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Possibilities of Combined Heat Recovery and Air Pollution Control Systems

V. Frank Mach

POSSIBILITIES OF COMBINED HEAT RECOVERY
AND AIR POLLUTION CONTROL SYSTEMS

V. Frank Mach, Ph.D.
Minnesota Energy Agency
St. Paul, Minnesota

Abstract

Combined heat recovery with air pollution control is applicable on many industrial high temperature emissions. Some methods are discussed in this paper. Two examples illustrate that such a combination offers benefit in both energy conservation and less costly protection of the environment.

1. INTRODUCTION

Many processes in metallurgical, chemical, petrochemical, brick, clay, glass, etc., industries produce high temperature emissions to the atmosphere. In most cases, emitted gas is polluted, usually dust loaded, and therefore, some type of air pollution control device must be provided to clean the hot gas stream.

Air pollution control is expensive, primarily due to the large volume of the gas to be cleaned, rather than the concentration of pollutants. If the gas is hot, pollution control becomes even more expensive. The temperature of hot gas must be reduced to a level which is acceptable for an air pollution control device. The high temperature is an unfavorable factor for air pollution control, since it

- increases the volume of gas that has to be cleaned.
- reduces the scope of available cleaning methods.
- requires a usage of more costly materials.
- requires special temperature controls.

In conventional practice, dilution with ambient air, spraying of water, or natural convection and radiation are the most common methods of cooling a hot gas stream before an air purification device. All of these methods are based on the degradation of heat. This heat in the hot gas stream is wasted, and in addition, an extra cost is payed for its degradation.

Today, heat has a substantionally greater value than several years ago. In light of this, it would be advantageous to recycle the heat contained in the hot gas stream to the original process or other useful applications. Heat from the gas stream can be transferred to a process gas or air (combustion air, make-up air, etc.), to liquid (feed water, processing, heating, etc.), to stream, etc., and then, the cooled gas can be cleaned.

Some estmates [R1] indicate that more than 200,000 stationary sources of air emissions are in the U.S. industry. There is no proven data about the portion of hot emissions, but it can be expected that several thousands of hot emissions are included in this amount.

On a national scale, there is a large potential for combined heat recovery and air pollution control systems. Properly reused heat from hot gas streams offers the benefit in both energy conservation and less costly protection of the environment.

2. CONVENTIONAL METHODS OF SOLID-GAS SEPARATION

There are several methods available for the separation of particles from emitted gas. Depending upon physical and chemical properties and local specific conditions, a cyclone, electrostatic precipitator, scrubber, fabric filter, or some combination of those, can be applied. All of these methods are known, and are proven in the practice with various degrees of satisfaction.

However, fabric filters are probably the most common air purification devices in the industry. They offer satisfactory cleaning efficiency for a wide range of particulate matter; they work with only moderate energy consumption and relatively low maintenance requirements. In addition, a fabric filter can readily be designed to allow operation to continue when maintenance is required.

An industrial fabric filter consists of a number of cloth tubes (bags) through which a gas, laden with particles, is passed. Particulates in the gas stream are collected on a fabric media, allowing the clean gas to pass through to the atmosphere. The filtration media is made from various types of natural or synthetic fibers. For filtration of high temperature industrial emissions usually synthetic fibers are used as follows:

Material	Maximum Temperature
Polyester	300°F
"Nomex" Nylon	450°F
Teflon	500°F
Glass	550°F

If the temperature of a hot gas stream is higher than the above shown limits, then the hot gas must be cooled before entering the air purification device. In the conventional practice, three basic cooling methods, all based on wasting of heat, are applied.

2.1 DILUTION WITH AMBIENT AIR

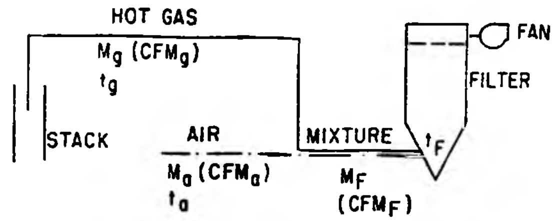

FIG. 1: DILUTION WITH AMBIENT AIR

Cold ambient air is bled into a hot gas stream to produce a mixture having the required temperature. The system must be designed for maximum operating temperatures and for maximum flow rate of the hot gas stream. For variable operating conditions, some type of temperature control is needed. Usually a motorized damper is inserted into the inlet of the cold air, and positioned by a temperature controller of the mixture entering the filter.

