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## Heat Recovery Boilers

### INTRODUCTION

Heat recovery boilers, also known as waste heat recovery boilers or heat recovery steam generators (HRSGs), form an inevitable part of chemical plants, refineries, power plants, and process systems. They are classified in several ways, as can be seen in [Fig. 2.1](#), according to the application, the type of boiler used, whether the flue gas is used for process or mainly for energy recovery, cleanliness of the gas, and boiler configuration, to mention a few. The main classification is based on whether the boiler is used for process purposes or for energy recovery. Process waste heat boilers are used to cool waste gas streams from a given inlet temperature to a desired exit temperature for further processing purposes. An example can be found in the chemical industry in a sulfuric acid or hydrogen plant where the gas stream is cooled to a particular gas temperature and then taken to a reactor for further processing. The exit gas temperature from the boiler is an important parameter affecting the downstream process reactions and hence is controlled by using a gas bypass system. Steam generation is of secondary importance in such plants. In energy recovery applications, on the other hand, the gas is cooled as much as possible while avoiding low temperature corrosion. Examples can be found in gas turbine exhaust heat recovery or flue gas heat

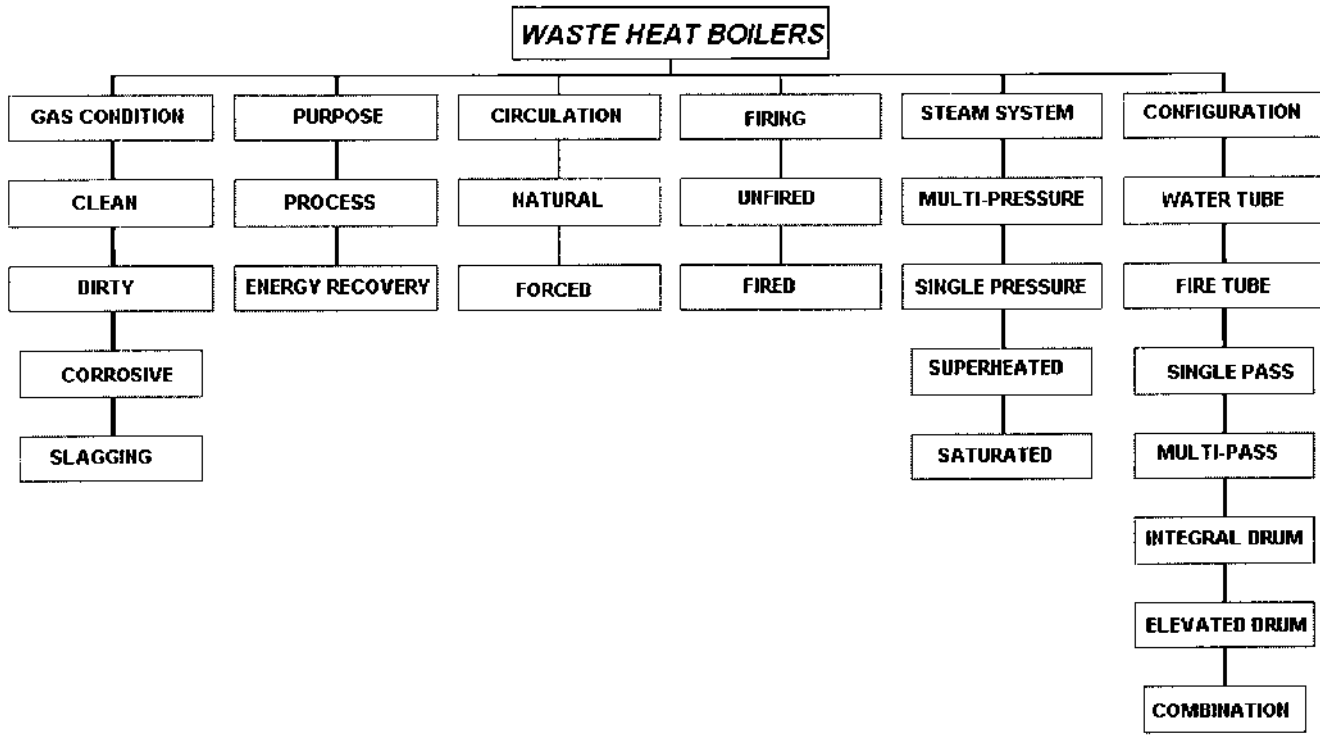


FIGURE 2.1 Classification of waste heat boilers.

recovery from incinerators, furnaces, and kilns. The objective here is to maximize energy recovery.

