Waste Heat Recovery: *Fundamentals*

Introduction

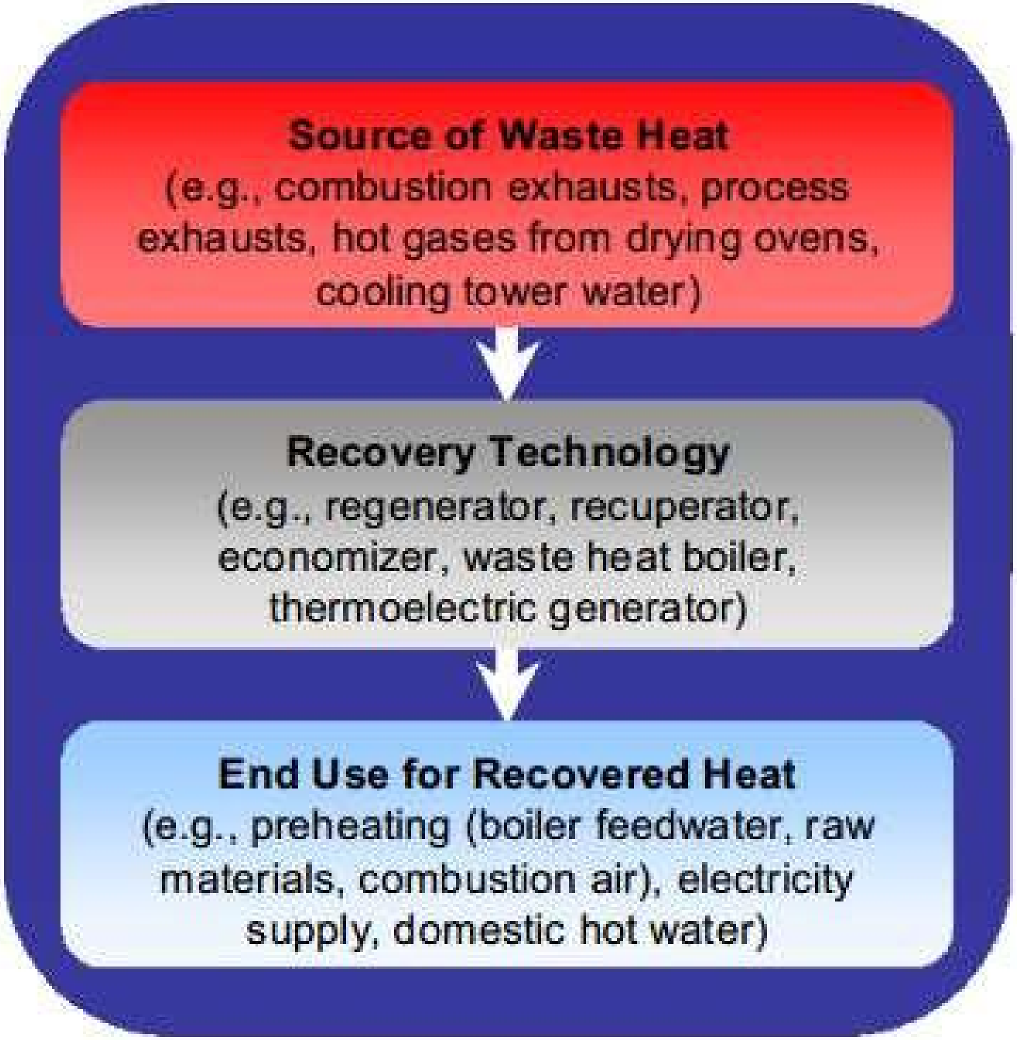
- A valuable alternative approach to improving overall energy efficiency is to capture and reuse the lost or "waste heat" that is intrinsic to all industrial manufacturing

- Captured and reused waste heat is an emission free substitute for costly purchased fuels or electricity

- In some cases, such as industrial furnaces, efficiency improvements resulting from waste heat recovery can improve energy efficiency by 10% to as much as 50%

- RD&D opportunities include optimizing existing recovery technologies as well as developing new heat recovery technologies.

Existing technologies can be further improved to maximize recovery, expand application constraints, and improve economic feasibility



RD&D Opportunity	Barriers Addressed									
	Long Payback Periods	Material Constraints and Costs	Maintenance Costs	Economies of Scale	Lack of End-use	Heat Transfer Rates	Environmental Concerns	Process Control and Product Quality	Process-specific Constraints	Inaccessibility
Develop low-cost, novel materials for resistance to corrosive contaminants and to high temperatures		X	X							
Economically scale-down heat recovery equipment (value-engineer)	X	X		X						
Develop economic heat recovery systems that can be easily cleaned after exposure to chemically active gases			X	X		X				
Develop novel manufacturing processes that avoid introducing contaminants into off-gases in energy-intensive manufacturing processes		X	X				X	X	X	
Develop low-cost dry gas cleaning systems		X	X			X	X	X		
Develop and demonstrate low-temperature heat recovery technologies, including heat pumps and low-temperature electricity generation.		X			X					
Develop alternative end-uses for waste heat					X					
Develop novel heat exchanger designs with increased heat transfer coefficients	X	X				X				
Develop process-specific heat recovery technologies				X		X	X	X	X	X
Reduce the technical challenges and costs of process-specific feed preheating systems	X			X		X		X	X	
Evaluate and develop opportunities for recovery from unconventional waste heat sources (e.g., sidewall losses)									X	X
Promote new heat recovery technologies such as solid-state generation					X					X
Promote low-cost manufacturing techniques for the technologies described above	X	X	X	X	X	X	X	X	X	X

Waste Heat Sources	Uses for Waste Heat
• Combustion Exhausts: Glass melting furnace Cement kiln Fume incinerator Aluminum reverberatory furnace Boiler • Process off-gases: Steel electric arc furnace Aluminum reverberatory furnace • Cooling water from: Furnaces Air compressors Internal combustion engines • Conductive, convective, and radiative losses from equipment: Hall-Hèroult cells [a] • Conductive, convective, and radiative losses from heated products: Hot cokes Blast furnace slags [a]	• Combustion air preheating • Boiler feedwater preheating • Load preheating • Power generation • Steam generation for use in: power generation mechanical power process steam • Space heating • Water preheating • Transfer to liquid or gaseous process streams

a. Not currently recoverable with existing technology

Furnace Efficiency Increases with Combustion Air Preheat:

