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A high turndown, ultra low emission low-swirl burner for natural gas, on-demand water heaters

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Abstract

Previous research has shown that on-demand water heaters are, on average, approximately 37% more efficient than storage water heaters. However, approximately 98% of water heaters in the U.S. use storage water heaters while the remaining 2% are on-demand. A major market barrier to deployment of on-demand water heaters is their high retail cost, which is due in part to their reliance on multi-stage burner banks that require complex electronic controls. This project aims to research and develop a cost-effective, efficient, ultra-low emission burner for next generation natural gas on-demand water heaters in residential and commercial buildings. To meet these requirements, researchers at the Lawrence Berkeley National Laboratory (LBNL) are adapting and testing the low-swirl burner (LSB) technology for commercially available on-demand water heaters. In this report, a low-swirl burner is researched, developed, and evaluated to meet targeted on-demand water heater performance metrics. Performance metrics for a new LSB design are identified by characterizing performance of current on-demand water heaters using published literature and technical specifications, and through experimental evaluations that measure fuel consumption and emissions output over a range of operating conditions. Next, target metrics and design criteria for the LSB are used to create six 3D printed prototypes for preliminary investigations. Prototype designs that proved the most promising were fabricated out of metal and tested further to evaluate the LSB's full performance potential. After conducting a full performance evaluation on two designs, we found that one LSB design is capable of meeting or exceeding almost all the target performance metrics for on-demand water heaters. Specifically, this LSB demonstrated flame stability when operating from 4.07 kBTU/hr up to 204 kBTU/hr (50:1 turndown), compliance with SCAQMD Rule 1146.2 (14 ng/J or 20 ppm NO_X @ 3% O_2), and lower CO emissions than state-of-the art water heaters. Overall, the results from this research show that the LSB could provide a simple, low cost burner solution for significantly extending operating range of on-demand water heaters while providing low NO_X and CO emissions.

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Acronyms and Abbreviations

ANSI	American National Standards Institute
BTU	British Thermal Unit
CO	Carbon monoxide
CO_2	Carbon Dioxide
CSA	Canadian Standards Association
DOE	Department of Energy
GPM	Gallons per minute
J	Joule
in. w.c.	Inches water column
kW	kilowatt
LBNL	Lawrence Berkley National Laboratory
LSB	Low-Swirl Burner
MJ	Megajoules
msd	measured
NDIR	Non-dispersive infrared
ng	nanograms
NO_2	Nitrogen dioxide
NO_X	Nitrogen oxide
NYSERDA	New York State Energy Research and Development Authority
O_2	Oxygen
PG&E	Pacific Gas and Electric Company
ϕ	Equivalence ratio
ppm	Parts per million
R	ratio of swirler inner channel radius to outer channel radius (r_c/r_b)
r_b	Radius of the outer channel of the LSB swirler
r_c	Radius of the center channel of the LSB swirler
SCAQMD	South Coast Air Quality Management District
UHP	Ultra high purity

1 Introduction

In the U.S., approximately 98% of water heaters use a large storage tank to hold preheated water while the remaining 2% are on-demand and produce hot water with minimal storage (< 2 gallons). On average, on-demand water heaters have been shown to be 37% more efficient than storage water heaters (Bohac et al., 2010). The main market barrier to deployment of on-demand water heaters is their high retail cost. State-of-the art on-demand water heaters are expensive in part due to their reliance on multi-stage burner banks that require complex electronic controls. These multi-stage burners are deemed necessary to meet the wide load range of residential on-demand water heaters (i.e. high turndown to supply a wide range of low to high flow rates of hot water), a thermal range wider than many industrial heaters and gas turbines. An effective approach to reduce burner complexity is using a single set of burners connected to a common fuel manifold controlled by one valve. Simplifying the fuel modulating system can reduce manufacturing costs up to 18%, resulting in a reduced payback period, further market penetration, and greater energy savings through increased on-demand water heater sales.

The purpose of this project is to research and develop a cost-effective, efficient, ultra-low emission burner for new natural gas on-demand water heaters in residential and commercial buildings. The new water heater design requires a robust single-stage burner with high turndown that reduces manufacturing costs, increases overall efficiency, and minimizes pollutant emissions. In order to meet these requirements, Lawrence Berkeley National Laboratory (LBNL) researched the application its Low-swirl Burner (LSB) technology for on-demand, gas-fueled water heaters. The LSB is simple, robust, and fuel-flexible; it offers high-performance with ultra-low emissions while requiring less control hardware (Cheng 2008).

In this report, performance metrics for a new LSB design are identified by characterizing performance of current on-demand water heaters using published literature and technical specifications, and through experimental evaluations that measure fuel consumption and emissions output over a range of operating conditions. Next, target metrics and design criteria for the LSB are used to create six 3D printed prototypes for preliminary investigations. Lastly, prototype designs that proved the most promising were fabricated out of metal and tested further to evaluate the LSB's full performance potential. After conducting full performance evaluations, conclusions are drawn and recommendations for future work are provided.

2 Baseline Performance of On-Demand Water Heaters

Performance metrics for a LSB on-demand water heater system were identified by characterizing performance of current on-demand water heaters. Three state-of-the-art on-demand water heaters (see Table 1) were purchased new and characterized using published literature, technical specifications, and experimental methods. Water heaters were selected based on considerations of technology and availability. Preliminary characterization included identifying the burner design, required controls (e.g. number of burner banks, solenoids, control valves), and documenting published efficiency and system specifications (i.e. burner rating, operating range, minimum gas pressure, and overall turndown).

Experiments, conducted at LBNL, characterized water heaters by measuring fuel consumption and emissions output over a range of operating conditions. Specifically, gas consumption, burner firing rate, and exhaust emissions were measured at 1 GPM, 2 GPM, and 4 GPM water flow rates. Emissions measurements included carbon monoxide (CO), carbon dioxide (CO_2), oxygen (O_2), nitrogen oxides (NO_X), nitric oxide (NO), and nitrogen dioxide (NO_2). The following sections provide further details on the experimental setup, equipment, and procedure, as well as calculations for data analysis.

Table 1. State-of-the-art on-demand water heaters selected for characterization

Manufacturer & Model	**Technology**[1]	**Serial Number**	**Rating (Btu/h)**	**Energy Factor Rating**
Rheem RTG-84DVLN	Ultra-low NO_X, non-condensing	RHUNM421211336	11,000-180,000	0.82
Rheem ECOH200DVLN	Ultra-low NO_X, condensing	M0331609365	11,000-199,000	0.94
A.O. Smith ATI-540H-N	Ultra-low NO_X, condensing	1604E001155	15,000-199,000	0.95

[1]Ultra-low NO_X implies the water heater meets SCAQMD rule 1146.2 for on-demand water heaters.

2.1 Experimental Setup

Water heaters were installed in the test facilities at LBNL used for LNG interchangeability and energy efficiency experiments (Rapp and Singer, 2014; Singer et al., 2010). The laboratory test bay was constructed to accommodate both storage and on-demand water heaters. The test bay included a water supply system and outflow water was routed to a laboratory sink. Exhaust venting for storage and on-demand water heaters were built to exhaust combustion gases into the laboratory exhaust system. Water heaters were installed to draw room air for combustion. Schematics of the sampling configurations for the water heaters are shown in Figure 1 and Figure 2; detailed photographs of the water heater installation and sampling configurations are provided in the Appendix. For each experiment, the following variables were recorded and monitored: flue temperature, flue emissions (including CO, CO_2, NO, NO_X, and O_2), ambient temperature, and ambient CO_2.

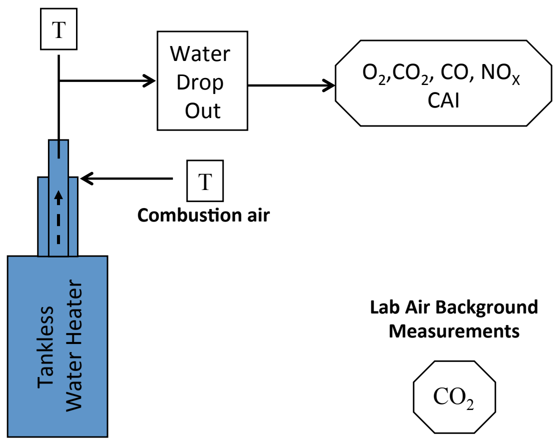


Figure 1. Experimental configuration for the Rheem RTG-84DVLN water heater

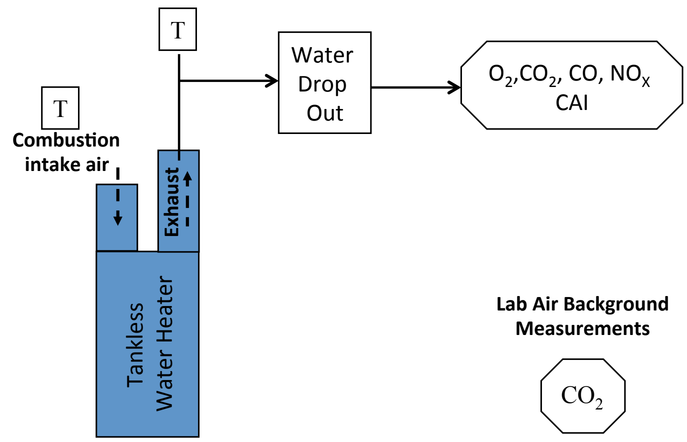


Figure 2. Experimental configuration for the Rheem ECOH200 DVLN and A.O. Smith ATI-540H-N on-demand water heaters.

CO, CO_2, and O_2 in the exhaust stream of the appliance were measured using a CAI 600 non-dispersive infrared analyzer (NDIR). NO and NO_X were measured using a CAI 650 chemiluminescence analyzer. It should be noted that the CAI 650 calculates NO_2 as the difference between NO and NO_X. Ambient CO_2 was monitored using a PP Systems SBA-5 NDIR analyzer. Additional details for equipment used for sampling gaseous analytes can be found in Table 2.

Prior to conducting the first experiment of the day, gas analyzers were operated for a minimum of 30-minutes and then calibrated. Certified calibration gases were used for calibration. Ultra-zero air and ultra high purity (UHP, 99.999%) nitrogen were used to zero the CAI instruments. All calibration gases were placed into Cali-5-Bond calibration bags (calibrated.com/bags) to simplify transportation to the instrument. Bag size was selected to provide a sufficient quantity of gas to allow multiple calibrations. Calibration bags were emptied and refilled daily to maintain purity of the calibration gas. Further details of the calibration gases used for the CAI instruments are shown in Table 3.

Fuel volumetric flow rate was measured using a Singer DTM-115 (1-L dial) dry gas meter and a Fox gas flow meter. The gas transfer lines were primarily ¾-inch steel, with the final connection made with a flexible ¾-inch stainless steel connector sized for the appliance. Water volumetric flow rate was measured using an Omega pulse meter, rated up to 4 GPM, and an inline rotameter. Ambient temperature and exhaust gas temperature were measured using Omega J-type thermocouples. Details for the measurement equipment and its location are summarized in Table 4.

Table 2. Instrumentation and calibration levels for gaseous analytes[1]

Equipment[1]	**Analyte**	**Method**	**Operating Range**	**Linearity/Drift[2]**
CAI NDIR 600	CO_2	Non-dispersive infrared	0–15%	<1% of full scale
	O_2	Paramagnetism	0–25%	
	CO	Non-dispersive infrared	0–200 ppm	
CAI 650	NO & NO_X	Chemiluminescence	0–30 ppm	<1% of full scale
PP Systems SBA-5	CO_2	Non-dispersive infrared	0–1000 ppm	< 1% of span conc.

[1] California Analytical Instruments, Orange, CA (http://www.gasanalyzers.com/); PP Systems, Amesbury, MA (ppsystems.com).
[2] Indicators of accuracy provided by the manufacturer

Table 3. Calibration gases used for experiments

Analyte	**Concentration**	**Rated Precision**	**Balance**	**Supplier**
CO_2	12%	±2%	Air	Praxair
O_2	12%	±2%	N_2	Airgas
CO	30.0 ppmv	±2%	N_2	Airgas
NO	20.2 ppmv	±1%	N_2	Scott Specialty Gases

Table 4. Measurement equipment for all experiments

Measured Quantity	**Location(s)**	**Device(s)[1]**
Fuel volume & flow	Upstream of the water heater	Singer DTM-115 dry gas meter, CFH-Air @ ½" diff, 5 psi W.P., 1- and 1/10-liter dials; flow rate timed by data acquisition system
Water volumetric flow	Before water heater at the cold water inlet after to expansion tank	Omega FTB-4607 pulse meter used for measurement before water heater
Water volumetric flow	After water heater at the hot water supply	A rotameter with ±2% accuracy; used only for on-demand water heater testing
Ambient and Exhaust Gas Temperatures	Ambient temperature was measured near the combustion air inlet. Flue temperature was measured 12-inches into the exhaust vent.	Thermocouple (J-Type), insulated wire, Omega

[1] Singer American Meter (americanmeter.com), obtained via Miners & Pisani, San Leandro, CA; McMaster-Carr rotameter (http://www.mcmaster.com/); Omega Engineering, Stamford, CT (omega.com)

2.2 Experimental Methods for Characterizing On-Demand Water Heaters

Burner experimental operating cycles developed by Rapp and Singer (2014) and Singer et al. (2010), were used to capture key features of realistic use patterns with a total cycle time that would allow completion of three to four experiments – with setup and calibration – in a single day. Originally, the range of operation for each test cycle was intended to capture and characterize the limitations of the burner. However, due to limitations of faucet water supply for the experimental setup, the maximum water flow rate achievable was 4 GPM, which corresponds to about 100,000 Btu/hr output for the water heater burner. Therefore, emission measurements from the LSB when operating above 100,000 BTU/hr will be compared only to SCAQMD Rule 1146.2 NOx requirements. LSB emissions measurements when operating below 100,000 BTU/hr will be compared to emission measurements from the on-demand water heaters. It should be noted that the on-demand water heater experiments were not designed to test the compliance of the water heaters to standards and codes, but instead provide baseline data to compare with the LSB performance experiments.

