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STUDY OF CONDENSING ECONOMIZERS IN INDUSTRIAL APPLICATIONS

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ABSTRACT

Condensing economizers increase the thermal efficiency of boilers by recovering sensible and latent heat from exhaust gas. A considerable amount of waste heat in boiler flue gases is in the form of latent heat of water vapor. This energy cannot be recovered until the flue gases are cooled to a temperature below the dew point. These economizers are currently being used commercially for this purpose in a wide range of applications. Performance is dependent upon application-specific factors affecting the utility of recovered heat. Condensing economizers can also capture flue gas particulates. In this paper, the primary focus is on introduction of condensing economizer's for efficiency improvement of natural gas fired boiler. The secondary focus of this paper is to reduce or to control the particulate emission from natural gas fired boiler.

INTRODUCTION

Condensing economizers are heat exchangers which recovers energy from flue gas leaving boilers. In these systems, the flue gas temperature is reduced below the dew point of the water vapor. Both sensible and latent heat is recovered from the flue gas and boiler system thermal efficiency increases markedly. Some residential appliances are now commercially available with integral condensing economizers. In other cases a condensing economizers maybe added on to an existing boiler or furnace. With commercial and industrial scale equipment these economizers have been used to a limited degree and are always refit to conventional boilers. Both direct and indirect contact economizers are available although the indirect are more common. Both direct and indirect contact economizers are available through the indirect are more common. With condensing systems flue gas exit temperatures of above 38 Deg C (100 F) and boiler or furnace system thermal efficiencies (based on gas analysis only and fuel higher heating value) of 95 % are not uncommon.

To date, condensing economizers have most commonly been used on gas- fired equipment. However, there have also been some applications to oil- and wood-fired boilers. Relative to other fuels, the condensate from natural gas is less corrosive. In addition, gas combustion products have higher moisture content which leads to increased water vapor dew points and increased energy efficiency improvement with condensation.An important factor in the application of condensing economizers is utility of hat at the low temperature required for condensation. In the residential sector most of the available products are for gas-fired warm air furnaces. In warm air heating systems the return air temperature to the furnace is generally less than 27 Deg C (80 F). Hydronic residential heating system, in contrast, often has return water temperatures well above 49 Deg C (120 F) and generally above the dew point of water vapors in the flue gas. Application of condensing economizers to hydronic systems requires oversized radiators in the heated apaces to reduce the return water temperature. Circulating water to preheat building make-up air has also been used. In the commercial and high industrial sectors preheating of make-up or domestic water is a common application. In many applications the flue temperature after the economizer is slightly higher than the dew point. These "near condensing" systems must be built to withstand corrosion resulting from transient or local condensation. Corrosion of condensing heat exchanger surfaces has been an area of considerable emphasis and stainless steel, Teflon coating or coverings, Teflon heat exchangers, glass heat exchangers, and plastic exhaust system components have been used. In gas fired units, where acid attack is less severe, economizers used in the experimental part of this project, all surface exposed to the flue gas were manufactured with a thin covering of Teflon to prevent acid attack. Utility application of condensing economizers has been very limited to date. Recently Consolidated Edison Company of New York has installed a condensing economizer at their 74th street station in a test/demonstration effort. This site has both steam send out and electric capacity and the economizer simply preheat cold make-up water. The economizer is on a slipstream of the flue gas flow from three oil fired boilers with a steaming capacity of

272000 kg/hr each. Two economizers were designed to handle a total 145000kg/hr of flue gas, which represents one third of the flue gas flow at average conditions. The typical gas temperature entering the economizer is 163 Deg C (325 F). The gas leaves the economizer at 29 to 38 Deg C (85 to 100 F) and the mixed gas enters the stack for the economizer exhaust. The improvement in the plant heat rate with the economizer averages 800 Btu/ kWh. It is planned to keep the economizer in operation for 20 years.

LITERATURE REVIEW

Condensing Boilers

Combustion of hydrocarbon-rich fuels, such as natural gas, oil, coal and biomass, in air yields two primary products, carbon dioxide and water vapor, entrained in the relatively inert nitrogen of the air. Conventional boilers transfer most of the sensible heat of this reaction to water as hot water or steam. Condensing boilers are designed to capture a fraction of the latent heat, i.e., the energy released by condensing water vapour in the flue gas. By extracting this latent heat in the condensing boiler, the whole system can achieve higher efficiency levels. To capture this energy, the flue gas requires a heat sink that is cool enough to allow water condensation. For heating boilers that use the returning water from the system as a heat sink, this requires return water temperature below 60°C.

