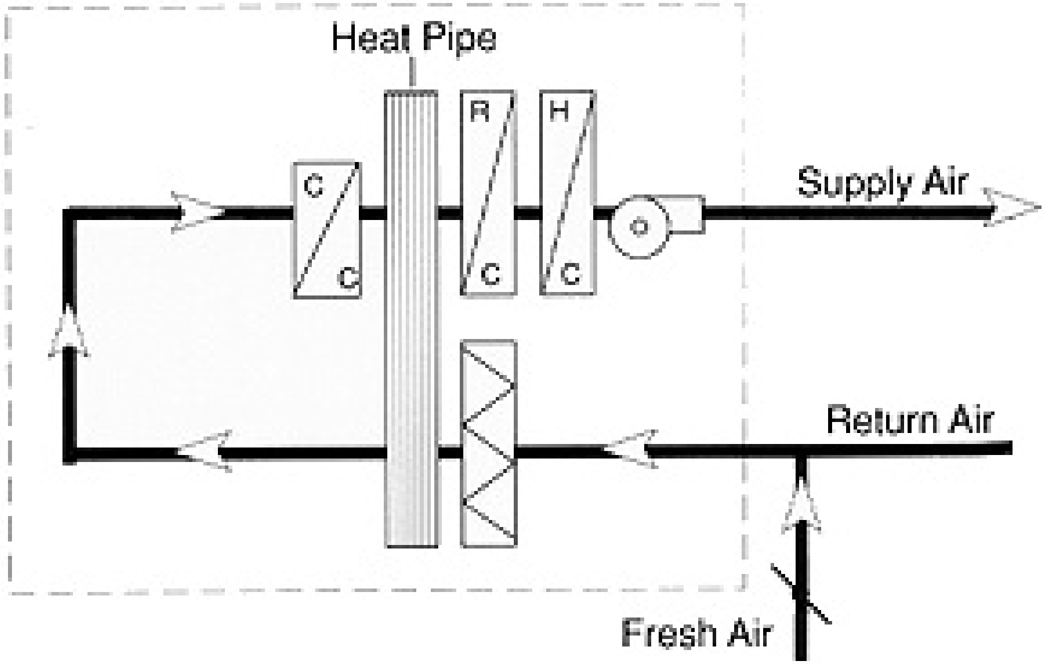
Heat pipe application concept for HVAC systems



(Source: Basic Principles of Heat Pipes and History, In book: Heat Pipe Design and Technology (pp.1-41) http://dx.doi.org/10.1007/978-3-319-29841-2_1)

Heat pipe's free pre-cool and pre-heat principle





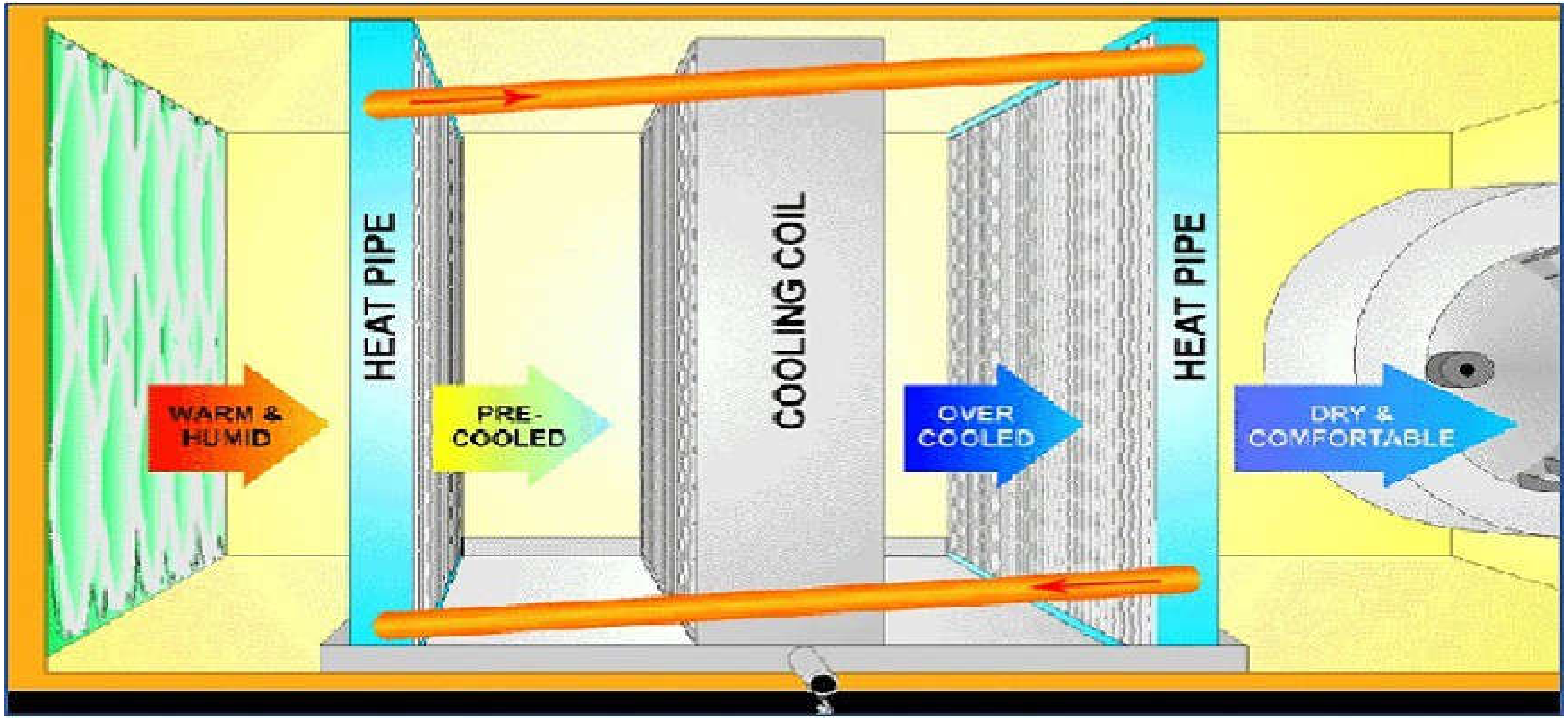
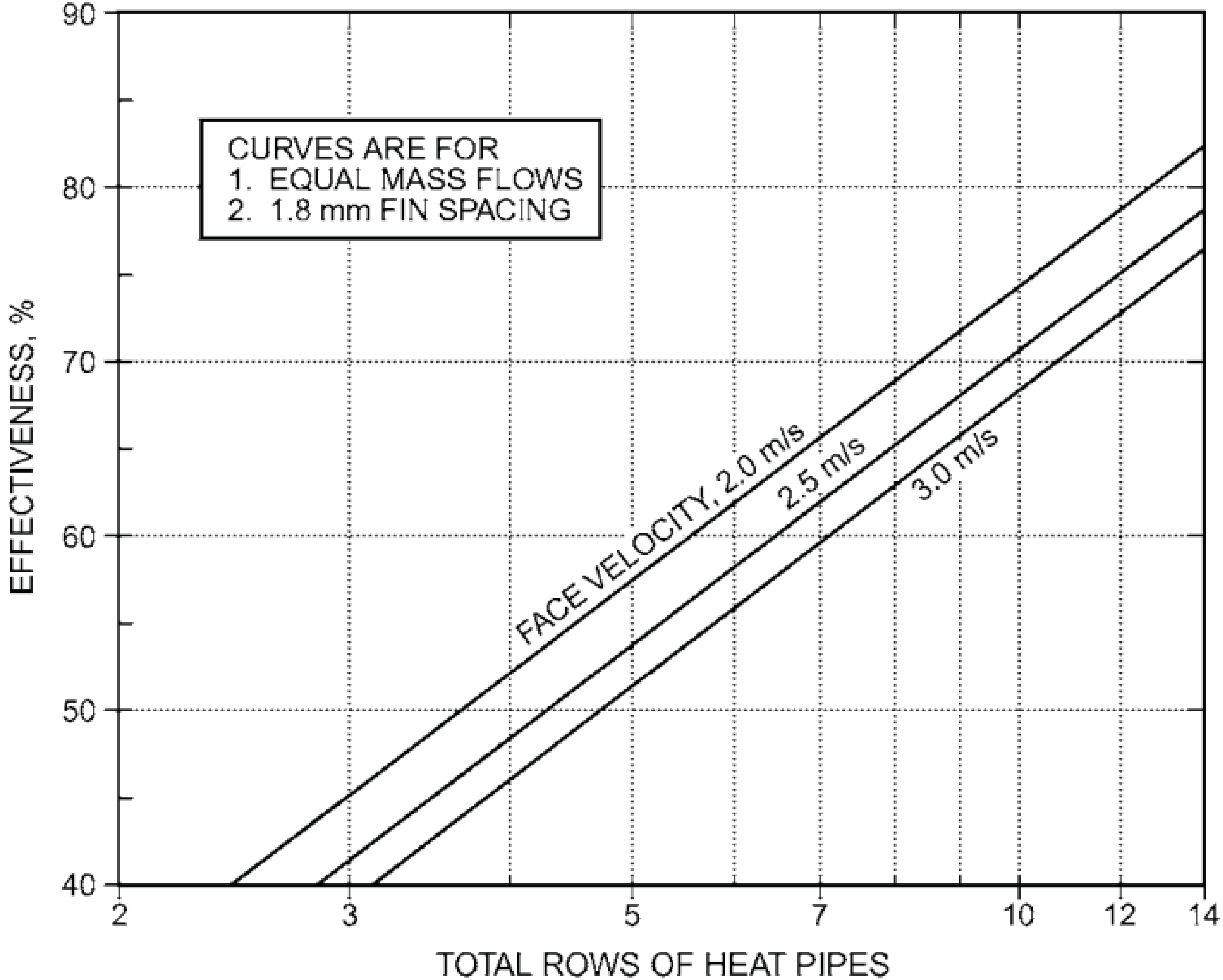


Figure 2. Heat pipe exchanger effectiveness



(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 26 – Air-to-Air Energy Recovery Equipment)

Example. Sensible Heat Energy Recovery in a Heat Pipe

Outdoor air at 10°C enters a six-row heat pipe with a flow rate of 5 kg/s and a face velocity of 2.5 m/s. Exhaust air enters the heat pipe with the same velocity and flow rate but at 24°C. The pressure drop across the heat pipe is 150 Pa. The supply air density is 1.35 kg/m^3. The efficiency of the electric motor and the connected fan are 90 and 75%, respectively. Assuming the performance characteristics of the heat pipe are as shown in Figure 2, determine the sensible effectiveness, exit temperature of supply air to the space, energy recovered, and power supplied to the fan motor.

Solution:

From Figure 2, at face velocity of 2.5 m/s and with six rows, the effectiveness is about **58%**. Because the mass flow rate of the airstreams is the same and assuming their specific heat of 1 kJ/(kg K) is the same, then the exit temperature of the supply air to the space can be obtained from $t_2 = t_1 - \varepsilon_s \dfrac{C_{min}}{m_s c_{ps}}(t_1 - t_3)$

t_2 = 10 – 0.58 [5 kg/s x 1 kJ/(kg K)]/[5 kg/s x 1 kJ/(kg K)] (10 – 24) = **18.12°C**

The sensible energy recovered can be obtained from $q_s = 60 m_s c_{ps}(t_2 - t_1) = Q_s \rho_s c_{ps}(t_2 - t_1)$

q_s = (5 kg/s)[1 kJ/(kg K)](18.12 – 10) = **40.6 kW**

The supply air fan power can be obtained from $P_s = Q_s \Delta p_s / \eta_f$

P_s = (150 Pa) /[(0.9)(0.75)] = 823 W or 0.823 kW

Because there are two airstreams, neglecting the difference in the air densities of the airstreams, the total pumping power of the heat pipe is twice the above value (i.e., **1.65 kW**).

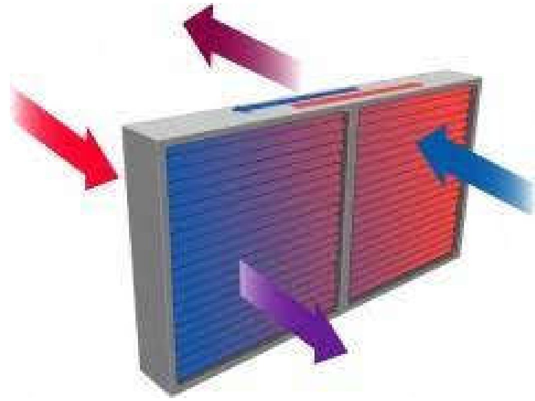
(Source: 2016 ASHRAE Handbook—HVAC Systems and Equipment, Chapter 26 – Air-to-Air Energy Recovery Equipment)

Air-to-air energy recovery

- Major merits of heat pipe:
  - Passive operation: No energy input is required
  - Long life: No moving parts and no wear out
  - Isolated air streams: By dividing plates, assuring an excellent seal to prevent cross contamination
  - Minimum maintenance: Only maintenance recommended is periodic cleaning
  - Summer and winter: The same heat pipe can be used for both summer cooling and winter heat recovery without any changeover mechanism

Air-to-air energy recovery

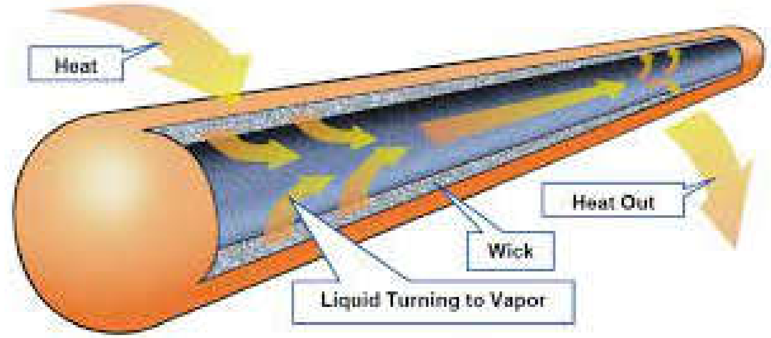
- Heat pipe (cont'd)
  - Advantages:



    - Robust construction. No moving parts
    - Relatively high-pressure difference between airstreams is possible, limited by baffle separating plate
    - Little or no possibility of cross-contamination of air streams (airtight construction is required)
    - Relatively high heat transfer rate
    - May be designed for easy removal and cleaning
    - The number of heat pipe rows can be selected to suit the required heat transfer rate

Air-to-air energy recovery

- Heat pipe (cont'd)
  - Disadvantages:

