

## 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

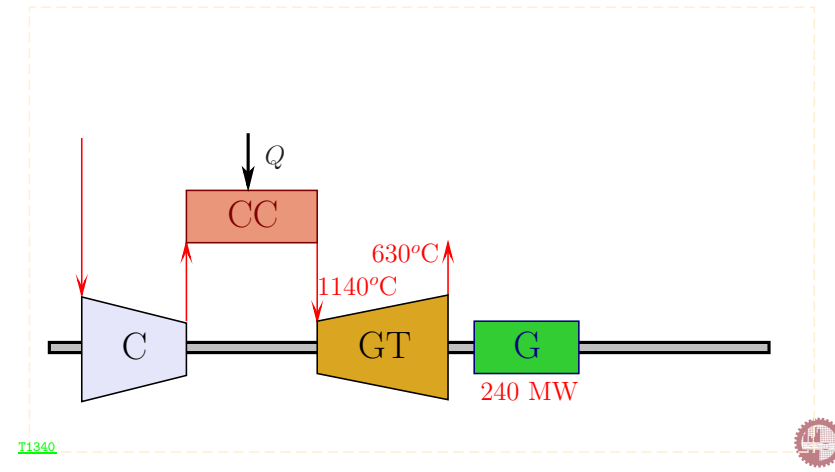


## Classifications of WHR Equipment

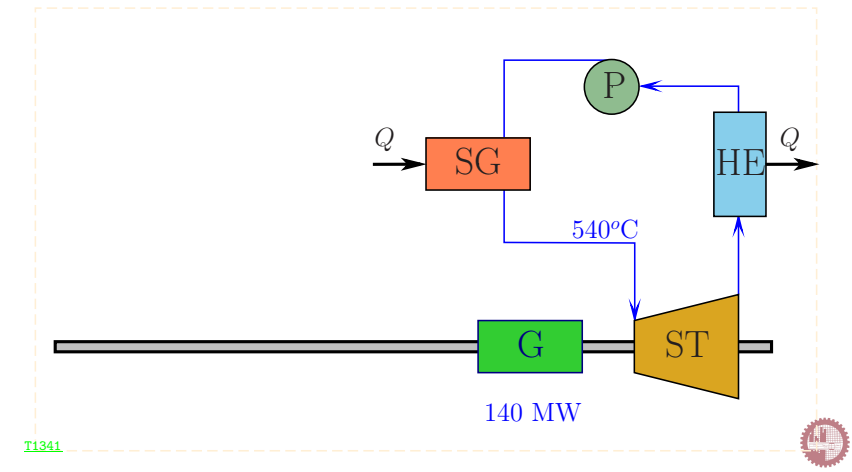
- **Gas-to-gas heat exchanger** (Graphite heat exchangers, stack-type recuperators, direct contact recuperator, plate fin (ceramic and metal) heat exchangers and ceramic tubes)
- **Gas-to-liquid heat exchanger** (waste heat boilers, economizers and power generators)
- **Liquid-to-liquid heat exchanger** (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)



