ENERGY EFFICIENCY ON BOILER SYSTEMS

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International Workshop on Energy Audits
Diponegoro University,
Semarang, August 2 – 3, 2010

Chapter 1
Boilers and Steam Utilities

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1.2 Types of Boiler

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1.4 Boiling Heat Transfer

1.5 Boiler Efficiency

1.6 Energy Conservation Opportunities in Boiler System

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Pumps and Pumping System

Objective of Energy Management

- To achieve and maintain optimum energy procurement and utilization, throughout the organization

- To minimize energy costs/waste without affecting production & quality

- To minimize environmental effects.

Energy Audits

Definition

"the verification, monitoring and analysis of use of energy including submission of technical report containing recommendations for improving energy efficiency with cost benefit analysis and an action plan to reduce energy consumption "

Source : A.THUMANN, Handbook on Energy Audits 5thEdition 1998. The Fairmont Press

PLEASE REMEMBER !!!

An energy audit is not done once and for all.

It is **an ongoing process** of comparison between theory and practice , leading to an ever practice, leading to an ever-improving understanding of what energy is being used, why it is being used, how it is being used and at what cost."

What is a boiler ?

A boiler is an enclosed vessel that provides a means for combustion heat to be transferred to water until it becomes heated water or steam.

- The hot water or steam under pressure is then usable for transferring the heat to a process.
- When water at atmospheric pressure is boiled into steam its volume increases about 1,600 times, producing a force that is almost as explosive as gunpowder.
- This causes the boiler to be an equipment that must be treated with utmost care.

Boiler System

Feed Water System

Provides water to the boiler and regulates it automatically to meet the steam demand.

Steam System

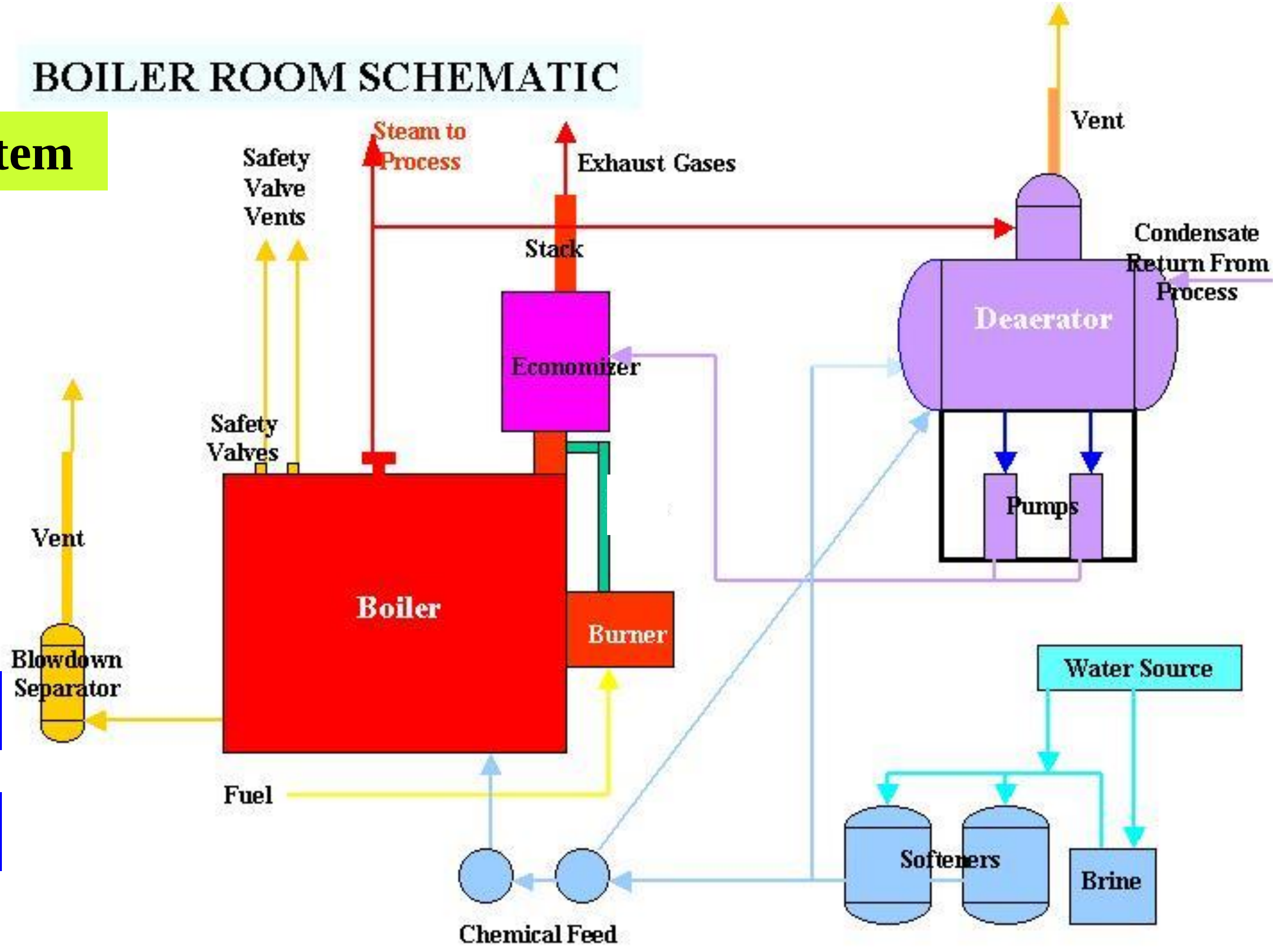
Collects and controls the steam produced in the boiler and distributed the steam through a piping system to the point of use.

Fuel System

Provide fuel to generate the necessary heat, normally by combustion process.

Boiler Systems

- ✓Water treatment system
- ✓Feed water system
- ✓Steam System
- ✓Blow down system
- ✓Fuel supply system
- ✓Air Supply system
- ✓Flue gas system



Feed Water System

The water supplied to the boiler that is converted into steam is called **feed water.**

The 2 sources of feed water are:

(1) **Condensate or condensed steam** returned from the processes

(2) **Makeup water (treated raw water)** which must come from outside the boiler room and plant processes.

Types of Boilers

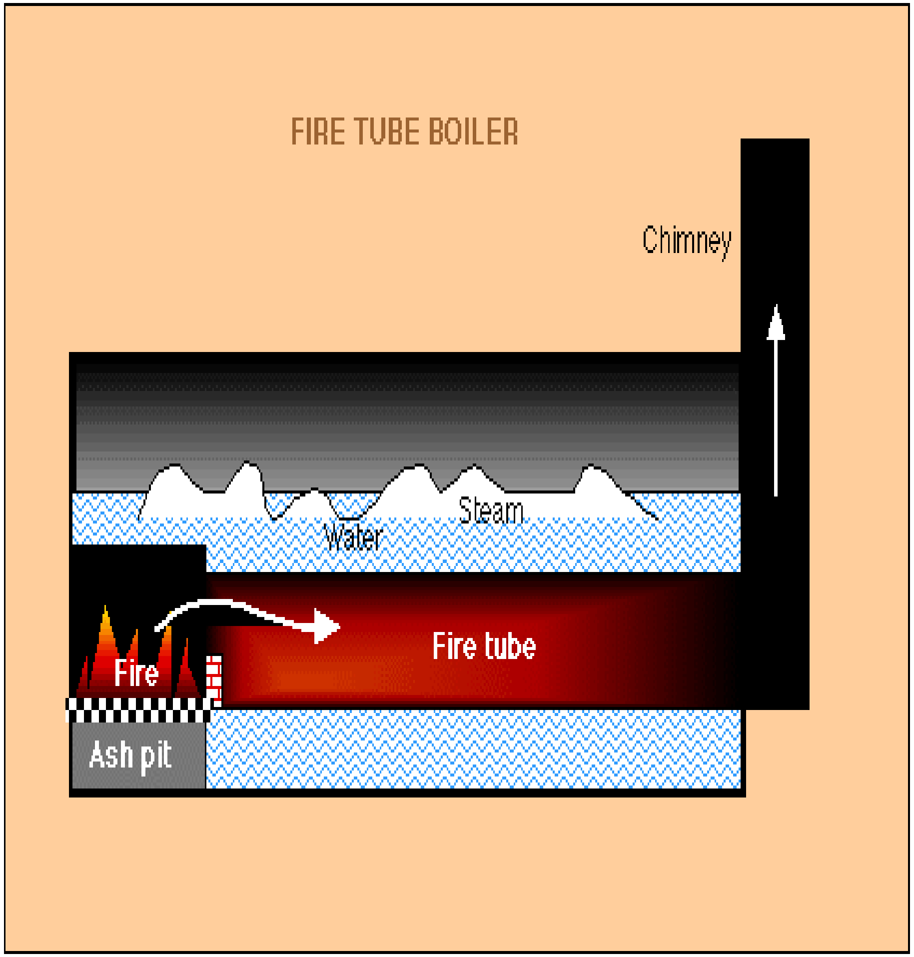
Two basic types of boiler: **Water Tube Boilers** and **Fire Tube Boilers**

- **Packaged Boiler**
- **FBC Boiler**
- **Spreader Stoker Boiler**
- **Chain- or Traveling Grate Boiler**
- **Atmospheric Fluidized Bed Combustion**
- **Pressurized Fluidized Bed Combustion**
- **Atmospheric Circulating Fluidized Bed Combustion**
- **Pulverized Fuel Boiler**
- **Waste Heat Boiler**

Fire Tube Boilers

Is the most common boilers in industry :

- Cheap
- Relatively small steam capacities (12,000 kg/hour)
- Low to medium steam pressures (18 kg/cm2)
- Operates with oil, gas or solid fuels