Modes of Condensation

When condensation of the moisture in the flue gas occurs in a condensing boiler, the condensate can accumulate on the cold surface in one of two ways (Marto, 1991). If the water wets the cold surface, the condensate will form a continuous film (film wise condensation). If the water does not wet the surface, it will form into numerous microscopic droplets (drop wise condensation). Drop wise condensation leads to much lower thermal resistances to heat transfer than film wise condensation. However, long-term drop wise condensation conditions are very difficult to sustain. Film wise condensation is normally encountered in industrial applications and drop wise condensation can only be maintained under controlled conditions with special surface coatings or additives to the vapor. All surface condensers today are designed to operate in the film wise mode. The cooled surface in condensing boilers may be of any orientation, though vertical and near-horizontal geometries are preferred (Chisholm, 1980). In vertical condensing boilers, a film of condensate (condensed from flue gases) will fall under the influence of gravity thickening downstream with increasing load. Film flow will be laminar near the top of the tube but may become turbulent at high loadings (Figure 2.1(a)). The film surface is usually covered with ripples or waves which influence the condensation process. The influence of the gas flow is important. If the gas flow is concurrent with condensate, the surface shear causes film thinning. On the other hand a small counter-current flow will cause film thickening (Figure 2.1(b) (c)) while a larger flow may cause flooding and eventually flow reversal (Figure 2.1 (d) (e)). A flow of gas across tubes will lead to a non-axis symmetric liquid distribution with thinning of the film on the upstream side and thickening in the wake.The heat transfer resistance of the condensate film is directly proportional to its thickness and is reduced by wave effects and turbulence. Co current and cross gaseous flows cause film thinning and reduce heat transfer resistance. In horizontal condensing boilers with condensation outside tubes, the gas stream may flow vertically upwards or downwards across the tubes, or horizontally in a direction parallel to or perpendicular to the tubes. The boilers are usually vertically baffled to produce a combination of horizontal cross flow and parallel flow. In perfectly horizontal condensers, the condensate drips vertically from the uppermost tubes leading to thicker films and higher heat transfer resistance of the lower tube rows. This phenomenon is known as condensate inundation. If the tubes are inclined at even modest angles to the horizontal, the liquid flows in the direction of the slope, at least as far as any vertical baffle.

During film condensation in tube bundles, the conditions are significantly different from a single tube (Kakac and Liu, 2002). The presence of neighboring tubes creates several added complexities, as shown in Figure 2.2. In the idealized case (Figure 2.2a), the condensate from a given tube is assumed to drain by gravity to the lower tubes in a continuous, laminar sheet. Actually, the condensate from one tube may not fall on the tube directly below it. The inundation largely depends on the spacing-to-diameter ratio of the tubes and on whether the tubes are arranged in a staggered or in-line configuration. As shown in Figure 2.2b, the condensate may flow sideways down the tube bundles. Experiments have shown that condensate does not drain from a horizontal tube in a continuous sheet but in discrete droplets along the tube axis.

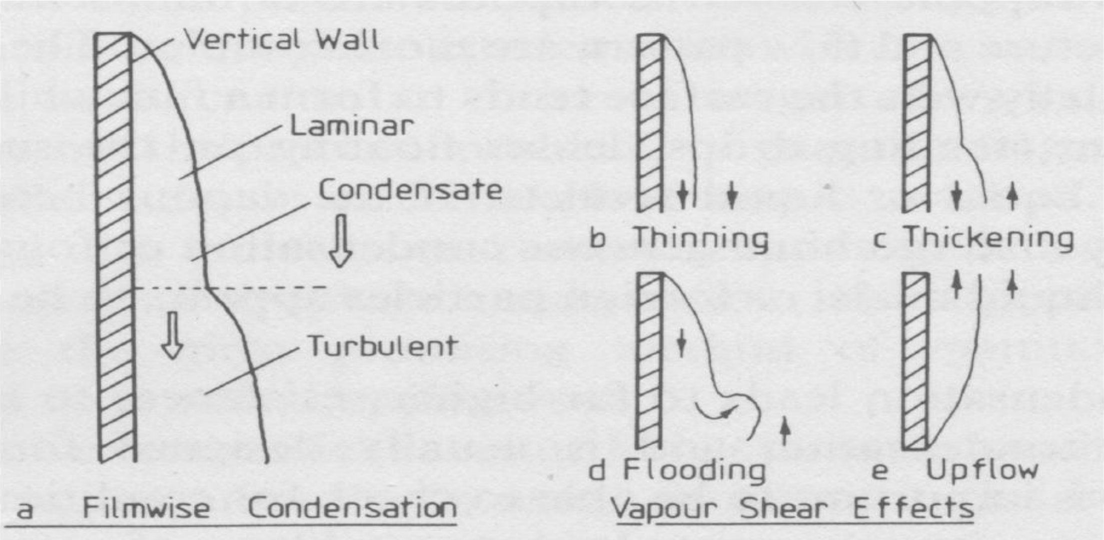

Fig 2.1 Film condensation on vertical surface

When these droplets strike the lower tube, considerable splashing can occur (Figure 2.2c), causing ripples and turbulence in the condensate film. Moreover, large gas velocity can also create significant shear forces on the condensate, stripping it away from the film (Figure 2.2d).

