**FIG. 24-55**   SOFC 25-kW system package. (*Courtesy of Westinghouse Electric Corporation.*)

must be removed before the reformer. Typically, a hydrodesulfurizer combined with a zinc oxide absorber is used.

The desulfurized natural gas is mixed with the recycled depleted fuel stream containing steam formed in the fuel cell. About 75 percent of the methane is converted to hydrogen and carbon monoxide in the prereformer. The hydrogen-rich fuel is then passed over the fuel cell anode, where 85 percent is converted to electricity. The balance is burned with depleted air in the combustion zone.

The hot combustion gas preheats the fresh air and the prereformer, and can be used further to generate steam. The system is cooled with 200 to 300 percent excess air. A 25-kW SOFC generator system is shown in Fig. 24-55.

# ENERGY RECOVERY

Most processing energy enters and then leaves the process as energy, separate from the product. The energy enters as electricity, steam, fossil fuels, etc. and then leaves, released to the environment as heat, through "coolers," hot combustion flue gases, waste heat, etc. Recovering heat to be used elsewhere in the process is important to increase process efficiency and minimize cost. Minimizing the total annualized costs for this flow of energy through the process is a complex engineering task in itself, separate from classic process design. Since these costs include the costs for getting energy into *and* out of the process, they should be evaluated together, as elements integrated within a larger system. Such a holistic system evaluation impacts how the overall project will be designed (utilities supply, reaction and separations design, pinch analyses, 3D process layout, plot plan, etc.). Therefore, evaluation and selection of the process energy technology system should be performed at the start of the project design cycle, during **technology selection VIP** (see the subsection "Value-Improving Practices" in Sec. 9), when the **potential to influence project costs exists at its maximum value.**

Following the 1970s energy crisis, enhanced technology systems have been developed which can **significantly reduce** the **annualized costs for process energy.** Several of these technologies are presented below, because they are broadly applicable, have a rapid payback, and can make a significant reduction in overall annualized energy costs. Wet surface air coolers (WSACs), an evaporative cooling technology, are presented in Sec. 12.

## ECONOMIZERS

**GENERAL REFERENCES:**  "Latest Advances in the Understanding of Acid Dew-point Corrosion: Corrosion and Stress Corrosion Cracking in Combustion Gas Condensates," W.M.M. Huijbregts and R.G.I. Leferink, *Anti-Corrosion Methods and Materials*, vol. 51, no. 3, 2004, pp. 173–188 (http://www.hbscc.nl/); "Get Acid Dew Points of Flue Gas," A.G. Okkes, *Hydrocarbon Processing*, July 1987, pp. 53–55.; Lahtvee, T., Schaus, O., *Study of Materials to Resist Corrosion in Condensing Gas-Fired Furnaces*, Final Report to Gas Research Institute, GRI-80/0133, February, 1982; Ball, D., et al., *Condensing Heat Exchanger Systems for Oil-Fired Residential/Commercial Furnaces and Boilers: Phase I and II*, US DOE BNL-51617, 1982; Razgaitis, R., et al., *Condensing Heat Exchanger Systems for Residential/Commercial Furnaces: Phase III*, US DOE BNL-51770, 1984; Razgaitis, R., et al., *Condensing Heat Exchanger Systems for Residential/Commercial Furnaces and Boilers. Phase IV*, BNL-51943, 1985; Butcher, T.A., Park, N., and Litzke, W., "Condensing Economizers: Thermal Performance and Particulate Removal Efficiencies," in ASME *Two Phase Flow and Heat Transfer, HTD,* vol. 197, 1992 (for U.S. DOE reports see: http://www.osti.gov/energycitations).

Economizers improve boiler thermal efficiency by recovering heat from the combustion flue gases exhausted from the steam boiler section. The recovered heat is used to heat colder streams (heat sinks), before ultimate discharge of the waste gas to atmosphere. This recovered heat displaces the need to burn additional fuel to heat these same streams.