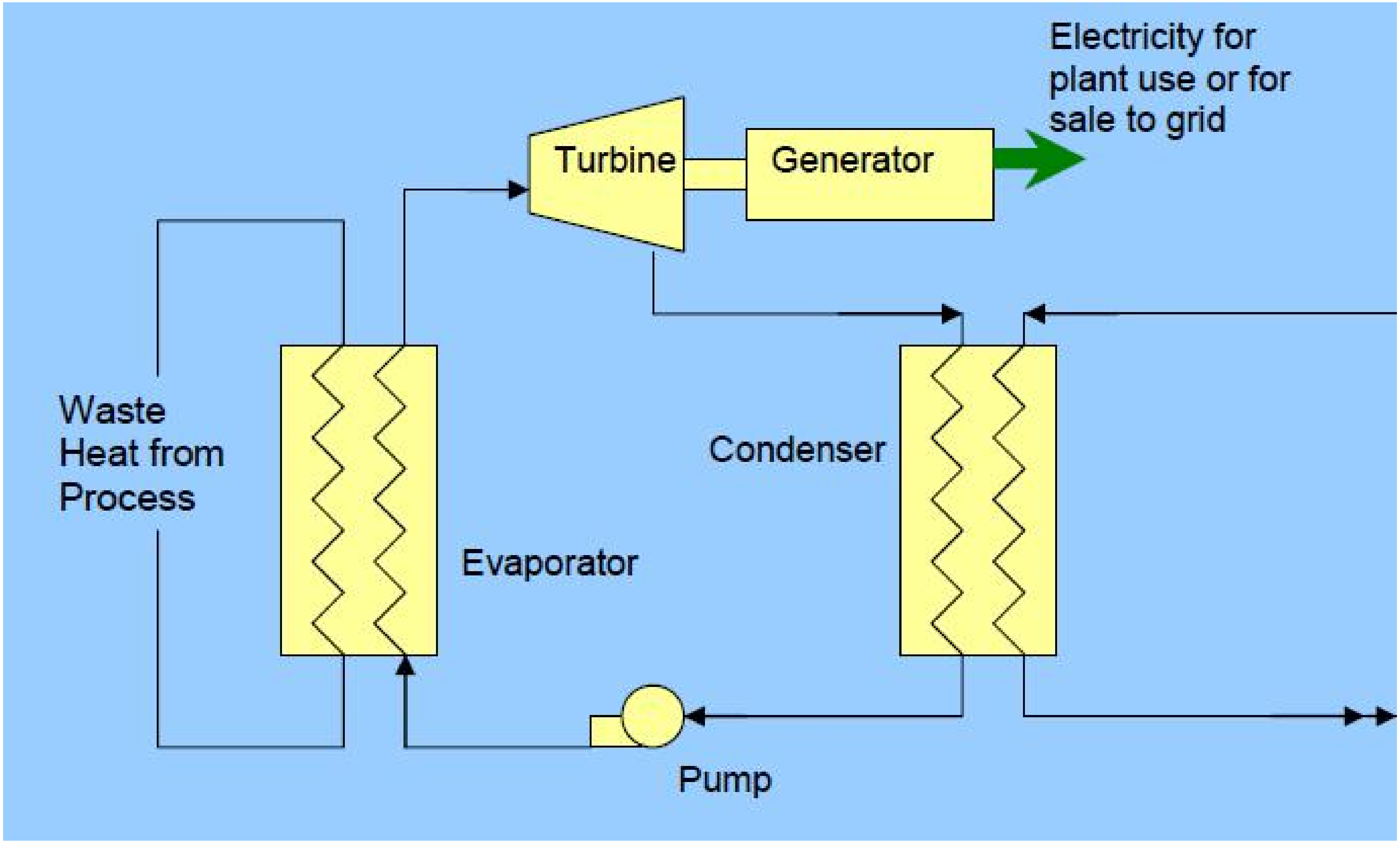
Furnace Outlet Temperature	Combustion Air Preheat Temperature				
	400°F [204°C]	600°F [316°C]	800°F [427°C]	1,000°F [538°C]	1,200°F [649°C]
2,600°F [1,427°C]	22%	30%	37%	43%	48%
2,400°F [1,316°C]	18%	26%	33%	38%	43%
2,200°F [1,204°C]	16%	23%	29%	34%	39%
2,000°F [1,093°C]	14%	20%	26%	31%	36%
1,800°F [982°C]	13%	19%	24%	29%	33%
1,600°F [871°C]	11%	17%	22%	26%	30%
1,400°F [760°C]	10%	16%	20%	25%	28%

Source: EPA 2003, Wise Rules for Energy Efficiency. Based on a natural gas furnace with 10% excess air.

Factors Affecting Waste Heat Recovery Feasibility

- *Heat quantity,*
- *Heat temperature/quality,*
- *Composition,*
- *Minimum allowed temperature, and*
- *Operating schedules, availability, and other logistics*

Waste Heat Recovery with Rankine Cycle



High Temperature Heat Recovery

Table: Typical waste heat temperature at high temperature range from various sources

Types of Devices	*Temperature (°C)*
Nickel refining furnace	1370 – 1650
Aluminium refining furnace	650 –760
Zinc refining furnace	760 – 1100
Copper refining furnace	760 – 815
Steel heating furnace	925 – 1050
Copper reverberatory furnace	900 – 1100
Open hearth furnace	650 – 700
Cement kiln (Dry process)	620 – 730
Glass melting furnace	1000 – 1550
Hydrogen plants	650 – 1000
Solid waste incinerators	650 – 1000
Fume incinerators	650 – 1450

Medium Temperature Heat Recovery

Table: Typical waste heat temperature at medium temperature range from various sources

Types of Devices	*Temperature (^0C)*
Steam boiler exhaust	**230 – 480**
Gas turbine exhaust	**370 – 540**
Reciprocating engine exhaust	**315 – 600**
Reciprocating engine exhaust (turbo charged)	**230 – 370**
Heat treatment furnace	**425 – 650**
Drying & baking ovens	**230 – 600**
Catalytic crackers	**425 – 650**
Annealing furnace cooling systems	**425 – 650**

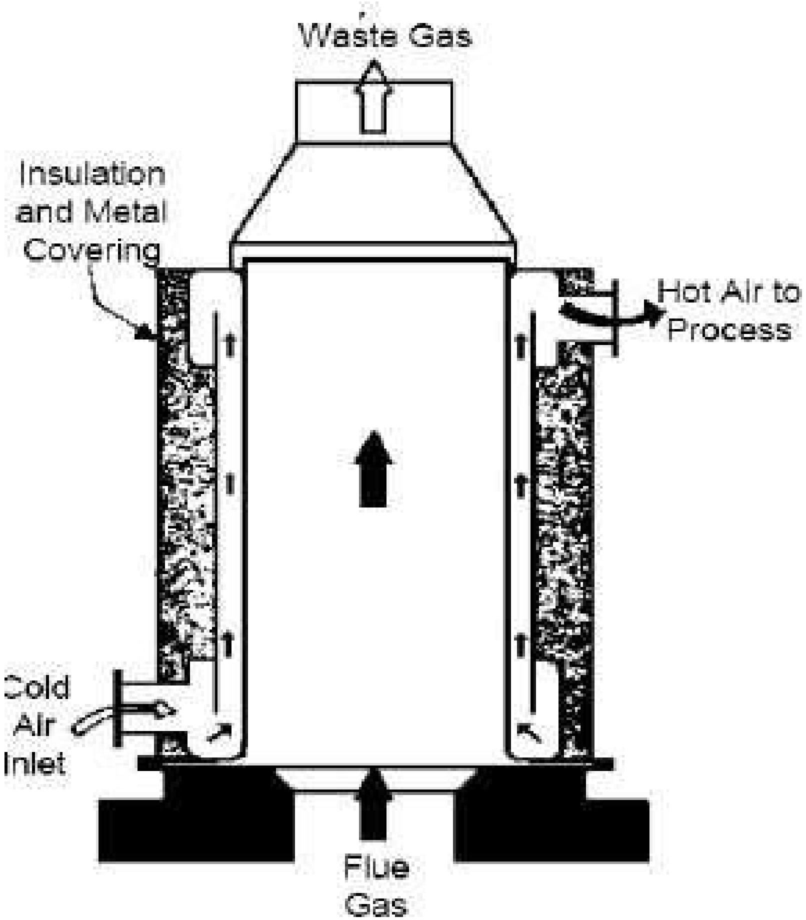
Low Temperature Heat Recovery

Source	*Temperature ^0C*
Process steam condensate	55-88
Cooling water from: Furnace doors	32-55
Bearings	32-88
Welding machines	32-88
Injection molding machines	32-88
Annealing furnaces	66-230
Forming dies	27-88
Air compressors	27-50
Pumps	27-88
Internal combustion engines	66-120
Air conditioning and refrigeration condensers	32–43
Liquid still condensers	32-88
Drying, baking and curing ovens	93-230
Hot processed liquids	32-232
Hot processed solids	93-232

Waste Heat Recovery Technologies

1. Recuperators:

- Recover exhaust gas waste heat in medium to high temperature applications such as soaking or annealing ovens, melting furnaces, afterburners, gas incinerators, radiant tube burners, and reheat furnaces.
- Recuperators can be based on radiation, convection, or combinations
- Recuperators are constructed out of either metallic or ceramic materials. Metallic recuperators are used in applications with temperatures below 2,000ºF [1,093ºC], while heat recovery at higher temperatures is better suited to ceramic tube recuperators.
- These can operate with hot side temperatures as high as 2,800ºF [1,538ºC] and cold side temperatures of about 1,800°F [982ºC].