With an acceptable degree of approximation, the following equation can be used for sizing:

Required volume of diluting air

$$CFM_a \cong SCFM_g \times \frac{t_g - t_f}{t_F - t_a} \quad (1)$$

Total volume of the mixture entering the filter

$$CFM_F \cong CFM_g \times \frac{460 + t_F}{460 + t_g} \times \left(1 + \frac{t_g - t_F}{t_F - t_a}\right). \quad (2)$$

Because of simplicity, this method is used widely. However, since a filter must be sized to handle both -- gas and diluting air stream -- the system becomes very costly if applied for high temperature (800°F or more) emissions.

2.2 EVAPORATIVE COOLING

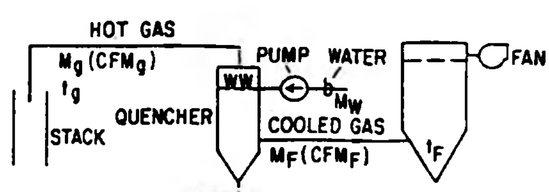

FIG. 2: EVAPORATIVE COOLING

Spraying of water into a hot gas stream is more efficient than cooling with diluting air, and therefore, it is frequently employed where large amounts of cooling is required.

Water droplets in the hot gas stream are evaporized, and each one (1) lb of water consumes approximately 1150-1200 Btu of heat. The size of droplets, temperature gradient, turbulence and retention time, are important factors for the intensity of evaporization.

The required quantity of cooling water can be estimated by the equation

$$M_W \doteq \frac{M_g\left(h_g - h_F\right)}{h_{water\ vapor} - h_{water}} \qquad (3)$$

or the rule of thumb gives for consumption of water in gallons per minute

$$GPM \simeq 2 \times 10^{-6} \times SCFM_g \left(t_g - t_F\right) \qquad (4)$$

and for the volume of the gas entering a filter

$$CFM_F \simeq CFM_g \times \frac{520 + t_F}{520 + t_g} + 225\ GOM. \qquad (5)$$

Evaporized water increases the moisture content of the gas that has to be cleaned. In some cases it makes cleaning more difficult, or a condensation in the filter can be reached. For large amounts of cooling, the consumption of water is considerable. If sprinklers or nozzles are applied for spraying, serious control problems can occur due to the plugging of these devices.

2.3 NATURAL CONVECTION AND RADIATION

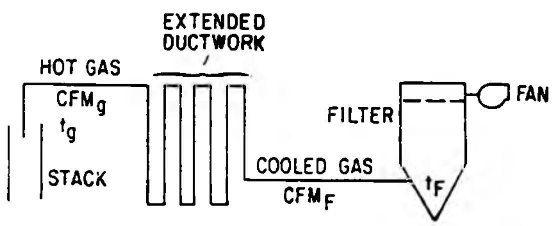

FIG. 3: NATURAL CONVECTION AND RADIATION

In order to eliminate a usage of diluting air or cooling water, the hot gas is cooled by heat losses of extended ductwork between a stack and an air purification device.

A large ductwork is usually required for cooling of the gas. For instance, the experience from several installations where a dust loaded gas is cooled from 1000°F to 500°F, indicates an actual heat loss of 42" dia. duct in the range of 2200 Btu/hr/sq. ft. For heat removal of 30×10^6 Btu/hr, almost a quarter mile, such a duct is needed.

Naturally, the ductwork is costly, but there is also a considerable pressure drop, problems with space availability, etc. However, a smaller filter can be applied, since the volume of the gas that has to be cleaned is

$$CFM_F = CFM_g \times \frac{460 + t_F}{460 + t_g}. \qquad (6)$$

It can be summarized that all three conventional systems waste the entire heat content of the hot gas. In order to protect an air pollution control device against overheating, the hot gas is cooled, and for the degradation of heat, an extra cost is paid. Dilution with ambient air requires the usage of a large and costly filter; evaporative cooling requires the providing of a cooling quencher and a continuous supply of cooling water; natural convection and radiation requires extended ductwork. All these provisions are costly, and with no return on investment.

3. COMBINED HEAT RECOVERY AND AIR POLLUTION CONTROL SYSTEMS

Many high temperature processes emit gases having a temperature of 800-2300°F, even more. Many are operated 4000-6000 hours/year, some of them, namely large systems, work continuously. Large amounts of heat are available for recovery in this field.