Water heaters were operated for at least one operating cycle prior to conducting experiments. All experiments were conducted using PG&E line gas. The line gas composition and heating values, supplied by PG&E, were recorded daily and are provided in Table 5.

Table 5. PG&E Line Gas Composition and Heating Values

Manufacturer and Model	Trial	N_2 (%-mole)	CO_2 (%-mole)	HHV (Btu/scf)	Wobbe number
Rheem RTG-84DVLN	Trial 1*	0.59	0.78	1031	1349
	Trial 2*	0.59	0.80	1030	1348
	Trial 3	0.45	0.84	1037	1353
Rheem ECOH200 DVLN	Trial 1	0.45	0.84	1037	1353
	Trial 2	0.46	0.84	1036	1353
A.O. Smith ATI-540H-N	Trial 1	0.46	0.84	1036	1353
	Trial 2	0.46	0.84	1036	1353

[1] Gas quality information provided by PG&E online pipeline data, BTU area J01 (2016).

Prior to conducting formal experiments, a purge burn, lasting at least 10 minutes, was conducted to flush the system and validate water heater functionality. Additionally, burners were operated through a series of short range-finding burns to determine appropriate instrument range and calibration levels. After the purge burn, the water heater was turned off and allowed to cool at least 10-minutes prior to conducting experiments. For each formal experiment, water heaters were operated at three different flow rates intended to cover the vast majority of typical use. The standard flow rates were 1, 2, and 4 gallons per minute (GPM), with 8-minute burns following 10-minute cooling periods. Burners were turned on and off by opening and closing the solenoid valve controlling the hot water supply.

2.3 Data Reduction and Analysis Methods

Raw data from each experiment was collected and analyzed by the following methods to obtain the results reported in Section 3.

Fuel flow rate ($ft^3\ h^{-1}$) was calculated from fuel consumption measured for each burn divided by the total time of the burn. The firing rate was determined by multiplying the calculated fuel flow rate and higher heating value of the fuel.

Exhaust pollutant concentrations of CO, NO_X, NO, and NO_2 are normalized to reference conditions of dry, air-free (0% O_2) and 3% O_2 using measurements of O_2. It should be noted that for this study, NO_2 is estimated as the difference between NO_X and NO as measured by a chemiluminescence detector. The air-free concentration C_i of pollutant i was calculated using the measured O_2 concentration as,

$$C_i(@0\%O_2) = \left(C_{i,msd} - C_{i,bkg}\right)\left[\frac{20.95}{20.95 - O_{2,msd}(\%)}\right], \quad (1)$$

where $C_{i,msd}$ is the concentration of i, $O_{2,msd}$ is the concentration of O_2 (both measured over the period of interest), and $C_{i,bkg}$ is the background concentration of pollutant i. This equation assumes analytes are sampled at the same location as O_2. Concentrations at 3% O_2 were calculated using Equation (2) below:

$$C_i(@3\%O_2) = \left(C_{i,msd} - C_{i,bkg}\right)\left[\frac{20.95 - 3}{20.95 - O_{2,msd}(\%)}\right]. \quad (2)$$

Pollutant emission rates were also normalized to fuel energy (nanograms of pollutant emitted per Joule of fuel energy, or ng/J). Emission rates were normalized to fuel energy to account for variations in energy density associated with fuel composition changes. The calculation is presented in Equation (3), which includes both the input terms and the required unit conversions:

$$E_i\left[\frac{\mu g}{KJ}\right] = \frac{\left(\frac{10^{-6}\text{mol i}}{\text{mol air}}\right)}{\left(\frac{10^{-2}\text{mol CO}_2}{\text{mol air}}\right)}\left(\frac{\text{mol CO}_2}{\text{MJ fuel}}\right)\left(\frac{\text{gram i}}{\text{mol i}}\right)\left(\frac{\text{MJ}}{10^3\text{KJ}}\right)\left(\frac{10^6\mu g}{\text{gram}}\right). \quad (3)$$

The first term on the right-hand side of the equation is the ratio of background-corrected (or air-free) concentration of analyte i (in ppm) to the concentration of CO_2 (in percent). The second term on the right-hand side is calculated based on fuel composition. The third term on the right-hand side is the molecular mass of the analyte. The fourth and fifth terms are unit conversions. This equation is written for the case of near-complete combustion; it can be more generically formulated to consider exhaust carbon – including both CO and CO_2 – rather than carbon dioxide alone. The distinction is important only in cases of very high CO emissions, on the order of thousands of parts per million.

Rearranging Equation (3) yields the following:

$$E_i\left[\frac{\mu g}{KJ}\right] = \left(\frac{C_{i,AF}[ppm]}{Theor.\,CO_2[\%]}\right)\left(\frac{mol\ CO_2}{MJ\ fuel}\right)(M_i)(10^{-1}). \qquad (4)$$

For illustration, consider experiments using a natural gas with 95.8% methane, 2.14% ethane, 0.29% propane, 0.10% butanes, 0.85% N_2, and 0.84% CO_2; this fuel has a Wobbe number of 1333 Btu/scf, a theoretical CO_2 dry exhaust fraction of 0.1183, and 1.11 moles (mol) CO_2 per MJ of fuel energy. Inserting these values into Equation (4) above, and considering the case of CO (molecular mass of 28 grams per mole [g/mol]) sampled directly yields the following:

$$E_i\left[\frac{\mu g}{KJ}\right] = \left(\frac{C_{i,AF}[ppm]}{11.83}\right)(1.11)(28)(10^{-1}) = (0.262)C_{i,AF}[ppm].$$

For this fuel, a dry air-free concentration of 1000 ppm corresponds to a CO emission rate of 262 ng/J.

In order to capture transient and steady-state pollutant emissions, the average emissions measurements are reported for the entire duration of burner operation (full-burn) and during the last 5-miutes of burner operation.

2.4 Preliminary characterization of on-demand water heaters

Technical specifications for the on-demand water heaters are presented in Table 6. The data in Table 6 was collected from published literature, service manuals, and technical specifications.

Overall, the engineering design for the burner and the burner control system for the three on-demand water heaters were very similar. All three water heaters used four valves to control the fuel supplied to the burner assembly, one to regulate the main gas valve line and three to control gas flow to the burner. Air supplied to the burner was controlled using a variable speed fan motor or pulse width modulated fan motor. Technical specifications for the fan motors, which drive combustion air, were not readily available.

The burner designs for all three water heaters were configured to operate using a fuel-rich regime to act as a pilot to improve stability, and fuel-lean (oxygen-rich) regime to complete combustion of gases and meet stringent air emissions regulations (see Figure 3). In order to achieve the rated turn down, the burner was divided into three separate, individually controlled zones (or burner banks) that can fire sequentially or simultaneously to control heat output for heating water, as shown in Figure 4. The overall turndown for the water heaters ranged from 13.3 to 18.2.

Figure 3. Image of Rheem ECOH200DVLN burner as viewed through the site-glass. The small, bright-blue flames are the fuel-rich regime and the pale-blue, almost transparent flames are the fuel-lean (oxygen-rich) regime.

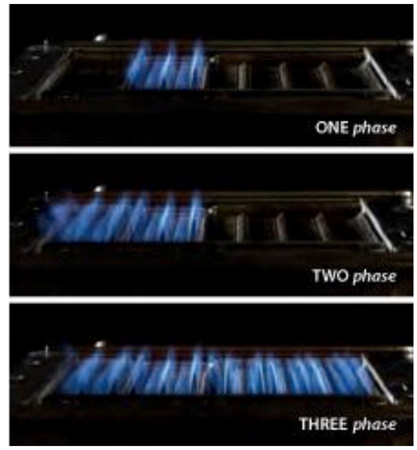


Figure 4. Example of Navien condensing on-demand water heater burner operating in stages, using three burner banks, to control heat output for heating water (Navien, 2013).

Table 6. Technical specifications of on-demand water heaters

Manufacturer & Model	Rheem RTG-84DVLN	Rheem ECOH200DVLN	A.O. Smith ATI-540H-N
Technology[1]	Ultra-low NO_X, non-condensing	Ultra-low NO_X, condensing	Ultra-low NO_X, condensing
Serial Number	RHUNM421211336	M0331609365	1604E001155
Rating (Btu/h)	11,000-180,000	11,000-199,000	15,000-199,000
Energy Factor Rating	0.82	0.94	0.95
Number of Burner Banks	3	3	3
Fuel Control Valves	4 solenoid valves 1 regulating valve	4 solenoid valves 1 regulating valve	4 solenoid valves 1 regulating valve
Minimum Gas Pressure	4.0 in. w.c.	4.0 in. w.c.	5.0 in. w.c.
Max Manifold Pressure	2.8 in. w.c.	3.9 in. w.c.	2.8 in. w.c.
System Turndown	16.4	18.2	13.3

[1]Ultra-low NO_X implies the water heater meets SCAQMD rule 1146.2 for on-demand water heaters.

2.5 Baseline performance of on-demand water heaters

Experimental results for characterizing performance and emissions of on-demand water heaters are presented in Table 7. The emission measurements represent the average, air-free emission over the entire eight-minute burn for each operating condition. The maximum firing rate of the water heaters was not obtained due to the limitations in water flow of the experimental setup, as described previously. Each water heater is rated to a maximum water flow of 10 GPM, but LBNL's experimental facility is only capable of water flows up to about 4 GPM.

NOx emissions for the water heaters along with the SCAQMD Rule 1146.2 requirement (14 ng/J) are shown in Figure 5. The results show that several experiments exceed the SCAQMD Rule 1146.2 limit, but as noted in the Section 2.2, these experiments do not conform to the SCAQMD 1146.2 protocol. Additionally, these experiments were not designed to test the compliance of the water heaters to standards and codes. The purpose of these experiments was to provide benchmark data for designing and testing a future LSB for on-demand water heaters at the LBNL facility.

The turndown for each burner bank ranged from two to four and was estimated by measuring fuel consumption rates over a range of water flow operating conditions. Based on measured oxygen concentrations in the exhaust vent, the water heaters entrain additional air to dilute the exhaust gases before they are vented. Because the exhaust gases are diluted with additional air, the burner equivalence ratio could not be determined based on the O_2 and CO_2 measurements. Equivalence ratio information and blower specifications, which are considered proprietary, will be obtained from the manufacturer and considered when designing a LSB for on-demand water heaters. Additional experimental details and emissions analysis for each water heater experiment can be found in the Appendix.

Table 7. Experimental performance and air-free emissions data measured from on-demand water heaters over entire burn.

		Water Flow (GPM)	CO[1] (ng/J)	NO[1,2] (ng/J)	NO_X[1,2] (ng/J)	Fuel Flow[3] (ft^3 h^{-1})	Firing Rate[3] (kBTU/h)
Rheem RTG-84DVLN	Trial 1*	1	51.2	9.1	16.1	34.1	35.1
		2	31.1	6.5	11.2	54.4	56.1
		4	24.5	4.7	8.3	110	113.4
	Trial 2*	1	36.4	6.5	11.6	33.4	34.4
		2	30.2	6.0	10.7	56.5	58.2
		4	25.0	4.3	7.6	105.4	108.6
	Trial 3	1	37.7	10.3	13.7	29.9	30.9
		2	32.2	8.5	11.7	50.8	52.6
		4	26.7	5.7	8.3	105.5	109.3
Rheem ECOH200 DVLN	Trial 1	1	37.4	14.3	18.0	31.0	32.2
		2	28.6	12.2	14.9	53.0	55.0
		4	21.0	6.0	7.8	78.3	81.2
	Trial 2	1	36.5	14.2	17.9	31.3	32.4
		2	29.5	12.5	15.5	55.6	57.6
		4	20.5	5.9	7.7	103.3	107.1
A.O. Smith ATI-540H-N	Trial 1	1	20.6	3.1	3.9	27.3	28.3
		2	24.1	4.4	6.0	48.7	50.5
		4	58.4	3.2	4.7	100.6	104.3
	Trial 2	1	27.4	8.6	10.9	30.0	31.1
		2	27.9	4.1	5.9	49.6	51.4
		4	47.8	3.0	4.4	96.5	100.0

* Data taken from Rapp and Singer 2014. Note: Water heater outlet temperature was set to 118 °F, not 120°F.
[1] Air-free concentrations (using O_2) averaged over last 5 min of each burn
[2] Calculation assumes molecular mass of NO_2 for NO and NO_X (46 g/mol)
[3] Fuel flow rate (ft^3 h^{-1}) calculated by dividing fuel volume measured from Singer dry gas meter by burn time; firing rate calculated from calculated fuel flow rate and higher heating value from fuel composition. Fuel flow rate, firing rate and manifold pressure calculated over the entire burn.

