ASTFE
American Society
of Thermal and Fluids Engineers

9th Thermal and Fluids Engineering Conference (TFEC)
April, 21-24, 2024
Partially online virtual and in person at Oregon State University, Corvallis, OR, USA
TFEC-2024-50752

DEVELOPMENT OF CLEAN CONDENSING FURNACE USING ADVANCED CATALYST

Zhiming Gao*

Oak Ridge National Laboratory
Oak Ridge, TN

ABSTRACT

A clean condensing furnace was developed by using acidic gas reduction (AGR) catalysts. The AGR catalyst technology is capable of minimizing condensate acidity and NOx emissions in advanced gas furnace. In the study, different AGR catalyst materials were explored. The AGR with low Pt/Rh loading achieves an improved annual fuel utilization efficiency (AFUE) without impairing the performance in achieving neutral condensate and ultralow NOx emissions. The AGR with low Pt/Rh loading enables even better ability to convert NOx. Moreover, the low-cost AGR realizes nearly zero cold-start CO emissions, as is attractive in the battle to keep public safe from dangerous CO in furnaces.

KEY WORDS: Condensing furnace; catalyst; acidic gas reduction; condensate; emissions

1. INTRODUCTION

In the U.S., over 47 million homes use natural gas furnaces for space heating [1], contributing 130.1 million tons of CO_2 as well as substantial environmentally pollutant emissions like nitrogen oxides (NO_x), sulfur oxides (SOx), carbon monoxide (CO), hydrocarbon (HC), methane (CH_4), and other compounds. Two types of residential furnaces, including condensing and non-condensing furnaces, are available in the current market. In a non-condensing furnace, typical 160°C exhaust gases are carried out of the furnace via a chimney that funnels these gases into the outside air. Unlike non-condensing furnaces, condensing furnaces have second heat exchangers that capture the heat from the condensing vapor and reducing the flue gas temperature to less than 40oC. Therefore, condensing furnaces can achieve 10%–20% more energy efficient than non-condensing furnaces. Over the lifetime of a typical furnace (15–20 years), condensing furnaces can result in a lot of energy savings and carbon emissions reduction. However, condensing furnaces generate substantial acidic water, as well as NO_x, CO, HC and methane emissions, exacerbating long-term environmental issues related to soil, water and air [2]. California is enacting new standards for residential and commercial furnace emission levels, i.e. 14 nanogram/joule or less, to limit the amount of NOx emissions released into the air [3]. Acidic condensate removal and treatment, i.e. a secondary drainage system, the potential for frozen condensate, and greater installation and maintenance costs, have also been identified as issues that limits the market penetration of condensing furnaces.

Therefore, we developed a clean condensing furnace technology using advanced catalyst designated for acidic gas reduction (AGR), which can remove more than 99.9% of acidic gases and other emissions, including >95% NO_x redox, and ~100% oxidation of formic acid /CO/HC/CH_4. This leads to a neutral condensate discharge that can be released directly into the sewer system or recycled to use in the indoor humidification, eliminating the need for a secondary drainage system or a condensate neutralizer. Moreover, this technology allows for a simpler and less expensive furnace design by employing a large low-cost secondary HX, which can yield high furnace efficiencies at low cost. In the paper, various precious metal loading in achieving the clean condensing furnace technology were explored.

*Corresponding Author: gaoz@ornl.gov

2. METHODS

2.1 AGR Catalyst and AGR Component

We collaborated with our industrial partner in developing two monolithic AGR catalysts based on two catalyst formulae, including one sample with heavy Pt loading and the other sample with low Pt/Rh loading. The latter reduces the precious metal loading by 38% compared to the former. Moreover, the AGR catalyst with heavy Pt loading was fabricated based on two 400-cpsi monolithic substrate blocks; the AGR catalyst with low Pt/Rh loading was fabricated based on two 300-cpsi monolithic substrate blocks. The AGR catalysts developed are expected to reduce NOx, oxidize CO, HC and CH_4, as well as SO_x trapping removal.

