**Acidic Gas Reduction for Residential Natural Gas Furnace**

**Highlights:**

- AGR allows neutral condensate and near zero $NO_x$ emissions from gas furnaces
- AGR catalyst with low Pt/Rh loading enables better ability to convert $NO_x$
- Multiple compact AGR allows the compact the AGR-enabled furnace.

## Introduction

The United States has more than 119 million homes, and 47% of overall households rely on natural gas as their primary heating fuel. Most US homes still use noncondensing units with an annual fuel utilization efficiency (AFUE) of ~80% because of the release of flue gas to the outdoor environment at temperatures exceeding 160°C. One effective approach for improving non-condensing furnace efficiency is to decrease the temperature of the flue gas by using a large, low-cost heat exchanger (HX) to preheat cold air for space heating. However, sulfur, nitrogen, and carbon, which typically exist in natural gas, form key acidic gases (e.g., $SO_x$, $NO_x$, formic gases) in the flue gas. If the flue gas cools below the dew points, the acidic gases combine with water vapor to generate an acidic condensate of pH ~3.42–3.76 [1], which is more acidic than typical acid rain at pH ~4.2–4.4. The acidic condensate can cause serious corrosion and fouling problems. In high-efficiency, condensing natural gas furnaces, a typical strategy of avoiding corrosion and fouling from acidic condensation is to use corrosion-resistant super-ferritic stainless steel alloy HXs [2]. Super-ferritic stainless steel costs 10 times more than regular aluminized steel. This high cost limits the market penetration of efficient condensing furnaces. Meanwhile, current furnaces generate nearly 40 ng/J of $NO_x$ emissions, as well as other emissions such as CO, HC, and $CH_4$. The acidic water, $NO_x$, CO, HC, and $CH_4$ emissions lead to long-term environmental concerns for soil, water, and air. California is enacting new standards for residential and commercial furnace emission levels (i.e., 14 ng/J or less) to limit the amount of $NO_x$ emissions released into the air [3]. The new California standards stipulate fines ranging from $225 to $400 for noncompliance. Thus, a low-cost acidic gas reduction (AGR) catalyst technology [4] is introduced to achieve >95% $NO_x$ redox, 100% $SO_x$ trapping, and ~100% oxidation of formic gas and CO/HC/$CH_4$, enabling a novel condensing natural gas furnace with an ultraclean (i.e., nearly zero) flue gas and neutral condensate that is environmentally friendly.

## AGR and AGR-Enabled Furnace

The two AGR catalyst were fabricated with monolithic substrates washcoating with different catalyst formulations, including (1) low-cost $TiO_2$ and $CuO_2$, with a small amount of the precious metal Pt, and (2) low-cost $TiO_2$, $CuO_2$, $CeO_2$, with a small amount of the precious metal Pt/Rh. One of the key differences between the two formulations is that the Pt/Rh AGR achieves 38% less precious metal loading than the Pt AGR. Figure 1(a)–(d) demonstrate a prototype of the clean and efficient residential natural gas furnace enabled with the AGR component, which was retrofitted from a commercially available 80,000 Btu/h natural gas condensing furnace. The commercial furnace includes six inshot burners in which natural gas is mixed and burned with air. Air is drawn into the furnace burners by an induced draft fan, and natural gas comes in through a valve and rushes through an orifice which siphons in fresh air around venturi openings

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at the head of the burner. The flue gas heats up the house through a high-temperature heat exchanger and a condensing heat exchanger in sequence. The 2 L AGR component was integrated with the primary heat exchanger (HX) in the furnace, where it is connected into the third row of the primary HX. The AGR catalyst is made from a ceramic honeycomb substrate shown in Figure 1(a). It adds a limited pressure drop, but the tested results indicate that a regular induced draft fan installed in the furnace is able to overcome the limited pressure drop penalty. The AGR-enabled furnace experimental setup and testing procedure followed the instrument and testing requirements provided in ANSI/ASHRAE Standard 103-2017 [5]. As a baseline, the OEM furnace was also tested.