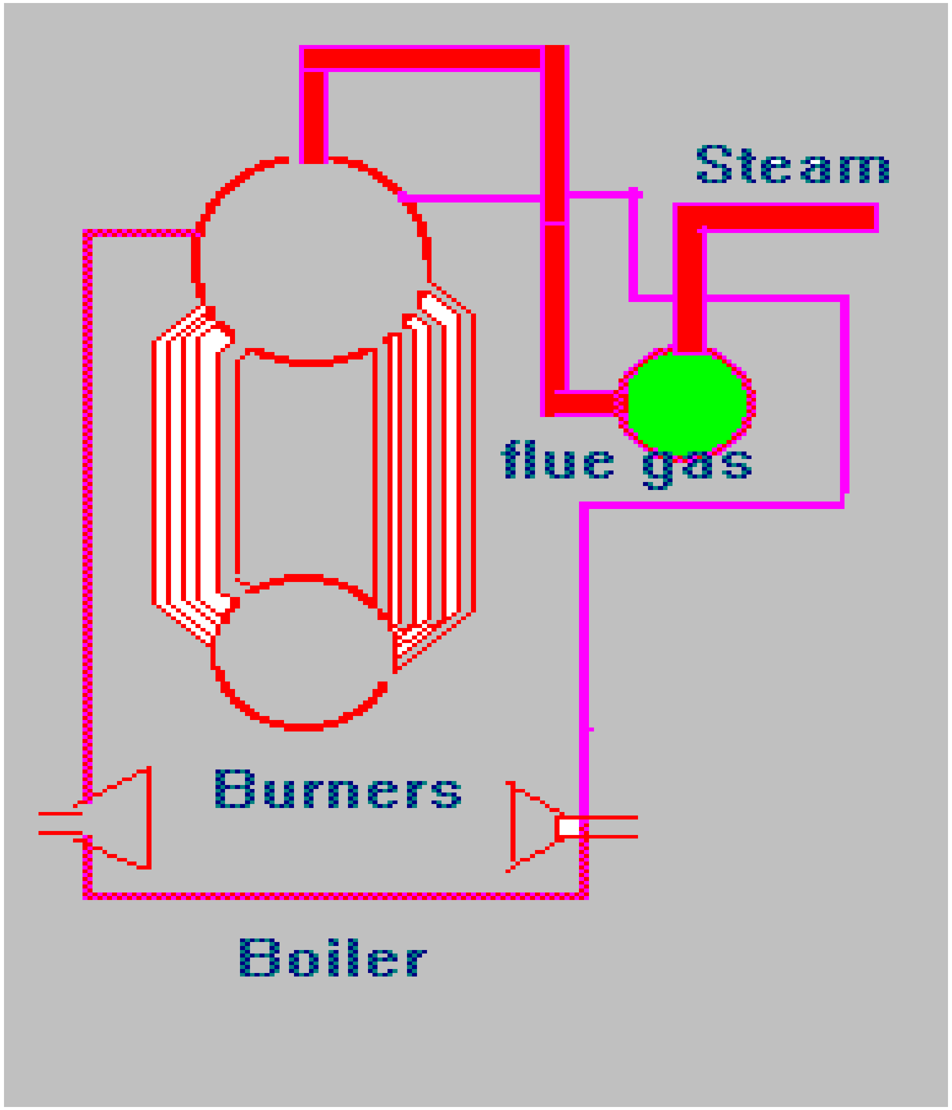
Water Tube Boiler

Application

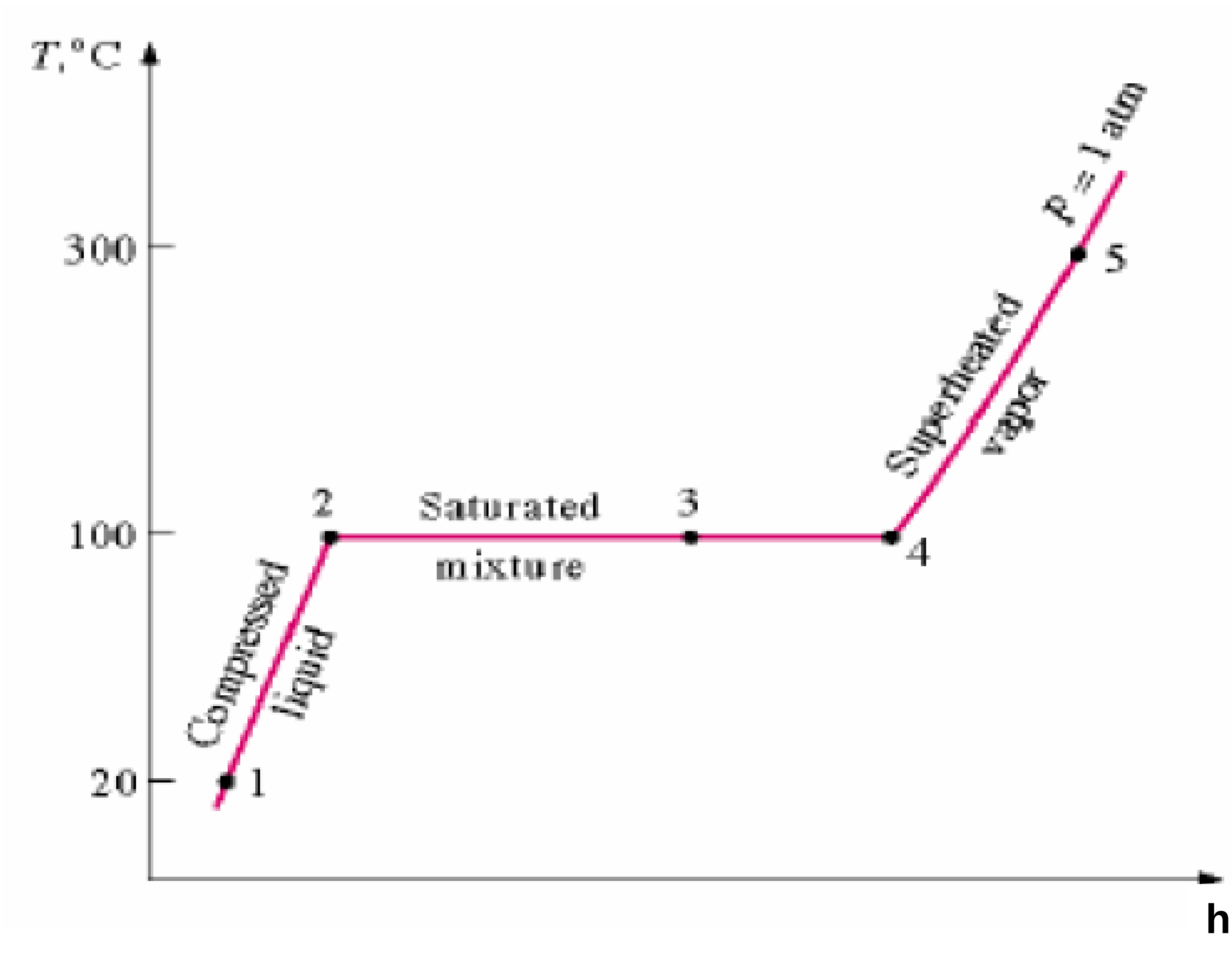
- Used for Power Plants
- Steam capacities range from 4.5- 120 t/hr

Characteristics

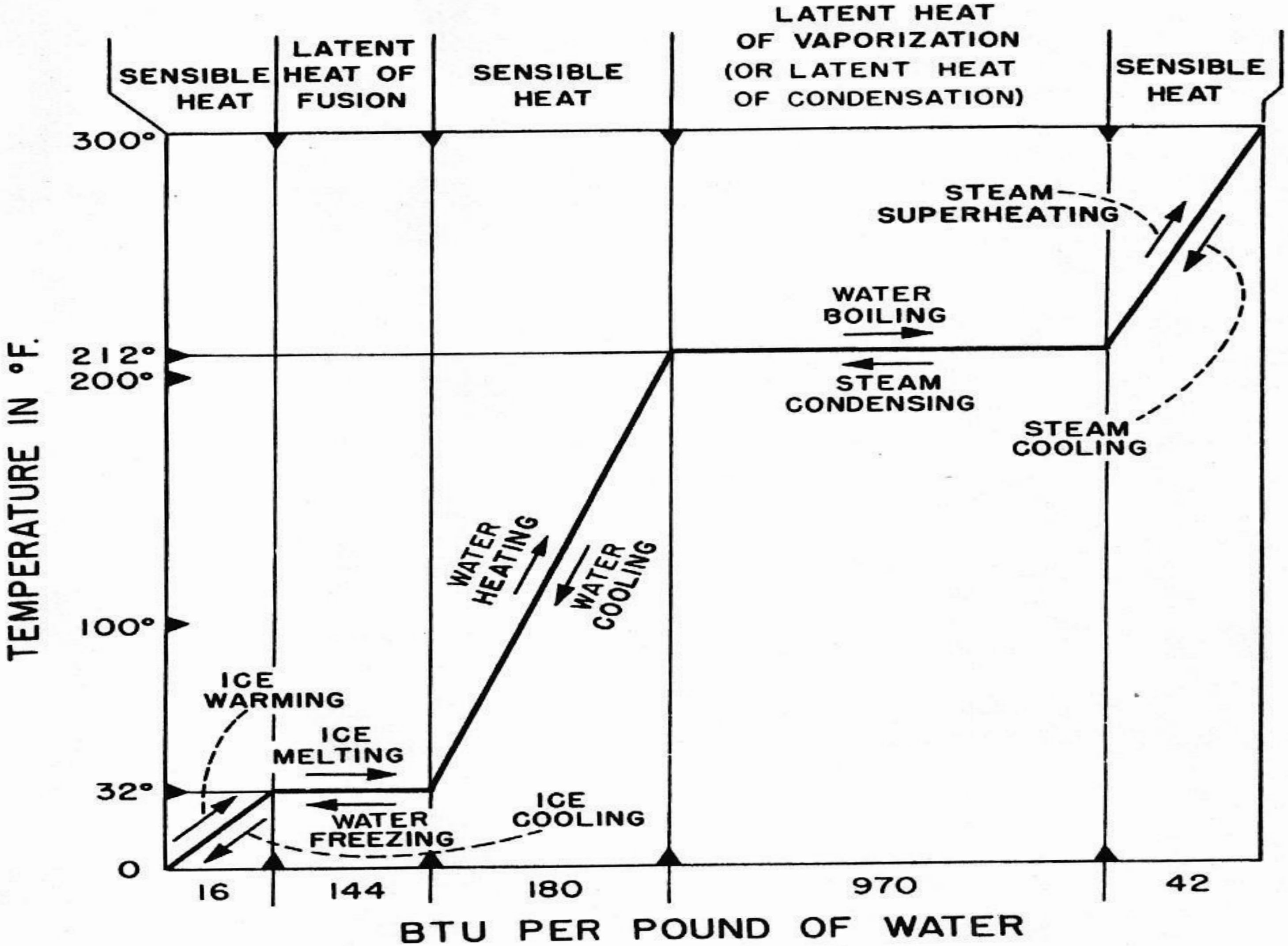
- High Capital Cost
- Used for high pressure high capacity steam boiler
- Demands more controls
- Calls for very stringent water quality