AGR component design, fabrication, and assembly are complete and shown in Figure 1 and Figure 2. The AGR component consists of a 2-liter adsorber shell canister and accessory parts in addition to the monolith adsorber (see Figure 1(a)-1(d)) [2,4]. The AGR catalyst is positioned within the shell canister. A non-toxic silica fiber mat is added between the shell canister and catalyst to fix the catalyst to the metal shell and prevent any vibration. The divergent cone and the convergent cone are used to connect the shell canister and monolith catalyst with accessory parts. In addition, a metal net mounted is added in each cone to avoid the horizontal movement of the catalyst (see Figure 1(b) and 1(d)). In the AGR assembly (see Figure 2), accessory parts include several elbows, tubes and bolted flange clamps, which are used to connect the AGR component to furnace HXs. In Figure 2, the holes along the horizontal tubes are used to connect HXs in a natural gas furnace. The connection via the bolted flange clamps allows easy replacement of the AGR catalyst.

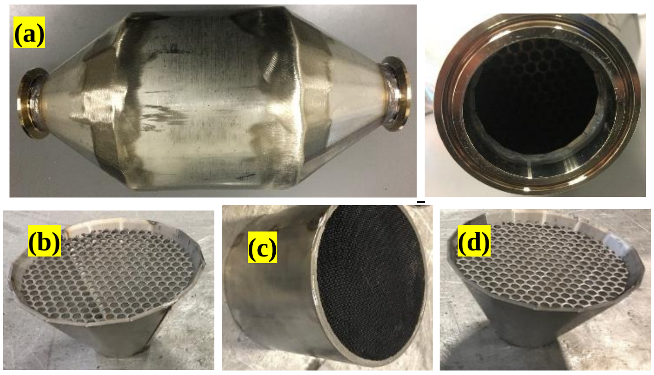

Fig. 1: *The AGR component: (a) the overall AGR component; (b) divergent cone; (c) the 2-liter shell canister with the monolith catalyst; (d) convergent cone.*

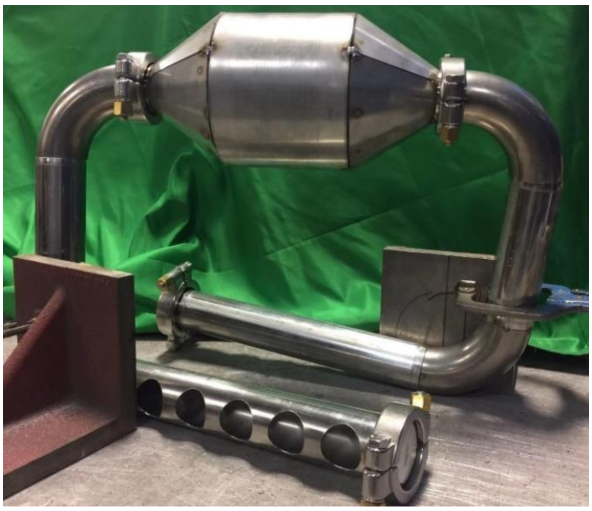

Fig. 2: *The 2-L AGR assembly including accessory parts connected to the primary HXs in natural gas furnaces.*

2.2 Furnace Retrofitting and AGR Integration

A Rheem 80,000 BTU/hr natural gas condensing furnace was retrofitted to integrate the assembled AGR component as shown in Figure 3(a). The AGR component was connected into the third row of the primary HX. Finally, the integrated system is reinstalled into an original Rheem condensing furnace without any geometry modification. The new furnace is shown in Figure 3(b). The retrofitted furnace does not alter original furnace configuration but just includes AGR. This feature can help OEMs to adopt the proposed AGR technology in the project without changing the OEM manufacturing process or adding extra material incremental costs.