The testing results show that the AGR catalysts are capable of continuous $NO_x$ redox and oxidation of $CO/HC/CH_4$ and formic gases. Figure 2 shows the condensate acidity, $NO_x$ emissions, and AFUE comparison of the AGR-enabled condensing furnaces—with the original commercial furnace at 80,000 Btu/h heating capacity. Compared with the acidic condensate of pH ~3.42–3.76 in the OEM furnace, the AGR-enabled furnace enabled an acidic condensate of pH ~7 (Figure 2(a)), which accomplishes 99.9% acidic content removal. Moreover, the results show that AGR enables $NO_x$ emission at levels ranging from 0 to 1 ng/J, which is much lower than the 14 ng/J value for California new furnace emissions standards and 40 ng/J value for US Environmental Protection Agency (EPA) furnace emissions requirements (Figure 2(b)). Figure 3 exhibits how AGR enables ultraclean CO emissions even at cold starts, an advantage in the effort to keep the public safe from dangerous CO. Typically, a concentration of 70 ppm of CO is sufficient to produce acute, negative effects in healthy adults. In addition, although the test furnace is certified to ANSI safety standards with the baseline CO emissions, lower CO emissions would always be preferred to simplify passing ANSI certification and to create larger margins to unsafe operating conditions. Moreover, the oxidation of $CO/HC/CH_4$ and formic gas can recover energy from the emissions and slightly improve the AFUE of the furnace, as shown in Figure 2(c). Compared with the Pt AGR, the Pt/Rh AGR with low precious metal loading achieved better results in $NO_x$ reduction and AFUE improvement. Thus, significant opportunities exist to optimize AGR catalysis at low cost.

The AGR catalyst is also capable of continuously trapping $SO_x$. The typical sulfur concentration in the US natural gas pipeline (i.e., 1 to 4 ppm) is low; therefore, a furnace would need to run several years to degrade the AGR capability for $SO_x$ trapping. The authors' previous results conservatively demonstrated the need for a regeneration event every three years or more [1]. Once the AGR degrades, the AGR component can be disassembled from the furnace for regeneration and to recycle the trapped $SO_x$ in an offline regeneration reactor. This can effectively avoid environmental issues related to $SO_x$ slip. Note that $SO_x$ trapping degradation does not affect the AGR capability in achieving neutral condensate and ultralow $NO_x$ emissions. Furnace manufacturers highly recommend annually scheduled maintenance [6]. Thus, it is appropriate to combine the regular furnace maintenance with AGR regeneration service.

The condensing furnace with the Pt AGT component was operated for approximately 400 h to test long-term reliability and durability. Figure 4(a) shows the pH values of the condensate collected during the 400 h testing period. The recorded pH values remained at ~7, with 99.9% acidic content removal achieved, during the tested period. Meanwhile, all the furnace components, including the fan, combustion system, and control, continued to work normally. Following the 400-h test, $NO_x$ and formic gas/$CO/HC/CH_4$ were still removed effectively or oxidized without a cost penalty. Figure 4(b) compares $NO_x$ emissions before and after the 400 h test. Additionally, the 400 h long-duration test did not occur any incident of flue gas leakage due to the AGR component and did not arise abnormal pressure drop of the AGR component either.

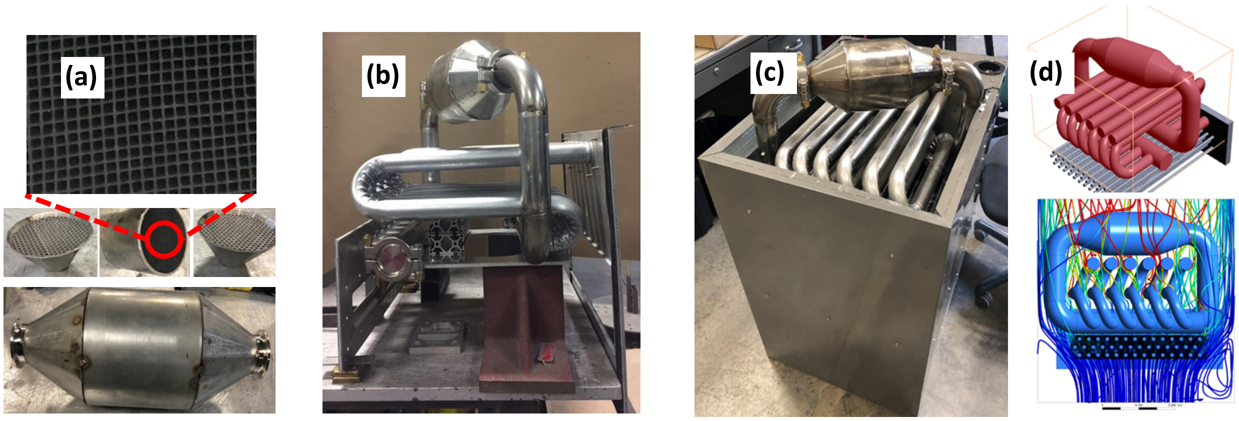


Figure 1: The retrofitted condensing furnace with an AGR component. (a) AGR catalyst and housing; (b) AGR integration with furnace primary HX; (c) a prototype AGR-enabled furnace; and (d) cartoon illustration of AGR integration with furnace primary HX.