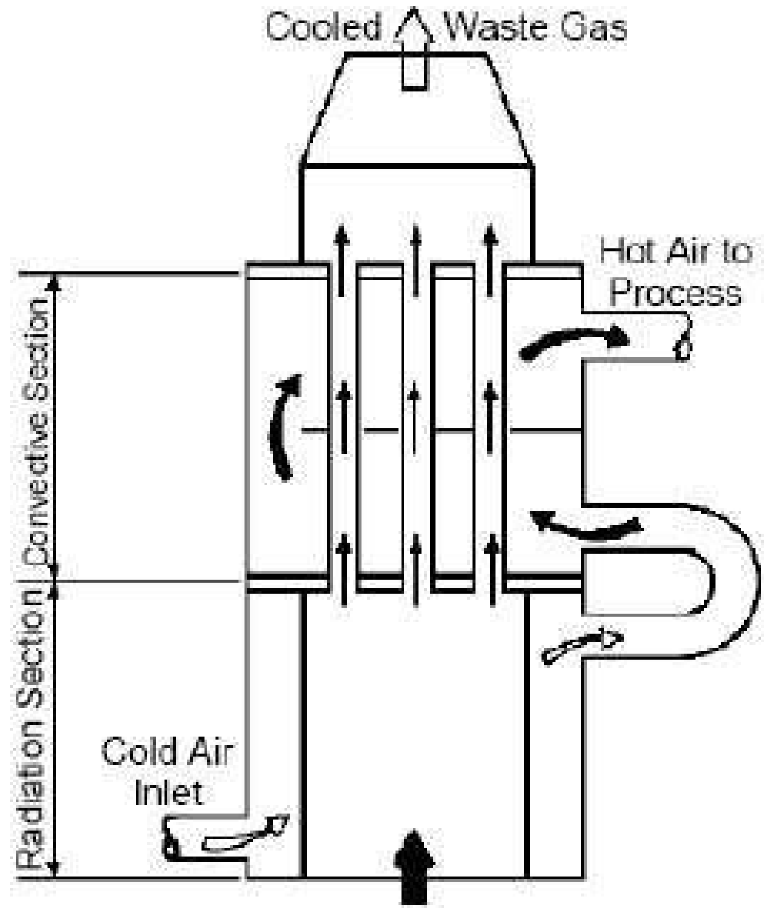


(a)

(b)

Figure 4 - (a) Metallic Radiation Recuperator Design (Source: PG & E), **(b) Radiation Recuperator Installed at Glass Melter** (Source: ALSTOM)

(a)



(b) -

Figure 5 - (a) Convection Recuperator (Source: Allstom, 2007), **-**
(b) Combined Radiation/Convection Recuperator (Source: PG&E)

2. Regenerators:

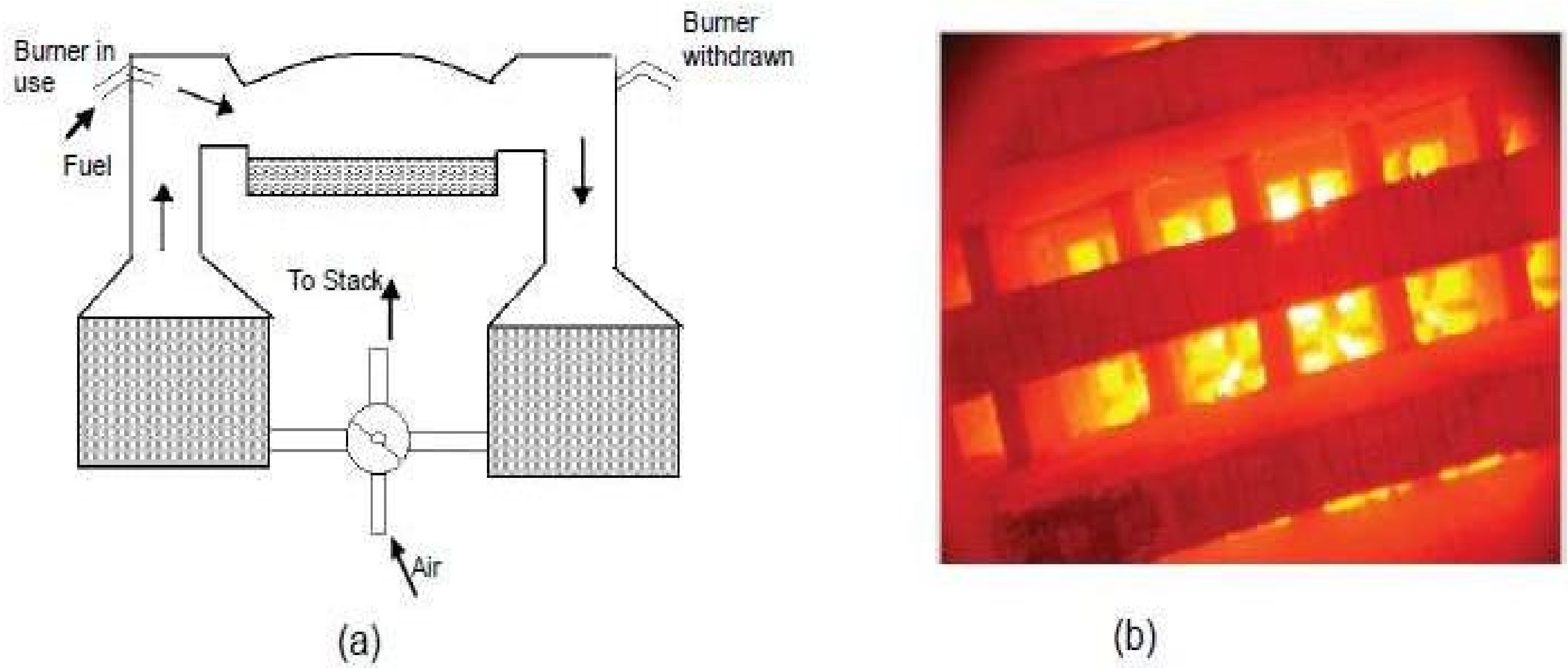
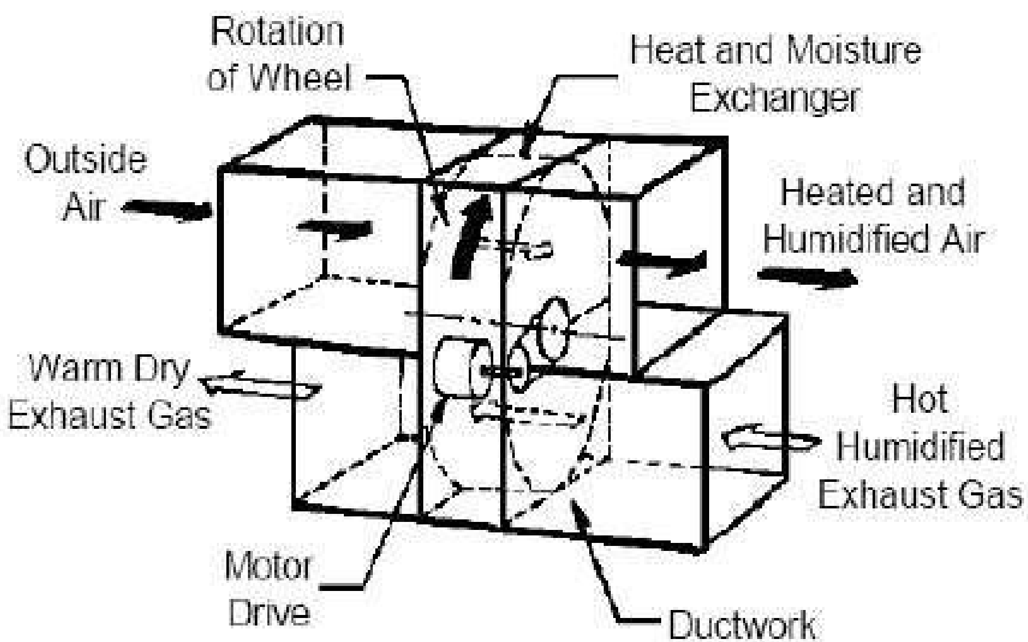


