Paper ID APEN-MIT-2020_315
Applied Energy Symposium: MIT A+B
August 12-14, 2020 • Cambridge, USA

Experimental Investigation of a Novel Membrane-based Condensing Heat Exchanger used for High Efficiency Furnaces

Brian L. Bischoff
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA
bischoffbl@ornl.gov

Lingshi Wang
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA
wangl2@ornl.gov

Xiaobing Liu
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA
liux2@ornl.gov

Van D. Baxter
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA
baxtervd@ornl.gov

Kyle R. Gluesenkamp
Energy and Transportation Science Division
Oak Ridge National Laboratory
Oak Ridge, TN, USA
gluesenkampk@ornl.gov

Abstract—Building space heating consumes approximately a third of all global natural gas end use, contributing significantly to global warming. Higher efficiency (aka, condensing) furnaces hold only about 25% of the furnace market in US buildings. One reason for this is that the condensing heat exchanger must use highly expensive, needs corrosion-resistant materials due to acidic components in the furnace flue gas stream. Increasing the market share of high efficiency furnace is beneficial to reducing greenhouse gas emissions. This study developed and tested a benchtop prototype of a novel membrane-based condensing (heat recovery) heat exchanger for high efficiency furnace to achieve non-acidic condensation via nano-porous membranes. Test results show that both sensible and latent heat are recovered with a fraction of latent heat recovery varies from 39% to 73%. The amount of water condensed through the membrane heat exchanger increases with the increase of flue gas flow rate while it decreases by increasing coolant temperature. The fraction of latent heat recovery decreases with the increase of flue gas flow rate and coolant temperature. The pH value of condensed water was only mildly acidic, varying from 5.0 to 6.3 without any additional treatment. It achieves significant improvement when compared with the conventional condensing furnace. Therefore, feasibility of the membrane-based condensing heat exchanger has been experimentally verified, and it has potential to enable wider market penetration of highly energy-efficient condensing furnaces by reducing costs for dealing with the acid condensation.

Keywords—membrane-based condensing heat exchanger, capillary condensation, furnace, experimental investigation, Annual Fuel Utilization Efficiency

I. INTRODUCTION

Building equipment efficiency plays an important role in reducing primary energy consumption. According to the most recent Energy Information Administration (EIA) estimates, residential and commercial buildings will consume 38.22 quads or 37.6% the total US primary energy consumption in the year 2030 [1], continuing to exceed industrial and transportation energy consumption. Natural gas consumption for building space heating alone is 4.47 quads [1]. It releases tremendous amounts of greenhouse emissions and is a significant contributor to the global warming problem. There are two main types of furnace on the market: condensing furnace and non-condensing furnace. The condensing furnace having 95% Annual Fuel Utilization Efficiency (AFUE) is the high efficiency furnace. Combustion products in the condensing furnace include CO_2, H_2O, excess air and small amounts of acid gases. Condensation of water occurs on the heat exchanger (HX) as the temperature is lowered below the dew point. When this occurs, the acid gases can dissolve in the condensed water making the condensate acidic. As such, more expensive stainless steel or aluminum alloy heat exchangers are employed to avoid corrosion issues [2]. Furthermore, the drainage requires the addition of a neutralizing salt system to treat the condensate. Due to these drawbacks, condensing furnaces only accounted for ~25% of total US furnace market in 2016 [3]. The non-condensing furnace having ~80% AFUE is more commonly used in US than the condensing furnace due to low cost, despite its lower AFUE. A more feasible method to reduce the total natural gas consumption from furnaces is increasing the AFUE of non-condensing furnace by recovering the exhaust heat (both sensible and latent) of the flue gas without acid condensation rather than directly replacing non-condensing furnaces with conventional condensing furnaces. The potential annual energy savings would be about 0.51 quads when the non-condensing furnace (80% AFUE) achieves gas furnace AFUE in the same range as those of conventional condensing furnaces (95% or better).