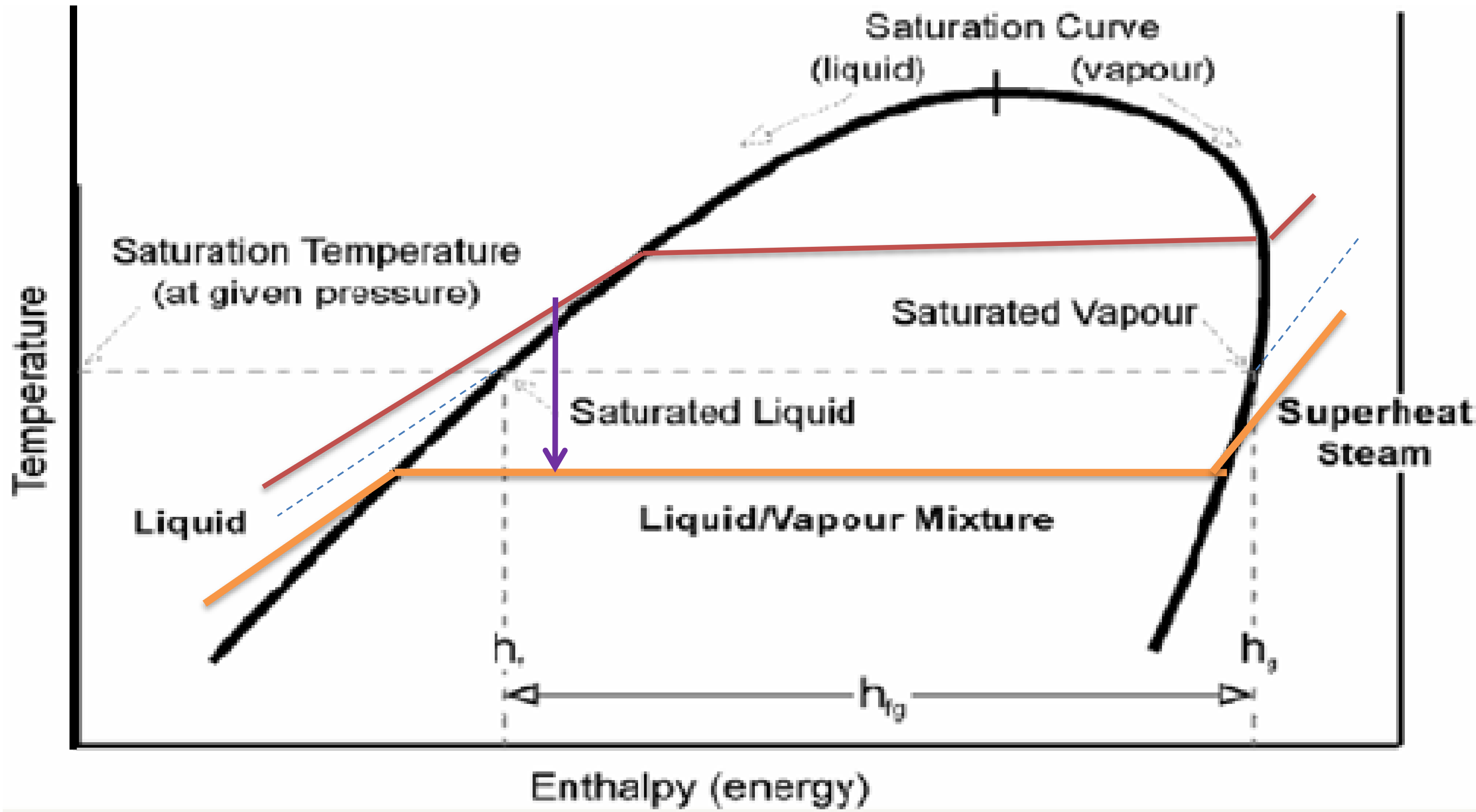
Thermodynamic Process



Thermodynamic Process



Thermodynamic Process



STEAM PROPERTIES

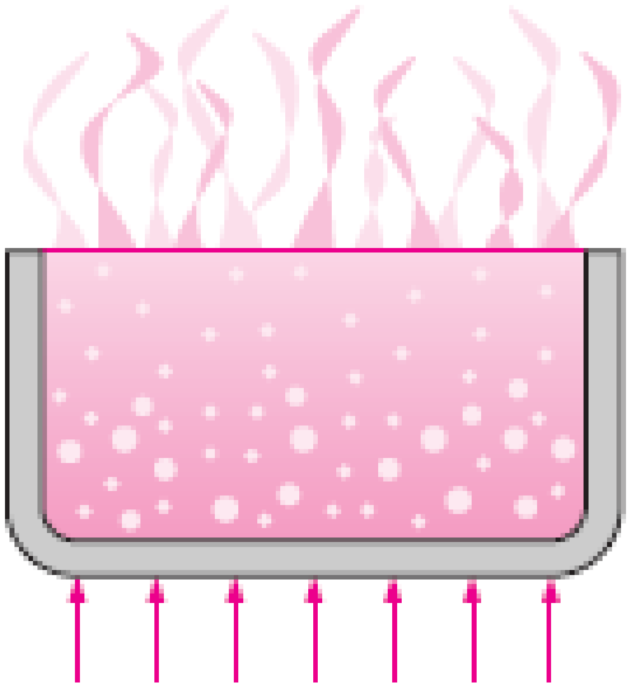
Pressure (kg/cm^2)	Temperature °C	Enthalpy in Kcal/kg			Specific Volume (m^3/kg)
		Water (h_f)	Evaporation (h_{fg})	Steam (h_g)	
1	100	100.09	539.06	639.15	1.673
2	120	119.92	526.26	646.18	0.901
3	133	133.42	517.15	650.57	0.616
4	143	143.70	509.96	653.66	0.470
5	151	152.13	503.90	656.03	0.381
6	158	159.33	498.59	657.92	0.321
7	164	165.67	493.82	659.49	0.277
8	170	171.35	489.46	660.81	0.244

Energy Units

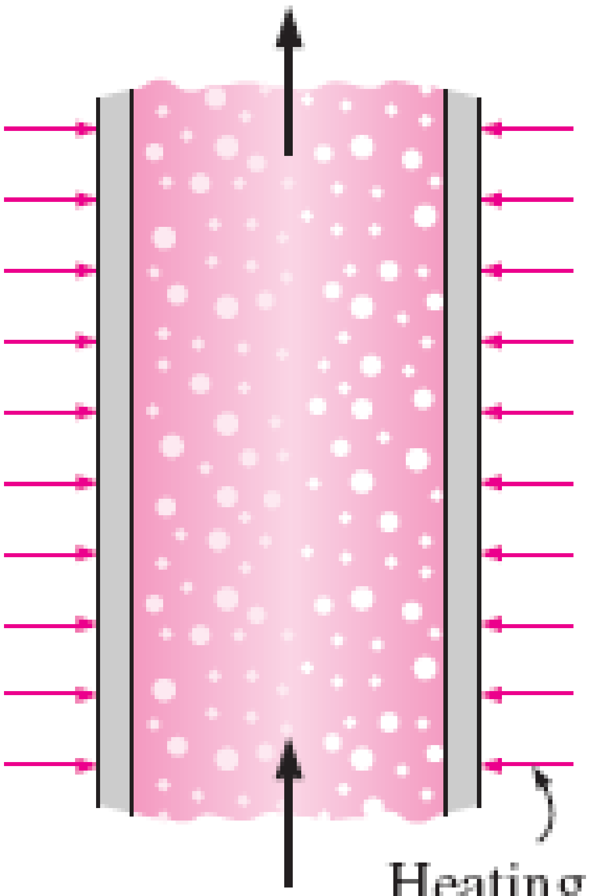
- Boilers are often rated in “Boiler Horsepower” (BHP) rather than Btus per hour.
- 1 BHP is defined as the amount of energy it takes to convert 34.5 pounds of water to steam in one hour at 212 degrees Fahrenheit.
- A boiler HP equals 33,472 Btu/hour.