As shown in Fig. 4, the hot gas before an air purification device can be cooled by a heat exchanger from t_1 to t_1'. Quantity of heat

$$Q = M_1\left(h_1 - h_1'\right) = M_1 \times SpH\left(t_1 - t_1'\right) \qquad (7)$$

is a heat available for recovery. It can be transferred into appropriate cooling medium and utilized for plant needs.

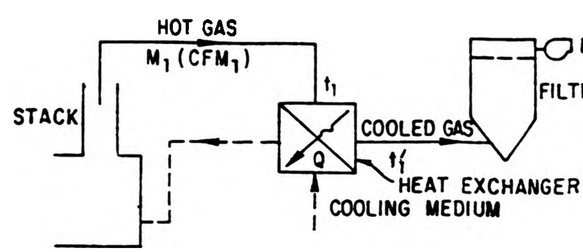

FIG. 4: A HEAT RECOVERY SYSTEM

Depending on specific local conditions, various cooling medium can be used. For instance:

Cooling Medium		Usage
Entering	Leaving	
Air (Gas)	Hot Air (Hot Gas)	combustion air for furnaces, kilns, boilers, ovens, dryers; make-up air for processing; make-up air for ventilation, etc.
Water (Liquid	Hot Water (Hot Liquid)	hot water for processing; make-up water; feed water; heating & ventilating, etc.
Water (or Condensate)	Steam	for processing; power; heating; ventilating; air conditioning; etc.

Such a combined system offers two advantages to a user:

(a) Saving of energy (fuels), since the recovered heat substitutes a heat being normally generated in a furnace, boiler, etc.

(b) Usage of a smaller and less costly filter in comparison with conventional cooling by diluting air or spraying of water.

In many cases a substantial savings can be obtained. For preliminary estimates, a graph in Fig. 5 gives an idea about possible heat recovery from a hot exhaust gas. Table 1 shows the cost of gross heat in various fuels (conversion efficiency is not included), and Table 2 shows the average cost of industrial fabric filters in 1977.

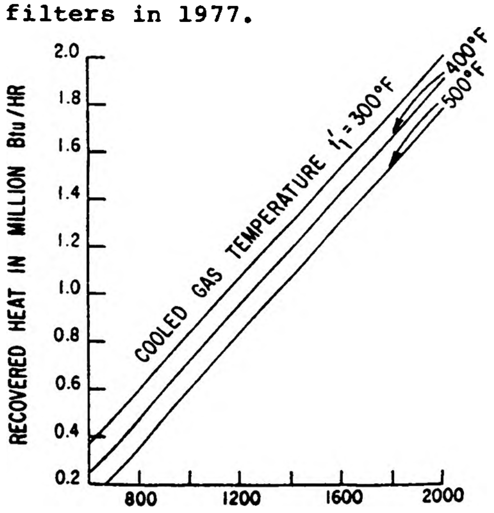

FIG. 5: APPROXIMATE HEAT REMOVAL FROM 1000 SCFM OF A GAS

TABLE 1: COST OF GROSS HEAT IN SOME FUELS

Fuel	Heat Content	Cost of Fuel	Cost of Heat in Dollars/ Million Btu
Natural Gas	1000 Btu/ cu. ft.	$1.5-2.5/ 1000/cu.ft.	1.5- 2/5
Fuel Oil	150,000 Btu/lb	$0.35- 0.45/gal.	2.3- 3.0
Coal	12,000 Btu/lb	$ 25- 35/ton	1.0- 1.5
Coke	13,000 Btu/lb	$120- 150/ton	4.6- 5.8
Electricity	3412 Btu/kWh	$0.03- 0.05/kWh	8.8-14.7

TABLE 2: AVERAGE COST OF INDUSTRIAL FABRIC FILTERS IN DOLLARS PER CFM OF GAS TO BE CLEANED (1977)

Air to Cloth Ratio	Flow Rate in CFM				
	20,000	40,000	60,000	100,000	Cost
2	3.50 4.20 0.69	3.20 3.90 0.57	3.10 3.80 0.56	3.05 3.75 0.56	PB NB I
3	2.83 3.50 0.58	2.56 3.11 0.42	2.46 2.98 0.39	2.43 2.96 0.38	PB NB I
4	2.12 2.54 0.46	1.91 2.34 0.32	1.85 2.29 0.29	1.83 2.27 0.28	PB NB I
6	1.51 1.81 0.36	1.30 1.62 0.24	1.25 1.55 0.20	1.22 1.50 0.20	PB NB I
8	1.15 1.35 0.28	1.02 1.21 0.20	0.98 1.18 0.18	0.97 1.17 0.17	PB NB I

Notes: PB - cost of a filter having polyster bags
NB - cost of a filter having nomex bags
I - cost of thermal insulation (if required)
In above shown costs are included: cost of a filter w/bags, a screw conveyor, "high temperature provisions", explosion proof, platform and a ladder.

