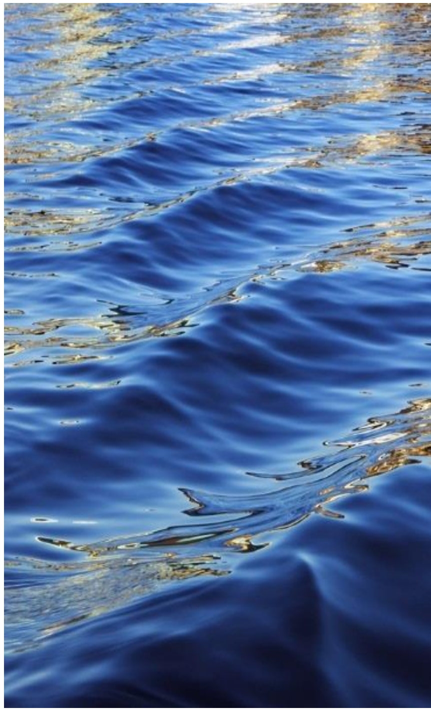
Environmental Thermal Engineering

Lecture Note #9

Professor Min Soo KIM



Ice Thermal Storage System

Ice Thermal Storage System

❑ Introduction

In midnight (22:00~08:00), refrigerator operates with cheap midnight electric power and stores coldness in ice storage tank, then using them for cooling in daytime. It can reduce operating hours in daytime, so driving cost is much cheaper than other systems.

Ice Thermal Storage System

❑ Ice

- Latent energy, so system is compact
- Most feasible for small and moderate thermal storage systems
- Less efficient as the leaving water temperature is reduced
- Requires better insulation

※ Reducing delivery temperatures, so as to reduce duct sizes and fan expenses as well as do a better job at dehumidifying has encouraged the use of ice storage systems.

❑ Chilled Water

- Sensible storage
- Less expensive per unit volume of storage
- Most feasible for large thermal storage systems
- Requires large storage tanks

Characteristics of Ice Thermal Storage System

❑ Economic

- Power cost reduction, power-saving effect caused by using cheap midnight electric power.

❑ High efficiency

- Confident cooling system with cold ice wind.
- Maximizing efficiency by controlling calorific value in heat storage tank with requirement

❑ National

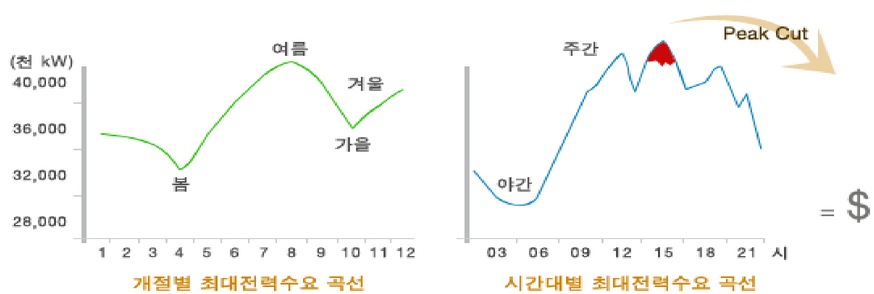
- National electric cost can be reduced by creating midnight load

❑ Pollution free

- No pollution using clean fuel electricity

❑ Adaptable

- Good adaptability for load change in future with enlargement and alteration



Operating method

Midnight operation (ice making operation)	Daytime operation (cooling operation)
Operation in midnight is for ice making part. In this part, just outdoor unit and heat storage tank are operated. Refrigerant from outdoor unit as below zero temperature flows through coil in heat storage tank and makes ice around coil.	Operation in daytime is for cooling part with ice in heat storage tank made in midnight. In this part, just heat storage tank and indoor unit are operated. Water passing through ice in heat storage tank become cool and go into indoor unit, so make pleasant cooling.

Applications

- Commercial office buildings
- Convention centers
- District cooling
- Theaters
- Retail
- Institutional
- Healthcare
- Worship facilities
- School

Ice on coil 형

Ice capsule 형

Ice Slurry 형

Geothermal Heat Pumps (Ground Source Heat Pumps)

What is Geothermal?

- Heat of the Earth [Geo (Earth) + Thermal (Heat)].
- The majority of the available energy on this planet is heat energy, or thermal.
- The six miles of the Earth's crust contains 50,000 times as much energy as the fossil fuels oil, coal and gas.

Geothermal power plant at the Geysers, California, USA, the largest dry steam production field in the world

What is Geothermal Heat Pump?

- Operates on the same principle as an air-conditioner or air-source heat pump.
- Instead of transferring heat with the outside air, geo exchange system uses the earth as its heat source of heat sink.
- The earth connection is either a series of buried pipes (closed loop) or water wells (open loop).
- GHPs don't create heat; they move it from one area to another.

Geothermal heat pump

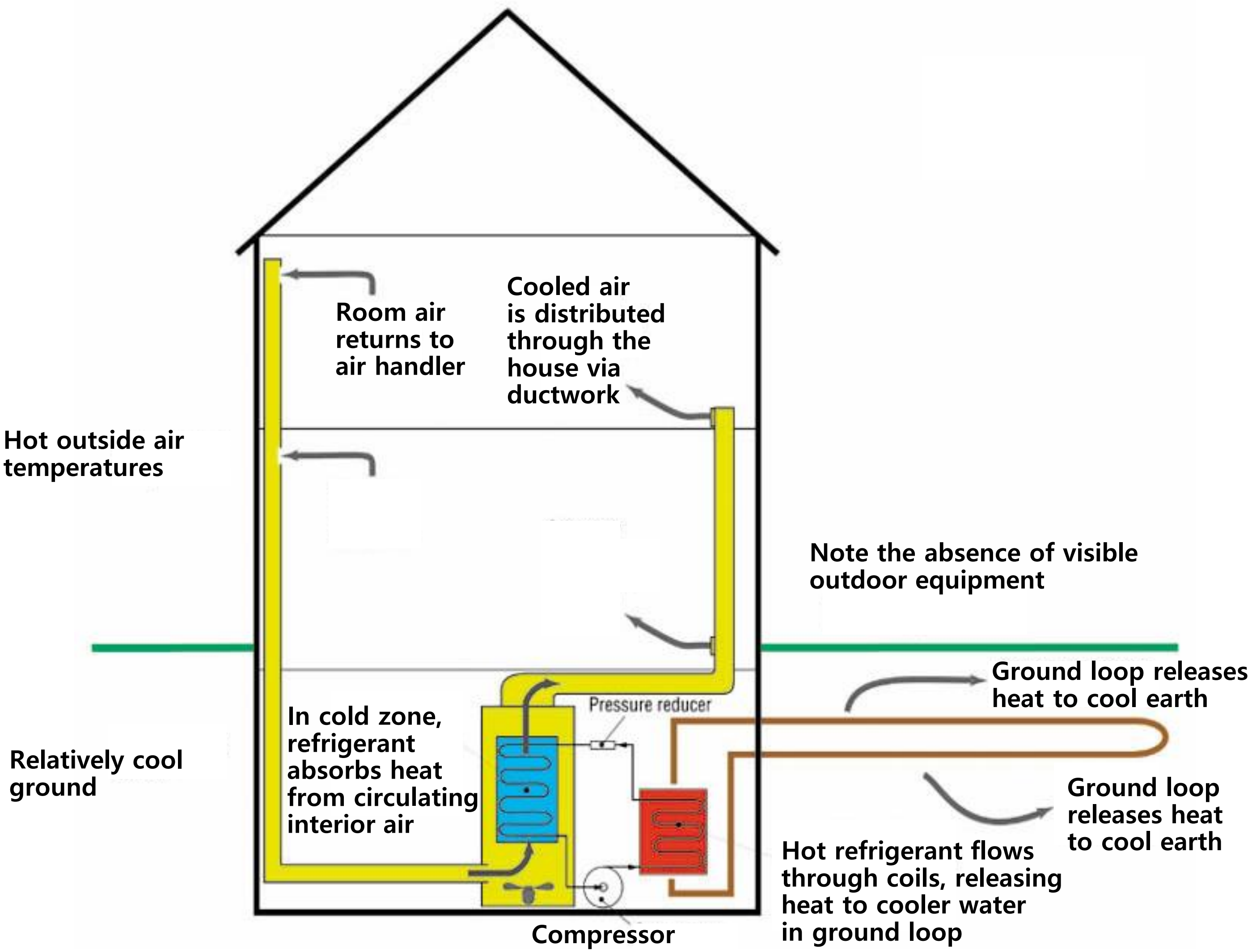


FIGURE Residential Geo Exchange System (Cooling Mode)

Geothermal heat pump

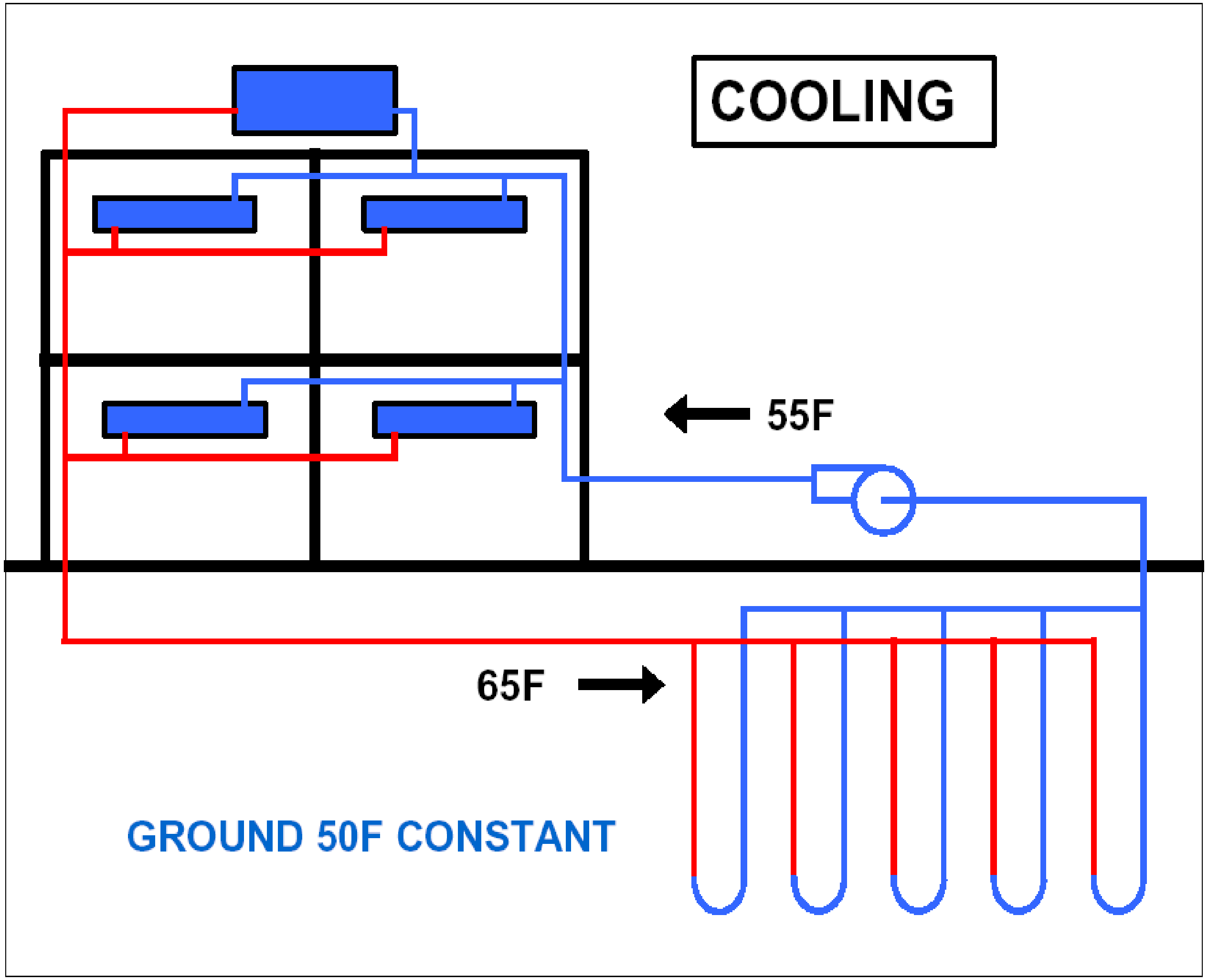


FIGURE Cooling Mode

Geothermal heat pump

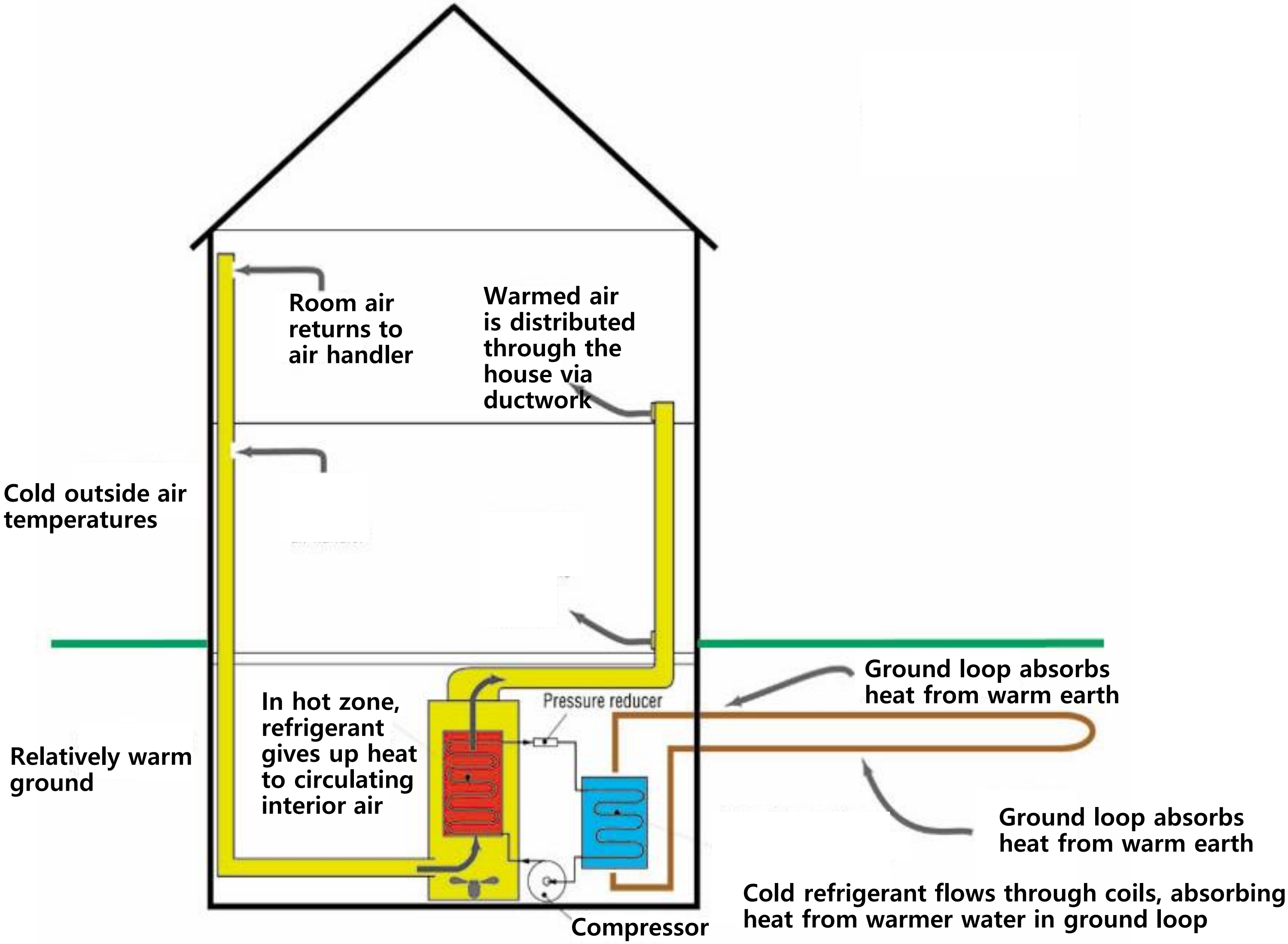


FIGURE Residential Geo Exchange System (Heating Mode)

