# M2-8: Waste Heat Recovery

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Capacity Development Training Program on
**Energy Auditing and Energy Management**





## Factors Affecting Waste Heat Recovery

- Temperature of waste heat source
- Minimum temperature to which waste heat can be cooled
- Temperature to which the designed fluid is to be heated
- Flow rate of the fluid
- Chemical composition of waste fluid
- Properties of waste fluid ($C_p$, $\mu$, $\rho$, $k$)
- Corrosive elements in the exhaust fluid





## Common Methods to Utilize Waste Heat

- Direct utilization
- Energy cascading
- Cogeneration
- Recuperators
- Regenerators
- Waste heat boilers

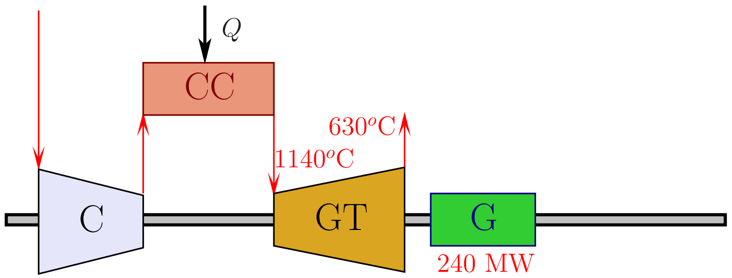




## Classifications of WHR Equipment

- **Gas-to-gas heat exchanger** (Graphite heat exchangers, stack-type recuperators, direct contact recuperator, plate fin (ceramic and metal)heat exchangers and ceramic tubes)
- **Gas-to-liquid heat exchanger** (waste heat boilers, economizers and power generators)
- **Liquid-to-liquid heat exchanger** (shell-and-tube, spiral, coil, finned-tube, plate-and-frame (plate), and run-around heat exchangers)
- **Other low-temperature WHR equipment** (heat pumps, and heat pipes)

## Gas Turbine Cycle

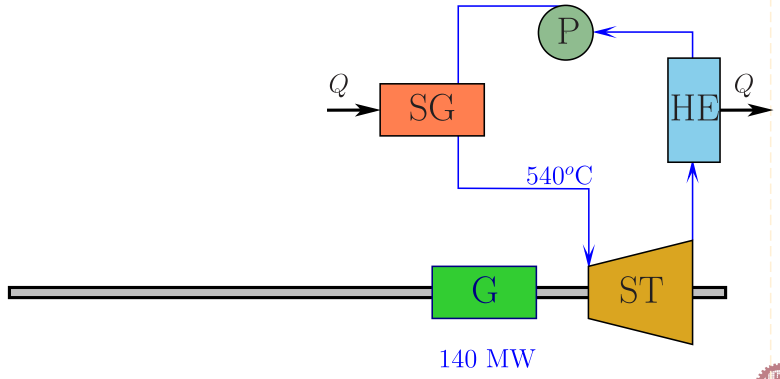



T1340





## Rankine Cycle

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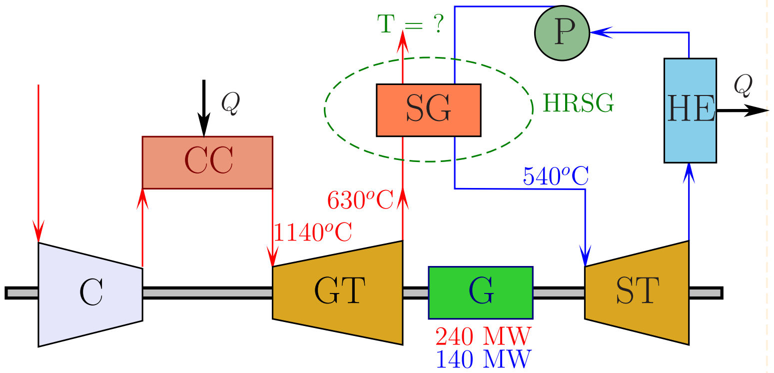
## Combined Gas Turbine + Rankine Cycle