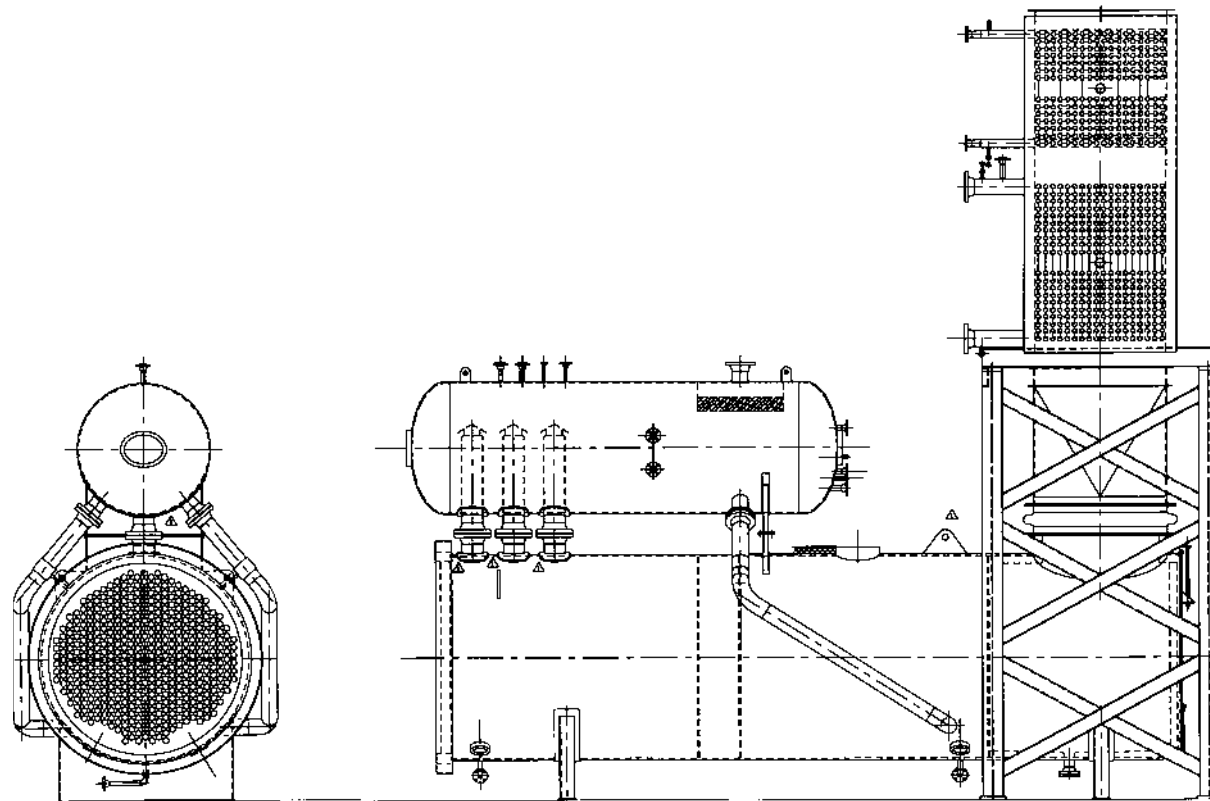
If the gas stream is clean, water tube boilers with extended surfaces may be used. In solid or liquid waste incineration applications, the gas is generally dirty and may contain corrosive compounds, acid vapors, ash, and particulates. If the ash contains compounds of sodium, potassium, or nonferrous metals, slagging is likely on heat transfer surfaces if these compounds become molten. In these cases, bare tube boilers with provision for cleaning the tubes with soot blowers or a rapping mechanism are used. A water-cooled furnace, which cools the gas stream to a temperature below the ash melting temperature and hence minimizes slagging on the convective surfaces, may also be necessary.

Generally if the gas inlet temperature is high, say above 1400°F, a single-pressure heat recovery system is adequate to cool the gases to about 300–350°F. In gas turbine exhaust heat recovery applications with a low inlet gas temperature to the HRSG of 900–1000°F, a single-pressure heat recovery system cannot cool the gases adequately and a multipressure steam system is often required.