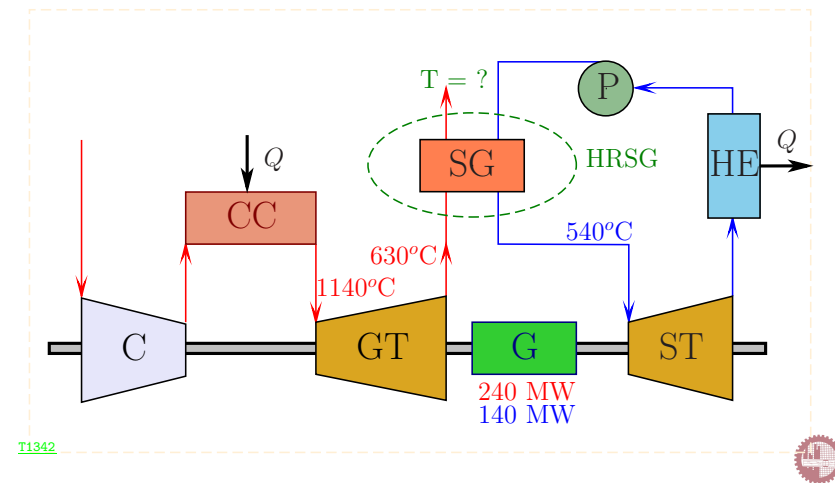
## Gas Turbine Cycle



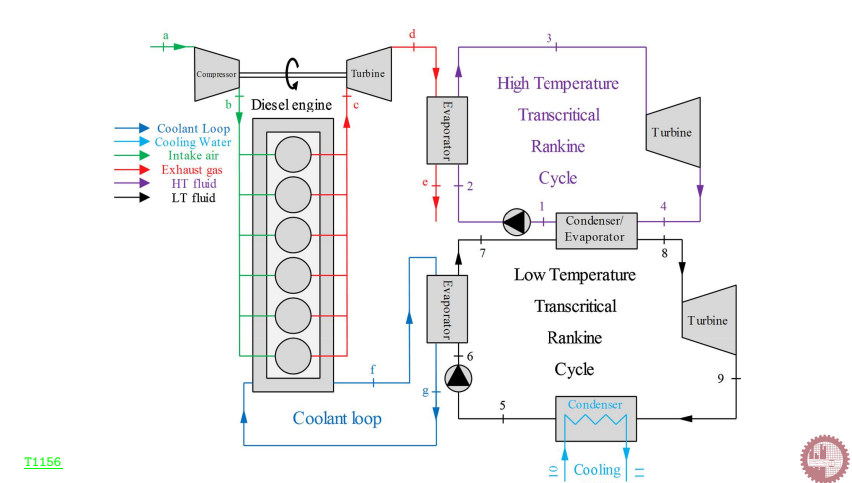
## Rankine Cycle



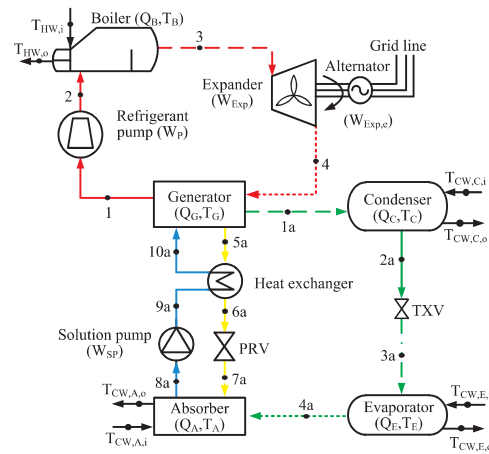
## Combined Gas Turbine + Rankine Cycle



## Engine Waste Heat Recovery using ORC



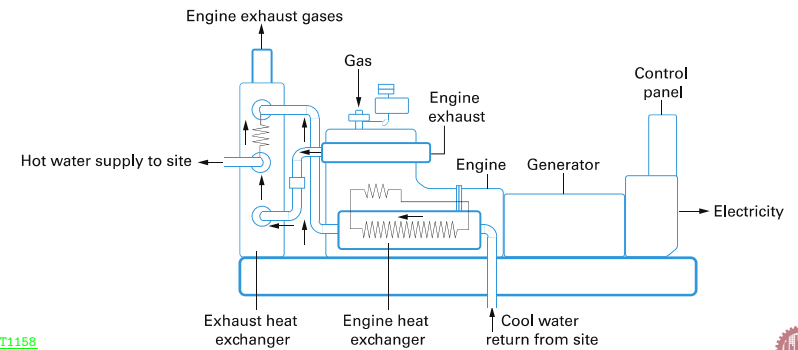
## ORC + Absorption Refrigeration System



T1157

## Combined Heat and Power (CHP) & WHR

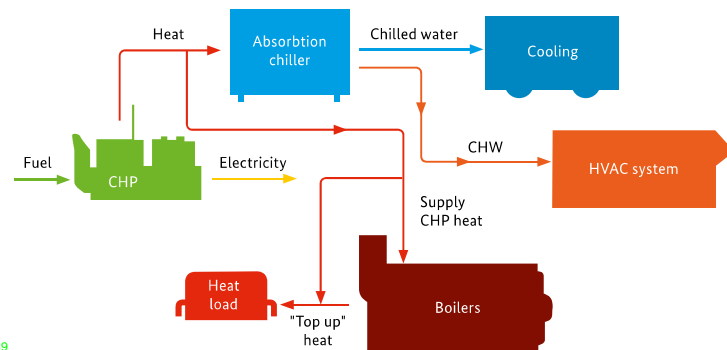
- CHP plants achieve a significant degree of energy efficiency by simultaneously generating electricity and heat.