Fig. 3: *(a) The integration of the fabricated AGR assembly with the primary HX of the Rheem condensing furnace; (b) the retrofitted furnace with AGR component.*

2.3 Furnace Experimental Setup

The instruments and gas sampling tubes were set up in the retrofitted condensing furnace with AGR component. Figure 3(b) shows the overall configuration with these instruments. Briefly, two Type-K thermocouples and one gas-sampling tube were installed before and after the AGR component, to measure and monitor flue gas temperature and species. The thermocouples were also installed in the second row of the high-temperature serpentine tubular heat. This will be used to monitor the temperature profile of the serpentine tubular heat exchanger. In addition, other testing instruments used for residential furnace, particularly on AFUE and emissions, were installed based on ANSI/ASHRAE standard testing procedures [5].

The AGR-enabled condensing furnace was tested in a furnace testing chamber. Figure 4 shows the overall test-ready unit configuration including the furnace, platinum, gas sampling pipelines and instruments added into the furnace unit. A LABVIEW-based data acquisition system was established to record all the measured data. All appropriate tests follow ANSI/ASHRAE standard testing procedures.

Fig. 4: *The AGR-enabled 80 KBTU/h condensing furnace tested in a furnace testing chamber.*

2.4 AFUE Analysis Tool

The AFUE analysis of residential and light commercial furnaces follows ANSI/ASHRAE Standard 103-2017 (i.e. Method of Testing for Annual Fuel Utilization Efficiency of Residential Central Furnaces and Boilers) [5,6]. The analysis is a complex method based on furnace configuration and specific components equipped. Analysis requires fairly detailed furnace testing and measurement data. Thus, an AFUE analysis tool using Microsoft Excel enabled with VBA was developed. The tool consists of three worksheets: unit and configuration selection; geometry and measurement data input; and AFUE plus key results. Figure 5 shows each sheet of AFUE Analysis Tool. This tool can be used to estimate the AFUE of both condensing and non-condensing furnaces with single-stage, two-stage and step-modulating functions. The tool was validated with experimental data from this project and other ORNL natural gas furnace projects.

