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On the development of an innovative gas-fired heating appliance based on a zeolite-water adsorption heat pump; system description and seasonal gas utilization efficiency

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ABSTRACT

The main objective of this work is to introduce an innovative hybrid heating appliance incorporating a gas condensing boiler and a zeolite-water adsorption heat pump. The condensing boiler is applied to drive the zeolite-water heat pump for the heating base-load and to assist the heat pump in the so called “mixed operation” mode, in which both the heat pump and the condensing boiler are working in series to cover medium heating demands. Peak heating demands are covered by the condensing boiler in the so called “direct heating” mode. The three operation modes of the hybrid heating appliance have been technically described.

In addition, the laboratory test conditions for estimating the seasonal heating performance according to the German Guideline VDI 4650-2 have been introduced. For both heating systems 35/28 °C and 55/45 °C, which represent the typical operating conditions of floor and high temperature radiating heating systems in Europe, seasonal heating gas utilization efficiencies of 1.34 and 1.26 have been measured, respectively with a ground heat source.

In two field test installations in one-family houses in Germany, the introduced heating appliance showed 27% more seasonal gas utilization efficiency for heating and domestic hot water production, which is equivalent to a CO_2-emission reduction of 20% compared to the gas condensing boiler technology.

1. Introduction

The spread of natural gas on the European market was based, among other factors, on developments of low-pollution burners and energy-efficient low-temperature boilers. The role of natural gas as a modern and ecologically compatible energy source was substantially extended by the introduction of gas condensing boiler technology in the 1990s. The heating market has subsequently become the largest consumption sector for natural gas. However, since 2005, and particularly in the new buildings sector, the growth of the gas heating market has been clearly reduced, with a decline in service connection density from 80% to now less than 60%. In addition, expansion of the gas supply networks has reached the limits of economic feasibility [1].

The gas industry, therefore, were obliged to respond to customers' increased environmental awareness and demands for autonomous solutions with innovative and modern heating technologies utilizing renewable energy. Along with the established condensing boilers plus solar energy solutions, gas heat pumps, in particular, enable end users to meet the market's political demands for high-efficiency heating systems in conjunction with renewable energy utilization.

In addition, sorption heat pumps have attracted considerable attention due to their lower environmental impact compared to that of conventional vapour compression heat pumps using HCFCs and HFCs, since sorption systems make use of natural refrigerants (e.g. ammonia or water), which have zero global warming potential. For these reasons, German gas utilities and the key European manufacturers of gas heating appliances have established the Initiative Gas Heat Pump (IGHP) in 2008 as a concerted action to carry out laboratory and field tests, prepare the market and work out the required standards framework for the market introduction of gas heat pump-based heating appliances [1].

The first gas-driven sorption heat pump technology in the IGHP-framework is continuously operating and utilizes ammonia-water as a working pair [2]. This technology is available in the heating

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power range of 40 kW. Despite its remarkably high efficiency, the high toxicity of ammonia together with the high ammonia content (7 kg per unit) put, however, a big restriction on the wide distribution of this technology into the market.

A quite efficient, direct-fired, ammonia-water-helium, diffusion absorption heat pump technology has been developed [3]. The severe measures required to avoid leakage in in-house installations because of the high toxicity of ammonia led to high fabrication costs, so that the producing company has decided not to bring this technology into the market.

The second type of gas-driven heat pump technology in the IGHP framework is a hybrid heating appliance, comprising a gas condensing boiler to drive an intermittent zeolite-water adsorption heat pump module and to meet the peak load if the required heat demand exceeds the heating capacity of the heat pump module [4–9]. This technology has been introduced into the German market in April 2010. The developed zeolite heat pump module is referred to as a two-heat exchanger module, as it incorporates two heat exchangers. The top heat exchanger, in a hermetically sealed adsorption heat pump module, functions either as a desorber or an adsorber, while the lower heat exchanger works as a condenser or evaporator, respectively. This technology utilizes zeolite (as an adsorbent) in the form of loose pellets between the fins of a finned-tube adsorber heat exchanger, with water as a refrigerant. Zeolite-water as a working pair is indeed completely environment friendly and non-toxic. However, the application of loose pellets together with the two-heat exchanger module implies a serious of efficiency drawbacks, including e.g. high internal losses and very slow kinetics.