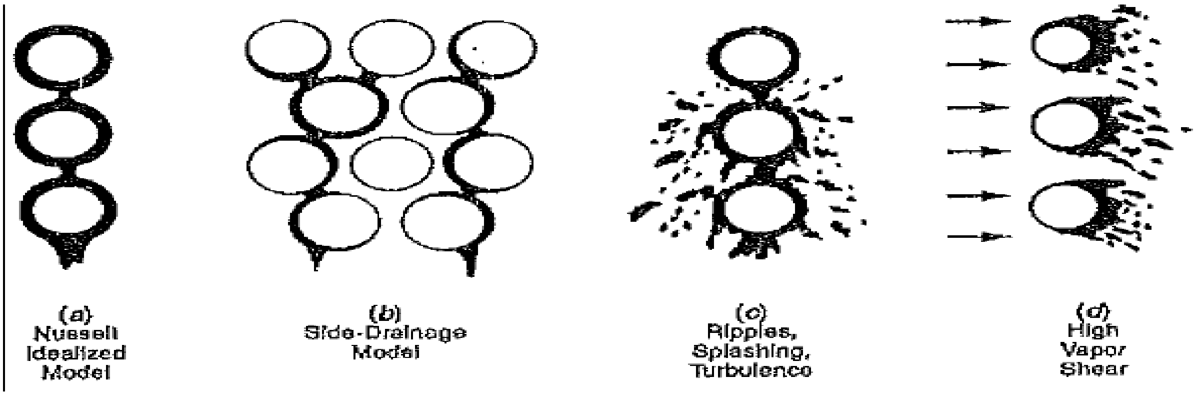
(a) Nusselt Idealized Model
(b) Side-Drainage Model
(c) Ripples, Splashing, Turbulence
(d) High Vapor Shear

Fig 2.2 Condensate flow in condensing boilers

Gas-fired Condensing Boilers

Typically, non-condensing boilers have atmospheric burners, cast iron heat exchangers and metal or masonry chimneys. The products of combustion (flue gases) are maintained at a sufficiently high temperature (resulting in low heat transfer efficiency) to allow them to exit the system using natural convection. If the flue gases do not contain enough heat to maintain proper stack buoyancy, the combustion products will spill back into the building. In addition, if the internal flue surface temperature is allowed to drop below the dew point, moisture in the combustion products will condense on the internal walls of the heat exchanger and flues. As the condensate is very acidic, it will corrode the heat exchanger walls and damage metal and masonry chimneys. By not capturing any latent heat from flue gases, non-condensing boilers operate at low efficiency. However, due to their relatively low cost of fabrication, they dominate the market, and can use either natural gas or distillate for fuel.As the temperature of the flue gas at the exit of a conventional gas fired boiler is usually high, a great amount of heat energy is lost to the environment. In the flue gas, both sensible heat and latent heat can be recovered by adding a condensing heat exchanger. Thus, the condensing boiler efficiency can be increased by as much as 10% (Comakli, 2008).

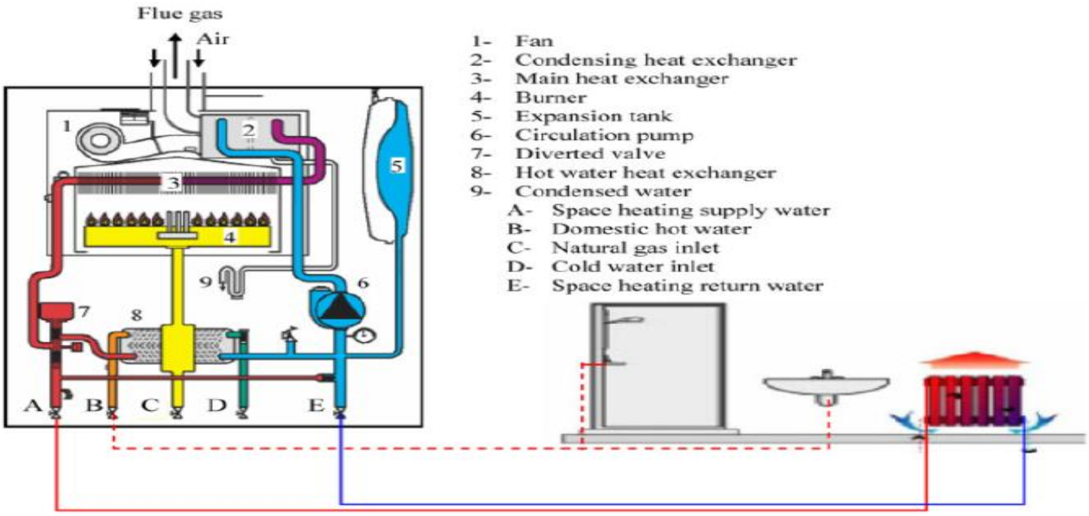

Fig 2.3 Schematic arrangement of a condensing boiler for house heating

Condensing boilers run at a positive pressure with forced-draft power burners or pulse combustion instead of atmospheric draft to pull gases through the firebox and heat exchanger. These boilers are equipped with stainless steel or other corrosion-resistant material since they are designed to tolerate the transient presence of condensate in the boiler. Condensing boilers operate at high efficiency by capturing some of the latent heat and most of the sensible heat of combustion. In addition, these boilers operate at high efficiency even at part-load conditions when return water temperatures from space heating equipment are low. Because of the relatively low flue gas temperatures, condensing boilers require flue construction that accommodates condensation downstream of the boiler.

The development of the condensation technique for heating applications presents major opportunities in decreasing gas consumption in apartment houses, independent houses, commercial building and official buildings. Figure 2.4 presents a schematic arrangement of a condensing boiler for house heating. For condensing boilers, the boiler efficiency can reach a theoretical maximum value over 110% based on the lower heating value of fuels (Comakli, 2008). For natural gas, the boiler efficiency is dependent upon the flue gas temperature, with air/fuel ratio as a parameter shown in Figure 2.2.