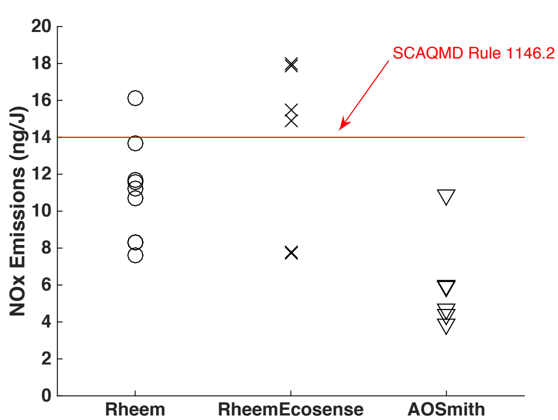


Figure 5. Measured NO_X emissions from three on-demand water heaters averaged over the eight-minute burn. The horizontal line represents SCAQMD Rule 1146.2 (14 ng/J NO_X).

2.6 Low-swirl Burner Performance Metrics

Performance metrics for designing a new Low-swirl Burner for on-demand water heater system were identified by characterizing performance of current on-demand water heaters. Three state-of-the-art on-demand water heaters were characterized using published literature and technical specifications, and through experimental evaluations, measuring fuel consumption and emissions output over a range of operating conditions.

From the published literature, technical specifications, and experimental evaluations, performance metrics for the LSB design are the following:

- Require no more than 3 valves for controlling fuel supplied to the burner
- Comply with SCAQMD Rule 1146.2 (14 ng/J or 20 ppm NO_X @ 3% O_2)
- Operate over a heat output range from 11,000 up to 199,000 kBTU/hr, the standard operating range of most on-demand water heaters
- Demonstrate a turndown of at least 20:1 and up to 30:1
- Maintain a back-pressure equal to or less than the manifold pressure of state-of-the-art water heaters (~ 3 in. w.c.)
- Operate within the limits of the air fan motor and gas supply specifications

Proprietary information such as operating equivalence ratio and fan motor specifications to supply air will be obtained from the manufacturer and considered when designing the LSB for on-demand water heaters.

3 Designing a Low-Swirl Burner for On-Demand Water Heaters

The low-swirl burner (LSB) was first introduced to the research community by Chan et al. (1992) as a useful research burner for fundamental studies of premixed turbulent flames. The LSB was shown to operate stably over a wide range of fuel-air ratios, thermal inputs, and turbulence intensities. NO_X emissions can be as low as a few ppm (Bowman, 1992, Yegan 1998, Cheng (2008)), due to the low flame temperatures generated by lean (oxygen rich) premixed combustion, thus eliminating the need for emission reduction methods such as catalysts, fuel-air staging, or flue gas recirculation. Ultra low NO_X emissions can also be achieved without sacrificing CO emissions or system efficiency.

Due to its capability to stabilize ultra-lean premixed flames with low emissions, the LSB generated interest from the gas appliance industry for use as an economical low NO_X burner. The gas turbine industry has already optimized and integrated the LSB into their technologies and some research has been conducted investigating the feasibility of using an LSB in small boilers and furnaces. However, few advances have been made for optimizing the LSB for residential applications, especially on-demand water heaters.

In this section, target metrics and design criteria for the LSB are used to design and fabricate six 3D printed LSB prototypes for preliminary investigations. Preliminary tests on prototype designs include flame shape evaluation, lean blowoff limit, differential pressure limitations, and turndown. Preliminary experiments were designed to validate the LSB can operate over a heat output range from 11,000 up to 199,000 kBTU/hr (the standard operating range of most on-demand water heaters), achieve a 20:1 turndown, and maintain a back-pressure equal to or less than the target manifold pressure for on-demand water heaters (~3 in. w.c.), and operate within the limits of the air fan motor and gas supply specifications. LSB designs with the most promising results are identified for metal fabrication and full performance evaluation.

3.1 Low-swirl burner design and operation

The practical advantage of the LSB is its design simplicity and wide operating range. The LSB uses a patented swirler to create a high velocity annulus swirl jets surrounding a central non-swirling plug flow. The high velocity annular swirl jets create a radial mean pressure gradient that uniformly diverges the plug flow. This configuration enables the flame to propagate upstream against the decelerating divergent flow and stabilize itself at the position where the local flow velocity equals the flame speed, creating a lifted flame detached from the burner (see Figure 6). LSB flames do not easily blowoff as the flow downstream of the flame zone is slower than the flame speed, while flashback occurrences are limited as the flow upstream of the flame front is generally faster than the flame speed.

Figure 6. The lifted flame produced by the low-swirl burner

3.1.1 Low-swirl burner components

The LSB consists of two major components, a swirler and an exit tube (see Figure 7A). The LSB operates by passing premixed fuel and air through the swirler, and out a straight exit tube (about 4 times as long as the outer radius of the swirler), where the mixture is ignited and a floating flame stabilizes. The stable, floating flame created by the LSB can be described by the following four zones shown in Figure 7A: ① the unburned fuel-air mixture is at too high a velocity to ignite; ② the flow diverges and velocity of the fuel-air mixture decreases; ③ a stable flame is established and burns the fuel-air mixture at a downward velocity that equals the local velocity of the unburned fuel-air mixture exiting the burner; ④: fuel-air mixture has been combusted and combustion products leave the burner.

The swirler is designed to split the flow between a swirling outer channel with a radius of r_c containing swirl vanes at an angle α, and a non-swirling center channel with a radius of r_b containing a perforated plate (see Figure 7B). The center channel is critical to the LSB swirler design because it inhibits recirculation and promotes the formation of flow divergence downstream of the nozzle exit. This establishes a stable, lean premixed turbulent flame. The perforated plate assists with controlling the pressure drop across the swirler, increases turbulence, maintains a uniform flow through the center channel, and controls the division of flow between the inner and outer channels. The ratio, R, of the center channel outer radius, r_c to the outer channel radius of the swirler, r_b, is an important parameter of the swirler ($R = r_c/r_b$) that also relates to the pressure drop across burner.

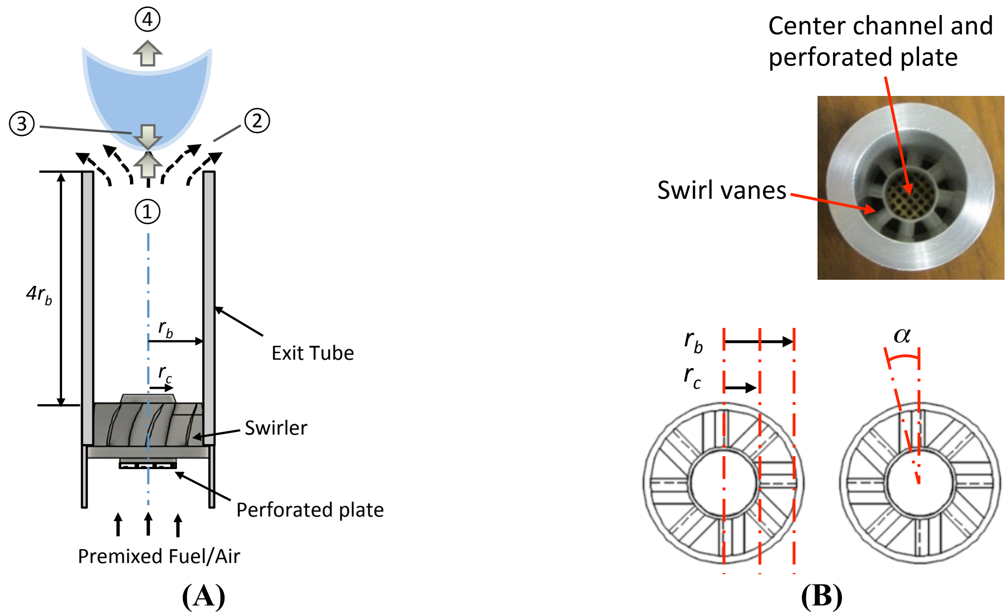


Figure 7. Low-swirl burner design and components. (A) shows the overall burner design and flame stabilization mechanism. (B) shows detailed design of the swirler.

3.1.2 Estimating thermal output and flame stability

Thermal output and the corresponding turndown of the LSB are dictated by the outer diameter of the swirler ($2r_b$) and the velocity of the fuel-air mixture (bulk flow velocity). A basic formula for estimating bulk flow velocity (U_o) as a function of thermal input and area is shown by,

$$U_0 = (\dot{m}_{air} / \rho_{air} + \dot{m}_{fuel} / \rho_{fuel}) / A \qquad (5)$$

where $\dot{m}_{air}$ is the mass flow rate of air, $\dot{m}_{fuel}$ is the mass flow rate of the fuel, A is the cross sectional area of the burner ($2\pi r_b^2$), ρ_{air} is the density of the air, and ρ_{fuel} is the density of the fuel. Thermal heat output is estimated by multiplying $\dot{m}_{fuel}$ by the heating value of the fuel (e.g. 1010 BTU/scf for methane). To appropriately size the burner for a given thermal output range, the minimum and maximum bulk flow velocity are calculated and burner diameter is adjusted until the bulk flow velocity range is within stable operating design limits defined by the equivalence ratio.

Equivalence ratio is a measure of the fuel to air ratio and is defined as the actual fuel-air ratio divided by the stoichiometric fuel-air ratio:

$$\phi = \frac{\left(\frac{\mathrm{m_{fuel}}}{\mathrm{m_{air}}}\right)_{\mathrm{actual}}}{\left(\frac{\mathrm{m_{fuel}}}{\mathrm{m_{air}}}\right)_{\mathrm{stoichiometric}}} \qquad (6)$$

where m_{fuel} is the mass of the fuel and m_{air} is the mass of the air. For fuel rich conditions, ϕ is greater than 1, for fuel lean conditions (oxygen rich), ϕ is less than 1, and for stoichiometric conditions ϕ is equal to 1. If the flame becomes too fuel lean, then the flame extinguishes.

The amount of swirl in the resulting flow is characterized by a theoretical swirl number, *S*. The swirl number is key design parameter for controlling the divergence rate of the LSB flow field and characterizing the amount of swirl in the flow. Definition of the swirl number S is based on the ratio of angular to axial flow momentum in the flow field (Claypole and Syred, 1981) and defined as follows (Johnson et al. (2005); Littlejohn et al. (2002)):

$$S = \frac{2}{3}\tan\alpha \frac{1-R^3}{1-R^2+[m^2(1/R^2-1)^2]R^2} \tag{7}$$

where α is the vane angle from the vertical axis, *m* is the mass flux ration and represents the ratio of the mass flux through the center channel, m_c, and the swirl annulus, m_s, ($m = m_c/m_s$), and *R* is the ratio of the center channel radius and the LSB swirler outer channel radius ($R = r_c/r_b$). For a given *R*, the swirl number, *S*, will increase with increasing flow rate. The term "strong swirl" is applied to those burners with an *S* greater than 0.6 as the onset of recirculation occurs at this level of swirl intensity. Since the LSB stabilizes a flame without using recirculation as a means of stabilization, the LSB should be designed with an *S* below 0.6.

3.1.3 Aerodynamic Drag Coefficient

The aerodynamic drag coefficient is an indicator of the pressure drop across the LSB. The aerodynamic drag coefficient is defined as,

$$C_d = \frac{2\Delta P}{\rho U_0^2} \tag{8}$$

where ΔP is the pressure drop across the swirler, ρ is the density of air, and U_0 is the bulk flow velocity. By rearranging Equation 2 as,

$$\Delta P = \frac{1}{2} C_d \rho U_0^2 \tag{9}$$

the drag coefficient can be calculated by measuring upstream static air pressure at various air flow rates and fitting the results to a second order polynomial.

3.2 Optimizing the low-swirl burner swirler

In order to design an LSB swirler that meets performance metrics for on-demand water heaters, previous research parametrically investigating LSB geometry and design principals were implemented to create a basic geometry. Design considerations included research investigating the LSB's ability to support ultra-lean and highly turbulent flames (Littlejohn et al., 2010; Cheng et al., 2000) and the effects of varying LSB swirler geometries on performance (Therkelsen et al., 2012). This research provided necessary background to design a basic LSB swirler geometry for on-demand water heaters. Specifically, previous research provided design guidelines for the following: flame stability measurements with lean blowoff limits; NO_x and CO emissions; and pressure drop across the swirler.

For flame stability, previous research (Dedat and Cheng, 1995) indicates that the minimum bulk flow velocity be about 6.56 ft/s (2 m/s) for methane-air mixtures around an equivalence ratio of 0.70. The maximum bulk flow velocity is typically limited by the experimental system, not the burner.

For emissions design guidelines, Cheng et al. (2000) measured NO_x emission less than 15 ppm (corrected to 3% O_2) for natural gas firing rate between 719 kBTU/hr (210 kW) and 990 kBTU/hr (280 kW) and an equivalence ratio (ϕ) between 0.8 and 0.9. Reducing the equivalence ratio to 0.7 decreased the measured NO_x emission to 4 ppm (at 3% O_2). These results indicate that the LSB can comply with SCAQMD Rule 1146.2 (14 ng/J or 20 ppm NO_X at 3% O_2) when operating at equivalence ratios less than 0.9 (lean premixed combustion). NO_x emissions are strongly dependent on the flame temperature and in turn equivalence ratio. Therefore, decreasing equivalence ratio further to 0.7 will further decrease NO_x emissions by decreasing flame temperature. Additionally, Therkelsen et al. (2012) also found that the lean blowoff limit, NO_x emissions, and CO emissions are not highly sensitive to the LSB geometric variations. (using methane).