Erected cost: approximately 1.3 x F.O.B. cost

Operating cost: approximately $0.075/ACFM per year

Maintenance cost: depends upon type of filter, filtration media, physical and chemical properties of cleaned gas and method of operation. Therefore the maintenance cost is in the range of 10-25% of original installed cost per year.

(Source: Library of General Resource Corporation, Hopkins, Minnesota)

It may be necessary, namely for large systems, to provide a technical and economic comparison of several applicable heat recovery methods or arrangements in order to obtain an optimum system for local specific conditions. In the evaluation, a system must be considered as a complex beginning at a source of waste heat and ending at heat consuming equipment, including an air purification device, and with all accessories. Criteria like space availability, reliability, and maintenance requirement also are important for final selection of the system.

It should be considered that we are dealing with a high temperature emission which must be provided with an air pollution control in any case. Air pollution control, a base of the combined system. Heat recovery is a practical substitution of conventional cooling systems, and recovered heat is a by-product.

3.1 GAS-TO-AIR HEAT RECOVERY

A part of the waste heat from a high temperature emission can be utilized for preheating of process air or gas. A typical example is, for instance, preheating of air for combustion processes. It can be applied for kilns, furnaces, ovens, dryers, calcinators, etc.

Gas-to-air heat recovery is usually a non-pressure system since both, exhaust gas and preheated air, are exposed to a pressure of several inches of WC. It simplifies the requirements on the construction of a heat exchanger and its tightness. Nevertheless, crosscontamination of both streams is undesirable.

Although many types of gas-to-gas heat exchangers are available on the market, many of them are not suitable to handle high temperature, dust loaded gases. For instance:

Heat wheels (see diagram in Fig. 6) where applied for the preheating of combustion air for a remelt aluminum furnace. It was expected that the air for the combustion will be preheated to 1000-1100^{o}F by a flue gas having a temperature of 1500-1800^{o}F. After a few days of operation, the stainless steel wheels were plugged by dust, deformed, and completely destroyed.

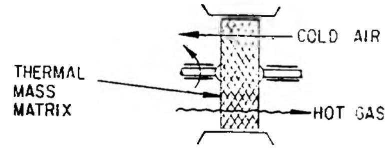

FIG. 6: HEAT WHEEL

Heat pipes (see Fig. 7) normally have 6 to 15 fins per inch are also sensitive on cleanliness of the gas. In addition, their usage is limited to approximately 600^{o}F.

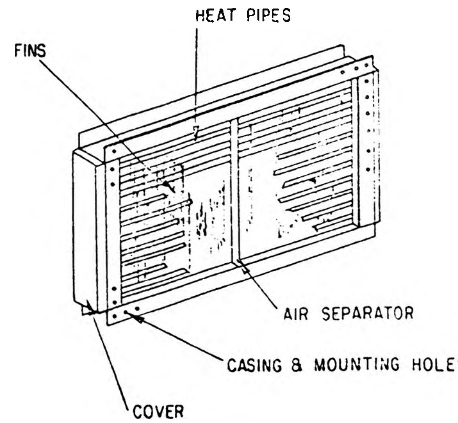

FIG. 7: HEAT PIPE HEAT RECOVERY UNIT

Plate-fin heat exchangers (see Fig. 8) can be applied for higher temperatures, if constructed of sufficient material. However, they can be easily plugged by dust in a hot gas stream.

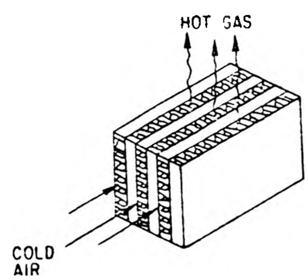

FIG. 8: PLATE-FIN HEAT EXCHANGER

Fouling, or even plugging, is a difficult problem for many heat exchangers. Although some cleaning devices are available, the best way is a prevention of fouling. For that is needed:

(a) Dust loaded gas shall be dry. In order to eliminate condensation in the gas or on heat transfer surfaces, the gas should not be cooled below 400-350^{o}F.

