Traditional and Non-Traditional Applications of Condensing Heat Exchangers

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ABSTRACT

Combustion processes are commonplace in industrial facilities. The chemical process of rapidly combining a fuel with oxygen produces heat that is used for many purposes. Water is formed during this reaction and is mixed with other combustion byproducts as a vapor because of the associated high temperatures. The release of this vapor with the other flue gases represents a substantial loss of energy. Both latent and sensible heat can be recovered by cooling flue gases to the point that condensation occurs. This is accomplished by transferring heat to a suitable media supplied at a lower temperature; often boiler make-up water. This type of "economizer" can boost the overall efficiency of a boiler plant several percentage points. However, economizers do not normally operated at condensing temperatures since the resulting condensate can be corrosive. This problem can be avoided by using heat exchangers constructed from corrosion resistant materials or having surface treatments designed to shield the contact surfaces so the available latent heat can be recovered.

This paper examines the use of condensing heat exchangers to produce hot water for process and cleaning applications. NYSERDA is currently supporting three projects that use condensing heat exchangers to recover latent heat. These applications include two boiler plants and one site condensing water vapor from an industrial fryer stack. The circumstances, methods, and issues considered in each application are presented, as are the available analytical and qualitative results.

Introduction

Boiler economizers are an effective means to recover waste heat from flue gas. In traditional applications economizers are used to heat feedwater as indicated in Figure 1. This is attractive in high pressure boilers because the flue gas is usually at a temperature 50°F to 150°F above the corresponding saturated steam temperature. At an operating pressure of 150 psig that would equate to a stack temperature of 400°F to 500°F. Considerable heat can be recovered from flue gas in these circumstances although it is normal practice to only sensibly cool the flue gas to a minimum temperature of 300°F to 350°F. This operation still allows a significant amount of heat to be lost up the stack. This is common practice to avoid the formation of acidic condensate and potential for any degradation of the boiler stack or economizer itself. Economizers are not often used with small packaged boilers because the operating pressures tend to be lower and the potential for heat recovery without causing condensation is limited. Consequently, such applications often prove to be uneconomical unless the subject boiler operates almost continuously or other mitigating factors apply.

Figure 1. Standard Non-Condensing Economizer Application

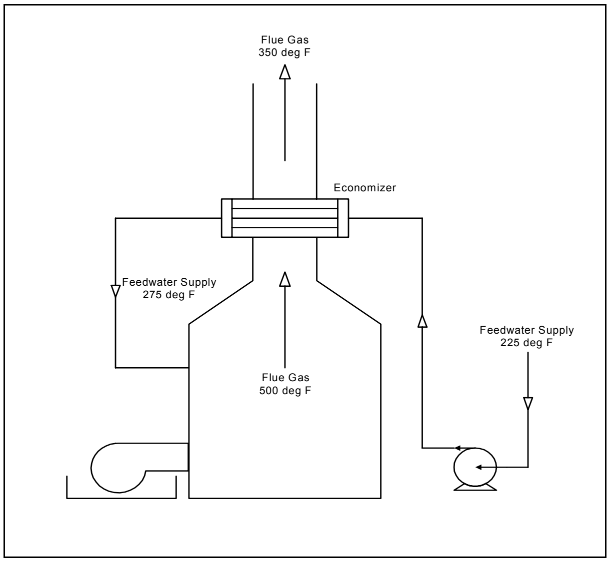
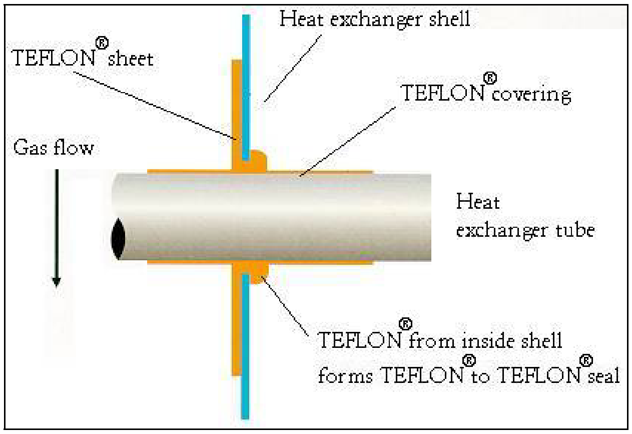


Figure 2. Teflon Coated Heat Exchanger Tube



Source: Condensing Heat Exchanger Corp.