Previous research (Therkelsen et al., 2012) shows that the swirler geometry, specifically vane shape, and the center plat design can be optimized to match the desired pressure drop for a given application. They demonstrated that the drag coefficient is directly proportional to the ratio of swirler channels, ($R = r_c/r_b$) but insensitive to vane angle, α. Therefore, increasing R increases the pressure drop across the swirler. Additionally, increasing the number of vanes will increase the pressure drop across the swirler.

3.3 Preliminary low-swirl burner swirler designs

The main considerations for designing a new LSB for on-demand water heaters will be ensuring it operates over a wide range of turndown ratio at least 20:1 and up to 30:1 with minimum heat input of 11,000 Btu/hr (3.25 kW) and a back pressure equal to or less than 3 inches w.c. (the lowest manifold pressure of state-of-the-art water heaters). These parameters are primarily controlled by (1) burner diameter, (2) the number of vanes, (3) the ratio of the center channel radius to the LSB swirler outer channel radius ($R = r_c/r_b$), and (4) the total flow area blocked by the center plate.

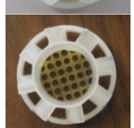
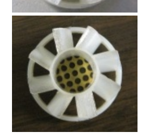
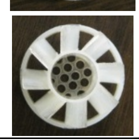
The diameter of the LSB was determined using Eqn. (5), assuming a minimum thermal output of 11,000 Btu/hr (3.2 kW) at a bulk flow velocity of 8.2 ft/s (2.5 m/s), and an equivalence ratio of 0.7. This calculation yields the diameter of the LSB ($2r_b$) to be approximately 1-inch (2.54 cm). At a thermal output of 199,000 Btu/hr (58.4 kW), the calculated bulk flow velocity is 151 ft/s (46 m/s) at an equivalence ratio of 0.7 and 131 ft/s (40 m/s) at an equivalence ratio 0.8.

Based on geometries used in previous research (Cheng et al., 2000; Therkelsen et al., 2012), eight vanes with a curved vane angle of 37° was used as a baseline geometry for all the LSB swirler designs. This number of vanes and vane angle was shown to minimize the pressure drop across the swirler, while still maintaining a stable flame for the desired heat output range.

Center channel, non-swirling, radii were selected using results from previous research (Therkelsen et el., 2012) that demonstrated the pressure drop across the LSB swirler increases with increasing *R*. To minimize the pressure drop across the LSB swirler, while maintaining a stable lean premixed flame over the operating range, center channel radii of 0.25 inches (*R*=0.5) and 0.33 inches (*R*=0.66) were selected.

For preliminary testing, the center plate design was varied to identify optimum operation and stability. The center plate designs also help maintain a uniform radial flow distribution, generate turbulence, and control the swirl number. A range of hole configurations, hole diameters, and flow blockage areas were tested to balance the pressure drop across the bypass and the swirl vanes. Table 8 summarizes the design details for the six LBS swirler identified for preliminary performance testing.

Table 8. Six preliminary low-swirl burner swirler designs for on-demand water heaters.

R=0.66 (r_c=0.33 inch, r_b=0.5 inch)				**R=0.5 (r_c=0.25 inch, r_b=0.5 inch)**			
Swirler Design	Center plate Blockage (hole dia.)	Swirl Number		Swirler Design	Center plate Blockage (hole dia.)	Swirl Number	
SW1	67 % (0.059-inch)	0.49		SW4	65 % (0.047-inch)	0.42	
SW2	68 % (0.067-inch)	0.5		SW5	58 % (0.067-inch)	0.40	
SW3	60 % (0.09-inch)	0.48		SW6	52 % (0.09-inch)	0.39	

3.4 Experimental methods for preliminary evaluation

Preliminary experiments for evaluation the six LSB swirler designs included investigating flame shape, measuring the lean blowoff limit, measuring the differential pressure across the swirlers, and calculating the turndown.

Flame shape provides qualitative information on the stability of a given LSB swirler design and guidance for flame shape when integrating the burner with a combustion system. The lean blowoff limit of methane-air flames is measured by gradually lowering fuel concentration until the flame extinguishes.

The differential pressure across the swirler was measured using a static pressure tap located 1 inch upstream of the swirler and ambient pressure. Because presence of the flame had almost no effect on the differential pressure across the swirler (measurements were within the bias of the manometer), differential pressure measurements were conducted using a non-reacting flow (air only).

Turndown of the LSB was calculated by dividing the measured maximum heat output by the minimum heat output. The maximum heat output was limited to 200 kBTU/hr, the maximum heat output of on-demand water heaters, while the lowest heat output was measured by operating at a bulk flow velocity of about 6.56 ft/s (2 m/s). Although this velocity over estimates the minimum heat output, it was chosen to prevent flashback and preserve the plastic swirlers for additional experiments. The actual minimum heat output, determined by lowering the bulk flow (air and fuel) velocity until the flame extinguished or attached to the swirler, would be measured using the metal sintered swirler designs. At each operating condition, the equivalence ratio (fuel-air ratio) was varied to extend the heat output range, but remained within the limits to meet emissions requirements.

3.5 Low-swirl burner preliminary test results

Results for the performance tests on the six LSB swirler designs (listed in Table 8) are presented in the following sections. Performance tests of the LSB swirler designs include:

- investigating flame shape for stability
- validating stable operation near the lean blowoff limit to meet ultra-low NO_x emission
- validating low differential pressure across the swirler to meet low manifold pressures and blower limitations
- validating heat output range and potential turndown ratio of at least 20:1

3.5.1 Flame shape

Images of methane-air flames generated by different swirler designs at equivalence ratio of 0.65 and a thermal output of 41kBTU/hr (12 kW) are shown in Figure 8. The top images (SW1, SW2, and SW3) use the swirler design with R=0.66, while the bottom images (SW4, SW5, and SW6) are from the swirler design with R=0.5. The images show that the center plate design with smaller diameter holes, and higher swirl number, generates a narrower and taller flame (SW1 and SW4), while the larger diameter holes allow too much of the fuel-air mixture through the center channel of the swirler, generating a smaller and weaker swirled flame (SW3 and SW6). SW2 and SW5 also have similar hole sizes and the same pattern, but the designs show no obvious flame shape and stability benefit over SW1 and SW4 at this single operating condition. The flame images also do not show any obvious difference between the swirlers with different swirler channel ratios, R.

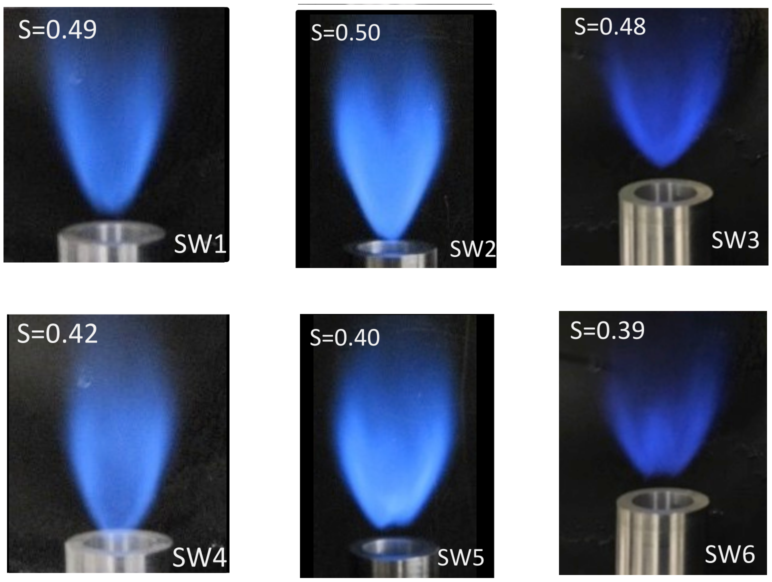


Figure 8. Flame shape from six low-swirl burner swirler designs operating at a heat output of 41kBTU/hr (12 kW) and an equivalence ratio of 0.65.

3.5.2 Lean blowoff limit

Swirler designs SW2, SW4, and SW5 were evaluated to identify the lowest fuel-air ratio (measured by equivalence ratio) at which the flame does not extinguish (i.e. the lean blowoff limit). This limit provides an initial assessment of NO_X emissions, as larger equivalence ratios will generate more NO_X emissions.

As shown in Figure 9, the lean blowoff limit reaches a minimum around 30 kBTU/hr (8.8 kW) and begins to increases with slight deviations between the different LSB swirler designs with increasing and decreasing heat output. However, the lean blowoff limit across all heat outputs for all the swirler designs was less than 0.7, indicating that the swirler designs should meet the ultra-low NO_x emission requirement. Because the lean blowoff limit for SW2, SW4, and SW5 were below 0.7 and similar across the range of heat output, no additional swirlers were tested.

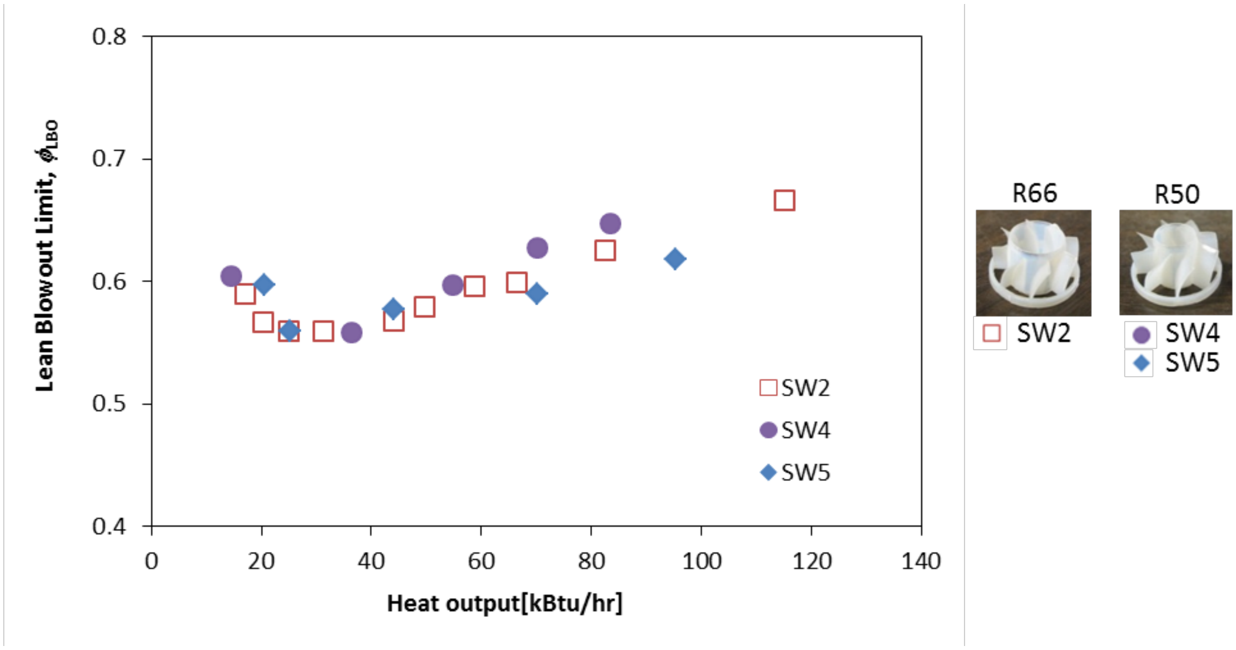


Figure 9. Lean blowoff limit, measured by fuel-air ratio (equivalence ratio), as a function of heat output for swirlers SW2 (center plate blockage area of 68%, R=0.66), SW4 (center plate blockage area of 65%, R=0.5), and SW5 (center plate blockage area of 58%, R=0.5).

3.5.3 Differential pressure across the swirler and air flow requirements

Figure 10 shows the differential pressure across each swirler design as a function of estimated heat output. The estimated heat output was calculated using the bulk flow velocity and assuming an equivalence ratio of 0.65. The lowest pressure in the manifold for commercial water heaters was selected as the target metric (3 in. w.c.) and is indicated by the red dotted line. The results show that the maximum heat output to meet this target ranges from 107 kBTU/hr (31 kW) to 150 kBTU/hr (44 kW), depending on the swirler design. Increasing the equivalence ratio to 0.8 could increase the heat output from the swirler design up to 170 kBTU/hr (50 kW), but may exceed target NO_X emissions.

The LSB with smaller center channel radius of *R*=0.5 resulted lower differential pressures than larger center channel radius swirlers with *R* = 0.66. The differential pressure across the swirler increases with increasing center channel blockage area because it forces more flow through the swirling outer channel. Additionally, the smaller radius center channel swirlers (*R*=0.5) have larger swirl area and a smaller center channel, resulting in lower differential pressures. This combined with center plates with larger diameter holes and less blockage area further reduces the differential pressure across the swirler. Therefore, these results indicate that swirlers SW4, SW5, and SW6 are better suited than the other designs to meet the target intake manifold pressure limit, as they have a smaller center channel radius.