T1158

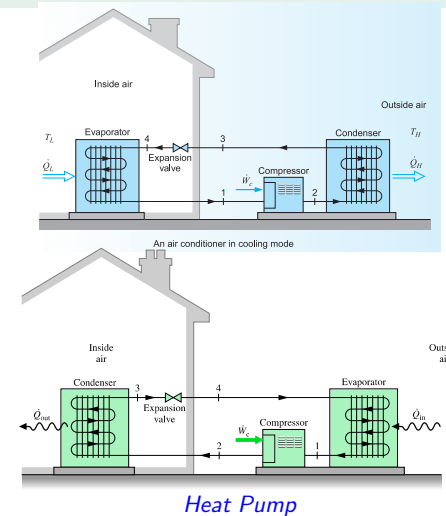
## Combined Heating, Cooling and Power

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



T1159

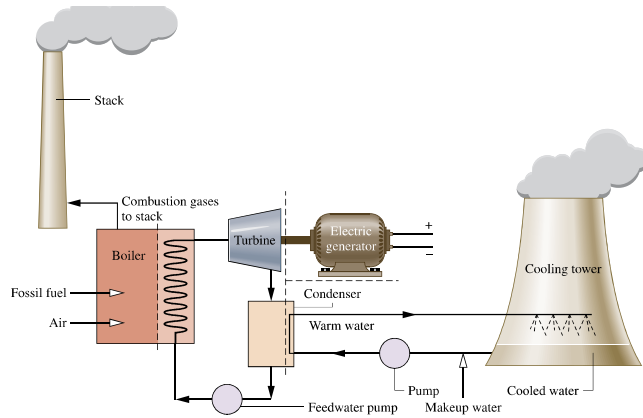
## AC & Heat Pump



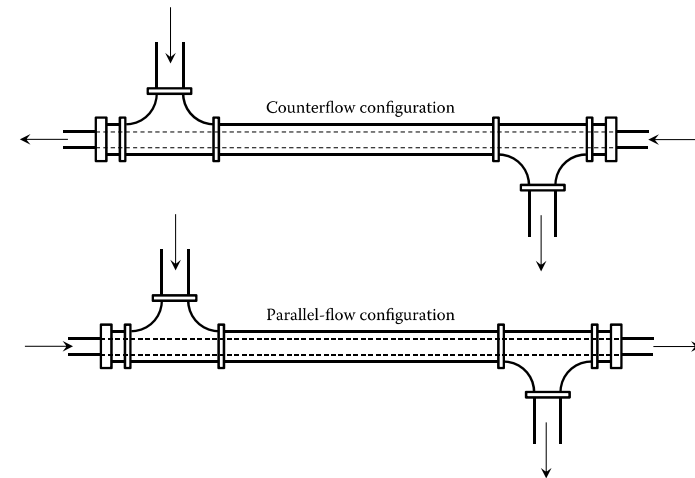
T144

T268

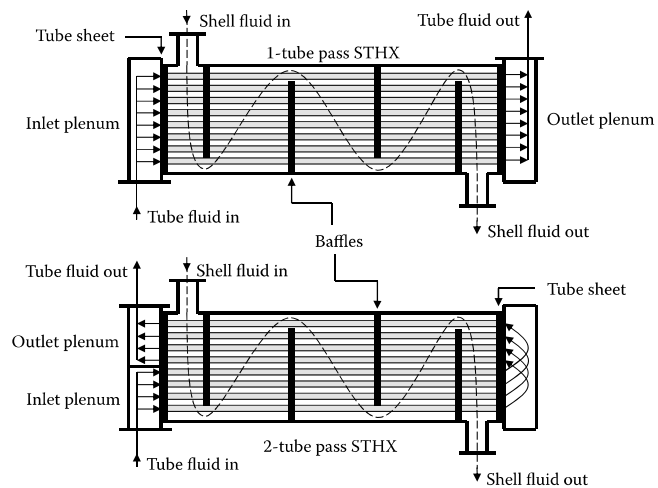
## Applications of Heat Exchangers



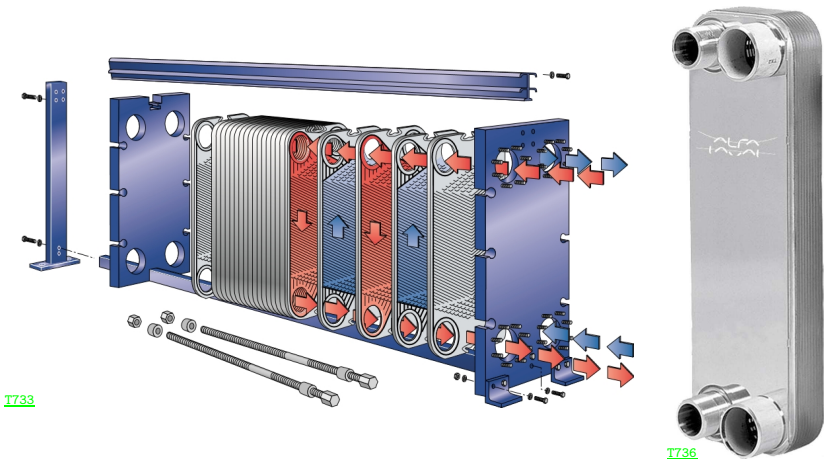
T193

*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

*Gasketed plate HX.*

Heat Transfer Equipment

The top diagram shows a shell-and-tube heat exchanger with fluid flow paths indicated by red and blue arrows. The bottom diagram shows a spiral-plate heat exchanger with two sections: a condenser and an evaporator/re-boiler. The condenser section shows vapours entering and water/condensate exiting. The evaporator/re-boiler section shows vapour entering and liquid exiting, with hot water and inerts also indicated.

T731

Condenser

Evaporator/re-boiler

Vapours

Water

Hot water

Inerts

Condensate

Liquid

*Spiral-plate HX.*

T732

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Heat Transfer Equipment

The top part shows parallel flow (a) and counter flow (b) heat exchangers with hot and cold fluid inlet/outlet arrows. The bottom part shows cross-flow heat exchangers: (a) both fluids unmixed and (b) one fluid mixed, one fluid unmixed, with tube flow and cross-flow directions indicated.

T724

(a) Parallel flow

(b) Counter flow

*Parallel-flow and Counter-flow HX*

