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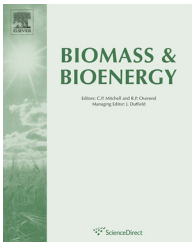

Techno-economic study of a heat pump enhanced flue gas heat recovery for biomass boilers

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ABSTRACT

An active condensation system for the heat recovery of biomass boilers is evaluated. The active condensation system utilizes the flue gas enthalpy exiting the boiler by combining a quench and a compression heat pump. The system is modelled by mass and energy balances. This study evaluates the operating costs, primary energy efficiency and greenhouse gas emissions on an Austrian data basis for four test cases. Two pellet boilers (10 kW and 100 kW) and two wood chip boilers (100 kW and 10 MW) are considered. The economic analysis shows a decrease in operating costs between 2% and 13%. Meanwhile the primary energy efficiency is increased by 3–21%. The greenhouse gas emissions in CO_2 equivalents are calculated to 15.3–27.9 kg MWh^{-1} based on an Austrian electricity mix. The payback time is evaluated on a net present value (NPV) method, showing a payback time of 2–12 years for the 10 MW wood chip test case.

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1. Introduction

1.1. Background

In Europe, biomass is the dominating renewable source for residential heating and hot water production. Today 80% of the total energy consumption of households in the EU-27 is required for heating (67%) and hot water provision (13%) [1]. During the last decade, biomass boilers have made a major comeback due to increasing prices for fossil fuels and the renewable character of the fuel. In particular the introduction of automatic boilers based on pellet and wood chips has made biomass boilers convenient to use and thus a low CO_2 alternative to fossil fuelled ones. In fact, from 2004 to 2010 biomass boiler sales increased by 84% in the EU [2]. In 2007 the total number of biomass boilers installed is estimated at 8 million. For example, in Austria 10,000 pellet, 6000 log wood, and 4000

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Nomenclature

COP	coefficient of performance (heat pump) [–]
d	interest rate [–]
GCV	gross calorific value [J kg^{-1}]
h	specific enthalpy [J kg^{-1}]
K	costs [€]
$\dot{m}$	mass flow [kg s^{-1}]
n	time [a]
NCV	net calorific value [J kg^{-1}]
NPV	net present value [€]
P	power [J s^{-1}]
$\dot{Q}$	heat flow [J s^{-1}]
r	inflation rate [–]
t	time [a]
T	temperature [K or °C]
w	weight fraction [–]
x	water content of the flue gas (per dry mass) [–]
η	efficiency [–]

subscripts

b	boiler
Ca	Carnot
cw	water circulating between quench and heat pump
e	electric
f	fuel
fg	flue gas
fgd	dry flue gas
g	gaseous
hp	heat pump
i	installation
l	liquid
m	maintenance
q	quench
rf	return flow
t	time [a]
tot	total (system)
wb	wet based

superscripts

sat	saturated

wood chip boilers with a nominal heat output up to 100 kW and 700 biomass boilers with a nominal heat output >100 kW were installed in 2011 [3].

Today small-scale biomass boilers for heating and hot water provision are highly efficient. State of the art boilers reach efficiencies of 85%–89% (pellets) and 73%–81% (wood chips) under testing conditions based on the gross calorific value [4]. Nevertheless these boilers do have losses that mainly originate from the thermal energy of the flue gas, which leaves the boiler at temperatures of 70–200 °C, depending on the boiler technology. These losses can be divided into the sensible heat of the flue gas and the latent heat of the water vapour in the flue gas. The sensible heat losses depend nearly linearly on the temperature of the flue gas. In contrast, the latent heat can only be recovered if the flue gas is cooled down below the dew temperature of the water vapour in the flue gas.

In the field of oil and especially gas burners, condensing heat exchangers are a state of the art technology. Energy efficiency enhancements of 10–14% for gas and 5–7% for oil burners based on the net calorific value (NCV) are achievable [5]. For an application of these heat exchangers in biomass boilers corrosion and fouling poses a challenge. Some condensing heat exchangers for small scale biomass boilers exist [6]. These heat exchangers are either integrated into commercially available boilers or can be retrofitted to existing ones. Ceramics, carbon and stainless steel are applied as heat exchanger materials to avoid corrosion. Most of the heat exchangers need to be cleaned periodically because of fouling. Using these heat exchangers flue gas temperatures of 5–20 °C above the return flow temperature can be reached. An example is introduced in Ref. [7], which enhances the energy efficiency to 103% (+12%) based on the NCV. This improvement is valid for a return temperature of 35 °C. For biomass boilers with a nominal thermal output ≥100 kW a variety of flue gas condensation systems has already been installed [6]. State of the art CHP and district heating plants usually contain an internal heat recovery system including an air preheater, economizer, etc. Additionally these systems do not only focus on the energetic efficiency but also on cleaning the flue gas from fly ash, particulate matter and condensable gaseous air pollutants with scrubbers or filters. Furthermore some systems perform a devaporization. These facilities are usually individually adapted to the actual plant design (e.g. Ref. [8]). They are cost intensive and show a large space need.

Fig. 1 shows the efficiency (NCV based) of a boiler, counting only flue gas losses. As can be seen, the efficiency strongly increases if the flue gas is cooled below the dew point, which is between 40 and 60 °C, depending on the fuel moisture content. To regain the enthalpy contained in the flue gas, a heat sink below the dew temperature is needed, but this is usually not available because the return flow temperature of the heating system is too high. Integrating a heat pump with a sink temperature lower than the return flow overcomes this limitation.

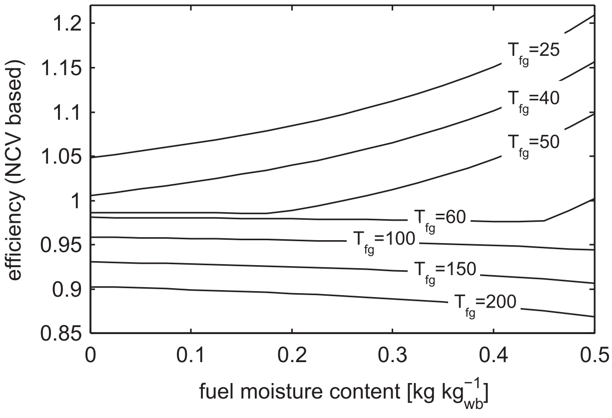

Fig. 1 – Efficiency (heat output per fuel energy input) of a biomass boiler depending on flue gas temperature T_{fg} and fuel moisture content (air stoichiometry is 1.5, dry biomass composition is $C_{0.5}O_{0.44}H_{0.06}$, all inputs at 25 °C, only water condensation, no other losses being considered).

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