This study applied advanced membrane technologies [4,5] to achieve very high AFUE furnace performance by recovering latent heat (e.g., the heat of condensation of the water vapor) from high-temperature flue gases of a conventional non-condensing furnace. A conductive inorganic membrane was used to condense water from the flue gas by capillary condensation. This conductive membrane will transfer both the sensible heat of the flue gas and the latent heat of the condensed water to the air being conditioned. Unlike the water that condenses on the surface of a conventional heat exchanger, the water that is condensed in the pores is not acidic. A bench scale membrane-based condensing heat exchanger was developed and tested on a conventional non-condensing furnace, a parametric study was also conducted to investigate the influence of operating conditions on the performance of this membrane-based condensing heat exchanger.

II. Principle of Separation of Water Vapor by Capillary Condensation

The water separation from the flue gas of furnace by the membrane-based heat exchanger involves a process called capillary condensation. The nano-porous membranes have pores in the range of 5 to 20 nm and can separate gases using capillary condensation [6]. Capillary condensation occurs through a process where the vapors first adsorb onto the surface of a micropore. As the concentration of vapors increases, multilayer adsorption takes place until the surface tension causes the pores to completely fill with liquid. These surface tension forces are higher in smaller pores and cause a concave meniscus at the interface between the liquid and vapor, as seen in Fig. 1. This concave meniscus lowers the vapor pressure above the liquid in the pores with the relationship defined by the Kelvin Equation (Eq. 1).

$$\ln\left(\frac{P}{P_{sat}}\right) = \frac{-2\gamma V_m}{r_k RT} \quad (1)$$

Where P/P_{sat} is the ratio of the vapor pressure to the saturation vapor pressure, γ is the surface tension of the fluid, V_m is the molar volume of the fluid, r_k is the Kelvin radius (pore radius – adsorbed thickness).

In capillary condensation, separation occurs when one constituent condenses in the pores and blocks transport of the other non-condensable gases. In our case, our membrane was designed to condense the water produced from the combustion of natural gas while blocking the remaining flue gases such as oxygen, nitrogen, carbon dioxide, along with acid gases SOx and NOx. Heat is released during this condensation process and recovered by the membrane. Because the condensation occurs at a higher temperature than conventional condensation and the condensation occurs within the pores and not in the bulk, condensation and recovery of latent energy can occur without lowering the complete flue gas stream.

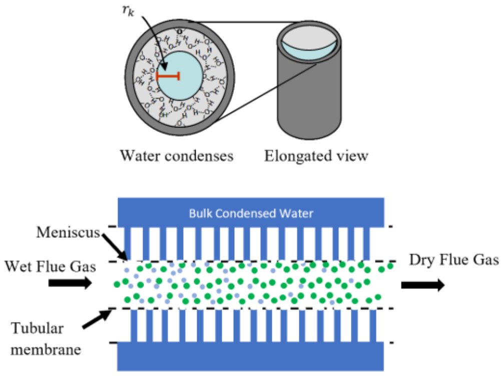

Fig. 1 Capillary condensation principle: (a) concave meniscus; (b) condensation through membrane.

III. Experimental Apparatus of a Novel Membrane-Based Condensing Heat Exchanger Used for High Efficiency Furnaces

The bench scale membrane heat exchanger is comprised of a tubular metallic-based nano-porous membrane and a custom double-walled holder which serves two functions, as shown in Fig. 2.

The designed membrane tube is metallic supported and nano-porous alumina-coated porous membrane tube, which has an average pore size of approximately 8 nm and a dimension of Φ 11.2 mm x L 22.86 cm x δ 0.51 mm. Nano-porous membranes (5-20 nm pores) can lower the vapor pressure to less than 50% of the saturation vapor pressure resulting in a higher latent heat recovery than a standard condensing furnace. A thin layer of aluminum oxide was applied to the inside surface of the tubular porous 434 stainless steel support. The aluminum oxide being hydrophilic condensed the water and the heat was transferred through the stainless steel support to the outer membrane shell.

