Energy and Buildings 43 (2011) 2320–2328

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

A novel water heater using injected hydrogen combustion exhaust

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ARTICLE INFO

Article history:
Received 26 July 2010
Received in revised form 22 April 2011
Accepted 28 May 2011

Keywords:
Combustion
Energy conversion
Fluid flow
Gas turbines
Heating
Hydrogen
Oxygen
Thermal power generation
Water heater
Water heating

ABSTRACT

With the aim of mitigating the necessity of water storage when using electric heaters and the losses and pollutant emissions produced by natural gas heaters, this article proposes a water heater based on a gas turbine system, fed with hydrogen and oxygen obtained by electrolysis within the same unit.

By applying a thermodynamic analysis to the whole process, a global energy efficiency of 100% can be obtained. This high efficiency makes sense because the electrolysis losses occur in the form of heat losses, which can be used by the cold water. Because the potential of the electrolysis increases, the heat generation due to the electrolysis heat losses increases and, although the electrolysis efficiency is reduced, the global energy efficiency of the water heater remains at 100%. However, the increase in the electrolysis potential also reduces the response speed of the heater, because of the switch in both convection and conduction heat transfer. Convection heat transfer takes place when the combustion exhaust is injected directly in the cold water flow, downstream of the turbine, avoiding the losses associated with a heat exchanger and a high-temperature exhaust. The electrolysis heat losses are transferred to the water by conduction through the electrolyser walls.

1. Introduction

Domestic water heating represents a not inconsiderable part of the total energy consumption in buildings. For example, a study developed by Ndiaye [1] mentioned that 13% of the total energy consumed in residential buildings in Oshawa (Canada) is used to heat water.

To introduce the context of this work, an overview of the heaters (also called boilers) used currently is presented. The more common water heating alternatives used in buildings are combustion heaters (usually fed with natural gas, but they may also operate with fuel, biomass, etc.), electric storage water heaters, and solar water heating systems. Fuel cells have been proposed to combined heat and power generation (CHP) within building facilities.

The most common combustion water heaters used at present are natural gas water heaters. In this type of heater, a gas–water heat exchanger transfers the heat content in the exhaust gas to the cold water (Fig. 1). The efficiency of a conventional natural gas-fired boiler is approximately 90% [2], and it can be improved by adding a condensing heat exchanger to recover the latent heat of the steam entrained in the flue gas. The efficiency of condensing water heaters is approximately 95% [2]. A study developed by Che et al. [2] explains and compares these technologies. Condensing water heaters have several disadvantages: pollutant emissions, damage risks associated with the transport infrastructure, and the high cost of amortisation and maintenance of this infrastructure. The exit exhaust gas temperature (200 °C for the conventional heater and 50 °C for the condensing heater) causes a significant amount of heat energy losses, especially in the case of conventional gas heaters. In addition, combustion gas heaters start up slowly, using a large amount of water (several litres in a few seconds) until the steady-state regime is reached (when the heat exchanger achieves the steady-state regime temperature).

An electric storage water heater uses electric elements to heat the water. The use of electric resistance involves a slower time rate of response. Because of this, the system includes a storage tank, with the associated heat losses through the walls. The electric elements work intermittently to compensate for these losses. A study developed by Sowmy and Prado [4] shows an average energy efficiency of 75% (from 62% to 85%), considering standby heat losses and the need for technological improvements. Stratification and running out of warm water are problems associated to this technology. To supply additional energy in case the warm water supply is depleted, there are hybrid systems with both gas and electricity, such as shown in Fig. 2. The water heater that uses injected hydrogen combustion exhaust can replace the complementary gas system, making the same features possible without the need for a gas infrastructure.

Solar thermal collectors present a great advantage because the primary energy used is free and not a pollutant (zero emission),

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0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2011.05.024

Nomenclature

ΔG_e	change in Gibbs free energy of the electrolysis process (kW)
$\Delta \bar{g}_f$	change in Gibbs free energy of formation (kJ mol^{-1})
ΔH_e	change in enthalpy of the electrolysis process (kW)
$\Delta \bar{h}_f$	change in enthalpy of formation (kJ mol^{-1})
ΔH_w	increase of the water enthalpy (kW)
CFD	computational fluid dynamics
CHP	combined heat and power
$c_{p\,w}$	specific heat capacity of the water at constant pressure (kJ kg^{-1} K^{-1})
E	electrolysis electrical energy demand (kW)
HHV_{H_2}	hydrogen higher heat value (kJ kg^{-1})
$H_{w\,in}$	enthalpy of the water upstream (kW)
$H_{w\,out}$	enthalpy of the water downstream (kW)
LHV_{H_2}	hydrogen lower heat value (kJ kg^{-1})
$\dot{m}_{exhaust}$	exhaust mass flow (kg s^{-1})
$\dot{m}_{H_2}$	hydrogen mass flow (kJ kg^{-1})
$\dot{m}_w$	warm water mass flow (kJ kg^{-1})
η	global energy efficiency of the water heater
η_e	electrolysis efficiency
PEM	proton exchange membrane
Q_{comb}	heat generated at the combustion reaction (kW)
$Q_{comb\,chamb}$	heat transferred through the combustion chamber walls (kW)
Q_{conv}	convective heat transferred from the exhaust gas (kW)
Q_{irr}	heat generation due to irreversibilities of the PEM electrolyser (overpotential losses) (kW)
$Q_{loss\,elect}$	electrolyser heat losses through the walls (kW)
$T_e \Delta S_e$	thermal energy demand of the electrolysis process, due to entropy generation (kW)
$T_e \Delta \bar{s}_f$	thermal energy demand of the electrolysis process, due to the entropy of formation (kJ mol^{-1})
$T_{w\,in}$	cold water temperature upstream (°C)
$T_{w\,out}$	warm water temperature downstream (°C)
V_{ideal}	ideal electric potential of the PEM electrolyser (V)
V	real electric potential of the PEM electrolyser (V).