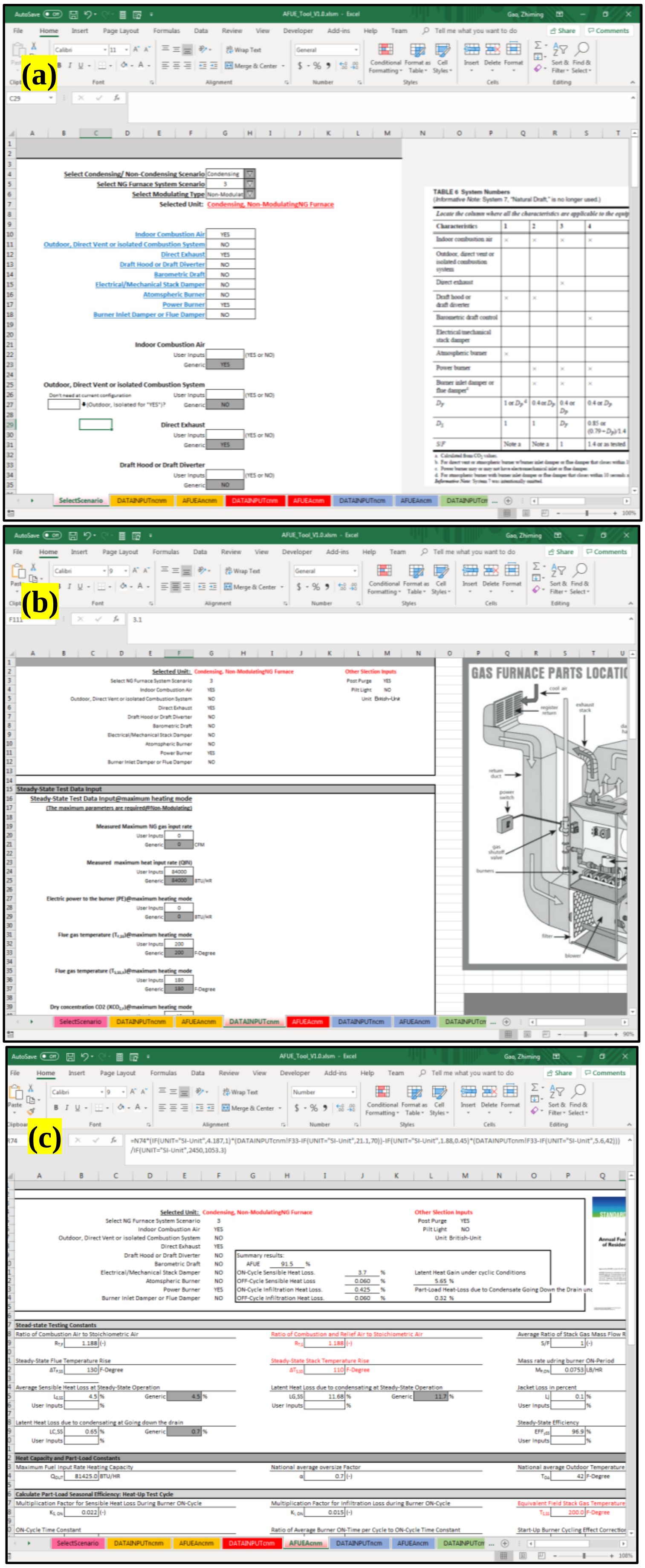

***Fig. 5:** The AFUE Analysis Tool with user-friendly interface, easy-to-use and comprehensive coverage.*

3. RESULTS AND DISCUSSION

The standard testing of the retrofitted condensing gas furnace integrated with different AGR components were conducted to measure the AFUE, condensate pH values, and emissions. Figure 6(a) compares the condensate acidity of the AGR-enabled furnace with the original OEM furnace without AGR component. The pH of the condensate collected from the OEM furnace is around 3, which is more acidity than acid rain = ~ 4.3. The experimental data confirms that the AGR component enables the pH of slightly above 7 in the retrofitted condensing furnace. This indicates that the AGR component removes at least 99.9% of acidic content from the condensate. Compared to the Pt-only AGR sample component, the Pt/Rh AGR sample component achieve the similar performance of neutral condensate.

The capacitance of AGR on NOx reduction is shown in Figure 6(b). Compared to 40 ng/J of NOx emissions from the original OEM furnace, the heavy Pt loading AGR enables the retrofitted furnaces to achieve 2 ng/J of NOx, and the low Pt/Rh loading AGR enables the retrofitted furnaces to achieve ~0 ng/J of NOx. The 0-2 ng/J of NOx represents 0-2 PPM of NOx measured by the instrument, as is already close to the instrument resolution of 1 PPM. Thus, the AGRs decrease the NOx emissions by more than 95% in the tested furnace. In California's South Coast, new regulations for residential and commercial furnace emission require all furnaces installed as of October 2019 to meet 65% lower NOx emissions (from 40 to 14 ng/J or less) [3]. Compared to the 14 ng/J limits under the new standards, the retrofitted furnace integrated with AGRs provides approximately 90% lower NOx emissions, realizing an ultraclean flue gas while simultaneously enabling an eco-friendly condensate.