Geothermal heat pump

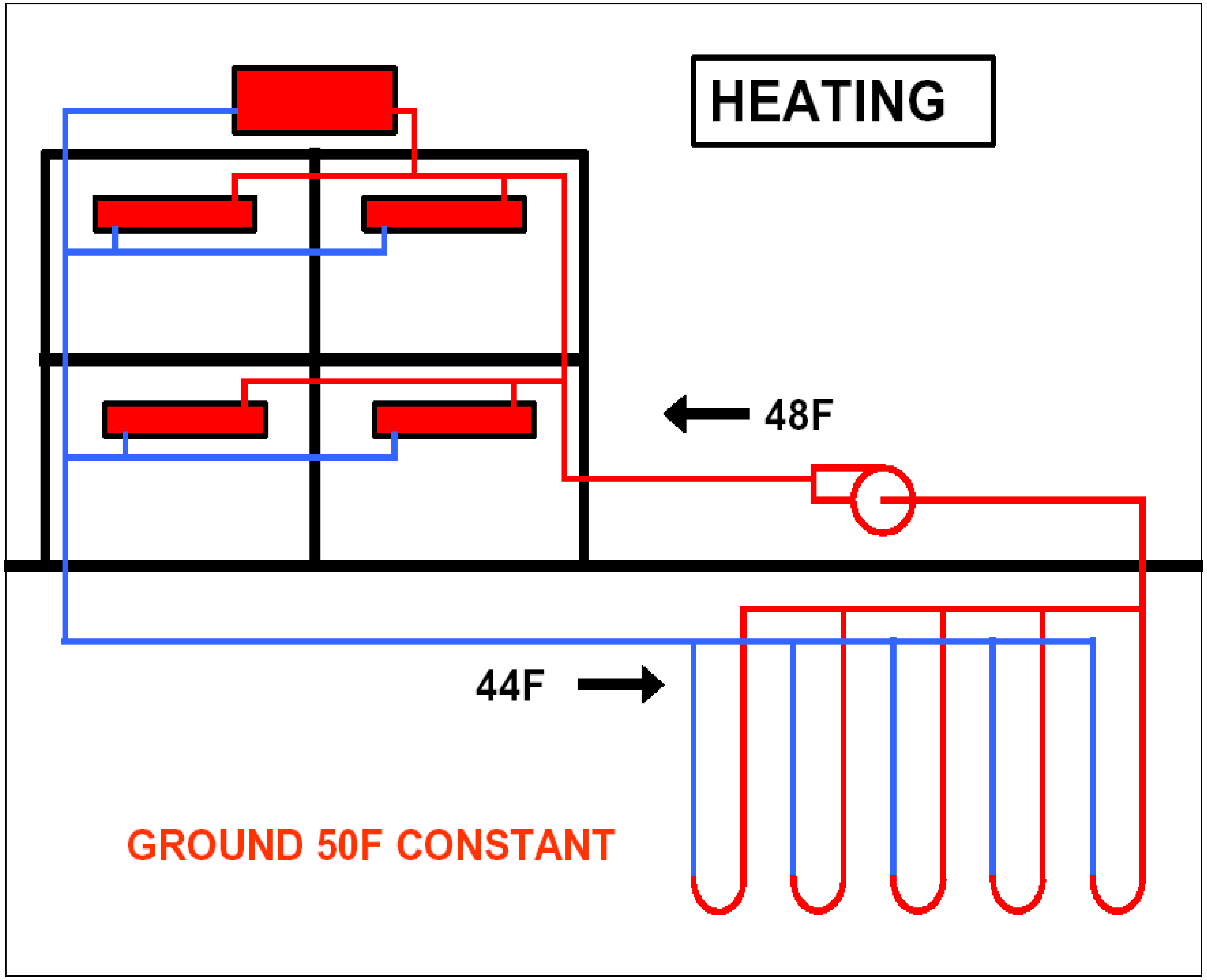


FIGURE Heating Mode

Geothermal Circulation Fluids

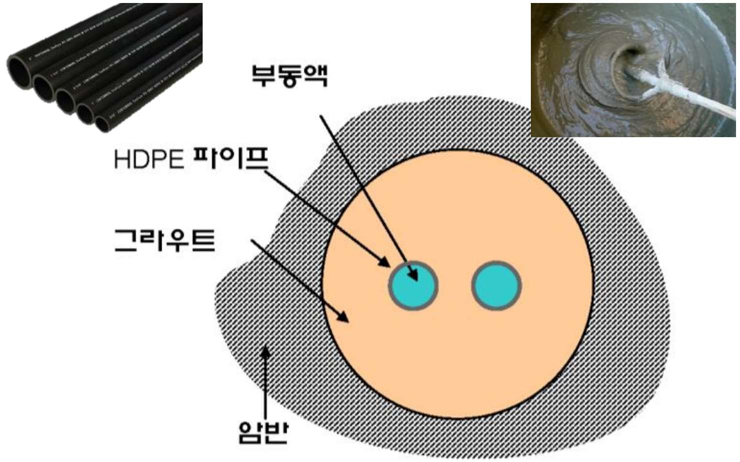
❑ Ideal Circulating Fluids

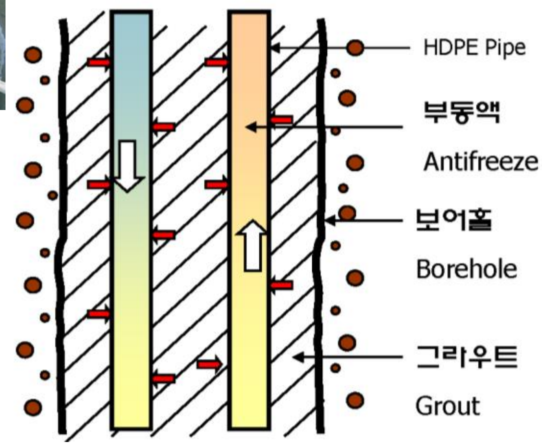
- Excellent heat transfer capability, low viscosity
- Harmless to the underground environment.
- Cheap, Long durability

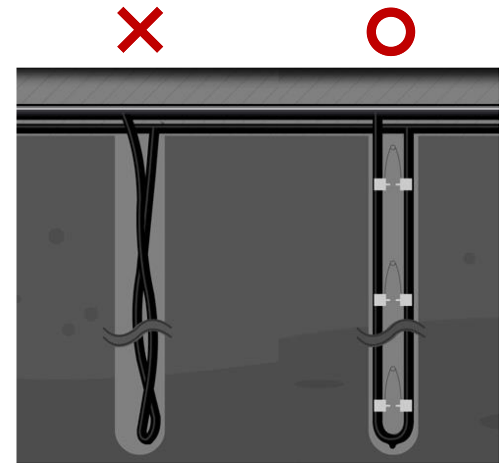
❑ Typical Circulation Fluids

- Ethanol, C2H5OH) / Water
- Calcium chloride, CaCl2) / Water
- Sodium chloride, NaCl) / Water
- Potassium carbonate, K2CO3) / Water
- Ethylene glycol, HOCH2CH2OH) / Water
- Propylene glycol, CH3CHOHCH2OH) / Water
- Methanol, CH3OH)/ Water
- Potassium acetate, CH3CHOOK) / Water

Materials & Structure of the Vertical Type







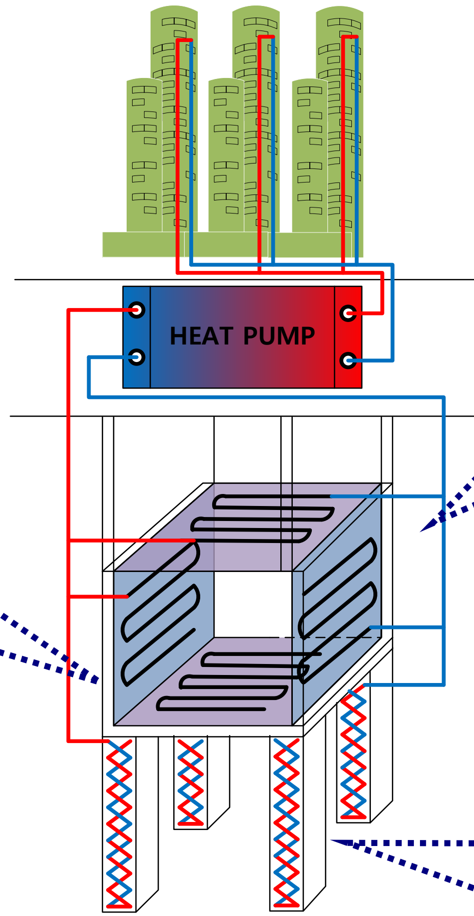
❑ Purpose of Grout

- Prevent underground intrusion of pollutants.
- Fill in between the underground and PE pipes and make thermal contact.
- High thermal conductivity.

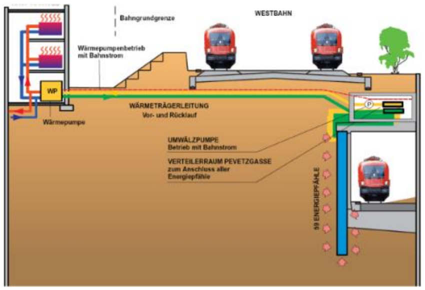
❑ Types of Grout

- Bentonite-based grout
  - ➢ Bentonite grout
  - ➢ Thermal-reinforced bentonite gout
- Cement-based grout
  - ➢ Normal cement
  - ➢ Cement-additive mixed cement

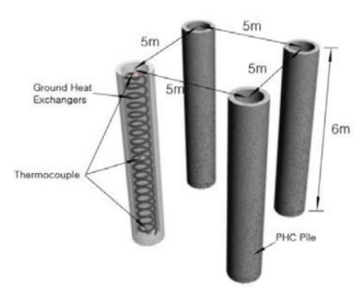
Types of GHP systems



Slab-type GHX



Wall-type GHX



Pile-type GHX

Ref. http://www.enercret.com/

Types of GHP systems

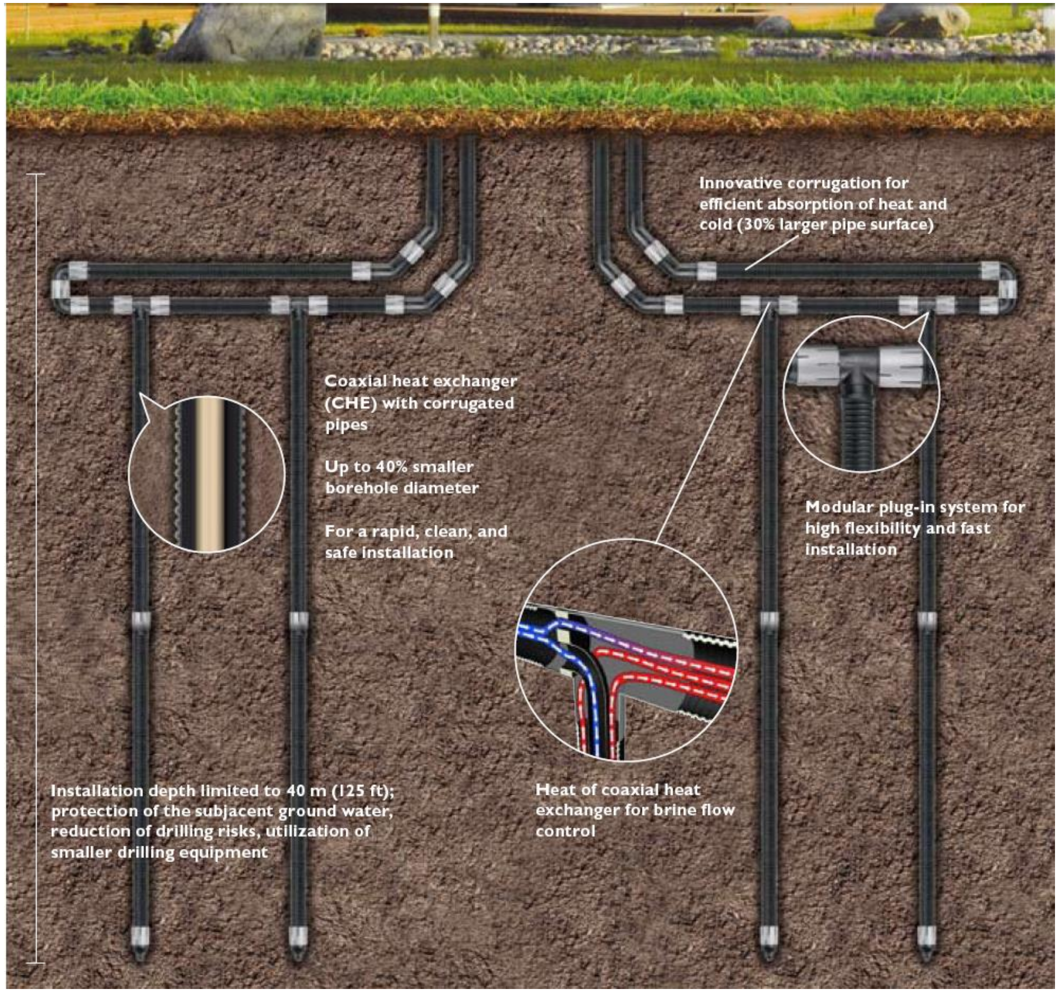


FIGURE Corrugation-Type GHP

Benefits of GHP systems

- ❑ Energy efficient (25~50% Better)
- ❑ Low operating cost
- ❑ Design flexibility
- ❑ Low environmental impact.
- ❑ Low maintenance
- ❑ Durability

Refrigeration System using CO_2

CO_2 - BACKGROUND

The Ozone Story 1

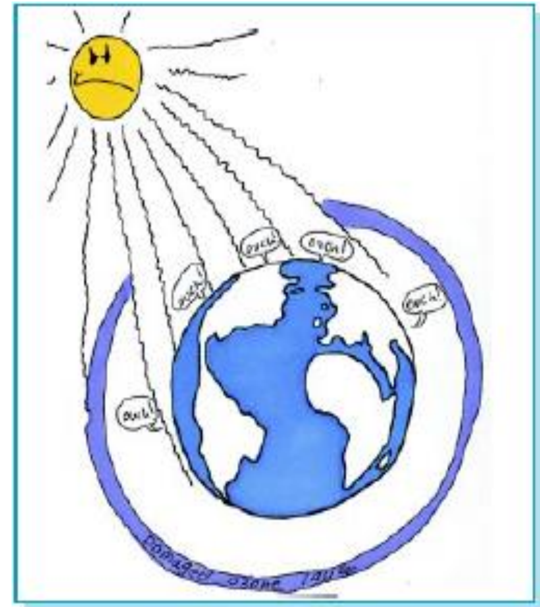
"The ozone layer is a thin layer of ozone in the atmosphere, 10 – 50 km above the earth."

"The ozone layer absorbs most of the harmful ultraviolet-B (UV-B) radiation from the sun."

"Wonder gas" CFCs were invented in 1928 for commercial applications."

CO_2 - BACKGROUND

The Ozone Story 2



"...use of CFCs increases rapidly..."

"Scientists discover a link between CFCs and ozone layer depletion."

"If the ozone layer depletes, more harmful UV-B radiation will reach the earth through the damaged ozone layer."

CO_2 - BACKGROUND

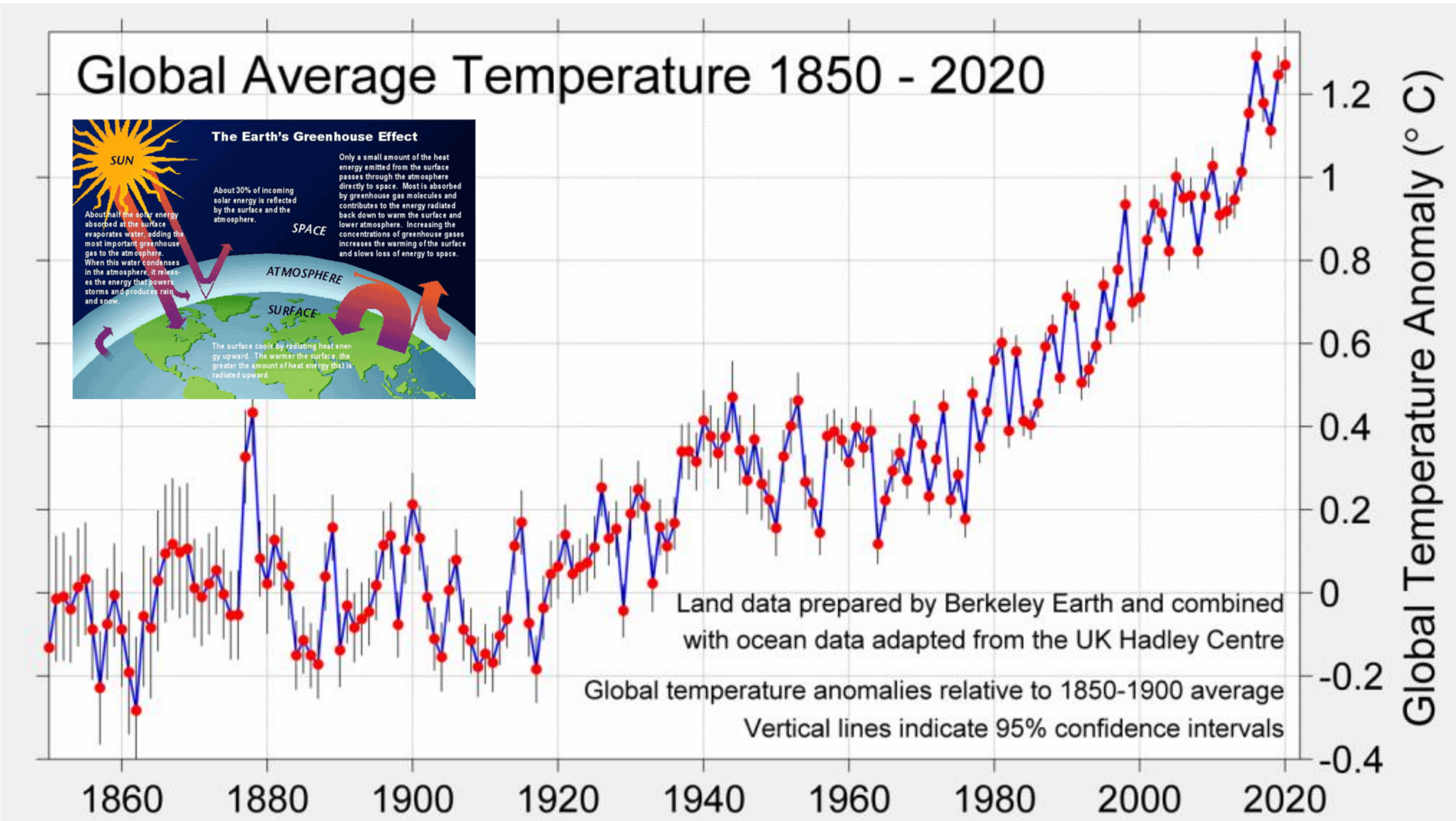
The Ozone Story 3

"In 1978, the United States of America, Canada, Sweden and Norway ban the use of CFCs in aerosols."

"Parties agree to completely phase out CFCs by the year 2000, and to establish a Multilateral Fund to assist developing countries. US$240 million was allocated for 1991 - 1993."

"In 1992, it was decided that the developed countries phase out HCFCs by 2030, freeze methyl bromide by 1995 and that the phase out of CFCs be brought forward to 1996."