Figure 6 - (a) Regenerative Furnace Diagram,
(b) Checkerwork in Glass Regenerative Furnace (Source: GS Energy & Environment, 2007)

- Regenerators are most frequently used with glass furnaces and coke ovens, and were historically used with steel open hearth furnaces, before these furnaces were replaced by more efficient designs.
- They are also used to preheat the hot blast provided to blast stoves used in iron making; however, regenerators in blast stoves are not a heat recovery application, but simply the means by which heat released from gas combustion is transferred to the hot blast air.
- Regenerator systems are specially suited for high temperature applications with dirty exhausts.
- One major disadvantage is the large size and capital costs, which are significantly greater than costs of recuperators

3. Heat Wheels (Rotary Regenerator)

- Operates similar to fixed regenerators in that heat transfer is facilitated by storing heat in a porous media, and by alternating the flow of hot and cold gases through the regenerator.
- Uses a rotating porous disc placed across two parallel



- The disc, composed of a high heat capacity material, rotates between the two ducts and transfers heat from the hot gas duct to the cold gas duct.
- Heat wheels are generally restricted to low and medium temperature applications due to the thermal stress created by high temperatures.
- Large temperature differences between the two ducts can lead to differential expansion and large deformations, compromising the integrity of duct wheel air seals.
- Another challenge with heat wheels is preventing cross contamination between the two gas streams, as contaminants can be transported in the wheel's porous material.

- One advantage of the heat wheel is that it can be designed to recover moisture as well as heat from clean gas streams.
- When designed with hygroscopic materials, moisture can be transferred from one duct to the other. This makes heat wheels particularly useful in air conditioning applications, where incoming hot humid air transfers heat and moisture to cold outgoing air.
- Besides its main application in space heating and air conditioning systems, heat wheels are also used to a limited extent in medium temperature applications.
- They have also been developed for high temperature furnace applications such as aluminum furnaces
- They are also occasionally used for recovery from boiler exhausts, but more economical recuperators and economizers are usually preferred.

4. Passive Air Preheater:

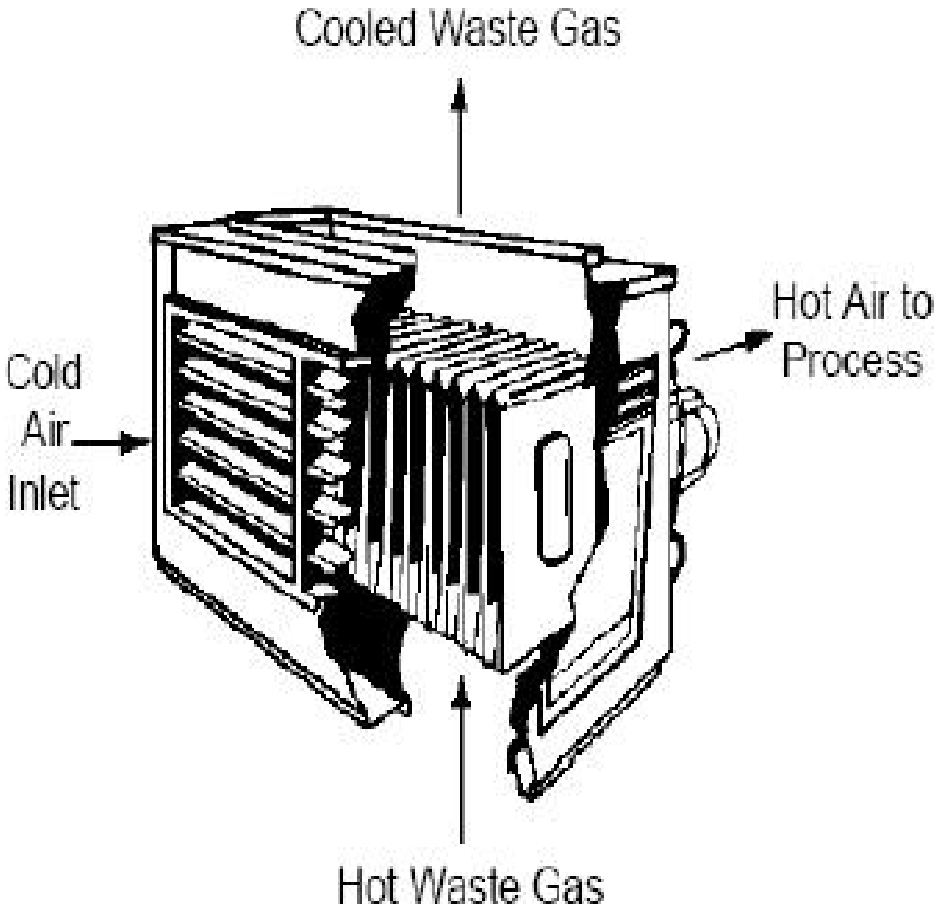
- Passive air preheaters are gas to gas heat recovery devices for low to medium temperature applications where cross contamination between gas streams must be prevented.
- Applications include ovens, steam boilers, gas turbine exhaust, secondary recovery from furnaces, and recovery from conditioned air.

Passive preheaters can be of two types –

1. **the plate type**
2. **Heat pipe.**

1. Plate Type Exchanger

- **Consists of multiple parallel plates that create separate channels for hot and cold gas streams.**
- **Hot and cold flow between alternate plates and allow significant areas for heat transfer.**
- **They are often bulkier, more costly, and more susceptible to fouling problems.**



2. Heat Pipe Heat Exchanger

- The heat pipe heat exchanger consists of several pipes with sealed ends.