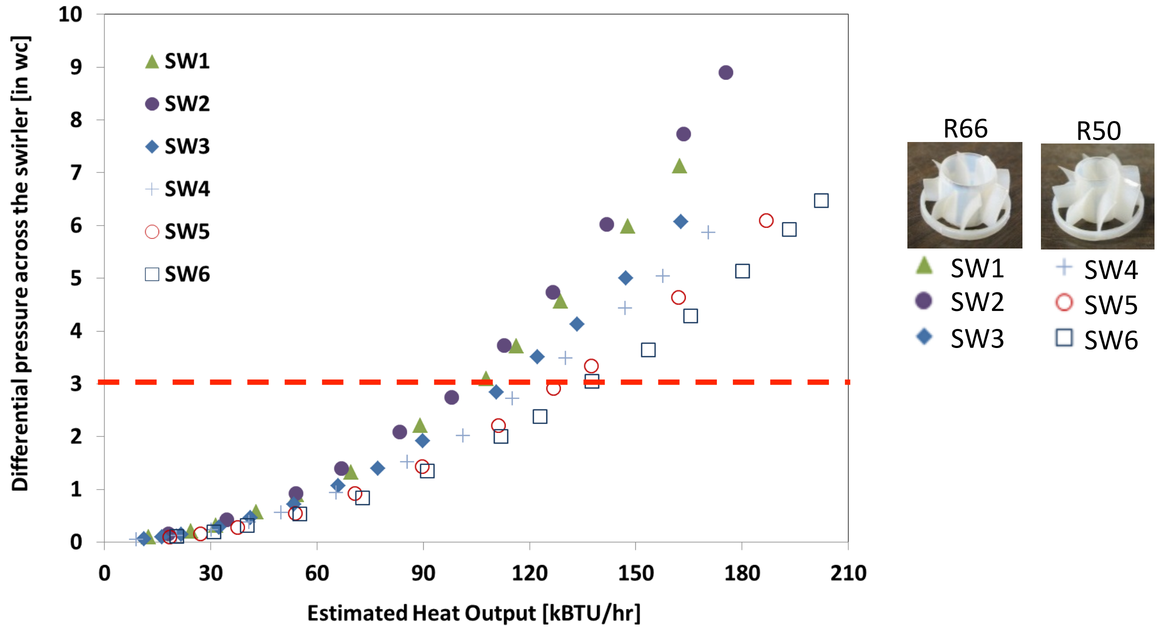


Figure 10. Pressure drop as a function of estimated heat output of six swirler designs. Red dotted line indicated the lower targeted manifold pressure of water heater (~3 in. w.c.). R66 and R50 represent the ratio of the center channel radius to the swirler outer channel radius of 0.66 and 0.5, respectively.

The maximum air flow rate to operate the LSB at 200 kBTU/hr (58.6 kW) was measured to be around 46 scfm (1300 slpm). This air flow rate is within the limitations of a blower for on-demand water heaters. However, as shown in Figure 10, this flow rate may exceed the target manifold pressure.

3.5.4 Turndown

All six LSB swirler designs were capable of stable operation at 200 kBTU/hr (58.6 kW) and the lowest tested heat output of 15,000 Btu/hr (4.5 kW). Stable operation of SW4 and SW5 across the target heat output range is shown in Figure 11. As stated previously, the lowest heat output for these experiments was limited to prevent flashback and damage to the plastic burners. From these preliminary experiments, all the swirlers showed the potential to achieve a turndown ratio of 20:1 or more by extending the lower end of operation. However, swirler designs SW1, SW2, and SW3, (with a larger center channel radius, R=0.66), will exceed the target manifold pressure limit at lower heat outputs than swirler designs SW4, SW5, and SW6. If a higher manifold pressure in the water heater is permitted (as it is with some designs), then a single LSB can be used for the entire water heater operating range. However, if manifold pressure is restricted to a lower limit (3 in. w.c. to 3.9 in. w.c.), then two LSB swirlers, will be required to meet the upper heat output requirement. Use of a single LSB swirler or two LSB swirlers would require no more than 3 valves for controlling fuel supply.

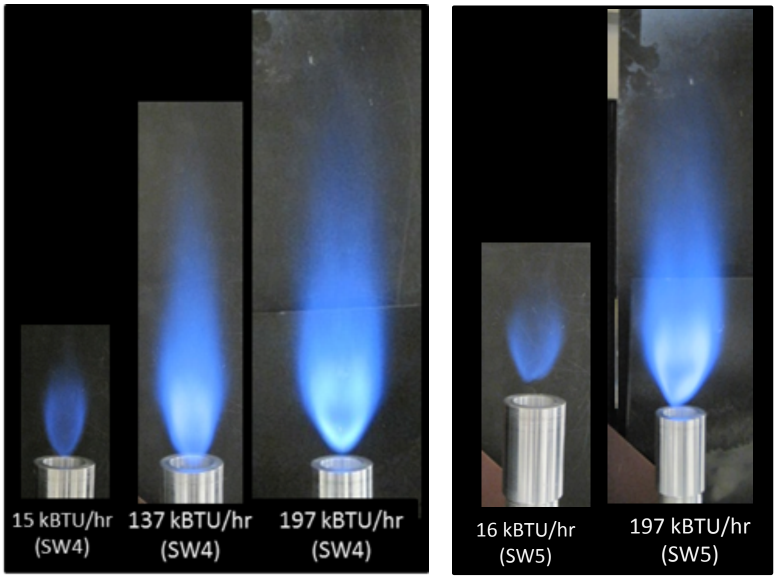


Figure 11. Photographs of stable methane-air flames using SW4 and SW5 operating at the typical heat output limits for on-demand water heaters at an equivalence ratio of 0.65.

3.6 Summary of LSB preliminary design experiments

Based on previous research, and applying the design and operating parameters of on-demand water heaters, the basic geometry of the LSB should be approximately 1-inch (2.54 cm) in diameter with eight vanes at an angle of 37 degrees. From this basic geometry, six LSB designs capable of meeting the performance metrics and design constraints of state-of-the-art on-demand water heaters were fabricated and tested. Three of LSB swirlers have a ratio of center channel radius to swirler outer channel radius of 0.66 (center channel radius of 0.33-inch), while the remaining three have a ratio of 0.5 (0.25-inch center channel radius). Multiple center perforated plate designs with different blockage areas were selected and combined with the two LSB swirlers. Flame shape, lean blowoff limit, differential pressure, and turndown capability within the target heat output range were evaluated.

Experimental results from the six LSB swirler designs indicated that swirler designs SW4 (R=0.5, 65 % blockage area with 0.047-inch diameter holes, and a swirl number of 0.42) and SW5 (R=0.5, 58% blockage area with 0.067-inch diameter holes, and swirl number of 0.4) show the most promise for meeting target metrics for on-demand water heaters. Both designs showed stable operation from 15,000 Btu/hr (4.5 kW) to 200 kBTU/hr (58.6 kW) with the lowest differential pressure.

4 Full Performance Evaluation of Low-Swirl Burner

One of the challenges associated with on-demand water heaters is providing hot water during low-flow use conditions such as hand washing (less than 0.5 GPM or ~2.0 LPM of water flow). State-of-the-art on-demand water heaters provide hot water as low as 0.5 GPM, which corresponds to the lowest operating heat output (~11,000 BTU/hr). Below this flow rate, the water is provided to the user cold.

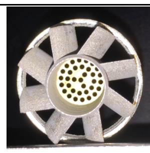
Based on preliminary experiments using the 3D printed plastic swirlers, designs SW4 (R=0.5, 65 % blockage area with 0.047-inch diameter holes, and a swirl number of 0.42) and SW5 (R=0.5, 58% blockage area with 0.067-inch diameter holes, and swirl number of 0.4) proved to be the most capable for extending the lower operating range while meeting performance target metrics. These two swirler designs were fabricated out of metal using direct metal laser sintering for full performance evaluation experiments. These experiments were used to validate that at least one of the LSB swirlers is capable of meeting the following performance metrics:

- Complies with SCAQMD Rule 1146.2 (14 ng/J or 20 ppm NO_X @ 3% O_2)
- Demonstrates flame stability when operating over a heat output range of 11,000 up to 199,000 BTU/hr
- Demonstrates a turndown of at least 20:1 by operating lower than 11,000 BTU/hr
- Meets design target metrics by operating with no more than two LSBs to require no more than 3 valves for controlling fuel supplied to the burner.

4.1 Overview of metal low-swirl burner designs

Preliminary experiments using the 3D printed plastic swirlers indicated that swirlers SW4 and SW5 could extend the low heat output and turndown of on-demand water heaters. Because the absolute lowest operating condition of these swirler designs was not identified during preliminary experiments, due to the risk of damaging the plastic 3D swirlers and rendering them useless, they were printed using direct metal laser sintering for full performance evaluation. Table 9 provides detailed design specifications for metal swirler designs SW4 and SW5.

Table 9: Metal swirler designs for full performance evaluation.

Swirler Design		Center Radius (r_c)	Burner Radius (r_b)	Center Plate Blockage	Center Plate Hole Diameter	Swirl Number
SW4		0.25 inches	0.5 inches	65 %	0.047 inches	0.42
SW5		0.25 inches	0.5 inches	58 %	0.067 inches	0.40

4.2 Experimental methods

To ensure both metal swirler designs meet target performance metrics for on-demand water heaters, turndown and flame stability were first measured and evaluated. The swirler design capable of meeting water heater performance targets and providing the lowest, stable heat output was evaluated further using Particle Image Velocimetry (PIV). The aerodynamic drag and emissions were also measured from the final selected swirler design.

4.2.1 Turndown

Turndown of the metal swirler designs was first measured by operating both swirler designs in the open. The lowest operating point was determined by lowering the bulk flow (air and fuel) velocity until the flame extinguished or attached to the swirler. The highest operating condition was measured by increasing the bulk flow (air and fuel) velocity until the flame blew out. Due to constraints with the experimental setup, and the maximum operating conditions of on-demand water heaters, swirlers were not operated above ~200 kBTU/hr. Additionally, equivalence ratio (fuel-air ratio) was varied to extend the heat output range, but remained within the limits to meet emissions requirements.

4.2.2 Flame stability

In order to increase flame stability and extend the lowest operating point of the burner, a quarl (or diffuser) was added to the burner, as shown in Figure 12. The quarl directs the divergence of the burner fluid flow field and reduces interplay between the flame and the surrounding environment. A quartz enclosure (see Figure 12) was also added to the system to simulate realistic operating condition, as the final burner will be enclosed within an on-demand water heater. Flame stability with the quarl and quartz enclosure was evaluated for both swirler designs at the lowest and highest heat output.

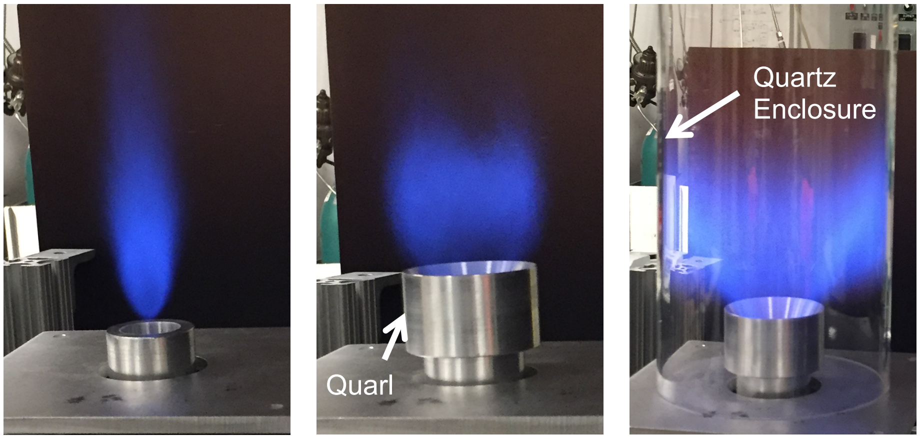


Figure 12. Quarl and quartz enclosure used to extend operating range of the low-swirl burner.

4.2.3 Particle Image Velocimetry

Particle Image Velocimetry (PIV) is a laser-based technique that characterizes the flow patterns of fluid mechanical processes such as a flame. This includes flow velocity, flow direction, and turbulent fluctuations in two dimensions. The PIV system consists of a New Wave Solo PIV laser with double 120 mJ pulses at 532 nm and a Kodak/Red Lake ES 4.0 digital camera with 2048 X 2048 pixel resolution. The optics captured a field of view of approximately 13 cm X 13 cm covering the nearfiled as well as the farfield of the flames with 0.065 mm/pixel resolution. A cyclone type particle seeder seeded the airflow with 0.6-0.8 μm Al_2O_3 particles. Figure 13 shows an image of the laser sheet going through a seeded flame. Data acquisition and analysis were performed using software developed by Wernet (1999). Sets of 300 image pairs were recorded for each experiment to produce mean velocity images.

The flow pattern of the open flame produced by the swirler design with the highest turndown was measured at four operating conditions between 11 kBTU/hr and 199 kBTU/hr (the common minimum and maximum heat output for an on-demand water heater) at a set equivalence ratio (fuel-air ratio). Flow field features were also compared to reference targets to verify the operability of the design.

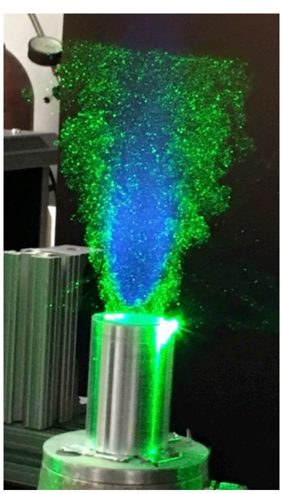


Figure 13. Image of laser sheet (green) through seeded flame (blue)

4.2.4 Aerodynamic drag coefficient

For the swirler design with the highest turndown, differential pressure across the swirler (static pressure upstream of the swirler and ambient) was measured over a range of airflow rates that correspond to the heat output range of an on-demand water heater (11 kBTU/hr to 199 kBTU/hr). The measured differential pressure and Equation 9 were then used to calculate the aerodynamic drag coefficient. The differential pressure across the swirler was also compared to the published manifold pressure of state-of-the-art water heaters (ranges from 3 in. w.c. to 3.9 in. w.c.).