Boiling Heat Transfer

Classification of Boiling

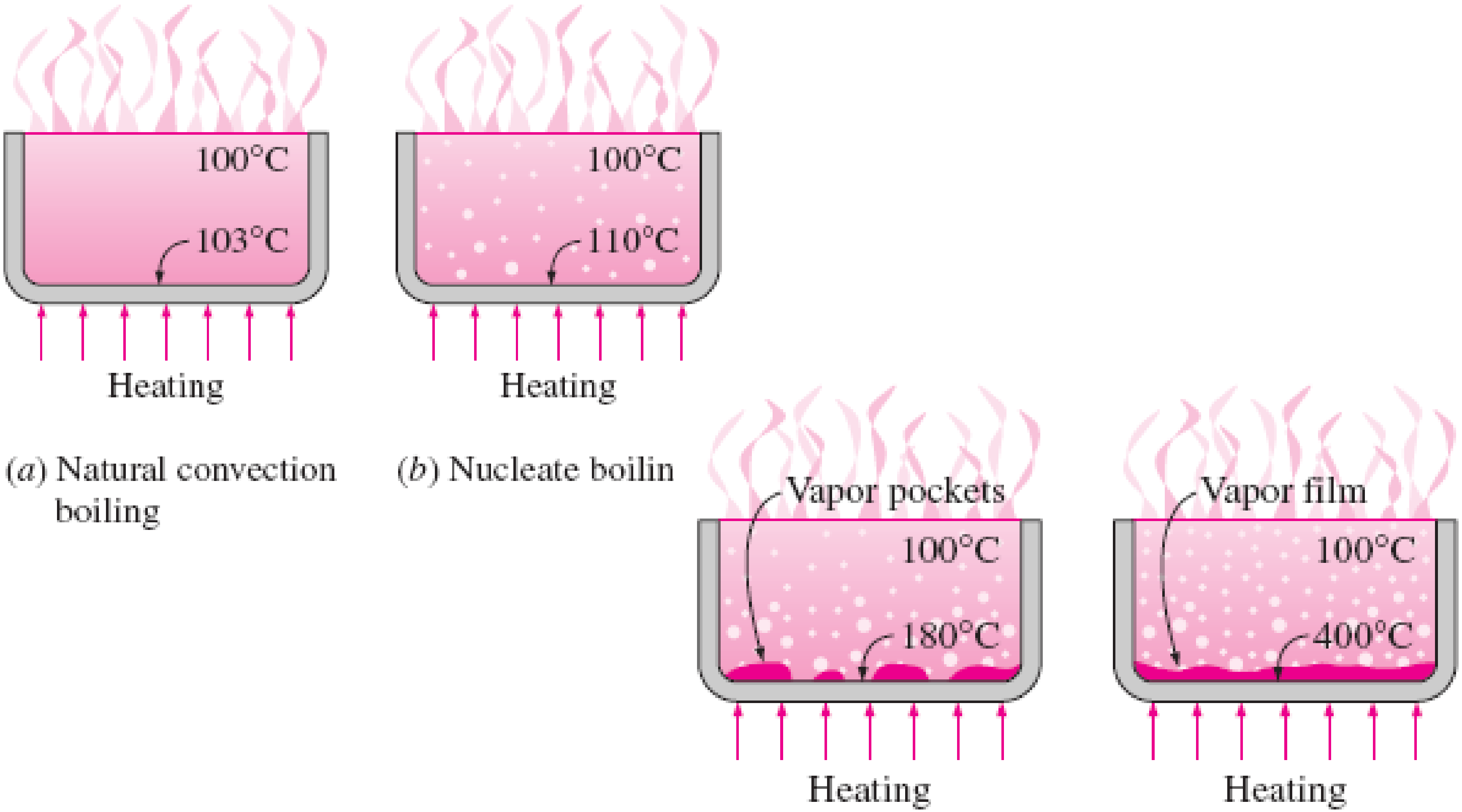


(a) Pool boiling



(b) Flow boiling

Pool Boiling Regimes



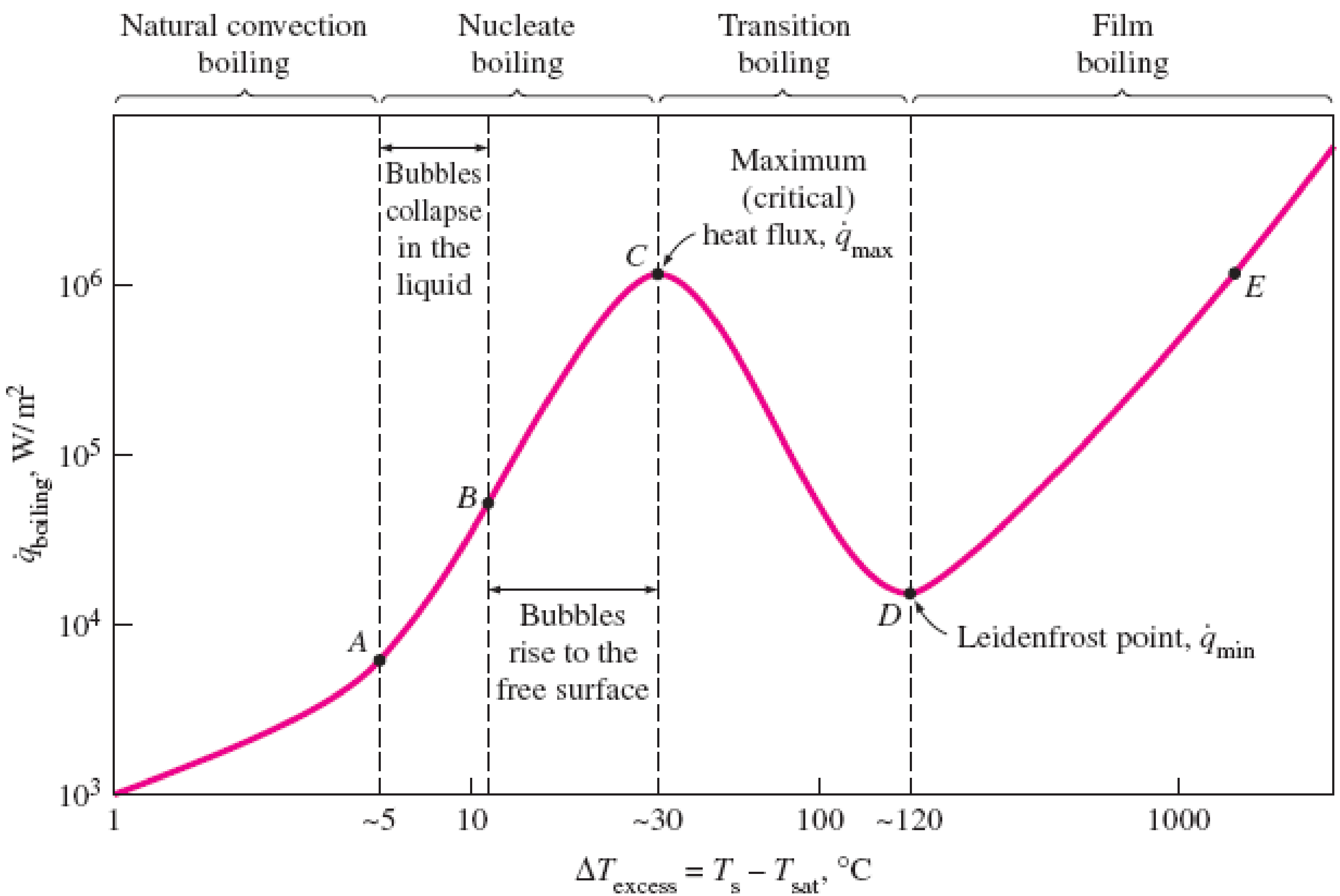
(*a*) Natural convection boiling

(*b*) Nucleate boilin

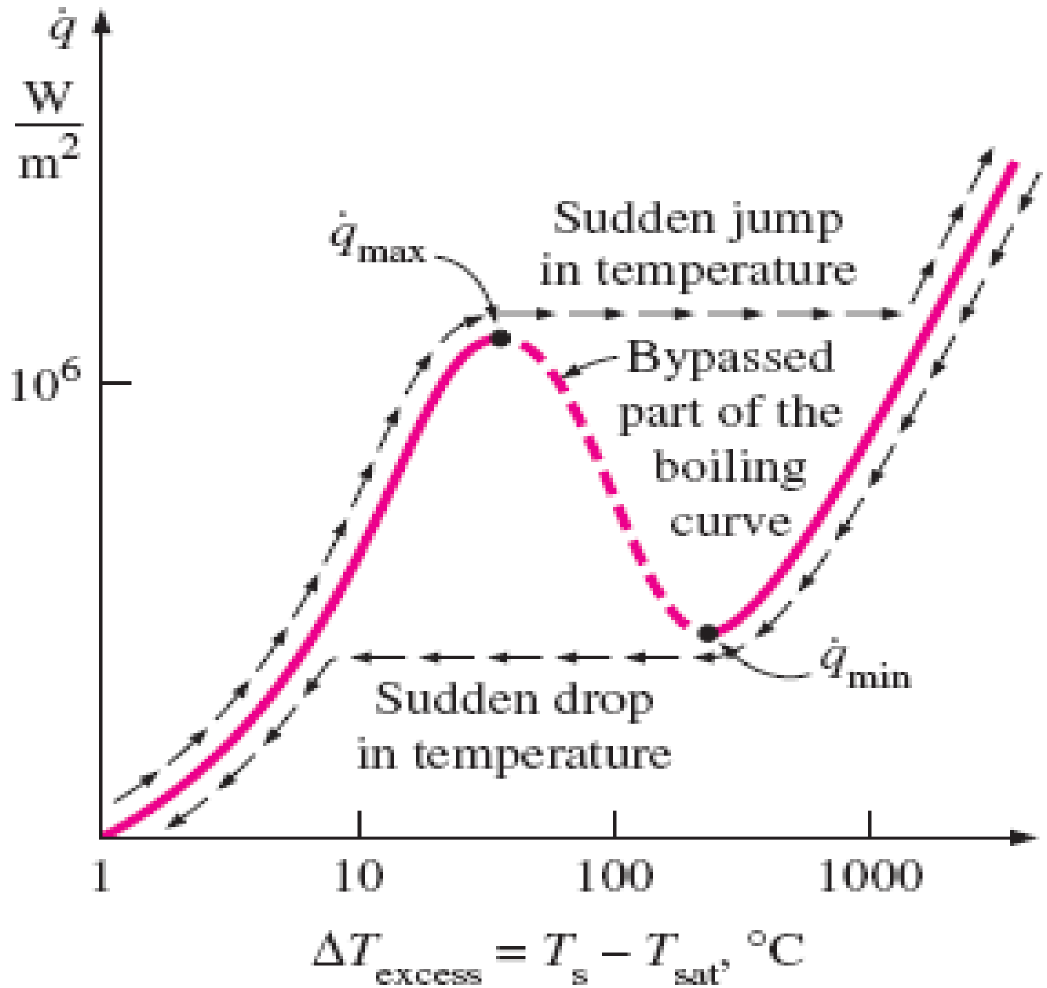
(*c*) Transition boiling

(*d*) Film boiling

Boiling Curve



Typical boiling curve for water at 1 atm pressure.



The actual boiling curve obtained with heated platinum wire in water as the heat flux is increased and then decreased.

Heat Transfer Correlation for PB

$$\dot{q}_{nucleate} = \mu_l \, h_{fg} \left[\frac{g(\rho_l - \rho_v)}{\sigma} \right]^{1/2} \left[\frac{C_p(T_s - T_{sat})}{C_{sf} \, h_{fg} \, Pr_l^n} \right]^3$$

Nucleate boiling

$$\dot{q}_{max} = C_{cr} \, h_{fg} [\sigma g \rho_v^2 (\rho_l - \rho_v)]^{1/4}$$

Peak heat flux

$$\dot{q}_{min} = 0.09 \rho_v \, h_{fg} \left[\frac{\sigma g(\rho_l - \rho_v)}{(\rho_l + \rho_v)^2} \right]^{1/4}$$

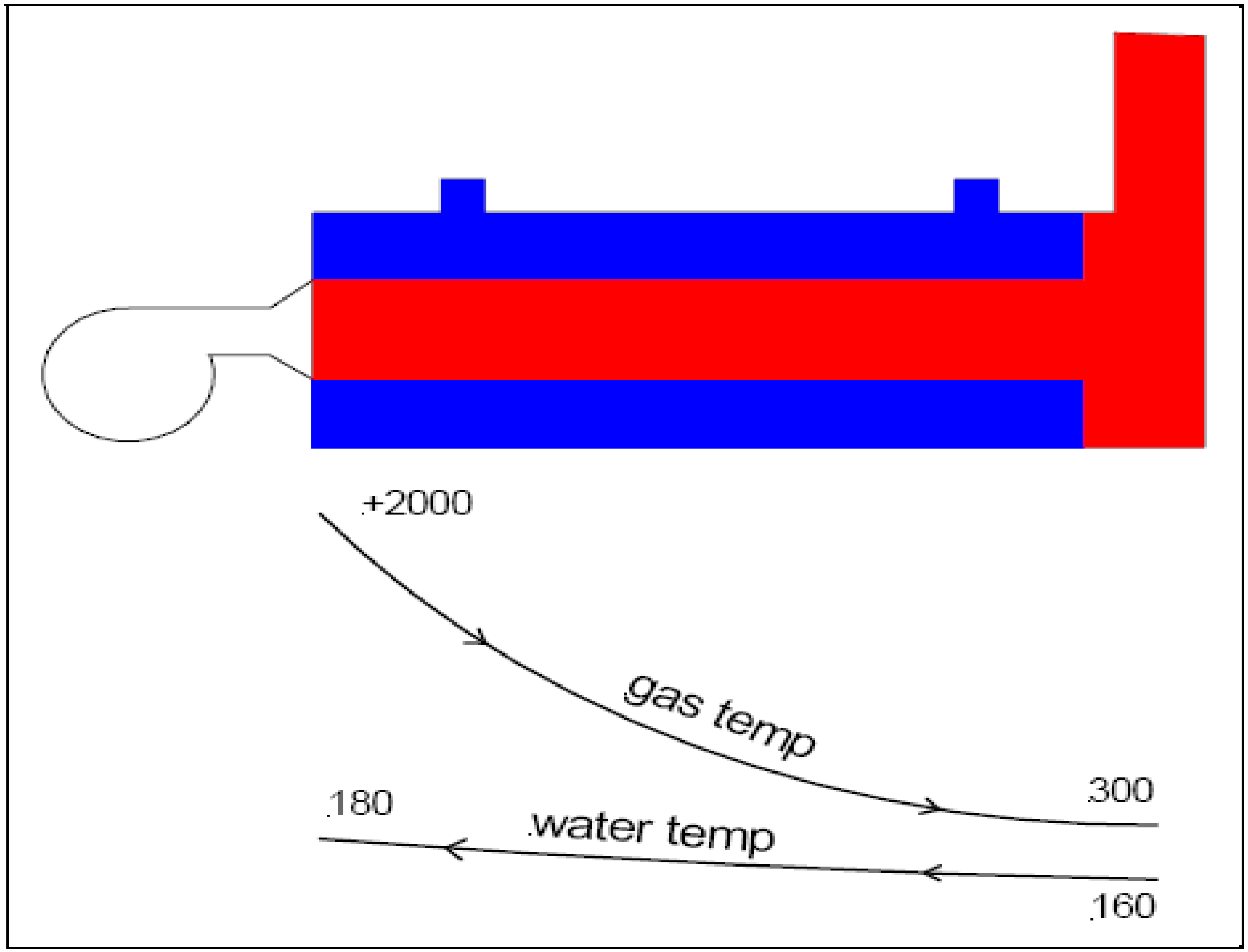
Minimum heat flux

$$\dot{q}_{film} = C_{film} \left[\frac{g k_v^3 \rho_v (\rho_l - \rho_v)[h_{fg} + 0.4 C_{pv} (T_s - T_{sat})]}{\mu_v D(T_s - T_{sat})} \right]^{1/4} (T_s - T_{sat})$$