CO_2 - BACKGROUND



CO_2 - BACKGROUND

Preservation Measures of Ozone Layer Destruction

- **Prohibition on use of high Ozone depletion potential refrigerant (CFC, HCFC)**

- **Development of alternative refrigerant (HFC)**

- **Replacement of natural refrigerant :**
  - Carbon dioxide (CO2),
  - Hydrocarbon (HC),
  - Ammonia (NH3),
  - Water,
  - Air, and
  - Others

CO_2 - BACKGROUND

Early CO_2 history

1850: British Patent (A. Twining) mentions CO_2

1866: First reported use (T. C. Lowe - USA)

1881: First system in Europe (C. Linde – Germany)

1886: F. Windhausen British Patent

1890-:J & E Hall systems

Carbon Dioxide (CO_2) Refrigerant

❑ Advantages

- Not toxic, Odorless, Non flammable, Non explosive
- Global Warming Potential(GWP) : 1
  Ozone Depletion Potential(ODP) : 0
- Large refrigeration capacity, Small compression ratio
- Possibility of device weight lightening, availability with low price
- Good suitability with metal material

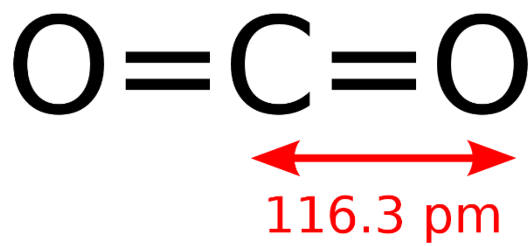
❑ Disadvantages

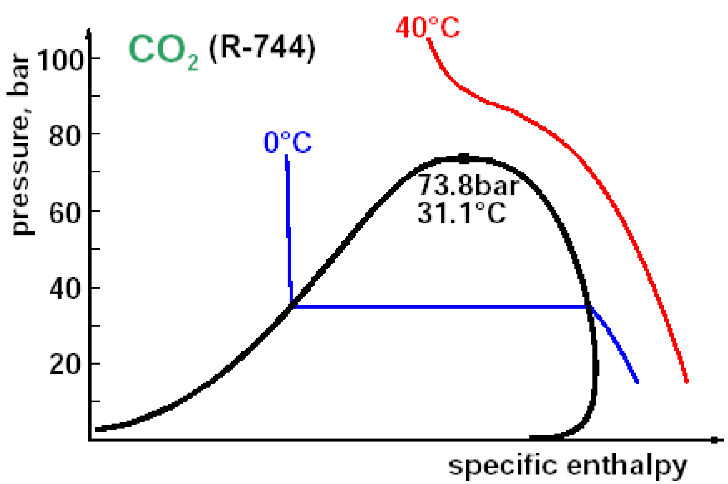
- Low critical temperature(31 ℃),
- High working pressure

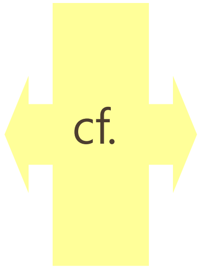
CO_2 - Properties

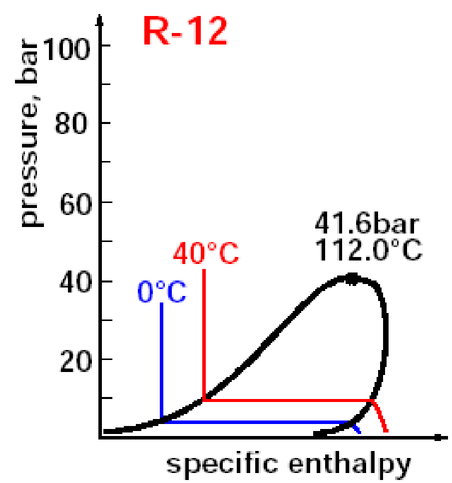
TABLE Thermophysical properties of CO_2 (McLinden *et al.*(1998)

Property	Value
Chemical formula	CO2
Molecular weight (kg/kmol)	44.01
Critical temperature (K)	304.21
Critical pressure (MPa)	7.384
Critical density (kg/m3)	466.5
Normal boiling temperature (K)	194.75









CO_2 - Properties

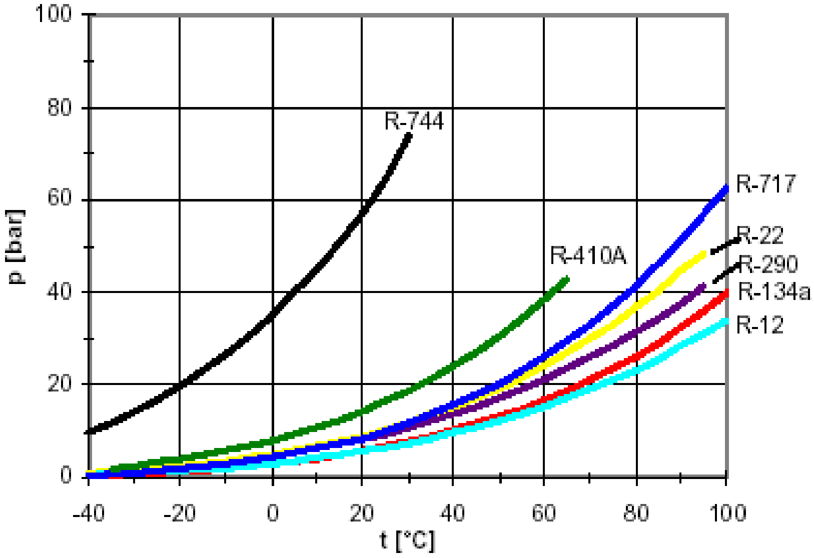


FIGURE Saturation Pressure

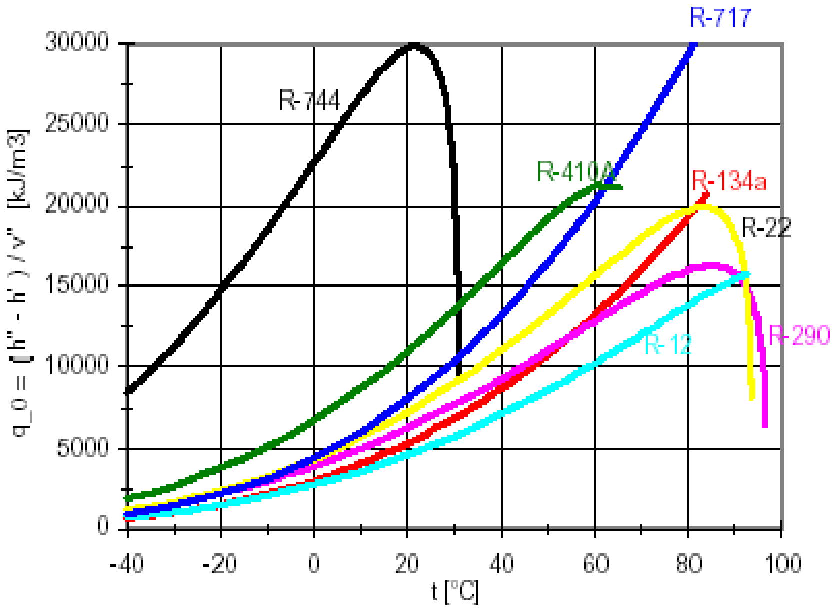
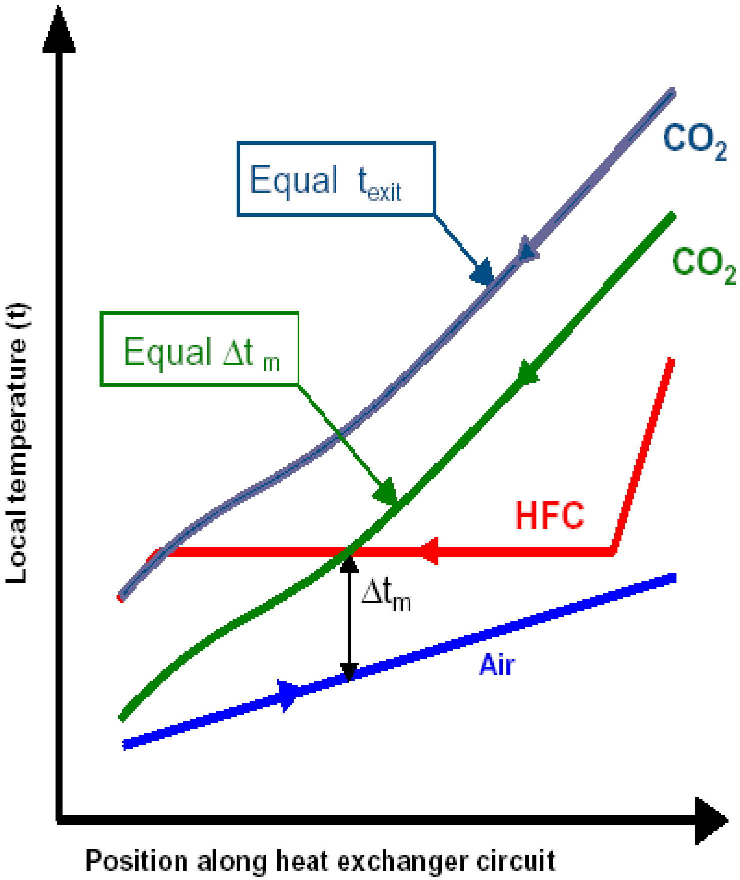
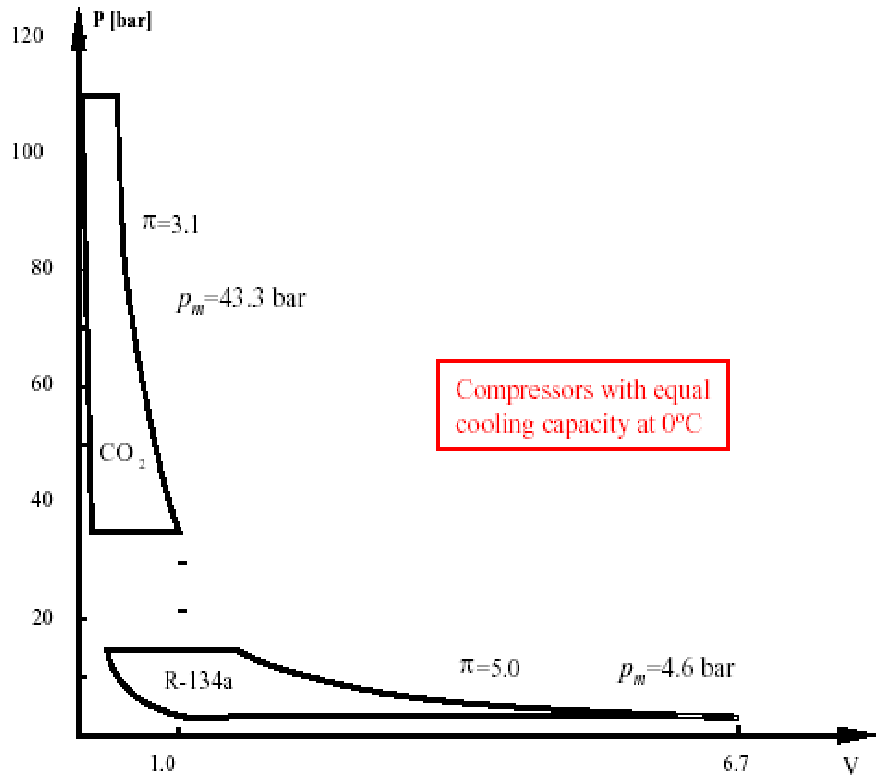


FIGURE Volumetric Cooling Capacity

CO_2 - Properties



"Gliding" temperature gives small approach

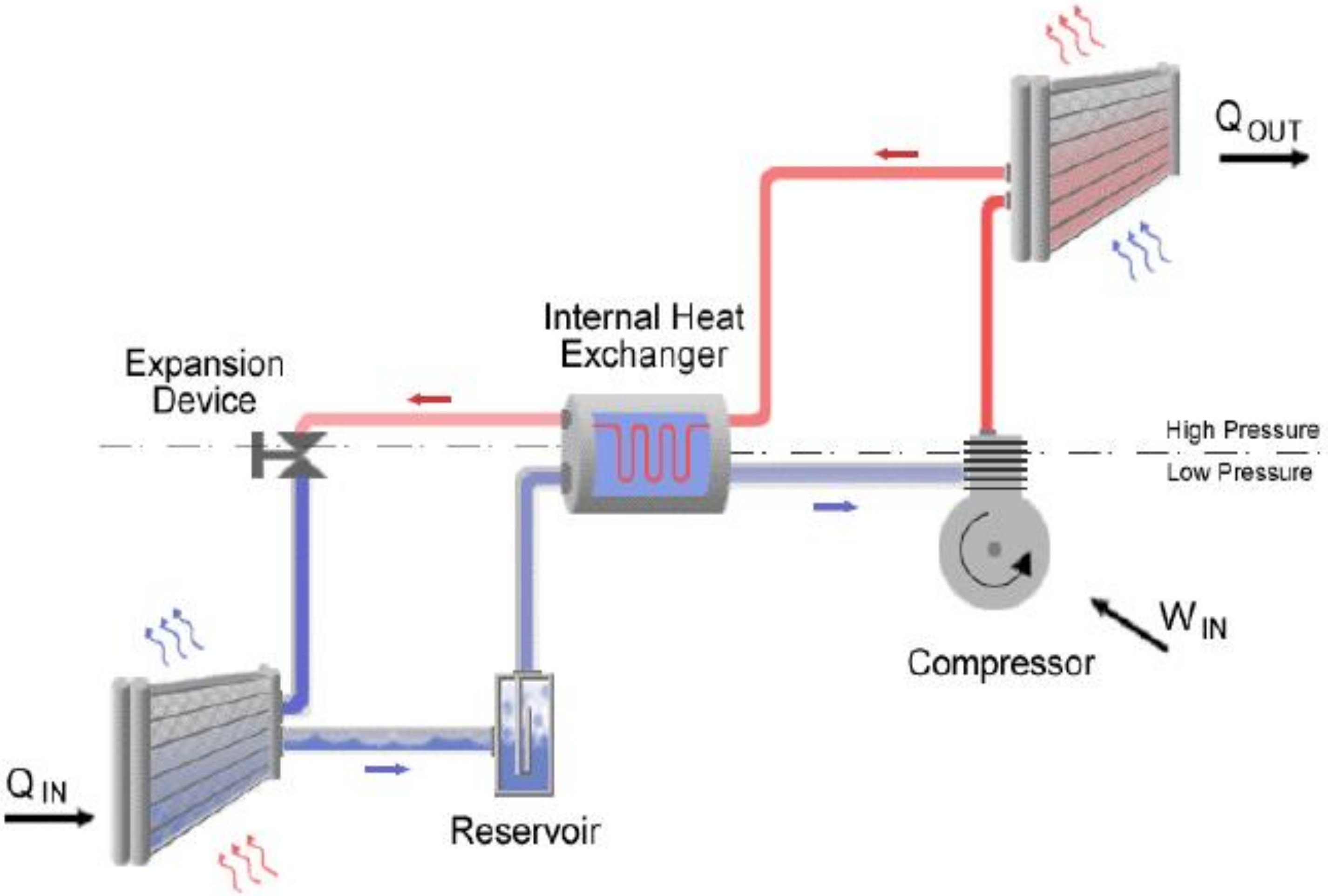


Low pressure ratio gives high efficiency

FIGURE Heat Rejection Temperature Profile

FIGURE Compression Process

CO_2 Circuit


Q OUT
High Pressure
Low Pressure
Internal Heat Exchanger
Expansion Device
Compressor
W IN
Q IN
Reservoir