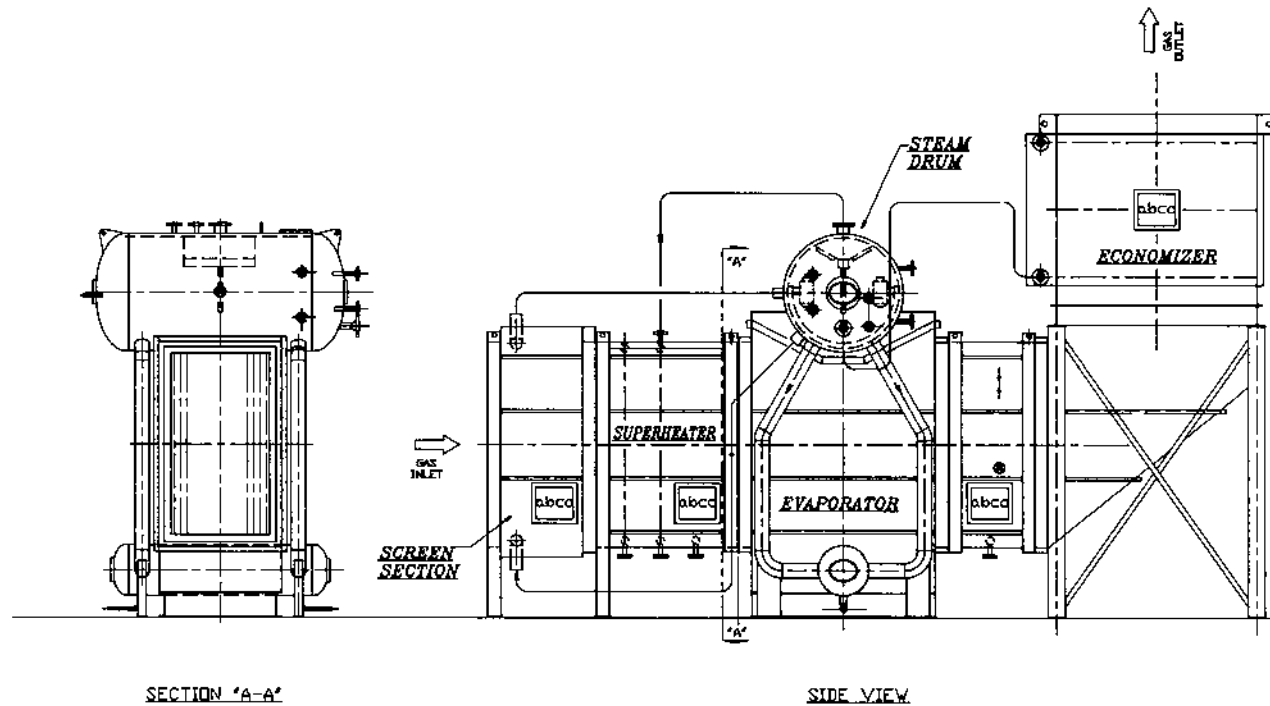
In the United States HRSGs are generally of natural circulation design, whereas in Europe it is very common to see once-through and forced circulation designs. The features of these boilers are discussed later.

Flue gas analysis is important to the design of the boiler. A large amount of water vapor or hydrogen increases the specific heat and thermal conductivity of the gas and hence the boiler duty and heat flux. For example, the reformed gas in hydrogen plants has a large volume of hydrogen and water vapor, which increases the heat transfer coefficient by 500–800% compared to typical flue gases. Hence heat flux is of concern in these types of boilers. Hydrogen chloride (HCl) vapor in the flue gases indicates corrosive potential, particularly if a superheater operating at high metal temperatures, say exceeding 900°F, is present. The presence of sulfur trioxide (SO<sub>3</sub>) vapor and HCl also suggests low temperature corrosion problems due to their low acid dew points. Flue gas pressure in waste heat boilers is typically atmospheric or a few inches of water column (in. WC) above or below atmospheric pressure; however, there are applications such as the use of a reformed gas boiler or synthesis gas boiler in hydrogen or ammonia plants where the gas pressure could be as high as 300–1500 psig (see [Chap. 8, Table 8.46](#)). Fire tube boilers are generally preferred for these applications, though special water tube boiler designed with heat transfer surfaces located inside pressure vessels have been built.

A common classification of boilers is based on whether the gas flows inside or outside the tubes. In fire tube boilers, the flue gases flow inside the tubes ([Fig. 2.2](#)), whereas in water tube boilers, the gas flows outside the tubes as shown in [Fig. 2.3](#). The features of each type are discussed in the following section.