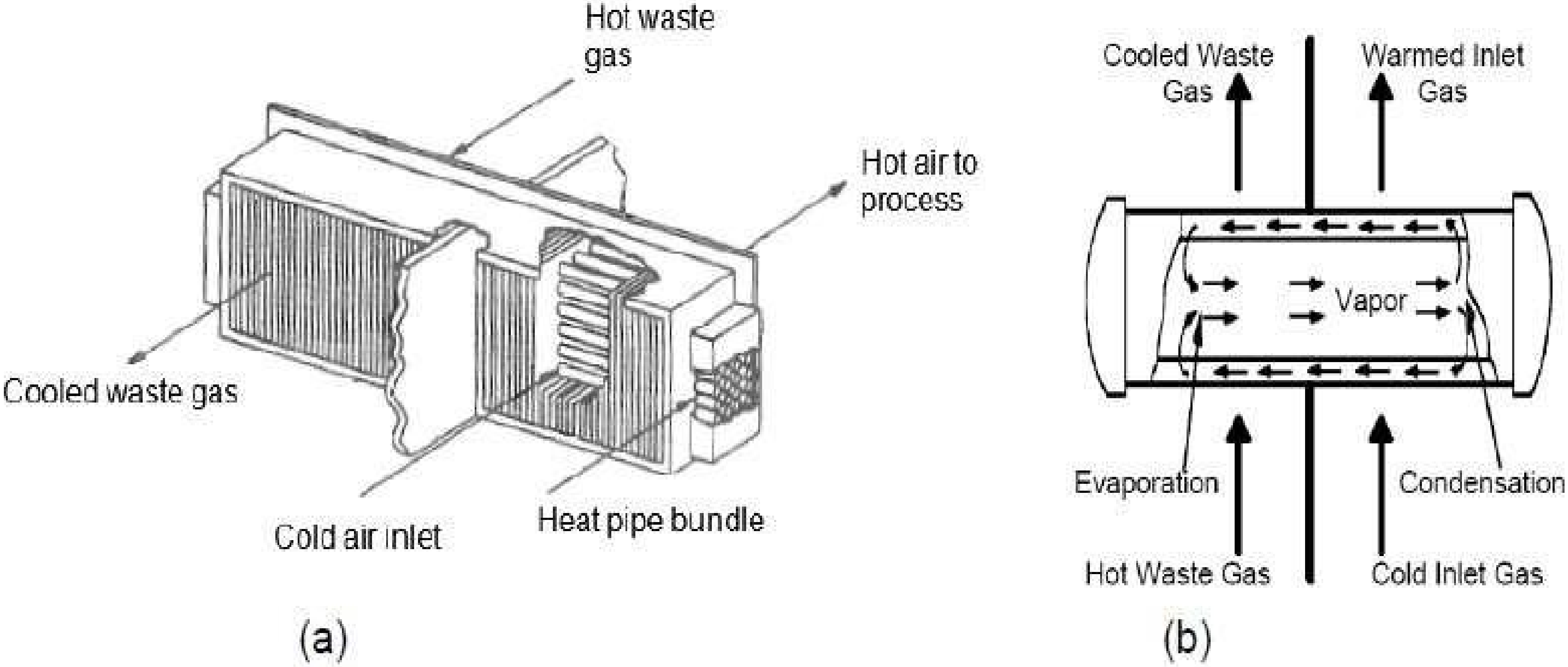


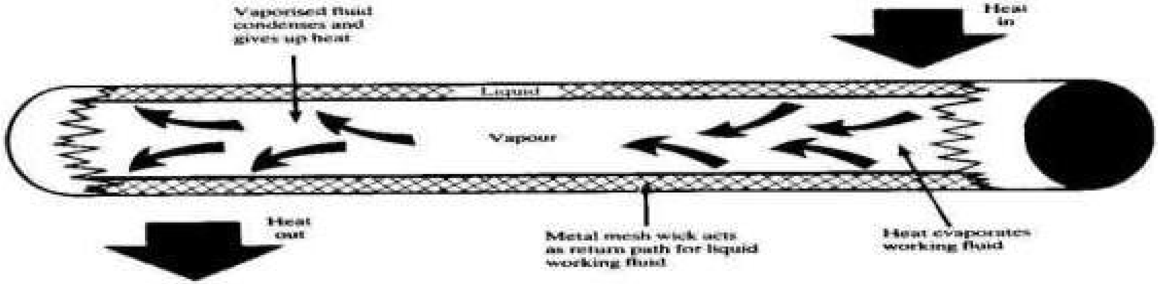
Figure 9 - (a) Heat Pipe Heat Exchanger (Source: Turner, 2006), **(b) Heat Pipe** (Source: PG&E, 1997)

- Each pipe contains a capillary wick structure that facilitates movement of the working fluid between the hot and cold ends of the pipe.

- Hot gases pass over one end of the heat pipe, causing the working fluid inside the pipe to evaporate.

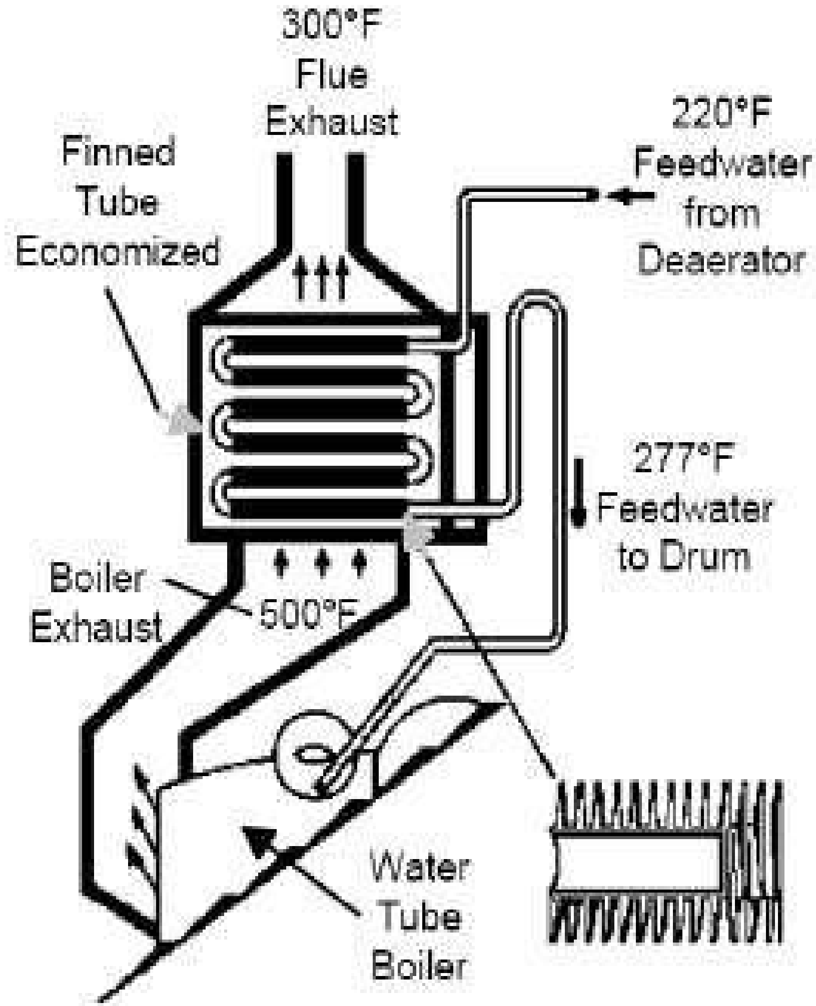
- Pressure gradients along the pipe cause the hot vapor to move to the other end of the pipe, where the vapor condenses and transfers heat to the cold gas.

- The condensate th the pipe via capilla



5. Economizers /Finned Tube Heat Exchangers

- Used to recover heat from low to medium temperature exhaust gases for heating liquids.
- Applications include boiler feed water preheating, hot process liquids, hot water for space heating, or domestic hot water
- Consists of a round tube with attached fins that maximize surface area and heat transfer rates.
- Liquid flows through the tubes and receive heat