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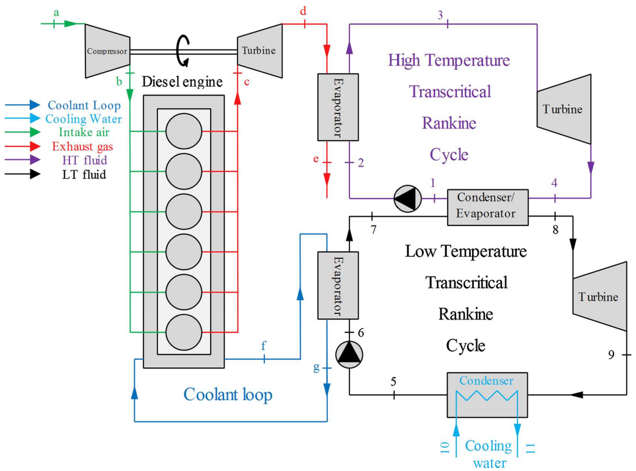
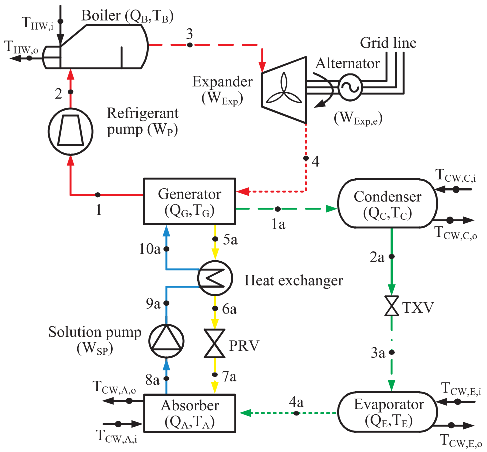
## Engine Waste Heat Recovery using ORC




T1156

## ORC + Absorption Refrigeration System



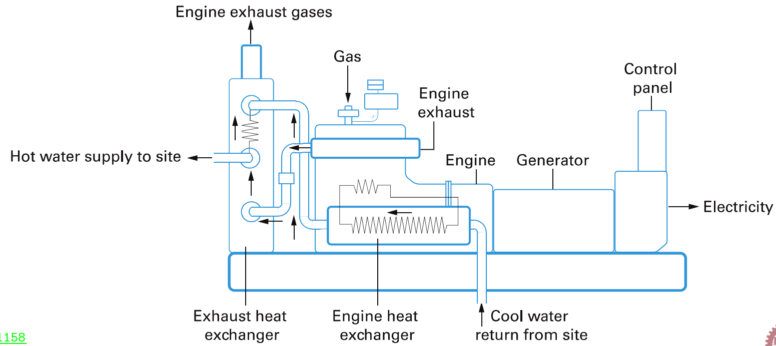

T1157





## Combined Heat and Power (CHP) & WHR

- **CHP** plants achieve a significant degree of energy efficiency by simultaneously generating electricity and heat.



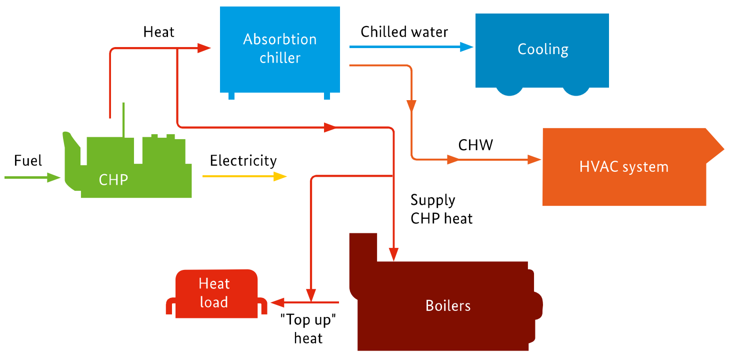

T1158





## Combined Heating, Cooling and Power

- Overall efficiency is further improved by **tri-generation** - using additional absorption chillers to convert waste heat into cooling.