**FIGURE 2.2** Fire tube waste heat boiler with superheater and economizer. (Courtesy of ABCO Industries, Abilene, TX.)



**FIGURE 2.3** Water tube waste heat boiler with superheater and economizer. (Courtesy of ABCO Industries, Abilene, TX.)

## WATER TUBE VERSUS FIRE TUBE BOILERS

Table 2.1 shows a few aspects of fire tube and water tube waste heat boilers. Generally water tube boilers are suitable for large gas flows exceeding millions of pounds per hour and can handle high steam pressures and temperatures. Fire tube boilers are suitable for low steam pressures, generally below 500 psig. Table 2.2 shows the effect of pressure on tube thickness in both types of boilers, and one can see why fire tube boilers are not suggested for high steam pressure applications.

In water tube boilers, extended surfaces can be used to make them compact if the gas stream is clean, as discussed in Q8.21. Flue gas pressure drop will also be lower than for an equivalent fire tube boiler owing to the compactness of the design. Water tube boilers can be smaller and weigh less, particularly if the gas flow is large, exceeding 100,000 lb/h. Superheaters can be used in both types. In a water tube boiler they can be located in an optimum gas temperature zone. A shield screen section or a large convection section precedes the superheater. In a fire tube boiler, the superheater has to be located at either the gas inlet or exit, making the design less flexible and vulnerable to slagging or corrosion. If the waste gas is slagging in nature, a water tube boiler is desired because the surfaces can be cleaned by using retractable soot blowers. In general, the type of boiler to

**TABLE 2.1** A Comparison of Fire Tube and Water Tube Boilers

Variable	Fire tube boiler	Water tube boiler
Gas flow	Small—less than 50,000 lb/h	50,000 to millions of lb/h
Gas inlet temperature	Low to adiabatic combustion	Low to adiabatic combustion
Gas pressure	High—even as high as 2000 psig	Generally less than 2 psig
Firing	Possible	Possible
Type of heating surface	Bare tube	Bare and finned tubes
Superheater location	At inlet or exit of boiler	Anywhere in the gas path using screen section
Water inventory	High	Low
Heat flux-steam side	Generally low	Can be high with finned tubes
Multiple steam pressure	No	Yes
Soot blower location	Inlet or exit of boiler	Anywhere inside boiler surfaces
Multiple modules	No	Yes

**TABLE 2.2** Tube Thickness vs. Steam Pressure—ASME Sec 1

Tube thickness <sup>a</sup> (in.)	External pressure (psig)	Internal pressure (psig)
0.105	575	1147
0.120	686	1339
0.135	800	1533
0.150	921	1730
0.180	1172	2137

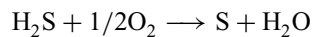
<sup>a</sup>2 in. OD, SA 178a and SA 192 carbon steel tubes at 700°F.

be used for a particular case is determined by the experience of the manufacturer. Sometimes a combination of fire and water tube boilers is used to suit special needs.

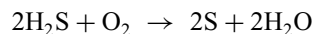
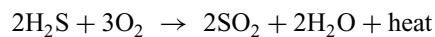
## HEAT RECOVERY IN SULFUR PLANTS

A sulfur plant forms an important part of a gas processing system in a refinery. Sulfur is present in natural gas as hydrogen sulfide (H<sub>2</sub>S); it is the by-product of processing natural gas and refining high sulfur crude oils. For process and combustion applications, the sulfur in the natural gas has to be removed. Sulfur recovery refers to the conversion of hydrogen sulfide to elemental sulfur. The most common process for sulfur removal is the Claus process, which recovers about 95–97% of the hydrogen sulfide in the feedstream. Waste heat boilers are an important part of this process (Fig. 2.4).

The Claus process used today is a modification of a process first used in 1883, in which H<sub>2</sub>S was reacted over a catalyst with air to form elemental sulfur and water. The reaction is expressed as



Control of this exothermic reaction was difficult, and sulfur recovery efficiency was low. Modifications later included burning one third of the H<sub>2</sub>S to produce sulfur dioxide, SO<sub>2</sub>, which is reacted with the remaining H<sub>2</sub>S to produce elemental sulfur. This process consists of multistage catalytic oxidation of hydrogen sulfide according to the reactions



Each catalytic stage consists of a gas reheater, a catalyst chamber, and a condenser as shown in Fig. 2.4.