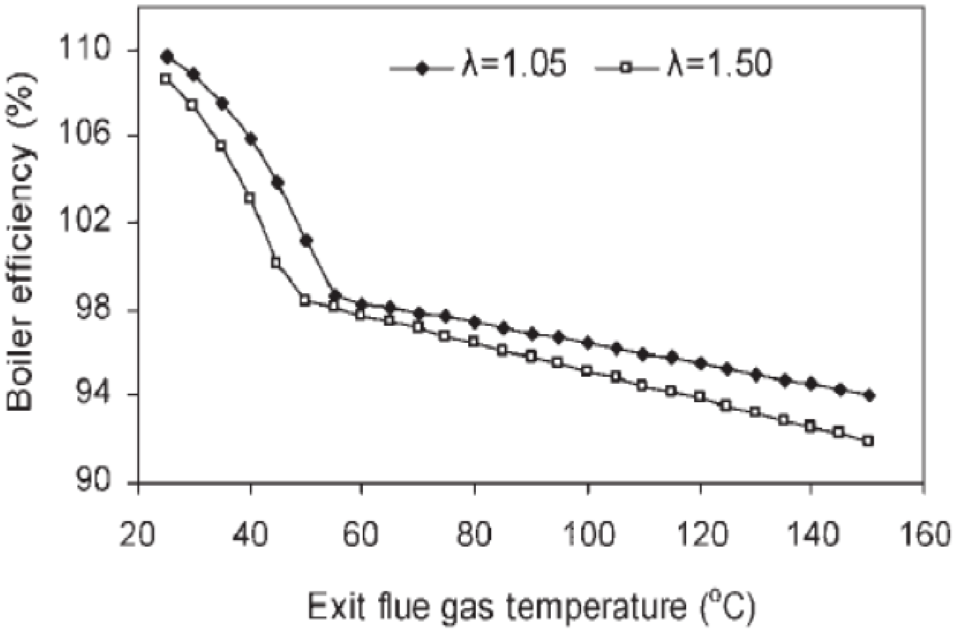

Fig.2.4 Efficiency of a condensing boiler versus exit flue gas temperature under Different access air ratios

Flue Gas Condensers

The application of flue gas condensers to recover waste (latent) heat from flue gases is much wider than the stand-alone gas-fired condensing boilers. Flue gas condensers can be designed not only for power plants, but also for all commercial and industrial facilities as well. Energy recovered by the flue gas condensers can be used in district heating and cooling schemes or put back into an industrial process. Moreover, with flue gas condensers, a large amount of water can also be recovered from flue gases that otherwise is exhausted to the atmosphere. There are two types of flue gas condensers developed for industrial application:

Indirect and direct contact condensers, as shown in Figures 2.5 and 2.6

.An indirect contact condenser removes heat from hot flue gases by passing them through one or more shell-and-tube or tubular heat exchangers. This condenser can heat fluids to a temperature of 90°C while achieving exit gas temperatures as low as 25°C (depending on the temperature of the cooling fluid). The indirect contact condenser is able to preheat water to a higher outlet or process supply temperature than the direct contact condenser. However, the condenser must be designed to withstand corrosion from condensed water vapor. The condensed water is acidic and must be neutralized if it is to be discharged into the sewer system or used as process water.

The indirect contact condensers can be further categorized into three types: pipe condenser, lamella condenser, and combi condenser (Nederhoff, 2003). In a pipe condenser, the flue gases flow through pipes that are surrounded by cold water. The water flows along the pipes but in opposite direction of the gas. In this system, the temperature of the flue gases can get as low as the temperature of the incoming water.

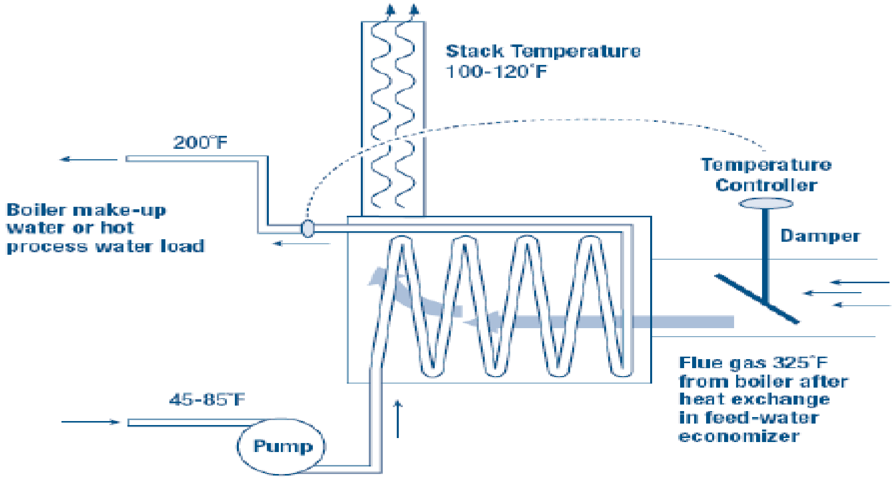

Fig.2.5 Indirect contact flue gas condenser

In the lamella condensers, the pipes contain cold water and are surrounded by flue gases. The pipes have aluminum lamellas (fins) attached to them to enlarge the contact surface with the gases. The flue gases are blown over and across the cold pipes and lamellas. The lamellas are not as cold as the pipes and the gases cannot be cooled as low as the temperature of the incoming water. This makes a lamella condenser less effective than the pipe condenser.