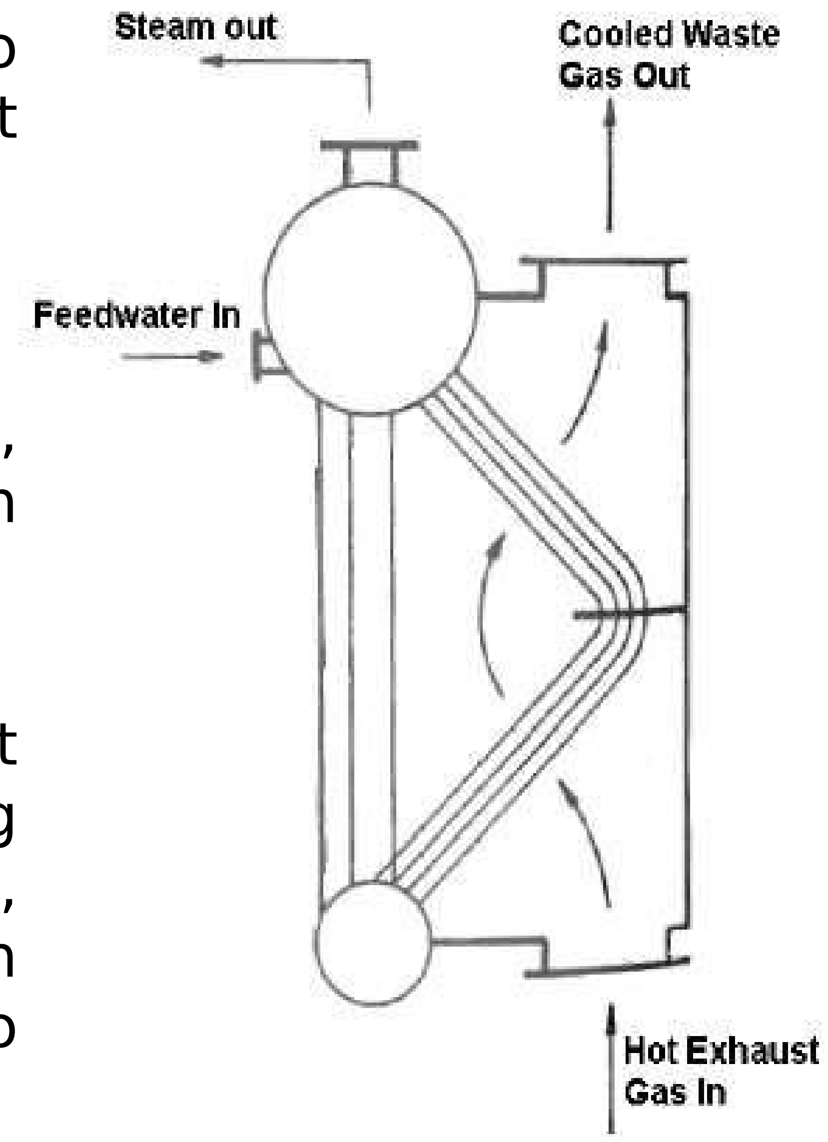


6. Waste Heat Boilers

- Example: the **two pass boiler** shown in Figure are water tube boilers that use medium to high temperature exhaust gases to generate steam.

- Waste heat boilers are available in a variety of capacities, allowing for gas intakes from 1000 to 1 million ft^3/min.

- In cases where the waste heat is not sufficient for producing desired levels of steam, auxiliary burners or an afterburner can be added to attain higher steam output.



Low Temperature Energy Recovery Options and Technologies

- There are various applications where low grade waste heat has been cost effectively recovered for use in industrial facilities.

- The large quantities of waste heat available in the range of 100- 400°F [38-200°C].

- Much industrial waste heat is in the low temperature range. For example, combustion systems such as boilers frequently use recovery technologies that exhaust gases at around 300350°F [150°-180°C], accounting for at least 460 TBtu of waste heat per year.

- Large quantities of waste heat can be found in industrial cooling water and cooling air; for example cooling of air compressors alone accounts for about 18 TBtu of waste heat per year.

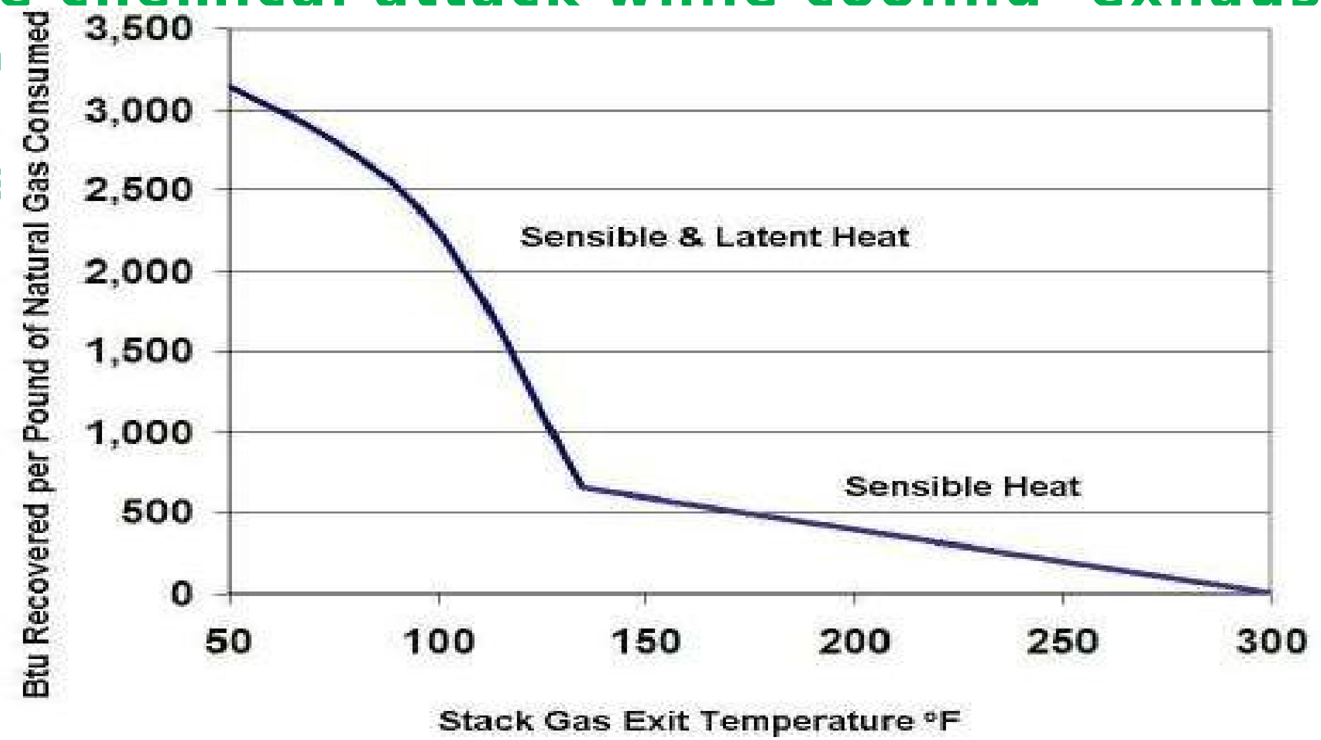
- One integrated steel mill in Japan successfully installed a power generation plant with a **3.5 MW** capacity using cooling water at only 208°F [98°C]

- In the case of combustion exhaust gases, substantial heat can be recovered if water vapor contained in the gases is cooled to lower temperatures.
- Minimum temperature limits around 250-300°F [120-150°C] are frequently employed in order to prevent water in the exhaust gases from condensing and depositing corrosive substances on the heat exchanger surface.

- **However, cooling the flue gas further could significantly increase heat recovery by allowing the latent heat of vaporization to be recovered. A pound of water requires 1,000 Btu of energy to evaporate. Conversely, if a pound of water vapor condenses, it transfers 1,000 Btu to its environment.**

- **This latent heat comprises a significant portion of the energy contained in exhaust gases. Technologies that can minimize chemical attack while cooling exhaust gases belov ... e significant in ... g the latent hea**

Heat Recovery Curve for Gas Boiler (Source: Schneider, 2015)



Challenges to Recovering Low Temperature Waste Heat

Corrosion of the heat exchanger surface: As water vapor contained in the exhaust gas cools, some of it will condense and deposit corrosive solids and liquids on the heat exchange surface. The heat exchanger must be designed to withstand exposure to these corrosive deposits. This generally requires using advanced materials

Large heat exchange surfaces required for heat transfer: Heat transfer rates are a function of the thermal conductivity of the heat exchange material, the temperature difference between the two fluid streams, and the surface area of the heat exchanger. Since low temperature waste heat will involve a smaller temperature gradient between two fluid streams, larger surface areas are required for heat transfer.