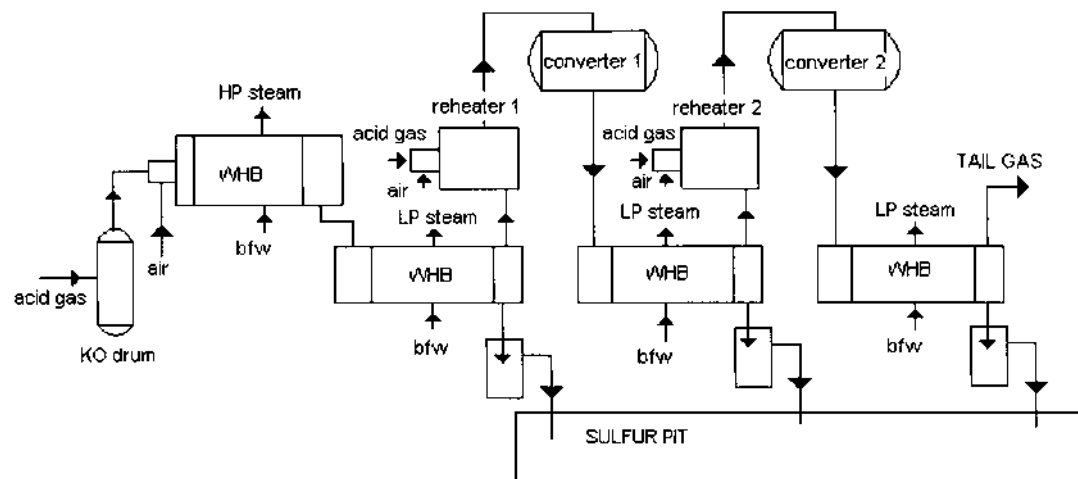
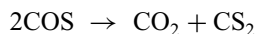
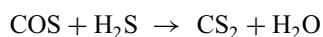
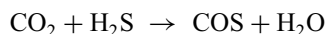


FIGURE 2.4 Claus process for sulfur recovery.



In addition to the oxidation of H<sub>2</sub>S to SO<sub>2</sub> and the reaction of SO<sub>2</sub> with H<sub>2</sub>S in the reaction furnace, many other side reactions occur, such as



The gas stream contains CO<sub>2</sub>, H<sub>2</sub>S, SO<sub>2</sub>, H<sub>2</sub>, CH<sub>4</sub>, and water vapor in addition to various species of sulfur. The duty of the boiler behind the sulfur combustor includes both sensible heat from cooling of the gas stream from 2600°F to about 650°F and the duty associated with the transformation of various species of sulfur. The reaction furnace normally operates at 1800–2800°F, and the flue gases are cooled in a waste heat boiler (Fig. 2.5), in which saturated steam at about 600 psig is generated. This is typically of two-gas-pass design, though single-pass designs have been used. The gas is cooled to about 1200°F in the first pass and finally to about 650°F in the two-pass boiler.

Figure 2.6 shows the boiler for a large sulfur recovery plant, which consists of two separate shells for each pass connected to a common steam drum. The steam drum is external to the boiler. The external downcomer and riser system ensures adequate cooling of the tubes and the tube sheet, which is refractory-lined; ferrules are also used for further protection of the tube sheet. Ferrules are generally made of ceramic material and are used to transfer the heat from the hot flue gases (at about 2800°F) to the tubes, which are cooled by water. The refractory on the tube sheet, which is about 4 in. thick and made of a high grade, high density castable, lowers the tube sheet temperature at the hot end and thus limits the thermal stress across it. The inlet gas chamber is also refractory-lined. The casing is kept above 350–400°F through a combination of internal and external insulation to minimize concerns regarding acid dew point corrosion. This is often referred to as “hot casing.” Q8.56 discusses this concept. The exit gas chamber is externally insulated, as are also the drum, downcomer, riser pipes, and exchanger. The high pressure saturated steam, which is generated at about 600–650 psig, is purified by using steam drum internals and sent for process use. About 65–70% of the sulfur is removed in the boiler as liquid sulfur by using heated drains.

Though the boiler generally operates above the sulfur dew point, some sulfur may condense at partial loads and during transient start-up or shutdown mode. The cooled gases exiting the exchanger are reheated to maintain acceptable reaction rates and to ensure that process gases remain above the sulfur dew point and are sent to the catalyst beds for further conversion as shown in Fig. 2.4. The catalytic reactors using alumina or bauxite catalysts operate at lower temperatures, ranging from 200 to 315°C. Because this reaction represents an equilibrium chemical reaction, it is not possible for a Claus plant to convert all of the

