

Feasibility Study of Sorption Heat Recovery Systems Used in Heating Appliances

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Abstract: The technical feasibility of two sorption systems used for heat recovery in conventional heating appliances has been investigated. A brief overview of knowledge on sorbents, sorption systems and fuel combustion processes is provided. An absorption system is presented and its suitability for heat recovery in this application has been analysed. Analyses of the effect of fuel type on heat recovery indicated that heating appliances fired by natural gas would result in more energy being recovered from the flue gas, and hence provide higher recovery efficiency. A simple payback period analysis showed that sorption systems would have advantages over condensing heat recovery systems in terms of their economic benefits.

Keywords: Heat recovery; Sorption; Flue Gas; Efficiency; Combustion; Moisture Contents; Dew point

1. INTRODUCTION

For any heating systems, the issue of energy recovery is important. Energy recovery increases thermal efficiency and hence reduces both fuel consumption and environmental pollution. Boilers, power stations, combined heat and power (CHP) plants and industrial dryers are examples of established technologies, which produce heat and/or power in their operations. In all cases, part of the heat energy lost due to combustion can be recovered using large heat exchangers, economizers and desuperheaters.

Limitation of dew point is a major obstacle to enhancing the efficiency of a heat recovery appliance. Using a condensing boiler allows the system to operate below the dew point and recover part of waste heat. However, a stainless steel heat exchanger has to be employed to avoid corrosion caused by acidic gases dissolved from the water, which would result in increased capital cost. Sorption technology offers an alternative approach for heat recovery. Although the capital cost of a sorption system is slightly higher than that of other heat recovery systems, this can be offset by the use of a low-cost cast iron heat exchanger. This combination offers substantial potential to recover waste heat through dehumidification of the products of combustion from any given fuel. Furthermore, it also has the potential to assist the removal of unwanted gases and toxic materials arising from combustion.

2. SORBENTS (DESICCANTS) AND THEIR CHARACTERISTICS

Sorbents can be generally classified into liquid absorbents and solid adsorbents. For liquid absorption, air is brought into contact with a liquid absorbent. As the absorbent has a vapour pressure lower than water at the same temperature, the air passing over the solution approaches this reduced

vapour pressure, and therefore is dehumidified. The behaviours of a liquid absorbent depend on its chemical composition, temperature and concentration. Commonly available liquid absorbents are lithium chloride and ammonia solutions and these all have especially high water-holding capacities^[1]. In standard practice, the absorbent temperature and concentration are adjustable, i.e., temperature controlled by simple heaters and coolers, and concentration by heating the desiccant to drive moisture out into a waste air-stream, or directly to the ambient.

A solid adsorbent has a large internal surface area per unit mass, and is able to attract moisture due to the electrostatic field at the desiccant surface. The field is not uniform in either force or charge, so specific sites on the desiccant surface attract water molecules that have a net opposite charge. When the complete surface is covered, the adsorbent can still hold more moisture because vapour condenses into the first water layer and fills the capillaries throughout the material. As with liquid absorbents, the ability of an adsorbent to attract moisture depends on the difference in vapour pressure between its surface and the air. Generally, the adsorption behaviour of a solid adsorbent depends on its total surface area, total volume of capillaries, and range of capillary diameters. A larger surface area gives the adsorbent a larger capacity at low relative humidities. Large capillaries provide a high capacity for condensed water, which gives the adsorbent a higher capacity at high relative humidities. A narrow range of capillary diameters makes an adsorbent more selective with regard to the vapour molecules it can hold^[2].

The capacity of solid adsorbents is generally less than the capacity of liquid absorbents. However, solid adsorbents do have several other favourable characteristics. Firstly, molecular sieves continue to adsorb moisture even when they are quite hot, allowing dehumidification of very warm airstreams. Secondly, several solid adsorbents can be

manufactured to precise tolerances, with pore diameters that can be closely controlled. This means they can be tailored to adsorb molecules of a specific diameter. This selective adsorption characteristic is useful in many applications. For example, several desiccants with different pore sizes can be combined in series to remove first water and then other specific contaminants from an air stream^[3].

There are several types of solid adsorbents, including silica gels, zeolites, synthetic zeolites (molecular sieves), activated aluminas, carbons, and synthetic polymers. Of these silica gels, zeolites and synthetic zeolites are mostly common used^[4].