Condensing economizers can alleviate some of these shortcomings and find application with both large and small boilers. These heat exchangers allow both sensible and latent heat to be recovered from the effluent gases. Depending on the heat exchanger design, materials such as coatings or condensate dilution can be used to provide corrosion protection. This paper considers the use of Teflon® covered heat exchangers, Figure 2, in several different situations including a domestic hot water (DHW) heater and two process applications. Although the dew point of acids formed in the exhaust might be substantially higher, Figure 3 illustrates how the incipient dew point temperature of water vapor from flue gas varies with fuel choice and excess air. This occurs because of the reduced partial pressure the vapor exerts in the mixture of gases being vented. The water vapor condenses at a saturation temperature corresponding to its partial pressure in the mixture. Assuming ideal gas behavior, the partial pressure (and thus saturation temperature) can be estimated as;

Equation 1.

$$P_{H_2O} = \frac{V_{H_2O}}{V_{total}} \times P_{total}$$

where, P_{H2O} = Partial pressure of the water vapor
P_{total} = Total pressure of the mixture
V_{H2O} = Volume of water vapor in the mixture
V_{total} = Total volume of the mixture

As vapor is condensed the proportion of water vapor in the mixture decreases and the partial pressure is further depressed. Hence, recovering any significant portion of the available latent heat requires the cold media be at a temperature reasonably lower than the intended terminal temperature of the flue gas to take advantage of the condensing feature.

Water is a natural byproduct of combustion resulting from the combination of oxygen in the supply air and hydrogen in the fuel. Consequently, the amount of water vapor and the potential for latent heat recovery varies with fuel type as indicated in Table 1. Additional moisture is entertained in the combustion air or can be transported in the fuel itself although the latter particularly should be at a minimum. Figure 4 shows the potential energy savings that result from condensing these vapors from the flue gas. If the characteristics of the heat sink allow the temperature of the flue gas to be reduced to the range suggested in Figure 4, boiler efficiency can be improved by 10 percent or more; the overall efficiency can exceed 90 percent.

Figure 3. Water Vapor Dew Point

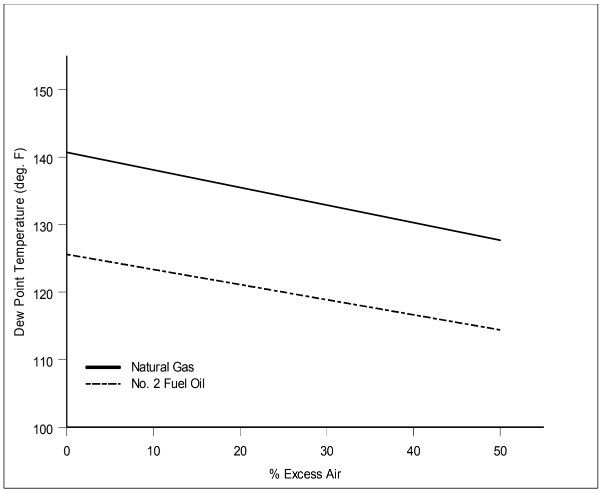


Figure 4. Heat Recovery (Nat. Gas)

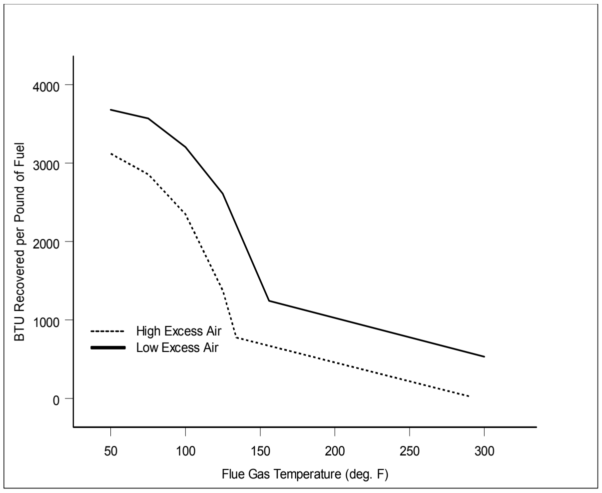


Table 1. Water Formation from Stoichiometric Combustion

	Stoichiometric Air Requirements	**Water formed in Flue Gas Content from Stoichiometric Combustion with Air**	
Constituents	lb/lb Fuel	lb/lb Fuel	ft^3/ft^3 Fuel
Hydrogen	34.28	8.94	1.0
Methane	17.24	2.25	2.0
Propane	15.68	1.63	4.0

Source: 2001 ASHRAE Fundamentals Handbook

Case Study #1 – Fryer Operation

A study was undertaken at a food processor to determine if waste heat from a fryer stack could be economically recovered to offset other thermal loads at the site. This was accomplished by studying select energy demands at the facility and using this information to conduct both performance and economic analyses of several alternative system configurations.