Normally, after being heated, these streams are used in the boiler area (deaerator feedwater, cold return condensate, boiler feedwater, RO feedwater) or in the combustion chamber (air preheat). However, economizers can be used to recover and supply heat elsewhere, such as hot process water or hot utility water, especially as used in the food processing and pulp/paper industries. Additionally, recovered flue gas waste heat can be used indirectly; i.e., remote process streams can be heated locally with hot steam condensate, and then the cooled return steam condensate can be reheated in the flue gas economizer. An

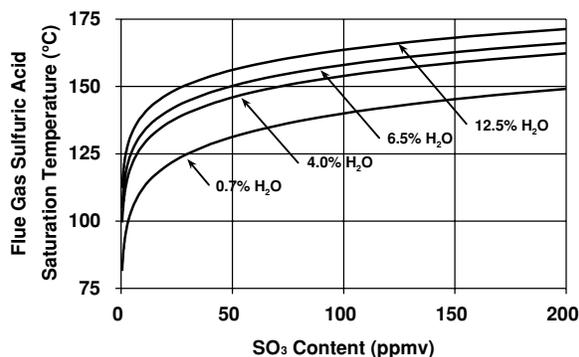**24-52    ENERGY RESOURCES, CONVERSION, AND UTILIZATION**



**FIG. 24-56**   Calculated sulfuric acid dew points, as a function of $SO_3$ content, for various flue gas water vapor concentrations. (*Courtesy  W. M. M. Huijbregts, 2004.*)



**FIG. 24-57**   Calculated flue gas water vapor dew points, for different fuel types, as a function of excess air [Orimulsion (28.3% water), Pittsburgh Seam 8 (5% water)]. (*Courtesy  T. A. Butcher, US DOE; www.bnl.gov.*)

extension of these concepts is provided by the application of using hot water to vaporize LNG: hot-water-based liquid is used to vaporize the process stream [LNG: stored near 122 K (−151ºC), returning near 273 K (0ºC)] to the hot water heater. Before entering the hot water heater, the cooled stream recovers flue gas waste heat in a condensing economizer.

**Acid Dew Point**   For fossil fuels, the acid dew point temperature is that temperature at which the actual mixed acid vapor pressure equals the mixed acid vapor saturation pressure. The mixed acid dew point can be approximated by the sulfuric acid dew point (Fig. 24-56). It can be described as a function of the $SO_3$ and water content of the flue gas (Huijbregts). These concentrations result from the sulfur, hydrogen, and free water content of the fuel; the relative humidity of the air; and the amount of excess air used. Using the equation of Verhoff, where $T$ is degrees $K$ and $P$ is mm Hg (see Okkes, A.G.):

$$T_{\text{dew}} (SO_3) = 1000/[2.276 - 0.0294 \ln(P_{\text{H2O}}) - 0.0858 \ln(P_{\text{SO3}})$$
$$+ 0.0062 \ln(P_{\text{H2O}} P_{\text{SO3}})] \qquad (24\text{-}59)$$

The corrosiveness of flue gas condensate is further complicated by the presence of other components ($Cl^{-1}$, $NO_3^{-1}$, etc.). The sources of these components can be either the fuel or the combustion air (salt, ammonia, Freon, chlorine, chlorinated VOCs, etc.), usually producing a more corrosive condensate.

**Water Dew Point**   For flue gas, the water dew point is that temperature at which the actual water vapor pressure equals the water saturation vapor pressure. Cooling the flue gas below this temperature will result in the formation of liquid water [or ice, below 273 K (0ºC)]. For example, burning natural gas with 3 percent excess oxygen (15 percent excess air), the flue gas water dew point would be (Fig. 24-57) ~330 K (56.7ºC).

**Boiler Thermal Efficiency**   Traditionally, boiler thermal efficiency is calculated $Q_{\text{OUT}}/Q_{\text{IN}}$, where $Q_{\text{IN}}$ is the LHV (lower heating value) of the fuel. A rule of thumb for economizers is that boiler efficiency increases by ~1 percent for every 22ºC (40ºF) drop in temperature of the dry flue gas. These two statements do not reveal the considerable quantity of **additional heat**, available to be recovered through **condensation of the water vapor** in the flue gas, which is lost to atmosphere with hot flue gas. Based on fuel HHV (higher heating value), the total latent heat loss can be substantial: an additional 9.6 percent (natural gas), 8.0 percent (propane), 6.5 percent (heating oil).

**Conventional Economizers**   Conventional economizers can be constructed from relatively inexpensive materials, such as low-alloy carbon steels, if they will be operated dry on the gas side, with flue gas side metal temperatures above the acid dew point. This practice is done to protect the economizer from corrosion, caused by the acidic flue gas condensate. Conventional economizers can also be con-
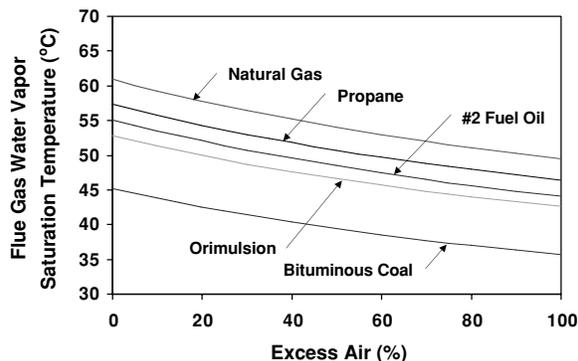
structed from more expensive materials, and can be operated below the acid dew point, but above the water dew point. This practice permits greater heat recovery, but with a generally lower payback. A compromise practice for operation below the acid dew point is to use less expensive but less corrosion-resistant materials, accepting an accelerated rate of corrosion, and periodically replacing the damaged heat-transfer surfaces when needed. Nevertheless, when high-sulfur fuel is burned (oil, coal, etc.), typically the water inlet feed to a conventional economizer is preheated to a temperature above the anticipated acid dew point.