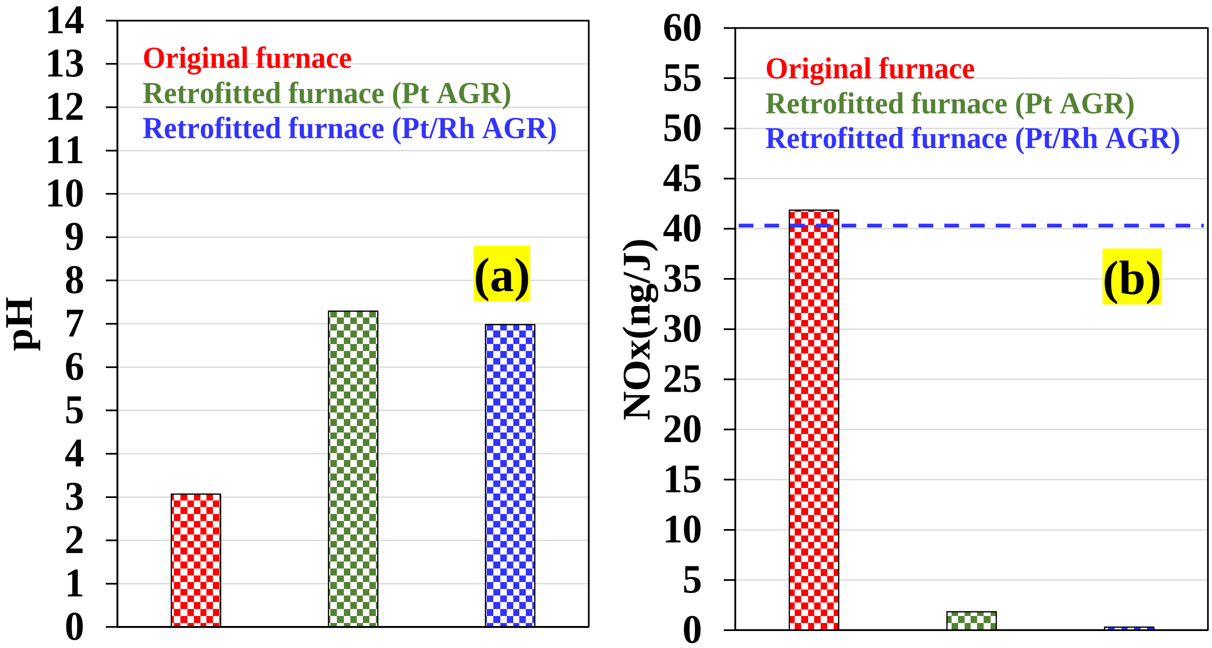

Fig. 6: *(a) Condensate acidity and (b) NOx emissions of the retrofitted furnaces with various AGR precious metal loading compared with the original OEM furnace at 80KBtu/hour.*

Figure 7 displays the comparison of AFUE among the OEM condensing furnace and the retrofitted condensing furnace with different AGRs. The AGRs boost AFUE. The major reason is that the AGRs installed in the retrofitted furnace can oxidize CO, HC, methane and formic acid, although CO, HC, methane and formic acid are limited in flue gas. As a result, the furnace recovers energy from the unburnt fuel energy which typically is lost in the original OEM furnaces. Compared to the heavy Pt loading AGR, the low Pt/Rh loading AGR further improves a AFUE of 1%. The furnace with the Pt/Rh AGR achieves a maximum AFUE of 97%, which is significantly higher than the OEM furnace while achieving less AGR cost.

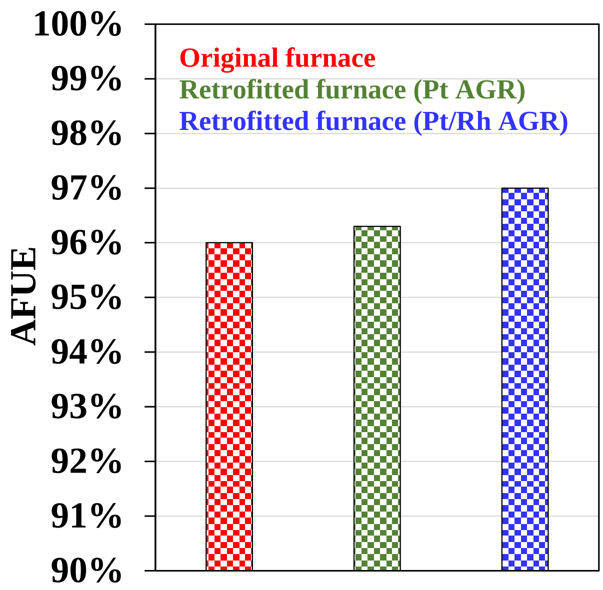

Fig. 7: *AFUE Performance comparison between the retrofitted condensing furnace with the AGR and the original OEM condensing furnace at 80KBTU/HR.*