4.2.5 Gaseous emissions

To ensure the LSB design with the highest turndown meets SCAQMD 1146.2 emission requirements and is within emission design targets, CO and NO_X emissions were measured at four conditions corresponding to the PIV data. Gaseous emissions were measured using LBNL's standard procedure by sampling products at the center of the flame using a quarl and quartz enclosure (shown in Figure 14).

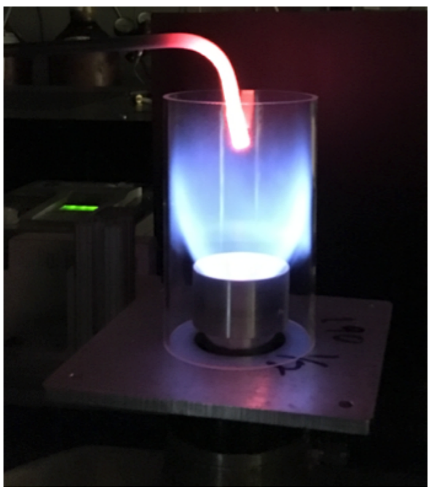


Figure 14. Emissions sampling setup for the low-swirl burner. The probe is placed in the center above the flame.

4.3 Full performance evaluation results

To identify the swirler design most capable of meeting and exceeding on-demand water heater performance target metrics, swirler designs SW4 and SW5 were fabricated out of metal and evaluated for turndown and flame stability. SW4 was evaluated further using Particle Image Velocimetry (PIV) because it met and exceeded water heater performance targets. The aerodynamic drag and emissions were also measured.

4.3.1 Turndown

As stated in the previous section, the maximum heat output tested with both burners was ~200 kBTU/hr due to limitations in the experimental setup and the heat output limit of commercial on-demand water heaters. As shown in Figure 15, the minimum heat output of SW4 was about three times lower than the minimum heat output of SW5 and state-of-the-art on-demand water heaters (~11 kBTU/hr). SW4 has a turndown ratio of 48:1 (operating from 4.08 kBTU/hr up to 196 kBTU/hr), while SW5 has a turndown ratio of 16.5:1 (operating from 12.2 kBTU/hr up to 201 kBTU/hr).

Although SW4 had a significantly higher turndown than SW5, SW5 was capable of operating stably across the heat output range at a single equivalence ratio ($\phi = 0.65$), while SW4 required an increase in equivalence ratio ($\phi = 0.73$) to operate stably at the highest heat output (196 kBTU/hr). This increase in equivalence ratio may result in exceeding emission standards. Additionally, at the lowest heat output, SW4 displayed some instability but did not extinguish during continuous operation. Because SW4 is capable of operating at a much lower heat output than SW5, increasing flame stability of SW4 at the lowest and highest heat output using a single equivalence ratio is highly desirable. One method for improving stability across all operating conditions is by adding a quarl and a quartz enclosure.

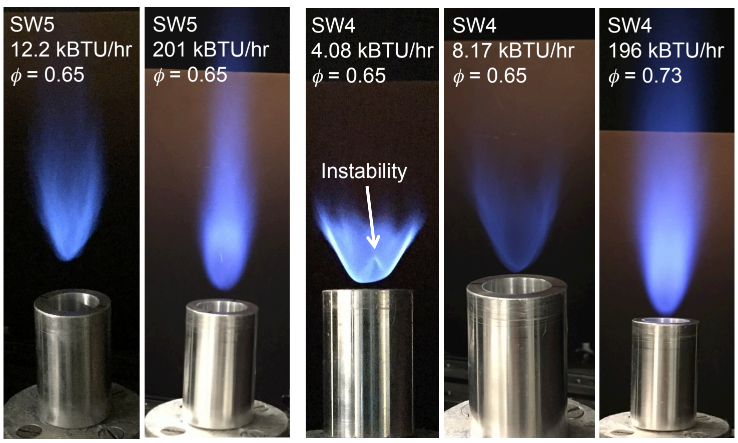


Figure 15. Stable methane-air flames using SW4 and SW5 operating at minimum heat output and maximum heat output before extinguishing. At the lowest operating condition for SW4 (4.08 kBTU/hr), the flame displayed some instability, but did not extinguish during operation. ϕ is the equivalence ratio.

4.3.2 Increasing Flame Stability

To increase flame stability at the lowest and highest heat output, a quarl and quartz enclosure was added to SW4 and SW5. As shown in Figure 16, adding the quarl and quartz enclosure allowed the SW4 to operate with a 50:1 turndown at a single equivalence ratio (ϕ=0.65). For SW5, the quarl and quartz enclosure extended the lowest heat output from 12.2 kBTU/hr to 8.15 kBTU/hr, increasing the turndown ratio to about 25:1. Because SW4 offers the highest turndown and lowest heat output, it was selected for further evaluation (PIV, aerodynamic drag, and emissions).

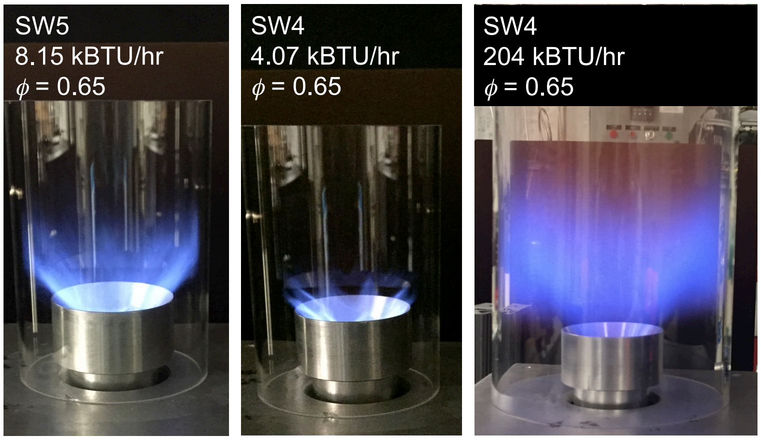


Figure 16. Increasing flame stability and extending operating range of SW4 and SW5 using a quarl and quartz enclosure.

4.3.3 Flame Flow Field using PIV

Centerline velocity and the flame flow field of swirler design SW4 was investigated using PIV. The centerline velocity profiles, shown in Figure 17, indicate that the flame becomes unstable at the lowest heat outputs (less than 38 kBTU/hr) because the axial velocity of the bulk flow (u_z) at the LSB exit is approaching the flame speed. Even slight variations in flow uniformity can influence the formation of the divergent flow and cause a flame shift. Using a quarl to guide the divergent flow (and also shield the near-field region from interacting with room air) can stabilize the flame for use in on-demand water heaters, as shown in the previous section.

At higher heat outputs (greater than 38 kBTU/hr), the velocity profiles are more consistent, as the turbulent divergent flow is fully developed and assumes similarity features reported by Cheng et al (2009). A large recirculation (indicated by negative values of u_z/U_o) is also formed. The trends of these profiles are consistent with those measured previously on larger LSBs (Cheng, 2009). Because swirler SW4 has a higher swirler number than other LSB developed for commercial use (attained by have a larger blockage of the center plate), the flame position is close to the burner exit. Consequently, the near-field divergent flow, shown by an immediate decrease in u_z/U_0 at the burner exit, is not well captured by PIV.

Figure 18 compares the velocity vector flow filed obtained in from swirler SW4 (1-inch diameter at 108 kBTU/hr) and an LSB developed for use in a turbine (2.75-inch diameter at 300 kBTU/hr). The bulk flow velocity of SW4 is higher than the bulk flow velocity of the LSB developed for a turbine. Despite the differences in the bulk flow velocities, the basic features of the velocity fields are the same. The two high velocity swirl regions that formed at the burner rim are clearly shown. In the center, a low velocity region where the flame stabilizes is also shown. Both swirlers show the formation of recirculation zones (blue regions in the center of the images). Due to the higher bulk flow velocity and higher swirler number for SW4, the size and strength of its recirculation zone is larger and stronger than the other LSB. These results also agree well with previous data (Therkelsen 2012) that shows an upstream drift in the recirculation location with increase velocity in addition to stronger flow recirculation with increasing swirl number.

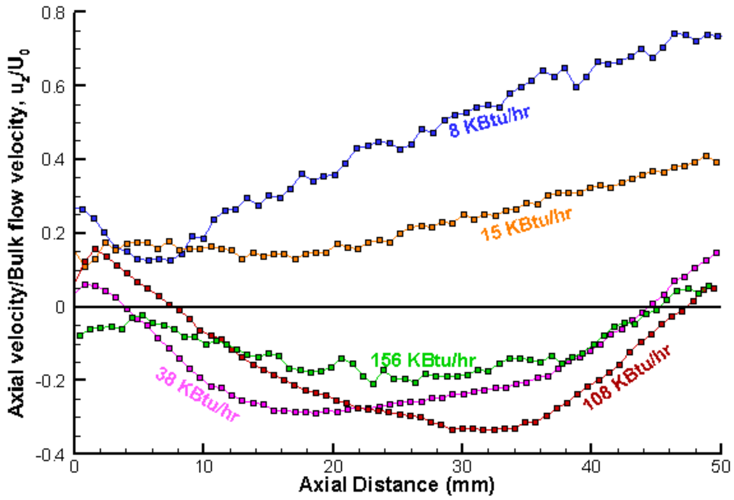
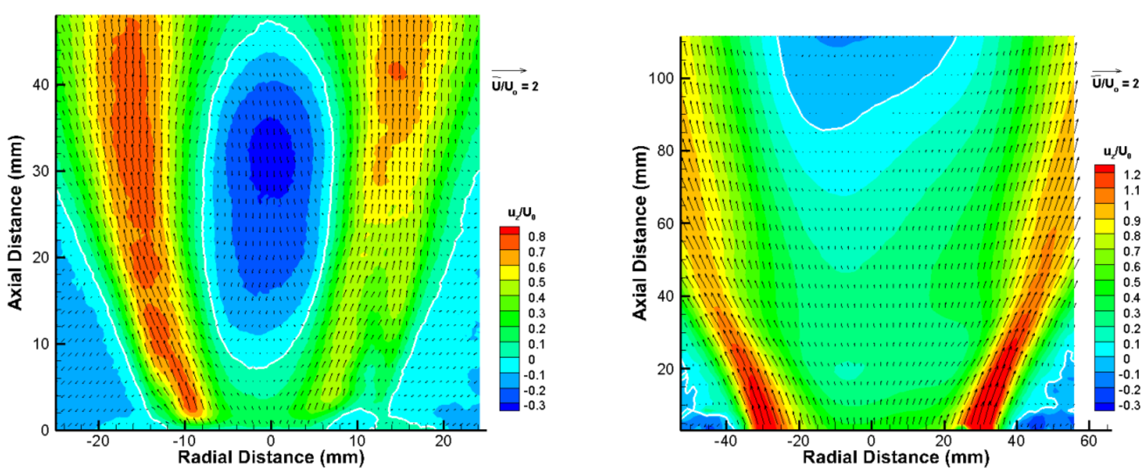


Figure 17. Centerline velocities measured using PIV. Heat outputs less than 38 kBTU/hr show flow instabilities while higher heat outputs show stability as the turbulent divergent flow is fully developed.



SW4 Swirler
(1-inch, 108 kBTU/hr)

Turbine Swirler
(2.65-inch, 300 kBTU/hr)

Figure 18. Velocity vector flow field of swirler SW4 developed for on-demand water heaters and a swirler developed for use in a turbine.

The PIV data shows that the performance and flow features of swirler SW4 are the same as larger LSBs. However, the data obtained at low firing rate (low bulk flows) are significantly different. Since the set of PIV data on SW4 are the first of its kind for low bulk flow velocities (less than 3 m/s), much fundamental knowledge can be gained from the LSB flow field by conducting a more detailed analysis in the flow transition regimes.

4.3.4 Aerodynamic Drag Coefficient

The differential pressure across SW4 as a function of estimated heat output is shown in Figure 19. The estimated heat output was calculated using the bulk flow velocity and assuming an equivalence ratio of 0.65. Using this data and Equation 3, the drag coefficient for SW4 was calculated to be 0.73 and is an indicator of the low differential pressure across SW4.

The lowest published pressure in the manifold for commercial on-demand water heaters, 3 in. w.c., was selected as the target metric and is indicated by the red dotted line in Figure 19. The results show that the maximum heat output to meet this target is about 170 kBTU/hr. If a higher manifold pressure in the water heater is permitted (as it is with some designs), then a single LSB can be used for the entire water heater operating range. However, if manifold pressure is restricted to a lower limit (3 in. w.c. to 3.9 in. w.c.), then two LSB swirlers, likely SW5 as it has the lowest differential pressure, will be required to meet the upper heat output requirement. Use of a single LSB swirler or two LSB swirlers would require no more than 3 valves for controlling fuel supply.