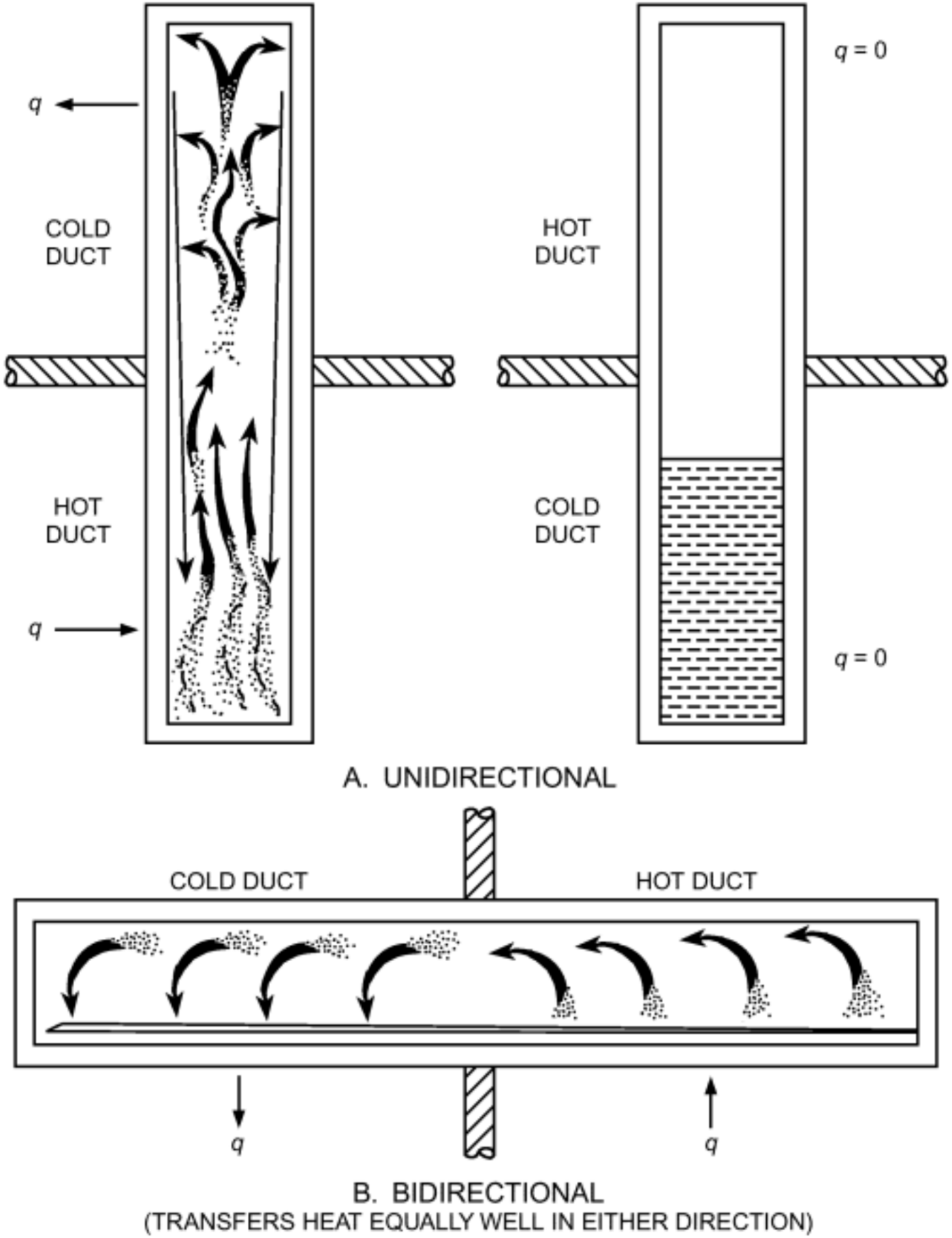


    - Relatively high capital cost
    - Sensible heat transfer only (except when condensation occurs on heat pipe surfaces in warmer air stream)
    - By-pass duct needed in summer to avoid overheating fresh air (in systems without air cooling). Control by tilt mechanism may be too expensive to justify

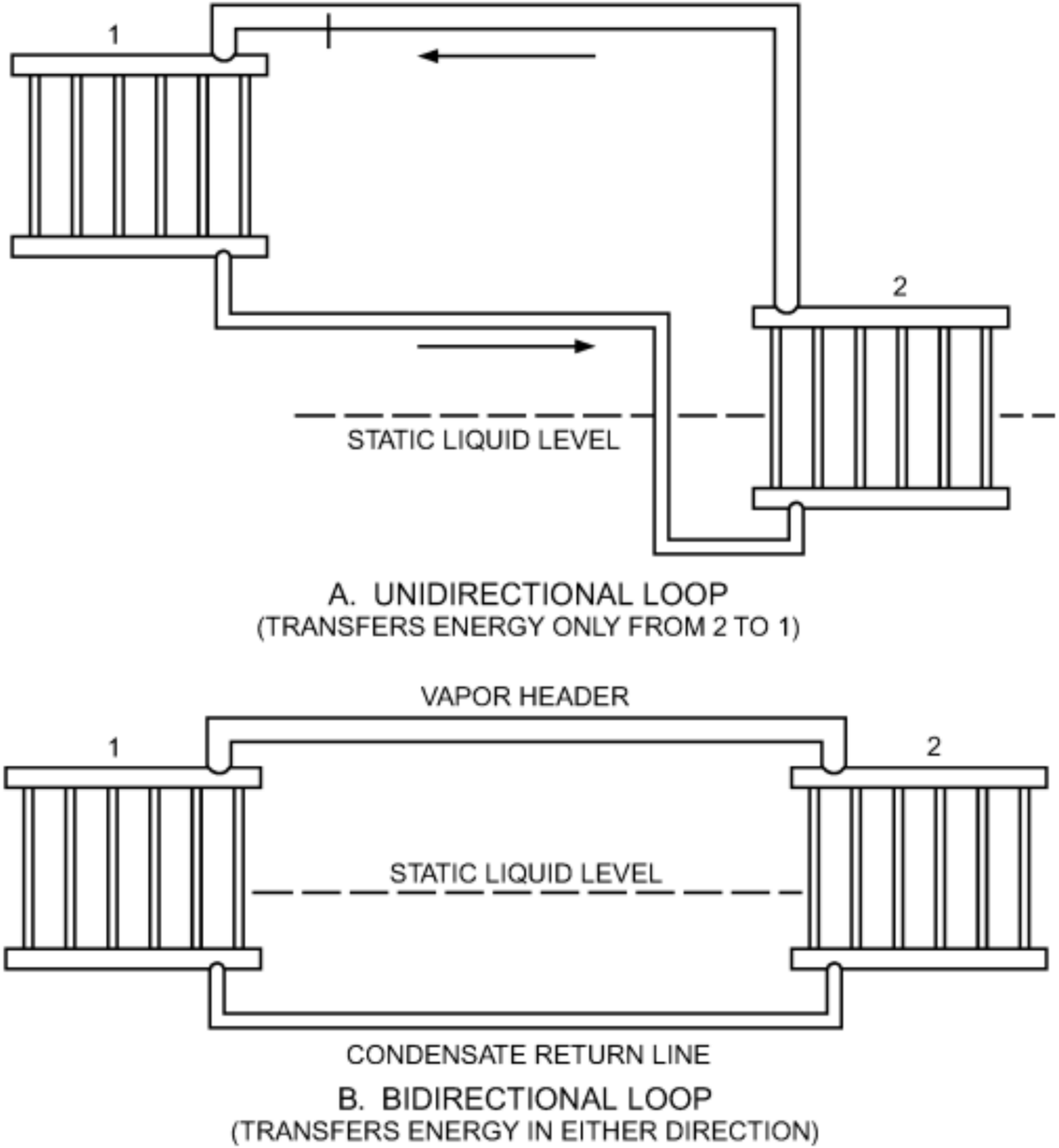
Air-to-air energy recovery

- Two-phase thermosiphon heat exchangers
  - 1. Sealed-tube thermosiphon: the evaporator and the condenser are usually at opposite ends of a bundle of straight, individual thermosiphon tubes, and the exhaust and supply ducts are adjacent to each other (similar to a heat pipe system)
  - 2. Coil-type thermosiphons: evaporator and condenser coils are installed independently in the ducts and are interconnected by the working fluid piping (similar to a coil energy recovery loop)

Sealed-Tube Thermosiphons



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



Coil-type thermosiphon loops

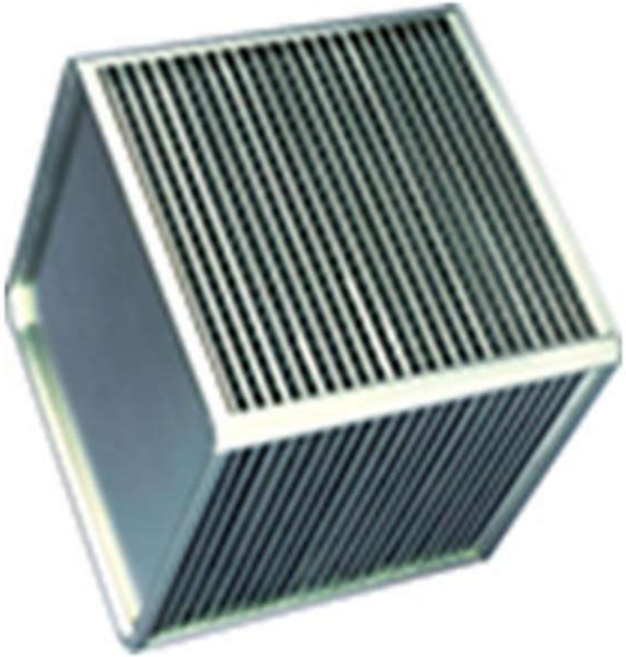
(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, SI edition, Chp. 9 Applied Heat Pump and Heat Recovery Systems)

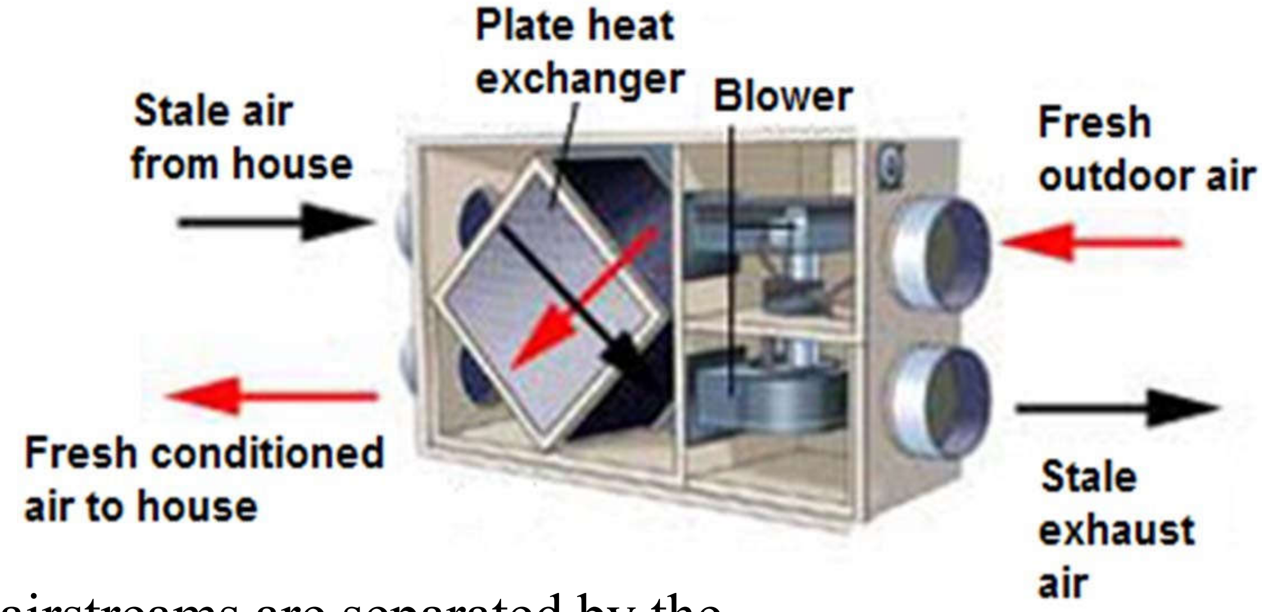
Air-to-air energy recovery

- Plate heat exchanger (mainly sensible heat)
  - Two airstreams are separated by metal plates, which are usually augmented with fins
  - Warm exhaust air heats a fixed plate, which, in turn, heats the incoming cool outdoor air on the other side of the plate
  - The effectiveness is a function of plate gaps and lengths, and air flow rate
  - A minimum effectiveness is 50%

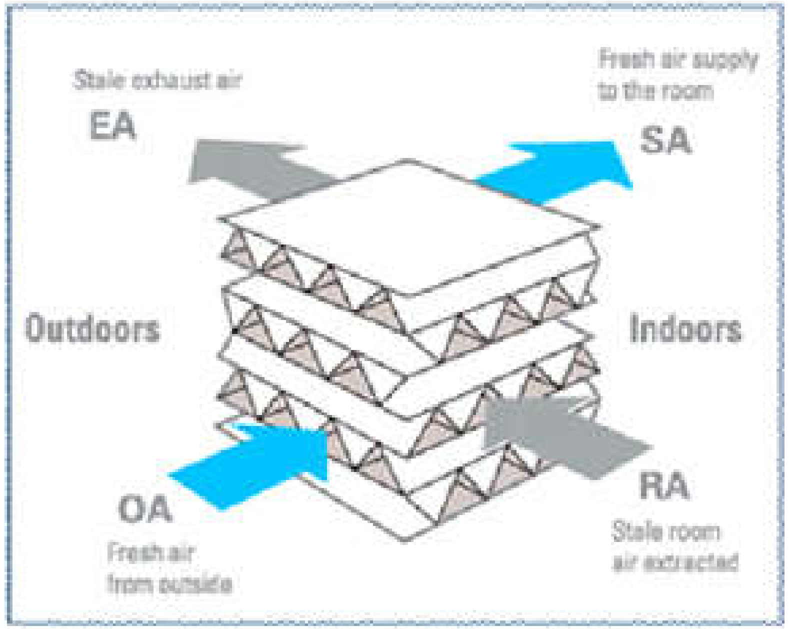
(See also: Module 49: Saving energy through simple HVAC heat recovery http://www.cibsejournal.com/cpd/modules/2013-02/)

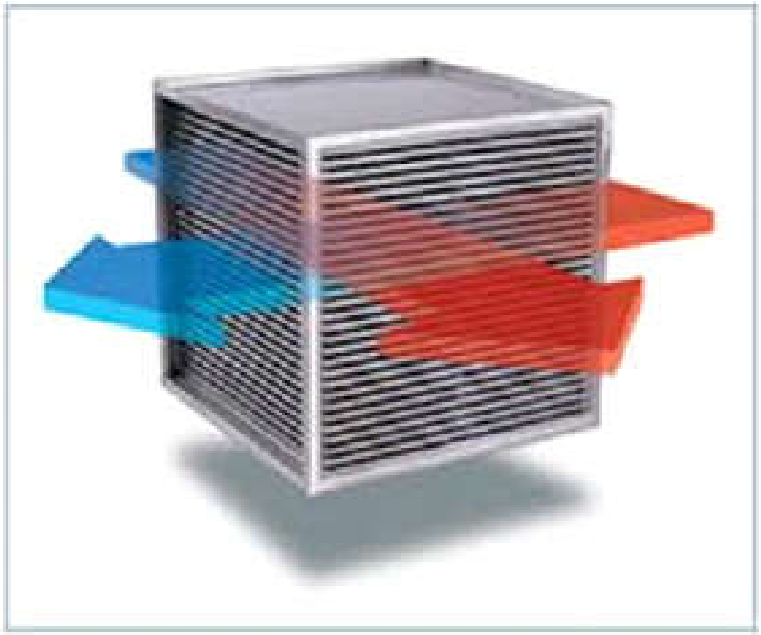
Plate heat exchanger (sensible heat)