Isotherm is a term used to define a desiccant's capacity to absorb moisture from the passing air. For any desiccant, its isotherm increases when the humidity of the passing air increases. Liquid desiccants (absorbents) have much higher isotherms than solid desiccants (adsorbents). The suitability of a given desiccant for a particular application is generally governed as much by the engineering of the mechanical system that presents the material to the airstreams, as by the characteristics of the material itself^[5].

Water sorption isotherms can also be calculated using selected theoretical models^[6], including Brunauer, Emmett and Teller (BET) equation and the Guggenheim-Anderson-deBoer (GAB) equation. The simple GAB equation relates α_w and EMC as follows:

$$EMC = \frac{X_m C_1 K \alpha_w}{(1 - K \alpha_w)(1 - K \alpha_w + C_1 K \alpha_w)} \quad (1)$$

The Arrhenius equation incorporates temperature effects into the GAB equation, relating a reaction rate constant (C_0 , K_0) with an activation energy (ΔH_c , ΔH_k).

$$C_1 = C_0 \exp(\Delta H_c / RT) \quad (2)$$

$$K = K_0 \exp(\Delta H_k / RT) \quad (3)$$

$$EMC = \frac{X_m (C_1 / T) K \alpha_w}{(1 - K \alpha_w)(1 - K \alpha_w + (C_1 / T) K \alpha_w)} \quad (4)$$

The GAB equation has been proven to be able to predict equilibrium moisture content to a reasonable accuracy.

The useful life of an absorbent (adsorbent) is a major concern in selecting a material for a desiccant system, and it depends largely on the quantity and type of contamination in the airstreams to be dried. Liquid absorbents are more susceptible to chemical reaction with airstream contaminants other than water vapour than are solid adsorbents, while solid adsorbents tend to be less chemically affected and more sensitive to clogging, depending on the type and quantity of particulate material in the airstream^[7]. In a boiler heat recovery application, desiccant equipment is designed to minimize the need for desiccant replacement, as desiccants are seldom replaced during normal service in the processing.

Desiccants, including absorbents and adsorbents, need to be regenerated before being re-circulated. This can be processed by heating them up to drive off water and then cooling them using cold mediums.

3. SORPTION SYSTEMS AVAILABLE FOR HEAT RECOVERY HEATING APPLIANCES

Sorption technology is suitable for recovering heat from the flue gas (exhaust) of commonly used heat equipment, e.g., boilers. Its major advantage lies in that the technology overcomes the limitation of dew point, a problem causing significant heat loss in conventional heating equipment. Figure 1 shows schematically the comparison of a sorption process and condensing heat recovery process on a psychometric chart. Assuming a flue gas (discharge) temperature of 50°C, the dew point would be 45°C and 25°C for the cases of condensing heat recovery and sorption recovery systems, respectively. It is found that the use of a sorption recovery system would result in an increased difference between the dew point and flue gas temperature, and so increased moisture abstraction and a reduced flow gas discharge temperature, with no dissolution of corrosive gases into the absorbed water. Furthermore, the sorption system is able to recover more heat than the condensing boiler does. In conventional gas boilers, heat transfer between the gas flame (1000°C) and circulated water (about 60°C) is carried out at a significantly high temperature difference. This is an ineffective way of using heat energy due to the considerable heat loss occurring in the process. Use of the sorption heat recovery system would lead to more effective energy utilization, as the high temperature gas flame (1000°C) is first used to heat the absorbent (to approximately 300°C), and then heat the circulated water (about 60°C), resulting in a much lower temperature difference during each of the heat transfer processes.

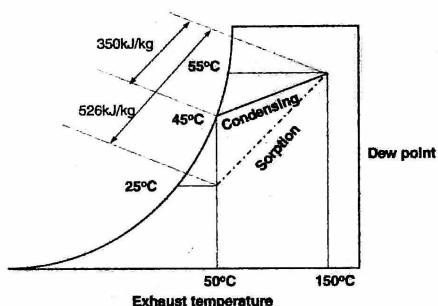


Figure 1. Comparison of a sorption process and condensing heat recovery process on a psychometric chart.

