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Coal power plant flue gas waste heat and water recovery

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ABSTRACT

An advanced waste heat and water recovery technology has been developed to extract a portion of the water vapor and its latent heat from flue gases based on a nanoporous ceramic membrane capillary condensation separation mechanism. The recovered water is of high quality and mineral free, therefore can be used as supplemental makeup water for almost all industrial processes. The technology was first developed and proven at industrial demonstration scale for gas-fired package boilers, and already commercialized. The technology was thereafter further developed to a two-stage design tailored to coal power plant flue gas applications. The recovered water and heat can be used directly to replace power plant boiler makeup water to improve its efficiency, and any remaining recovered water can be used for flue gas desulfurization (FGD) water makeup or other plant uses. The technology will be particularly beneficial for coal-fired power plants that use high-moisture coals and/or FGD for flue gas cleanup.

1. Introduction

A large portion of energy consumed today comes from hydrocarbon fuel combustion, and one of the major combustion products is water vapor [1]. For the coal power plants, water vapor exits with the flue gases at a volume percentage 12–16%. Other industrial processes such as drying, wet scrubbers, dry scrubbers, dewatering, and water chilling, produce flue gases with 20–90% moisture content. Typically the water vapor along with its substantial latent heat is exhausted into the atmosphere [2] limiting the thermal efficiency of these processes. If 40–60% of this water vapor and its latent heat could be recovered, thermal efficiency would increase more than 5% for most of these processes.

There were several conventional technologies for recovering waste heat from utility boiler flue gases, such as recuperators, regenerators, finned tube economizers, and passive air preheaters [3]. These technologies are typically used for medium- to high-temperature waste heat, and the challenge is the technologies have material constraints and temperature restrictions. Until now, there has been no practical commercial technology available for recovering water vapor and its substantial latent heat from power plant low temperature flue gases. Levy et al. [4,5] designed a pilot-scale water recovery system for boiler flue gas based on multiple condensing heat exchangers, and the results showed that the flue gas can be cooled to below 40 °C, and water capture efficiencies are 10–35% by using both makeup water and combustion air as cooling source. This water recovery technology needs special anti-corrosion tubing material for the condensing heat exchanger, with benefits of capturing acid and Hg in the condensate. Copen et al. [6] designed a pilot scale Water Extraction from Turbine Exhaust (WETEX) system to recover water vapor, and it can remove 23–63% water vapor from flue gas by volume. But these water recovery technologies need additional condensed water treatment for reusing the water, which is a very costly process. Also, condensing flue gas moisture in a traditional heat exchanger presents the problem of a large surface area requirement for the low-temperature flue gas, and also raises the issue of equipment corrosion by the acidic condensate.

Gas Technology Institute (GTI) has developed a new technology based on a nanoporous ceramic separation membrane to extract a portion of the water vapor and its latent heat from flue gases and return the recovered water and heat to the steam cycle. This is achieved through the use of its patented Transport Membrane Condenser (TMC). Water vapor passes through the membrane and then is condensed in direct contact with a low-temperature water stream. Contaminants such as CO_2, O_2, NOx, and SO_2 are inhibited from passing through the membrane by its high selectivity. The recovered water is of high quality and mineral free, therefore can be used as supplemental makeup water for almost all industrial processes. The TMC has been developed and proven at industrial demonstration scale for gas-fired package boilers and commercial laundry applications, and already commercialized. The TMC technology was developed by GTI as a key component for high-efficiency Super Boiler program, which was sponsored by the United States Department of Energy (DOE) and other industrial sponsors started from 2000.

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2. TMC technology development and previous work

2.1. Membrane water vapor separation mechanism and experimental study

Gas separation membranes generally can be categorized as porous and non-porous. The separation of a mixture by non-porous membranes results from differences in the solubility and diffusivity of the various components in the membrane material [7]. Non-porous membranes usually display high separation ratios however their transport fluxes are relatively low [8,9]. Porous membranes typically depend on some combination of molecular sieving, diffusivity, and surface effects to manage the segregation of gaseous species [10]. Porous membranes, depending on pore size can achieve higher transport fluxes than nonporous membranes but the separation ratio is usually much lower [8,11,12].

However, the vapor separation characteristics of porous membrane can be greatly improved under a condition, wherein the vapor condenses within the membrane pore structure to such an extent that it completely blocks the pores and prevents the transport of the non-condensable gas components. Under such a condition, which is designated as the membrane capillary condensation mode, one observes dramatic increases in the membrane separation factor towards the condensable component (e.g., water vapor) [13,14]. The condensed vapor transport through the membrane is thought to be governed by a pseudo-liquid phase transport; hence the mass transfer flux is much higher than expected from gas phase transport [15]. By working in this membrane capillary transport mode, porous membranes can achieve both high transport flux and high separation ratio.