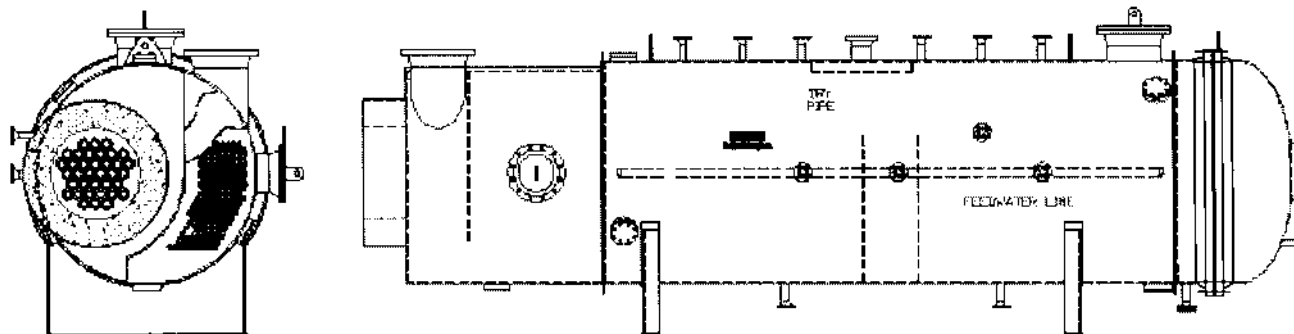
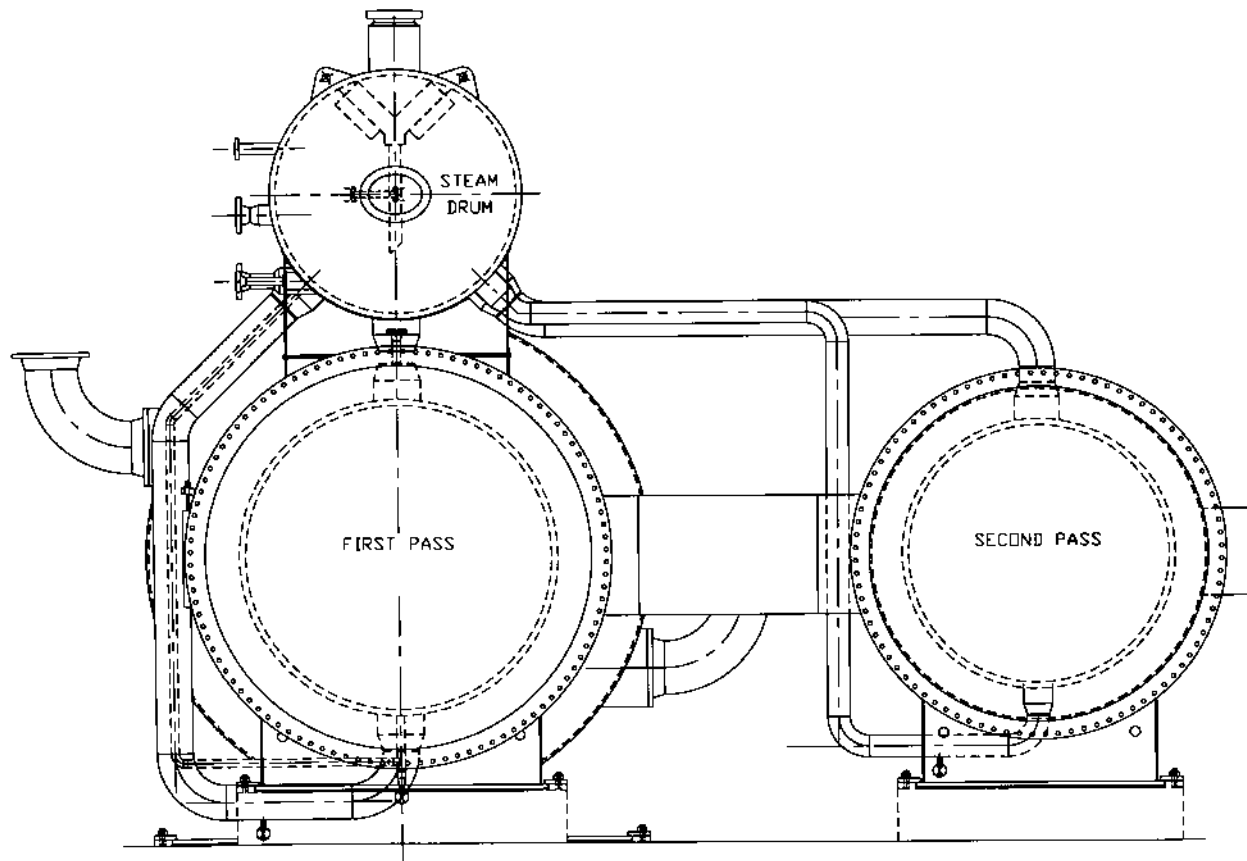
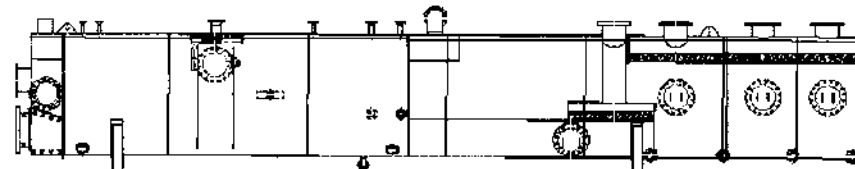
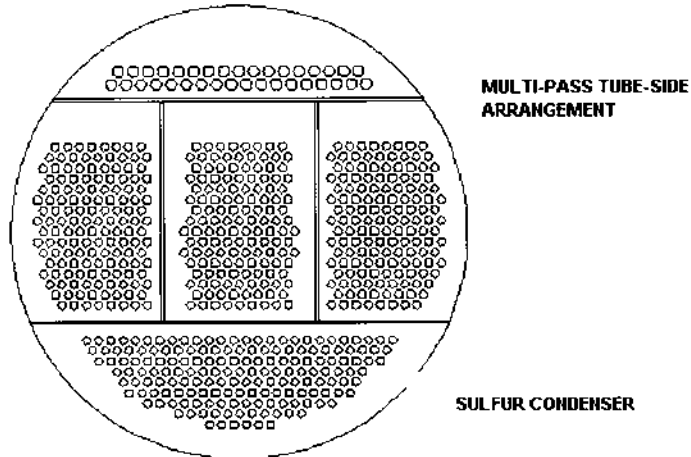


