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Research paper

Dynamic study of steam generation from low-grade waste heat in a zeolite–water adsorption heat pump

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ABSTRACT

A novel zeolite–water adsorption heat pump system based on a direct-contact heat exchange method to generate steam from low-grade waste gas and water has been proposed and examined experimentally. Superheated steam (200 °C, 0.1 MPa) is generated from hot water (70–80 °C) and dry air (100–130 °C). A dynamic model for steam generation process is developed to describe local mass and heat transfer. This model features a three-phase calculation and a moving water–gas interface. The calculations are carried out in the zeolite–water and zeolite–gas regions. Model outputs are compared with experimental results for validation. The thermal response inside the reactor and mass of steam generated is well predicted. Numerical results show that preheat process with low-temperature steam is an effective method to achieve local equilibrium quickly, thus generation process is enhanced by prolonging the time and increasing mass of the generated steam. Besides, high-pressure steam generation up to 0.5 MPa is possible from the validated dynamic model. Future work could be emphasized on enhancing high-pressure steam generation with preheat process or mass recovery operation.

1. Introduction

Utilization of waste heat has become an increasingly urgent task for modern industries such as chemical, steelmaking and metallurgical sections all over the world. Recycle of the industrial waste heat could not only cut the energy cost but also reduce the emission of heat to environment. Therefore, waste heat recovery technology has been developed and applied in many areas during the past decades. Recycle of high-grade waste heat is achieved relative easier and already used in industries by waste heat boiler [1] and heat pipe [2]. Low-grade waste heat could be reused by Organic Rankin Cycle [3], absorption heat pump [4], and adsorption heat pump (AHP) [5]. Specially, a great deal of waste water (≤80 °C) and waste gas (≤140 °C) could be found from chemical industries [6]. Meanwhile, high-temperature pressured steam produced from fossil fuel is needed in processes such as process heating and steam cracking. Thus, a kind of technology that could directly recycle the waste heat to steam will be a promising approach in the application filed.

AHPs have attracted researchers' attentions during the past years due to the advantages such as thermal driven by a wide temperature range, suitable for fluctuant conditions and simple structure [7]. AHPs systems have been seen as alternative technologies for cooling–heating application with various working pairs such as zeolite–water [8], silica gel–water [9] and activated carbon–ammonia [10]. Since zeolite–water pair was originally proposed more than 30 years ago [11], great efforts have been to enhance the overall heat transfer rate [12,13] in order to overcome the barrier for application. However, the size of the system is relatively larger with the existence of heat exchanger.

In our previous studies, a direct-contact heat exchange concept between porous adsorbent and heat exchange fluid was introduced to directly generate useful steam from hot water [8]. This novel steam generation system from zeolite–water AHPs has been proved experimentally and analyzed numerically [14]. Superheated steam (200 °C, 0.1 MPa) was generated from hot water (70–80 °C) and dry air (100–130 °C). When generation operation is the same, a peak in steam generation rate per unit mass of zeolite is determined at the regeneration time of 1200 s. However, how to prolong the effective time for steam generation is thought to be more important. Thus, further simulation work is to be done to study the

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dynamic character inside the packed bed to enhance effective steam generation time so as to improve the system efficiency.

In this study a dynamic model describing mass and heat transfer during the steam generation process is developed. Firstly, validation of the proposed model is confirmed from the comparison between simulation and experiment. Secondly, preheat process are numerically investigated to study the dynamic behavior inside packed bed and the influence on subsequent generation process. Lastly, pressured steam generation up to 0.5 MPa is discussed from validated model for further possible practical application.

2. Experimental setup

2.1. Apparatus

A schematic of the experimental apparatus is shown in Fig. 1. The setup is comprised of a cylindrical reactor, a thermostatic bath, a compressor, a condenser and an electronic balance. The reactor is made from stainless steel and has a height of 100 mm, an inner diameter of 71 mm and an outer diameter of 80 mm. Zeolite 13X, a hydrophilic material, is chosen as the adsorbent because it possesses sufficient heat of adsorption, tolerates liquid water and does not swell. Cylindrical particles of 1.6 mm diameter and 2–6 mm (mean 4 mm) lengths are used. The packed bed contains a 0.25 kg mass of dry zeolite at a void fraction of 0.4. K-type thermocouples (accuracy ± 1.5%) are used to measure the transient temperature change.