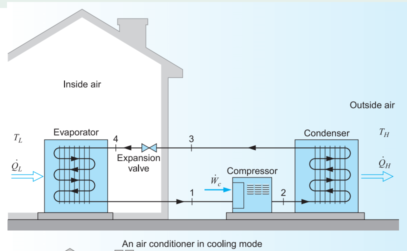

T1159



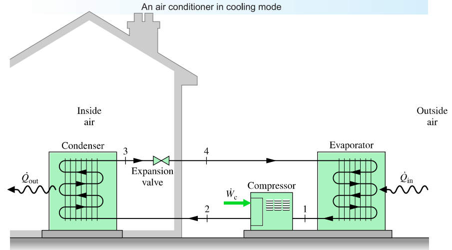


## AC & Heat Pump

T144

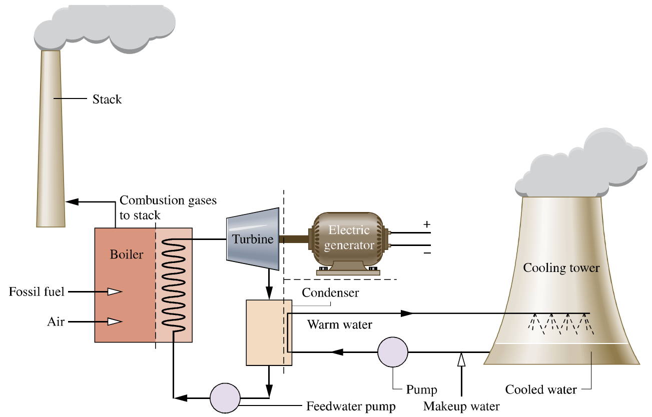



T268




*Heat Pump*

## Applications of Heat Exchangers

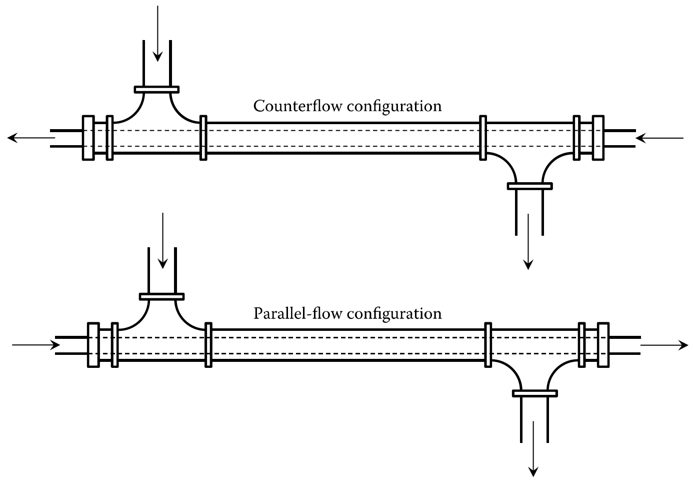



T193

*Components of a simple vapour power plant*





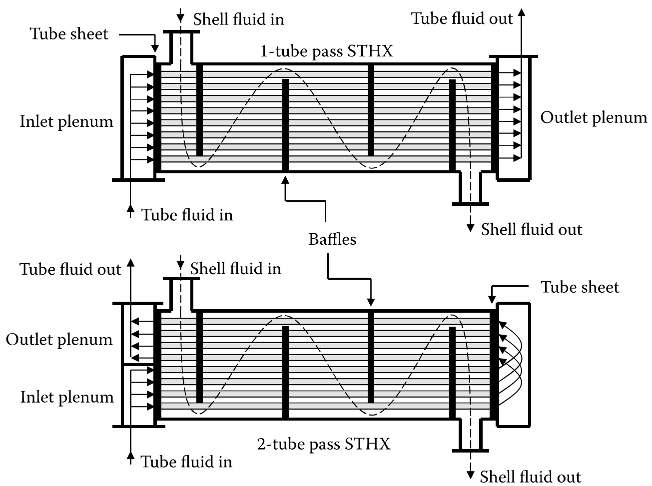



T734

*Counterflow and parallel-flow configurations for double-pipe heat exchangers.*





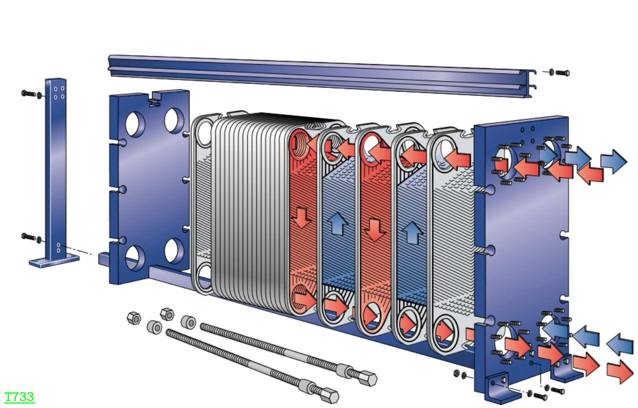



T735

*1-tube pass and 2-tube pass STHXs.*





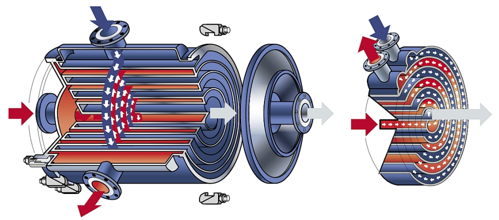


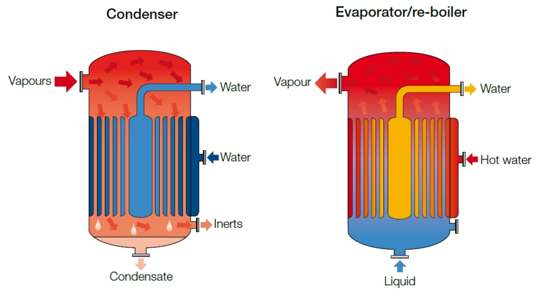
T733

T736

*Gascated plate HX.*

T731



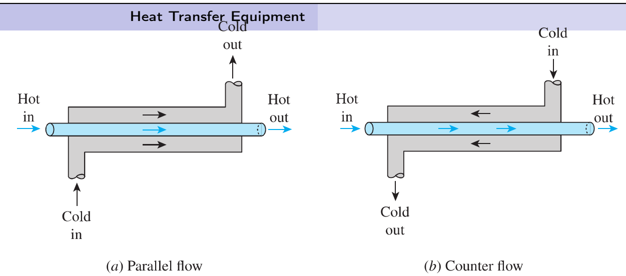



T732