FIGURE 2.5 Waste heat boiler for sulfur recovery plant. (Courtesy of ABCO Industries, Abilene, TX.)



**FIGURE 2.6** Multiple boiler passes connected to a common steam drum. (Courtesy of ABCO Industries, Abilene, TX.)



**FIGURE 2.7** Sulfur condenser. (Courtesy of ABCO Industries, Abilene, TX.)

incoming sulfur to elemental sulfur. Therefore two or more stages are used. Each catalytic stage can recover one half to two-thirds of the incoming sulfur. Acid gas is also introduced at each catalyst stage as shown. The gas stream from each stage is cooled in another low pressure boiler, called the sulfur condenser, which condenses some of the sulfur. These gas streams generate low pressure steam at about 50–70 psig in the sulfur condenser.

If the flue gas quantity is small, a single-shell fire tube boiler handles all the streams from the reactors (Fig. 2.7). Each stage has its own gas inlet and exit connections. The outlet gas temperatures of these exchangers are around 330–360°F. From the condenser of the final catalytic stage the process stream passes on to some form of tail gas treatment process. The tail gas contains H<sub>2</sub>S, SO<sub>2</sub>, sulfur vapor, and traces of other sulfur compounds and is further treated downstream and vented.

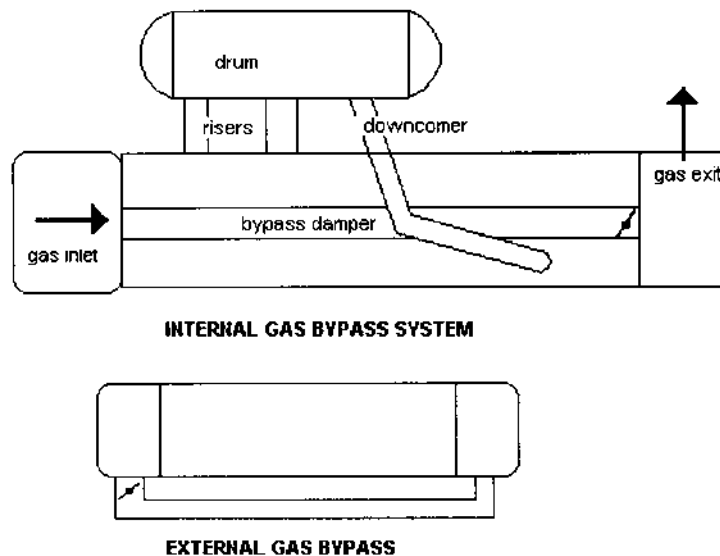
### **SULFURIC ACID PLANT HEAT RECOVERY**

Sulfuric acid is an important chemical that is manufactured using the contact process. Heat recovery plays a significant role in this system, whose main objective, is to cool the gas stream to a desired temperature for further processing.