CO_2 Heat Transfer

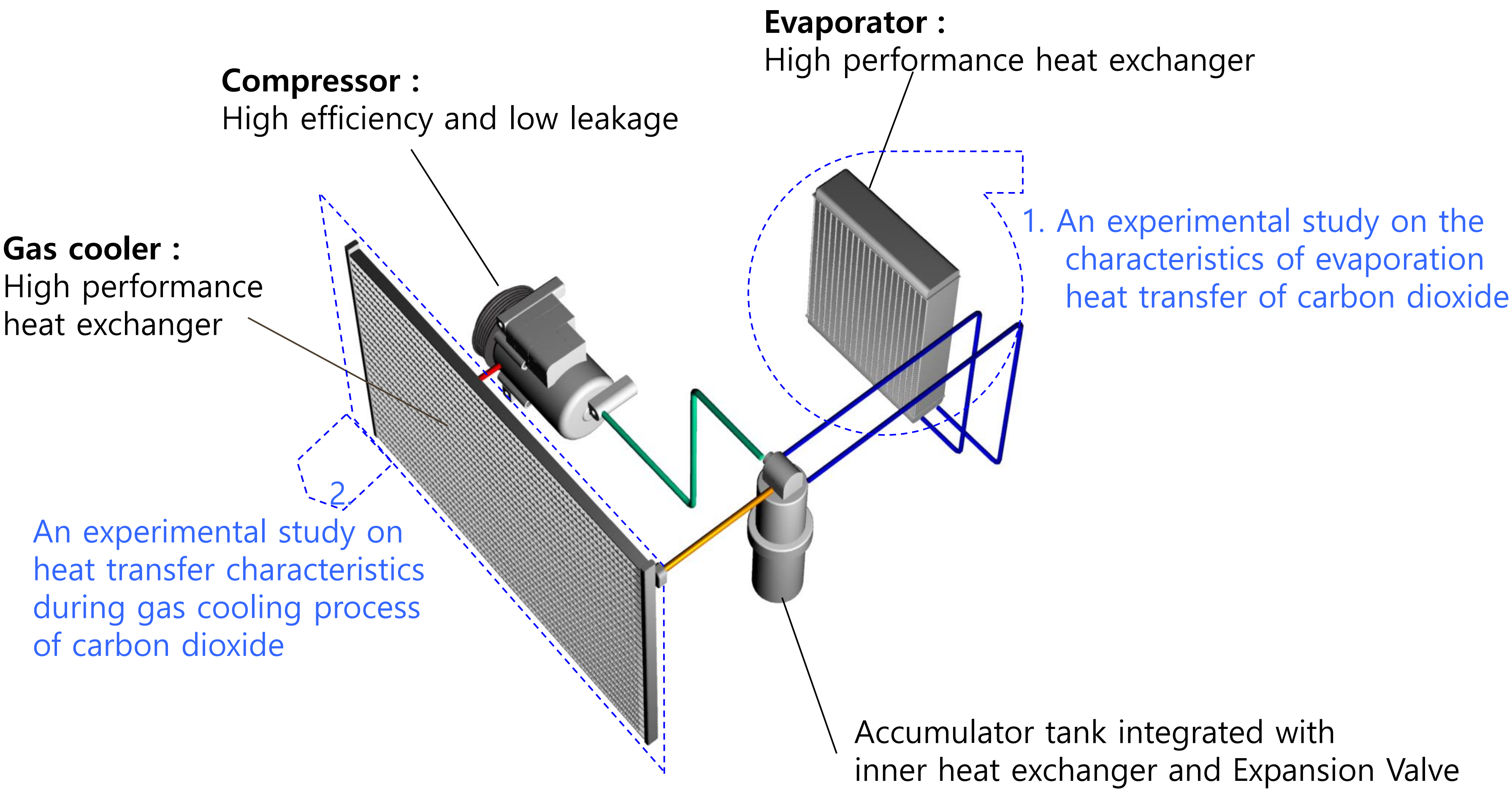
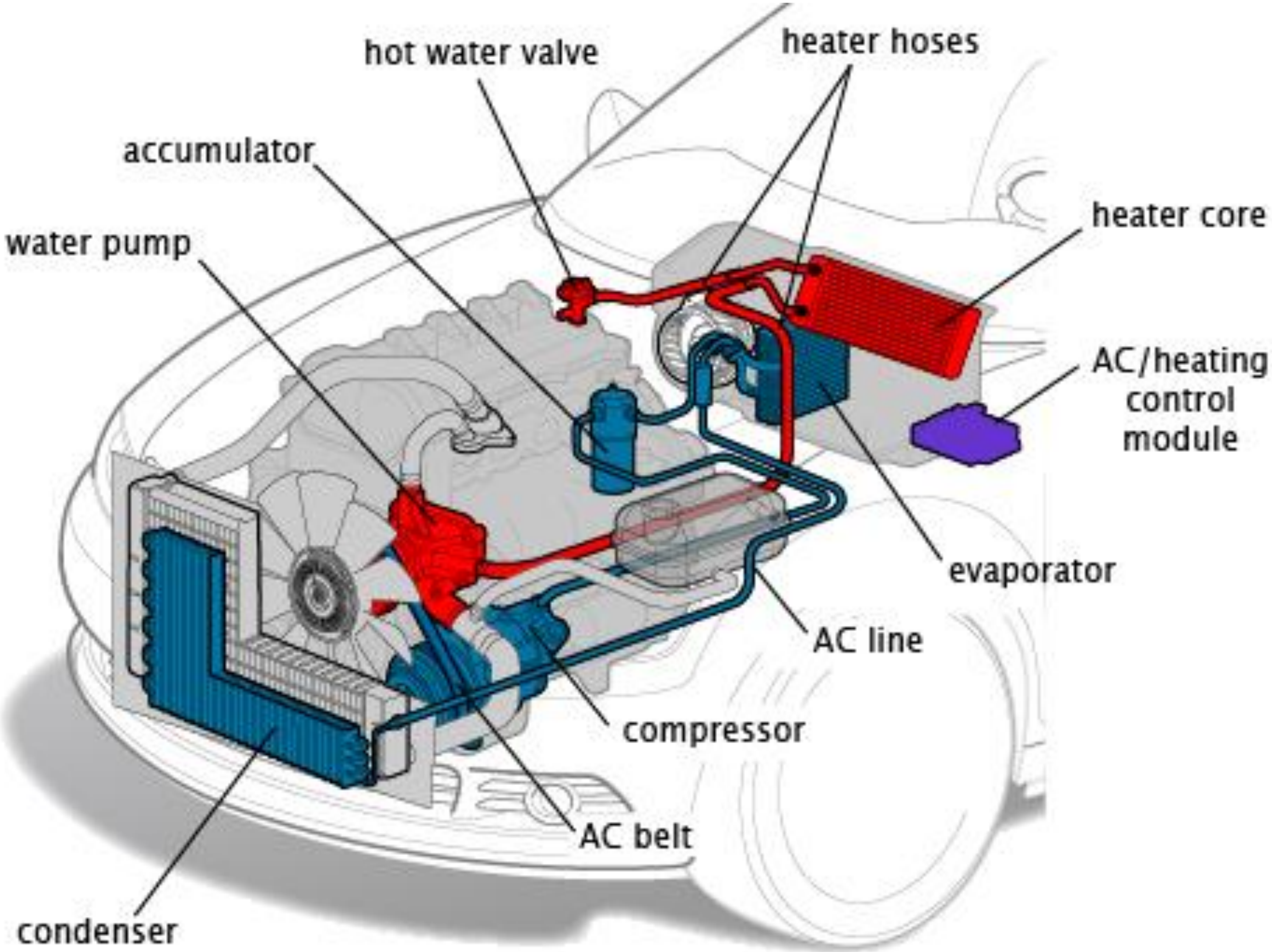


FIGURE Heat Transfer Characteristics of CO_2 (Experimental Study)

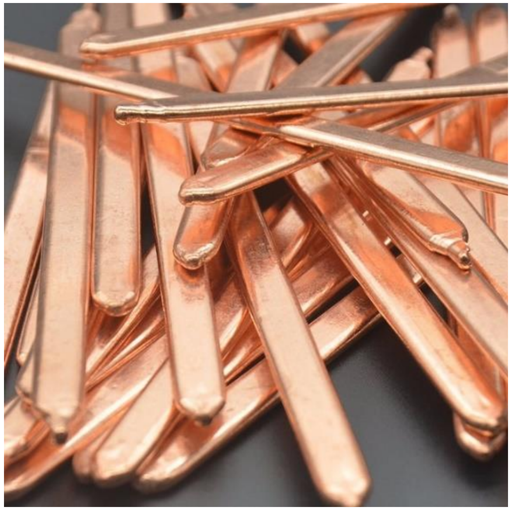
CO_2 Applications – Vehicle A/C

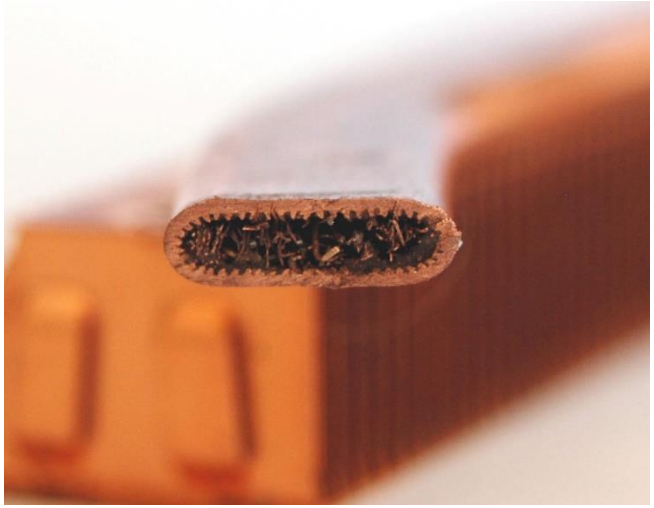


Heat Pipes

Necessity of Heat Pipes

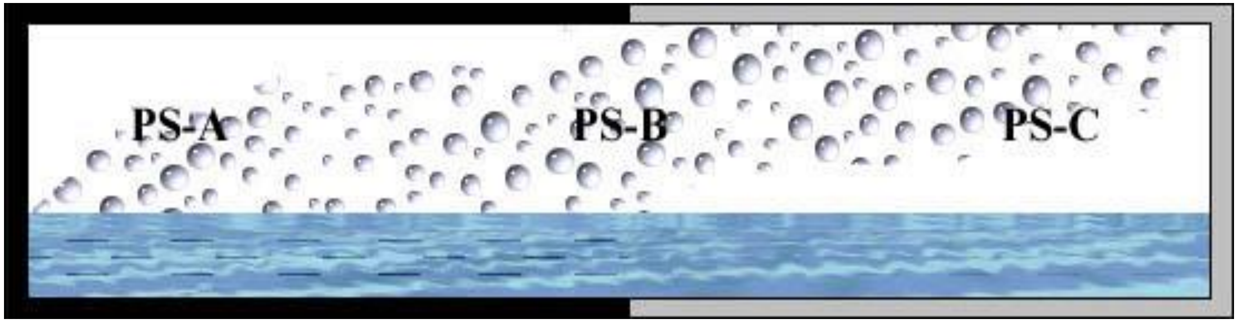
- ❑ **Miniaturization, high-powered, high-accumulated products are developed.**
  - ➢ A technology to remove the generated heat is required
- ❑ **Energy efficient and Eco-friendly method is required**
- ❑ **For the operation of the high-heating product, the temperature needs to be regulated**





Characteristics of Heat Pipes

- Very high effective thermal conductance (Using the latent heat)
- An isothermal surface of low thermal impedance (Saturation state)
- Simple structure & lightweight
- Little expense for maintenance and repairing (No driving part)
- Thermal diodes and switches (Heat flow in one direction only)
- Variable conductance heat pipe



Advantages of Heat Pipes

❑ Very high thermal conductivity

- Less temperature difference needed to transport heat than traditional materials (thermal conductivity up to 90 times greater than copper for the same size) resulting, in low thermal resistance.

❑ Power flattening

- A constant condenser heat flux can be maintained while the evaporator experiences variable heat fluxes.

❑ Efficient transport of concentrated heat

❑ Temperature Control

- The evaporator and condenser temperature can remain nearly constant (at Tsat) while heat flux into the evaporator may vary.

❑ Geometry control

- The condenser and evaporator can have different areas to fit variable area spaces. High heat flux inputs can be dissipated with low heat flux outputs only using natural or forced convection.

Structure of Heat Pipes

Airtight container
(evaporator, adiabatic & condenser section)
+
Operating fluid
+
Wick

- **A traditional heat pipe is a hollow cylinder filled with a vaporizable liquid.**

A : Heat is absorbed in the evaporating section.

B : Fluid boils to vapor phase.

C : Heat is released from the upper part of cylinder to the environment; vapor condenses to liquid phase.

D : Liquid returns by gravity to the lower part of cylinder (evaporating section).

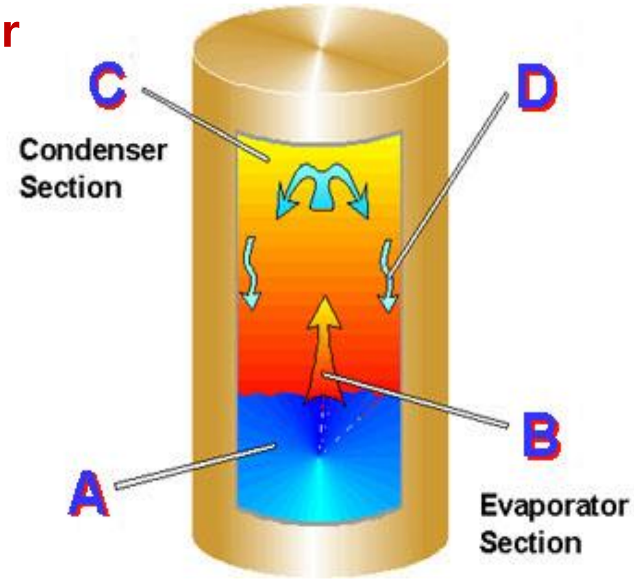
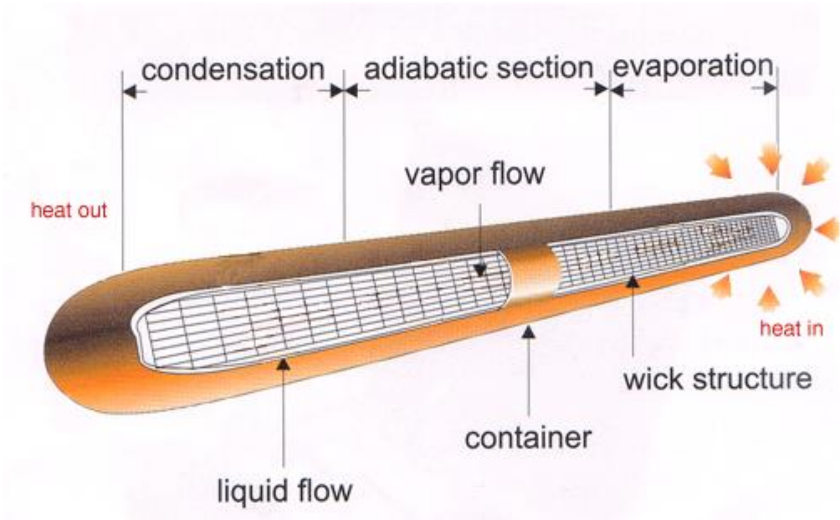
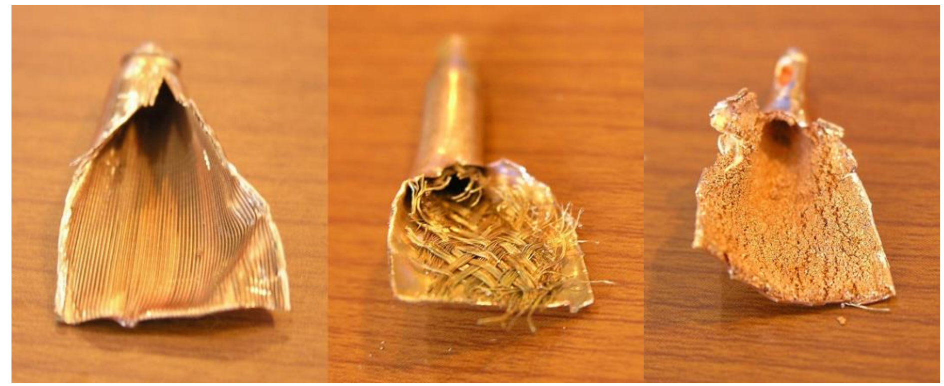
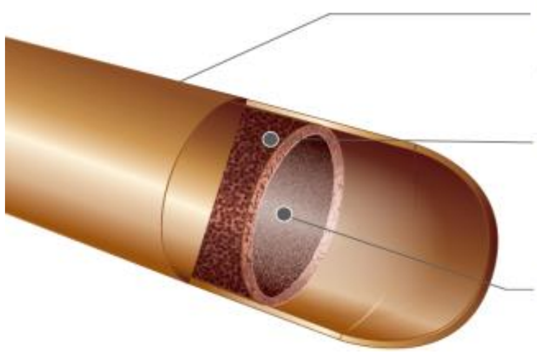


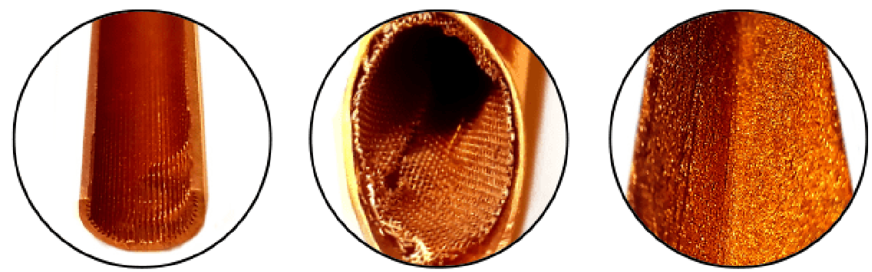
FIGURE Heat Pipe Structure

Structure of Heat Pipes









Grooved	Wire Mesh	Sintered
• Lowest cost • Lowest performance • Does not work well against gravity	• Most commonly used • Good performance • Works well against gravity	• Highest cost • Highest performance • Works best against gravity

Principle of Heat Pipes

❑ Heat transfer by the evaporation and condensation of a working fluid.

1. The fluid vaporized at the evaporator creates a pressure gradient in the pipe.
2. This pressure gradient forces the vapor to the cooler section where it condenses.
3. The working fluid is returned to the evaporator by capillary forces developed in the porous wick structure or by gravity.

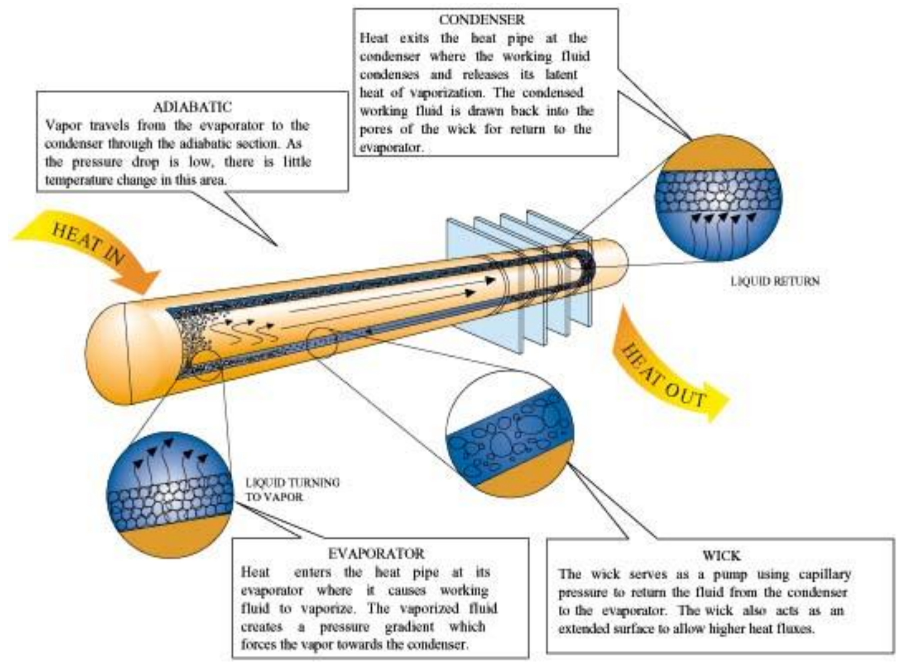


FIGURE The Operating Principle of Heat Pipes

Principle of Heat Pipes

❑ Ideal Thermodynamic Cycle

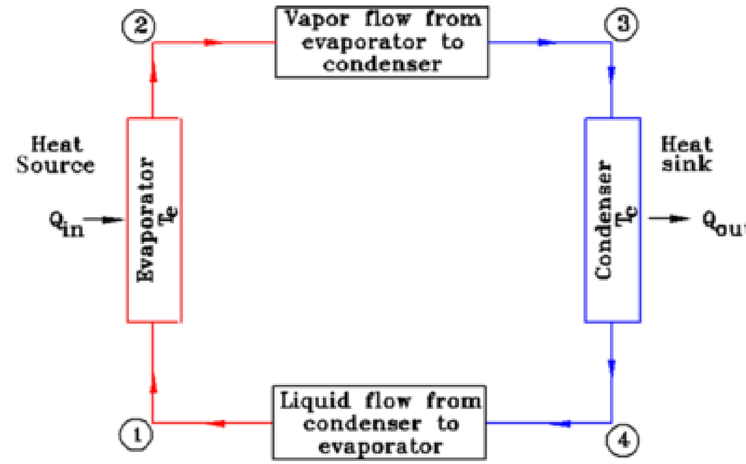
1-2 : Heat applied to evaporator through external sources vaporizes working fluid to a saturated (2′) or superheated (2) vapor.