(b) Dust loaded gas shall have enough high (conveying) velocity, roughly in the range of 3000 FPM. However, too high velocity increases pressure drop and it might develop erosion of the material in some local regions, like in the gas turns, etc. Some limits are shown in Table 3.

TABLE 3: DESIGN GAS VELOCITY THROUGH NET FREE FLOW AREA IN HEAT EXCHANGER TO PREVENT DUST EROSION

Type of Exhaust Gas	Maximum Velocity, FPM
Combustion of pulverized coal	4500
Combustion of coal on stoker	3000-3600
Combustion in cyclone furnace	5000
Blast-furnace gas	4500-6000
Gas with sand dust	3000-3600
Gas with cement dust	2700-3000
Gas with clay dust	3000-4000

(c) Passages for the conveying of dust loaded gases shall be straight and smooth.

The experience indicates that only tubular and plate type heat exchangers are suitable for the handling of dust loaded gases.

A tublar heat exchanger is essentially a nest of straight tubes expanded into tube sheets and enclosed in a suitably reinforced steel casing, and provided with gas and air inlet and outlet openings. The flow of hot gas through straight tubes is preferred. The smaller the diameter of the tubes, the more compact the heater. However, it is not recommended to use tubings less than 2-1/2 in. in diameter for dust loaded gases.

Plate type exchangers (see Fig. 9) use thin, flat, parallel plates with alternate wide and narrow spacing to match gas and air flow rates. A counter-flow arrangement is preferred.

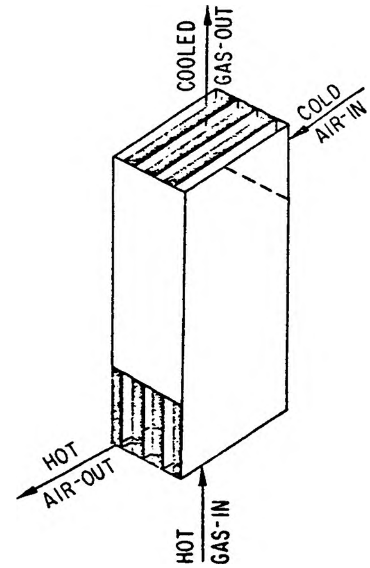

FIG. 9: PLATE TYPE HEAT EXCHANGER

Plate type heat exchangers are designed for low pressure applications (only 30-50 in. WC or less), but perform very well in handling dust loaded gases.

Generally, the gas-to-air heat exchangers are large in size. Reasons for that are: (1) low overall heat transfer coefficient (usually in the range of U = 2-4 Btu/sq. ft/hr/°F); and (2) large volumes of gas or air are handled on both sides of the heat transfer surface.

Material for the construction of the heat exchanger has to be selected by physical and chemical properties of the gas. If only a temperature is a determining factor, then the following materials are applicable:

carbon steel	up to 1000°F
alloys 18-20% Cr, 8-10% Ni	up to 1600°F
alloys 18-26% Cr, 18-22% Ni	up to 2000°F

However, for the final selection of material, a manufacturer of equipment shall be responsible.

At least one interesting application of gas-to-air heat recovery combined with an air pollution control is shown in the Appendix 1. It can be seen that a hot exhaust gas, having even high dust concentration, can be successfully handled by a gas-to-air heat exchanger. Profitability of the system is remarkable.

3.2 GAS-TO-LIQUID HEAT RECOVERY

In some cases, it would be more practical to transfer a part of the waste heat into water or another liquid needed for processing, heating or cooling, etc. While air or gas are not good media for the transporting of heat (a large ductwork is needed), in hot water the heat can be easily transported for a long distance. Another advantage of water is accumulation of heat in the distribution system. Finally, a special tank can be provided for the storage of heat, where non-uniform consumption or generation of waste heat occurs.

Gas-water heat exchangers are very well developed, and there is great experience with them, namely in the boiler industry. Frequently, these exchangers are constructed in a form of steel tube coils, provided with an enclosure and provisions for water and gas inlet - outlet connections. Inside of the tubes is heated water, thus permitting the use of heat exchangers also for high pressures, and outside of the tubes is a hot gas.

Because of dust loaded hot gas, it is essential to keep the metal temperature safely above the dew point of the gas in order to minimize fouling and possible corrosion problems. Such a temperature depends upon the composition of the gas. For instance, for exhaust gas (flue gas) from combustion, the Babcock and Wilcox Co. recommend the minimum metal temperatures as shown in Fig. 10.