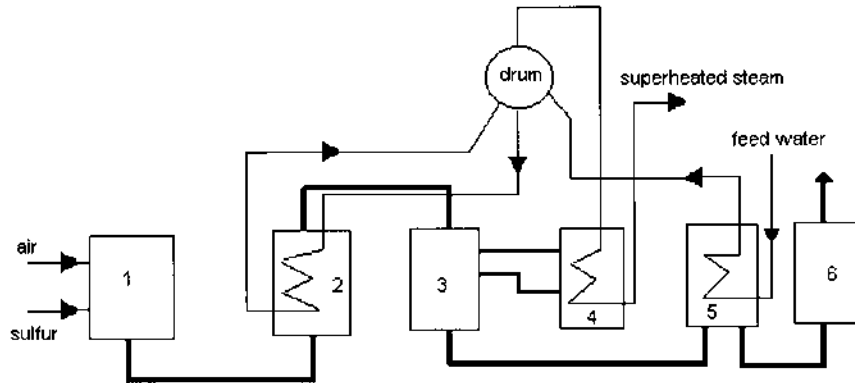
Raw sulfur is burned with air in a combustion chamber, generating sulfur dioxide, oxygen, and nitrogen. The gases, at about 1900°F and at a pressure of about 50 in. WC, pass through a waste heat boiler generating saturated or superheated steam. The boiler could be of fire tube or water tube design. The gases are cooled to about 800°F, which is the optimum temperature for conversion of SO<sub>2</sub> to SO<sub>3</sub>. The exit gas temperature from the boiler decreases as the load decreases.

In order to maintain the exit gas temperature at 800°F at varying loads, a gas bypass system is incorporated into the boiler, either internally or externally (Fig. 2.8). The gases then pass through a converter where SO<sub>2</sub> gets converted to SO<sub>3</sub> in a few stages in the presence of catalyst beds. The reactions are exothermic, and the gas temperature increases by 40–100°F. Air heating or superheating of steam is necessary to cool the gases back to 800°F. After the last stage of conversion, most of the SO<sub>2</sub> has been converted to SO<sub>3</sub>. The gas stream containing SO<sub>3</sub> gases at about 900°F is cooled in an economizer before being sent to an absorption tower. The flue gas stream is absorbed in dilute sulfuric acid to form concentrated sulfuric acid. The scheme is shown in Fig. 2.9. The steam thus generated in these waste heat boilers is used for process as well as for power generation.

The main boiler behind the sulfur combustor could be of fire tube or water tube design, depending on gas flow. Extended surfaces may also be used if the gas stream has no dust. Sometimes, owing to inadequate air filtration and poor



**FIGURE 2.8** Gas bypass systems for HRSG exit gas temperature control.



**FIGURE 2.9** Scheme of a sulfuric acid plant. 1, sulfur combustion furnace; 2, waste heat boiler; 3, contact apparatus; 4, superheater; 5, economizer; 6, absorption tower.

combustion, particulates are present in the flue gases, which could preclude the use of finned tubes. One has to be concerned about the casing design because of the possibility of sulfur condensation and corrosion. Soot blowing is not recommended, because it affects the gas analysis and adds moisture to the flue gases and may cause acid condensation.

Water-cooled furnace designs have an advantage in that the casing operates at the saturation temperature of steam, hence acid corrosion is unlikely. The main concern in sulfuric acid plants is corrosion due to acid condensation from moisture reacting with  $\text{SO}_3$ . This is minimized by starting up and shutting down the plants on clean fuels if possible and avoiding frequent start-ups and shutdowns, which induce a cooler environment for possible acid condensation over the exchanger or economizer tubes. The boiler and exchanger casings must also be maintained above the dew point by using a “hot casing” design, which reduces the heat loss to the surroundings while at the same time keeping the casing hot, above 350–400°F, as required. Boilers may be kept in hot standby if frequent shutdowns and start-ups are likely.

The feedwater temperature as it enters the economizer has to be high, often above 320°F, to minimize acid dew point corrosion because the gas contains  $\text{SO}_3$ . Carbon steel tubes with continuously welded solid fins have been used in several plants in the United States, whereas in Europe and Asia cast iron gilled tubes shrunk over carbon steel tubes are widely used. In a few projects, the sulfur deposits found their way between the gilled iron rings and the tubes and caused corrosion problems. The choice of tube materials is based on the preference and experience of the end user and the boiler supplier.