The cost of the sorption heat recovery system can be offset by using a low-cost cast iron heat exchanger. A cast iron boiler combined with a sorption heat recovery system may offer a great potential in terms of improved energy efficiency and

life cycle, which will be investigated in this proposed research.

The sorption heat recovery system could be either an absorption system or an adsorption system, or a combination of both absorption and adsorption.

Figure 2 shows a proposed absorption heat recovery system to be used with a cast iron boiler. Flue gas enters a dehumidifier where water vapour contained in the gas stream is absorbed by liquid absorbent. During the absorption process, latent heat carried by the vapour is released to the absorbent and the temperature of the absorbent rises. The diluted absorbent flows to a generator/condenser where the absorbent is heated by a high temperature gas flame for reactivation. In the process, water is driven out from the absorbent as a condensate, which is used to heat the return water. Furthermore, the absorbent from the generator is further cooled by passing it through a heat exchanger, where heat is exchanged between the desiccant and the boiler return water. The absorbent used may be aqueous lithium bromide (LiBr) or aqueous potassium formate solution. It is indicated [8] that the sorption results in a reduced dew point temperature of the exhaust flue gas, about 25°C, which is much lower than that for a condensing boiler (about 45°C), and therefore an increased boiler efficiency could be achieved. Furthermore, since the temperature of the discharged flue gas is less limited by the dew point than it is in condensing boilers, the materials used in constructing the sorption heat recovery system are less restricted by condensation and corrosion.

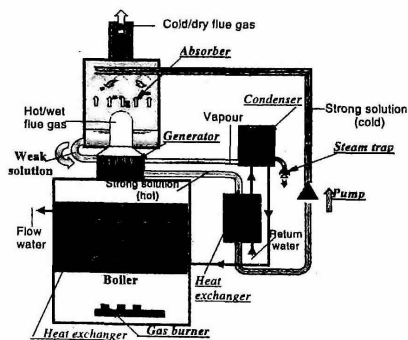


Figure 2. An absorption heat recovery system used in a cast iron boiler

Both absorption and adsorption systems have limitations when used for flue gas heat recovery. It is known that certain sulphur compounds react with LiCl to form lithium sulphate, which is not a desiccant. Hence continued operation over a period of time would result in reduced capacity for moisture absorption. This type of absorption system may therefore be less suitable for flue gas heat recovery from a life cycle point of view. However, as this system could remove sulphur-related products from a flue gas exhaust, it may be suitable for use with coal-fired boilers where sulphur compounds are produced

by the combustion of coal in the furnace [9]. This process would therefore provide environmental benefits in addition to the heat recovery. The techno-economics of such a system would need to be investigated in comparison with conventional flue gas desulphurisation techniques plus conventional heat recovery.

Adsorption systems may be more suitable for flue gas heat recovery than absorption systems as they are chemically more stable and easier to manufacture. Of the adsorbents referred to here, molecular sieve (synthetic zeolites) or zeolites may be the most suitable substances to use as they can adsorb moisture even when they are quite hot, allowing dehumidification of very warm airstreams, such as flue gas. In addition, pore diameters can be selected during manufacture to avoid clogging by large particles in the airstreams. To remove elements, such as CO₂, CO, SO₂, O₂, N₂, NO_x, microporous carbons could be incorporated into the adsorbent bed [10].

4. FUEL COMBUSTION CHARACTERISTICS FOR HEATING APPLIANCES

Hydrocarbons are commonly used as fuels for heating equipment, and are generally classified according to their physical state (gas, liquid, or solid). Different types of combustion equipment are used to burn fuels in the different physical states. Gaseous fuels can be burned in premix or diffusion burners. Liquid fuel burners include a means for atomising or vaporizing fuel into small droplets or a vapour, and must provide adequate mixing of fuel and air. Solid fuel combustion equipment must heat the fuel to vaporize sufficient volatiles to initiate and sustain combustion, provide residence time to complete combustion, and provide space for ash containment.

5. CONDENSATION AND CORROSION OF HEAT APPLIANCES

Fuel-burning systems that cycle on and off to meet demand, cool down during the off-cycle. When the appliance starts again, condensate forms briefly on surfaces until they are heated above the dew point. Low temperature corrosion occurs in system components (heat exchangers, flues, vents, chimneys) when their surfaces remain below the dew-point temperature of the flue gas constituents (water vapour, sulphides, chlorides, etc.) long enough to cause condensation. Corrosion increases as condensate dwell time increases.