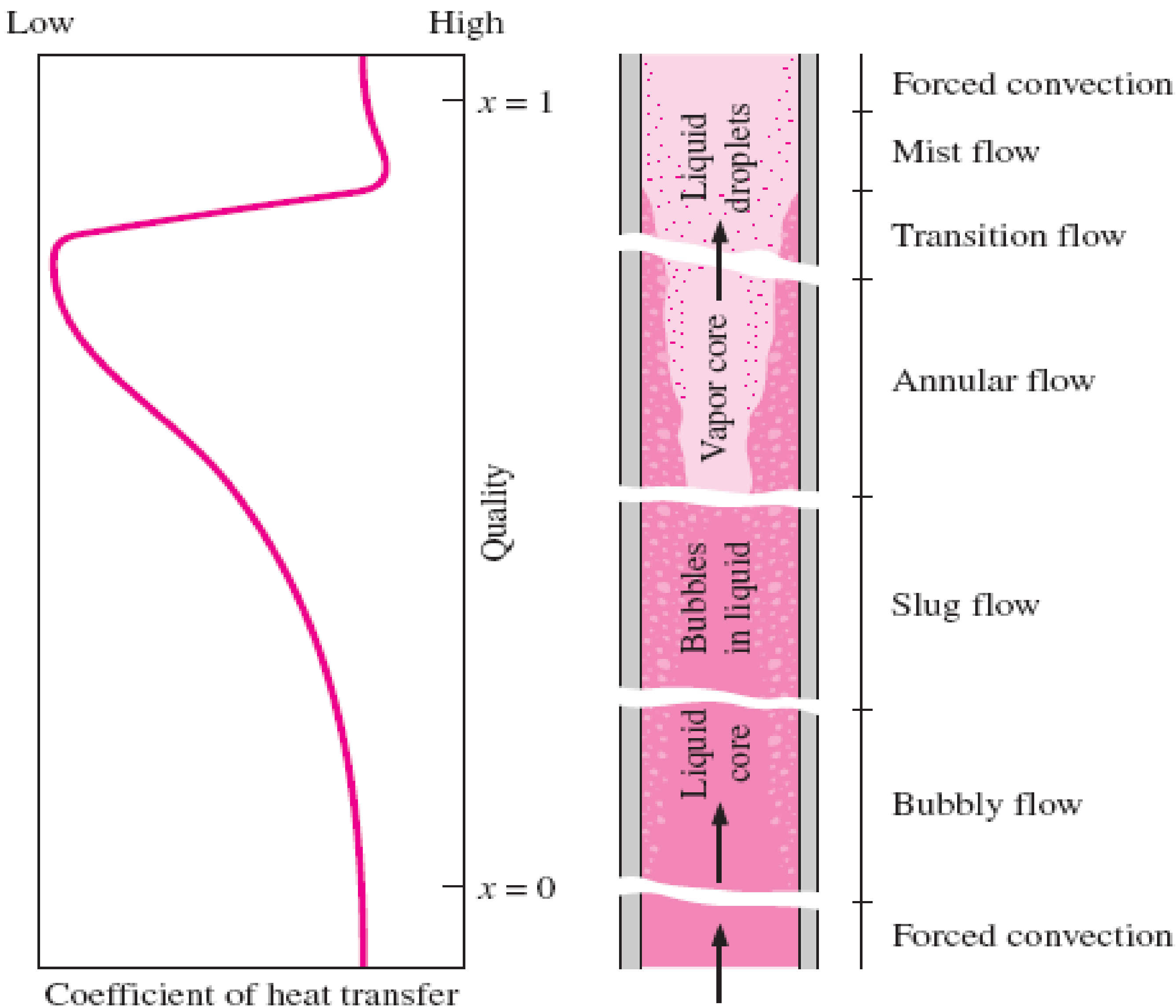
Film boiling

$$C_{film} = \begin{cases} 0.62 \text{ for horizontal cylinders} \\ 0.67 \text{ for spheres} \end{cases}$$

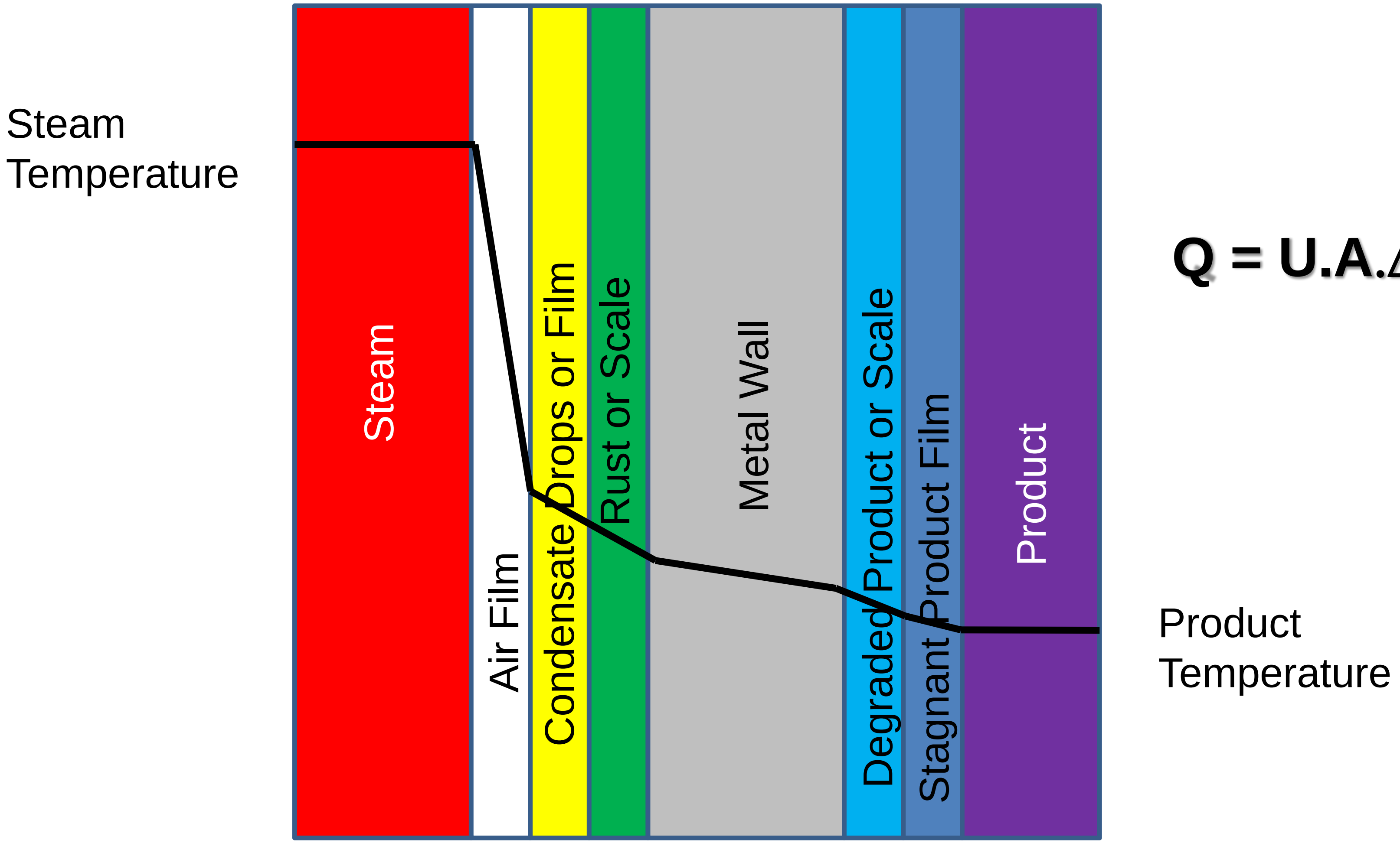
Heat Transfer Between Gas and Water



Heat Transfer Process



Thermal Resistance



$Q = U.A.\Delta T$

BOILER EFFICIENCY

- The several different methods of defining the efficiency of boilers can present a confusing picture.

- As prescribed by the ASME Power Test Code PTC 4, the fuel-to-steam efficiency of a boiler can be determined by two methods: the **Input-Output Method**, and the **Heat Loss Method**.

Input-Output (Direct) Method

- The Input-Output efficiency measurement method is based on the ratio of the output-to-input of the boiler.
- It is calculated by dividing the boiler output (in BTUs) by the boiler input (in BTUs) and multiplying by 100.
- The actual input and output of the boiler are determined through instrumentation and the resulting data is used in calculations that determine the fuel-to-steam efficiency.

Input-Output (Direct) Method

$$\text{Boiler Efficiency } (\eta) = \frac{\text{Heat Output}}{\text{Heat Input}} \times 100$$

$$\text{Boiler Efficiency } (\eta) = \frac{Q \times (h_g - h_f)}{q \times GCV} \times 100$$

Input-Output (Direct) Method

Parameters to be monitored for the calculation of boiler efficiency by direct method are:

- Quantity of steam generated per hour (Q) in kg/hr.
- Quantity of fuel used per hour (q) in kg/hr.
- The working pressure (in kg/cm2(g)) and superheat temperature (oC), if any
- The temperature of feed water (oC)
- Type of fuel and gross calorific value of the fuel (GCV) in kcal/kg of fuel

Efficiency Calculation by I/O Method

Type of boiler: Coal fired Boiler

Heat input data

Qty of coal consumed : 1.8 TPH

GCV of coal : 3200K.Cal/kg

Heat output data

- Qty of steam gen : 8 TPH
- Steam pr/temp: 10 kg/cm^2(g)/180^{0}C
- Enthalpy of steam(sat) at 10 kg/cm^2(g) pressure : 665 K.Cal/kg
- Feed water temperature : 85^0 C
- Enthalpy of feed water : 85 K.Cal/kg

Find out the boiler efficiency ?

Find out the Evaporation Ratio?

$$\text{Boiler efficiency } (\eta): = \frac{\mathbf{Q \times (H - h)}}{\mathbf{(q \times GCV)}} \mathbf{\times 100}$$

Where **Q** = Quantity of steam generated per hour (kg/hr)
H = Enthalpy of saturated steam (kcal/kg)
h = Enthalpy of feed water (kcal/kg)

q = Quantity of fuel used per hour (kg/hr)
GCV = Gross calorific value of the fuel (kcal/kg)

Boiler efficiency (η)= $\frac{\text{8 TPH x1000Kg/Tx (665–85) x 100}}{\text{1.8 TPH x 1000Kg/T x 3200}}$

= 80.0%

Evaporation Ratio = 8 Tonne of steam/1.8 Ton of coal

= 4.4

Heat Loss (Indirect) Method

- The Heat Balance efficiency measurement method is based on accounting for all the heat losses of the boiler.
- The actual measurement method consists of subtracting from 100 % the total percentage of: A) stack, B) radiation, and C) convection losses.
- The resulting value is the boiler's fuel-to-steam efficiency. The heat loss method accounts for stack, radiation and convection losses.

Indirect Method

Efficiency of boiler (n) = 100 - (i + ii + iii + iv + v + vi + vii)

Whereby the principle losses that occur in a boiler are loss of heat due to:

i. Dry flue gas
ii. Evaporation of water formed due to H_2 in fuel
iii. Evaporation of moisture in fuel
iv. Moisture present in combustion air
v. Unburnt fuel in fly ash
vi. Unburnt fuel in bottom ash
vii. Radiation and other unaccounted losses

Indirect Method

The data required for calculation of boiler efficiency using the indirect method are:

- Ultimate analysis of fuel (H_2, O_2, S, C, moisture content, ash content)
- Percentage of oxygen or CO_2 in the flue gas
- Flue gas temperature in oC (Tf)
- Ambient temperature in oC (Ta) and humidity of air in kg/kg of dry air
- GCV of fuel in kcal/kg
- Percentage combustible in ash (in case of solid fuels)
- GCV of ash in kcal/kg (in case of solid fuels)