*Spiral-plate HX.*

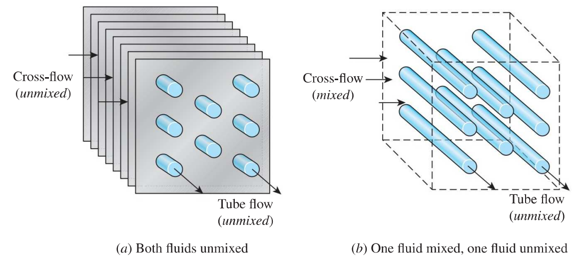







T724

*Parallel-flow and Counter-flow HX*



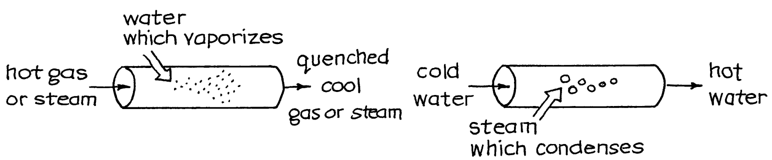

T725

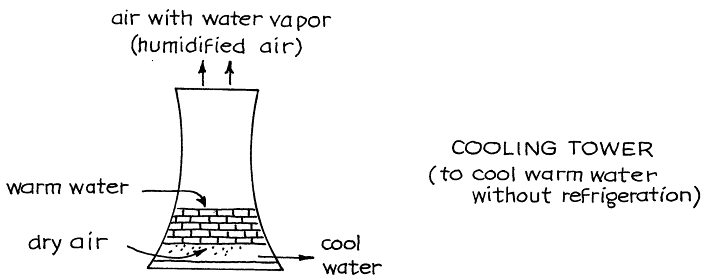
*Cross-flow HX*





## HX: Direct Contact



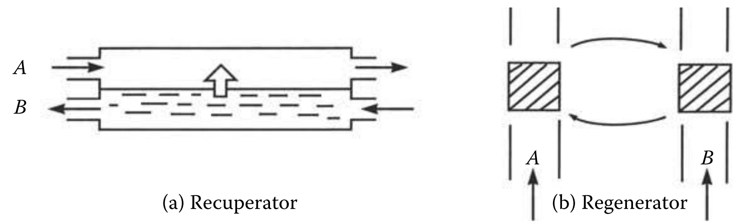

T647

*Fluid-fluid direct-contact exchangers where one phase can dissolve in the other.*





## HX: (a) Recuperator / (b) Regenerator

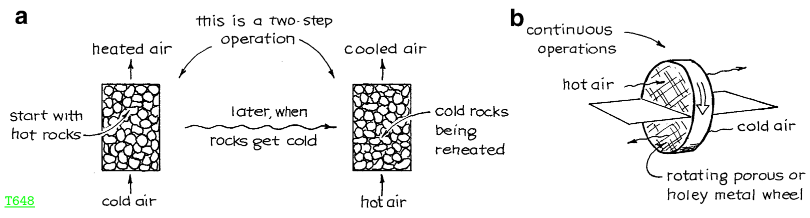



T642

**Recuperator:** Hot and cold fluids are separated by surfaces, and heat is transferred by combination of convection to and from the walls and conduction through the walls.