The heat transfer surface can be constructed of plain tubes, or extended surface tubes, being provided with some type of fins on outside diameter. The solid contact of fins with a tube is essential for a good heat transfer. Generally it is not recommended to use more than 2-3 fins/inch for handling dust loaded gases. The cleaning of the external surface can be provided by various types of soot blowers using high pressure steam (usually 100 Psi or more) or compressed air as a cleaning medium.

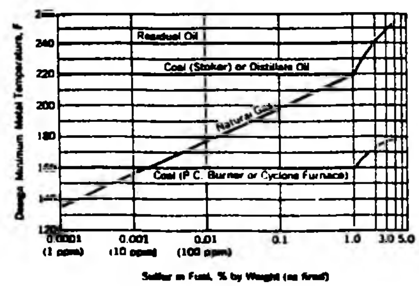

FIG. 10: LIMITING TUBE-METAL TEMPERATURES TO AVOID EXTERNAL CORROSION

The relationship between the heat available for heat recovery and the quantity of heated water is given by the equation

$$Q = M_g \times SpH_g\left(t_g - t_g'\right) \quad M_w\left(t_w' - t_w\right) \qquad (8)$$

where subscripts "g" and "w" designate gas and water.

3.3 UTILIZATION OF WASTE HEAT FOR GENERATION OF STEAM

Where practical, a part of normally wasted heat can be utilized for generation of steam as shown in Fig. 11. All or part of the steam requirements of a plant may be provided by waste heat boilers.

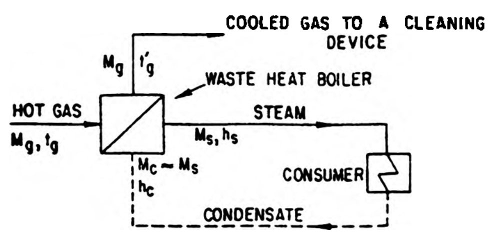

FIG. 11: UTILIZATION OF WASTE HEAT FOR GENERATION OF STEAM

There is a good experience in the construction of waste heat boilers and many types are available. For instance: Gas-tube boilers for relatively clean gases and for pressures of steam usually below 200 psi; Water-tube boilers, applicable also for higher pressures of steam, for relatively clean, or dust laden gases if provided with soot blowers; and Bent-tube boilers for heavy dust loadings, etc. In order to meet many variations in industrial applications, practically each waste heat boiler is custom designed.

Application of waste heat boilers is usually profitable for a continuously discharged gas having a temperature of 1000°F or higher.

Quantity of the steam generated from waste heat can be estimated by the equation

$$M_s = \frac{M_g \times SpH_g(t_g - t_g')}{h_s - h_c} \qquad (9)$$

Appendix 2 gives a simplified comparison of a conventional air pollution control system with a combined heat recovery using a waste heat boiler for cooling of the hot gas before a bag-house. It is evident that such a combination can fully pay expense on air pollution control, it can even be profitable for a user. And, conserved fuel is a bonus for all of us.

4 CONCLUSIONS

As a nation, we pay annually some 45 billion dollars for imported fuels, and several billion dollars on the protection of our environment. It hurts our economy. It may affect our lifestyle and our future.

Therefore, all means resulting in energy conservation and reduction of nonproductive expenses on environmental control shall be verified, evaluated and applied, where practical. Combined heat recovery and air pollution control represents a new departure from past practice. It is applicable on many industrial high temperature emissions, and two cases illustrate that it offers benefits in both energy conservation and less costly protection of the environment.

USED SYMBOLS

CFM, ACFM, SCFM - gas flow rate in cubic feet per minute

M - mass flow in pounds per hour

Q - quantity of heat in Btu/hr

S_pH - specific heat in Btu/lb°F

h - enthalpy in Btu/lb

t - temperature in °F

REFERENCES

1. Iron Age, February 20, 1978, Pg. 48
2. Babcock and Wilcox, "Steam, its Generation and Use", 38th Edition, N.Y. 1972.

APPENDIX 1: ONE EXAMPLE OF A GAS-TO-AIR HEAT RECOVERY COMBINED WITH AIR POLLUTION CONTROL IN A KAOLIN PROCESSING PLANT

Hot flue gas from a calcinator was originally cooled by dilution with ambient air, and then cleaned by a bag-house (see Fig. A1-a). Later, the company became interested in increasing the production, but the existing filter was unable to clean larger volumes of the gas.