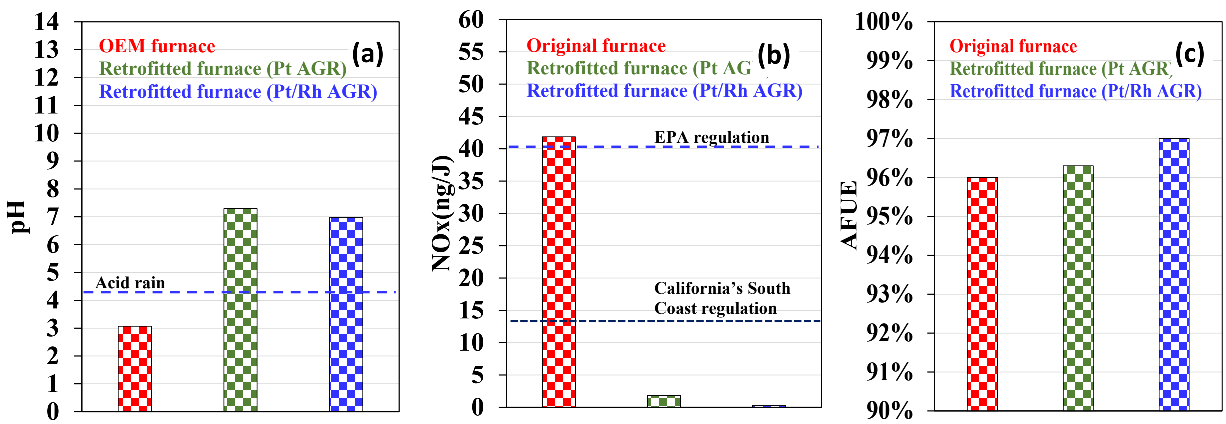


Figure 2: The performance of the retrofitted condensing furnace with AGR component. (a) Condensate acidity; (b) $NO_x$ emissions; and (c) AFUE.

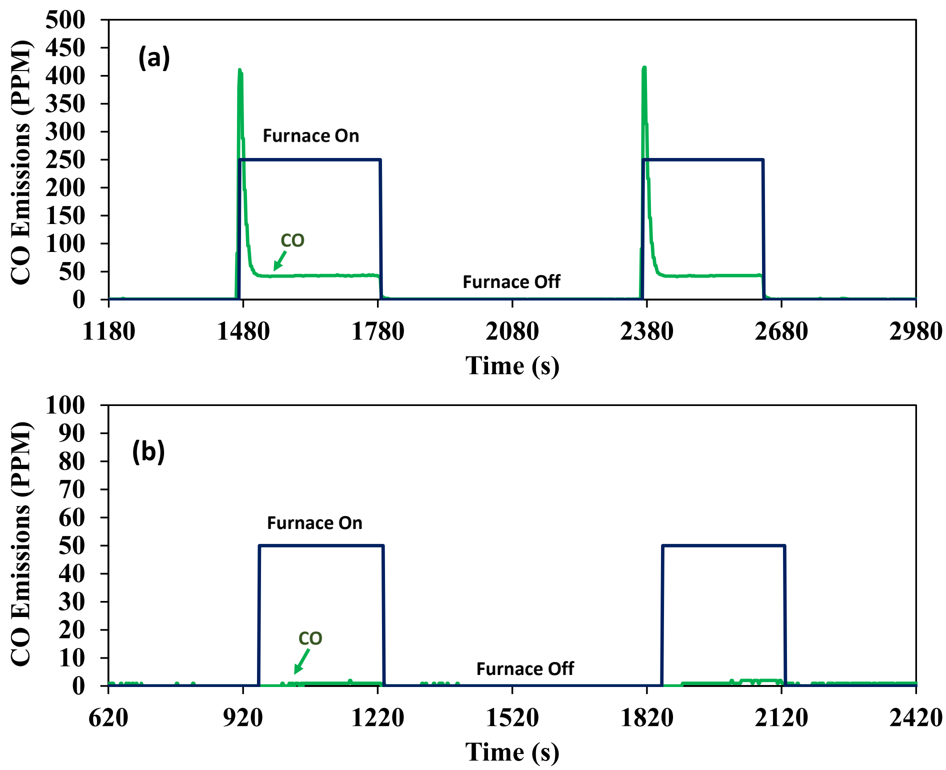


Figure 3: Cold-start CO oxidation comparison between (a) the OEM condensing furnace and (b) the retrofitted condensing furnace with the Pt/Rh AGR.