2.2. Operation

A zeolite–water AHP steam generation system consists of two processes: regeneration and generation. During regeneration process shown as dashed arrows in Fig. 1, dry air from the compressor is heated to a preset temperature (100–130 °C) and then flows through the reactor pushing wet gas out from the reactor. To estimate the humidity of the wet gas, the mass of water condensed and a humidity meter at the outlet are recorded. Regeneration is terminated at a preset time based on the design. After the regeneration, generation process commences at once. During the generation process shown in solid arrows, hot water (70–80 °C) from the thermostatic bath is pumped by a metering pump (accuracy ± 1%) to the packed bed of dry zeolite. As liquid water was adsorbed on zeolite, steam was generated due to heat of adsorption. Generated steam goes through the packed bed and finally measured after a condenser by an electronic balance (accuracy ± 0.1%). The simulation in this paper focuses on the generation process to study the methods to enhance steam generation.

3. Mathematical model

3.1. Assumptions and computational domain

The inlet water is adsorbed on zeolite sequentially from the bottom. While the generated steam moves upwards, some steam is adsorbed on the other zeolite until the zeolite reaches its local equilibrium state. Steam is thus expected to leave from the packed bed after whole region reaches equilibrium state.

The following assumptions are made:

1) Gas consists of air and steam and behaves as ideal gas,
2) Void fraction is uniform, and water level is horizontally uniform in the reactor,
3) Evaporation occurs solely at the water–gas interface as water evaporates at the boiling point,
4) Film condensation on the side wall is assumed when the steam dew point is larger than the wall temperature. Condensed water on the side wall goes back to water region directly.

Fig. 2 illustrates the computational domains in an axial symmetry coordinate system (*R*–*Z* axes). Steam generation process is featured as a three-phase calculation with a moving water–gas interface. The calculations are performed in two regions of zeolite–water and zeolite–gas to facilitate the simulation, where moving interface is assumed the horizontal layer of mesh at the begin time for each calculation [15]. The side wall region is included to consider transient heat transfer between the reactor and fluid (water and gas). The mathematical model is formulated to simulate the steam generation process.

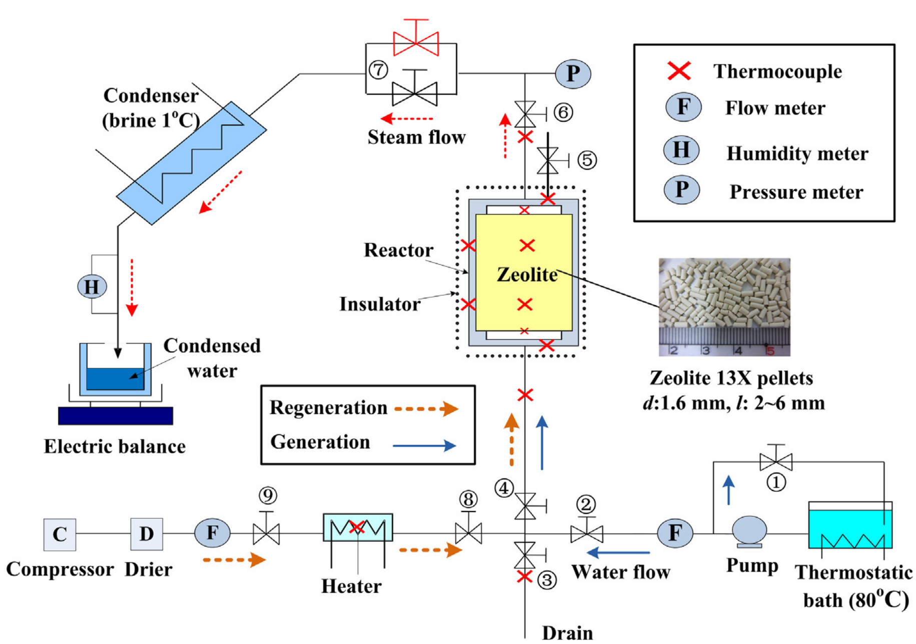

Fig. 1. Schematic illustration of experimental setup.