Condensation and corrosion can be prevented using several methods, including maintaining flue gas temperature at a higher level, employing a condensing boiler rather than a conventional cast iron boiler, as well as incorporating a sorption device in the chimney to reduce moisture content as well as the concentration of toxic gases in the flue gas. These methods are useful in practical applications but may give rise to some other problems. For example, increasing flue gas temperature will result in reduced boiler efficiency, and so increased heat loss. Use of a condensing boiler allows condensation of the moisture and recovery of the condensed heat from

the flue gas before the flue gas is delivered to the chimney. This maintains boiler efficiency, as well as reduces condensation and therefore the incidence of corrosion in the chimney. This practice however, will lead to an increase in boiler cost due to inclusion of an additional heat exchanger made of a corrosion-resistance material.

6. PERFORMANCE ANALYSIS OF THE SORPTION HEAT RECOVERY SYSTEM

This analysis is based on a combined boiler/absorption system, which is presented in Figure 2. The boiler is made of cast-iron and has efficiency in the range 80% to 85%, at standard operation condition (without sorption system). The fuels available for this system are limited to natural gas and liquefied petroleum gases, including natural gases with high, medium and low heat values, commercial pentane, commercial butane and commercial mixtures of pentane and butane. Principle of fuel combustion and data of fuel characteristics are detailed in Refs 11, 12 and 13, and the compositions of the fuels and resultant flue gas are indicated in Table 1. A sorption system is fitted closely with the boiler and use LiCl as the working solution. The absorber bed is incorporated with the boiler chimney where moisture from boiler flue gas is extracted and its temperature reduced subsequently. The LiCl solution absorbs the moisture and become a weak solution, which is passed through a heat exchanger (i.e., generator) to allow the moisture vaporised, thus resulting in a hot strong solution. Both the hot solution and the vapour driven out of the solution are used to pre-heat the boiler return water by passing them through a heat-exchanger and a condenser, with one for each. Thus the heat taken from the boiler flue gas is completely utilised and the purpose of heat recovery achieved. The solution out of the heat exchanger becomes cold and so is able to absorb flue gas moisture again, and the vapour condensed after coming out the condenser.

Air required for combustion is calculated for each type of fuel using the method indicated in Ref. 13, by assuming the excess air of 15%, and the results are summarised in Table 1. Variation of the ratio of the excess air affects boiler operating performance and sorption dehumidification, and this is investigated in this section.

The constituents of the flue gas for the cases investigated are also presented in Table 1. With natural gases, larger quantities of flue gas are generated, and correspondingly, the flue gas energy losses are higher, compared to the liquefied gases. This means that more energy is potentially recoverable from the flue gas using sorption technology.

The moisture contents and dew points of the flue gases arising from the combustion of selected fuels are presented in Figure 3. It was found that both the moisture content and dew point of the flue gases are higher in the case of natural gases, and lower for the case of liquefied petroleum gases. A sorption system works more effectively under high moisture conditions,

and hence the system is more suitable for the natural-gas fired situations.

The variation of boiler efficiency with fuel type is shown in Figure 4. It can be seen that the efficiencies for the natural-gas fired cases are lower than those for the liquefied-gas fired appliances. Since a sorption system can absorb moisture more efficiently when the boiler operation efficiency is lower, the system is more suitable for the natural-gas fired situations.

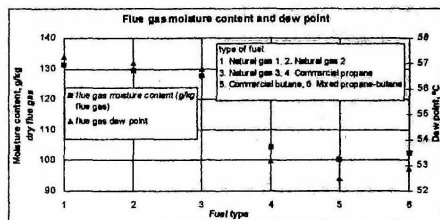


Figure 3. Summary of fuel combustion results – flue gas moisture content and dew point

A sorption system can be designed to absorb moisture at rates varying from 10% to 90%, or even more, by selecting a suitable absorbent (adsorbent), solution temperature and concentration, as well as system configuration. The action of sorption will result in reduced dew point and moisture content of the flue gas, and so reduced flue gas energy loss and increased boiler efficiency. The greater the moisture absorbed, the less the flue gas energy loss, and the higher the boiler operating efficiency, as shown in Figure 5 and 6.