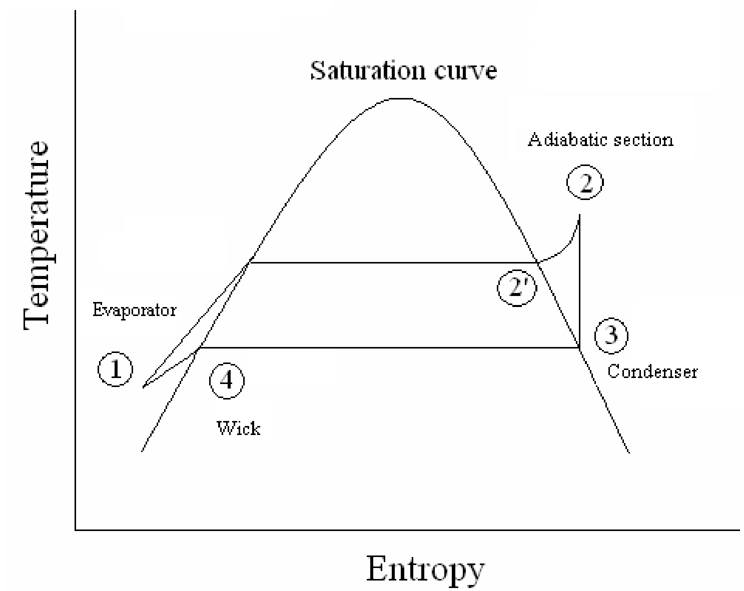
2-3 : Vapor pressure drives vapor through adiabatic section to condenser.

3-4 : Vapor condenses, releasing heat to a **heat sink.**

4-1 : Capillary pressure created by menisci in wick pumps condensed fluid into evaporator section.

Process starts over.



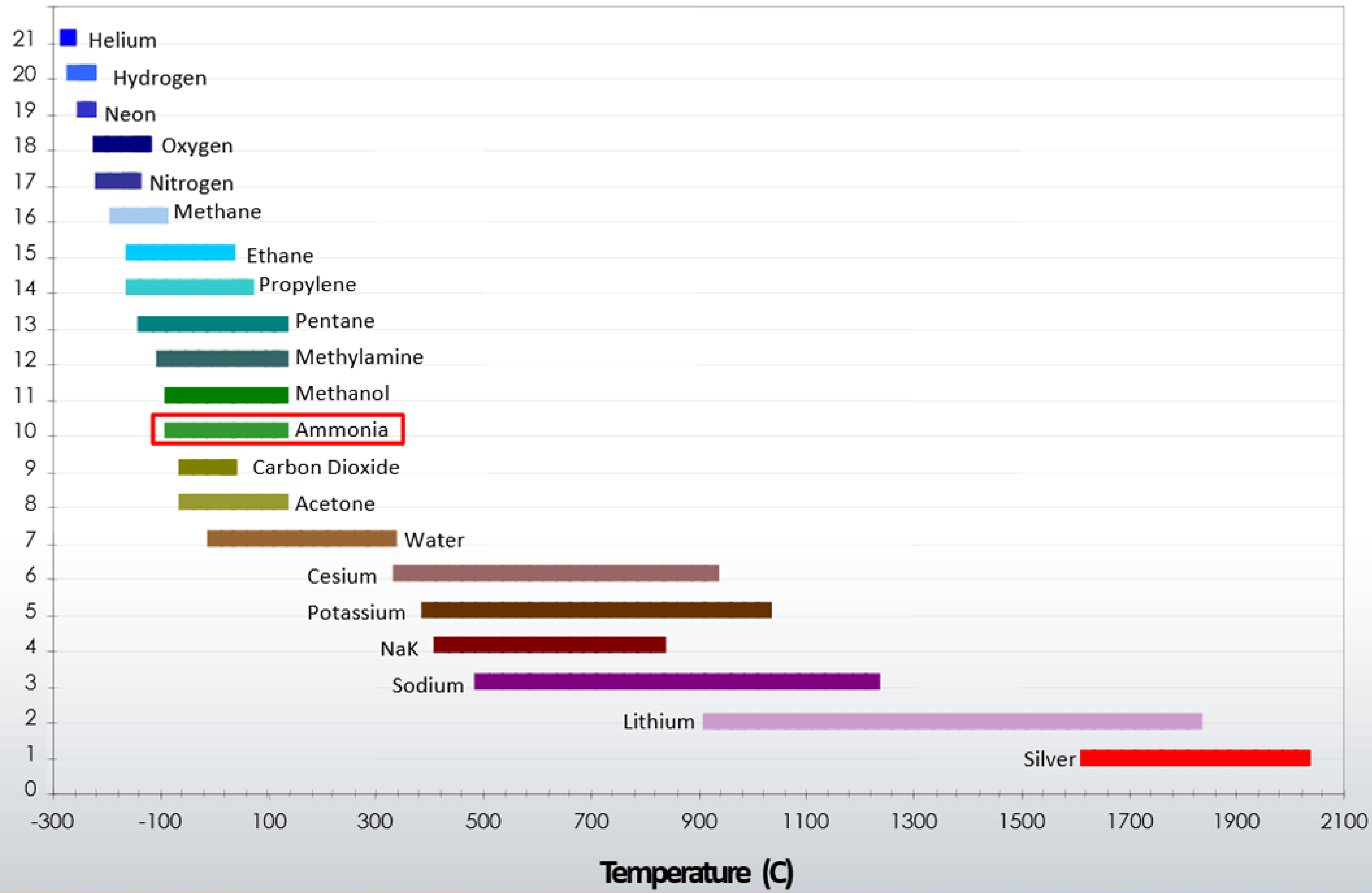


Working fluids of Heat Pipes

TABLE Operating medium and temperature

Medium	Melting point (℃)	Boiling point at 1 atm (℃)	Useful range (℃)
Ammonia	-78	-33	-60~100
Freon 11	-111	24	-40~120
Freon 113	-35	48	-10~100
Acetone	-95	57	0~120
Methanol	-98	64	10~130
Flutec pp2	-50	76	10~160
Ethanol	-112	78	0~130
Water	0	100	30~200
Flutec pp9	-70	160	0~225
Thermex	12	257	150~395

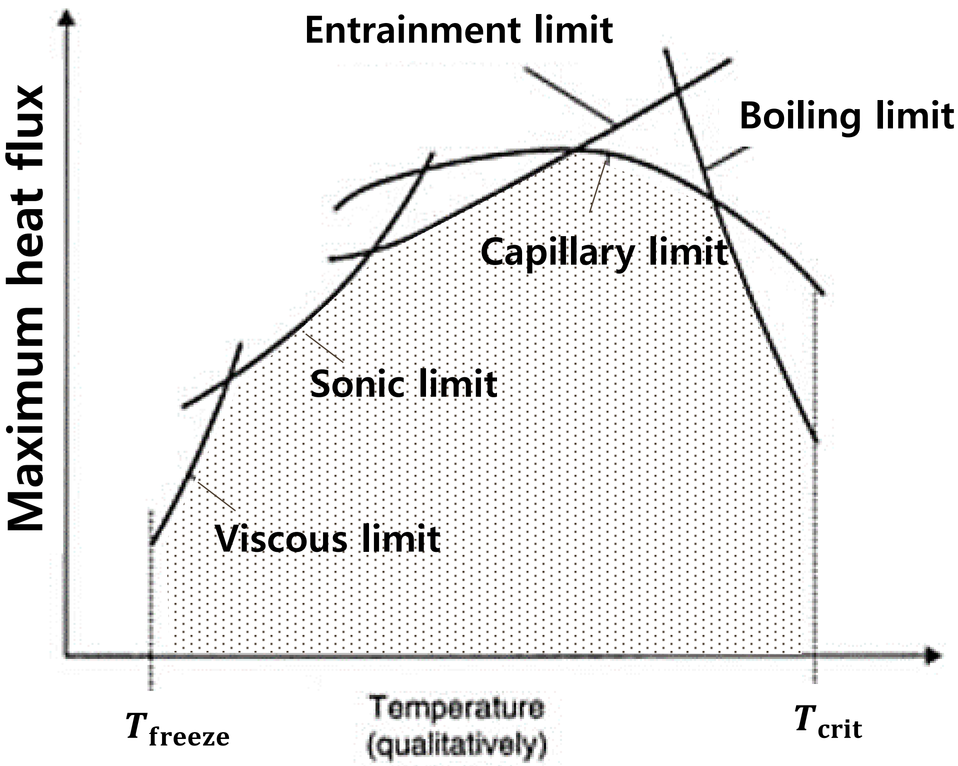
Working fluids of Heat Pipes



Heat Pipes

Operating Limitations

- The heat pipe has four major operating regimes, each setting a limit of performance in either heat transfer rate (axial or radial) or temperature drop.



- Vapor Pressure or Viscous Limit
- Sonic Limit
- Entrainment Limit
- Circulation Limit
- Boiling Limit

Ref. http://www.thermopedia.com/content/835/

Design of Heat Pipes

❑ Design process

1. Problem setting
2. Select material (working fluid, wall)
3. Select wig structure
4. Apply design theory
5. Choose and evaluate the optimal solution

1. Problem setting

- Decide heat load and operating temperature beyond design parameters
- Decide size, location and form of heat source and needle
- Decide boundary condition
- Decide whether gravity or non-gravity condition

Design of Heat Pipes

2. Select material

1) The working fluid

- Relevant to container's material (Chemical reaction, Strength)
- Consider melting point, boiling point and critical point (Working temperature is between melting point and critical point)
- Generally, bigger density, surface tension and latent heat of vaporization and smaller liquid's viscosity is better.

2) Select wall material

- Consider weight, tensile strength and thermal conductivity
- Attention to compatibility with fluid (Corrosion by chemical reaction, non-condensing gas generation is fatal to heat pipe's performance)

Design of Heat Pipes

3. Select wig structure

- Choose the form between screen and groove
- Choose the simplest structure if it meet all of the required characteristics
- Consider the wig's property such as pore radius, porosity, permeability

4. Apply design theory

- Vapor fluid's maximum Mach number is 0.2.
  (Under this condition, vapor is assumed to incompressible and axial temperature gradient is disregarded.)

Application of Heat Pipes

1. Means of thermal control of electronic/electric device
2. Aerospace area (Thermal control of spacecraft)
3. Collecting waste heat system
4. Air-conditioning and cooling system
5. Soil stabilization

Thermal Control of Electronic Devices

❑ Introduction

In modern society, bigger and faster electronics appear. The increasing density of heat-generated devices causes cooling problems. As a result, Heat pipes receive attention because of their efficient cooling.

Especially, the recent issue is the increasing demand for the Notebook PC's built-in battery's cooling for life extension and noise reduction. So heat-sink using heat pipe is favored now.

Thermal Control of Electronic Devices

❑ Heat-sink using heat pipes

- Heat-sink moves heat generated by the semiconductor by heat pipe from heat-sensitive circuit board and device.
- Heat is moved to heat pipe's condensation unit which is attaching the fan.
- Heat is removed by natural or forced convection.

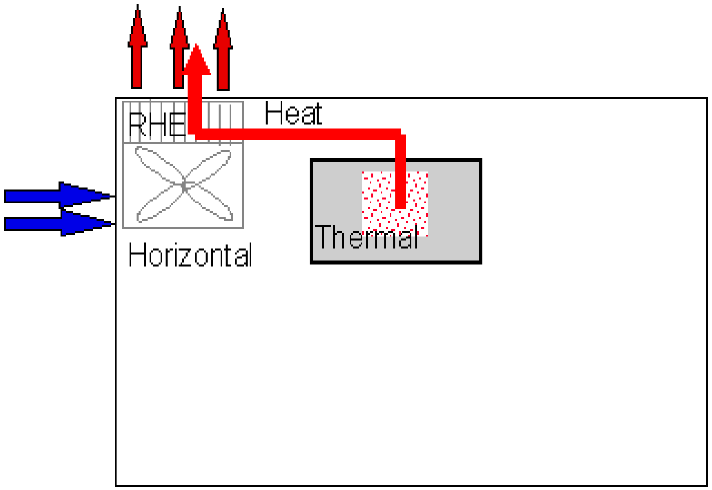


FIGURE Remote Heat Exchange

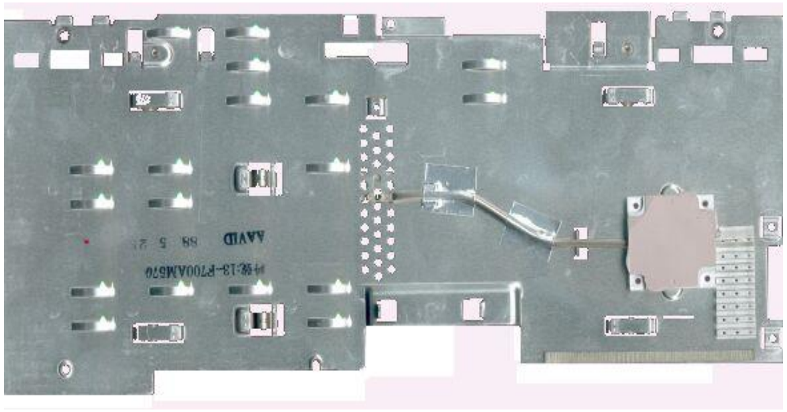


FIGURE Sample of heat-sink

Thermal Control of Spacecraft

1. Introduction

- Space Flight's major problem at the beginning
  (A Temperature difference of non-rotating satellite due to sunlight on a single side can occur critical problems on the electric satellite system.)
  『Solution: Heat Pipe』

- In the late1960s, heat pipes were beginning to use in the USA and Europe.

- In the early 1970s, NASA and EPA began to build up data about designing, manufacturing, and testing Heat Pipes.

Thermal Control of Spacecraft

2. Requirements of Thermal Controller for Satellite

- Should be able to produce proper temperature condition for optimum performance of various equipments of satellite.

- Proper method to protect them from thermal transformations should be used.

- In case of satellite, thermal controller should operate in zero gravity condition and should be small and light. Also its durability and reliability is important.

- Internal modules and components should be able to be manufactured concentrated.

Waste Heat Recovery System

- **Heat pipe can be used efficiently in heat recovery for following reasons;**
  - Small end-to-end temperature drops
  - The ability to control and transport high heat rates at various temperature levels

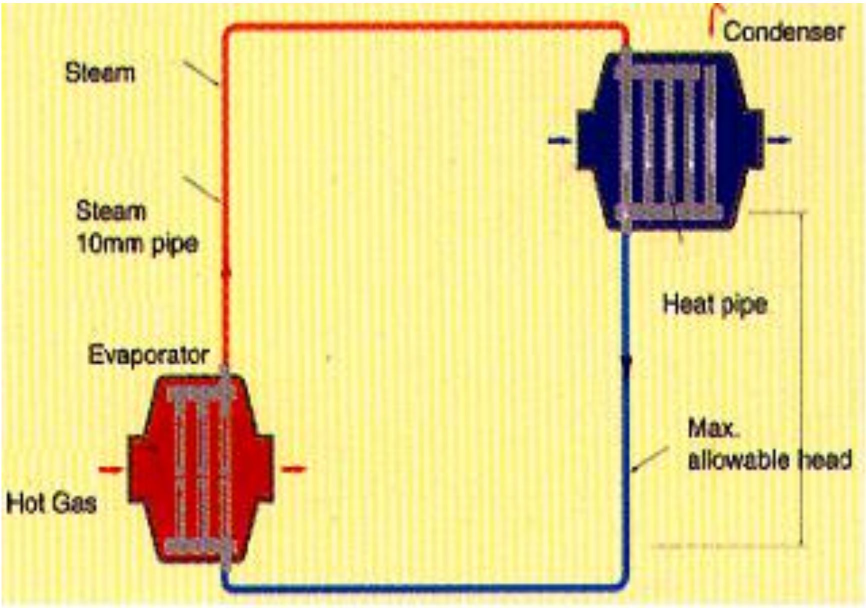


FIGURE Heat pipe for waste heat recovery

Waste Heat Recovery System

❑ Heat Exchangers vs. Heat Pipes

1. Using heat exchanger

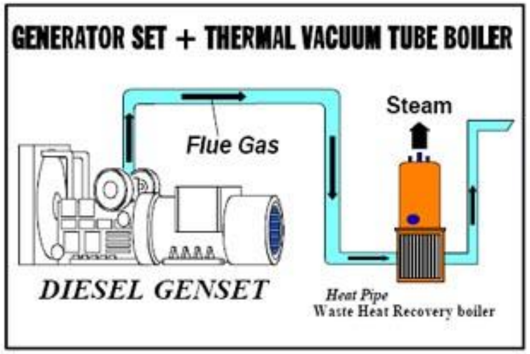
- Large surface area due to low heat transfer coefficient of exhaust gas
- Duct-connection is required between exhaust gas outlet and waste heat recover
  - ➢ **Device enlargement**

2. Using separable heat pipes

- Connect high temperature evaporator and low temperature condenser with adiabatic pipe.
  - ➢ **Duct cost saved**
- 30~50% of waste heat could be recovered.
- 5~10% of fuel saving.
- 1~3 years to recover investment cost.