but this source is discontinuous and usually insufficient to satisfy the warm water demand of a residential building. Because of both these and the heat losses throughout the storage tank walls [6], an external contribution of energy is necessary, which can be made by the water heater using injected hydrogen combustion exhaust (Fig. 3).

Currently, a new technology for heat production by means of a CHP (combined heat and power) fuel cell, which simultaneously produces electricity and heat, is being developed [7]. This system can be fed with hydrogen, natural gas, ethanol, etc. If natural gas or another hydrocarbon is used (using a reformer) as the combustible fuel, as in the example shown in Fig. 4, although the system will be highly efficient, pollutant gas emissions will also take place. The use of CHP fuel cells is very interesting because of their high efficiency (above 90%), but if only electricity or only heat is demanded (or the CHP demand point is out of the range of the fuel cell), the efficiency shrinks, especially if the system is insulated. The fuel cell CHP systems require a complementary energy source. Through injection of hydrogen combustion exhaust, a water heater can operate in tandem with a fuel cell, supplying energy in peak-load and unsteady periods.

With the aim of overcoming the disadvantages mentioned above, this article proposes a water heater that operates by injection of hydrogen combustion exhaust. A conceptual residential building application of this heater is described in the next section. Section 3 details the thermodynamic analysis (both a first law-based thermodynamic analysis applied to the heat and mass transfer, and a combined first and second law-based thermodynamic analysis applied to the electrolysis process). Section 4 presents the influence of the electrolysis electric potential on the most important thermodynamic parameters. A Sankey energy diagram clearly shows the energy flow throughout the process. Section 5 comments on the advantages of the proposed heater and gives advice about future steps.

2. Description of the heater

This water heater is a device based on the gas turbine cycle configuration [9]; the combustion reaction is fed with both hydrogen and oxygen. These are generated by electrolysis of water fed from the water supply network. Because the product of the combustion is high temperature steam, it can be injected directly into the cold water flow (heat and mass transfer), avoiding both heat exchanger and hot exhaust emission losses. Fig. 5 shows a conceptual design of the water heater using injected hydrogen combustion exhaust.

The operation cycle starts upstream, with the electrolysis water intake. This water is treated by means of a filtering process before being fed to the electrolysis process. Hydrogen and oxygen detach from the electrodes, and both accumulate in the top of the proton exchange membrane (PEM) electrolyser, from which both are extracted and directed to the combustion chamber. To allow elasticity between the electrolysis and the combustion process, there are both hydrogen and oxygen supply buffers. If an auxiliary storage device is available, the combustion reaction could be fed to this storage facility, which would act as a buffer. If a hydrogen supply network is available or the building has a centralised hydrogen production facility, the electrolysis system could be removed, and the combustion reaction could be fed directly with the hydrogen source [10].

The compressors and the turbine only have the function of combustion control and regulation to guarantee the flow. An electric motor/generator is coupled to govern the power axis. Neither the losses from increasing the power nor the energy generated by reducing the power are taken in consideration in the calculations because steady flow is assumed. Likewise, the hydrogen production is controlled by the electrolyser electric current.

Within the combustion chamber, a spark begins the combustion reaction. Hydrogen and oxygen react to produce high-temperature steam. The first heat transfer takes place through the walls of the combustion chamber. The steam (a product of the combustion) is injected directly into the cold water flow, transferring heat and mass to the cold water, warming it up. The heat and mass transfer avoids the need for a heat exchanger and the losses due to hot exhaust emissions.

Furthermore, the water heater with injected hydrogen combustion exhaust is a zero pollutant emission device.

A thermodynamic analysis of the whole cycle is conducted below.

3. Methodology

To study the global efficiency of the heater, a first law-based thermodynamic analysis is applied to the heat and mass transfer, and combined first and second law-based thermodynamic analysis is applied to the electrolysis process.