The facility uses high-pressure steam distributed from a central boiler plant to supply heat to the production lines for cooking various food products. Cooking oil for the in-house fryer is circulated through a steam heat exchanger to maintain the desired operating temperature. A combination of oil vapors, air and moisture driven off from the raw product is collected and exhausted from above the fryer vat. Moisture from the raw product is released as a vapor at atmospheric pressure and is the main component of the exhaust. Up to 30 percent of the exhaust volume consists of air that infiltrates from the open ends of the fryer. The air is evacuated along with the water vapor and traces of oil through ducted vents. Fans are used in the exhaust ducts to maintain a negative pressure inside the hood and induce the exhaust flow to the outdoors.

The exhaust that is produced by the fryer contains a significant amount of energy. An equivalent of approximately 17,000 pounds per hour of steam is normally released whenever the fryer is operating. Condensing this effluent would provide a significant opportunity for waste heat recovery. However, the quality of energy is low because the vapor is at atmospheric pressure and mixed with air; the vapor condensing temperature (~180°F) is depressed as predicted using Equation 1. Consequently, the recoverable heat can not be used to offset the load on the boiler plant directly. However, the energy can be diverted to other heat sinks in the facility including both process loads and to provide building space heating. Figure 5 describes the combined thermal load created by these heat sinks on a typical operating day.

A thermodynamic model of the proposed heat recovery system was developed to evaluate its performance based on a design similar to that shown in Figure 10. Since the availability of heat from the fryer and demand for the recovered energy was not always coincident, several variables were considered in the analysis, including:

- Timed availability of heat and coincident demand variations.
- Size of the primary heat exchanger (5, 10 or 17 million BTUH).
- Size of the thermal reservoir used to store hot water (0 to 150,000 gallons).
- Performance with and without the inclusion of the space heat load.
- Performance with and without the inclusion of some of the process loads

Figure 5. Profile of Total Heat Load and Average Heating Day

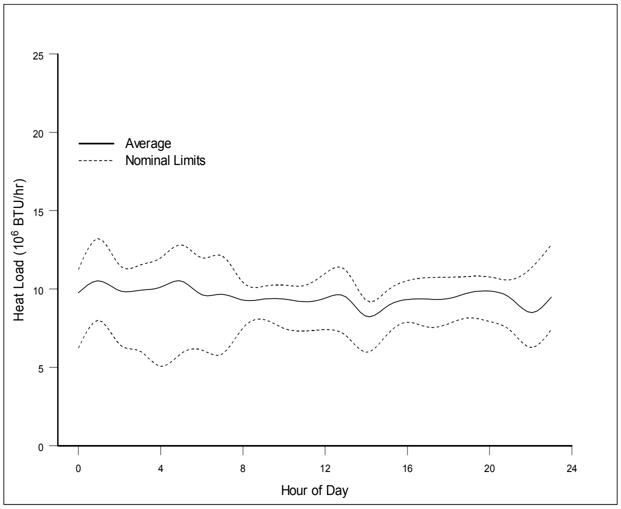
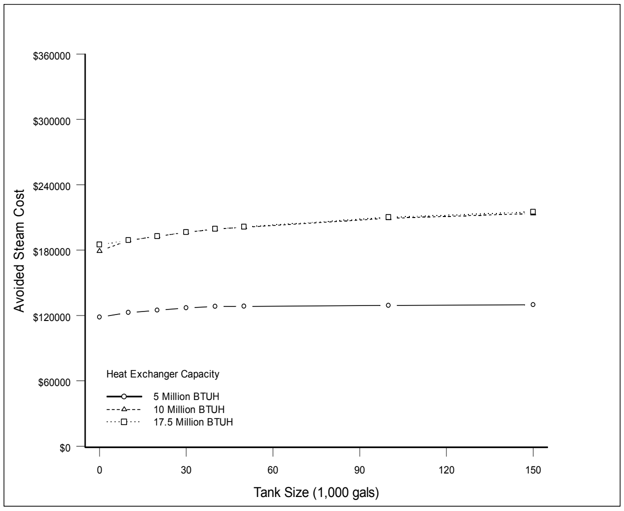