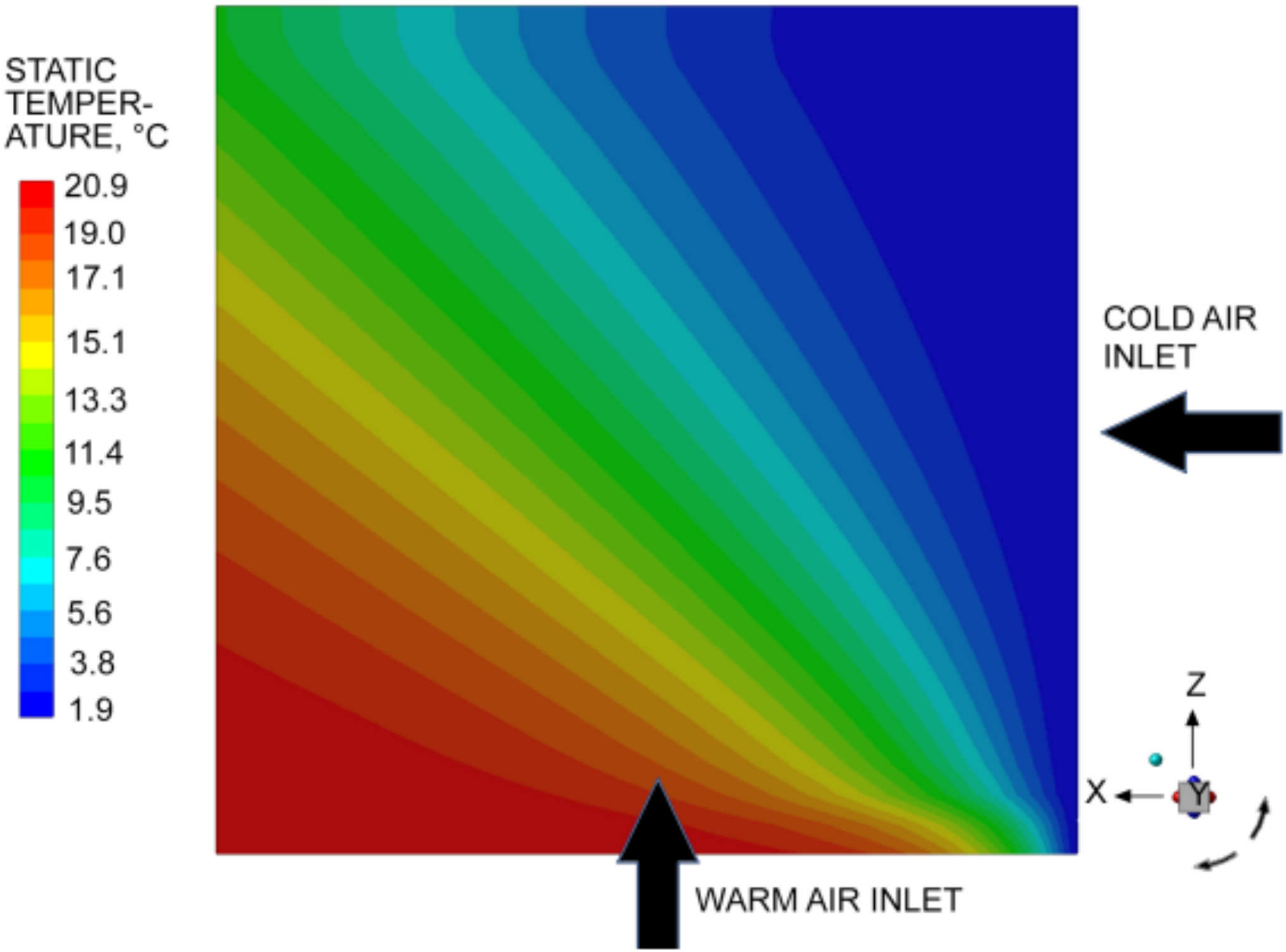


Two airstreams are separated by the plates to ensure no cross contamination.



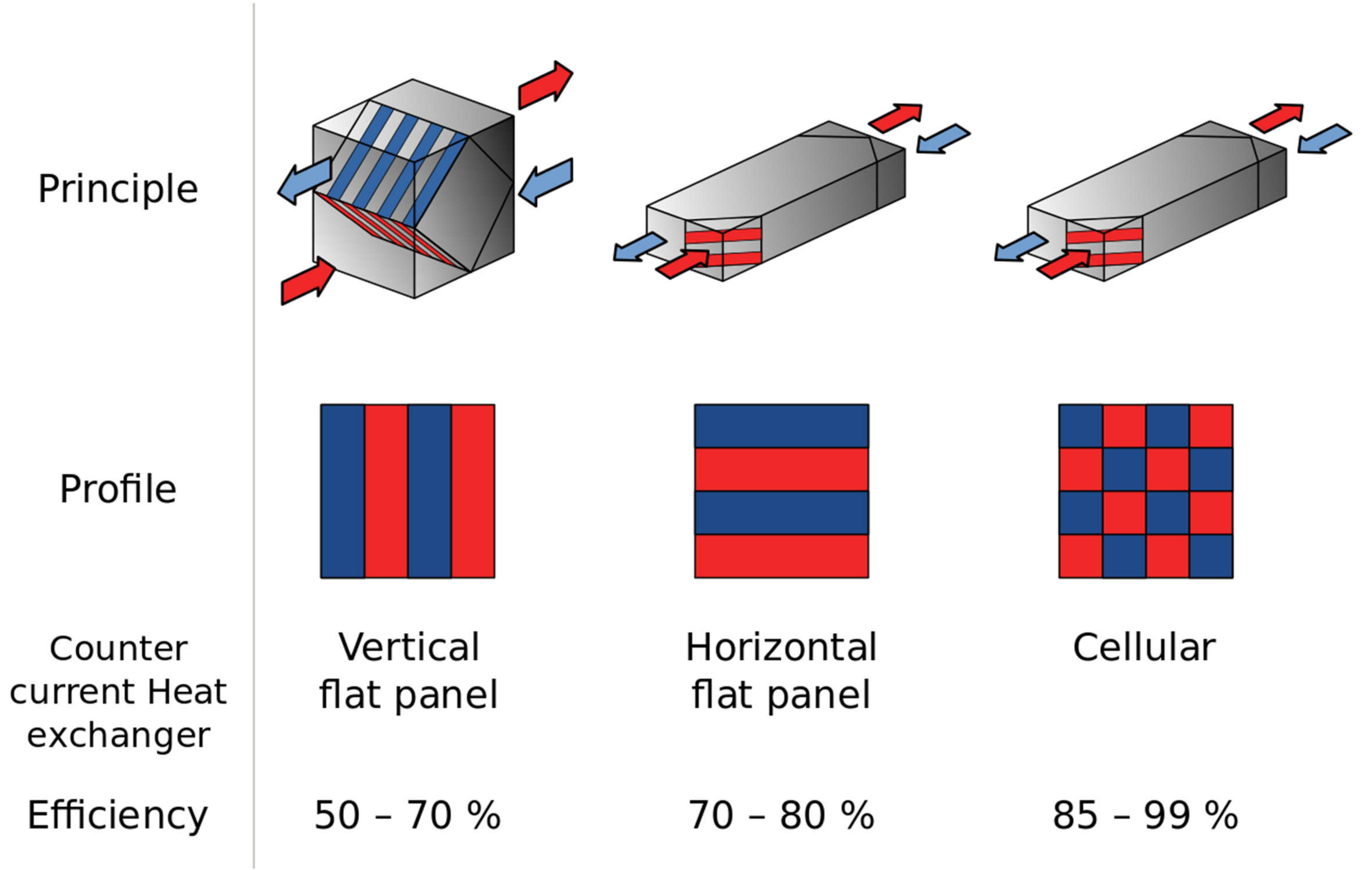


Temperature stratification at outlets of cross-flow heat exchanger



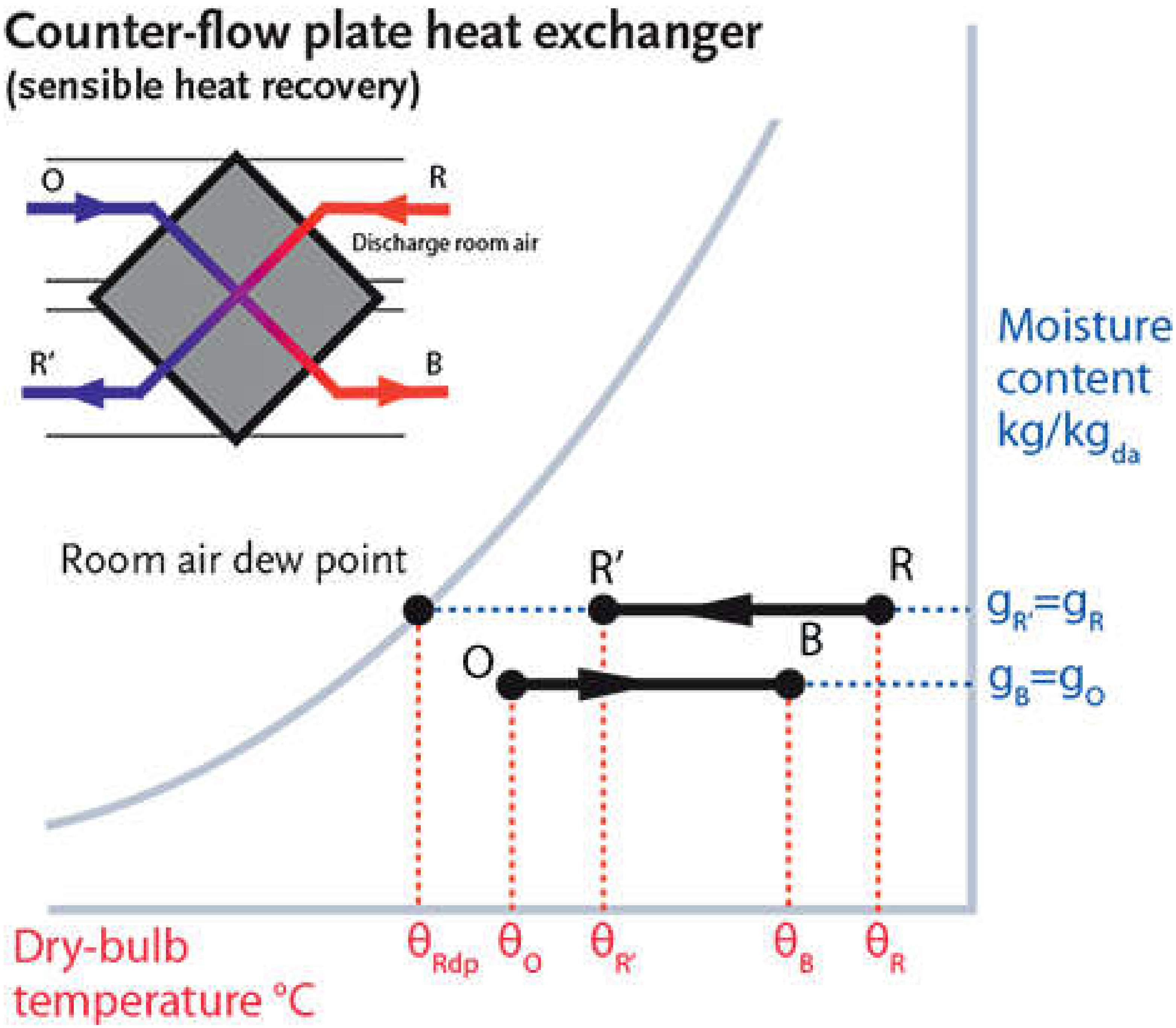
(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, Chapter 26. Air-to-Air Energy Recovery Equipment)

Different design of plate heat exchangers



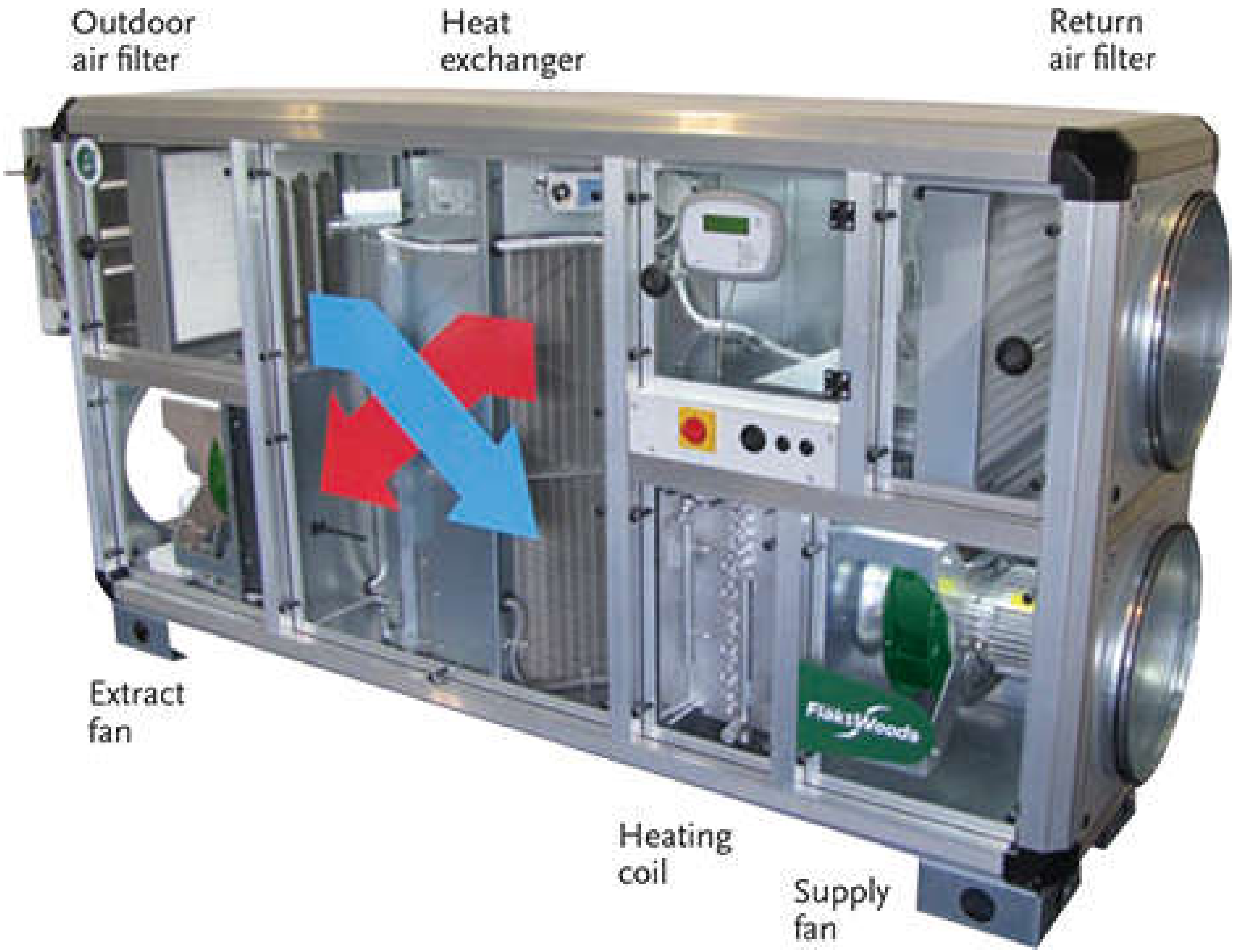
(Source: Energy recovery ventilation - Wikipedia http://en.wikipedia.org/wiki/Energy_recovery_ventilation)