Cross-flow (unmixed)

Tube flow (unmixed)

Cross-flow (mixed)

Tube flow (unmixed)

(a) Both fluids unmixed

(b) One fluid mixed, one fluid unmixed

*Cross-flow HX*

T725

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Heat Transfer Equipment

HX: Direct Contact

The top diagram shows a direct contact heat exchanger where hot gas or steam is quenched by cold water, resulting in cool gas or steam and steam which condenses. The bottom diagram shows a cooling tower where warm water is cooled by dry air, resulting in humidified air and cool water.

hot gas or steam

water which vaporizes

quenched

cool gas or steam

cold water

steam which condenses

hot water

air with water vapor (humidified air)

warm water

dry air

cool water

COOLING TOWER (to cool warm water without refrigeration)

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

T647

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Heat Transfer Equipment

HX: (a) Recuperator / (b) Regenerator

The top diagram shows a recuperator with two fluid streams (A and B) separated by a wall. The bottom diagram shows a regenerator with a matrix that alternates between being heated by fluid A and then transferring heat to fluid B.

A

B

(a) Recuperator

A

B

(b) Regenerator

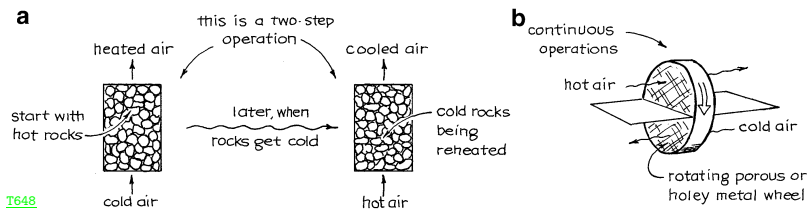
T642

**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.

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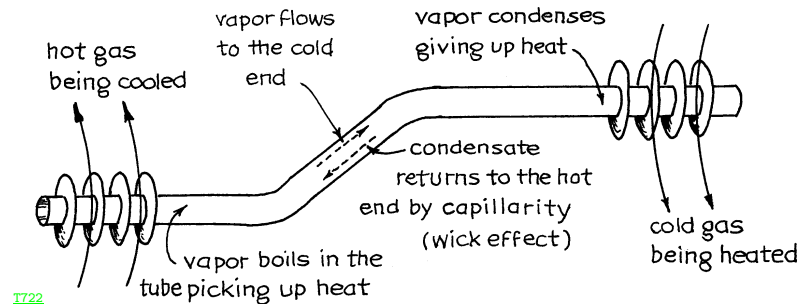
## HX: Regenerator