The inner shell collects the condensed water from the flue gas while the outer shell contains flowing cooling water (to simulate the conditioned air) to control the condensation temperature and recover the heat released through the condensation process (latent heat) and from the cooling of the flue gas (sensible heat). The holder was made from aluminum to increase heat conduction and employs sanitary flanges for sealing the inner collection shell. There are three ports on the holder. One connects to the inner shell to collect

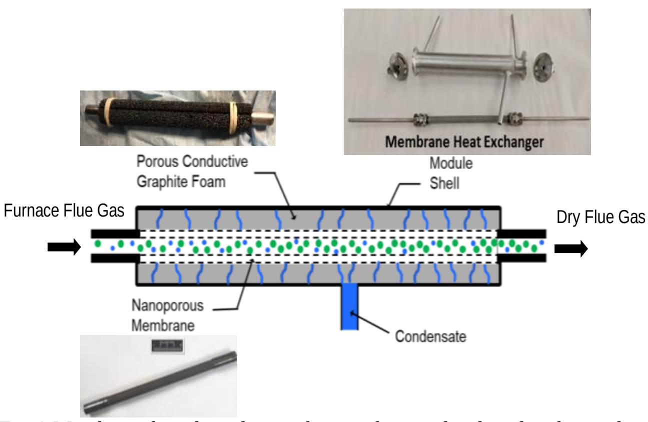

Fig. 2 Membrane-based condensing heat exchanger developed in this study.

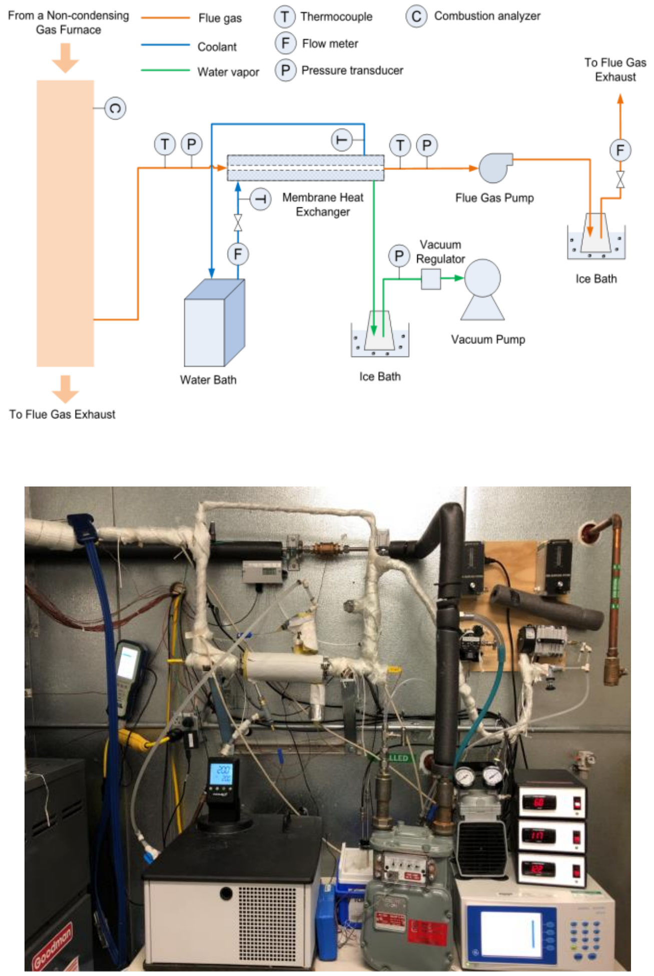

Fig. 3 Testing system for the membrane heat exchanger.

the condensed water and the other two carry the cooling water in and out of the outer shell. Prior to inserting the membrane, the membrane was wrapped in a clamshell made of porous conductive graphite foam. This foam is in contact with both the support side of the membrane and the inner surface of the collection shell to transfer the heat directly from the membrane to the cooling shell. The membrane assembly is formed by connecting the flue gas lines to the tubular membrane using Teflon Swagelok ferrules to minimize heat conduction from the membrane to the flue gas lines and the membrane assembly was connected to the sanitary flanges using Teflon ferrules to minimize heat transfer from the flue gas lines to the membrane shell.