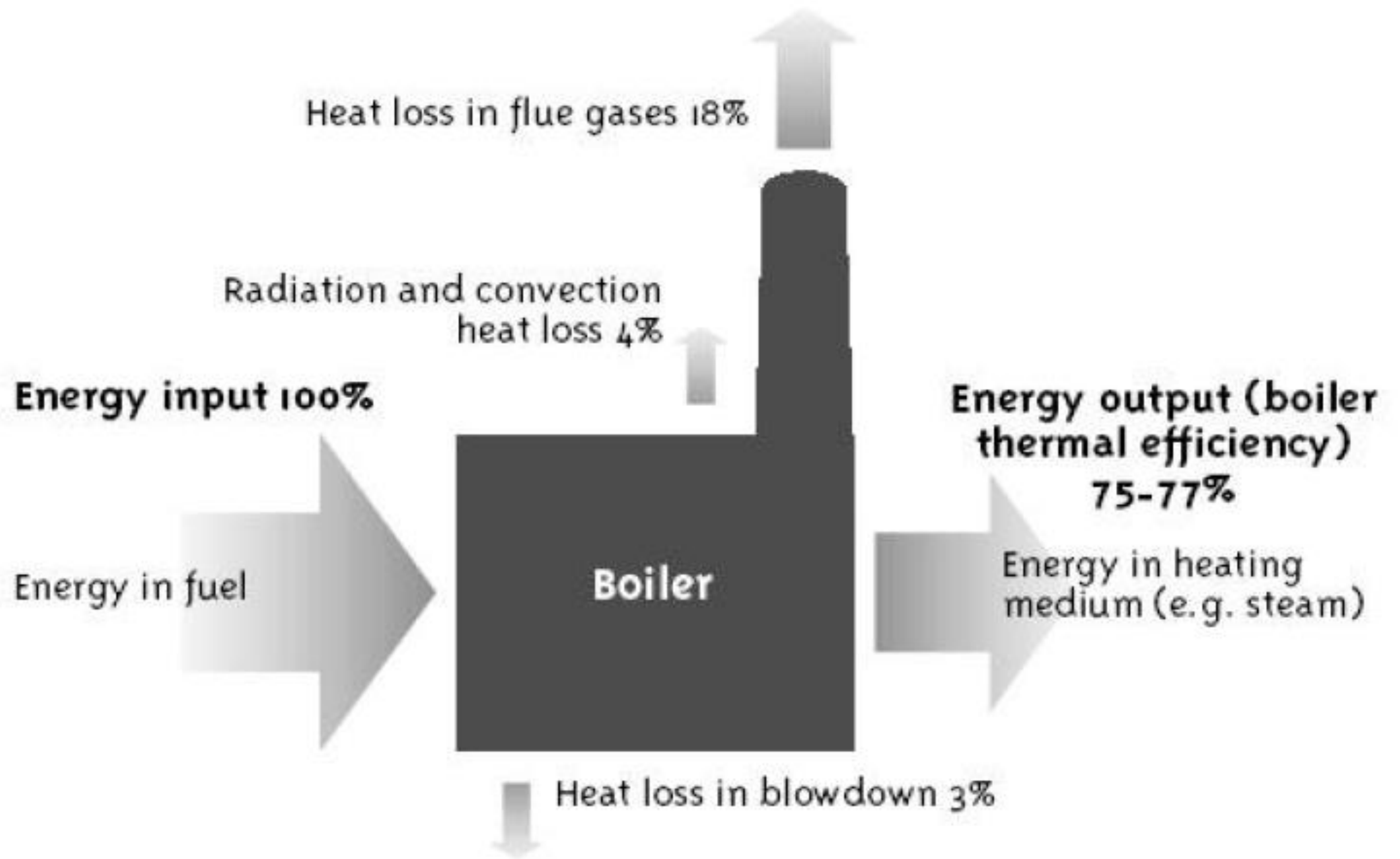
COMPONENTS OF EFFICIENCY

- Flue gas temperature
- Stack Losses
- Heating medium temperatures (steam pressures in the case of steam boilers)
- Radiation and convection losses
- Excess air

COMPONENTS OF EFFICIENCY

- Ambient air temperature
- Heating Medium Temperatures
- Fuel specification
- Steam quality (in the case of steam boilers)

The Flow of Energy



Boiler Heat Losses

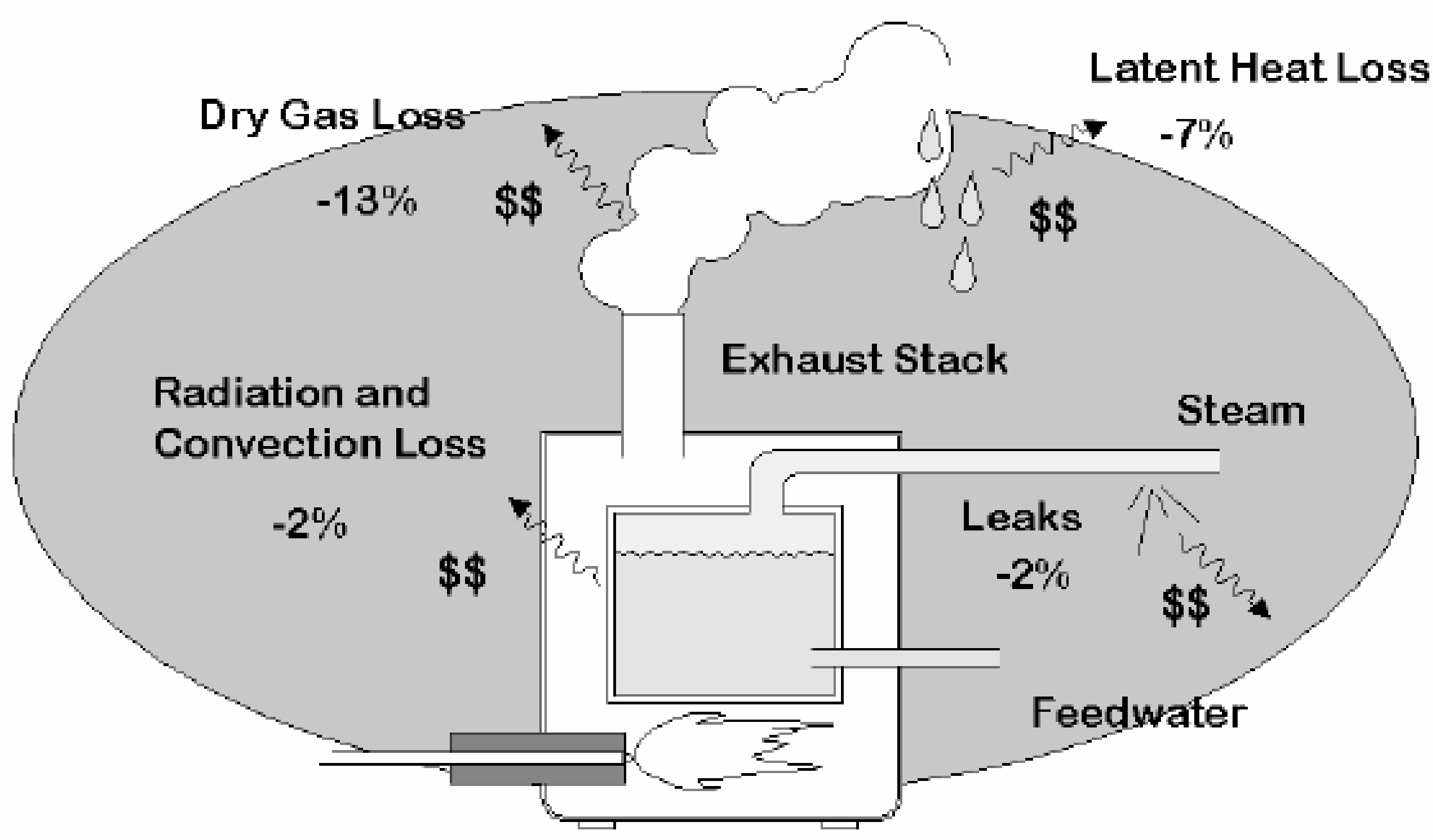
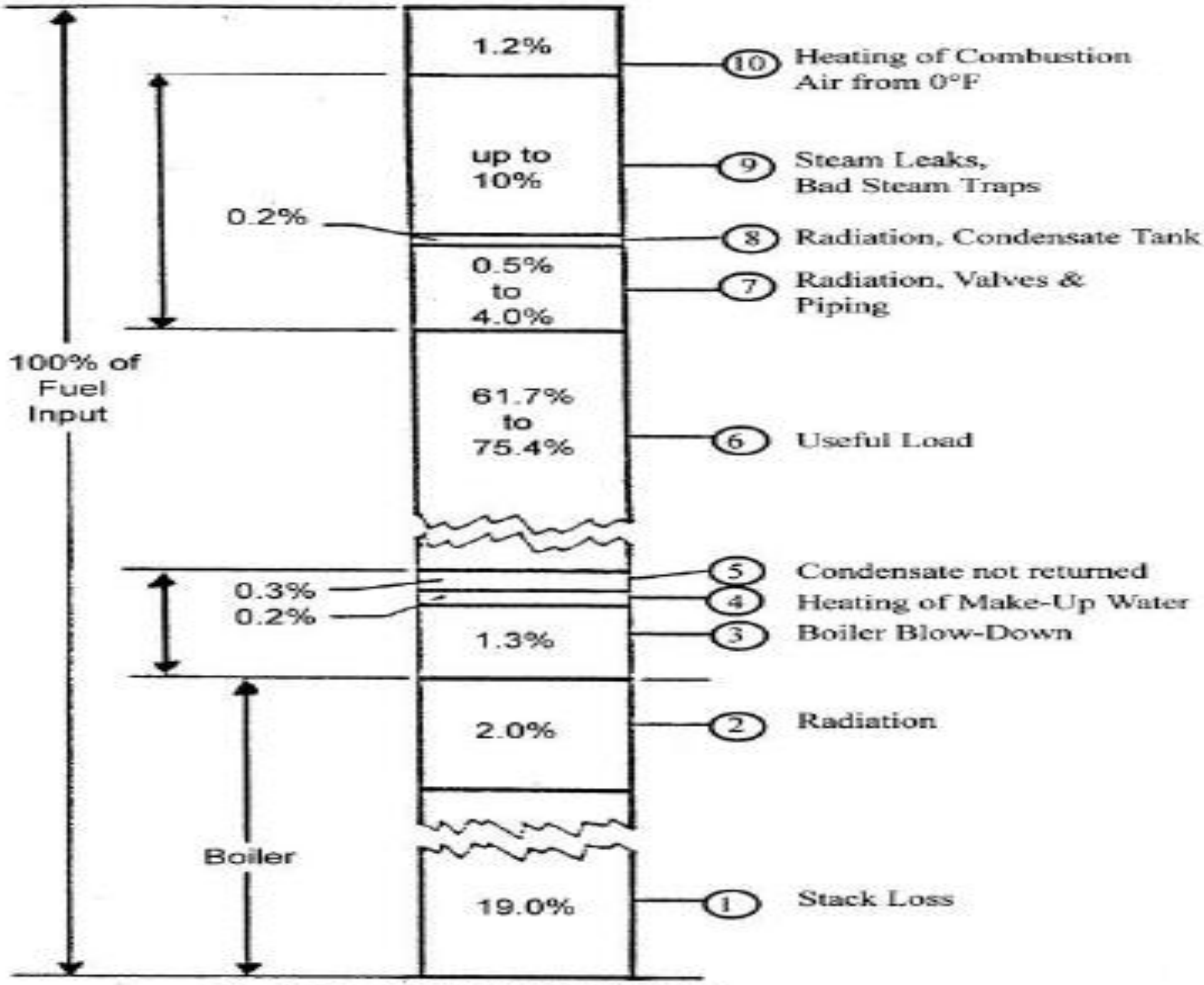
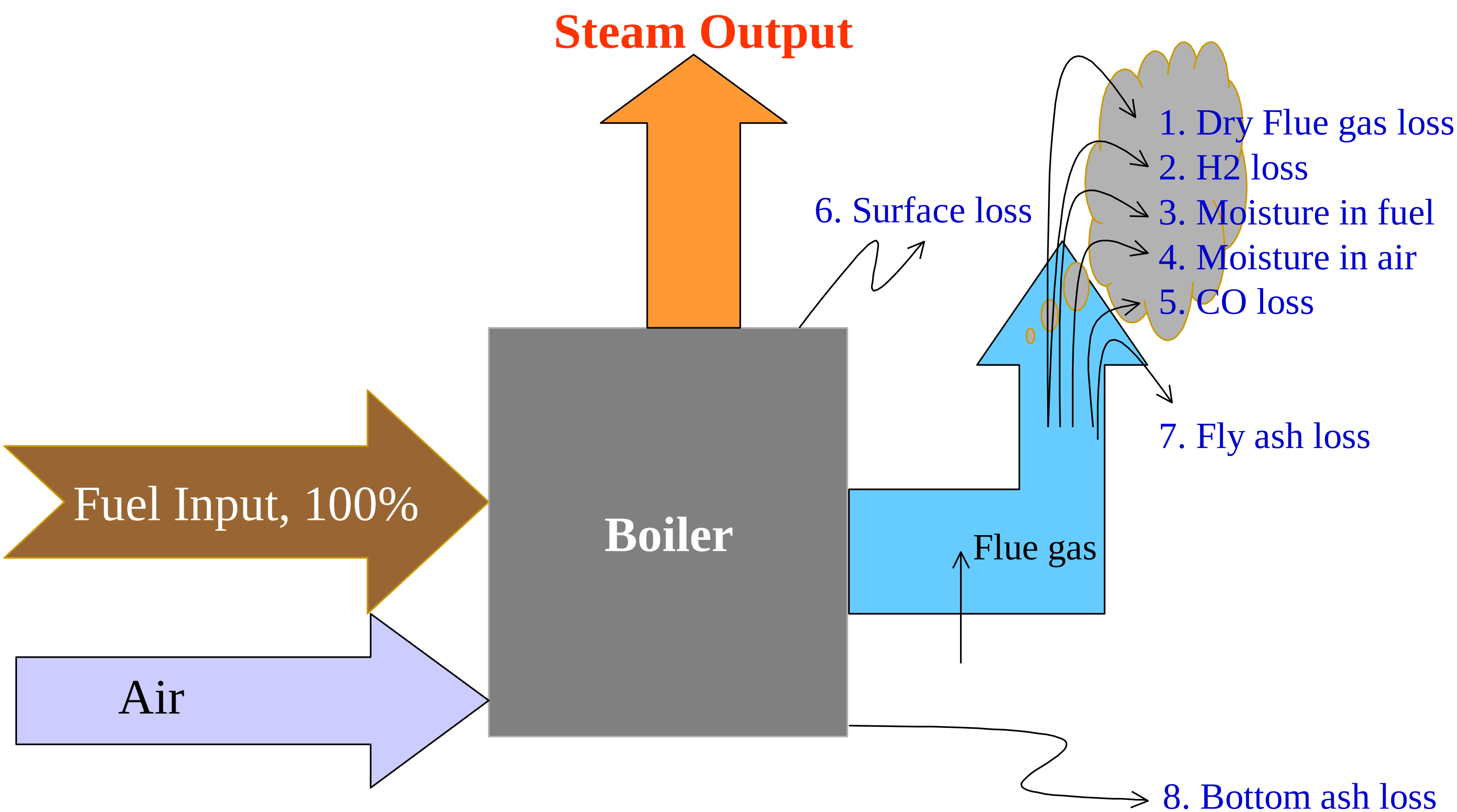