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

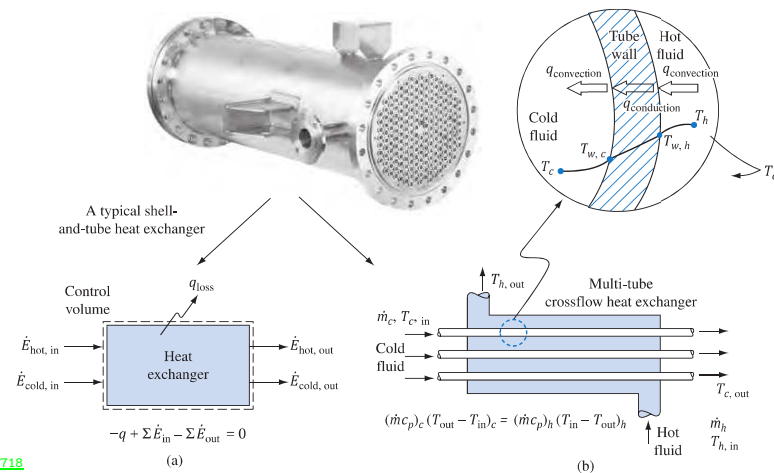


## HX: Heat Pipe



T722

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

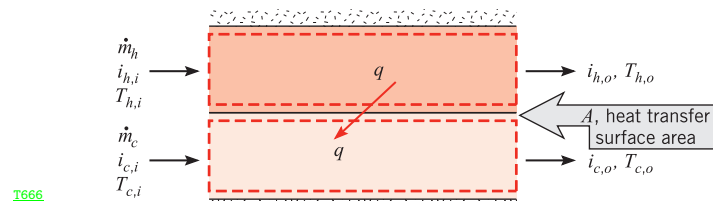


T718

*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



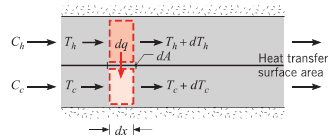
T666

- $\dot{q} = \dot{m}_h(i_{h,i} - i_{h,o}) = \dot{m}_h c_{p,h}(T_{h,i} - T_{h,o}) = C_h(T_{h,i} - T_{h,o})$
- $\dot{q} = \dot{m}_c(i_{c,o} - i_{c,i}) = \dot{m}_c c_{p,c}(T_{c,o} - T_{c,i}) = C_c(T_{c,o} - T_{c,i})$
- $\dot{q} = UA\Delta T_m$
- $i$  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<sup>2</sup> K]
- $\Delta T_m$  is an appropriate mean temperature difference.

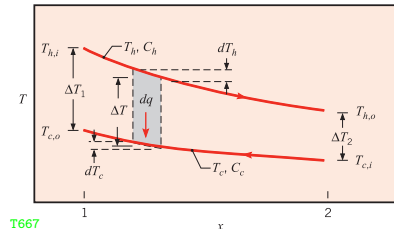
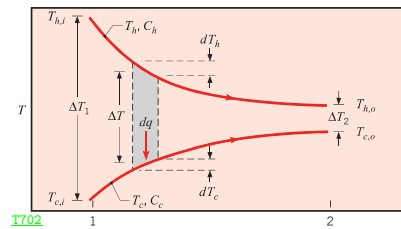
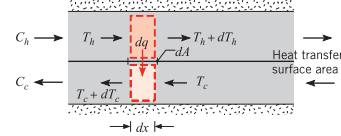


## LMTD: Heat Exchanger

## Parallel-flow HTX



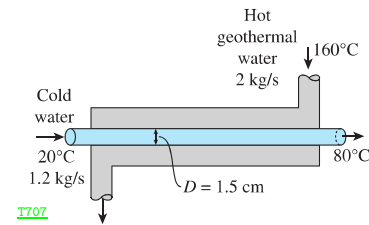
## Counter-flow HTX



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

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

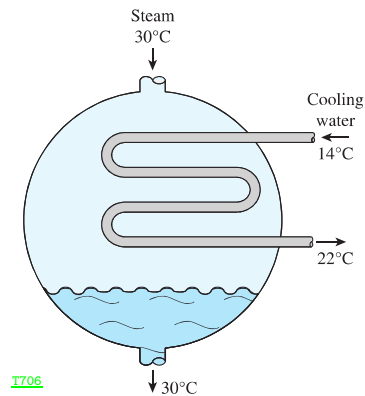
[109 m, 120 m]



T707

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

[1.09 MW]



T706