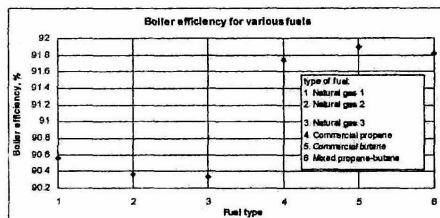


Figure 4. Variation of boiler efficiency with type of fuel used

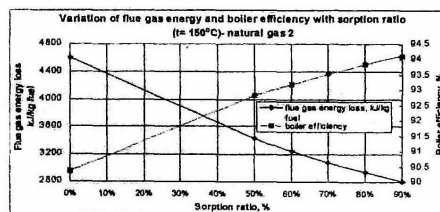


Figure 5. Variation of flue gas energy loss and boiler efficiency with sorption ratio (t=150°C) – natural gas 2

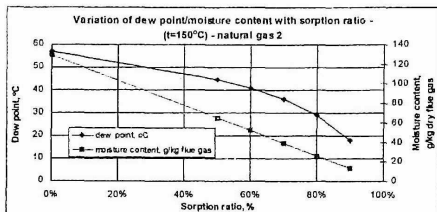


Figure 6. Variation of dew point/moisture content with sorption ratio ($t=150^{\circ}\text{C}$) – natural gas 2

The sorption will also enable reduced operating temperature due to reduction of the dew point, and this will result in increased boiler efficiency, as shown in Figure 7.

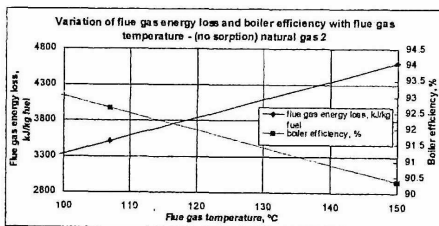


Figure 7. Variation of flue gas energy loss and boiler efficiency with flue gas temperature

7. LIFE-CYCLE COSTS AND PAYBACK PERIOD FOR THE PROPOSED TECHNOLOGY

A simple analysis to indicate the energy/environmental benefits, life-cycle cost and payback period of the absorption heat recovery system has been carried out by comparing the primary energy consumption of the combined sorption/boiler system with that of conventional boiler and condensing boiler systems. The results are outlined in Table 2. The analysis assumes that each system has a fixed output (Q_0) of 80kW. The conventional boiler and condensing boiler systems were assumed to operate on the same basis to enable comparison. Thus the gas energy required for each type of boiler can be written as:

$$Q_{\text{gas}} = \frac{Q_0}{\eta} \quad (5)$$

where η is the efficiency of the boilers. For the conventional and condensing boilers, the values are given as 83% and 93% respectively [14]. Use of sorption-dehumidification heat recovery may result in an increase in efficiency of up to 12% over a conventional boiler, giving an operating efficiency of 95%.

Assuming the annual operation period (h) of 1750 hours (about 20% of the year time), the annual

gas energy consumption of the selected systems (En_a) can be calculated using the following equation:

$$En_a = Q_{\text{gas}} h \quad (6)$$

The conversion factor between the consumed gas energy and the CO_2 emission is given as 0.19 kg/kWh [15]. Thus the annual CO_2 emission for the selected system can be written as

$$Em_{\text{CO}_2} = 0.19 En_a / 1000 \quad (7)$$

The heating systems are assumed to be fired by natural gas, which costs about (p) £0.009/kWh [16]. The annum cost of the gas consumption can be written as

$$C_{\text{gas}} = 0.009 En_a \quad (8)$$

The absorption heat recovery apparatus has life-cycle time of 30 years, and its annual maintenance cost is 5% of the capital investment [17]. Compared to the conventional boiler system, the payback period (pp_{sorp}) can be written as

$$pp_{\text{sorp}} = \frac{C_{p_{\text{sorp}}} - C_{p_{\text{con}}}}{(C_{\text{gas,con}} - C_{\text{gas,sorp}}) + (C_{m_{\text{con}}} - C_{m_{\text{sorp}}})} \quad (9)$$

where C_p is the capital cost, and C_m is the annum maintenance cost. The payback period of condensing boiler (pp_{con}) can be obtained using similar method.