Figure 2. Boiler Heat Losses



Btu BAR, GAS FIRED BOILER

What are the losses that occur in a boiler?



Efficiency **= 100 – (1+2+3+4+5+6+7+8)**

(by In Direct Method)

Effect of Excess Air on Boiler Efficiency

Combustion Efficiency for Natural Gas

Excess %		Combustion Efficiency				
		Flue gas temperature less combustion air temp, °F				
Air	Oxygen	200	300	400	500	600
9.5	2.0	85.4	83.1	80.8	78.4	76.0
15.0	3.0	85.2	82.8	80.4	77.9	75.4
28.1	5.0	84.7	82.1	79.5	76.7	74.0
44.9	7.0	84.1	81.2	78.2	75.2	72.1
81.6	10.0	82.8	79.3	75.6	71.9	68.2

Assumes complete combustion with no water vapor in the combustion air.

On well-designed natural gas-fired systems, an excess air level of 10% is attainable. An often stated rule of thumb is that boiler efficiency can be increased by 1% for each 15% reduction in excess air or 40°F reduction in stack gas temperature.

Example of Improving Efficiency

A boiler operates for 8,000 hours per year and consumes 500,000 MBtu of natural gas while producing 45,000 lb/hr of 150 psig steam.

Stack gas measurements indicate an excess air level of 44.9% with a flue gas less combustion air temperature of 400°F.

From the table, the boiler combustion efficiency is 78.2% (E1).

Tuning the boiler reduces the excess air to 9.5% with a flue gas less combustion air temperature of 300°F.

The boiler combustion efficiency increases to 83.1% (E2).

Assuming a steam value of $4.50/MBtu, the annual cost savings are:

Cost Savings = Fuel Consumption x (1 - E1/E2) x steam cost = 29,482 MBtu/yr x $4.50/MBtu = $132,671 annually

Enhancement of Boiler Efficiency

Boiler HP	Fuel Cost			
	$0.75	$1.00	$1.50	$2.00
100	$3,635	$4,847	$7,271	$9,694
200	$7,271	$9,694	$14,541	$19,389
300	$10,906	$14,541	$21,812	$29,083
500	$18,177	$24,236	$36,354	$48,471
800	$29,083	$38,777	$58,166	$77,554

Table 1. Possible savings per year with a 5% improvement in boiler efficiency (based on 3000 hours per year of operation).

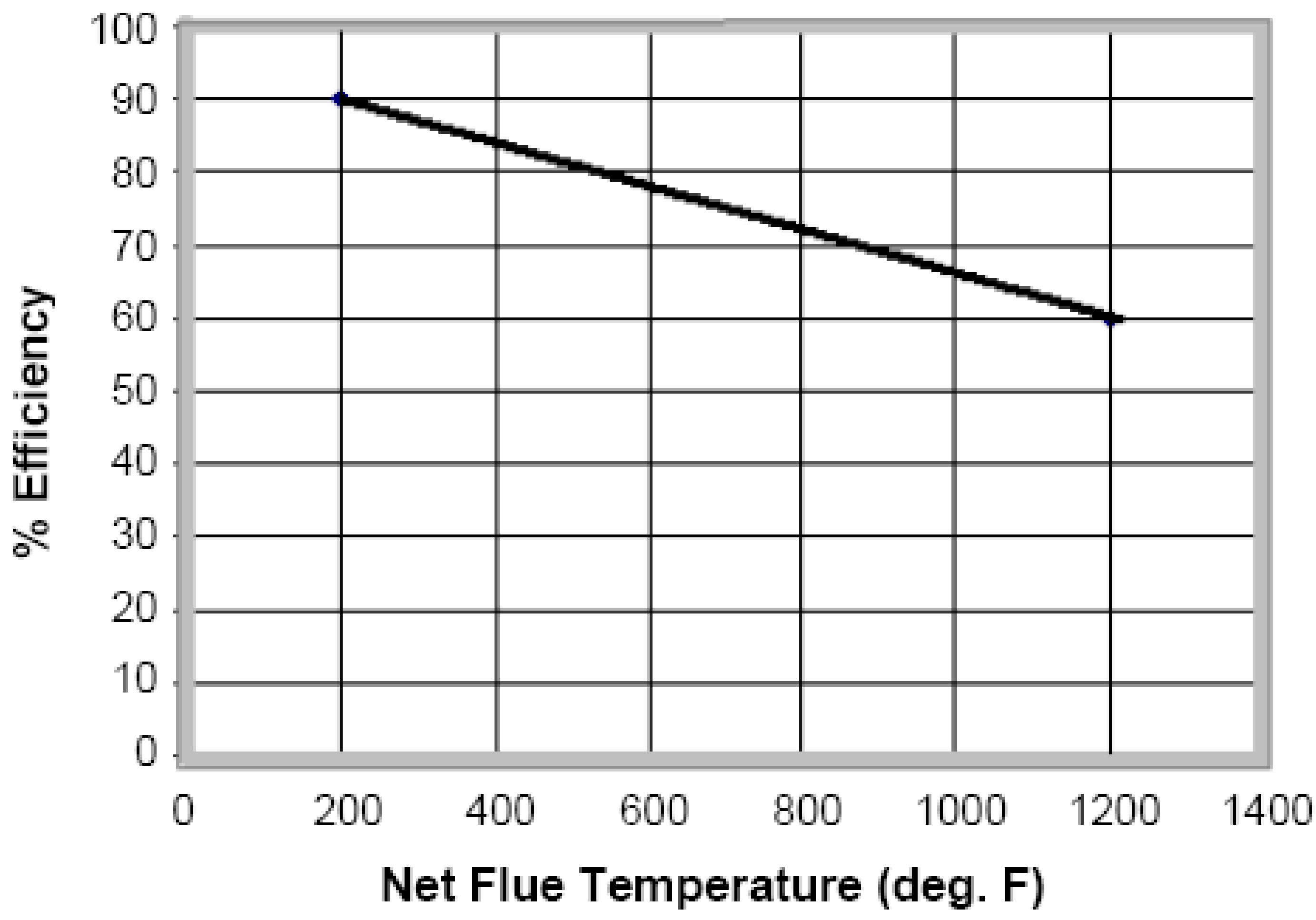
Energy Conservation Opportunities in Boilers

1. Reduce Stack Temperature

- Stack temperatures greater than 200° C indicates potential for recovery of waste heat.
- It also indicate the scaling of heat transfer/recovery equipment and hence the urgency of taking an early shut down for water / flue side cleaning.

➢ 22° C reduction in flue gas temperature increases boiler efficiency by 1%

Flue Temperature vs Efficiency (FO)



2. Combustion Air Preheating

- Combustion air preheating is an alternative to feedwater heating.

- In order to improve thermal efficiency by 1%, the combustion air temperature must be raised by 20 ^{o}C.

3. Complete Combustion

- Incomplete combustion can arise from a shortage of air or surplus of fuel or poor distribution of fuel.
- **In the case of oil and gas fired systems,** CO or smoke with normal or high excess air indicates burner system problems.

  Example: Poor mixing of fuel and air at the burner. Poor oil fires can result from improper viscosity, worn tips, carbonization on tips and deterioration of diffusers.
- **With coal firing**: Loss occurs as grit carry-over or carbon-in-ash (2% loss).

  Example :In chain grate stokers, large lumps will not burn out completely, while small pieces and fines may block the air passage, thus causing poor air distribution.