An experimental apparatus was developed to test the performance of the developed membrane-based condensing heat exchanger, as shown in Fig. 3. A small fraction of the flue gas from a non-condensing gas furnace was drawn through the membrane heat exchanger, in which the water vapor from the flue gas was condensed and the flue gas was also cooled by the cooling water running through the water jacket of the membrane heat exchanger. A vacuum pump was used to extract the condensed water from the membrane heat exchanger (i.e. membrane condensate) to a flask which was immersed in an ice bath. The dried and cooled flue gas from the membrane heat exchanger was drawn by a gas pump to another flask which was also immersed in an ice bath to collect the rest of water condensation from the flue gas near a freezing point (i.e. reject condensate), and then the flue gas finally exits from the testing system and out of the lab through an exhaust vent. The two ice baths can maximize the water collection and alleviate water vapor escape to exhaust. To keep or control the temperature of inlet flue gas and avoid unexpected condensation in the flue gas pipe, the flue gas pipe was insulated and also was heated by electric heaters wrapped in the insulation materials.

Controlled variables during the tests include flue gas flow rate, membrane HX inlet temperature and cooling water temperature. A combustion & emissions analyzer was used to determine the content of CO_2 and H_2O in the flue gas. A scale was used to weigh the collected water. The pH value of the collected water was measured by using a pH meter. Other measured parameters include cooling water flow rate and temperature, pressure drop of the membrane heat exchanger, and vacuum pressure of the vacuum pump. The specifications of the measurement instrumentation are shown in Table 1.

The performance of the membrane heat exchanger is evaluated by the following metrics.

Water collection rate (CR_w): the amount of water collected from the condensate or reject (m_w) per minute (g/min)

$$CR_w = \frac{m_w}{t} \tag{2}$$

Fraction of latent hear recovery (ε): the ratio of latent heat recovery from membrane condensate and total latent heat from condensed water in the flue gas

TABLE 1. SPECIFICATIONS OF THE MEASUREMENT INSTRUMENTATION.

Measured value	**Instrument**	**Range**	**Uncertainty**
Flue gas composition	PCA 400 Combustion & Emissions Analyzer	0 to 20.9% for O_2	±0.3% O_2
Temperature of coolant	Type-T thermocouple probes [Omega]	−325–700°F	±0.75%
Temperature of flue gas	Type-K thermocouple probes [Omega]	−325–1700°F	±0.75%
Flow rate of flue gas	AC250 temperature compensated gas meter	250 SCFH (7.1 m^3/h) (0.60 specific gravity gas) at 1/2-inch W.C. differential	1 pulse per cubic foot dry contact pulse
Flow rate of coolant	OMEGA FTB600B Series flow meters, Model FTB601B-T	100-2000 ml/min	±1%
PH value of collected water	Beckman 360 pH / Temp / mV Meter, Model 511212	0-14	±0.02 pH
Weight of collected water	Torbal AG4000 Scale	0-4000g	±0.01g

$$\varepsilon = \frac{r * CR_{w,mem}}{r * (CR_{w,mem} + CR_{w,rej})} \tag{3}$$

Where *r* represents the latent heat of vaporization (kJ/kg), *mem* represents membrane condensate, *rej* represents reject condensate.

pH value: a scale used to quantify the acidity of the collected water

$$pH = -\log_{10}[H^+] = \log_{10}\frac{1}{[H^+]} \tag{4}$$

Where *H+* represents hydrogen ion concentration in solution.

IV. Experimental Results of the Membrane Heat Exchanger

A series of tests were conducted to evaluate the performance of the membrane heat exchanger. The test conditions of one of the tests are shown in Table 2 and measured data over time during the test are shown in Fig. 4. The flue gas with an inlet temperature of 148.5 °C (which is near to the temperature of the flue gas from the non-condensing furnace at 156°C) and a flow rate of 0.419 cfm (11.9 L/min) flowed through the membrane heat exchanger. The cooling water temperature is 20 °C.