Psychrometry of cross-flow plate heat exchanger



(Source: Module 49: Saving energy through simple HVAC heat recovery http://www.cibsejournal.com/cpd/modules/2013-02/)

Plate heat exchanger with condensation in the discharging room air



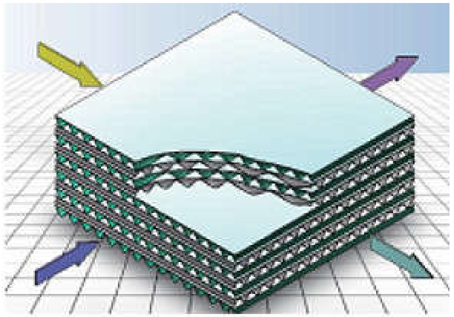
(Source: Module 49: Saving energy through simple HVAC heat recovery http://www.cibsejournal.com/cpd/modules/2013-02/)

Air-to-air energy recovery

- Plate heat exchanger (cont'd)
  - Advantages:
    - No moving parts
    - Little or no possibility of cross-contamination of air streams (airtight construction is required)
    - Materials and spacings can selected to suit applications
    - Easily cleaned when withdrawn from the duct
    - Some media types permit latent heat transfer by using a permeable membrane

Air-to-air energy recovery

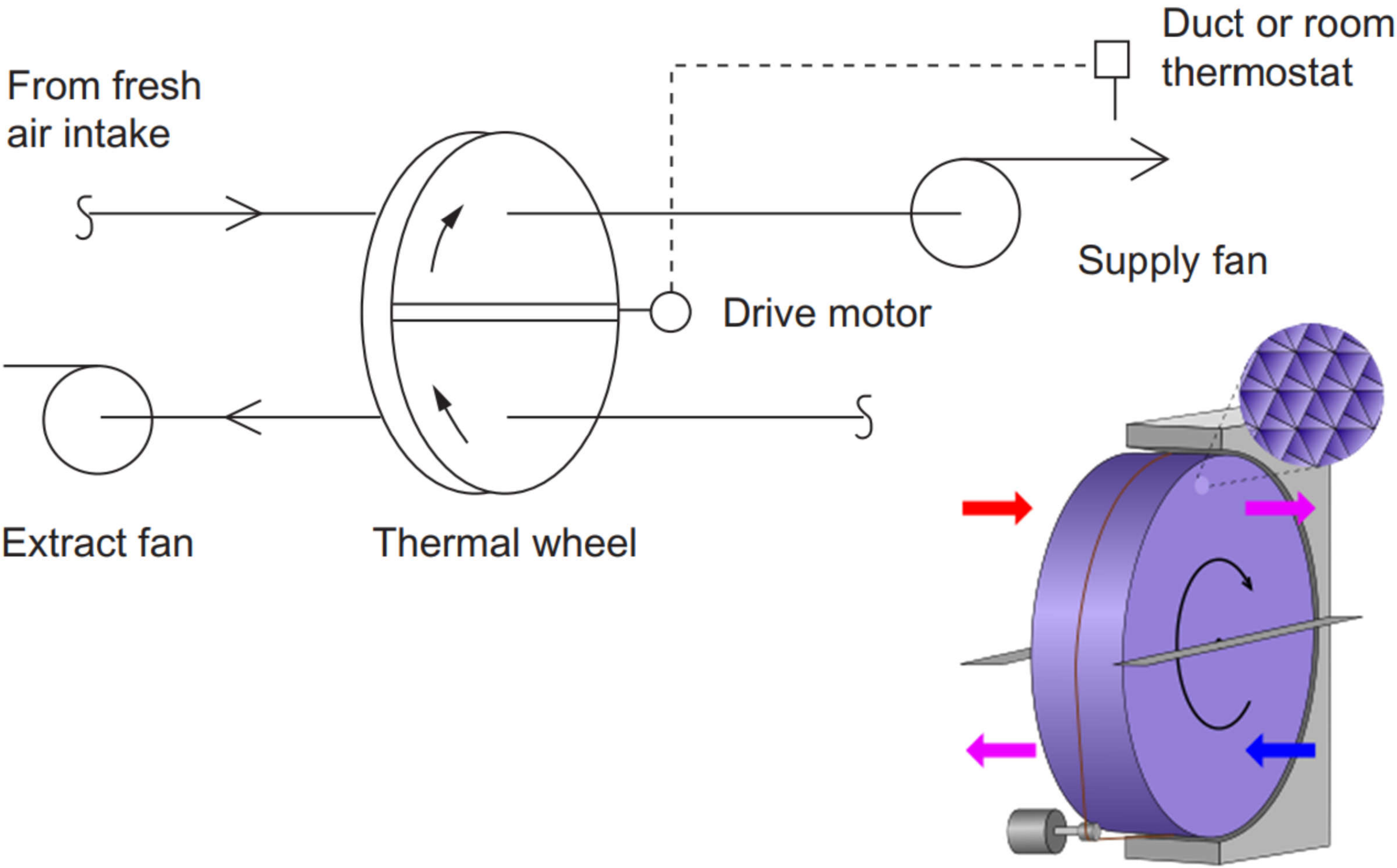
- Plate heat exchanger (cont'd)
  - Disadvantages:
    - Static pressure between fresh air and exhaust air is limited, depending on construction
    - A bypass may be needed to avoid over-heating fresh air in summer and to reduce power when recovery is not needed
    - Care in filtration is required to avoid fouling of surfaces



Air-to-air energy recovery

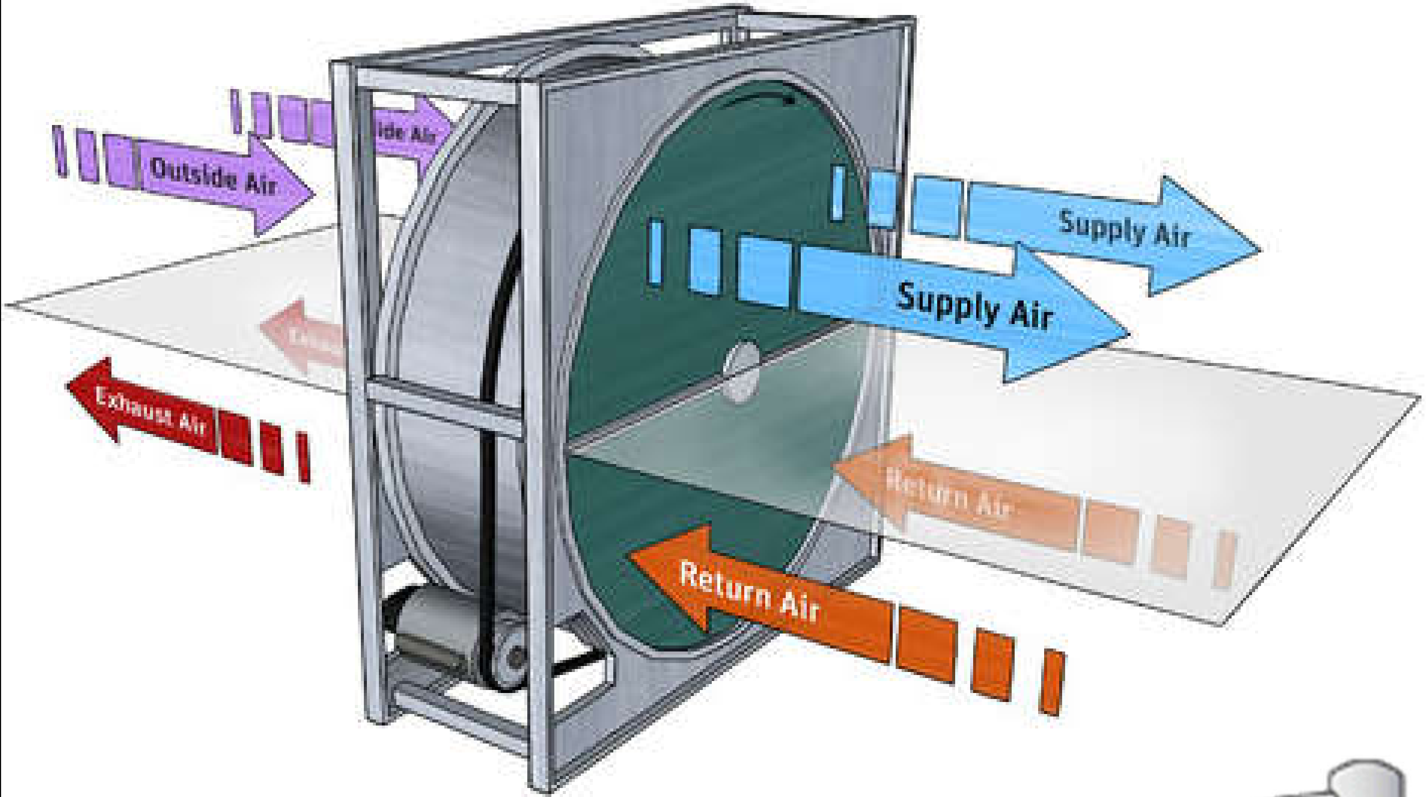
- Energy transfer wheel (or thermal wheel)
  - A rotating wheel which allows sensible and/or latent heat transfer between the incoming outdoor air and exhaust air in an HVAC system
    - The air duct connections are arranged so that each of the airstreams flow axially through approximately one half of the wheel in a counter-flow pattern
    - The range of heat recovery effectiveness is 70% to 80%
    - Cross leakage through the energy recovery wheels ranges from 2% to 5% between the supply and exhaust air streams

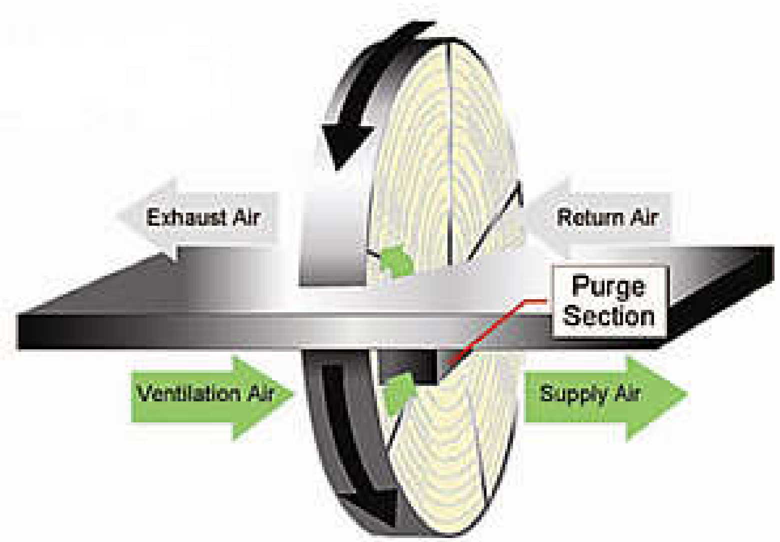
Schematic of thermal wheel in the HVAC system

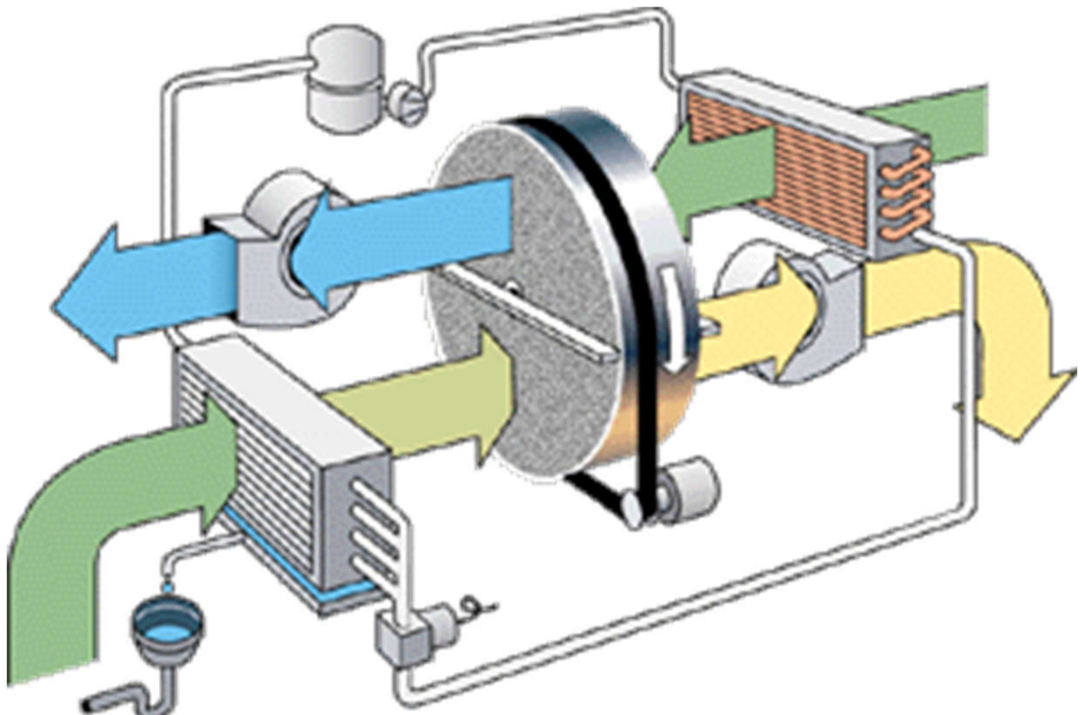


(Source: Legg R., 2017. *Air Conditioning System Design*, Elsevier Science & Technology, Oxford. & Thermal wheel - Wikipedia http://en.wikipedia.org/wiki/Thermal_wheel)