**Regenerator:** Hot and cold fluids alternatively occupy the same space in the exchange core (matrix). Matrix serves as the heat storage device that is periodically heated by the warmer fluid and then transfers heat to the cold fluid.

## HX: Regenerator

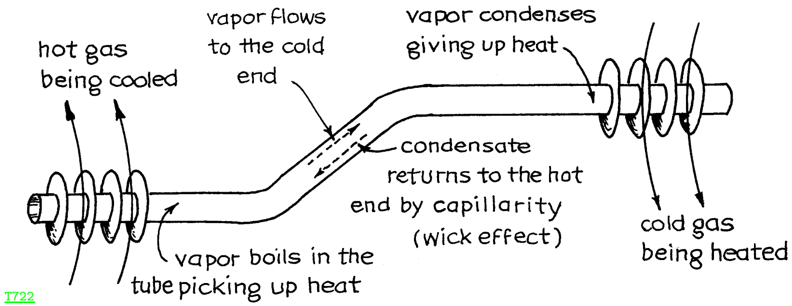



*Heat regenerators or heat storing exchangers: (a) Heat storing solids are stationary; (b) heat storing solids continuously circulate between hot and cold streams*





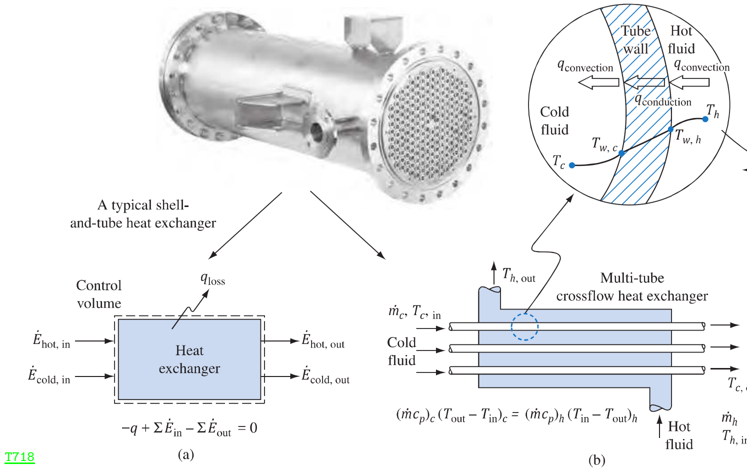
## HX: Heat Pipe




*The heat pipe transfers heat from one place to another, often far apart.*





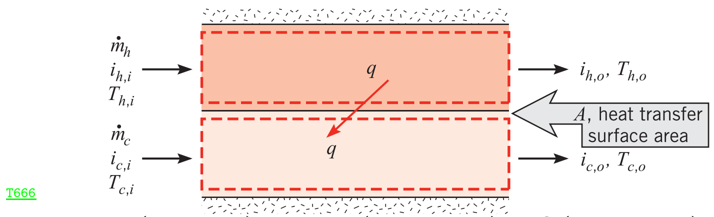



*Application of and contrast between (a) a thermodynamic and (b) a heat transfer model for a typical shell-and-tube heat exchanger used in chemical processing.*





