International Conference on Applied Energy 2019
Aug 12-15, 2019, Västerås, Sweden
Paper ID: #56

RECOVERING WATER FROM EXHAUST USING MACROPOROUS MEMBRANE AND MICROPOROUS MEMBRANE

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ABSTRACT

Recovering water from exhaust could solve the water-shortage problem for some power plants, and it is conductive to the spread of pollutants in the lower atmosphere. Transport membrane condenser (TMC) is a novel device used to recover water from exhaust. In the past, most researchers used mesoporous membrane to manufacture TMC, and the experiments were conducted using the artificial flue gas. In this paper, macroporous-TMC and microporous-TMC are proposed and designed. The water recovery performance of both kinds of TMCs are compared experimentally under real flue gas environment. According to the experimental results, the water recovery performance of macroporous-TMC is better than that of microporous-TMC. Furthermore, the effect of Re number of flue gas and cooling water on the water recovery performance are analyzed.

Keywords: macroporous membrane, microporous membrane, water recovery, exhaust

NONMENCLATURE

Abbreviations	
SEM	Scanning electron microscope
TMC	Transport membrane condenser
Symbols	
J_{rec}	Recovered water flux
m_f	Flue gas flowrate
p_s	Saturation pressure of water vapor
p_v	Partial pressure of water vapor
R_{gv}	Gas constant of water vapor
T	Flue gas temperature
η	Water recovery efficiency
ρ_v	Absolute humidity
ϕ	Relative humidity

1. INTRODUCTION

In power plants, the exhaust contains lots of moisture. The high humidity flue gas would increase overall humidity in the lower atmosphere, which is not conducive to the spread of pollutants in the lower atmosphere [1]. Therefore, the topic of how to recover moisture from exhaust receives more attention. Using fluorine plastic heat exchangers [2] to recover moisture from exhaust is a traditional method. However, some equipment would be corroded by the acidic condensate [3]. Transport membrane condenser (TMC) was originally proposed by the Gas Technology Institute to recover the moisture from exhaust in power plants [4].

A TMC is placed after the desulfurization tower. Its core component is an array of hydrophilic ceramic membrane tubes. The cooling water flows inside the membrane tubes, and the flue gas flows outside the membrane tubes. When flue gas flows through the membrane tubes, due to the action of the driving force, the water vapor permeates into the membrane and condenses into liquid water. At present, research on TMC mainly focuses on three aspects: (1) Experimental research. Ceramic membrane tubes were used to recover water from artificially prepared flue gas, to study the factors affecting water recovery performance [5, 6]. (2) Theoretical modelling. The numerical calculation method was used to evaluate the performance of TMC [7], and to optimize the arrangement of membrane tubes [8]. (3) Structure reformation of the traditional TMC. Yue et al. [9] used a multi-channel membrane tube instead of a single-channel membrane tube. Chen et al. [10], Macedonio et al. [11] changed the cooling medium in the

Selection and peer-review under responsibility of the scientific committee of the 11th Int. Conf. on Applied Energy (ICAE2019).
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membrane tube from water to air. The hydrophobic ceramic membranes [12] was used to make a novel TMC.

There are two limitations in the current studies about TMC. Firstly, the TMCs design in these studies were composed of mesoporous membranes, and the pore size of membrane is in the range of 2–50 nm. Secondly, except for the Gas Technology Institute, most research teams used artificially prepared flue gas to investigate the TMC performance. Based on the above limitations, two kinds of commercial membranes with the pore sizes of 1 μm and 0.4 nm are selected for the research objects in this paper. And the performance of macroporous-TMC and microporous-TMC are compared in a real flue gas environment.