A combi condenser consists of two condensers in one system: one condenser cools the flue gases down to 70°C, and the second takes care of further cooling from 70°C down to 40°C. The second condenser takes the condensation energy out of the flue gases. Generally, both condensers are lamella types. The first of the two condensers operates at a high temperature level, and delivers the heat to the return water of the normal pipe heating system. The second condenser operates at a much lower temperature level. This condenser is usually connected to a separate heating net that runs at a lower temperature. It is also possible that both are connected to the normal heating system. In this case, the second condenser pre-heats the cold water, and the first condenser then heats the water further to the required high temperature. A combi condenser retrieves nearly all energy that is present in the flue gases, and therefore achieves very high energy efficiency, but the investment costs are therefore higher than for a single condenser. Another heat recovery option is to use a direct contact condenser (Figure 2.6), which consists of a vapour-conditioning chamber followed by a counter current spray chamber. In the spray chamber, small droplets of cool liquid come into direct contact with the hot flue gas, providing a non-fouling heat transfer surface. The liquid droplets cool the stack gas, condense and remove the water vapor.

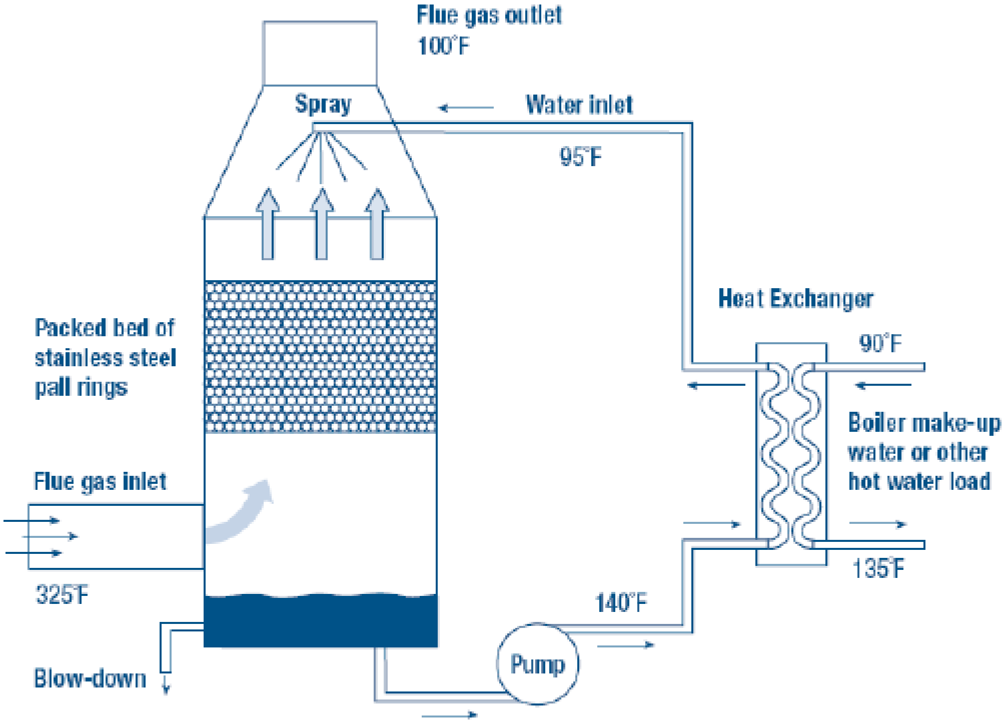

Figure 2.6 Direct contact flue gas condensers

The spray chamber may be equipped with packing to improve contact between the water spray and hot gas. A mist eliminator is required to prevent carryover of small droplets. The direct contact design offers high heat transfer coupled with water recovery capability since heated water can be collected for boiler feed water, space heating, or plant process needs. Recovered water will be acidic and may require treatment prior to use, including membrane technology, external heat exchangers, or pH control. Direct contact condensers operate close to atmospheric pressure; altitude and flue gas temperature limit the makeup water temperature to 40 to 60°C.

Condensers require site-specific engineering design and a thorough understanding of the effects of their operation on the existing steam system and water chemistry. If the pressure of the flue gases is increased, the dew point rises and there is greater potential for abstracting heat by means of condensation. If the system is pressurized to a pressure of 4bar, the condensation of moisture in the flue gases may occur at temperatures between 60°C and 115°C. For example, Fagersta Energetic AB, a Swedish company, developed an advanced project called the Bioturbo system, in which wet peat was burned in a pressurized fluidized bed, as shown Figure 8. This 3MW pilot plant was tested for over 1000 hours and operated successfully with peat containing water up to 78%. Very high overall efficiency was achieved during the operation. Flue gas temperatures were between 10°C and 20°C, and emissions were low (Fagersta Energetic, 2009a).