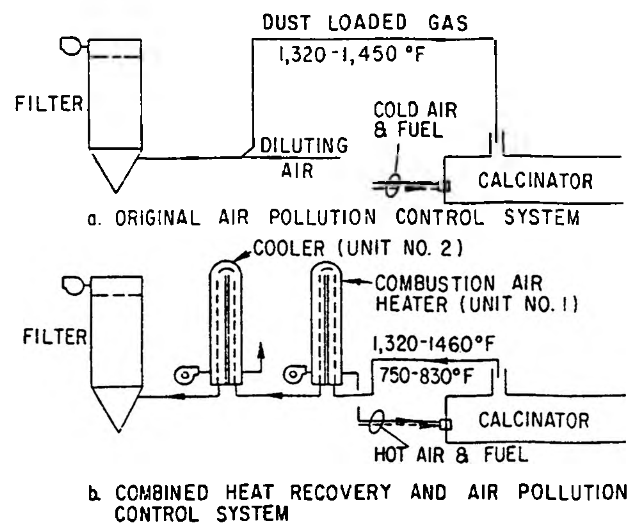

FIG. A1: ONE EXAMPLE OF COMBINED HEAT RECOVERY AND AIR POLLUTION CONTROL SYSTEM IN A KAOLIN PLANT

In order to reduce the quantity of diluting air, a forced draft cooler of the gas was provided. A tubular gas-to-air heat exchanger having 2 3/4-in. diameter tubing was installed. Results were unsatisfactory because of heavy fouling and even periodical plugging of some tubes.

Finally, the system was provided with two plate type heat exchangers as shown in Fig. A1-b. The unit #1, being constructed of stainless steel, is the heat recovery unit for the preheating of combustion air. It returns to the process approximately 6 mill. Btu/hr of waste heat, continuously. Because only a portion of waste heat can be transferred into combustion air, the second heat exchanger being constructed of carbon steel, cools the flue gas before an existing bag-house.

Due to the limited space availability, the exchangers are installed vertically in a U-shape. The height of the units is 51 feet, clearance between heat transfer plates is approximately 2 1/2 in. The system performs very well and is practically maintenance free.

Some data available for release:

Hot gas:	flue gas with kaolin dust, concentration 97 gr/SCF.
Unit #1:	hot gas inlet . . . 1460-1320^{o}F
	hot gas outlet . . 620- 700^{o}F
	combustion air inlet. . . . . 110^{o}F
	combustion air outlet . . . . . 830- 750^{o}F
	recovered heat, Btu/hr . . . (6.5-8.0) x 10^6
Unit #2:	hot gas inlet . . . 620- 700^{o}F
	hot gas outlet . . 230- 330^{o}F

Results:

1. Increased production in the ratio 70/40 = 1.75 times.
2. Consumption of natural gas increased 190/180 = 1.056 only.
3. ROI - 1 year approximately.