Figure 6. Performance Summary



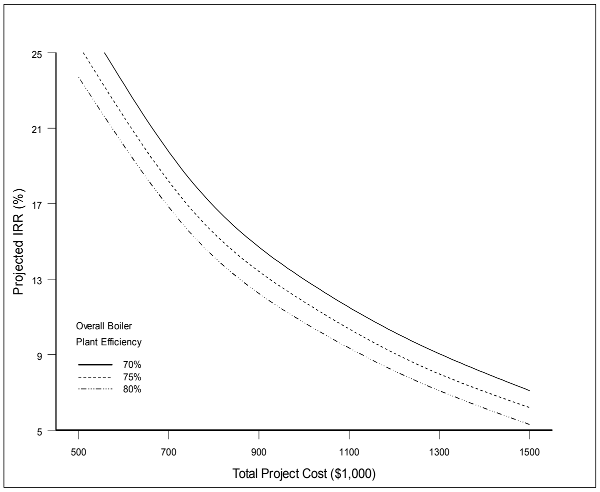
The results of the simulations were compiled in a series of plots similar to that shown in Figure 6. The results proved to be insensitive to the size of the thermal storage and capacity of the heat exchanger beyond 10 million BTUH.

The complexity and extensive piping required for the implementation of the project required a detailed budget estimate be developed rather than depending on estimating guides or simplified rules of thumb to derive the project cost. This information was provided by an outside contractor as presented in Table 2. Gross thermal savings equivalent to approximately $190,000 in fuel costs were expected as indicated in Figure 6. Net savings of $175,000 and a payback of 7.1 years were projected after allowing for the increased consumption of electricity due to the added parasitic loads and cost of maintenance likely to be incurred.

Table 2. Anticipated Project Costs

Cost Category	Reported Cost
Engineering and Design	$110,000
Major Equipment Purchases	$500,000
Instruments and Controls	$160,000
Equipment Fabrication and Assembly	$70,000
Rigging and On-Site Assembly	$50,000
Mechanical Construction	$100,000
Piping Construction	$200,000
Electrical Construction	$40,000
Start-up and Commissioning	$20,000
Total Cost	$1,250,000

Figure 7. IRR Sensitivity to Project Cost



The economic data was also used to calculate a projected internal rate of return (IRR). Inputs describing the project cost and expected annual savings were changed to test the sensitivity of the IRR in various scenarios against a base case depicting the existing facility and operations. Figure 7 documents the sensitivity of the IRR over a large range of implementation costs. The three curves included in Figure 7 represent different levels of boiler plant efficiency; a base case of 75 percent and extremes of 70 and 80 percent were used. As would be expected, a lower efficiency tends to accelerate the economic return while an assumed increase in efficiency would have the opposite effect. Within about 20 percent of the projected cost the IRR varies by only about 2 percentage points over the 10 percent difference in plant efficiency shown in Figure 7. However, a 20 percent reduction in the project cost from the base case would yield a 35 to 40 percent increase in the IRR regardless of the assumed plant efficiency; the equivalent of reducing the simple payback by 1.5 years.

Case Study #2 – Dairy DHW Production

It was proposed in this application that heat recovered from boiler flue gas be used to offset the thermal demand associated with the consumption of DHW used for cleaning purposes. Fresh water is supplied to the site by the local water authority at an incoming temperature of 40 to 60ºF before heating for distribution throughout the plant. The demand for hot water is nearly continuous. These characteristics make the DHW system an attractive heat sink despite the flue gas being at a comparatively low temperature (~325°F).

Short term field monitoring was conducted to develop data on the DHW consumption and service requirements. Specifically, the incoming cold water temperature, hot water supply temperature and coincident steam consumption were measured over a period of one week (a normal cycle of activity at the plant). This data was subsequently used in an energy balance to calculate the amount of DHW that was consumed during the corresponding interval. Figure 8 shows the average water temperature data by time of day at both the inlet and outlet of the existing steam hot water heater. The cold inlet temperature proved to be stable although there was some variation in the outlet water temperature as illustrated in Figure 8. The supply water temperature averaged about 125ºF.