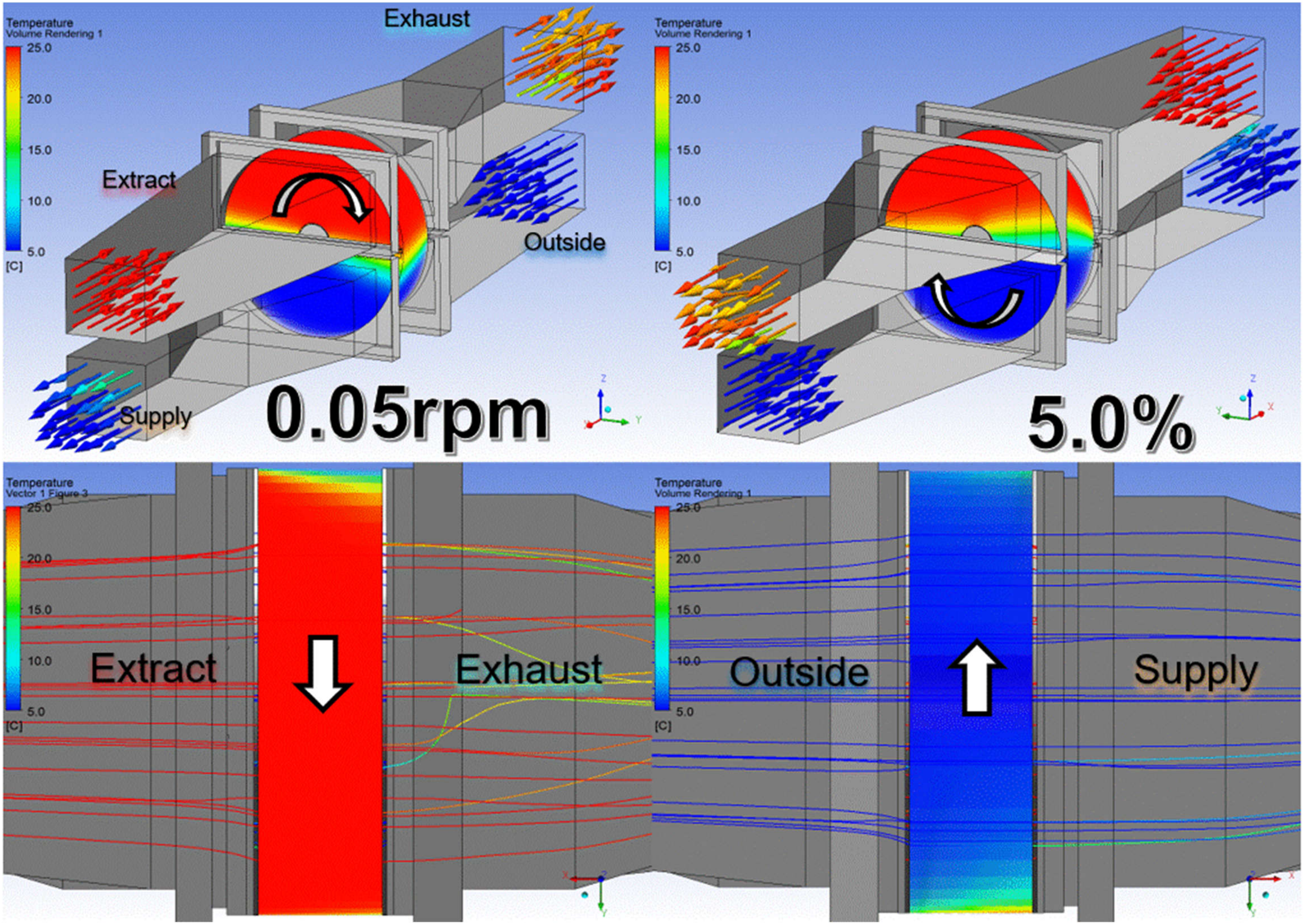
Energy transfer wheel (sensible and/or latent)





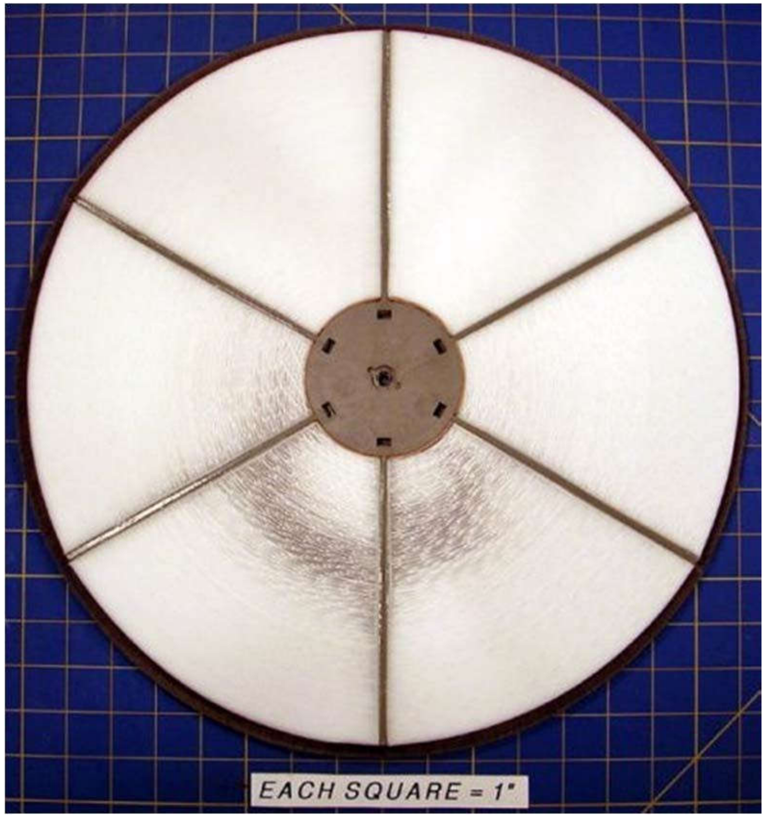


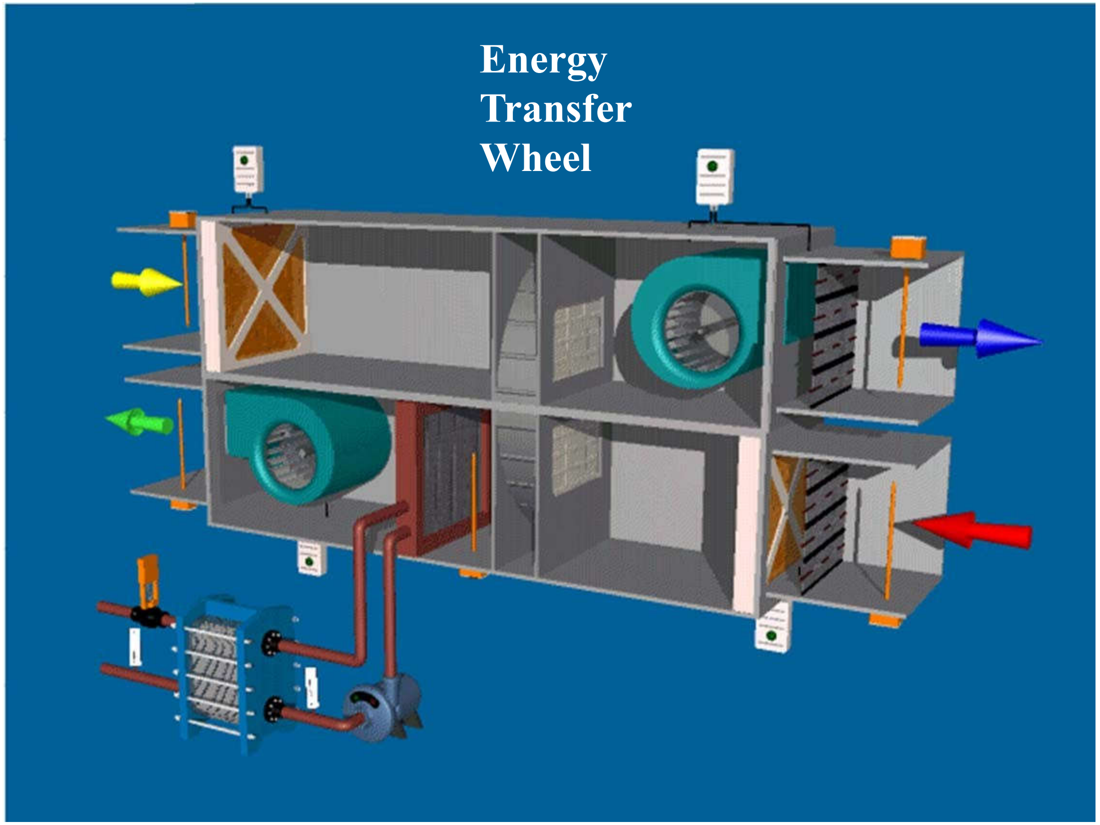
Temperature distribution inside a thermal wheel energy recovery device



(Source: https://swegonnorthamerica.com/learn/hvac-technology/air-to-air-energy-recovery/)

Energy transfer wheel (sensible and/or latent)

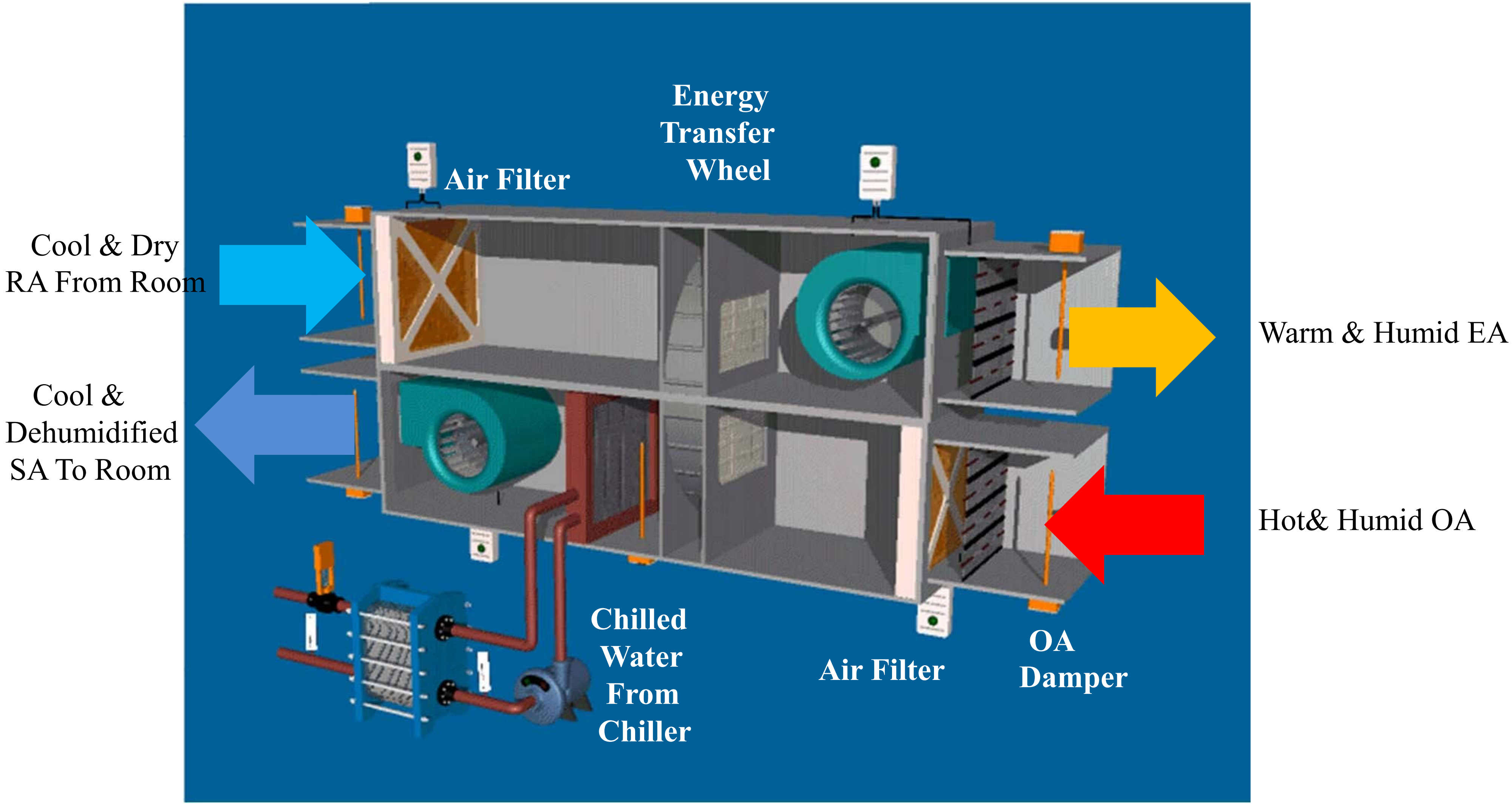




Sensible Wheel - This wheel is not coated with a desiccant and therefore transfers only sensible heat. The wheel can be constructed of almost any material (paper, metal or plastic) and transfers energy between two air streams as the mass of the material gains or loses heat to the opposite air stream. The wheel rotates at a speed of 25 to 50 revolutions per minute.

Enthalpy Wheel - It is similar to the sensible wheel except that a desiccant material such as silica gel is coated to the wheel's surface. As the wheel rotates, it can transfer latent heat (moisture) as well as sensible heat simultaneously.