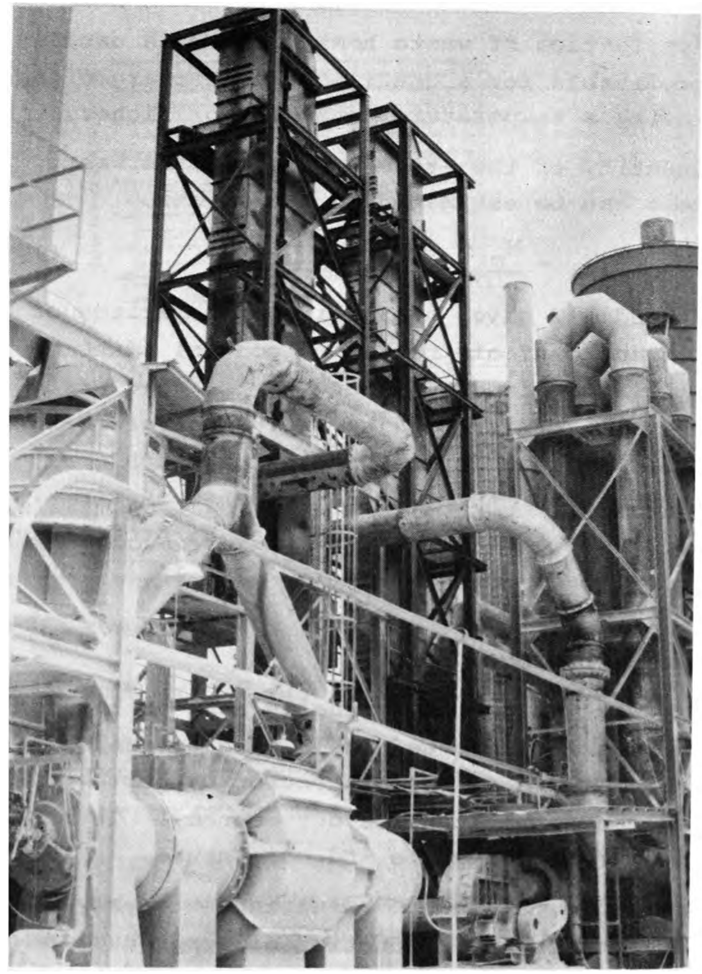

FIG. A2: PLATE TYPE HEAT EXCHANGER IN A KAOLIN PLANT

APPENDIX 2: A BRIEF COMPARISON OF TWO AIR POLLUTION CONTROL SYSTEMS

1. A conventional system using extended ductwork for cooling of the hot gas.
2. A combined heat recovery and air pollution control, generating process steam from waste heat.

Problem: A kiln emits 150,000 ACFM of the flue gas at 1000^{o}F. The gas, having 3-4 grains/cu. ft. of fine dust, 40-50% by weight size particles less than 10 microns has to be cleaned by a bag-house allowing continuous operation of the system. A maximum air-to-cloth ratio of 2 is required.

The particular plant has a powerhouse generating 60,000-80,000 lb/hr of steam 200 psi, 480^{o}F continuously, for processing. Existing boilers consume approximately 9.5 gal. of oil #6 for generation 1000 lb of steam. Present cost of oil #6 is $0.32/gallon, cost of generated steam is approximately $3.15/1000 lb.

SOLUTION

	Conventional System Using Natural Convection and Radiation for Cooling of the Gas (by Fig. 3)	Heat Recovery System Using a Waste Heat Boiler for Cooling of the Gas (by Fig. 11)
Flue Gas Emission	150,000 ACFM at 1000°F = 53,425 SCFM = 234,000 lb/hr	
Cooling of the Gas	by extended ductwork from 1000°F to 500°F	by waste heat boiler from 1000°F to 400°F
Heat Removal: Enthalpy entering/leaving Enthalpy difference Heat removal $Q = M \times \Delta h$	 252/116 Btu/lb 136 Btu/lb 31.8×10^6 Btu/hr	 252/85 Btu/lb 167 Btu/lb 39×10^6 Btu/hr
Bag-House: Volume of the gas to be cleaned Bags - materials Bags - number required	 98,640 ACFM at 500°F woven glass fiber 3200	 88,360 ACFM at 400°F woven glass fiber 2870
Cooling System	42" dia. duct, total length of 1320 ft., arranged into six arches vertically, each approximately 150 ft. high. Pressure drop 14" WC.	three-drum waste heat boiler producing 34,000 lb/hr of steam 200 psi, 480°F. Approximate dimensions 48 x 28 x 20 ft. Pressure drop 9" WC.
Installed Equipment Cost: Fabric filter w/accessories Extended ductwork Waste heat boiler w/accessories TOTAL	 \$575,000 \$150,000 --- \$725,000	 \$520,000 --- \$410,000 \$930,000
Operating and Maintenance Cost: Filter w/accessories Waste heat boiler w/accessories TOTAL	 \$65,000/yr -- \$65,000/yr	 \$53,000/yr \$25,000/yr \$78,000/yr
Yearly Cost of Gas Cleaning (10 - yr. basis)*	$\frac{725,000}{10}$ = \$ 72,500 + \$ 65,000 \$137,500	\$ 93,000 + \$ 78,000 \$171,000
Yearly Savings	None	Annual generation of steam in waste heat boiler: 34,000 x 8,4 00 = 285×10^6 lb. Assuming 4% heat losses, then the net quantity of steam is 273.6×10^6 lb/yr, and its cost is $273.6 \times 10^3 \times 3.15 \cong$ \$860,000/yr.
Conserved Fuel	None	$273.6 \times 10^3 \times 9.5 = \cong 2.6 \times 10^6$ gal. of oil #6 per year.

*No interest costs, taxes, insurance, etc. are included.