**Condensing Economizers**   Flue gas condensing waste heat economizers are designed to operate **below the flue gas water dew point.** This temperature can range from about 316 K (43ºC) to 333 K (60ºC), depending on the amount of hydrogen and water in the fuel, the amount of excess combustion air used, and the humidity of the air. [Higher flue gas water dew points can be encountered for other industrial applications, such as product driers, fryers (food processing), waste water incinerators, etc.] Such economizers recover **flue gas sensible heat** as well as **water vapor latent heat** from the hot flue gas. Fuel consumption is reduced in proportion to the efficiency increase.

Condensing economizers are constructed from inexpensive, but durable, corrosion-resistant materials. Extensive materials testing has been performed for operation in this service, including for coal combustion (Lahtvee, Ball, Razgaitis, and Butcher). The metallurgy for the tube-side liquid is determined by the liquid chemistry requirements (usually water-based liquid): 304 stainless steel is typical.

For gas-side materials, one available technology employs Teflon-covered metal tubing and Teflon tube sheets. This technology is often operated across both the acid and water dew points, and can accept inlet gas temperatures to 533 K (260ºC). Typical applications may achieve a cold-end $\Delta T$ below 45°C (80°F), improve the boiler thermal efficiency by ~10 percent (LHV basis), and have a simple payback of 2 to 3 years, based on **fuel avoidance** (Figs. 24-58 and 24-59).

A second technology employs metallic finned tubing, extruded over the water tubing. Aluminum 1000 series fins are preferred, for heat-transfer reasons in natural gas applications, but stainless steel (or other material) fins are used for higher temperatures and/or more corrosive flue gas. This second technology both is less expensive and has better heat transfer (per ft²). Consequently, for the same payback the cold-end approach can be lower, and the water outlet temperature and the boiler efficiency improvement higher. Flue gas condensate from combustion of natural gas typically has a pH of ~4.3, and aluminum fins are suitable. For more acidic (or erosive) flue gas conditions, other metallurgy (Incoloy® 825 and Hastelloy®), or a Hersite or equivalent coating, may be used to prevent corrosion damage (Fig. 24-60).
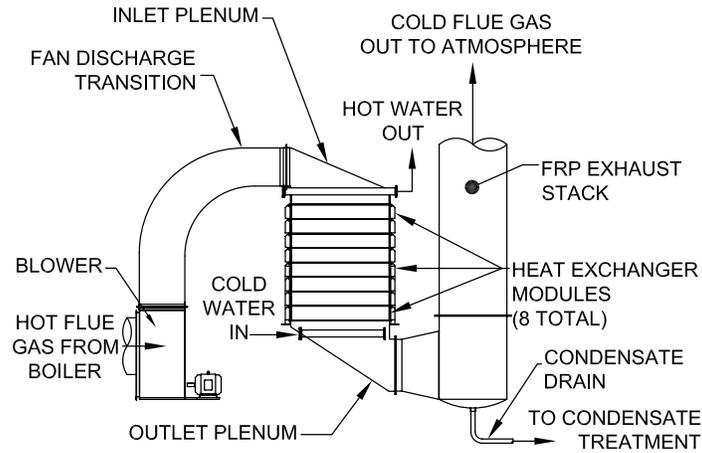
**FIG. 24-58** Standard equipment arrangement, flue gas condensing economizer waste heat recovery system (flow: left to right). The ID fan draws hot flue gas from the boiler, propelling it into the top of the condensing economizer. (*Courtesy CHX Condensing Heat Exchanger Co.; www.chxheat.com.*)