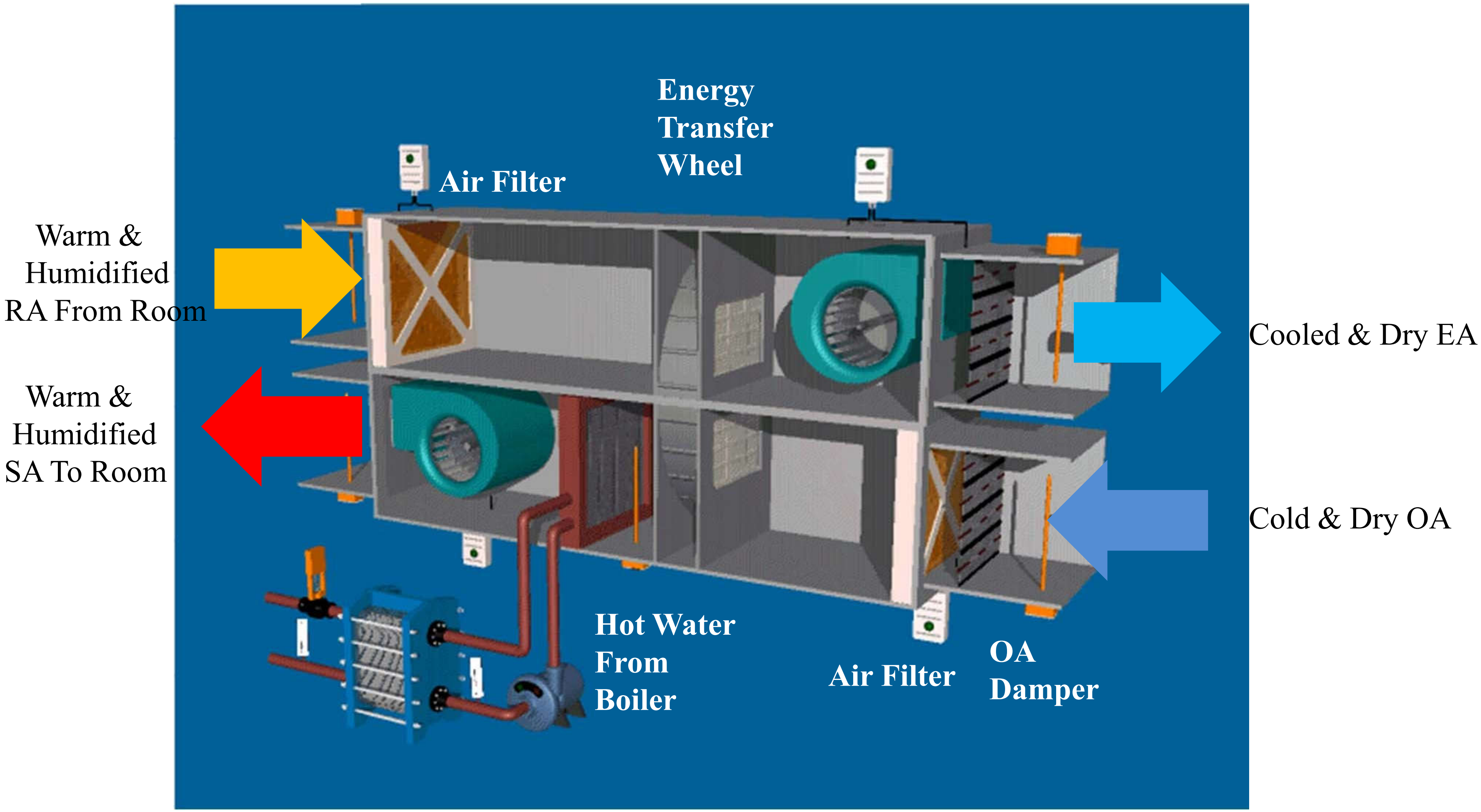
Energy transfer wheel (sensible and/or latent)
Pre- cooling and dehumidification of outdoor air (OA) in summer



RA: Return Air　　EA: Exhaust Air

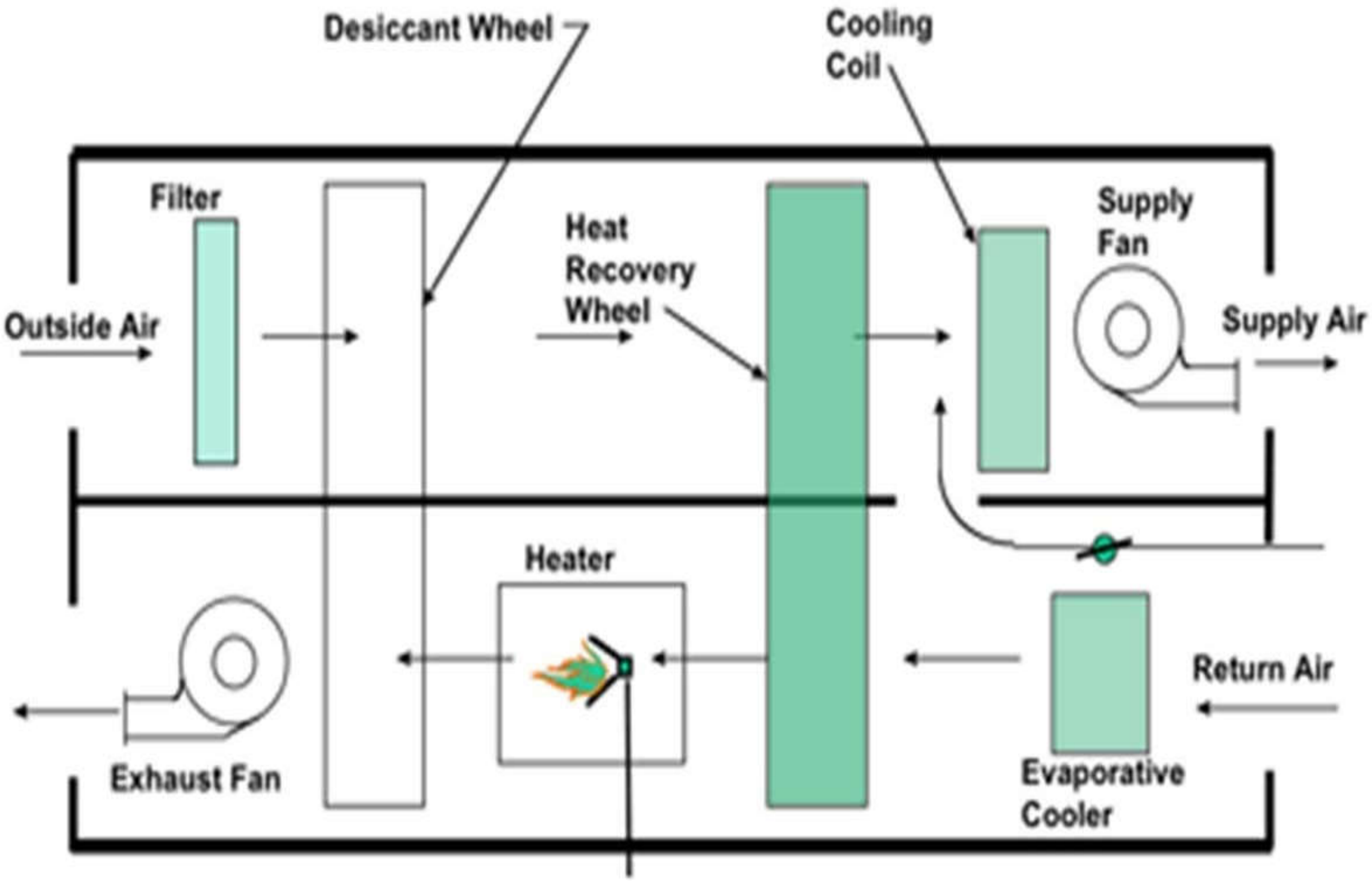
SA: Supply Air　　OA: Outdoor Air

Energy transfer wheel (sensible and/or latent)
Pre- heating and humidification of outdoor air (OA) in winter



RA: Return Air EA: Exhaust Air
SA: Supply Air OA: Outdoor Air

Desiccant cooling and heat recovery wheel



The wheel rotates slowly, typically at about 20 rpm.

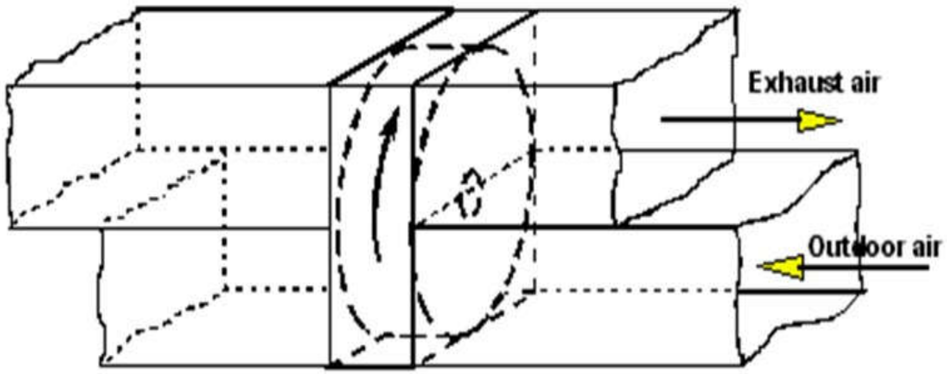
Gas is used as a fuel for cooling system (absorption chiller).

Desiccant wheel is used for dehumidification.

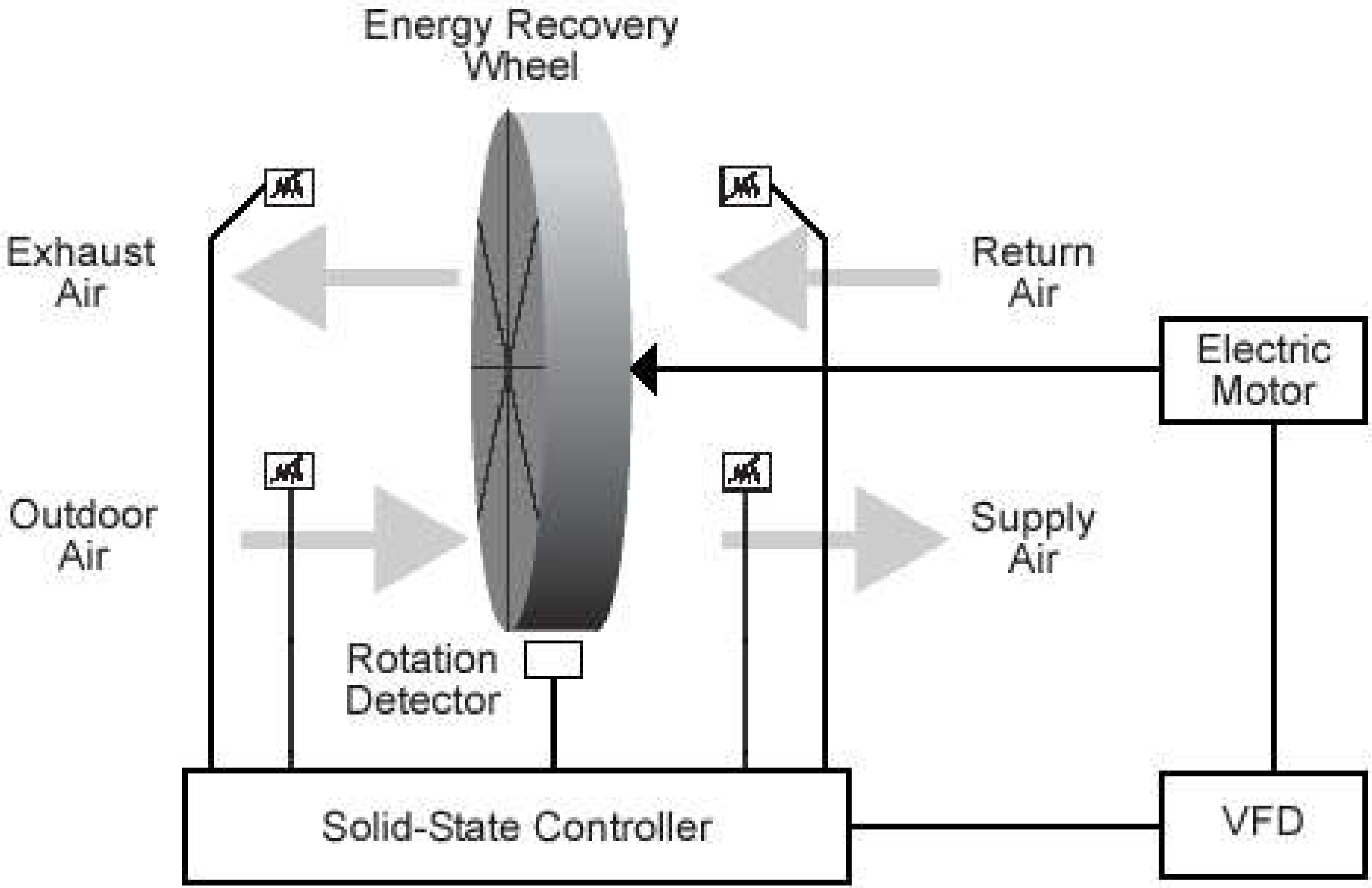
– Absorbs humidity from outside air in the first air stream.

– Desiccant wheel is dried out by a heater.

Cooling coil is used to reduce temperature.



Control of energy recovery wheel



It is monitored by a rotation detector which determines the angular velocity of the core. This sensor, along with air temperature sensors installed on either side of the wheel in both air streams, feed back to a solid-state controller which instructs a variable frequency drive (VFD) connected to the wheel motor. This VFD commands the motor to speeds between ¼ and 20 rpm to most efficiently transfer total energy between the air streams.

Air-to-air energy recovery

- Energy transfer wheel (cont'd)
  - Advantages:
    - Some wheels can transfer both sensible and latent heat
    - Relatively high heat-transfer efficiency (~70%), compared to other air-to-air heat recovery devices
    - Low energy consumption of the electric motor rotating the wheel
    - Matrix material and density can suit a wide range of applications
    - Can be used for either heating or cooling applications

Air-to-air energy recovery

- Energy transfer wheel (cont'd)
  - Disadvantages:
    - Regular air filter maintenance and replacement is essential as the wheel is difficult to clean
    - Static pressure in the fresh air stream must be higher than that in the exhaust air stream to limit cross-contamination and for successful purge operation
    - Large ratio of surface area to volume of matrix material make it susceptible to corrosion
    - Internal leakage can be an issue but should be limited to less than 5% in high quality units

Comparison of air-to-air energy recovery devices

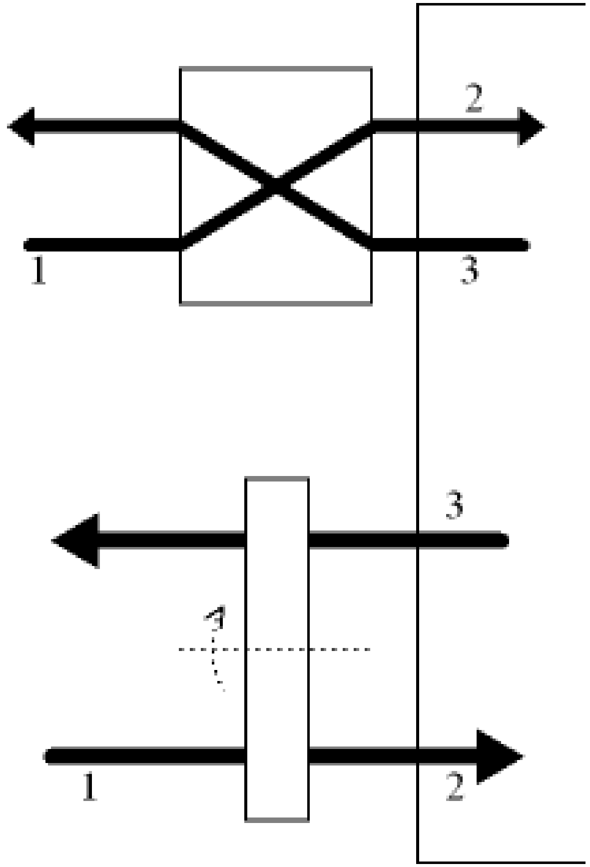
	Fixed Plate	Membrane Plate	Energy Wheel	Heat Wheel	Heat Pipe	Runaround Coil Loop	Thermosiphon
Airflow arrangements	Counterflow Cross flow[a]	Counterflow Cross flow[a]	Counterflow Parallel flow	Counterflow	Counterflow Parallel flow	—	Counterflow Parallel flow
Equipment size range, L/s	25 and up	25 and up	25 to 35 000 and up	25 to 35 000 and up	50 and up	50 and up	50 and up
Typical sensible effectiveness ($m_s = m_e$), %[c]	50 to 75	55 to 75	65 to 80	65 to 80	40 to 60[b]	45 to 65[b]	40 to 60
Typical latent effectiveness,* %[c]	0	25 to 60	50 to 80	0	0	0	0
Total effectiveness,* %[c]	20 to 50	35 to 70	55 to 80	25 to 60	15 to 35	—	—
Face velocity, m/s	1 to 5	1 to 3	2.5 to 5	2 to 5	2 to 4	1.5 to 3	2 to 4
Pressure drop, Pa	100 to 1000	100 to 500	100 to 300	100 to 300	150 to 500	150 to 500	150 to 500
EATR, %	0 to 2	0 to 5	0.5 to 10	0.5 to 10	0 to 1	0	0
OACF	0.97 to 1.06	0.97 to 1.06	0.99 to 1.1	1 to 1.2	0.99 to 1.01	1.0	1.0
Temperature range, °C	–60 to 800	–40 to 60	–55 to 800	–55 to 800	–40 to 93	–45 to 500	–40 to 40