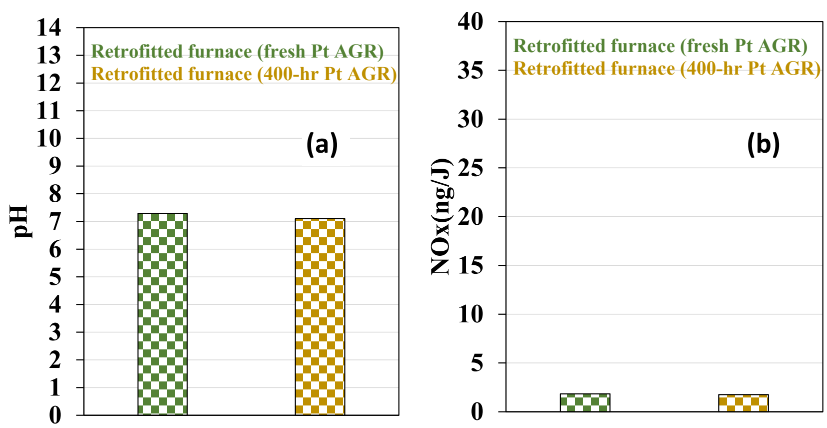


Figure 4: (a) The condensate acidity and (b) $NO_x$ of the Pt AGR-enabled furnace before and after the 400 h test.

## Discussion

Table 1 compares the AGR-enabled condensing furnace prototype with two popular commercial furnace technologies on cost, efficiency, condensate acidity, and emissions control. The overall cost penalty for a 2 L AGR-enabled furnace is \$120, less than the fine imposed by the new California standard. The neutral condensate, as enabled by AGR, allows it to be released into the sewer system or recycled for use in indoor humidification, eliminating the need for a second drainage system. The AGR technology not only allows for simple installation, but also for a more simple and less expensive furnace design by employing a large low-cost secondary HX instead of the specific corrosion-resistant super-ferritic stainless steel alloy HXs used in commercial furnaces. The large low-cost secondary HX can yield high furnace efficiencies at low cost. On the other hand, the novel furnace with AGR does not alter the original commercial unit configuration in the building. All the original furnace components, including the fan, combustion components, and control, continued to operate normally. This indicates high compatibility with commercial furnaces currently on the market. The proposed technology can be adopted without changing the OEM manufacturing process or incurring additional, higher costs. In addition, a significantly optimized space exists for the AGR assembly and integration in the design of new OEM furnace products. The reported AGR integration approach is a single large AGR (Figure 1(d)), but could be multiple compact AGR (Figure 5) with the primary tubular HX of any condensing furnaces. The such assembly style will make the compact AGR and AGR-enabled furnace.

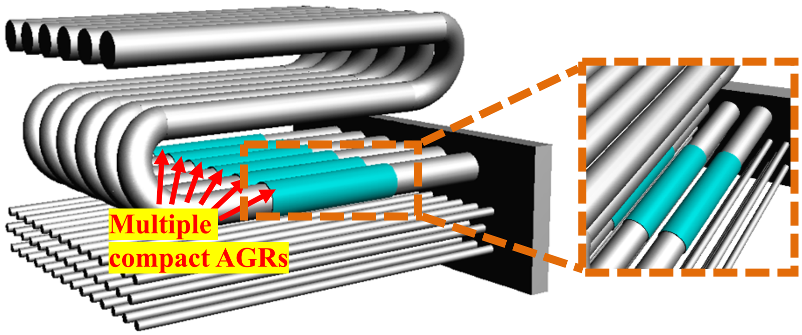


Figure 5: Multiple compact AGR integration with the tubular HX of natural gas furnaces

Table 1: Summary of the retrofitted AGR condensing furnace compared with two commercial furnace technologies, including two-stage modulating condensing and non-condensing furnaces.

| | Noncondensing furnace[a] | 2-stage modulating condensing furnace[b] | Ultraclean condensing furnace with 2 L AGR[c] |
|---|---|---|---|
| AFUE | 80% | 96% | 97% |
| Unit Price ($) | 834 | 1,448 | 1,098 |
| AGR cost ($) | - | - | ~120 |
| Condensate | - | Acidic (pH = 3-4) | Neutral (pH = ~7) |
| NOx emissions | ~40 ng/J | ~40 ng/J | 0-1 ng/J |
| SOx emissions | 1-2 PPM | <1 PPM | 0 PPM |
| Formic gas | 9-14 PPM | 9-14 PPM | 0 PPM |
| CO emissions | 400 PPM (cold start)<br>40 PPM (steady state) | 400 PPM (cold start)<br>45 PPM (steady state) | 1 PPM (cold start)<br>0 PPM (steady state) |
| Condensing heat exchanger | - | Corrosion-resistant stainless-steel alloy heat exchanger | Low-cost alumina alloy heat exchanger |

[a] A commercial 80% non-condensing furnace.
[b] A commercial 96% two-stage modulating condensing furnace.
[c] The furnace with AGR is retrofitted based on a commercial 92% non-modulating condensing furnace.

Overall, the ultraclean flue gas and neutral condensate gained by use of AGR technology enables furnaces to potentially achieve simpler installation, higher efficiency, and environmental protection. All these advantages will help reduce the furnace capital cost, lower installation and maintenance expenses, and grow market adoption of high-efficiency condensing furnaces.

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