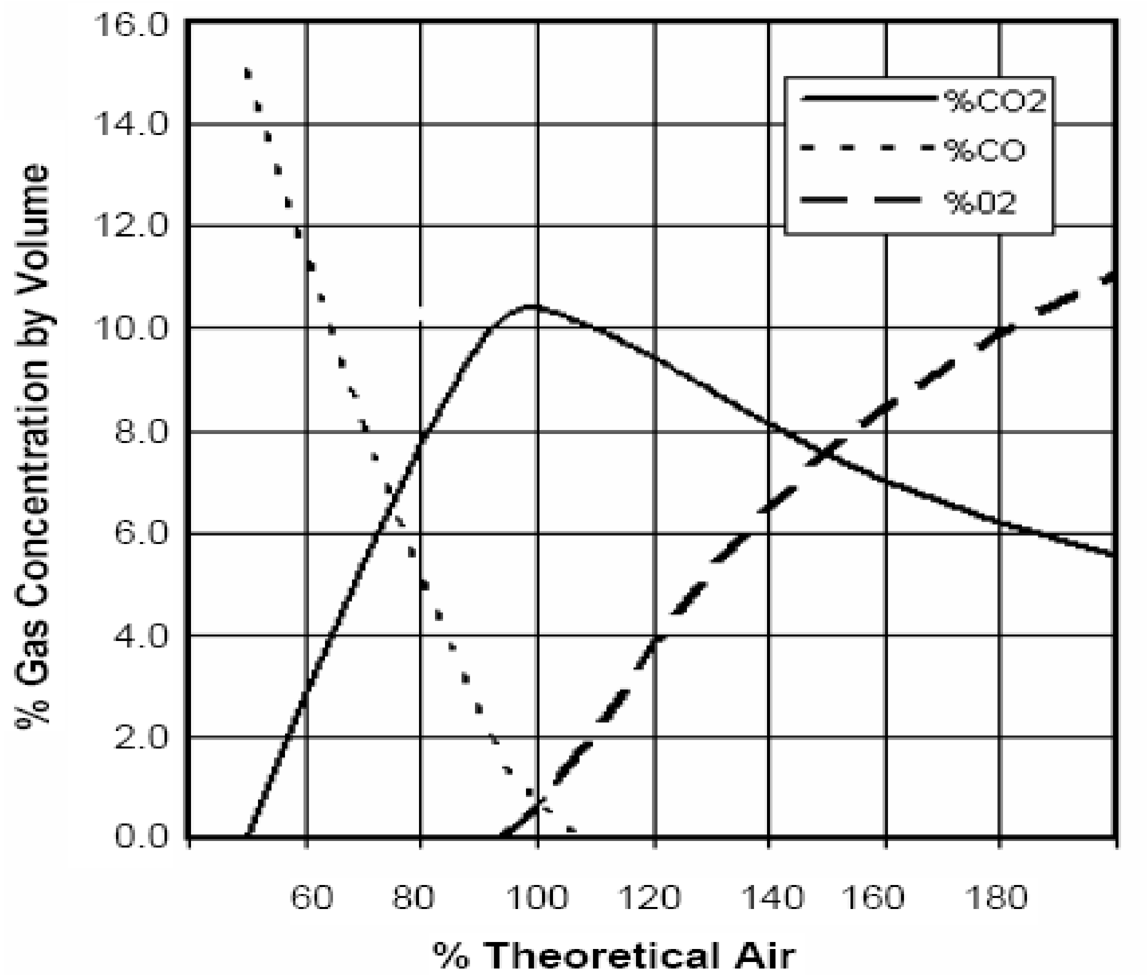
Increase in the fines in pulverized coal also increases carbon loss.

4. Control Excess Air For Every 1% Reduction In Excess Air ,0.6% Rise In Efficiency

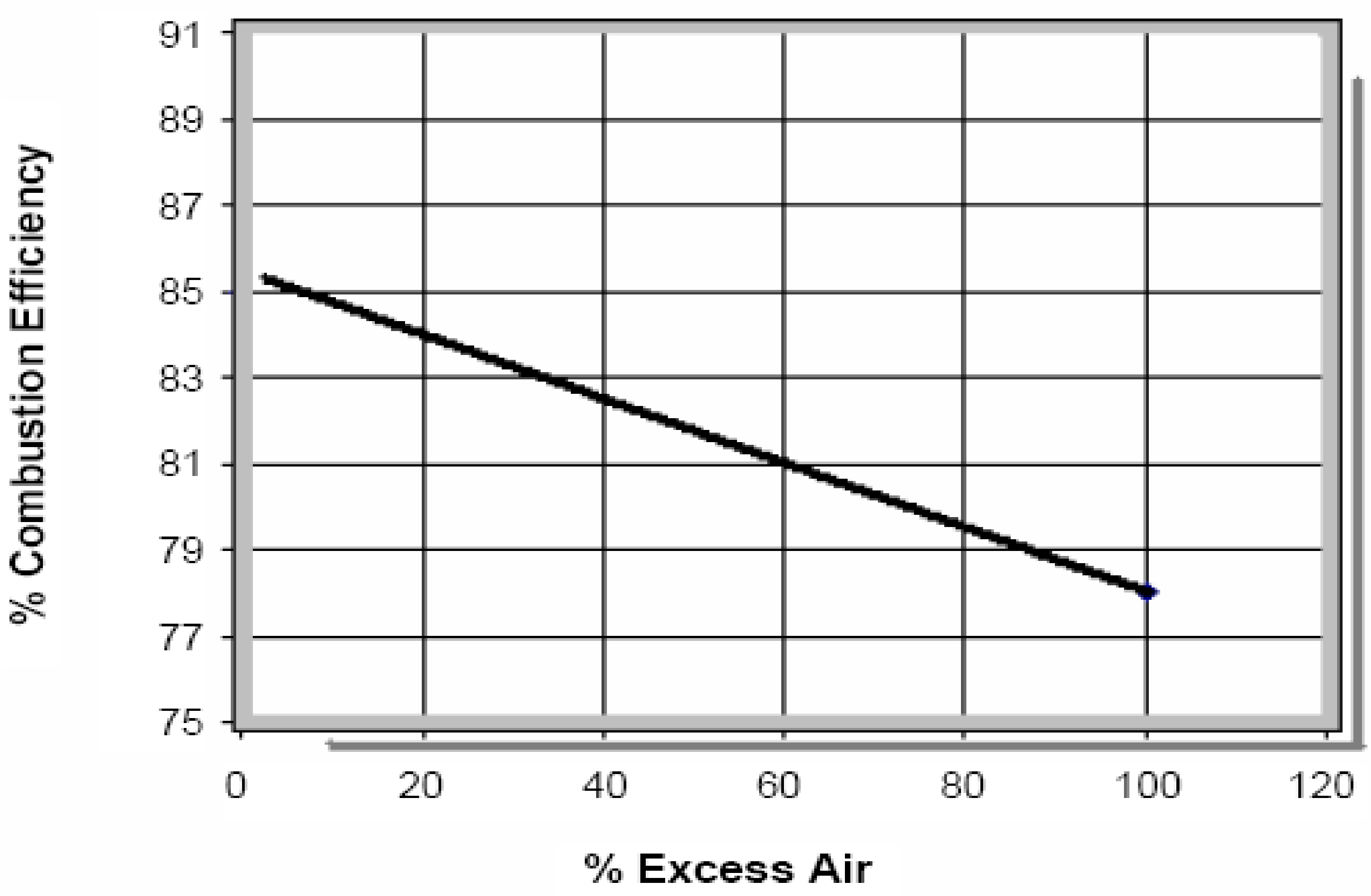
The optimum excess air level varies with furnace design, type of burner, fuel and process variables.. **Install oxygen trim system**

TABLE 2.5 EXCESS AIR LEVELS FOR DIFFERENT FUELS		
Fuel	**Type of Furnace or Burners**	**Excess Air (% by wt)**
Pulverised coal	Completely water-cooled furnace for slag-tap or dry-ash removal	15-20
	Partially water-cooled furnace for dry-ash removal	15-40
Coal	Spreader stoker	30-60
	Water-cooler vibrating-grate stokers	30-60
	Chain-grate and traveling-grate stokers	15-50
	Underfeed stoker	20-50
Fuel oil	Oil burners, register type	15-20
	Multi-fuel burners and flat-flame	20-30
Natural gas	High pressure burner	5-7
Wood	Dutch over (10-23% through grates) and Hofft type	20-25
Bagasse	All furnaces	25-35
Black liquor	Recovery furnaces for draft and soda-pulping processes	30-40

Effect of Excess Air on Combustion Gas Concentrations

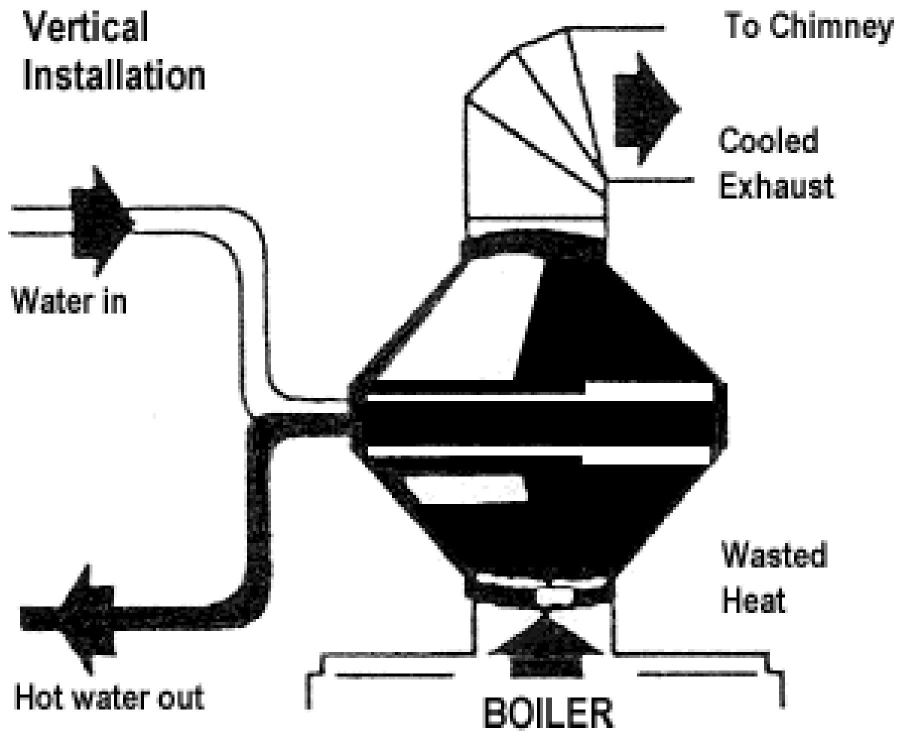


Combustion Efficiency vs Excess Air (FO)



5. Feed Water Preheating using Economiser

- For an older shell boiler, with a flue gas exit temperature of 260°C, an economizer could be used to reduce it to 200°C, Increase in overall thermal efficiency would be in the order of 3%.
- Condensing economizer(N.Gas) Flue gas reduction up to 65°C



Exhaust Heat Recovery

➢ 6°C raise in feed water temperature, by economiser/condensate recovery, corresponds to a 1% saving in fuel consumption

6. Reduction of Scaling and Soot Losses

- In oil and coal-fired boilers, soot buildup on tubes acts as an insulator against heat transfer. Any such deposits should be removed on a regular basis. Elevated stack temperatures may indicate excessive soot buildup. Also same result will occur due to scaling on the water side.

- High exit gas temperatures at normal excess air indicate poor heat transfer performance. This condition can result from a gradual build-up of gas-side or waterside deposits. Waterside deposits require a review of water treatment procedures and tube cleaning to remove deposits.

- Stack temperature should be checked and recorded regularly as an indicator of soot deposits. When the flue gas temperature rises about 20^{o}C above the temperature for a newly cleaned boiler, it is time to remove the soot deposits

7. Effect of Boiler Loading on Efficiency

- As the load falls, so does the value of the mass flow rate of the flue gases through the tubes. This reduction in flow rate for the same heat transfer area, reduced the exit flue gas temperatures by a small extent, reducing the sensible heat loss.
- Below half load, most combustion appliances need more excess air to burn the fuel completely and increases the sensible heat loss.
- Operation of boiler below 25% should be avoided
- Optimum efficiency occurs at 65-85% of full loads

Effect of Load on Boiler Efficiency

Fuel	Full Load Efficiency	Low Load Efficiency
Coal	85 %	75 %
Oil	80 %	72 %
Gas	75 %	70 %
Biomass	70 % (?)	60 % (?)

8. Boiler Replacement

If the existing boiler is :

Old and inefficient, not capable of firing cheaper substitution fuel, over or under-sized for present requirements, not designed for ideal loading conditions replacement option should be explored.

- Since boiler plants traditionally have a useful life of well over 25 years, replacement must be carefully studied.

THANK YOU

for your attention

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