Parameters of air leakage:
EATR = exhaust air transfer ratio
OACF = outdoor air correction factor

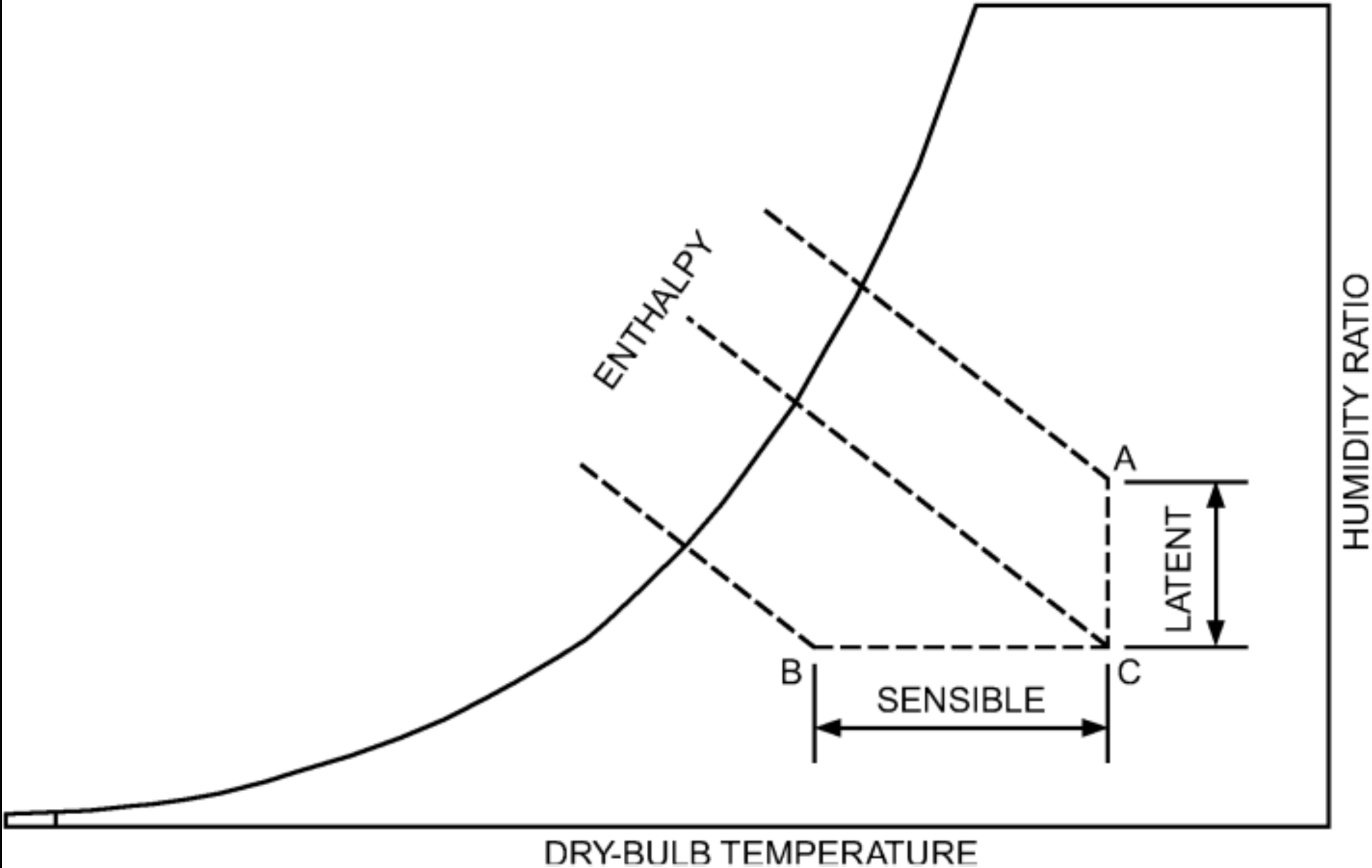
(Source: ASHRAE, 2020. *ASHRAE HVAC Systems and Equipment Handbook 2020*, Chapter 26. Air-to-Air Energy Recovery Equipment)

Design considerations

- Major factors on air-to-air energy recovery:
  - Air leakage (and carryover)
  - Air capacity of ventilator fans
  - Pressure drop & filtration
  - Maintenance (cleaning frequency)
  - Controls
  - Fouling & corrosion
  - Condensation & moisture recovery
  - Freeze-up (frost prevention)



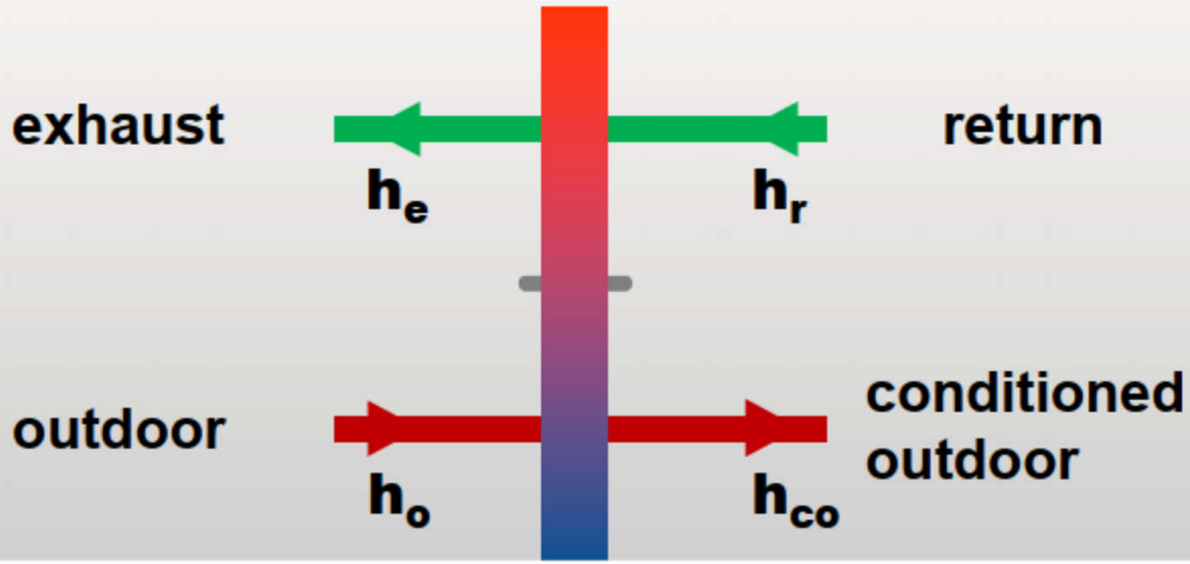
Maximum sensible and latent heat from process A-B (on a psychrometric chart)



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

Energy recovery effectiveness (ERE) for exhaust-air energy recovery

$$\text{ERE} = \frac{(h_o - h_{co})}{(h_o - h_r)}$$

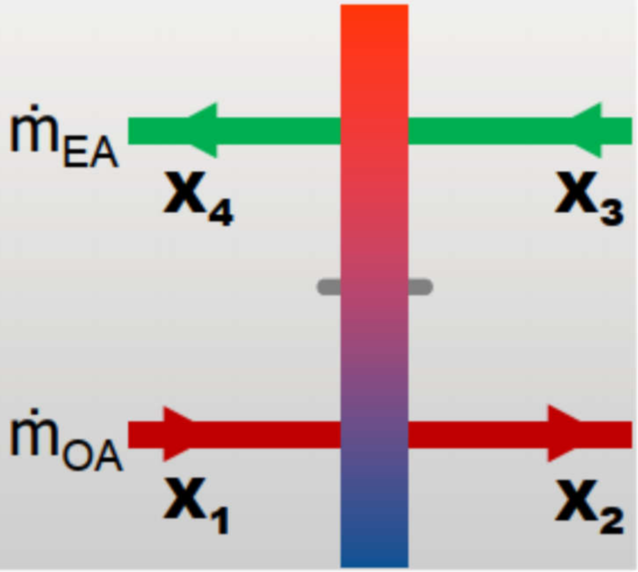


sensible effectiveness

$$\varepsilon_S = \frac{\dot{m}_{OA}}{\dot{m}_{min}} \times \frac{(T_1 - T_2)}{(T_1 - T_3)}$$

total effectiveness

$$\varepsilon_T = \frac{\dot{m}_{OA}}{\dot{m}_{min}} \times \frac{(h_1 - h_2)}{(h_1 - h_3)}$$



$\dot{m}_{min}$ = smaller of $\dot{m}_{OA}$ or $\dot{m}_{EA}$

(Source: 2012 Trane Engineers Newsletter LIVE: Air-to-Air Energy Recovery https://www.trane.com/content/dam/Trane/Commercial/global/products-systems/education-training/continuing-education-gbci-aia-pdh/Air-to-Air-Energy-Recovery/app-cmc046-en_material_vod.pdf)

Effectiveness and heat transfer for air-to-air energy recovery

Referring to Figure 1, the gross sensible effectiveness ε_s or $\varepsilon_{sensible}$ of an energy recovery ventilator is given as

$$\varepsilon_{sensible} = \frac{\dot{m}_2(c_{p,1}T_1 - c_{p,2}T_2)}{\dot{m}_{min}(c_{p,1}T_1 - c_{p,3}T_3)} \quad (2a)$$

Referring to Figure 1, the gross latent effectiveness ε_L or ε_{latent} of an energy recovery ventilator is given as

$$\varepsilon_{latent} = \frac{\dot{m}_2(h_{fg,1}W_1 - h_{fg,2}W_2)}{\dot{m}_{min}(h_{fg,1}W_1 - h_{fg,3}W_3)} \quad (2b)$$

Referring to Figure 1, the gross total effectiveness ε_T or ε_{total} of an energy recovery ventilator is given as

$$\varepsilon_{total} = \frac{\dot{m}_2(h_1 - h_2)}{\dot{m}_{min}(h_1 - h_3)} \quad (2c)$$

where

$\dot{m}_n$ = mass flow rate at station n, kg/s
$\dot{m}_{min}$ = minimum of $\dot{m}_2$ and $\dot{m}_3$, kg/s
$c_{p,n}$ = specific heat of dry air at station n, kJ/(kg·K)
h_{fg} = heat of vaporization of water, kJ/(kg·K)
T_n = dry-bulb temperature at station n, °C
W_n = humidity at station n, kg_w/kg_{da}
h_n = enthalpy at station n, kJ/kg

Note that in Equations (2a), (2b), and (2c), the denominators express the theoretical maximum sensible, latent, or total energy transfer.

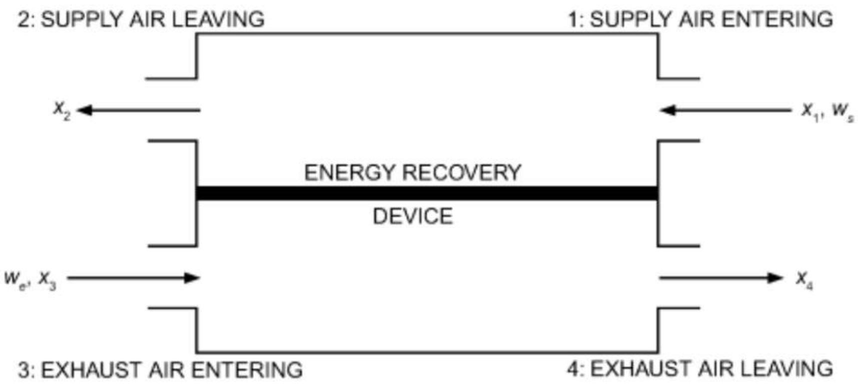


Fig. 1 Airstream Numbering Convention

The sensible heat energy transfer q_s in the energy recovery exchanger can be estimated from

$$q_s = \dot{m}_2(c_{p,1}T_1 - c_{p,2}T_2) = Q_2\rho_2(c_{p,1}T_1 - c_{p,2}T_2) \quad (5a)$$

where

q_s = sensible heat transfer, kW
c_p = specific heat of air, kJ/(kg·K)
Q_2 = volume flow rate of supply outlet air, m^3/s
ρ_2 = density of dry outlet supply air, kg/m^3
t_1, t_2, t_3 = inlet and exit temperatures of supply inlet, supply outlet, and exhaust inlet airstreams, respectively, K
$\dot{m}_2$ = mass flow rate of supply air inlet, kg/s

The latent heat transfer q_L in the energy recovery exchanger can be estimated from

$$q_L = \dot{m}_2(h_{fg,1}W_1 - h_{fg,2}W_2) = Q_2\rho_2(h_{fg,1}W_1 - h_{fg,2}W_2) \quad (5b)$$

where

q_L = latent heat transfer, kW
h_{fg} = enthalpy or heat of vaporization of water, kJ/kg
W_1, W_2, W_3 = inlet and exit humidity ratios of the supply inlet, supply outlet, and exhaust inlet airstreams, respectively, kg_w/kg_{da}

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

Example of heat transfer calculations for air-to-air energy recovery

Example 1. Inlet supply air enters an ERV with a flow rate of 4.41 m³/s at 35°C and 20% rh. Inlet exhaust air enters with a flow rate of 4.27 m³/s at 24°C and 50% rh. Assume that the energy exchanger was tested under ASHRAE *Standard* 84, which rated the sensible heat transfer effectiveness at 50% and the latent (water vapor) transfer effectiveness at 50%. With the simplifying assumptions that the specific heat of air is 1 kJ/(kg·K) and the latent heat of vaporization is 2560 kJ/kg, determine the sensible, latent, and net energy transferred in the exchanger.

