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# Condensing boiler applications in the process industry

Qun Chen *, Karen Finney, Hanning Li, Xiaohui Zhang, Jue Zhou, Vida Sharifi, Jim Swithenbank

*SUWIC, Department of Chemical & Process Engineering, Sheffield University, United Kingdom*

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ABSTRACT

Major challenging issues such as climate change, energy prices and fuel security have focussed the attention of process industries on their energy efficiency and opportunities for improvement. The main objective of this research study was to investigate technologies needed to exploit the large amount of low grade heat available from a flue gas condensing system through industrial condensing boilers. The technology and application of industrial condensing boilers in various heating systems were extensively reviewed. As the condensers require site-specific engineering design, a case study was carried out to investigate the feasibility (technically and economically) of applying condensing boilers in a large scale district heating system (40 MW). The study showed that by recovering the latent heat of water vapour in the flue gas through condensing boilers, the whole heating system could achieve significantly higher efficiency levels than conventional boilers. In addition to waste heat recovery, condensing boilers can also be optimised for emission abatement, especially for particle removal. Two technical barriers for the condensing boiler application are corrosion and return water temperatures. Highly corrosion-resistant material is required for condensing boiler manufacture. The thermal design of a "case study" single pass shell-and-tube condensing heat exchanger/condenser showed that a considerable amount of thermal resistance was on the shell-side. Based on the case study calculations, approximately 4900 $m^2$ of total heat transfer area was required, if stainless steel was used as a construction material. If the heat transfer area was made of carbon steel, then polypropylene could be used as the corrosion-resistant coating material outside the tubes. The addition of polypropylene coating increased the tube wall thermal resistance, hence the required heat transfer area was approximately 5800 $m^2$. Net Present Value (NPV) calculations showed that the choice of a carbon steel condenser ensured cash return in a relatively shorter period of time (i.e. 2 years) when compared to a stainless steel condenser (i.e. 5–7 years). Moreover, the NPV for the stainless steel was more sensitive to the change of the interest rate.



## 1. Introduction

Flue gases from waste to energy plants often contain 15–40% of the fuels' heat content. This heat is available over the range of temperature from 30 °C to 250 °C although the upper level may often be lower. Though waste heat can be recovered, little effort has been made to do this, as it can be difficult to utilise low-temperature heat and counteract corrosion. However, modern condensing natural gas fired domestic boilers are designed to recover this energy by use of suitable materials that avoid corrosion of the wet heat transfer surfaces [1]. In the case of domestic heating, the boiler efficiency is typically increased from 75% to 90%, i.e. the cost/energy saving is about 15% and there is a corresponding reduction in $CO_2$ emissions [2].

Industrial combustion systems are used predominantly for process heating or power production. The combustion usually takes place in a steam boiler fitted with a super-heater and economiser. These are followed by an air heater to preheat the combustion air, and its exit temperature is maintained above the acid dew point to avoid corrosion from the condensate and to ensure buoyancy of the flue gases. However, the industrial situation is now changing with the progressive requirement to use scrubbers and filters to remove acids and particulates from the exhaust, and it is timely to assess the new situation. Similarly to domestic condensing boilers, by the use of suitable materials (PTFE, aluminium, etc.) the exhaust could be cooled to about 30 °C with the recovery of both latent and sensible heat. In the case of natural gas, which contains a significant proportion of hydrogen in the molecule, this heat represents about 15% of the energy. In the case of biomass such as wood chips, this heat represents 6–8% of the fuel calorific value due to the hydrogen in the fuel and up to half the calorific value of the raw fuel due to its 50% moisture content. Thus recovery of energy by condensing the flue gases can recover both the energy due to the moisture in the feed and the water due to the hydrogen

* Corresponding author. Address: Department of Chemical & Process Engineering, Sheffield University, Mappin Street, Sheffield S1 3JD, United Kingdom. Tel.: +44 (0) 114 222 7563; fax: +44 (0) 114 222 7501.
*E-mail address:* q.chen@sheffield.ac.uk (Q. Chen).

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content of the fuel. The fact that one device can recover both components suggests that this is a preferable strategy to drying the feed and using two separate devices.

Sheffield University Waste Incineration Centre (SUWIC) has conducted an extensive literature review of industrial condensing boilers, looking into various technologies and the associated costs. In addition, extensive calculations have been carried out as part of a case study to investigate the thermal design of a condensing boiler in a large scale district heating plant (40 MW). This paper presents the results obtained from the above studies.

## 2. Industrial condensing boilers and their applications

Combustion in air yields water vapour and $CO_2$. Conventional boilers transfer most of the sensible heat of this reaction to hot water or steam, whereas condensing designs capture the latent heat – the energy released by condensing the vapour; extracting this heat achieves higher efficiencies.