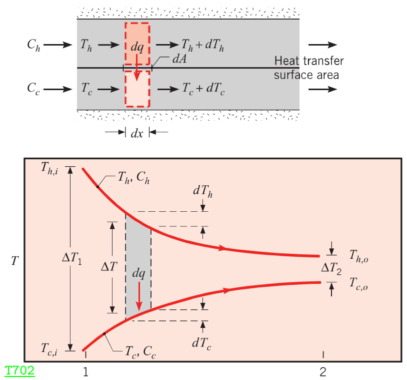
## Heat Exchanger: Energy Balance Equation



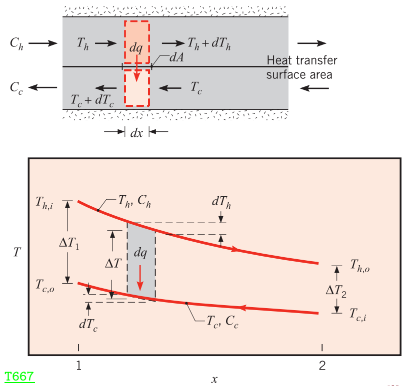

- $\dot{q} = \dot{m}_h(i_{h,i} - i_{h,o}) = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) = C_h(T_{h,i} - T_{h,o})$
- $\dot{q} = \dot{m}_c(i_{c,o} - i_{c,i}) = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) = C_c(T_{c,o} - T_{c,i})$
- $\dot{q} = UA\Delta T_m$
- $i$ is fluid enthalpy, subscripts $h$ & $c$ refer to hot & cold fluids, whereas the subscripts $i$ & $o$ designate fluid inlet & outlet conditions.
- $C \equiv \dot{m}c_p \equiv$ heat capacity rate [W/K]
- $U \equiv$ overall heat transfer coefficient [W/m$^2$ K]
- $\Delta T_m$ is an appropriate mean temperature difference.

# LMTD: Heat Exchanger

*Parallel-flow HTX* | *Counter- flow HTX*




T702




T667

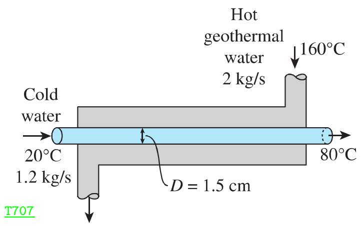
$$\dot{q} = UA\left[\frac{\Delta T_2 - \Delta T_1}{\ln(\Delta T_2/\Delta T_1)}\right] = UA\Delta T_{LM}$$





*Heat-Exchanger: Heating Water in a Counter-Flow Heat Exchanger: If $U_o$ = 640 W/m$^2$K, determine the length of the heat exchanger required to achieve the desired heating. Re-estimate the length for Parallel-Flow configuration.*

[109 m, 120 m]



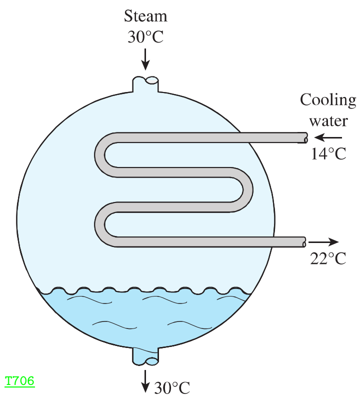

T707





*Steam Condenser: Steam condenser with surface area of the tubes is 45 m$^2$, and the overall heat transfer coefficient is 2100 W/m$^2$K. Estimate condenser capacity.*

[1.09 MW]




T706