Figure 8. Average Monitored Water Temperatures

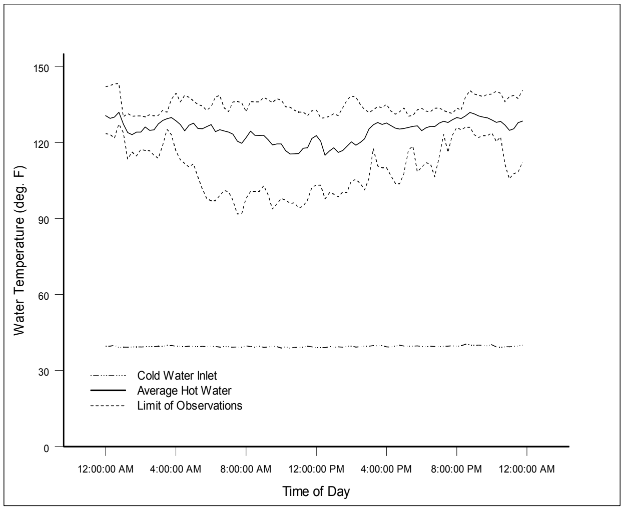


Figure 9. Average Water Consumption Profile Based on Monitored Data

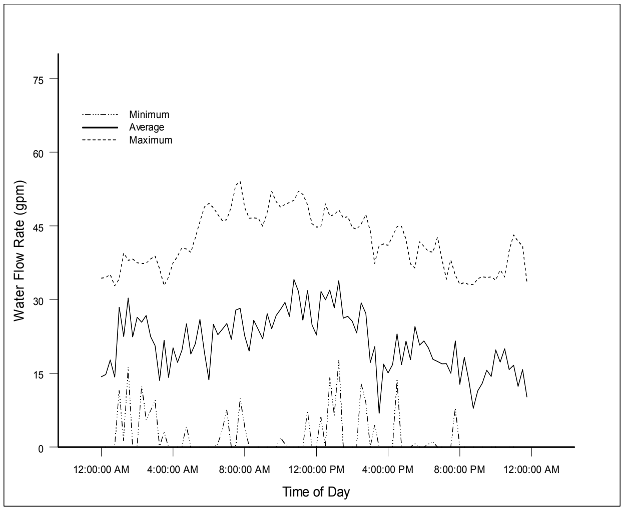


Figure 9 shows the estimated rate of flow derived from the field measurements. Based on these calculations the flow averaged approximately 20 gpm throughout the period and peaked at over 50 gpm. It was assumed the average flow rate was representative of daily requirements at the plant and was used subsequently to project the consumption and heating requirements on a monthly basis as indicated in Table 3.

Ideally, hourly profiles or data of even shorter duration would be available to analyze the performance of a condensing economizer. Insufficient data was available in this application particularly on the water side. Consequently, the analysis was completed using average results in the form shown in Figure 9. A heat exchanger designed for the averaged conditions was subsequently specified but having the capacity to meet the required DHW loads within the limits denoted in Figures 8 and 9. Hence, energy and fuel savings equivalent to those reported in Table 3 should be realized.

Table 3. Estimated DHW Consumption and Fuel Cost

Month	Supply Water Temp. (ºF)	Req'd. Heat (10^6 BTU)	Fuel Cost[1]
January	40	630	$6,320
February	41	570	$5,710
March	45	630	$6,320
April	51	610	$6,120
May	55	630	$6,320
June	58	610	$6,120
July	60	630	$6,320
August	59	630	$6,320
September	57	610	$6,120
October	52	630	$6,320
November	48	610	$6,120
December	43	630	$6,320
Avg./Total	51	7,440	$74,410

Note: 1. Calculated cost based on 80% boiler efficiency & fuel at $8.00/$10^6$BTU

Figure 10 shows a schematic of the proposed heat recovery system. As indicated, the existing boiler stack will be modified to accommodate the heat recovery system. These changes can be designed so as not to interfere with the boiler operation in the event a fault occurs. A storage tank was included in the system to provide some buffer capacity. Cold make-up water will be introduced at the bottom of the tank and hot water would be drawn off the top before passing through a steam heater that will boost the water temperature if insufficient heat is recovered from the flue gas or a sudden draw depletes the reservoir. The water temperature in the storage tank will provide the control point for the flow through the stack heat exchanger. In response to the reservoir temperature more or less water will be circulated through the exchanger. As the water temperature in the tank decreases, more water would be forced through the heat exchanger and diverted to the load. As the demand for hot water moderates, more of the water heated by the flue gas will be returned to the tank until the set-point temperature (~125°F) is restored. In the event there is no demand for hot water and the reservoir is fully heated the damper controls will respond by closing the bypass and discharge flue gas normally.