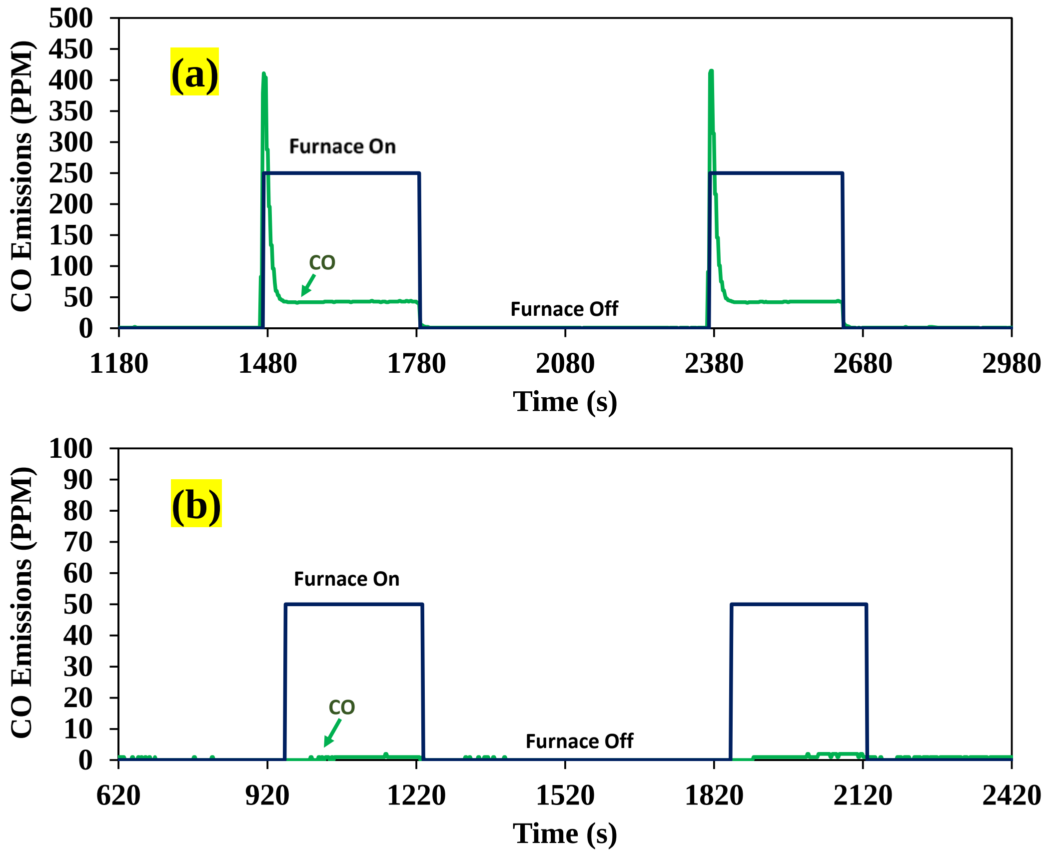

Fig. 8: *Cold-start CO oxidation comparison between the retrofitted condensing furnace with the Pt/Rh loading AGR and the original OEM condensing furnace at the heating capacity of 80 KBtu/hour. (a) the original OEM condensing unit; (b) the retrofitted condensing furnace with the low Pt/Rh loading AGR.*

Figure 8 shows cold-start CO oxidation comparison between the retrofitted condensing furnace with the low Pt/Rh loading AGR and the OEM condensing furnace. Clearly, the AGR enables the furnace at zero cold-start CO emissions compared to up to 400PPM shortly in the OEM condensing furnace. The cold-start CO emissions enabled in the Pt/Rh AGR is attractive in the battle to keep public safe from dangerous CO.

Typically a concentration of 70 ppm of CO is enough to produce acute negative effects in healthy adults, and a concentration of 400 ppm of CO is enough to produce unconsciousness and death over just a couple hours of exposure.