The results show that the water collection rate of membrane condensate is 0.258 g/min, and the water collection rate of reject condensate is 0.219 g/min. Fraction of latent heat recovery is 54.1%. The flue gas temperature

TABLE 2. TEST CONDITIONS AND RESULTS OF A CASE STUDY.

	Variable	Symbol	Unit	Measured data
Furnace	Flue gas temperature	TC_Flu	°C	156
Membrane Heat Exchanger	Inlet temperature	TC_Membrane_In	°C	148.5
	Outlet temperature	TC_Membrane_Out	°C	77.2
	Flue gas flow rate	FlueGas_CFM	CFM	0.419
Coolant	Inlet temperature	TC_Coolant_In	°C	19.8
	Outlet temperature	TC_Coolant_Out	°C	21.8
	Flow rate	Coolant_LPM	LPM	0.16
Flask	Temperature in reject flask	TC_Flask	°C	17.0

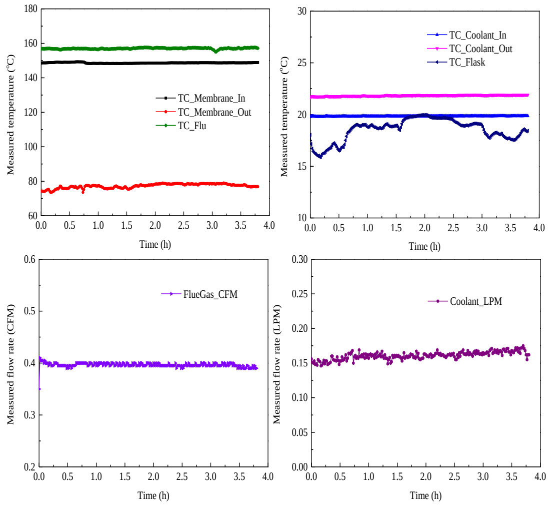

Fig. 4 Measured data during a typical test on the membrane heat exchanger.

also reduces from 148.5°C to 77.2 °C when it flows through the membrane heat exchanger. It indicates that both sensible and latent heat are recovered. The measured pH value of membrane condensate is 5.61, indicates that the acidity of membrane condensate is 99.2% lower than that of condensate from a conventional condensing furnace, which typically has a pH value of 3.5. The pH of reject condensate is 4.3, also indicates the acidity is largely reduced when it is compared to 3.5. As the condensate collected from the membrane heat exchanger is nearly neutral, it could be potentially used for other services (e.g., humidify heated air stream without need for supplemental humidifier, etc.) leading to water savings as well.

To better understand the performance of the membrane heat exchanger, a parametric study is conducted. The investigated operating parameters include the flue gas flow rate (2.27-15.5 L/min), the inlet temperature of membrane heat exchanger (100 °C, 148 °C) and the coolant temperature of the thermal bath (20 °C, 25 °C, 30 °C). The results of the parametric study also could be the guide for a scale-up, optimal design and operation for the high-efficiency furnaces integrated with the membrane heat exchanger.

Impacts of flue gas flow rate is studied, as shown in Fig. 5. Condensate rate and reject rate increase by increasing flue gas flow rate, while the fraction of latent heat recovery decreases from 0.649 to 0.469 with an increasing flue gas flow rate from 0.207 cfm to 0.535 cfm. The pH value of membrane condensate decreases from 5.75 to 5.24 and the pH of reject condensate increases from 3.09 to 3.47 by increasing flue gas flow rate. Therefore, the acidity removal effect for the membrane condensate is still good at the highest flow rate.