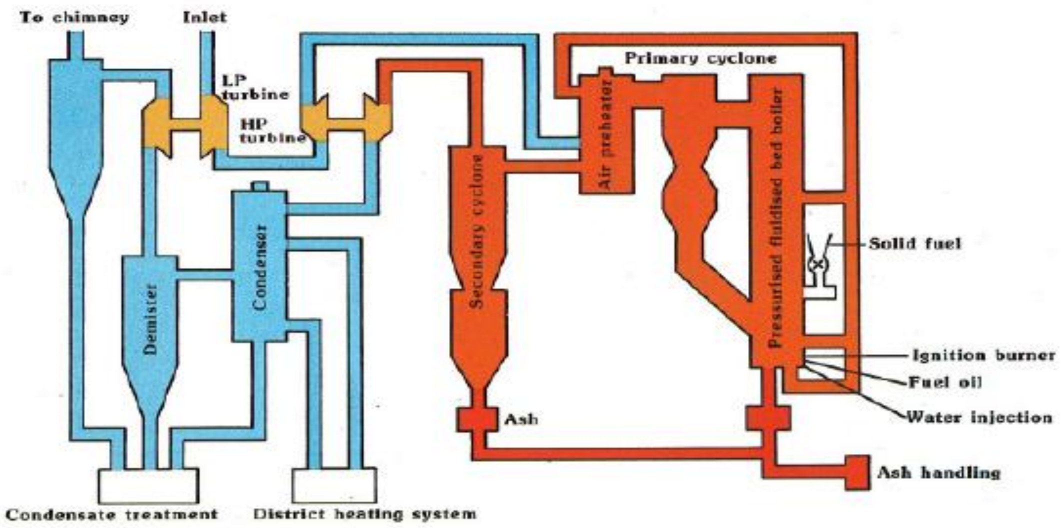

Figure 2.7 The Bio turbo system: a power plant with pressurized combustion system

ADVANTAGES OF CONDENSING ECONOMIZERS

Latent Heat Recovery

The most significant advantage of a condensing boiler is that the latent heat of water vapour can be recovered from the flue gas. This greatly improves the overall thermal efficiency of the system. Figure 5.1 shows the variations of the theoretical thermal efficiency (with reference to net calorific value) of a wood chip boiler with a condensing heat exchanger against exit flue gas temperatures under different excess air ratios. The fuel (wood chips) used in the plant has 50% moisture content, 25.6% C, 3.05% H, 20.45% O. With the increasing excess air ratio, the partial pressure of the water vapor in the flue gas decreases. This lowers the dew point of the flue gas. Meanwhile, more sensible heat is carried by non-condensable gas components under higher excess air ratio conditions. Consequently, at the same exit temperature of the flue gas, higher excess air ratio leads to lower thermal efficiency. As shown in Figure 5.1, the condensing heat exchanger/condenser recovers the latent heat of moisture when it is condensed. The recovery of the latent heat results in the thermal efficiency exceeding 100% with reference to the lower heating value of the input fuel.

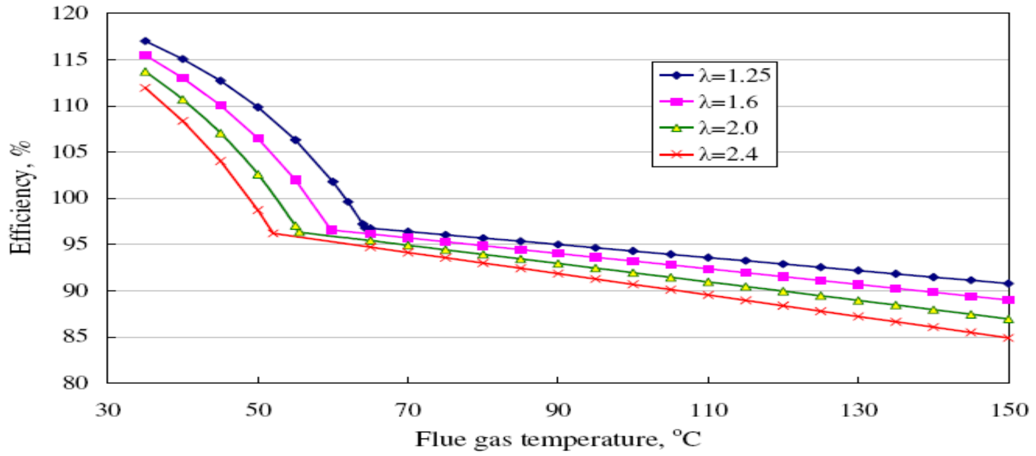

Figure 3.1 Theoretical efficiency of a wood chip boiler with a condenser versus exit Flue gas temperature under different excess air ratios

Emission Abatement

Wood combustion generates fine particles, which contribute significantly to the emissions from the energy sector. The common aerosol size distribution from wood combustion peaks at 50-400 nm with relatively high number concentrations. Condensing heat exchangers (condensers) can be optimized for simultaneous particle collection and waste heat recovery. The condensate forms a constant water film that can carry away any deposited particles. Sipula et al. (2009) studied particle and gaseous emissions of four different wood chip-fired district heating units in the size range of 5-15 MW. All of the units were equipped with cyclones to remove coarse particles from the flue gas. In addition, two of the rotating grate boilers were equipped with single field electrostatic precipitators (ESP), and one with a condensing flue gas scrubber (as shown in Figure 5.2). It was found that the condensing flue gas scrubber removed on average 44% of PM1 and 84% of total solid particles (TSP).