Based on the above analysis, a calculation is made which is detailed in Table 2. The results shows that the sorption system would save approximately 31,300kWh and 3,200kWh of primary energy per annum compared to conventional and condensing boiler systems respectively, and this would result in a reduction of CO_2 emission of up to 10 tonnes and 1.5 tonnes, respectively. The savings of gas cost would be approximately £165 and £30 per annum compared to the cost of conventional and condensing boiler operation, respectively. Compared to the conventional boiler system, the payback period of the sorption system would be 2.99 years, which is 0.63 year less than a typical condensing boiler system.

8. CONCLUSIONS

Sorption technology offer advantages over conventional heat recovery systems in that it overcomes the limitation of dew point, a major obstacle to enhancing the efficiency of heat recovery appliances. This would provide the potential to recover waste heat through dehumidification of the products of combustion from any particular fuel. Furthermore, it has also the potential to remove unwanted gases and toxic elements from the flue gas stream. Both adsorption and absorption systems are suitable for this application.

A sorption system can work more efficiently at high moisture and high dew point conditions. Since natural gases produce larger quantities of flue gases which contain larger amount of energy and moisture and have higher dew points than the liquefied petroleum gases, sorption technology is more suitable for natural gas fired appliances.

A sorption system can be designed to absorb moisture at different rates, by selecting a suitable absorbent (adsorbent), solution temperature and concentration, as well as system configuration. Sorption results in reduced dew point and moisture content of the flue gas, and so reduced flue gas energy loss and increased boiler efficiency. The more moisture absorbed, the lower the flue gas energy loss, and the higher the boiler operating efficiency. Sorption also reduces the flue gas discharge temperature due to the reduction of the dew point, and so improves boiler efficiency.

A sorption system has better economic and environmental benefits than a condensing boiler system.

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NOMENCLATURE

C = mass of carbon per unit of mass of fuel, corrected for carbon in ash, kg/kg of fuel
 CO, CO₂ = carbon monoxide and carbon dioxide in flue gases, % by volume
 C₁ = constant related to heat of sorption of the first layer
 C₀, K₀ = reaction rate constants
 C_{gas} = the annual cost of gas consumption of the selected boiler system, £/annum
 C_m = annual maintenance cost of the selected boiler system, £/annum
 C_p = capital cost of the selected boiler system, £
 c_{pg} = mean specific heat of flue gases as constant pressure, kJ/kg.K
 EMC = equilibrium moisture content, g/kg of dry sorbent
 Em_{CO2} = annual CO₂ emission for the selected boiler system, tonne
 E_{na} = annual gas energy consumption of the selected boiler system, kWh/annum
 h = boiler annual operation hours, h
 (h)_{lg} = enthalpy of superheated steam at flue gas temperature and 101.3kPa, kJ/kg
 (h)_{la} = enthalpy of saturated water vapour at air temperature, kJ/kg
 (h)_{la} = enthalpy of saturated steam at combustion air temperature, kJ/kg
 H₂ = hydrogen in fuel, % by mass
 K = factor related to heat of sorption of the multilayers
 M = humidity ratio of combustion air, mass of water vapour per mass of dry air
 m_a = mass of combustion air per mass of fuel used, kg/kg of fuel
 m_g = mass of dry flue gas per mass of fuel, kg/kg of fuel
 pp = payback period, year
 q₁ = useful heat, kJ/kg of fuel
 q₂ = heat loss in dry flue gases, kJ/kg of fuel
 q₃ = heat loss in water vapour from combustion of hydrogen, kJ/kg of fuel
 q₄ = heat loss in water vapour in combustion air, kJ/kg of fuel
 q₅ = heat loss from incomplete combustion of carbon, kJ/kg of fuel
 q₆ = heat loss from unburned carbon in ash, kJ/kg of fuel
 q₇ = unaccounted for heat losses, kJ/kg of fuel
 q_h = the higher value of per kg fuel gas
 R = universal gas constant (8.314 J/mol · K)
 T = absolute temperature, K
 t_a = temperature of combustion air, °C
 t_g = temperature of flue gases at exit of heating device, °C
 X_m = monolayer moisture content, g/kg of dry sorbent
 α_w = water activity
 η = boiler efficiency
 ΔH_c, ΔH_k = activation energies