Fig. 6 presents the impacts of membrane HX inlet temperature at different flue gas flow rates. Two membrane

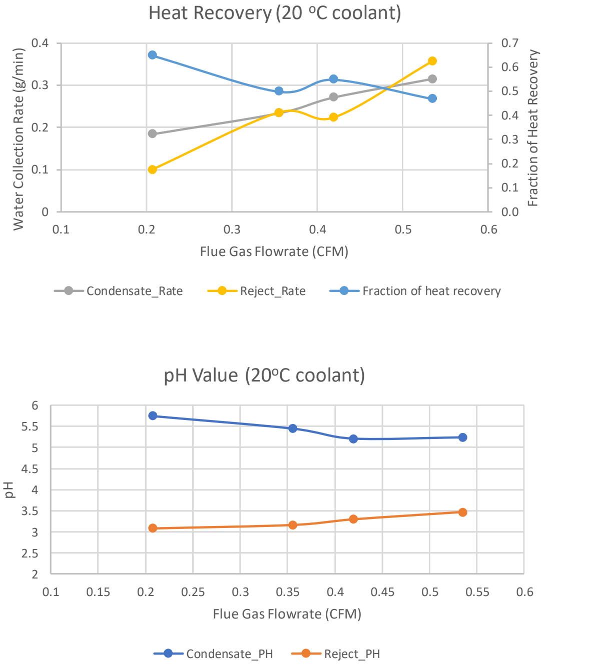

Fig. 5 Impacts of flue gas flow rate (at 148 °C membrane HX inlet temperature, 20 °C coolant).

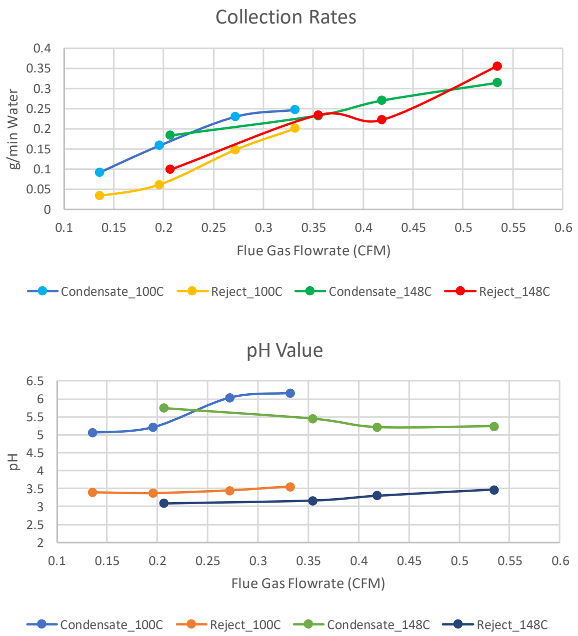

Fig. 6 Impacts of membrane HX inlet temperature (at 20 °C coolant).

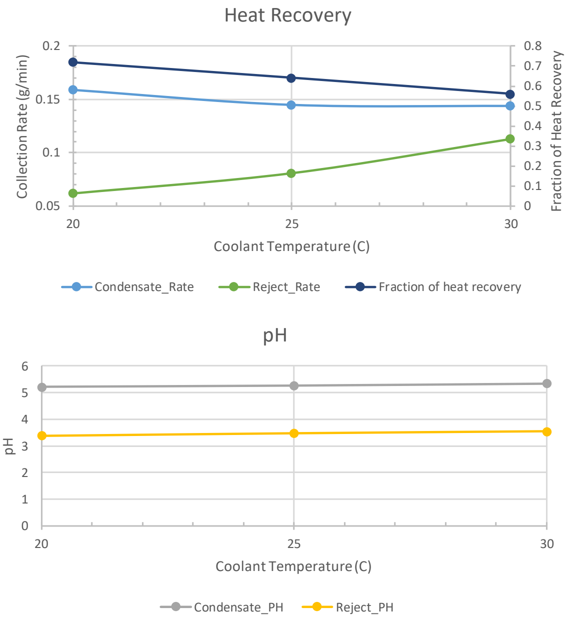

Fig. 7 Impacts of coolant temperature (at 100 °C membrane HX inlet temperature, 0.2 cfm flue gas flow rate).

HX inlet temperatures are investigated: 100 °C to 148 °C. The results indicate that the reject rate increases a little by increasing membrane HX inlet temperature from 100 °C to 148 °C, and condensate rate correspondingly decreases a little. The pH value of reject condensate decreases a little by increasing membrane HX inlet temperature, while the pH of membrane condensate doesn't show apparent relation with inlet temperature.