Finding a use for low temperature heat: Recovering heat in the low temperature range will only make sense if the plant has a use for low temperature heat. Potential end uses include domestic hot

Low Temperature HE Devices (CONCEPTS)

1. Deep Economizers:

Designed to cool exhaust gas to 150-160ºF [65ºC-71ºC] and to withstand the acidic condensate depositing on its surface. Designs include the following options:

- Installing a "throwaway" section on the cold end of the economizer.
- The tubing in the cold end will degrade over time and will need to be repeatedly replaced. The frequency of replacements will depend on the flue gas composition and the material of construction.
- Designing the economizer with stainless steel tubes. Stainless steel can withstand acidic gases better than the mild steel typically used in construction.
- Using carbon steel for the majority of the heat exchanger, but using stainless steel tubes in the cold end where acidic deposits will occur.

2. Indirect Contact Condensation Recovery:

- Indirect contact condensation recovery units cool gases to 100 to 110ºF [38-43ºC].

- In this range, the water vapor in gases will condense almost completely.

- Indirect contact exchangers consist of a shell & tube heat exchangers.

- They can be designed with stainless steel, glass, Teflon, or other advanced materials.

3. Direct Contact Condensation Recovery:

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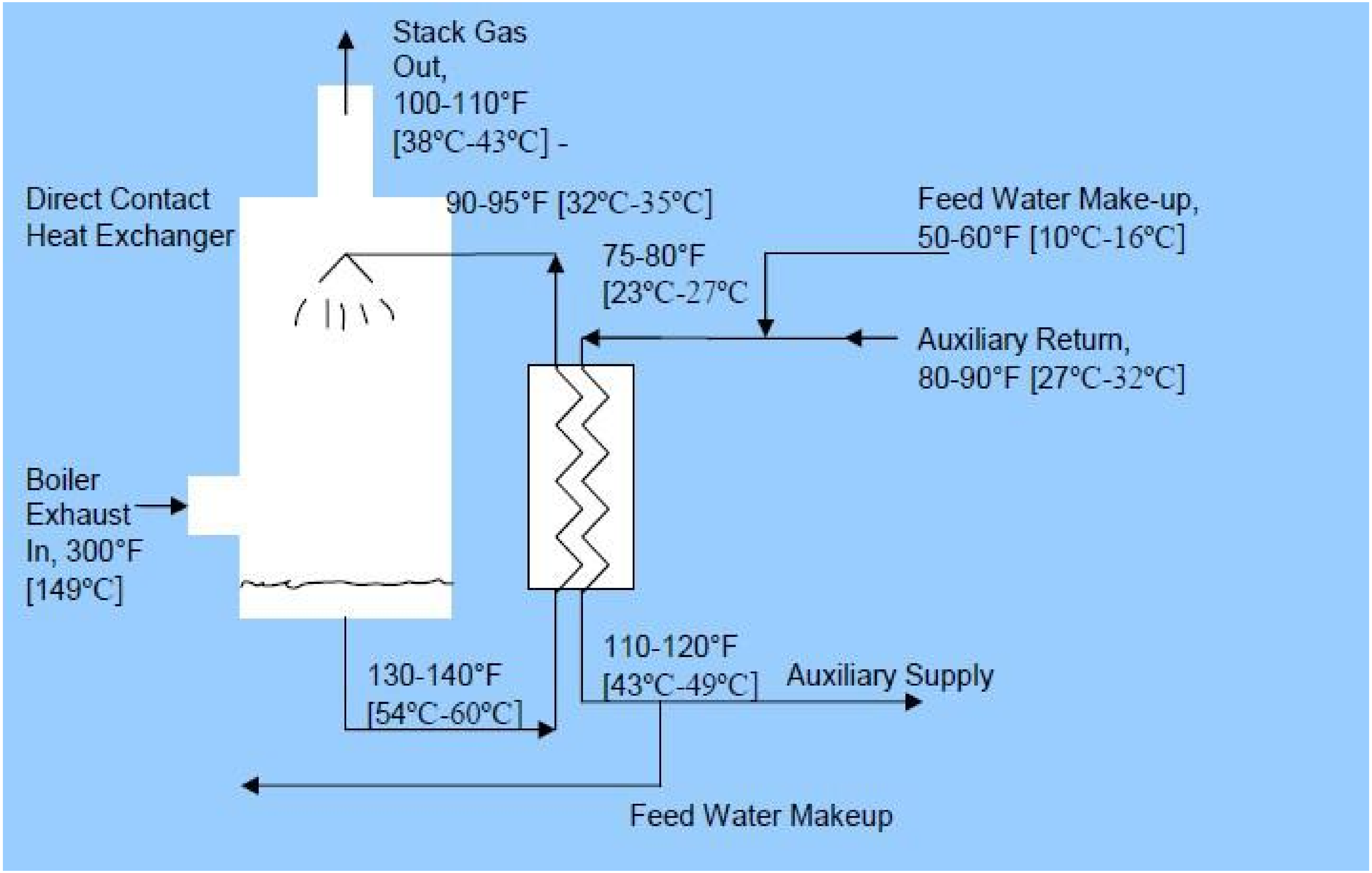

4. Heat Pumps:

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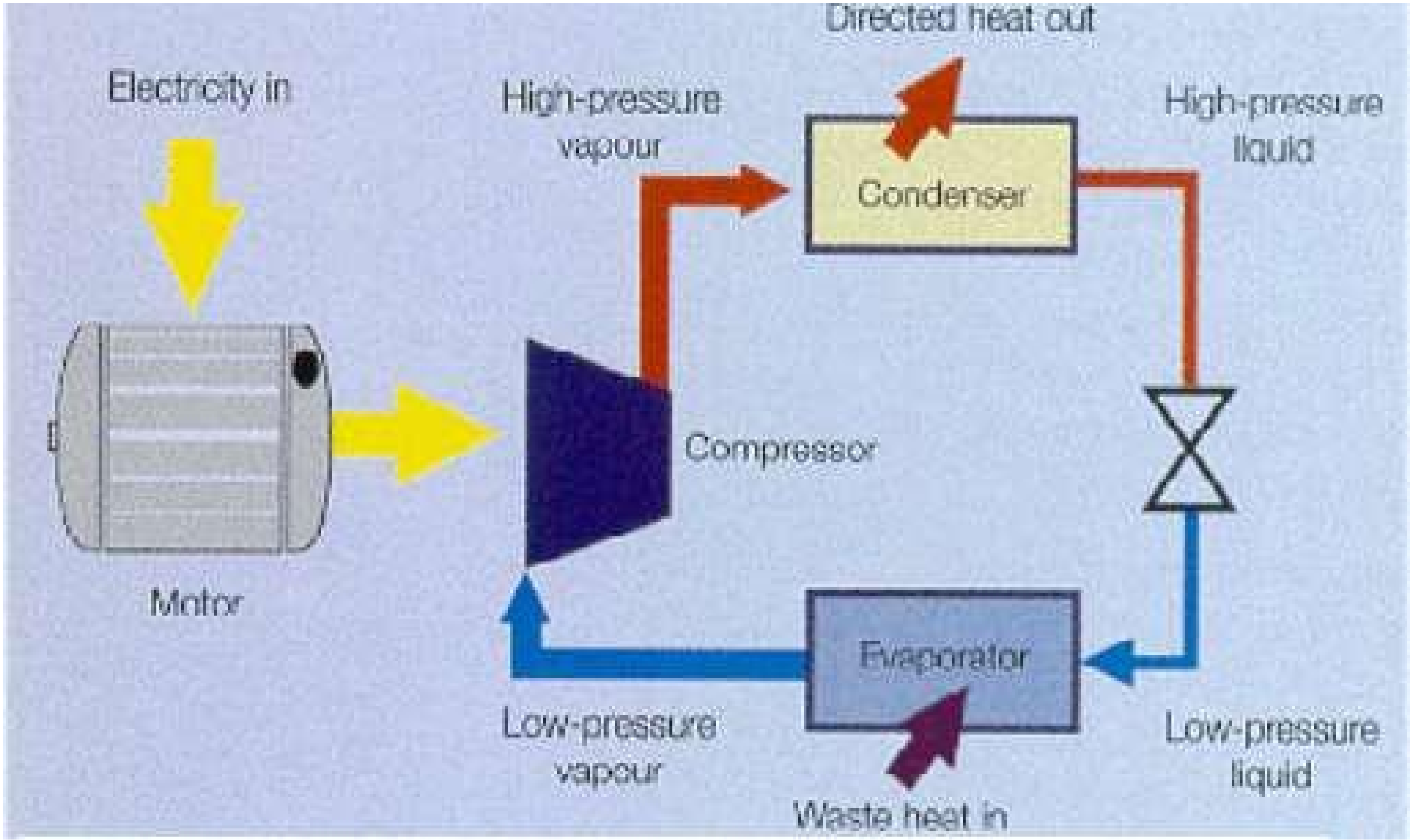