Waste Heat Recovery System

❑ Heat Recovery in Boiler



Material of pipe	Carbon steel, Stainless steel
OD of base pipe (mm)	OD ∅ 25 - 219 mm
Length of Fin pipe(m)	0.5 - 1.4 Meter
Materia of Fin	Carbon steel, Stainless steel
Height of Fin(mm)	13, 15, 18, 20, 25, 30 mm
Thickness of Fin(mm)	1, 1.3, 1.6, 2, 3 mm
Density of Fin(mm)	5 - 20 mm

http://www.hamadaboiler.com
http://www.korenergy.co.kr

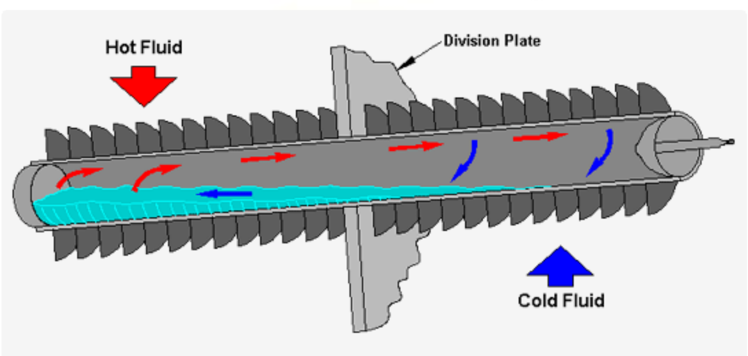


FIGURE A heat pipe tube

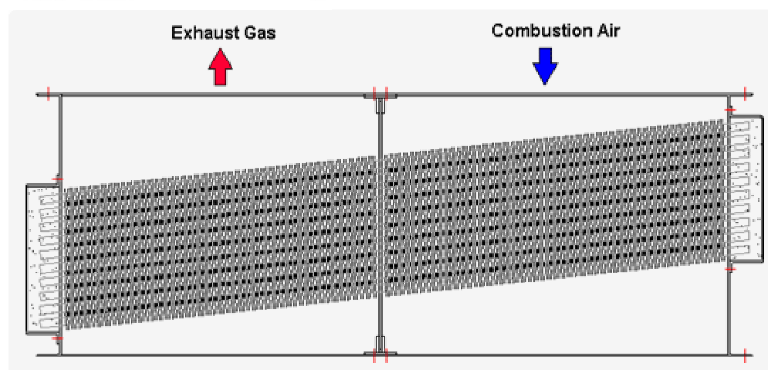


FIGURE Heat pipe type air preheater

Air-Conditioning and Cooling System

- **Heat pipe/cooling system concept, configuration and model parameter**

FIGURE Heat Pipe / Cooling Coil System

Air-Conditioning and Cooling System

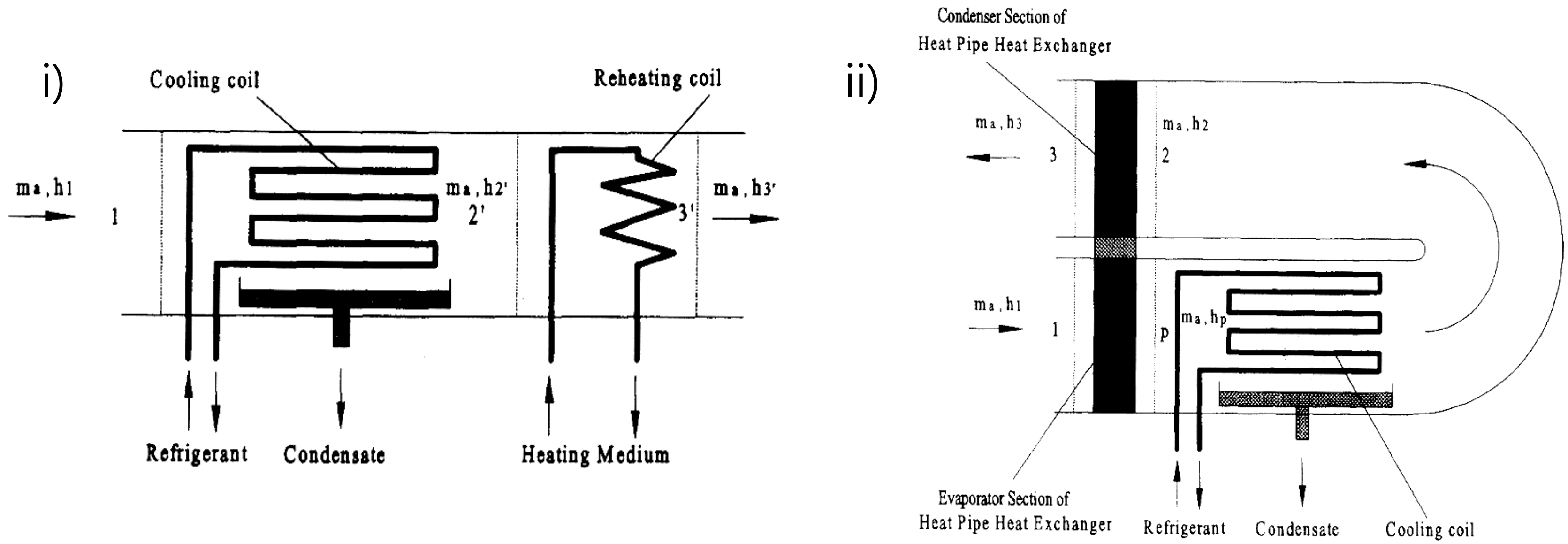


FIGURE Schematics of an air-conditioner with
i) conventional reheating coils, ii) heat pipe heat exchangers

Thermo-acoustic Refrigeration

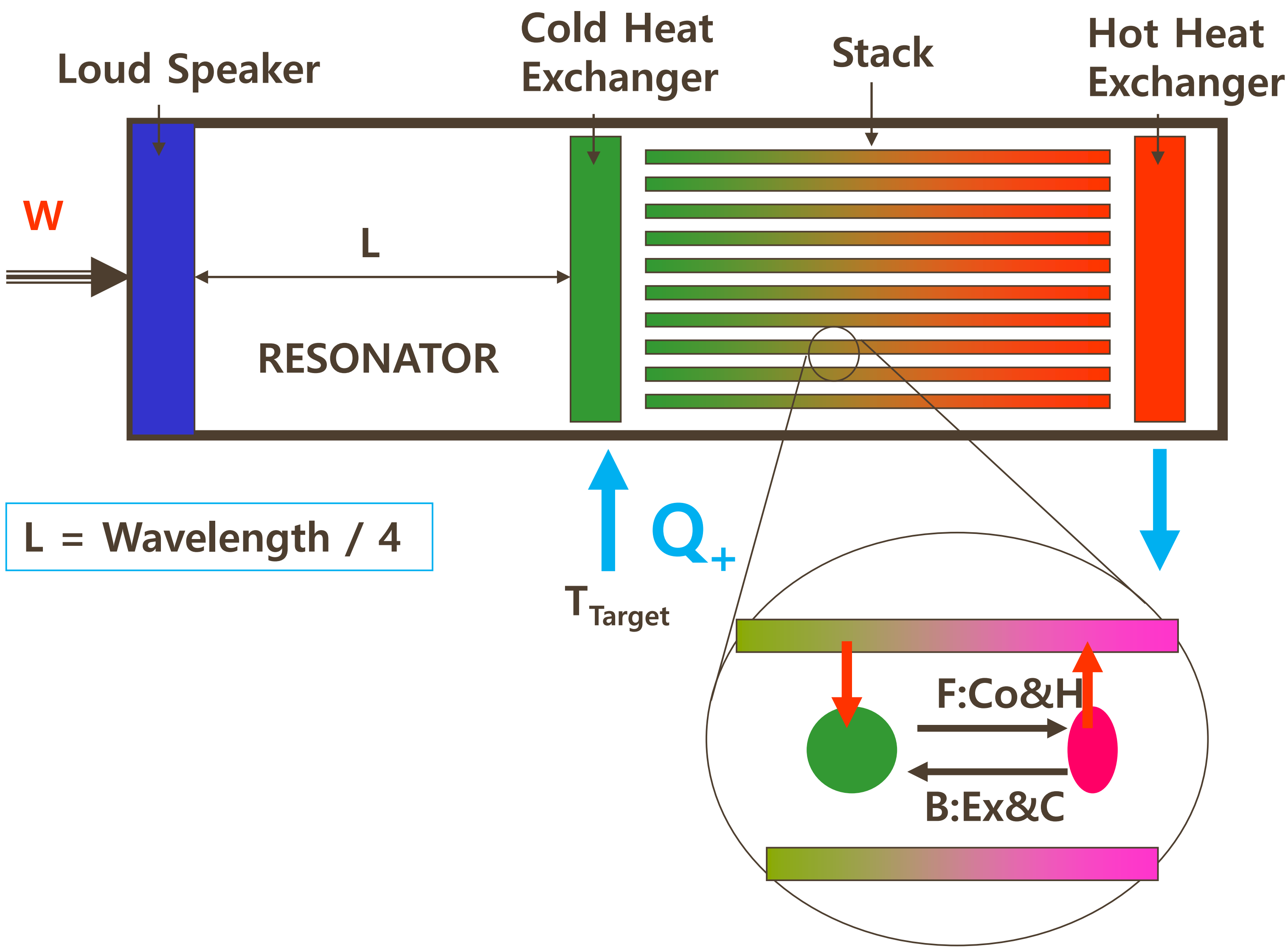
Thermo-acoustic Refrigeration

❑ Acoustic Waves

- **Transverse Pressure Waves**
- **Moving areas of High and Low Pressure**
- **Ideal Gas Law tells us:**
  - ➢ Adiabatic Compression at constant volume causes an increase in the temperature of an ideal gas.

$$\Delta T = \frac{\Delta PV}{mR}$$

Thermo-acoustic Refrigeration

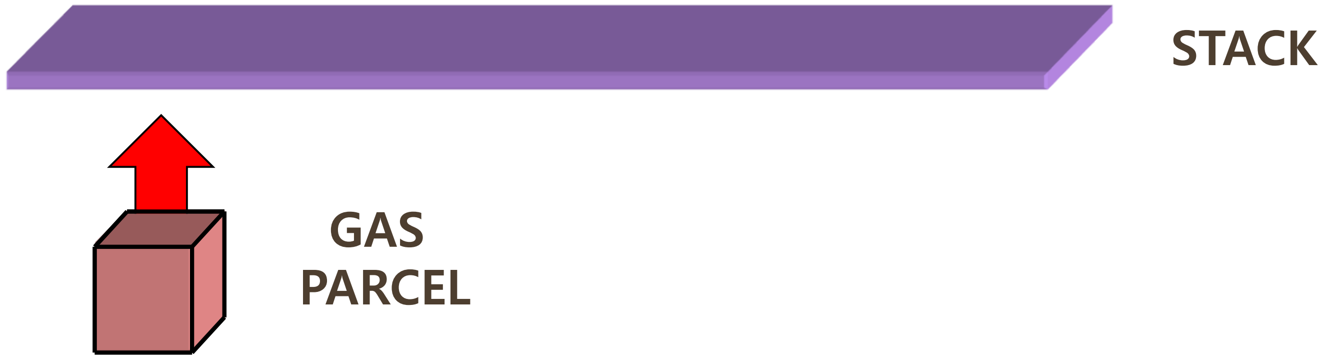


Thermo-acoustic Theory

- Gas is adiabatically compressed and translated.
- Gas heats up to a temperature greater than the local temperature of the stack.

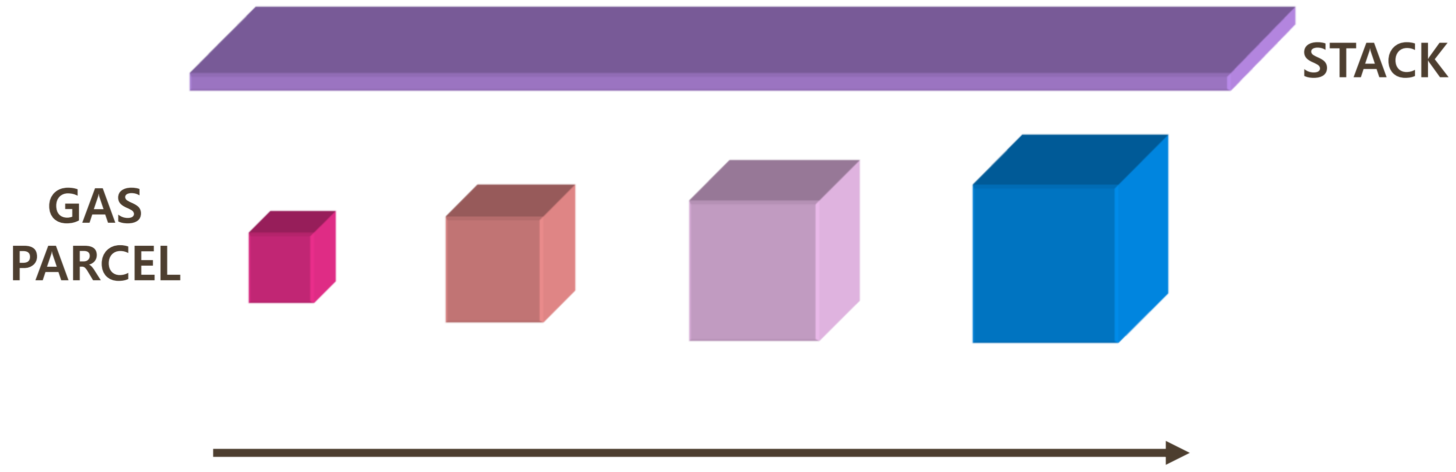
Thermo-acoustic Theory

- Gas transfers heat to the stack.
- Gas cools down and its volume slightly decreases.



Thermo-acoustic Theory

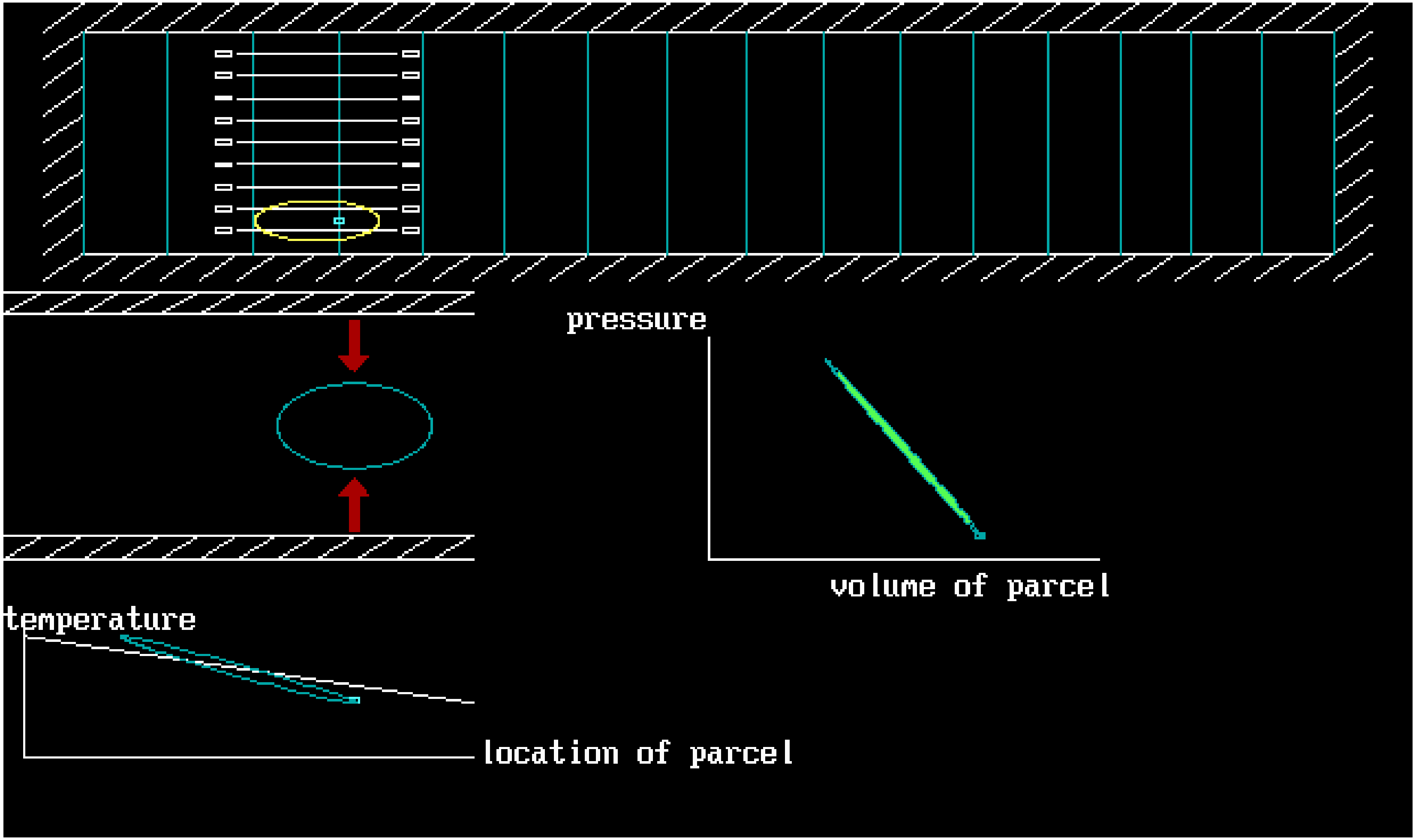
- Gas moves back to original location returning energy.
- Gas undergoes adiabatic expansion cooling down below local stack temperature.



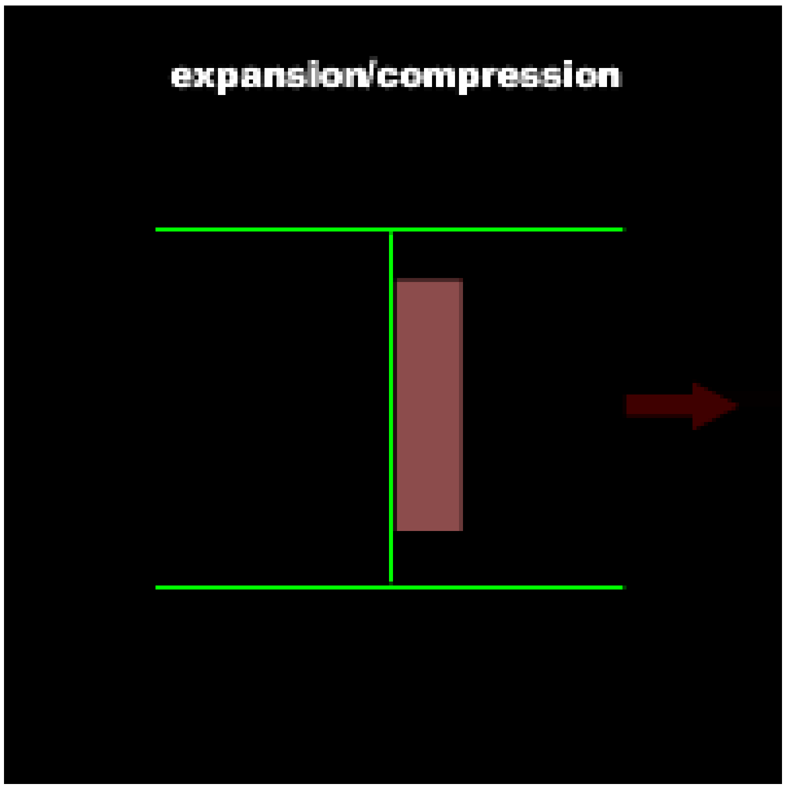
Thermo-acoustic Theory

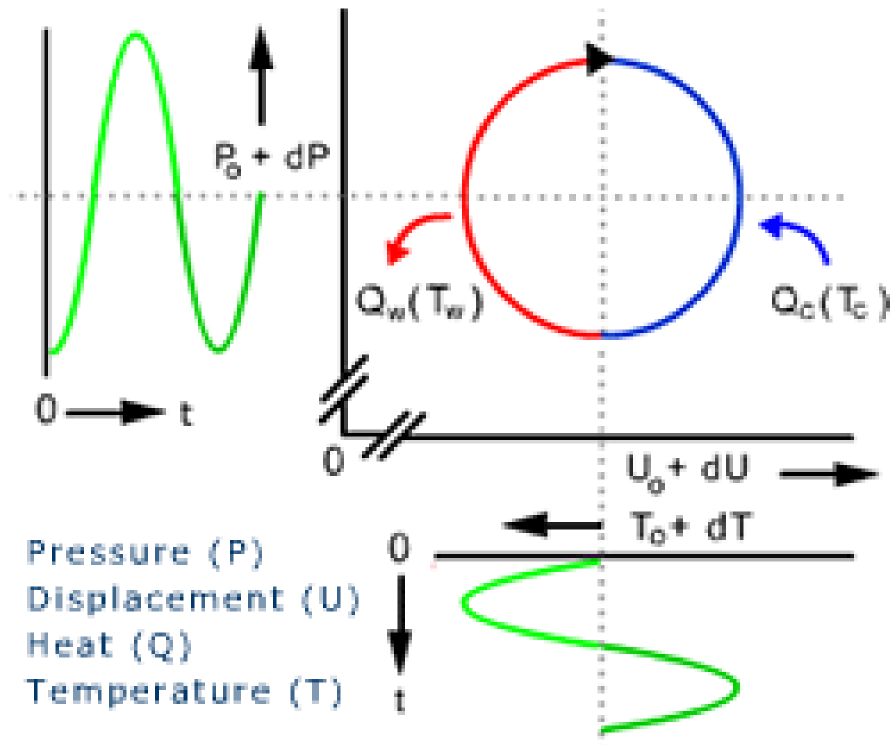
- Heat is transferred from the stack to the gas.
- Gas heats up and its volume increases.