This study introduces a more advanced hybrid heating appliance based on a zeolite-water adsorption heat pump. The following four features of the new heating appliance have been developed, in order to achieve an incremental improvement in the performance and to avoid the major drawbacks of the existing technology [4–9]:

1) The introduced heat pump module comprises three heat exchangers [10]; namely, adsorber-desorber, condenser, and evaporator, thus eliminating the specific internal heat losses emerging out of heating up and cooling down the same heat exchanger working periodically as an evaporator or condenser in Refs. [4–9].
2) A very stable and unique performing zeolite coating technology has been developed to apply zeolite on the surface of the adsorber heat exchanger in form of consolidated layers [11]. This technology offers specific heating powers of 1.6 kW/kg zeolite, which is ten times higher than the specific heating power obtained by applying loose zeolite pellets between the fins of the adsorber heat exchanger [12–14].
3) The evaporator is designed as a falling film evaporator [10], which is further optimized in Ref. [15] offering much higher evaporator capacities, to coop with very effective adsorber design, incorporating the consolidated layer adsorber heat exchanger.
4) The integration of the heat pump module, working as an intermittent heat pump, into the hydraulic scheme of the heating appliance offering quasi continuous heat delivery is associated with direct heat transfer between the heating water and either condenser or adsorber [16].

It is the main objective of this study to introduce the hydraulic concept and the operation modes of the new heating appliance based on a gas-driven zeolite water adsorption heat pump. In addition the seasonal performance of the introduced heating appliance has been experimentally investigated. Moreover, the test results of two typical heating net conditions as well as of two filed test installations in one-family houses in Germany have been introduced.

2. Working modes of the zeolite heating appliance

The zeolite heating appliance is a hybrid system comprising an indirect fired zeolite heat pump module with a gas burner and a couple of valves and heat exchangers. The heat pump module is designed to cover the base load (up to 50% of the heating appliance's rated heat load) in the so called heat pump operation mode, which, in turn, consists of two working phases; namely, desorption and adsorption phases. Fig. 1 depicts the flow scheme of the Zeolite heating appliance during the desorption phase. Since water is used as a refrigerant the module is operated under vacuum. Consequently, the heat pump module is designed as a vacuum sealed vessel comprising three heat exchangers. The upper is the adsorber-desorber, while the lower is the evaporator heat exchanger. The condenser is located on top of the vessel concentrically around the adsorber-desorber heat exchanger and its heat transfer path is formed between the upper section of the module's outside surface and a second concentrically mounted cylinder with a defined gap of (0.8–1.2 mm) to realize a quite efficient heat transfer.

2.1. Heat pump operation mode – low heat demand

The heat pump operation starts always with a desorption phase as depicted in Fig. 1. At the beginning of desorption phase all components are cooled down to the heating net return temperature by the previous adsorption phase. Inlet A of the control valve (CV) is closed which results in forming a second hydraulic circuit comprising sorber heat exchanger, gas-fired heating cell (HEX1) and pump (P1). The non-return valve (NRV2) combined with the closed inlet A of CV realize the hydraulic separation of this second circuit, which is termed as the sorber loop.

By switching on the gas burner after the pump P1, the heating water in the sorber loop is slowly heated up. As there is no expansion vessel in this sorber loop the pressure increases. However, the pressure increase is limited by the overflow valve (OV), which is mounted in parallel to the NRV-2 to guarantee a pressure difference of 2 bar over the heating water pressure in the heating circuit, which is always equipped with an expansion vessel (normally between 1 and 1.5 bar gauge). Doing so, the required desorption temperature of up to 125 °C can be realized in the sorber loop without any boiling [16]. As the zeolite desorption temperature lies between 80 and 125 °C, the exhaust gases leaving HEX1 are still hot and possess heat, which is recovered in the second exhaust heat exchanger (HEX2) by the heating water return flow before entering the heat pump condenser.

Heating up the sorber loop results in increasing the vacuum pressure inside the module as water vapour starts to regenerate from the zeolite. As soon as the vapour pressure exceeds the saturation pressure corresponding to the temperature of the heating water return flow entering the condenser, water vapour starts to condense on the internal surface of the module (condenser), and falls down to the bottom of the module. During the desorption phase the evaporator spiral heat exchanger is covered with refrigerant (water) as depicted in Fig. 1. The refrigerant surface together with an insulating plate made of a material with low heat conductivity realize a heat transfer barrier and minimize the condensation area on top of the evaporator at the beginning of the desorption phase. The falling condensate is directed to the top of the insulating plate by a conical guide plate, located directly below the condenser, to prevent the penetration of