Maintenance related to the operation of the economizer is expected to be minimal and generally account for no more than 2 to 3 man-weeks per year; the equivalent of about $4,000 to $6,000 in additional labor costs. Allowing for 95 percent availability on the primary boiler and the cost of electricity required for the parasitic loads, annual savings of about $62,000 are expected. A simple payback of two years should result from these savings based on the projected costs reported in Table 4.

Figure 10. Equipment Configuration & Piping for Economizer Application

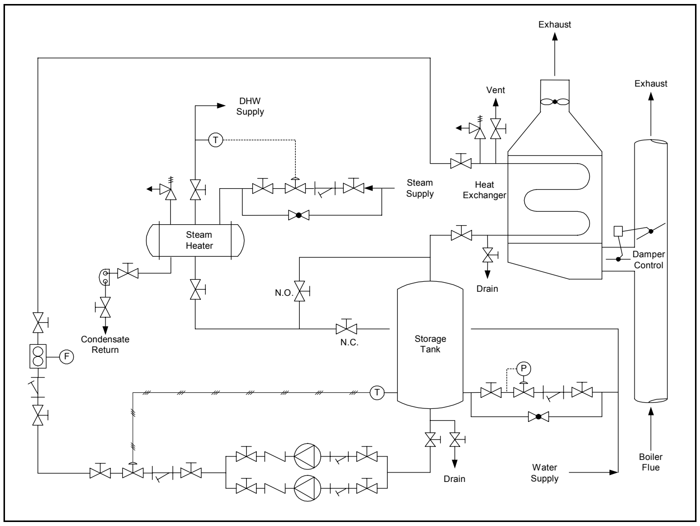


Table 4. Estimated Installed Cost

Description by Subsystem or Task	Estimated Installed Cost
Demolition	$2,500
CHX Heat Recovery Unit	$69,000
Installation of CHX unit	$11,130
Water supply to tank	$2,930
CHX circulating loop	$23,950
Steam heater	$14,470
Estimated Total Cost	$121,480

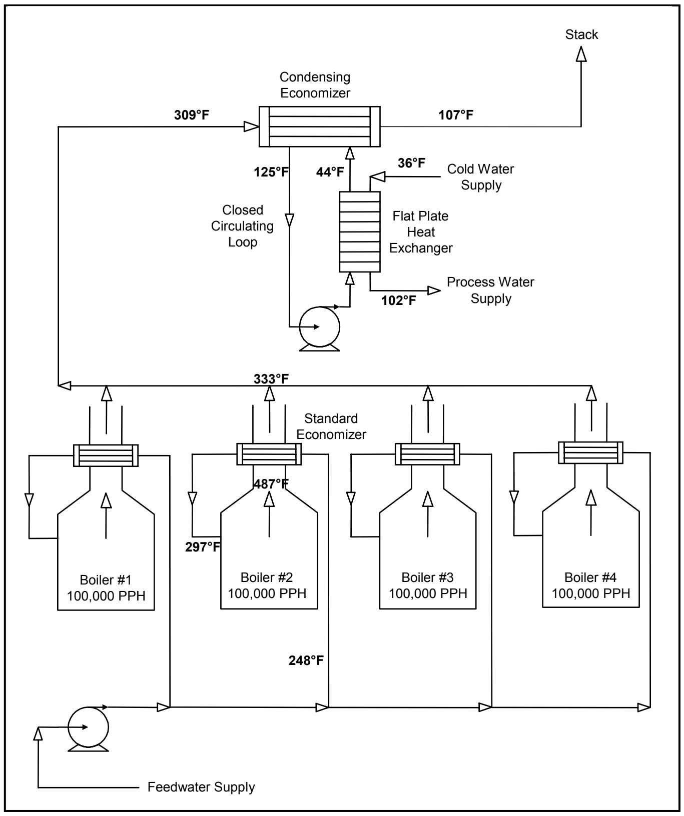
Case Study 3 – Cascade Configuration

Anheuser-Busch, Inc. in Baldwinsville, NY operates four steam boilers that are individually rated at 100,000 pph. Each boiler has a standard stack economizer which is utilized for pre-heating boiler feed water as indicated in Figure 11 and is configured to fire on natural gas, #6 fuel oil or biogas. A common breeching connects all the boilers to a single stack that incorporates a condensing heat exchanger designed to recover both sensible heat as well as a portion of the latent heat available in the combined flue gases.