Impacts of coolant temperature is also investigated, as shown in Fig. 7. The results show that the condensate rate and the fraction of heat recovery decrease by increasing the coolant temperature, while the reject rate increases obviously with an increasing coolant temperature. The maximum fraction of heat recovery is 0.719 when the coolant temperature is 20°C, and the fraction of heat recovery is 0.56 when the coolant temperature is 30°C. The pH values of membrane condensate and reject condensate just slightly increase by increasing coolant temperature, which indicates the coolant temperature almost has no influence on the acidity of the condensates.

V. Conclusions

A bench scale tubular membrane-based condensing heat exchanger was developed and tested on a conventional non-condensing furnace. Test results proved the membrane heat exchanger can recover latent heat of water vapor without generating acidic condensation.

The condensate rate and reject rate increase by increasing flue gas flow rate while the condensate rate decreases with a higher coolant temperature, and the fraction of latent heat recovery decreases by increasing flue gas flow rate and coolant temperature. The fraction of latent heat recovery varies from 39% to 73%. Both sensible and latent heat are recovered. The pH value of membrane condensate decreases with an increasing flue gas flow rate, while the coolant temperature almost has no influence on the acidity of the condensate. The pH value of the membrane condensate varies from 5.0 to 6.3, which means the acidity of condensate through the membrane is 97-99% lower than that of the conventional condensing furnace. Reduced acidity of condensate from membrane heat exchanger means lower cost materials can be used for components in contact with condensate.

The membrane heat exchanger has potential to enable wider market penetration of highly energy-efficient condensing furnaces by reducing costs for dealing with the acid condensation. The results of the parametric study could be the guide for a scale-up, optimal design and operation for the high-efficiency furnaces integrated with the membrane heat exchanger.

ACKNOWLEDGMENT

This work was funded by the Emerging Technologies Program of the Buildings Technologies Office at the US Department of Energy under contract DE-AC05-00OR22725 with UT-Battelle, LLC. This work has been authored by staff of UT-Battelle, LLC, under contract DE-AC05-00OR22725 with the US Department of Energy (DOE). The US government retains and the publisher, by accepting the presentation for publication, acknowledges that the US government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this presentation, or allow others to do so, for US government purposes. DOE will provide public access to these results of federally sponsored research in accordance with the DOE Public Access Plan (http://energy.gov/downloads/doe-public-access-plan).

REFERENCES

[1] EIA (US Energy Information Administration), Annual Energy Outlook 2017,Washington, DC. https://www.eia.gov/pressroom/presentations/sieminski_01052017.pdf

[2] J. Lutz, A. Lekov, P. Chan, C.D. Whitehead, S. Meyers, J. McMahon, "Life-cycle cost analysis of energy efficiency design options for residential furnaces and boilers", Energy, 2006, 31, 311–329.

[3] Energy Star, "Unit Shipment and Market Penetration Report Calendar Year 2016 Summary", 2016, https://www.energystar.gov/ia/partners/downloads/unit_shipment_data/2016_USD_Summary_Report.pdf?e7c1-fc08

[4] M. Z. Hu, C. Engtrakul, B. L. Bischoff, G. G. Jang, T. J. Theiss & M. F. Davis. "Superhydrophobic and superhydrophilic surface-enhanced separation performance of porous inorganic membranes for biomass-to-biofuel conversion applications", Separation Science and Technology, 2016, DOI:10.1080/01496395.2016.1260144.

[5] M.Z. Hu, B.L. Bischoff, M. E. Morales-Rodriguez, K. A. Gray, and B. H. Davison, "Superhydrophobic or Hydrophilic Porous Metallic/Ceramic Tubular Membranes for Continuous Separations of Biodiesel−Water W/O and O/W Emulsions", Ind. Eng. Chem. Res., 2019, 58, 1114−1122.

[6] S.J. Gregg, and K.S.W. Sing, "Adsorption, Surface Area and Porosity", 1982, Academic Press.