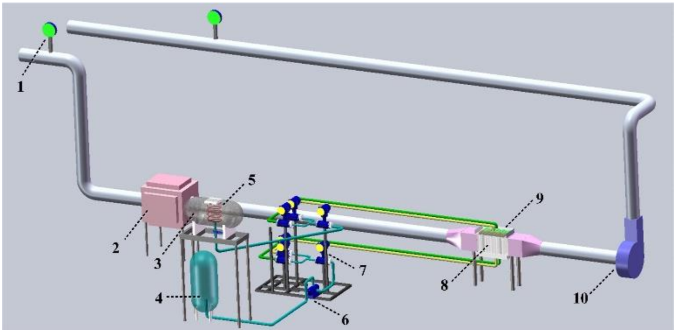
2. EXPERIMENTAL

In this paper, macroporous-TMC and microporous-TMC are designed for experiments. The structural parameters and arrangement of the two TMCs are identical. Each TMC contains 46 staggered membrane tubes and four support tubes. The only difference between the two TMCs is that the pore size of ceramic membranes are different. Macroporous-TMC is composed of the ceramic membranes with the pore sizes of 1 μm, while microporous-TMC is composed of the ceramic membranes with the pore sizes of 0.4 nm. The length, inner and outer diameters of both kinds of commercial membranes are 400 mm, 8 mm and 12 mm, respectively. In order to compare the difference between the two kinds of membranes, some performance characterization experiments of the membrane are carried out, including scanning electron microscope (SEM), membrane porosity and pore size distribution.

The two TMCs designed in this paper are used to recover the moisture from exhaust of the gas-fired boiler. The experimental platform is shown in Fig. 1. On the flue gas side, the two TMCs are placed side by side in the flue to ensure that they can recover moisture under the same flue gas conditions. On the cooling water side, the two TMCs have separate water paths. By adjusting the valve opening to ensure the same flowrate of cooling water through each TMC.

Water recovery efficiency is an important index that can evaluate the recovery performance of TMC. In the experiment, the relative humidity of flue gas is measured by humidity transmitter (produced by Vaisala Corporation, Finland). The water recovery efficiency can be determined as follows:

$$\eta = \frac{J_{rec}}{m_f \cdot \rho_v} = \frac{J_{rec}}{m_f \cdot \dfrac{p_v}{R_{gv} T}} = \frac{J_{rec} R_{gv} T}{\varphi m_f p_s} \tag{1}$$



1 – Anemometer; 2 – Gas heater; 3 – Supply water tank; 4 – Return water tank; 5 – Heating device; 6 – Self-priming pump; 7 – Flow meter; 8 – Microporous-TMC; 9 – Macroporous-TMC; 10 – Induced draft fan

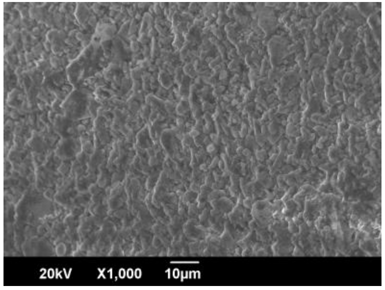
Fig. 1. Experimental platform

3. RESULTS AND DISCUSSION

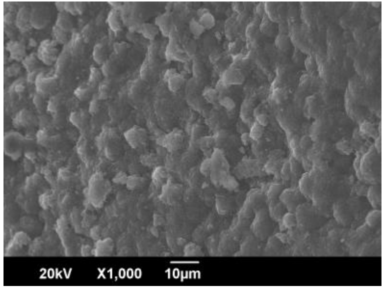
3.1 Membrane characterization

State the objectives of the work and provide an adequate background, avoiding a detailed literature survey or a summary of the results. The morphology of both kinds of membranes (outer surface side) are observed by JSM6490LV SEM (produced by JEOL Electronics Corporation, Japan), and the results are shown in Fig. 2. Compared with the macroporous membranes, there is a coating in the outer surface of the microporous membranes. In this paper, the average pore size of coating is 0.4 nm. According to Fig. 2, the structure of macroporous membrane is compact and the outer surface is smooth. This is because the macroporous membrane is sintered from particulate matters, and it is a basement membrane without coating. While the outer surface of microporous membrane is less smooth than that of macroporous membrane. Furthermore, some locations of the coating have a pore size greater than 0.4 nm.

The porosity and pore size distribution of both membranes are measured by the mercury intrusion method in the Beijing Centre for Physical & Chemical Analysis. The results are shown in Table 1. It is interesting to find that the results of both membranes are almost the same. This interesting results are related to the structure of microporous membrane. The structure of the microporous membrane can be divided into three layers: the selective layer, the transition layer and the basement membrane. The selective layer is the coating coated on the outer surface of the membrane. The pore size of selective layer is about 0.4 nm, while the pore size of basement membrane is about 1 μm. The huge differences in the pore size would produce a large transmembrane pressure gradient in the membrane. Thus, the role of the transition layer is to solve this problem, and the pore size of the transition layer is between the above two layers. The thicknesses of selective and transition layers are about 10 μm and 100 μm, while the thickness of basement membrane is about 2 mm. Therefore, porosity and pore size distribution are affected little by selective and transition layers.