Flue gas condensate at different temperatures, compositions and relative corrosivity condenses and exists at different positions within the condensing economizer. These positions are not fixed in space or time, but move back and forth, in response to changing load conditions in either stream. Condensing economizers are typically equipped with water spray nozzles for periodic washdown of the flue gas side, to be used (infrequently) for natural gas combustion, but more frequently for services having heavier pollutant loading, such as oil, coal, etc. Over
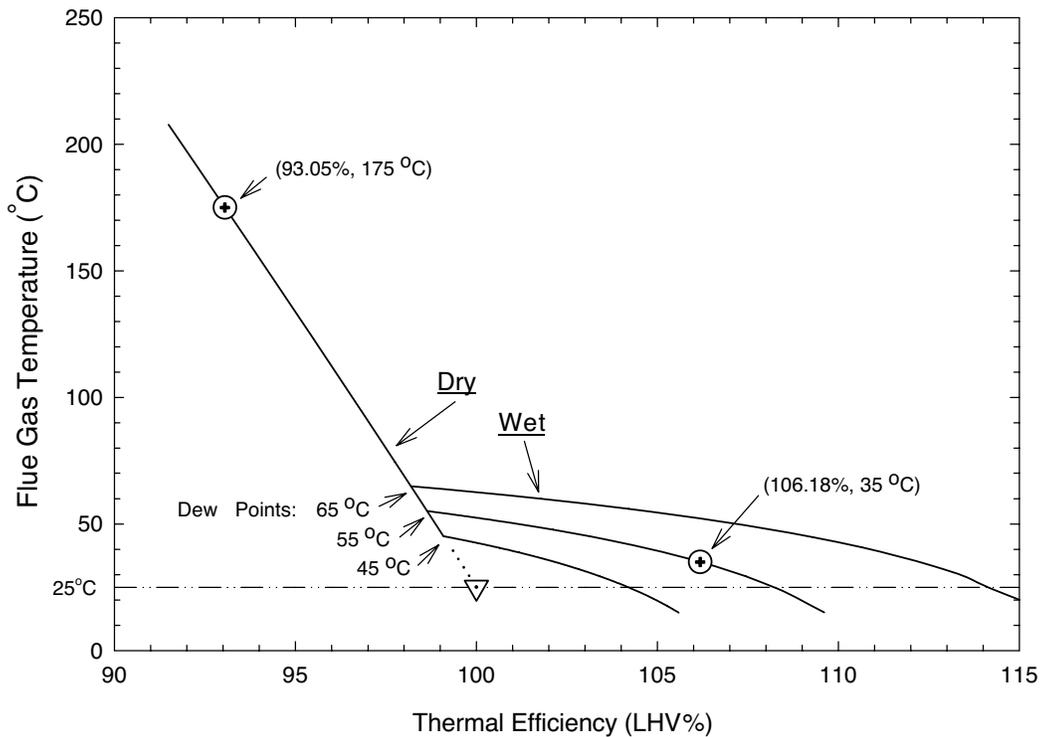


**FIG. 24-59** Characteristic curves for boiler thermal efficiency as a function of flue gas effluent temperature and flue gas water dew points. Based on the LHV of a fuel, and stoichiometric reaction, 100 percent efficiency would be achieved if sufficient combustion heat were recovered and removed, so that the temperature of the effluent flue gas was reduced to 25°C. For a flue gas with a 55°C dew point, recovering additional heat via condensation by cooling from 175 to 35°C (as shown) would increase the overall efficiency by more than 13 percent. (*Courtesy Combustion & Energy Systems, Ltd.; www.condexenergy.com.*)
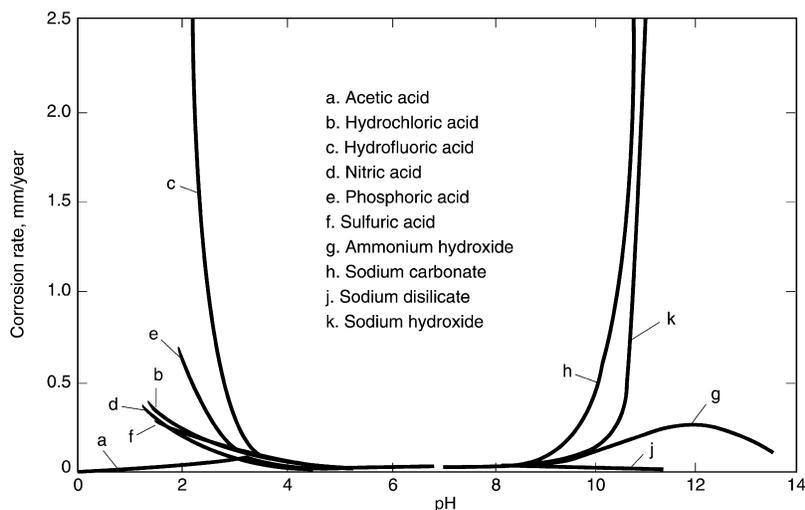
**FIG. 24-60**   Effect of corrosion on 1100-H14 aluminum alloy by various chemical solutions. Observe the minimal corrosion in the pH range from 4.0 to 9.0. The low corrosion rates in acetic acid, nitric acid, and ammonium hydroxide demonstrate that the nature of the individual ions in solution is more important than the degree of acidity or alkalinity. (*With permission from ASM International; www.asminternational.org. Courtesy of Combustion & Energy Systems, Ltd.; www.condexenergy.com.*)