The installation of Anheuser-Busch's condensing unit dates to 1987. In its original configuration water for plant processes and cleaning was heated directly in the condensing economizer. However, soon after the heat exchanger was installed water side corrosion started to appear on the inside surface of the tubes. This was caused by solid precipitants from the water which was drawn from a nearby lake. This fouling created an uneven temperature distribution along the tubes or "hot spots" that ultimately lead to the degradation of the material and loss of heat exchanger effectiveness. Anheuser-Busch subsequently reconfigured the system to correct this problem. As indicated in Figure 11, the new condensing unit was isolated from the lake water by using a closed-loop, plate-and-frame heat exchanger. This closed loop system allowed the water quality to be controlled in order to prevent water side corrosion from developing on the new condensing heat exchanger.

When the system was still in its original configuration Anheuser-Busch was incurring high maintenance costs and the heat exchanger was only operating at 40 percent of its rated capacity. Anheuser-Busch currently operates almost continuously (~8,000 hours per year) and with the new system configuration the annual fuel consumption has been reduced by about 6 percent. Heat recovery from the flue gases averages 14.6 MMBTUH of which about 8.7 MMBTUH is recovered by sensible cooling the flue gases and 5.9 MMBTUH is recovered as latent heat. This boiler arrangement with standard stack economizers and a condensing heat exchanger improves the boiler fuel to steam efficiency to approximately 95 percent.

Figure 11. Boiler Plant Schematic



Conclusions and Comments

Recovery of latent heat from flue gas or other effluents containing moisture can substantially boost operating efficiencies. However, taking full advantage of the features of a condensing economizer requires that an adequate low temperature heat sink exist. This is aggravated by the continuous depression of the partial pressure and corresponding saturation temperature as the fraction of water vapor in the total flow is reduced as condensation occurs. It is impossible to recover all of the latent heat available in any effluent vapor. The extent to which this is accomplished depends on the characteristics of the targeted heat sink, other technical factors and economic requirements.

Greater benefits can be achieved if thermal loads other than traditional feedwater heating can be identified. Production of hot water for process or cleaning purposes is a prime example. Fresh make-up water is supplied to most facilities at temperatures that might range from 40°F to

60°F depending on the geographic location and season. Space heating loads might be similarly satisfied at least on a seasonal basis.

Using latent heat to meet these loads is attractive since a high grade thermal resource (i.e., high pressure steam, natural gas fueled heaters, etc.) can usually be displaced. In most small to moderate sized facilities steam is generated in a single boiler. The operating pressure is determined by the requirements of a single end use or process and often exceeds what would normally be required to produce hot water. It is more thermodynamically advantageous to use the comparatively low quality heat available in a waste stream for this purpose rather than consuming more steam.

Such applications can be achieved even if a traditional feedwater heater is in service. The corrosion resistant features of condensing heat exchangers designed for use with flue gas makes it possible to recover substantial quantities of both sensible and latent heat that would otherwise be released to atmosphere. These same features make the use of these heat exchangers attractive in non-traditional services, especial in food preparation, since the exhaust from such processes is often heavily laden with moisture.

The design of these heat exchangers is also suitable for retrofit applications; the addition of a condensing economizer need not be considered during the initial plant design. Sufficient styles and configurations are available to accommodate a wide range of applications and physical circumstances. These heat exchangers are also tolerant of most boiler fuels although spray washers or similar devices might be required to keep the outer surfaces of the tubes clean as with burning #6 oil.

As the price of thermal fuels continues to escalate the application of condensing economizers should become more attractive as payback rates accelerate. Alternative applications beyond the recovery of heat from the flue gas of combustion appliances should become equally attractive assuming suitable heat sinks can be identified. Financial savings for the end user and additional societal benefits associated with the preservation of resources and emission reductions should accrue with greater application of this technology.

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