Separating water vapor from a gas stream is a typical example of membrane separation involving a condensable component with phase change heat transfer. Relatively little investigation has been done for porous membranes working in the capillary condensation mode in the past. This is due to both the complicated nature of the capillary transport mode and historic perceptions that recovered water vapors are not commercially valuable. Only when increases in energy and water costs occurred did the importance of recovering water vapor and its latent heat found in various industrial exhausts make economic sense and the exploration of new techniques began to receive further attention. In addition, fresh water has become more valuable over the past decade and therefore recovered high quality water adds value for the technology development. Water recovery from high moisture, elevated temperature waste streams is quite energy efficient since the water is already in a high energy state (vapor phase) and this energy can be eventually recovered along with the liquid water thereby increasing the overall system efficiency. It is the potential economic value of recovering such waste energy and water which justified investment in separating water vapor by membrane techniques.

GTI's experimental study found that a nanoporous ceramic membrane with a six nanometer mean pore size, when working in the Knudsen diffusion transport mode has low water vapor transport flux and poor separation characteristics, as expected. But when the gas stream is adequately cooled and the relative humidity of the flue gas increases, capillary transport mode is produced in the porous membrane. Water vapor transport flux then increases by a factor of more than 5 from the value measured in the Knudsen diffusion mode (Fig. 1) and the separation ratio is greatly improved by a factor of more than 100. Consequently, the onset of the membrane capillary condensation is a critical point for porous membrane vapor separation switching from a low performance mode to a high performance mode.

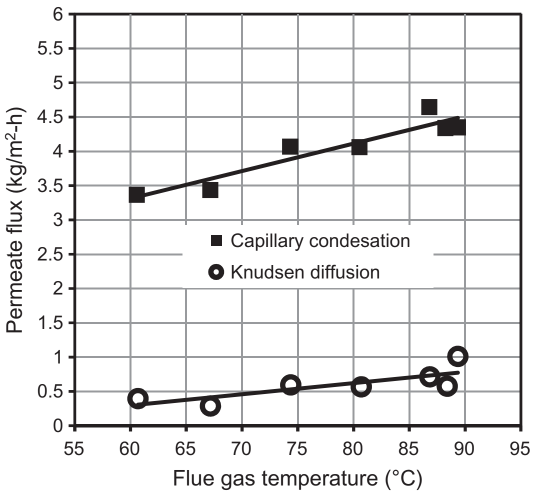

Fig. 1. Membrane transport mode effect.

2.2. Previous TMC development work for industrial boilers

Fig. 2 depicts the TMC concept for boiler applications with exhaust gas flowing on one side of a nanoporous ceramic membrane tube and cold boiler makeup water flowing counter-current on the opposing side. Water vapor from the flue gas is transported through the membrane structure by first condensing inside the inner separation membrane layer (60–80 Å pore size), then moving through the intermediate layer (500 Å pore size) and finally through the substrate (0.4 μm pore size). Other gas components in the flue gas are blocked from passing through the membrane by the condensed liquid. Condensed water along with its latent heat combines with the cold boiler makeup water, helping to raise its temperature prior to entering the boiler feed water tank or deaerator. A small vacuum is maintained on the water side of the TMC unit to prevent backflow of water due to liquid pressure head and also to provide additional driving force for water to pass through the membrane.

The first generation TMC design was based on commercially available membrane bundles, incorporated into an arrangement with flue gas flowing downward through the inside of the membrane tubes and boiler makeup water flowing counter currently upward in the TMC shell (Fig. 3, middle). The down flow configuration was necessary to attain maximum heat transfer due to natural convective flow of the water on the shell side of the TMC.

However, several improvements were required to reduce the module cost, installation cost, and maintainability to make the product marketable, particularly for the lucrative retrofit boiler

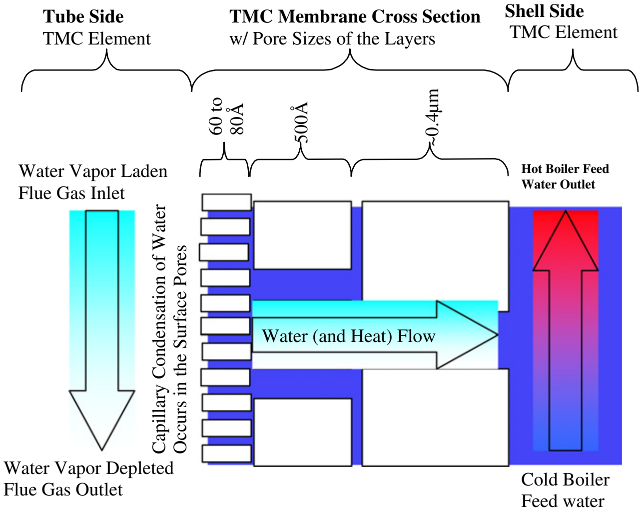

Fig. 2. TMC concept schematic.