200 such heat exchangers have been installed, some in service for more than 20 years (2005). This technology is suitable for heat recovery applications of any magnitude.

Several **environmental benefits** are gained through employment of this condensing technology. Burning less fuel proportionally reduces **collateral combustion emissions** ($NO_x$, $SO_x$, $CO$, $CO_2$ and particulates, including PM-2.5). Additionally, **flue gas pollutant removal** occurs in the condensing economizer, as has been extensively investigated, characterized, and modeled by the U.S. DOE (Butcher et al.) including applications burning coal and Orimulsion. Typically, the condensate will contain most (by mass, >90 percent) of the highly dissociated inorganic matter ($H_2SO_4$, HCl, $HNO_3$, $HNO_2$, $NH_3$, salts, etc.) and the **larger-diameter particulates ($>$10 $\mu$m)** and a lower but substantial fraction (>60 percent) of the **smaller-diameter particulates ($<$5 $\mu$m)**. Such gross pollutant removal can be a cost effective first stage for a traditional air pollution control system, by reducing the volume of the flue gas to be treated (water content and temperature) as well as reducing the concentration of the pollutants in the flue gas to be treated downstream. Unlike spray quenching, such indirect quench-cooling segregates the flue gas pollutants from the cooling system fluid, generating a much smaller, concentrated waste water stream for subsequent waste treatment. Although pollutant removal percentages are high, they are functions of the specific real-time mass- and heat-transfer conditions within the economizer. Condensate treatment from boiler economizers normally is neutralization, often using the boiler blowdown, and release to the sewer and sewage treatment.

## REGENERATORS

Storage of heat is a temporary operation since perfect thermal insulators are unknown; thus, heat is absorbed in solids or liquids as sensible or latent heat to be released later at designated times and conditions. The collection and release of heat can be achieved in two modes: on a batch basis, as in the checkerbrick regenerator for blast furnaces, or on a continuous basis, as in the Ljungstrom air heater.

**Checkerbrick Regenerators**   Preheating combustion air in open-hearth furnaces, ingot-soaking pits, glass-melting tanks, by-product coke ovens, heat-treating furnaces, and the like has been universally carried out in regenerators constructed of fireclay, chrome, or silica bricks of various shapes. Although many geometric arrangements have been used in practice, the so-called basketweave design has been adopted in most applications.

***Blast-Furnace Stoves***   Blast-furnace stoves are used to preheat the air that is blown into a blast furnace. A typical blast furnace, producing 1500 Mg (1650 U.S. ton) of pig iron per day, will be blown with 47.2 m³/s (100,000 std ft³/min) of atmospheric air preheated to temperatures ranging in normal practice from 755 to 922 K (900 to 1200°F). A set of four stoves is usually provided, each consisting of a vertical steel cylinder 7.3 m (24 ft) in diameter, 33 m (108 ft) high, topped with a spherical dome. Characteristic plan and elevation sections of a stove are shown in Fig. 24-61. The interior comprises three regions: in the cylindrical portion, (1) a side combustion chamber,
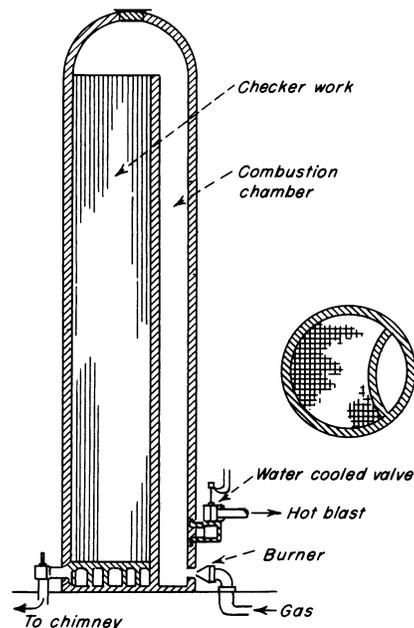


**FIG. 24-61**   Blast-furnace stove.