(a) Ceramic membrane with pore size of 1 μm



(b) Ceramic membrane with pore size of 0.4 nm

Fig. 2. Morphology of commercial ceramic membranes

Table 1 Porosity and pore size of the ceramic membranes

Macroporous membrane	Porosity	41.5348%
	Mean pore size	1.270 μm
Microporous membrane	Porosity	41.5159%
	Mean pore size	1.659 μm

3.2 Water recovery performance

By changing the physical parameters of flue gas and cooling water, the water recovery performance of two TMCs under different working conditions is studied experimentally. Figs. 3 and 4 show the effects of the Re number of flue gas and cooling water on the recovery performance, respectively. During the experiments, the temperatures of the flue gas and cooling water and are maintained at about 46 °C and 18 °C, respectively. Since the TMC is installed in the flue behind the desulfurization tower in the thermal power plant, and the flue gas temperature is usually below 50 °C. Therefore, it is reasonable to choose a flue gas temperature of 46 °C. In the experiments, the flow of the cooling water is in a laminar flow state, while the flow of the flue gas is in a turbulent state.

According to Figs. 3 and 4, the water recovery performance of the macroporous membrane is significantly better than that of the microporous membrane. This is due to the difference in the water recovery mechanisms of the two kinds of membranes. The pore size of the macroporous membrane is about 1 μm, and liquid water can penetrate directly into the membrane through the pores of the membrane. During the experiments, water vapor in the flue gas condenses on the outer surface of the macroporous membrane, and the formed condensed water penetrates into the membrane. The average pore size of the microporous membrane coating is 0.4 nm, and the diameter of water vapor molecule is 0.348 nm. Part of the water vapor could penetrate the microporous membrane in a gaseous state, and condense in the membrane to form condensed water. Since the average pore size of the microporous membrane coating and the diameter of the water vapor molecules are very close, the recovered water flux is lower than that of macroporous membrane.

The Re number can reflect the flow state of the fluid. In the experiments, since the temperatures of the flue gas and the cooling water do not change much, the value of Re number mainly depends on the fluid velocity. Increasing the velocity of flue gas or cooling water can enhance the convective heat transfer effect of the membrane, and increase the condensation rate of water vapor. Therefore, the recovered water flux increases as Re number of flue gas or cooling water increases. As the velocity of the flue gas increases, the time that the flue gas stays on the outer surface of the membrane is shortened gradually. Because the condensation process of water vapor, the permeation process of water vapor and liquid water requires a certain action time, the increase of the flue gas velocity is not conducive to the above processes. Therefore, the water recovery efficiency decreases as the Re number of flue gas increases. When the Re number of the cooling water changes, since the flue gas parameters are kept constant, the water recovery efficiency increases as the recovered water flux increases.

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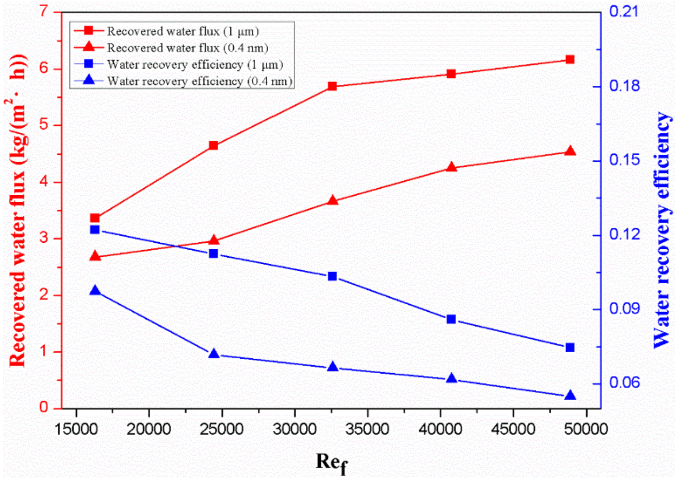