Solution:

From the psychrometric chart, the properties of air at 35°C and 20% rh are

$V_1 = 0.8825$ m³/kg $h_1 = 54.2$ kJ/kg $w_1 = 0.0071$ kg/kg of dry air

and the properties of air at 24°C and 50% rh are

$V_3 = 0.854$ m³/kg $h_3 = 48$ kJ/kg $w_3 = 0.0093$ kg/kg of dry air

The mass flow rate at state 1 is obtained from

$$\{ m_1 = \frac{Q_1}{v_1} = \frac{4.41 \text{ m}^3/\text{s}}{0.8825 \text{ m}^3/\text{kg}} = 5.0 \text{ kg/s} \}$$

Similarly, the mass flow rate at state 3 is obtained from

$$m_3 = \frac{Q_3}{v_3} = \frac{4.27 \text{ m}^3/\text{s}}{0.854 \text{ m}^3/\text{kg}} = 5.0 \text{ kg/s}$$

Exit temperatures of the supply airstream can be obtained from Equation (4a):

$$t_2 = \frac{50(1)35 - 0.50(50)\{(1)35 - (1)24\}}{(50)1} = 29.5°\text{C}$$

The leaving supply air humidity is

$$W_2 = \frac{\dot{m}_2 h_{fg,1} W_1 - \varepsilon_{latent} \dot{m}_{min}(h_{fg,1} W_1 - h_{fg,1} W_3)}{\dot{m}_2 h_{fg,2}} \qquad (4c)$$

$$q_s = \dot{m}_2(c_{p,1} T_1 - c_{p,2} T_2) = Q_2 \rho_2 (c_{p,1} T_1 - c_{p,2} T_2) \qquad (5a)$$

$$q_L = \dot{m}_2(h_{fg,1} W_1 - h_{fg,2} W_2) = Q_2 \rho_2 (h_{fg,1} W_1 - h_{fg,2} W_2) \qquad (5b)$$

$$q_{total} = \dot{m}_2(h_1 - h_2) = Q_2 \rho_2 (h_1 - h_2) \qquad (5d)$$

The exit humidity of the supply airstream is found from Equation (4c):

$$w_2 = \{5.0(2560)0.0071 - 0.50(5.0)[(2560)0.0071 - (2560)0.0093]\}/[(5.0)(2560)] = 0.0080 \text{ kg}_w/\text{kg}_{da}$$

The sensible heat transfer q_s in the exchanger is found from Equation (5a):

$$q_s = 5.0(1 \times 35 - 1 \times 29.5) = 27.5 \text{ kW}$$

The latent heat transfer q_L in the exchanger is found from Equation (5b):

$$q_L = 5.0[(2560)(0.0071) - (2560)(0.0080)] = -11.52 \text{ kW}$$

The net heat energy transfer q_s in the exchanger is found from Equation (5d):

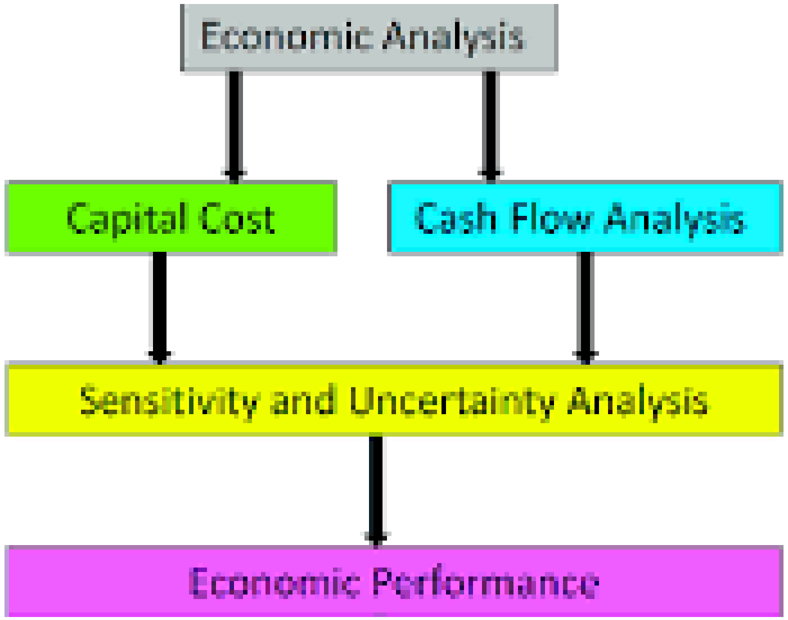
$$q = q_s + q_L = 27.5 - 11.52 = 15.98 \text{ kW}$$

If the incoming outdoor air conditions had been at 35°C and 14% rh, then the net energy gained by the exhaust airstream would have been zero.

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

Design considerations

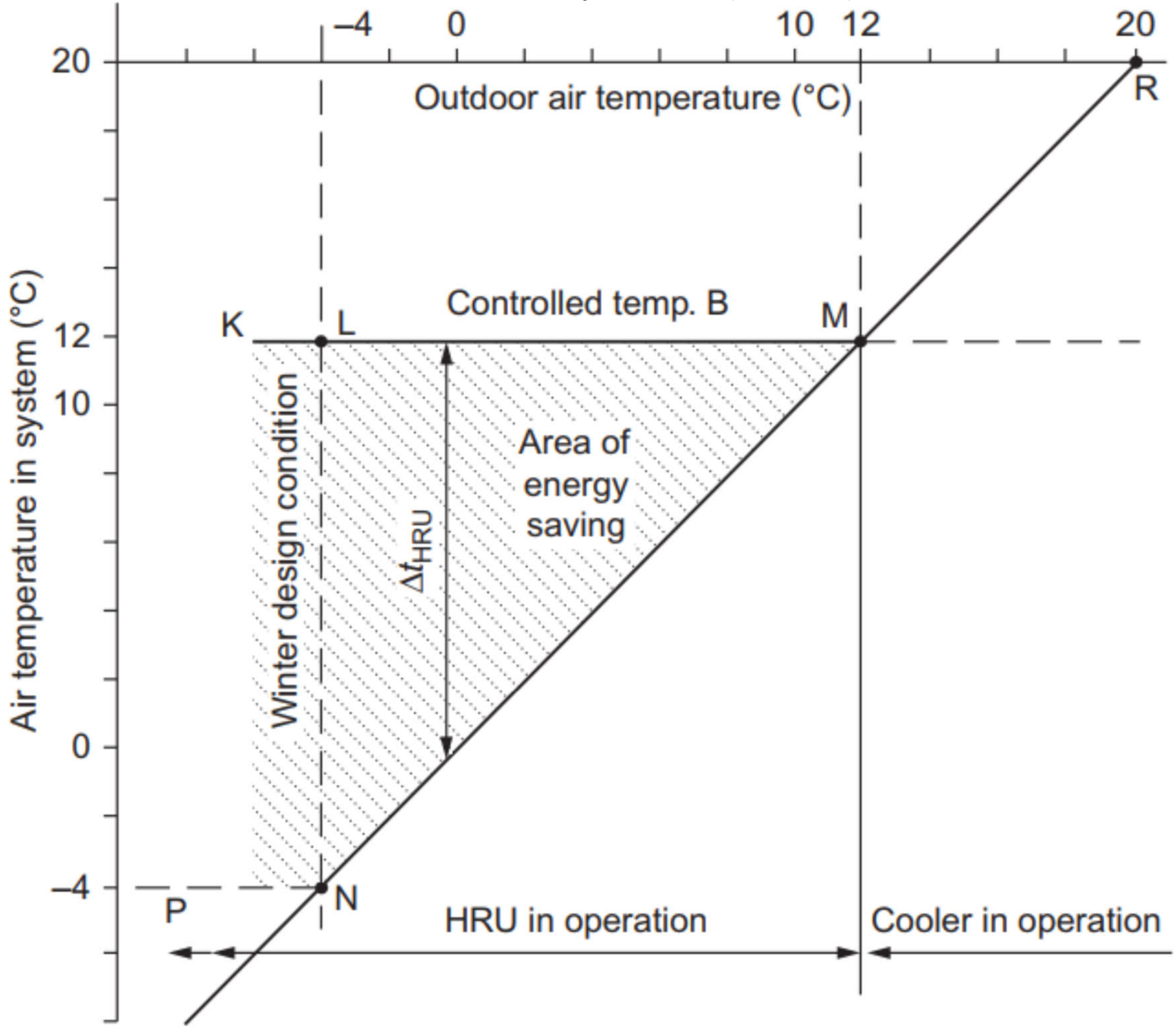
- Economic analysis:
  - Capital costs
    - Heat recovery drop
    - Associated controls
    - Ductwork connections
    - Filter in exhaust duct
    - Increase in fan size to deal with the additional pressure drops, supply and extract
    - Reduced heater and cooler battery sizes
    - Reduced boiler and refrigeration plant sizes



Design considerations

- Economic analysis: (cont'd)
  - Annual costs/savings:
    - Savings in energy for heating and cooling plant
    - Additional fan energy consumption
    - Energy consumption of ancillary equipment, e.g., motor for thermal wheel and pump for run-around system
    - Maintenance costs
  - Most economic studies using 100% outdoor air show a payback of 1 to 5 years. Will be improved with higher exhaust air temp. (when heating) and for systems with longer hours of operation

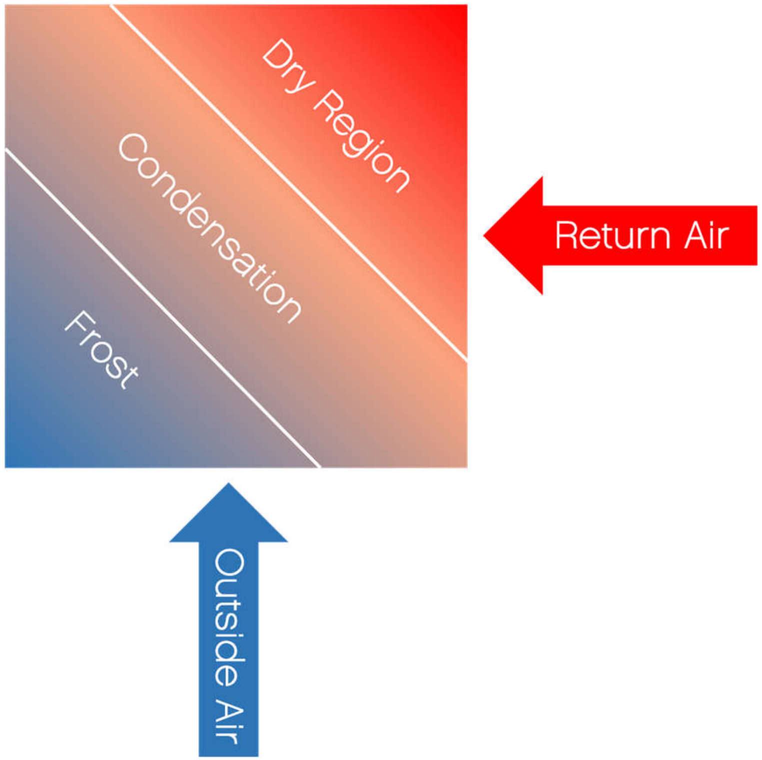
Example of load diagram for analysis of annual energy savings from a heat recovery unit (HRU)



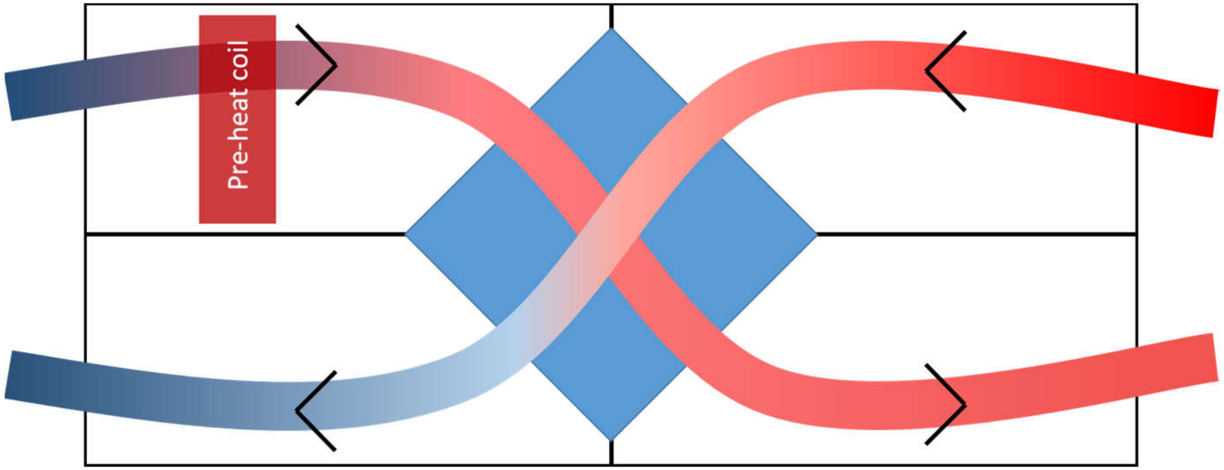
(Source: Legg R., 2017. *Air Conditioning System Design*, Elsevier Science & Technology, Oxford.)

Frost prevention methods for air-to-air energy recovery devices

Air-to-air energy recovery device	**Frost prevention method***
Coil loop (run-around coil)	Three-way mixing valve
Heat pipe	Face-and-bypass dampers
Fixed-plate heat exchanger	Frost damper
Fixed membrane heat exchanger	Face and bypass dampers
Total-energy wheel	Supply-side bypass damper

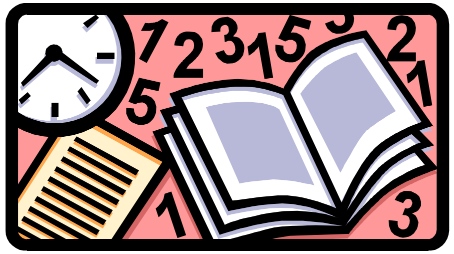


* Also, preheat of outdoor air (OA) or exhaust air (EA)



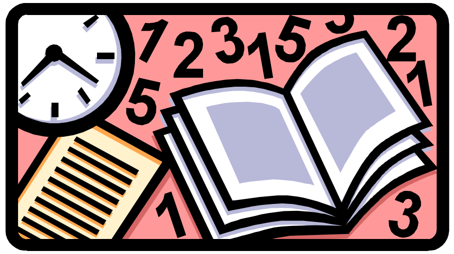
(Image source: https://www.linkedin.com/pulse/frost-formation-defrost-strategies-fixed-plate-heat-energy-mo-afshin/)

Further Reading



- Types of Heat Recovery System https://renewableenergyhub.co.uk/main/heat-recovery-systems-information/types-of-heat-recovery-system/
- Heat recovery ventilation - Wikipedia https://en.wikipedia.org/wiki/Heat_recovery_ventilation
- Module 49: Saving energy through simple HVAC heat recovery http://www.cibsejournal.com/cpd/modules/2013-02/
- Schild P. G., 2004. *Air-to-Air Heat Recovery in Ventilation Systems*, Ventilation Information Paper (VIP) No. 6, Air Infiltration and Ventilation Centre, Brussels, Belgium. https://www.aivc.org/sites/default/files/members_area/medias/pdf/VIP/VIP06_Heat_Recovery.pdf

References



- ASHRAE, 2020. *ASHRAE Handbook 2020 HVAC Systems and Equipment*, American Society of Heating, Refrigerating and Air-Conditioning Engineers Inc., Atlanta, GA.
  - Chapter 9. Applied Heat Pump and Heat Recovery Systems
  - Chapter 26. Air-to-Air Energy Recovery Equipment
- Bai H. Y., Liu P., Alonso M. J. & Mathisen H. M., 2022. A review of heat recovery technologies and their frost control for residential building ventilation in cold climate regions, *Renewable and Sustainable Energy Reviews*, 162: 112417. https://doi.org/10.1016/j.rser.2022.112417
- Cuce P. M. & Riffat S., 2015. A comprehensive review of heat recovery systems for building applications, *Renewable and Sustainable Energy Reviews*, 47: 665-682. https://doi.org/10.1016/j.rser.2015.03.087