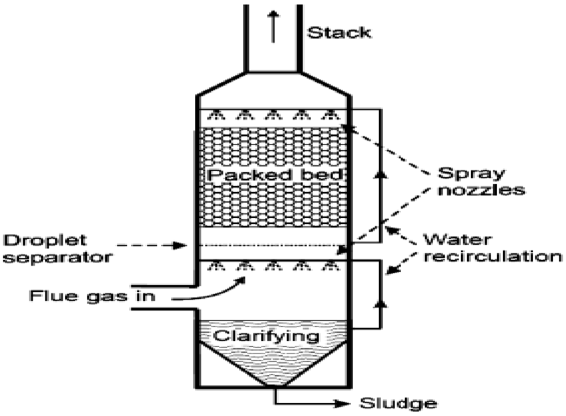

Figure 3.2 Schematic diagram of the condensing scrubber (Sipula et al. 2009)

Figure 3.3 shows the particle mass size distribution before and after the flue gas scrubber. As shown, particles with diameter smaller than 300nm and between 1.0 and 10µm were partially removed in the condensing scrubber. The average 44% decrease in fine particles, which were clearly below 500 nm in size, probably resulted from a combination of thermophoresis due to cool surfaces, and diffusiophoresis due to steam condensation. In addition, the particle sizes were found to grow inside the scrubber, as seen in the shift of the particle size distribution. Recently, a commercially available wet scrubbing process called "FLUE-ACE" has been developed. It consists of a condensing reactive scrubber that can be used for heat recovery and emissions control. The scrubber operates by cooling flue gas substantially below the dew point temperature, thus forcing the condensation of water vapor and other condensable.

This results in greater removal of condensable and fine particulates than can be achieved in a conventional wet scrubber. The FLUE-ACE wet scrubber has been demonstrated to remove 96-99% of flue gas SO2, NO2 and HCl. The High Performance (HP) FLUE-ACE model additionally removes greater than 98% of SO3 mist and fine particulates greater than 0.3µm in diameter. Due to the condensing action used for pollutant removal, it is expected that mercury removal in the scrubber can be greater than in a conventional wet scrubber. There are currently 13 commercial installations of the FLUE-ACE technology operating in Canada, all installed in the past 16 years. The majority of these installations provide acid gas control for smelting operations or paper mills, with the largest operating commercial installation treating a 75MW equivalent stream of gas. In addition to condensing scrubbers, condensing heat exchangers can also be used for wet scrubbing. Reported a pilot process consisting of a condensing heat exchanger with an FGD system. The condensing heat exchange cooled the flue gas to 20 – 30°C. Large water droplets were formed around the pollutants and then removed in the FGD system. The pilot process was tested in 1994 – 1995. Through this system, 58% Hg, 80–90% of PM and 95% SO2 were removed. In condensers, the particle separation mechanisms include inertial impaction and gravitational settling for larger particles and diffusion for the smallest particles. In addition to Brownian diffusion, important factors in the removal of fine particles include thermophoresis, induced by the temperature gradient between the flue gas and the cool surface, and diffusiophoresis, caused by the steam condensation on cool surfaces. Furthermore, in condensing scrubbers/heat exchangers, particle growth by water condensation can affect particle size distributions in the emission.

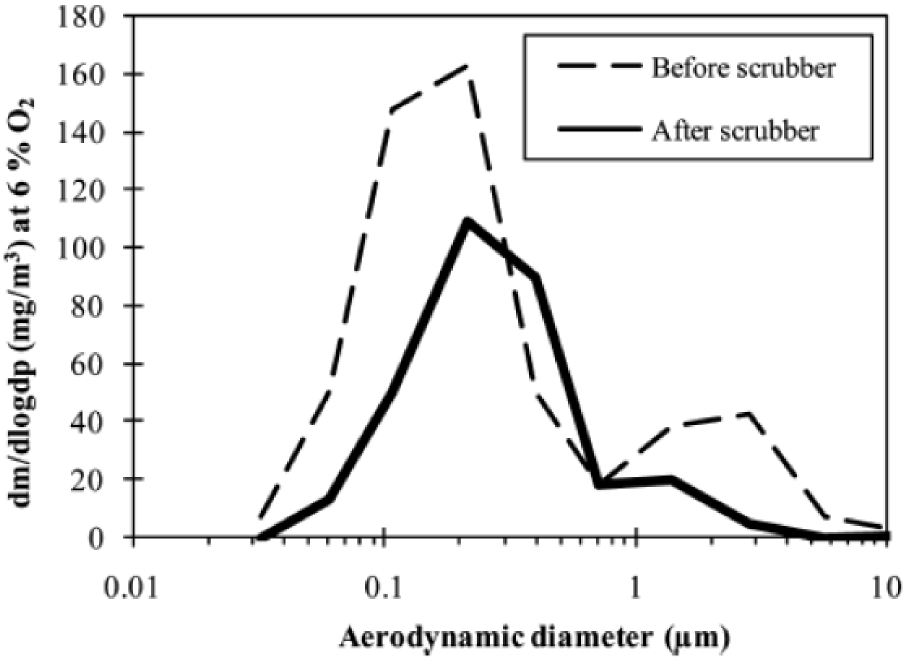

Figure 3.3 Particle mass size distributions before and after the flue gas scrubber