### 2.1. Flue gas condensers

The application of condensers to recover latent heat from flue gas is wider than stand-alone gas-fired condensing boilers, for power plants and commercial/industrial facilities. In general, there are two types of condensers: indirect and direct contact. Indirect contact condensers recover the latent heat by passing gas through condensing heat exchangers [3]. These can be sub-categorised into pipe condensers, lamella condensers and combi condensers [4]. The second option, direct contact condensers, consist of a vapour-conditioning chamber and a counter-current spray chamber, in which small droplets of cool liquid come into contact with the hot flue gas, providing a non-fouling heat transfer surface. The droplets cool, condense and remove water vapour. To improve contact between the spray and gas, the chamber may be equipped with packing. This offers high heat transfer and water recovery capabilities. Such condensers require site-specific engineering design and an understanding of their effects on the system.

### 2.2. Advantages of condensing boilers

#### 2.2.1. Latent heat recovery

Latent heat recovery is the most significant advantage of condensing boilers, greatly improving thermal efficiency. Fig. 1 shows this for a wood chip boiler with a condensing heat exchanger at different excess air ratios ($\lambda$). The fuel (wood chips) used in the boiler has 50% moisture content. As shown, the heat exchanger recovers the latent heat of the moisture when it is condensed, resulting in efficiencies exceeding 100% with reference to the lower heat value

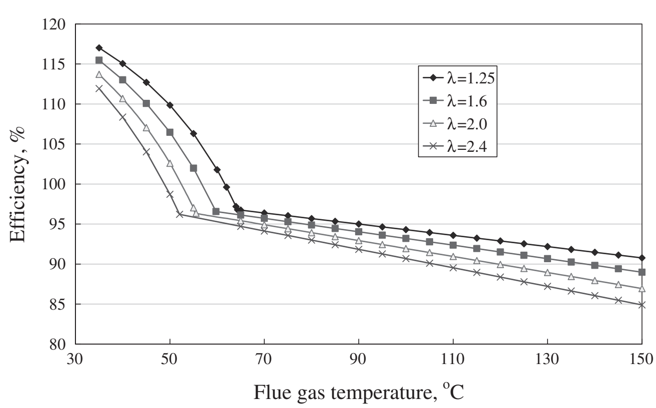


**Fig. 1.** Theoretical efficiency of a boiler/condenser changing with exit flue gas temperature.

of the fuel. On the other hand, increasing $\lambda$ decreases the vapour partial pressure in the gas and lowers its dew point; more sensible heat is carried by non-condensable gas, less vapour is condensed under higher $\lambda$ and at the same temperature, higher $\lambda$ lead to lower efficiencies.

#### 2.2.2. Emission abatement

Flue gas condensers can also reduce flue gas emissions, providing several environmental benefits. The condensate forms a constant film that can remove large particles and dissolve most of the highly dissociated inorganic matter, such as sulphuric acid, and chlorides [5]. Combustion generates fine particles, contributing significantly to energy sector emissions [6]. Sippula et al. [7] studied emissions of four wood chip-fired district heating units. All were equipped with cyclones to remove coarse particles. One had a condensing flue gas scrubber, which removed 44% of $PM_1$ and 84% of total solid particles, resulting from thermophoresis (induced by the temperature gradient between the gas and the surface) and diffusiophoresis (caused by steam condensing on cool surfaces). Other separation mechanisms include inertial impaction and gravitational settling for large particles and Brownian diffusion for small particles. Particle sizes grew inside the scrubber, causing a shift in the particle size distribution [7].

### 2.3. Technical barriers of condensing boilers and potential solutions

#### 2.3.1. Corrosion

Corrosion by corrosive combustion products causes cracks in low-temperature steel heat exchangers, where mechanical stresses are high [8]. Microscopic analyses reveal inter-granular corrosion, showing complete material grains becoming detached. The amount and composition of condensate needs to be known to avoid this [8,9]. To reduce corrosion and capture latent heat, condensing boilers need corrosion-resistant fabrication materials, careful installation and sophisticated controls. The specialised materials and terminal units are expensive and the installation costs are higher than conventional boilers [10]. Characterised by austenitic/ferritic material and high Cr, Mo and N contents, a typical material is high-performance steel. The most important material property is high thermal conductivity, as it increases heat transfer.

#### 2.3.2. Return water temperature

Return water temperature is the critical factor in the operation of heating systems [10]. Heat sinks are required to capture latent heat, which determines the boiler efficiency; less vapour is condensed at high temperatures, decreasing efficiency [11]. The return water serves as a heat sink in district heating systems; moisture condensation from the gas requires them to be cooled below their dew point, 55–65 °C for natural gas. The return water temperature from a central heating system must be about 30 °C. This requires an under-floor heating system or a high surface area of the radiators in the building. Similar considerations apply to district heating schemes if the latent heat of the moisture is to be recovered from the flue gases.

If the return water is not cool enough to directly serve as a heat sink, heat pumps can be coupled with condensing boilers in the application. A heat pump is a device that moves heat from a low temperature ‘source’ to a higher temperature ‘sink’. There are two main types: compression and absorption heat pumps. A compression heat pump is composed of a compressor, expansion valve and heat exchangers (evaporator and condenser) with a volatile working fluid circulating through the components in a closed circuit. In the evaporator, the heat source heats and evaporates the working liquid. The vapour is compressed to a higher pressure and temperature and enters the condenser, where it condenses to give off heat. The high-pressure fluid returns to its original state,