1. **In the evaporator the heat is extracted from the heat source to boil the circulating substance**
2. **The circulating substance is compressed by the compressor, raising its pressure and temperature**
3. **The heat is delivered to the condenser**

4. **The pressure of the circulating substance (working fluid) is reduced back to the evaporator condition in the throttling valve, where the cycle repeats.**

4.1. Thermo-compressors:

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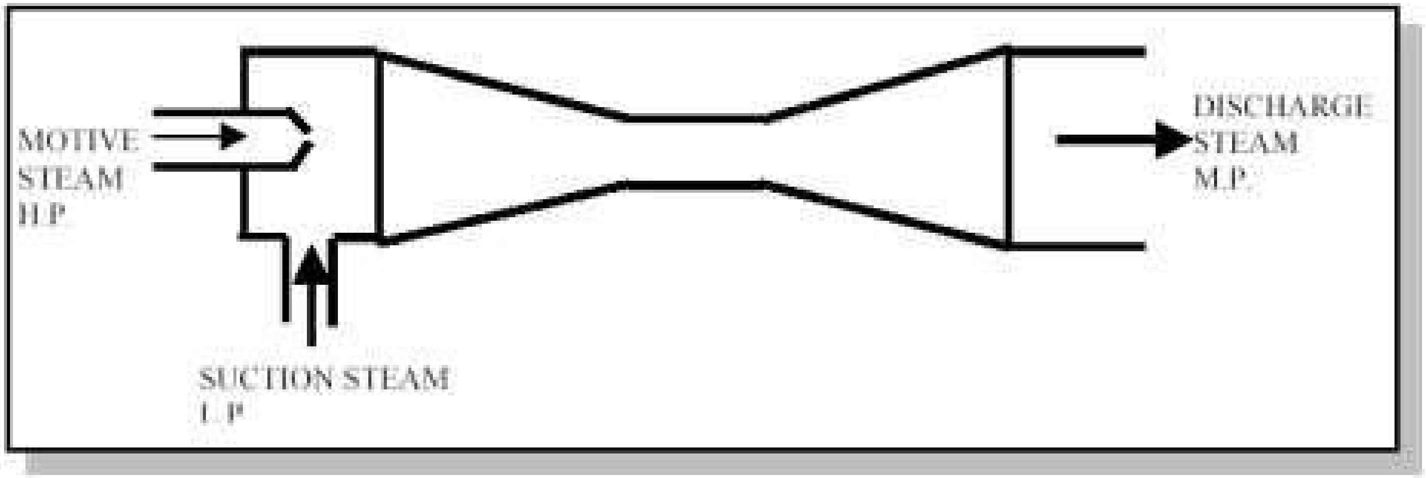
- **Compress low-pressure steam by very high-pressure steam and reuse as medium pressure steam**
- **Nozzle for acceleration of HP steam to a high velocity fluid.**



Direct Benefits

- Recovery of waste heat has a direct effect on the efficiency of the process.

- This is reflected by reduction in the utility consumption & costs, and process cost.

Indirect Benefits

- **Reduction in pollution**: A number of toxic combustible wastes such as carbon monoxide gas, sour gas, etc, releasing to atmosphere if/when burnt in the incinerators serves dual purpose i.e. recovers heat and reduces the environmental pollution levels.
- **Reduction in equipment sizes**: Waste heat recovery reduces the fuel consumption, which leads to reduction in the flue gas produced. This results in reduction in equipment sizes of all flue gas handling equipment

- **Reduction in auxiliary energy consumption:** Reduction in equipment

Recovery Method	Temperature Range	Typical Sources of Waste Heat	Typical Uses	Type of Heat Exchange (Gas-Gas, Gas-Liquid, etc.)	Recovers Moisture	Large Temperature Differentials Permitted	No Cross-Contamination	Corrosive Gases Permitted with Special Construction
Radiation Recuperator	H	Soaking or annealing ovens, melting furnaces, incinerators, radiant-tube burners, reheat furnace	Combustion air preheat	G-G		X	X	X
Convection Recuperator	M-H	Soaking or annealing ovens, melting furnaces, incinerators, radiant-tube burners, reheat furnace	Combustion air preheat	G-G		X	X	X
Metallic Heat Wheel	L-M	Boiler exhaust, curing and drying ovens	Combustion air preheat, space heat	G-G	b		c	x
Hygroscopic Heat Wheel	M	Boiler exhaust, curing and drying ovens	Combustion air preheat, space heat	G-G	X		c	X
Ceramic Heat Wheel	M-H	Large boilers, incinerator exhaust, melting furnaces	Combustion air preheat,	G-G		X		X
Plate-type Heat Exchanger	L,M	Exhaust from boilers, incinerators, & turbines Drying, curing, and baking ovens	Combustion air preheat, space heat	G-G, L-L		X	X	
Heat Pipe	L-H	Waste steam, air dryers, kilns (secondary recovery), reverberatory furnaces (secondary recovery) Drying, curing & baking ovens	Combustion air preheat, boiler makeup water preheat, domestic hot water, space heat	G-G,G-L		d	X	X
Finned-tube Heat Exchanger	L,M	Boiler exhaust	Boiler feedwater preheat	G-L		X	X	e
Waste-heat Boilers	L-H	Exhaust from gas turbines, reciprocating engines, incinerators, furnaces	Hot water or steam generation	G-L			X	e
Tube Shell-and Tube Exchanger	L,M	Refrigeration condensates, waste steam distillation condensates, waste steam distillation condensates, coolants from engines, air compressors, bearings & lubricants	Liquid feed flows requiring heating	G-L, L-L		X	X	

a. Sources: W. Turner. *Energy Management Handbook,* 2007; *PG&E Energy Efficiency Information* "Industrial Heat Recovery Strategies," 1997
b. claimed by some vendors
c. with a purge section added, cross-contamination can be limited to less than 1% by mass
d. allowable temperatures and temperature differential limited by the phase equilibrium properties of the internal fluid
e. can be constructed from corrosion-resistant materials, but consider possible extensive damage to equipment caused by leaks or tube ruptures

Reference

https://www.slideshare.net/vinay805/waste-heat-recovery-vinay-shukla-13152721

THANK YOU !!!