Overall, the monolithic AGR components enable the furnace to efficiently achieve not only 99.9% of acidic gas reduction (including NOx redox to N_2), leading to neutral condensate, but also accomplish formic gas/CO/HC/CH4 oxidation. Therefore, the AGR component can be utilized in a condensing natural gas furnace design to alleviate corrosion and long-term environmental issues associated with acidic condensates and flue gas emissions as well as enabling more efficient furnace operation. The low Pt/Rh loading AGR even results in improved AFUE without impairing the performance in achieving neutral condensate and ultralow NOx emissions.

4. CONCLUSIONS

Clean condensing furnace is achieved by using advanced AGR catalyst. Acidic gas reduction achieved by using AGR catalyst component can minimize furnace condensate acidity and NOx emissions. The AGR catalyst is capable of remove more than 99.9% of the acidic content from the furnace condensate, leading a neutral condensate with a pH of ~7; the AGR catalysts developed enables NOx emissions nearly at 0-2 ng/J; and the AGR catalysts can boost AFUE through the oxidation of CO/HC/CH_4 and formic gas to recover unburnt fuel energy.

The AGR with low Pt/Rh loading achieves an improved AFUE without impairing the performance in achieving neutral condensate and ultralow NOx emissions. The AGR with low Pt/Rh loading actually enables even better ability to convert NOx. Moreover, the AGR with low Pt/Rh loading allows the furnace to realize nearly zero cold-start CO emissions, as is attractive in the battle to keep public safe from dangerous CO. It is potential to develop a cost-effective AGR component enabling a clean condensing furnace and reducing installation and maintenance cost.

While the study focuses on acidic gas reduction in residential condensing furnaces, the AGR technology can also be widely applied for commercial rooftop units, gas heat pumps, gas-fired water heaters, and combustion boilers, etc. [7]. The commercial applications typically generate significantly acidic condensate. AGR technology can substantially alleviate building damage due to substantial acidic condensate.

ACKNOWLEDGMENT

This work was sponsored by the U.S. DOE Building Technologies Office. This research used resources at the Building Technologies Research and Integration Center, a DOE Office of Science User Facility operated by the Oak Ridge National Laboratory. We also thank ORNL colleagues who provided helps in the work.

REFERENCES

[1] EIA. https://www.eia.gov/energyexplained/use-of-energy/homes.php; 2021 [Accessed, 2 April 2022].

[2] Gao, Z, Gluesenkamp, K, Gehl, A., Pihl J., LaClair, T., Zhang, M., Sulejmanovic, D., Jeffrey M., Nawaz K., (2021) "Ultra-clean condensing gas furnace enabled with acidic gas reduction," Energy, 243:123068.

[3] Liberty. https://www.libertyplumbingheatingandair.com/california-new-furnace-emissions-standards/; 2021 [accessed 2 November 2023.

[4] Gao, Z., Momen, A.M., Pihl, J.A., LaClair, T.J., Shen, B., Liu, X., Gluesenkamp, K.R., Parks, I.J.E., Gao, P., Pawlowski, A.E., Nawaz, K. Monolithic gas trap adsorber for high efficiency, cost effective, low-emission condensing furnace. U.S. Patent Application 17/232,274, 2021.

[5] ANSI/ASHRAE. ANSI/ASHRAE 103-2017: method of testing for annual fuel utilization efficiency of residential central furnaces and boilers. 2017.

[6] Gao, Z., Gluesenkamp, K., Gehl, A.C., Pihl, J., Sulejmanovic, D., Zhang, M., et al. Clean Condensing Gas Furnace. No. ORNL/SPR-2022/2430. Oak Ridge National Laboratory, Oak Ridge, TN (United States), 2022.

[7] Gao, Z., Zhang, Y., Qian, S., Yang, W., Wu, Z., Gluesenkamp, K., Nawaz, K. and Gehl, A., (2023) “Nondestructive neutron imaging diagnosis of acidic gas reduction catalyst after 400-Hour operation in natural gas furnace,” Chemical Engineering Journal, 454:140099.