Thermo-acoustic Theory

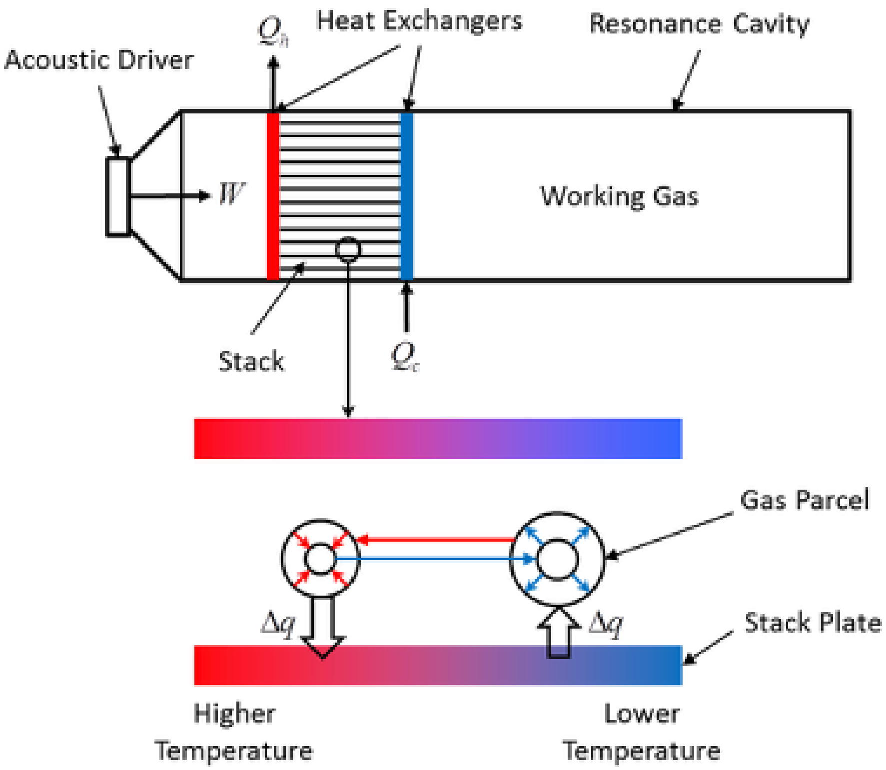


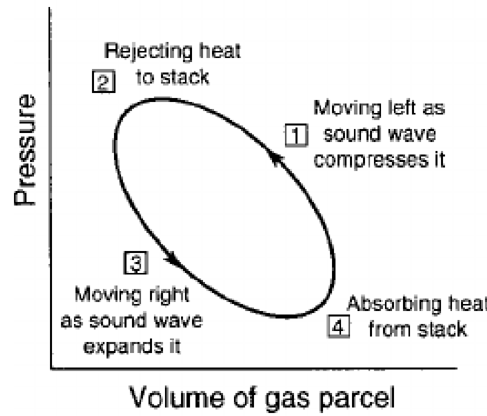
Thermo-acoustic Theory

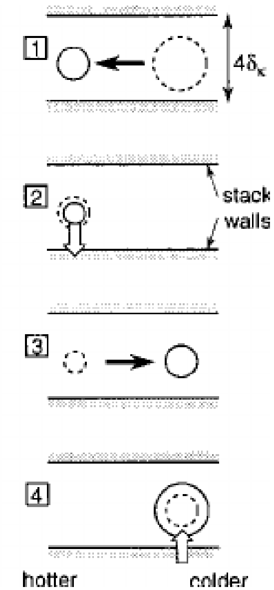


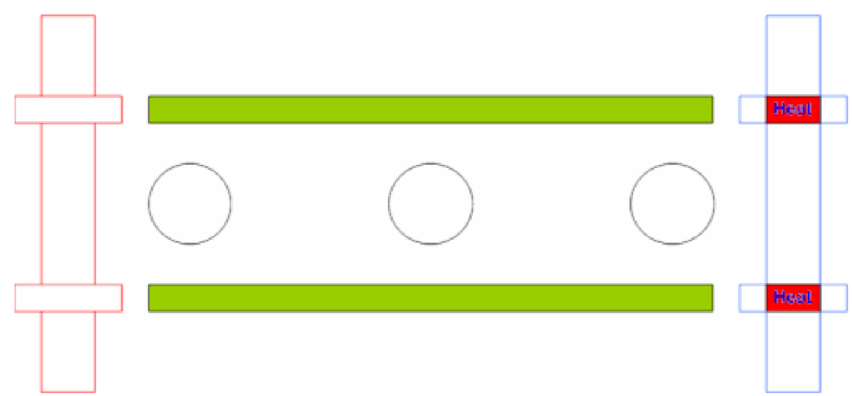


Thermo-acoustic Theory





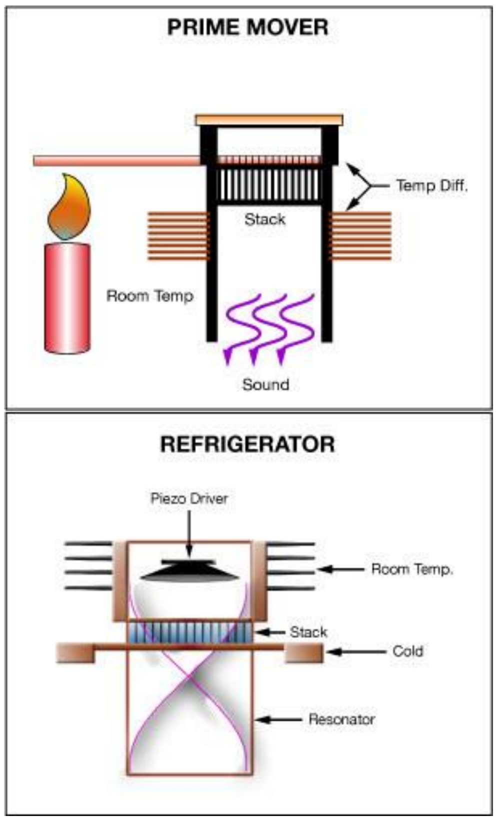




Ref. https://en.wikibooks.org/wiki/Engineering_Acoustics/Thermoacoustics

Thermo-acoustic Theory

- ❑ **Prime Mover :** **Heat** + **Resonator** → **Sound**
- ❑ **Refrigerator :** **Sound** + **Resonator** → **Heat**



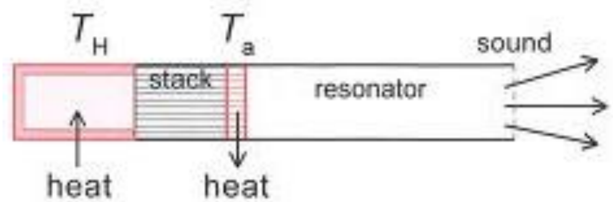


FIGURE Thermo-acoustic prime mover

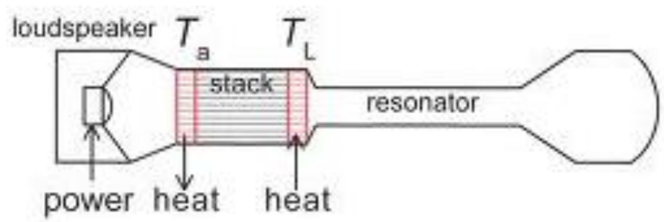


FIGURE Thermo-acoustic refrigerator

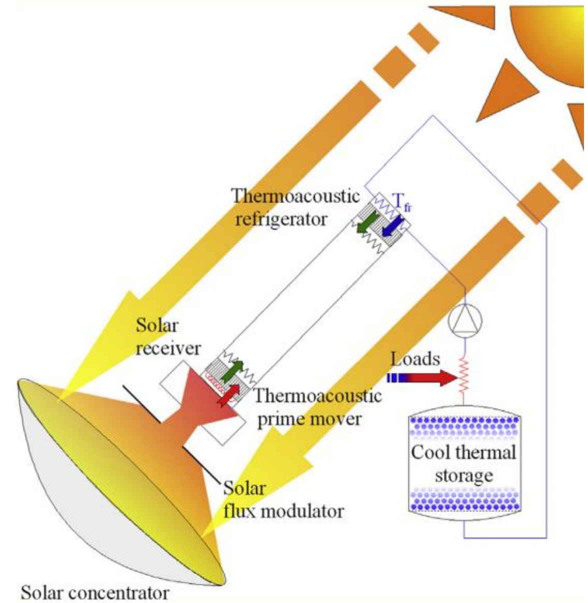
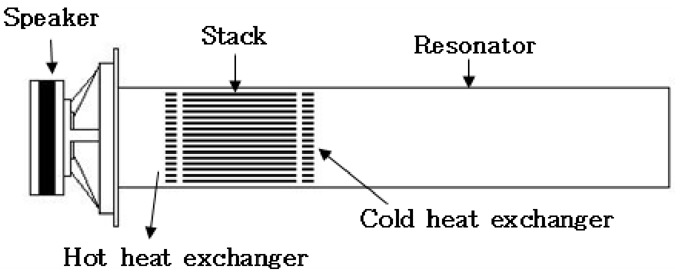
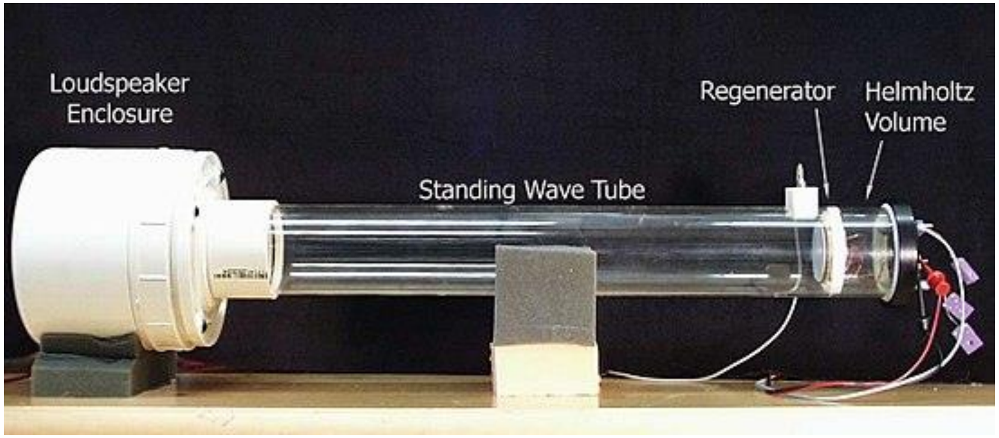


FIGURE Scheme of the solar driven thermo-acoustic refrigerator plant.

Ref. Maxim Perier-Muzet et al., 2014, Design and dynamic behaviour of a cold storage system combined with a solar powered thermoacoustic refrigerator, Applied thermal engineering, Vol 68, pp. 115-124

Thermo-acoustic Refrigeration





- Speaker
- Hot heat exchanger
- Cold heat exchanger
- Resonator
- Stack

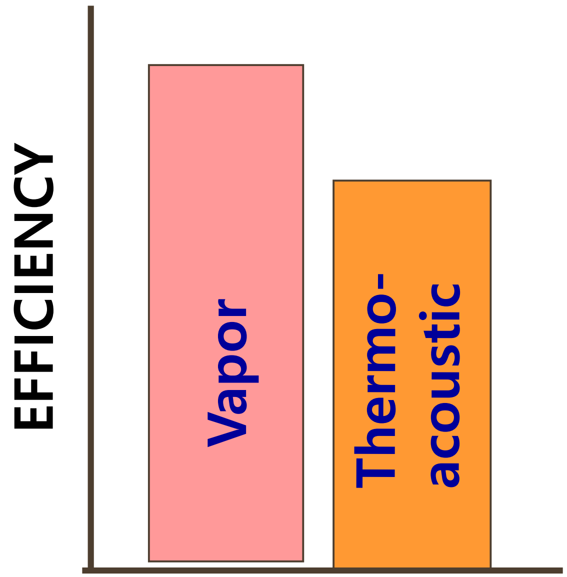
FIGURE Two stacks of different materials

Ref. https://en.wikibooks.org/wiki/Engineering_Acoustics/Thermoacoustics

Ref. https://sites.google.com/site/professorarturjjaworski/thermoacoustics

Thermo-acoustic Efficiency

- ❑ **Due to technical immaturity**
  - Heat exchangers
  - Sub-systems
- ❑ **Thermo-acoustic refrigerators are well suited to proportional control.**



Currently
20-30%
Less

Magnetic Cooling

Magnetic Heat Pump System

Development Status	Technology Options
R&D	Brayton-Cycle Heat Pump* Duplex-Stirling Heat Pump Evaporative Liquid Desiccant A/C Ground-Coupled Solid Desiccant A/C* Thermoacoustic Thermoelastic Thermoelectric* Thermotunneling
Emerging Technology	Ejector Heat Pump Magnetocaloric Membrane Heat Pump Standalone Liquid Desiccant A/C Vuilleumier Heat Pump
Commercially Available	Absorption Heat Pump Adsorption Heat Pump Evaporative Cooling Standalone Solid Desiccant A/C

* These technologies are commercially available either as supplements to vapor-compression technology or as the core technology in non-HVAC applications; however, their application as complete HVAC systems is still in the R&D stage.

FIGURE Emerging technologies for non-vapor-compression HVAC systems (DOE, 2014)

Technology	Theoretical Maximum Carnot Efficiency	State of Development
Thermoelectric	25-35%	Commercial
Thermionic	20-30%	Experimental
Thermo-tunneling	50-80%	Experimental
Thermoacoustic	60-100%	Prototype
Magnetic	50-60%	Prototype
Vapor Compression	70-80%	Commercial

FIGURE Carnot efficiencies of each refrigeration system and their extent of development (DOE, 2010)

Table 1
Exergetic efficiencies of cooling technologies.

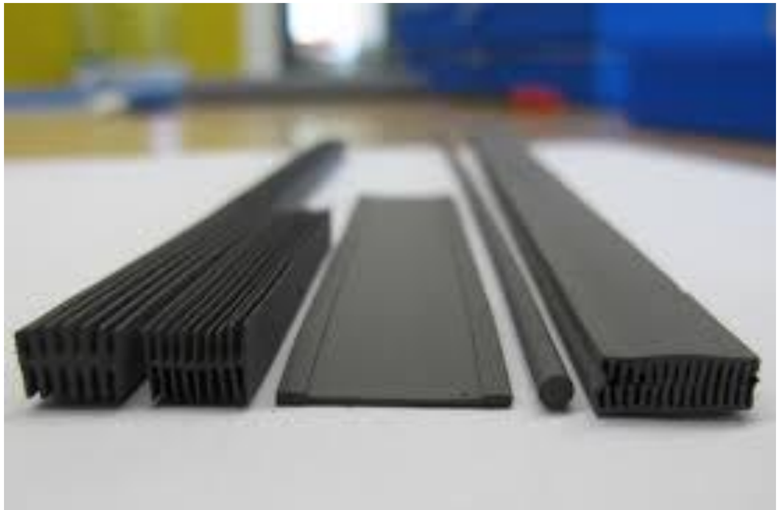
Cooling/refrigeration technology	Φ Parasitic losses not included	Φ Parasitic losses included
Vapor compression cycle	0.63 (e)	0.50 (e)
Magnetic refrigeration/cooling	0.2–0.6 (e)	

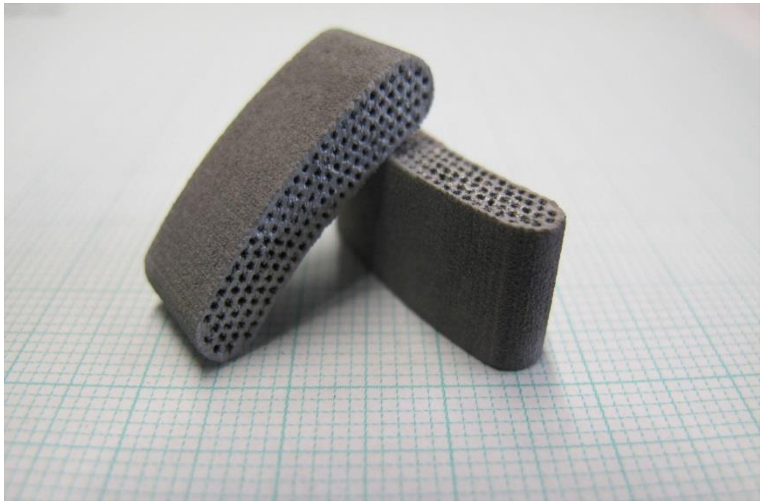
FIGURE Comparison of exergy efficacies between conventional vapor-compression and magnetic refrigeration cycle (Brown, 2014)

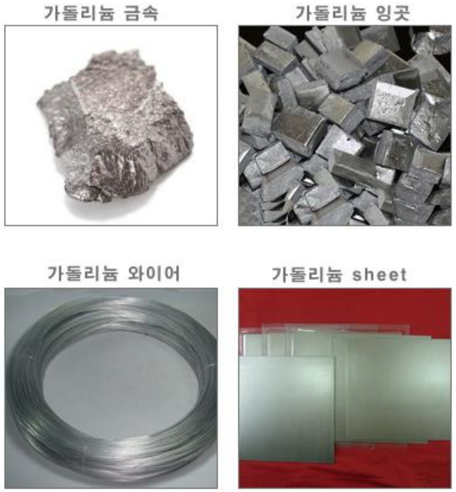
- Different types of refrigeration technologies are comprehensively under development to overcome the limitations of an inherent vapor-compression refrigeration cycle.
- So far, magnetocaloric refrigeration (MR) is evaluated as one of the emerging technologies by DOE, USA.
- The MR system is characterized by competitive Carnot and exergy efficiencies.