TECHNICAL BARRIERS

Corrosion

Because the products of combustion include materials that are highly corrosive, corrosion arising from condensing gases has been a problem in industry for many years (Huijbregts and Leferink. 2004). Corrosion-derived cracks were mostly found in the low temperature heat exchangers (typically operating at temperatures between 70 and 90°C). In general, the exchangers had been fabricated from steel St35.8, standard low-carbon steel for construction purposes. Most cracking occurred where mechanical stresses were relatively high. Microscopic analysis of samples revealed that inter granular corrosion had occurred and it was frequently reported that complete grains of material had become detached. In the case shown in Figure 6.1, nitrate stress corrosion cracking was identified as the cause of the failures.To avoid corrosion due to condensing gases, it is of vital importance to well understand the composition and amount of condensed liquid that could be formed in the condensing boilers. Descriptions and calculation methods of condensation have been extensively studied during the past few decades (Kiang, 1981; Huijbregts and Leferink. 2004). In clean air, the dew point can be directly obtained from the water vapor pressure.

When other gaseous species are present, such as SO3, SO2, HCl or NO2 in particular, the dew point will deviate from the ideal dew point line .Under the atmospheric pressure, dew point of the flue gas in the presence of these species can be calculated.

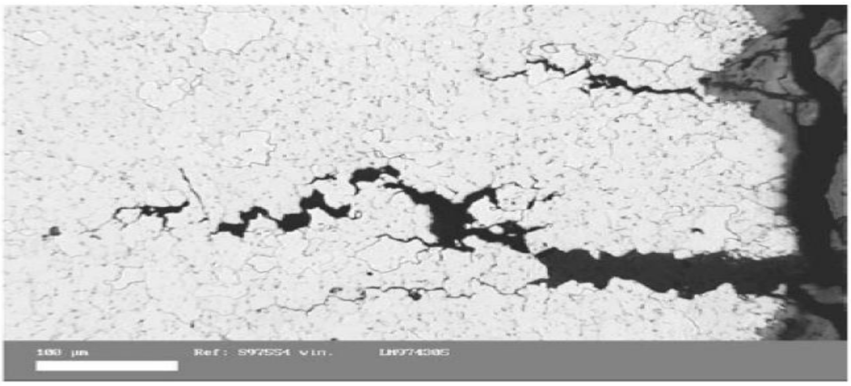

Figure 4.1 typical micrograph of stress corrosion cracking on the cross section of tube material

POTENTIAL SOLUTIONS

To capture as much latent heat as possible, and because the products of combustion include materials that are highly corrosive, condensing boilers require specialized materials for fabrication. To withstand these corrosive conditions, condensing boilers are made of stainless steel and other corrosion resistant (and sometimes costly) materials. They can require more sophisticated controls, and more careful installation, to achieve their potential. In addition, the terminal units (radiators, convectors, and fan-coils) connected to the condensing boiler tends to be more expensive due to the greater heat exchanger surface required to operate at lower water temperatures. Condensing boilers thus require specialized corrosive-resistant materials and sophisticated controls resulting in installed costs that are up to 3 times higher than that for a conventional boiler.

Table 5.1 stainless steel materials properties

Alloy Type	Alloy	UNS No.	Density lb/in^3	Conductivity Btu/hr·ft·F	Thermal Expansion in/in ×10^{-6}/F
27-29% Cr Ferritic	Sea-Cure®	S44660	0.28	9.5	5.4
	AL29-4C®	S44735	0.28	9.5	5.2
	FS 10	S44800	0.28	9.5	5.4
25% Cr Duplex	SAF2507®	S32750	0.28	8.2	7.2
6% Mo Austenitic	AL6XN®	N08367	0.29	7.9	8.5
	254SMO®	S31254	0.29	7.5	8.9
7% Mo Austenitic	654SMO®	S32654	0.29	7.5	8.5

One of the typical materials used for condensers are high performance Stainless Steel materials, which are characterized by high chromium contents together with molybdenum and nitrogen. They include both austenitic and ferrite material. They were developed by companies in the US, Europe and Japan. The properties of some of the materials are listed in Table 1. These are seawater corrosion resistant materials. Of all these properties, the most important is the thermal conductivity. The thermal conductivity affects the heat transfer capability of these alloys. The higher the thermal conductivity the higher the heat transfer capability. As shown in Table 5.1, the ferrite stainless steels have higher thermal conductivity than the austenitic alloys.

CONCLUSION

From the study conducted in this Paper, following conclusions are made.

- The technology and applications of industrial condensing economizers in natural gas fired boilers is reviewed and for very useful in waste heat recovery to lowering down the stack temperature and increase the overall efficiency of boiler.
- From literature review, it is observed that corrosion-derived cracks were mostly found in the low temperature heat exchangers (typically operating at temperature between 70 and 90 Deg C) where in present study, the stack temperature will lowers down below the 70 Deg C, so the proposed exchangers need to be fabricated from Stainless steel.

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