Fig. 3 Effect of Re number of flue gas on the water recovery performance

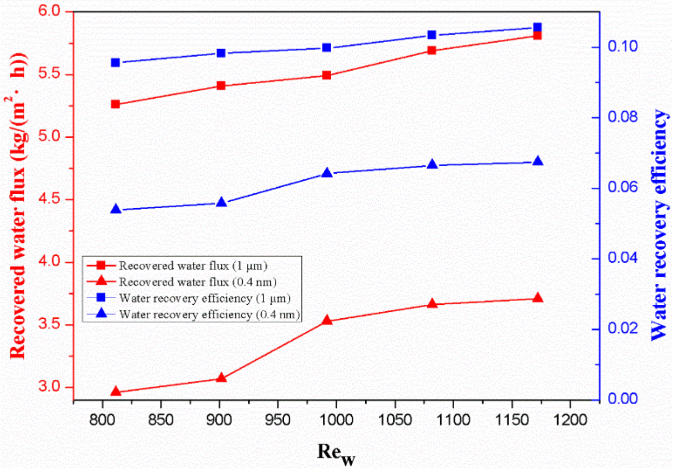

Fig. 4 Effect of Re number of cooling water on the water recovery performance

4. CONCLUSION

An experimental platform is established for comparing the water recovery performance between macroporous-TMC and microporous-TMC under the real flue gas conditions. According to the results, the water recovery performance of macroporous-TMC is better than that of microporous-TMC. Furthermore, when the temperatures of flue gas and cooling water are kept constant, the recovered water flux increases as Re number of flue gas or cooling water increases. However, increasing Re number of flue gas would reduce the water recovery efficiency.

ACKNOWLEDGEMENT

This work is financially supported by National Key R&D Program of China (2018YFB0604302), and Sino-foreign Joint Graduate Students Program of North China Electric Power University.

REFERENCE

[1] S.C. Ma, J Chai, K.L. Jiao, L. Ma, S.J. Zhu, K. Wu, Environmental influence and countermeasures for high humidity flue gas discharging from power plants, Sust. Energ. Rev. 2017;73:225–235.

[2] Y.Y. Xiong, H.Z. Tan, Y.B. Wang, W.G. Xu, H. Mikulcic, N. Duic, Pilot-scale study on water and latent heat recovery from flue gas using fluorine plastic heat exchangers, J. Clean. Prod. 2017;161:1416–1422.

[3] D. Gao, Z.H. Li, H. Zhang, H.P. Chen, C. Cheng, K. Liang, Moisture and latent heat recovery from flue gas by nonporous organic membranes, J. Clean. Prod. 2019;225:1065–1078.

[4] D.X. Wang, A.N. Bao, W. Kunc, W. Liss, Coal power plant flue gas waste heat and water recovery, Appl. Energ. 2012;91:341–348.

[5] H.P. Chen, Y.N. Zhou, S.T. Cao, X. Li, X. Su, L.S. An, D. Gao, Heat exchange and water recovery experiments of flue gas with using nanoporous ceramic membranes, Appl. Therm. Eng. 2017;110:686–694.

[6] S.F. Zhao, S.P. Yan, D.K. Wang, Y.B. Wei, H. Qi, T. Wu, P.H.M. Feron, Simultaneous heat and water recovery from flue gas by membrane condensation: Experimental investigation, Appl. Therm. Eng. 2017;113:843–850.

[7] Y.N. Zhou, H.P. Chen, T. Xie, B. Wang, L.S. An, Effect of mass transfer on heat transfer of microporous ceramic membranes for water recovery, Int. J. Heat Mass Tran. 2017;112:643–648.

[8] S. Soleimanikutanaei, C.X. Lin, D.X. Wang, Modeling and simulation of cross-flow transport membrane condenser heat exchangers, Int. Commun. Heat Mass. 2018;95:92–97.

[9] M.W. Yue, S.F. Zhao, P.H.M. Feron, H. Qi, Multichannel tubular ceramic membrane for water and heat recovery from waste gas streams, Ind. Eng. Chem. Res. 2016;55:2615–2622.

[10] H.P. Chen, Y.N. Zhou, X. Su, S.T. Cao, Y.D. Liu, D. Gao, L.S. An, Experimental study of water recovery from flue gas using hollow micro-nano porous ceramic composite membranes, J. Ind. Eng. Chem. 2018;57:349–355.

[11] F. Macedonio, A. Brunetti, G. Barbieri, E. Drioli, Membrane condenser configurations for water recovery from waste gases, Sep. Purif. Technol. 2017;181:60–68.

[12] H.W. Hu, G.H. Tang, D. Niu, Wettability modified nanoporous ceramic membrane for simultaneous residual heat and condensate recovery, Sci. Rep. 2016;6:27274.