Magnetic Cooling

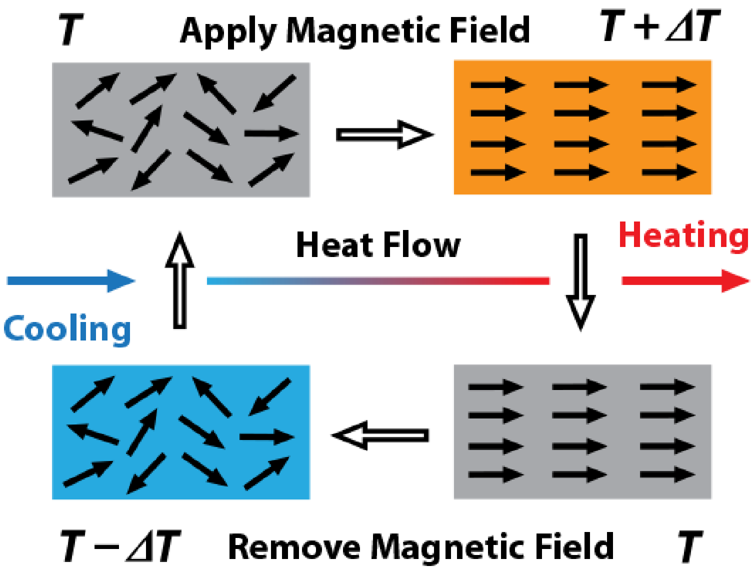
Magnetocaloric Materials

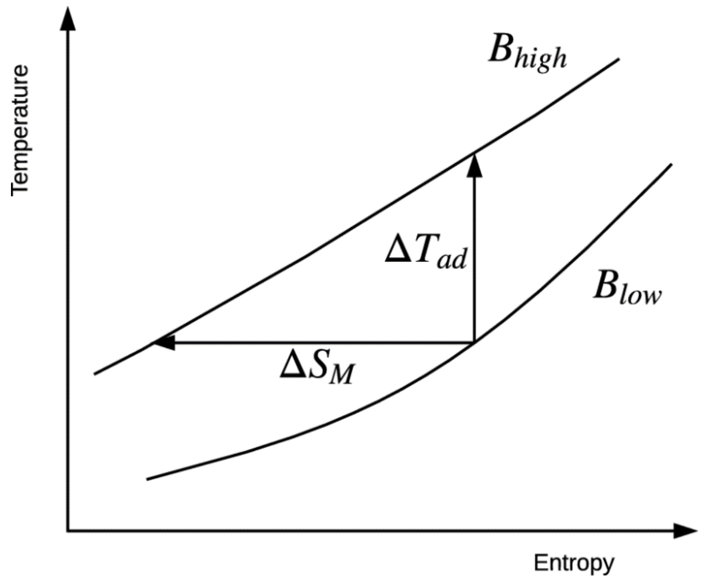






Magnetocaloric Materials





- Entropy change when magnetocaloric material under magnetization or demagnetization
- In reversible adiabatic process... $S_T(T,B) = S_M(T,B) + S_L(T) =$ constant
  - T : Temperature
  - B : Magnetic field
- Isochoric process
  - $ds_L = c_v \frac{dT}{T}$

Magnetic Cooling

Magnetocaloric Effect

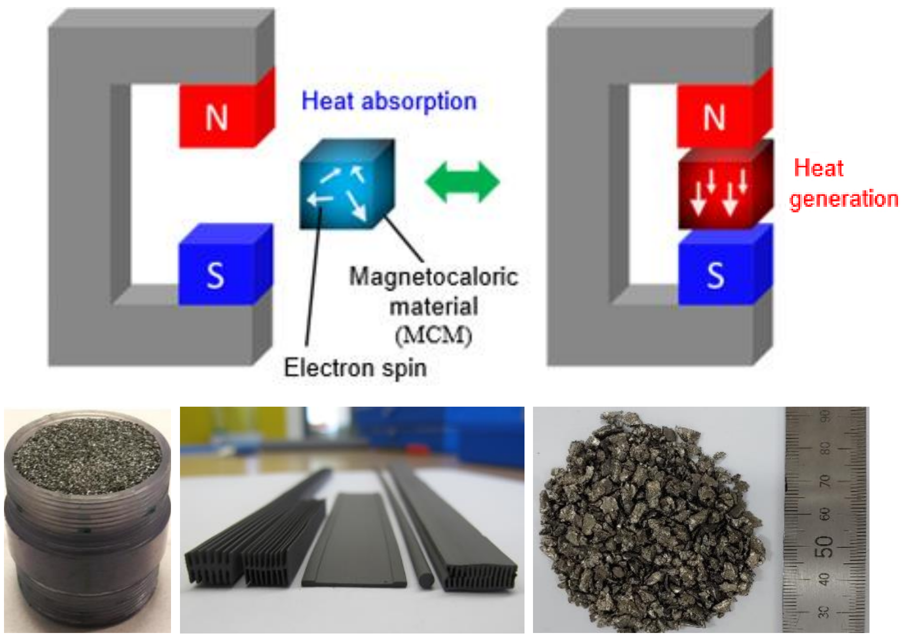


FIGURE (Top)Magnetocaloric effect (Fujikura). (Bottom) Different shapes of magnetocaloric materials (Navickaité, 2018, Fraunhofer IFAM)

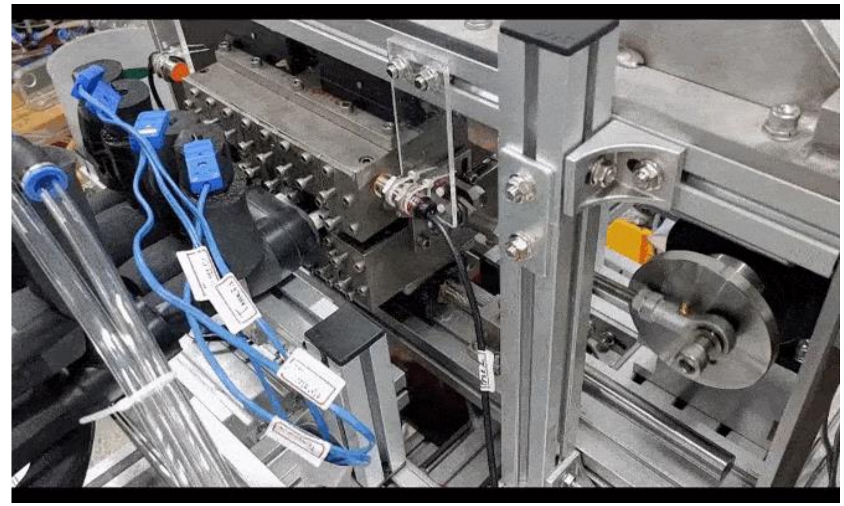
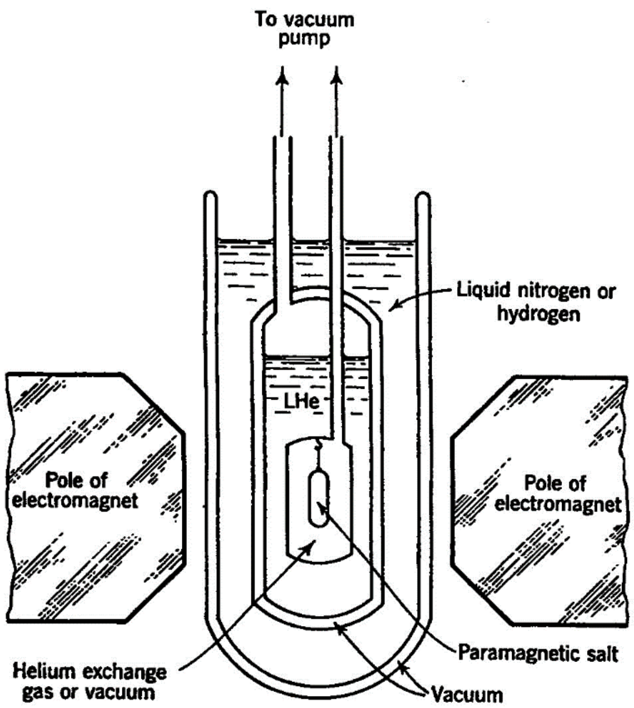


FIGURE Magnetization and demagnetization of AMRs

- Magnetocaloric effect (MCE) is reversible entropy change of a magnetocaloric material (MCM) due to the transition of arrangements of magnetic dipole under variation of magnetic field around it.
- Under the adiabatic process, temperature of the MCM rises up when magnetized, or falls down when demagnetized.

Magnetic Cooling

Apparatus for Magnetic Cooling



Magnetization and thermal equilibrium

- Paramagnetic salt, Gaseous He, LHE, LN and LH

LN, LH: Thermal Insulation

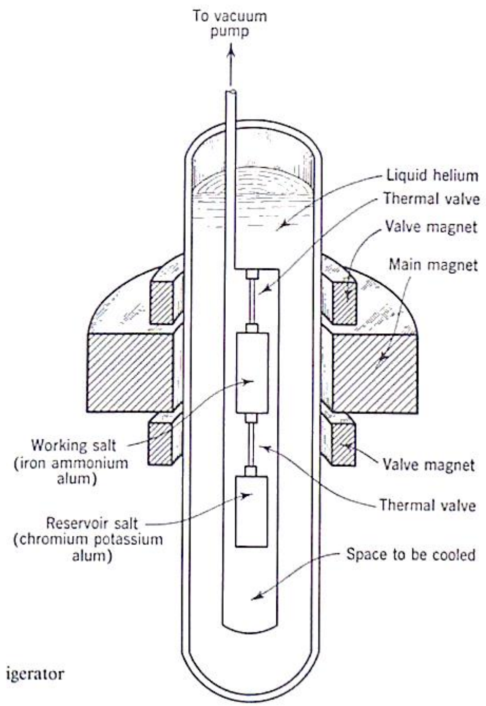
LHe to vaccum pump: Maintains LHe boiling → $T = 4.2K$

Gaseous He: Exchange gas

- Magnetization and thermal equilibrium
  - Paramagnetic salt, Gaseous He, LHE, LN and LH
- LN, LH: Thermal Insulation
- LHe to vaccum pump: Maintains LHe boiling → $T = 4.2K$
- Gaseous He: Exchange gas

Magnetic Cooling

Magnetic Refrigeration Systems



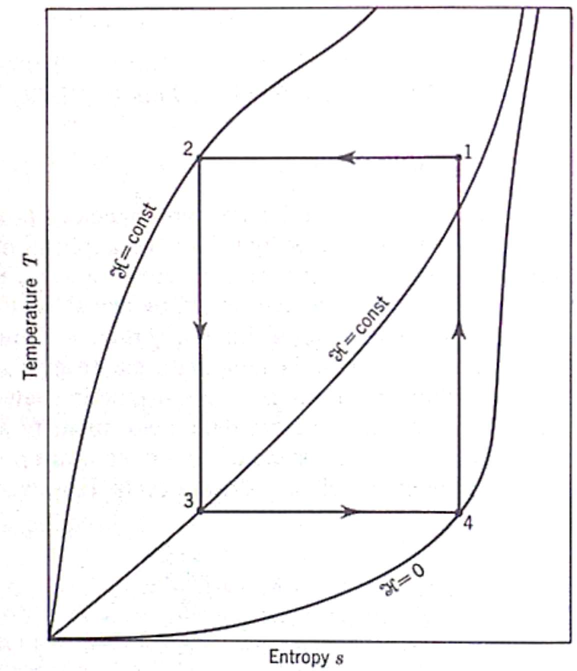
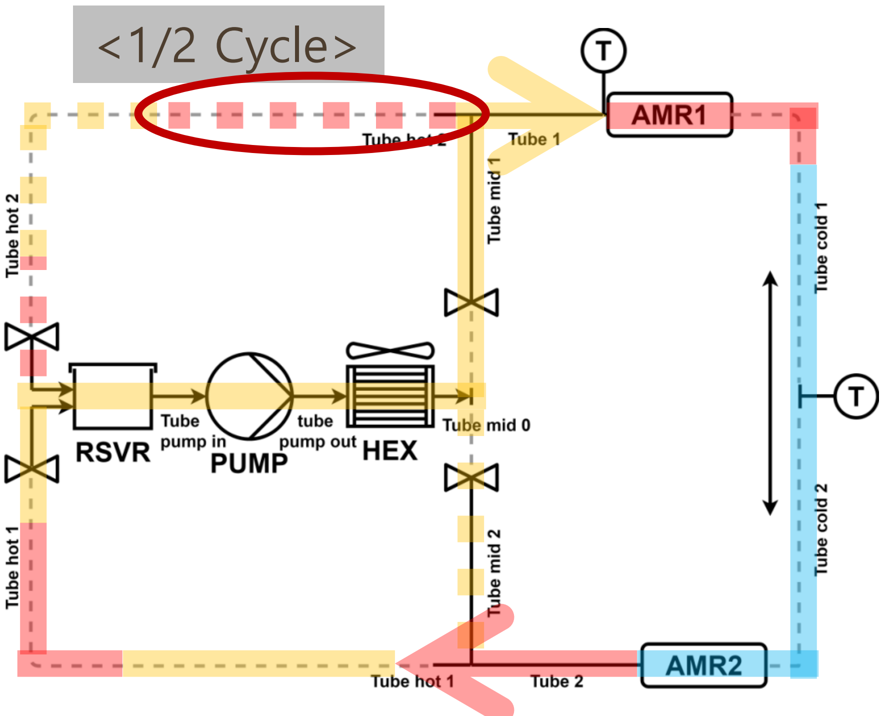
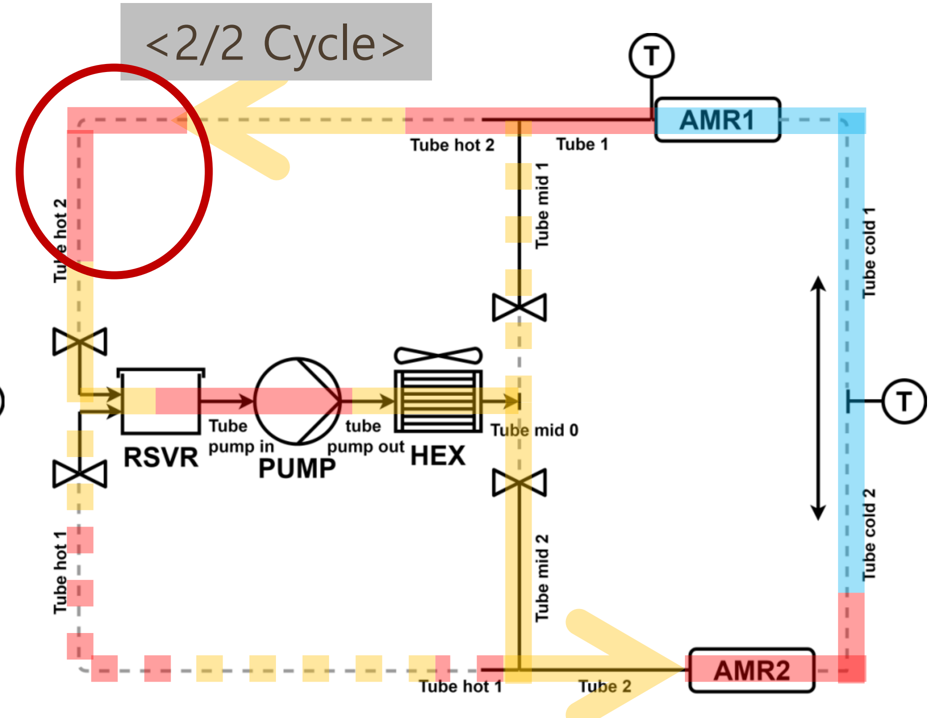


Fig. 5.27. Thermodynamic cycle for the magnetic refrigerator.

- Purpose: Reducing reservoir salt temperature
  - 1-2: Magnetized, -<-(w) –x- (r)
  - 2-3: Demagnetized, -x-(w)-x-(r)
  - 3-4: Demagnezied, -x-(w)-<-(r)
  - 4-1: Magnetized, -<-(w)-x-(r)

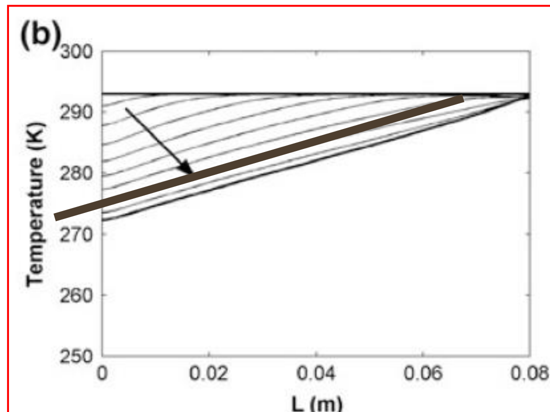
Magnetic Refrigeration Systems





RSVR : Reservoir,
AMR : Active Magnetic Regenerator

- **Hot fluid releases heat in the heat exchanger**
- **Total internal energy in the system reduces**



Question and Answer Session