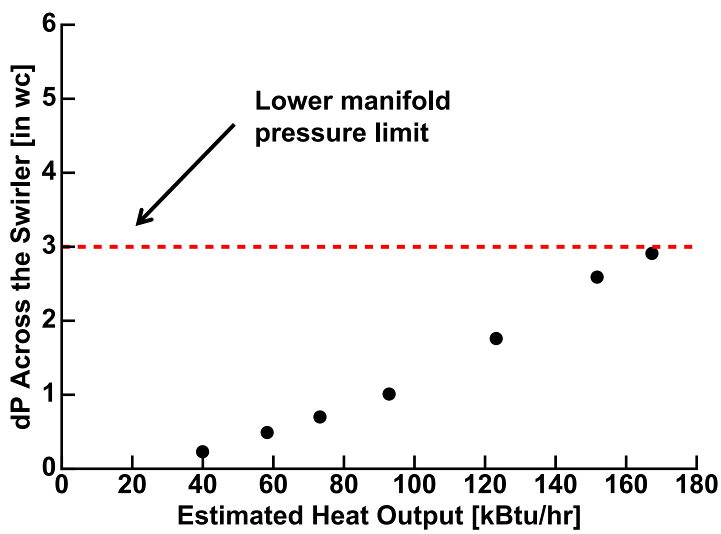


Figure 19. Pressure drop as a function of estimated heat output of swirler design SW4. Red dotted line indicated the lower targeted manifold pressure of water heater (~3 in. w.c.). The calculated drag coefficient of SW4 is 0.73.

4.3.5 Gaseous Emissions

Gaseous CO and NO_X emissions measured from SW4 at a constant equivalence ratio (ϕ=0.65) using a quarl and quartz enclosure are shown in Figure 20 and Figure 21. As shown in Figure 20, NO_X emissions measured from SW4 for all operating conditions were below SCAQMD Rule 1146.2, with a maximum of about 12 ng/J when operating at about 200 kBTU/hr. Unlike the on-demand water heaters tested, NO_X emissions for SW4 increased with increasing heat output. This increase is due to the increase in temperature caused by the quartz enclosure.

Much like NO_X emissions, CO emissions also increased with increasing firing rate for SW4 (see Figure 21). This increase is due to the flame interacting with the quartz enclosure. Although CO emissions increased with increasing heat output, the maximum CO measured from SW4 was still less than the lowest CO emissions measured from the state-of-the-art on-demand water heaters.

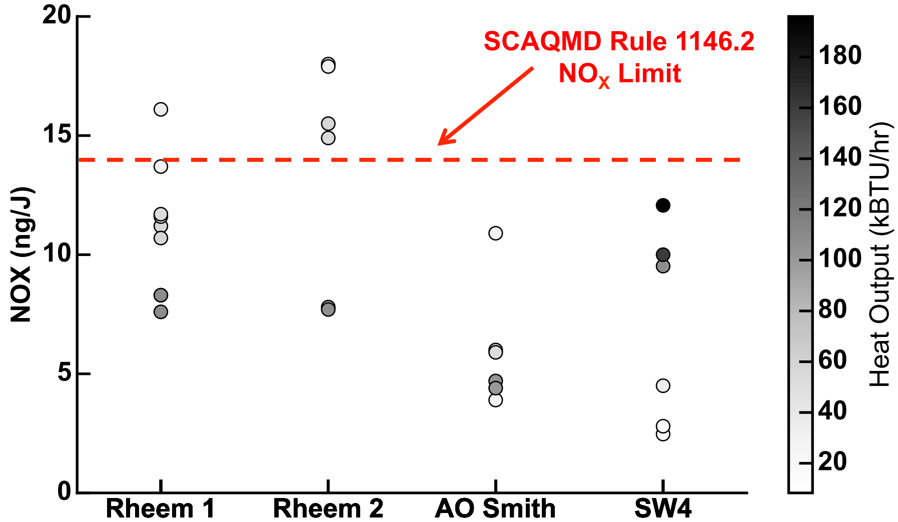


Figure 20. Gaseous nitrogen oxide (NO_X) emissions from state-of-the-art on-demand water heaters and SW4 measured using a quarl and quartz enclosure at a constant equivalence ratio, ϕ, of 0.65.

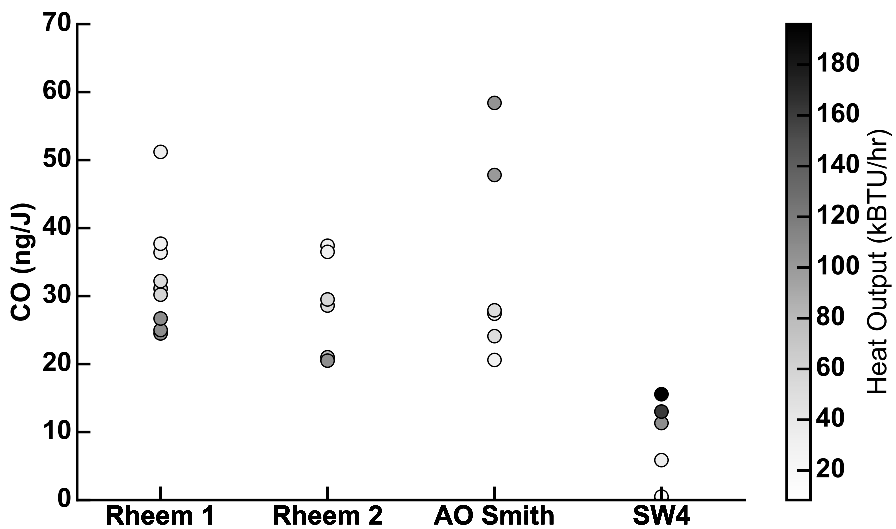


Figure 21. Gaseous carbon monoxide (CO) emissions from state-of-the-art on-demand water heaters and SW4 measured using a quarl and quartz enclosure at a constant equivalence ratio, ϕ, of 0.65.

4.4 Summary

Full performance evaluation on two swirler designs revealed that swirler design SW4 (R=0.5, 65 % blockage area with 0.047-inch diameter holes, and a swirl number of 0.42) was capable of meeting or exceeding almost all the target performance metrics for on-demand water heaters. Specifically, swirler SW4 demonstrated the following:

- Flame stability when operating from 4.07 kBTU/hr up to 204 kBTU/hr (50:1 turndown) at a single equivalence ratio (f = 0.65) with a quarl and quartz enclosure
- Compliance with SCAQMD Rule 1146.2 (14 ng/J or 20 ppm NO_X @ 3% O_2)
- Lower CO emissions than state-of-the art water heaters
- If a higher manifold pressure in the water heater is permitted (as it is with some designs), then a single LSB can be used for the entire water heater operating range. If manifold pressure is restricted to a lower limit (~3 in. w.c.), then two LSB swirlers will be required to meet the upper heat output requirement. Use of a single LSB swirler or two LSB swirlers would require no more than 3 valves for controlling fuel supply.

5 Conclusions and Recommendations

The results from this research show that the low-swirl burner (LSB) could provide a simple, low cost burner solution for significantly extending operating range of on-demand water heaters while providing low NO_X and CO emissions. Specifically, the LSB is capable of a 50:1 turndown, operating from 4.07 kBTU/hr up to 204 kBTU/hr while meeting SCAQMD rule 1146.2 (14 ng/J or 20 ppm NO_X @ 3% O_2). Follow-on research should include demonstrating the performance, turndown, and emissions improvements of the LSB by building and testing a prototype on-demand water heater test system in a laboratory setting. The laboratory prototype should be tested over a range of operating conditions and meet target performance and controls metrics, including compliance with ANSI Z21.10.3/CSA 4.3 (CSA America 2011), Energy Star (DOE 2009), and SCAQMD Rule 1146.2 (SCAQMD 2006). Additional research should be conducted to identify engineering challenges associated with integrating the LSB into an on-demand water heater. Other applications for the high turndown, ultra-low emissions, and fuel flexible LSB should also be explored.

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7 Appendix

A.1 Detailed Results for Rheem RTG-84DVLN

This Rheem direct vent, ultra-low NO_X (SCAQMD rule 1146.2 compliant) on-demand (tankless) water heater was installed in the test facilities at LBNL (see Figure A1). Table A1 provides a summary of the water heater information. Because the water heater is direct, power-vented, and uses concentric venting, the emissions sample lines and flue thermocouples were installed into the exit of the exhaust vent, shown in Figure A2. Temperature was sampled 12-inches into the exhaust vent and emissions were sampled 12-inches into the exhaust vent.

Data was previously collected on this water heater and the results are reported in Rapp and Singer (2014). To confirm experimental setup and data analysis, the water heater was operated for one experiment using the PG&E line gas. During this experiment, the water heater temperature was set to 120°F outlet water temperature and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. Pressure at the dry gas meter was 7 inches of water when the water heater was not operating and decreased to 6 inches of water when the water heater was operated. Detailed emissions measurements from this water heater are presented in Figure A3 and Tables A2 to A5.

Figure A1. Experimental setup for Rheem RTG-84DVLN installed in laboratory. Exhaust temperature probes and emissions sample port are located at water heater vent exit.

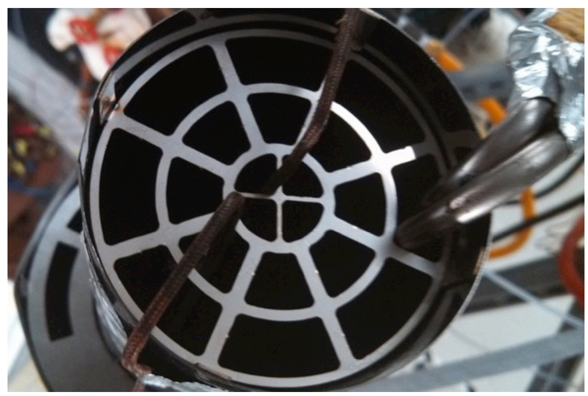

Figure A2. Detailed image of temperature probes and emissions sampling probes for Rheem RTG-84DVLN. Emissions was sampled 12-inches into the exhaust vent. Exhaust temperature was measured 12-inches into the exhaust vent in two locations.

Table A1. Appliance and burner information.

Burner category	Indoor, direct vent, ultra-low NO_X, automatic instantaneous water heater
Technology	Indoor, fan assisted, direct vent, SCAQMD rule 1146.2 compliant; contains an integrated condensate collector for vent, but is NOT considered a condensing unit.
Appliance manufacturer	Rheem
Model	RTG-84DVLN
Serial number	RHUNM421211336
Capacity	8.4 GPM @ 35°F rise 6.6 GPM @ 45°F rise 3.9 GPM @ 77°F rise
Recovery rating	184 Gallons/hr
Energy factor rating	0.82
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	4.0 in. w.c.
Manifold Pressure	2.8 in. w.c. (for max burner input)
Electrical rating	120 V, 60 Hz, < 2 Amps
Max burner input	180,000 Btu/hr
Min burner input	11,000 Btu/hr

Table A2. Burner operating times, fuel flow, firing rate, and sampling conditions for experiments with on-demand water heater RTG-84DVLN.

Burn Time	Fuel Flow ($ft^3\ h^{-1}$)	Firing Rate (kBTU/h)	Fox Fuel Flow ($ft^3\ h^{-1}$)	Fox Firing Rate (kBTU/h)	Air Temp[1] (°C)			Water Draw[2] (GPM)		
16:24:26-16:32:29	29.9	30.9	28.7	29.7	19.9	±	0.03	1.1	±	<0.1
16:42:33-16:50:33	50.8	52.6	48.5	50.3	19.9	±	0.02	2.0	±	0.1
17:00:36-17:08:37	105.5	109.3	102.2	105.9	20.0	±	0.04	4.0	±	<0.25

[1] Mean ± standard deviation measured over period of two sampling burns, measured in basement nearby to water heater, but not directly at air intake.
[2] The 4GPM for experiment 1 required a bypass valve to reach the desired water flow so flow rate was verified manually rather than through the omega flow sensor.

Table A3. Vent temperatures for experiments with on-demand water heater RTG-84DVLN.

Approximate Water Draw (GPM)	Vent Temp 1 (°C)			Vent Temp 2 (°C)		
1	61.1	±	0.1	59.9	±	0.1
2	64.4	±	0.2	63.0	±	0.2
4	77.8	±	0.4	76.1	±	0.4

Table A4. Calculated air-free concentrations over last 5 min of each burn, water heater RTG-84DVLN.

Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	153	1	25	8	34
2	130	3	21	8	29
4	108	6	14	6	20

Table A5. Calculated concentrations at 3% O_2 over last 5 min of each burn, water heater RTG-84DVLN.

Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	131	1	22	7	29
2	112	3	18	7	25
4	92	6	12	5	18

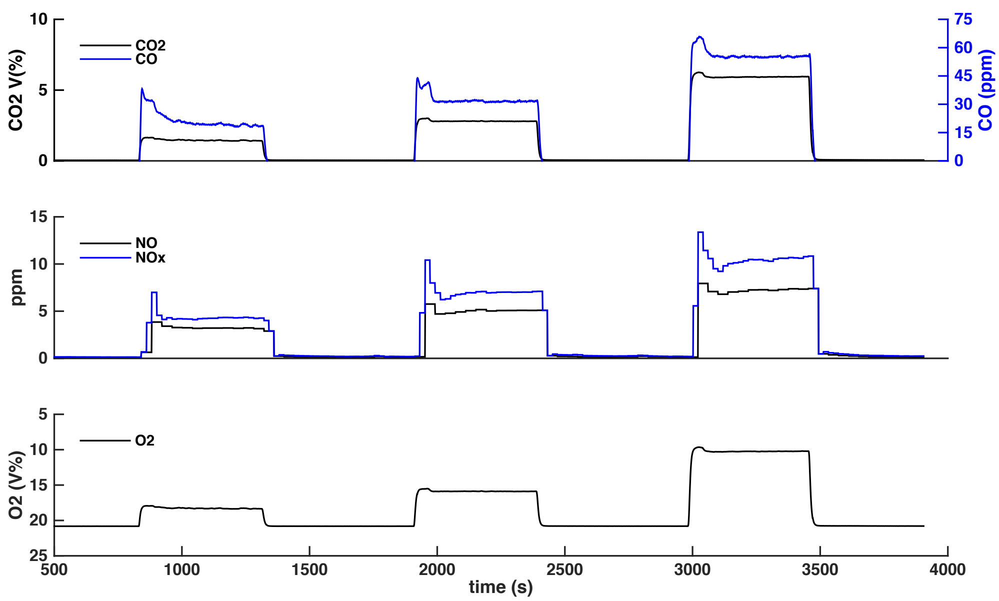

Figure A3. Measured analyte concentrations for on-demand water heater RTG-84DVLN

B.1 Detailed Results for A.O. Smith ATI-540H-N

This A.O. Smith direct vent, ultra-low NO_X (SCAQMD rule 1146.2 compliant), condensing on-demand (tankless) water heater was installed in the test facilities at LBNL (see Figure B1). Table B1 provides a summary of the water heater information. Because the water heater is direct, power-vented, and uses separate PVC venting for combustion air and exhaust gases, the emissions sample lines and flue thermocouples were installed into the exit of the exhaust vent. Temperature was sampled 12-inches into the exhaust vent and emissions were sampled 12-inches into the exhaust vent.

During all experiments, the water heater temperature was set to 120°F outlet water temperature and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. Pressure at the dry gas meter was 7 inches of water when the water heater was not operating and decreased to 6 inches of water when the water heater was operated. Detailed emissions measurements from this water heater are presented in Figure B3, Figure B4, and Tables B2 to B5.

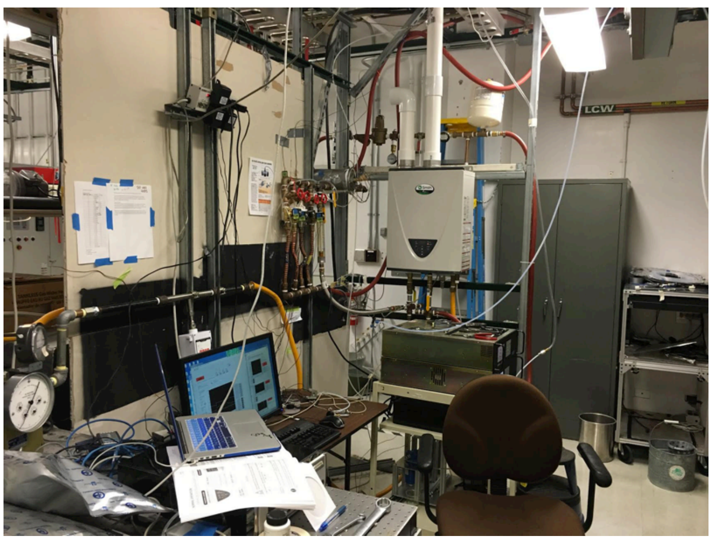

Figure B1. Experimental setup for A.O. Smith ATI-540H-N installed in laboratory. Exhaust temperature probes and emissions sample port are located at water heater vent exit.

Table B1. Appliance and burner information.

Burner category	Indoor, direct vent, ultra-low NO_X, automatic instantaneous water heater
Technology	Indoor, fan assisted, direct vent, SCAQMD rule 1146.2 compliant; contains an integrated condensate collector for vent, but is NOT considered a condensing unit.
Appliance manufacturer	AO Smith
Model	ATI-540H-N
Serial number	1604E001155
Energy factor rating	0.95
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	5.0 in. w.c.
Manifold Pressure	2.95 in. w.c.
Electrical rating	120V 60HZ Properly Grounded
Max burner input	199,000 Btu/hr
Min burner input	15,000 Btu/hr

Table B2. Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater ATI-540H-N.

Trial	Approximate Water Draw (GPM)	Burn Time	Fuel Flow[3] ($ft^3\ h^{-1}$)	Firing Rate[3] (kBTU/h)	Fox Fuel Flow[4] ($ft^3\ h^{-1}$)	Fox Firing Rate[4] (kBTU/h)
1	1	19:41:36-19:49:36	27.3	28.3	26.1	27.1
	2	19:59:49-20:07:49	48.7	50.5	47.1	48.8
	4	20:17:49-20:25:50	100.6	104.3	97.0	100.6
2	1	13:33:59-13:41:58	30.0	31.1	26.2	27.2
	2	13:50:59-13:58:57	49.6	51.4	47.6	49.4
	4	14:06:56-14:14:56	96.5	100.0	93.7	97.1

Table B3. Combustion air conditions and measured water flow[1] for experiments with on-demand water heater ATI-540H-N.

Trial	Air Temp (°C)			Water Draw (GPM)[2]			Vent Temp 1 (°C)			Vent Temp 2 (°C)		
1	19.5	±	0.1	1.1	±	0.1	27.8	±	0.3	28.1	±	0.3
	19.4	±	<0.1	2.0	±	0.1	31.3	±	0.1	31.6	±	0.1
	19.3	±	<0.1	4.0	±	<0.25	34.4	±	0.1	34.4	±	0.1
2	19.5	±	<0.1	0.9	±	0.3	32.8	±	1.1	32.6	±	1.2
	19.6	±	<0.1	1.9	±	0.1	31.5	±	0.3	31.6	±	0.3
	19.6	±	<0.1	4.0	±	<0.25	34.0	±	0.2	33.9	±	0.2

[1] Mean ± standard deviation measured over period of two sampling burns, measured in basement nearby to water heater, but not directly at air intake.

[2] The 4GPM for experiment 1 required a bypass valve to reach the desired water flow so flow rate was verified manually rather than through the omega flow sensor

Table B4. Calculated air-free concentrations over last 5 min of each burn, water heater ATI-540H-N.

Trial	Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	1	83	2	8	2	10
	2	98	2	11	4	15
	4	237	5	8	4	12
2	1	111	1	21	6	27
	2	113	2	10	5	15
	4	194	5	7	4	11

Table B5. Calculated concentrations at 3% O_2 over last 5 min of each burn, water heater ATI-540H-N.

Trial	Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	1	71	2	7	2	8
	2	84	2	9	3	13
	4	203	5	7	3	10
2	1	95	1	18	5	23
	2	97	2	9	4	12
	4	166	5	6	3	9

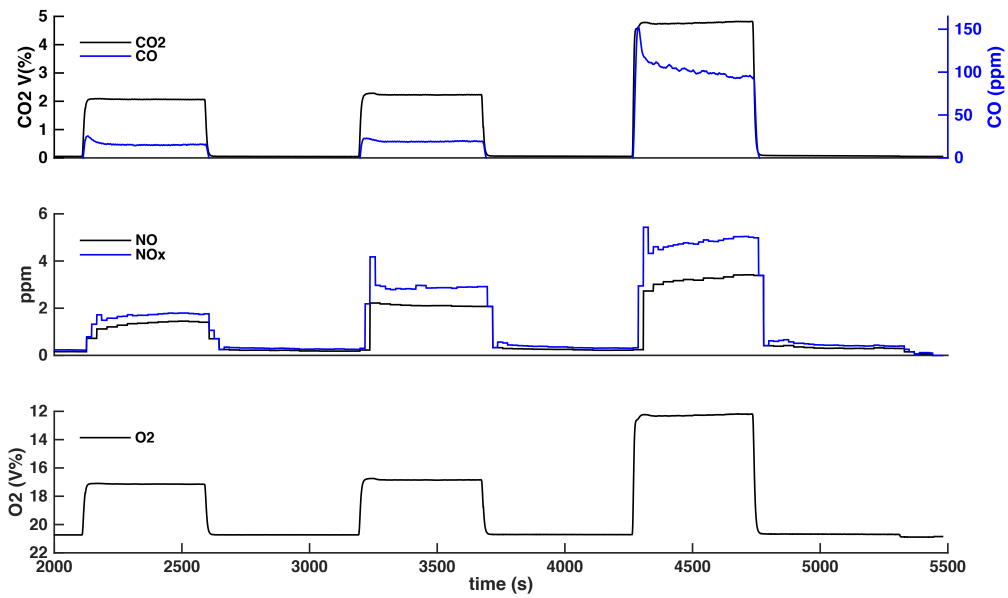

Figure B2: Measured analyte concentrations for on-demand water heater ATI-540H-N (Trial 1)

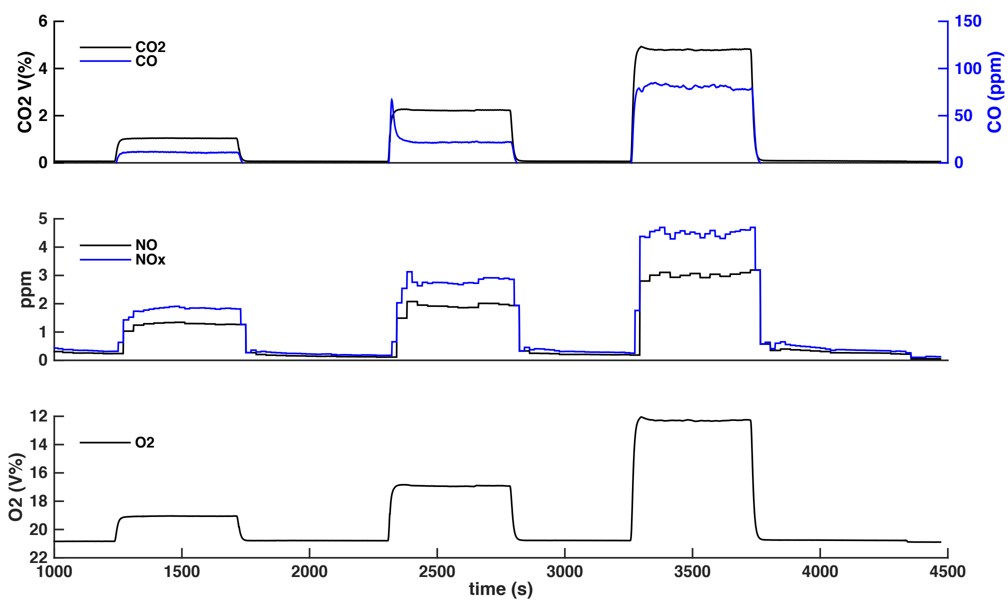

Figure B3: Measured analyte concentrations for on-demand water heater ATI-540H-N (Trial 2)

C.1 Detailed Results for Rheem ECOH200DVLN

This Rheem direct vent, ultra-low NO_X (SCAQMD rule 1146.2 compliant), condensing on-demand (tankless) water heater was installed in the test facilities at LBNL (see Figure C1). Table C1 provides a summary of the water heater information. Because the water heater is direct, power-vented, and uses separate PVC venting for combustion air and exhaust gases, the emissions sample lines and flue thermocouples were installed into the exit of the exhaust vent. Temperature was sampled 12-inches into the exhaust vent and emissions were sampled 12-inches into the exhaust vent.

During all experiments, the water heater temperature was set to 120°F outlet water temperature and water was drawn at three flow rates, 1GPM, 2GPM, and 4GPM. Pressure at the dry gas meter was 7 inches of water when the water heater was not operating and decreased to 6 inches of water when the water heater was operated. Detailed emissions measurements from this water heater are presented in Figure C3, Figure C4, and Tables C2 to C5.

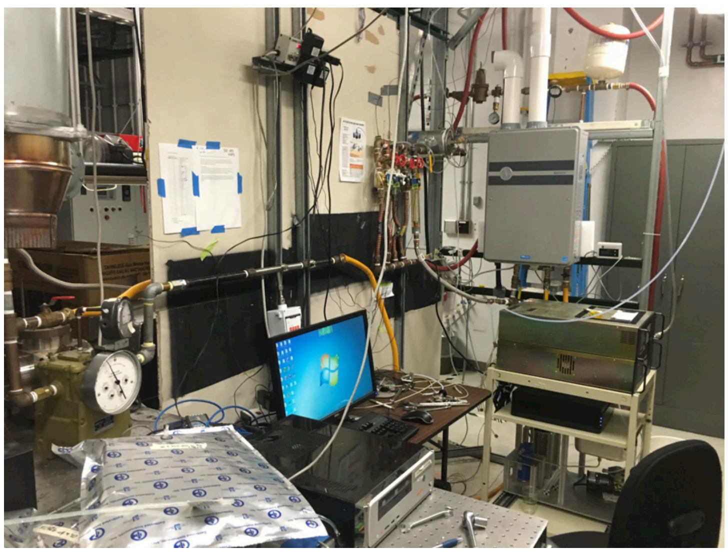

Figure C1. Experimental setup for Rheem ECOH200DVLN installed in laboratory. Exhaust temperature probes and emissions sample port are located at water heater vent exit.

Table C1. Appliance and burner information.

Burner category	Indoor, direct vent, ultra-low NO_X, automatic instantaneous water heater
Technology	Indoor, fan assisted, direct vent, SCAQMD rule 1146.2 compliant; contains an integrated condensate collector for vent, but is NOT considered a condensing unit.
Appliance manufacturer	Rheem
Model	ECOH200DVLN
Serial number	M0331609365
Energy factor rating	0.94
Max inlet gas pressure	10.5 in. w.c.
Min inlet gas pressure	5.0 in. w.c.
Manifold Pressure	3.9 in. w.c.
Electrical rating	120 V, 60 Hz, < 2 Amps
Max burner input	199,900 Btu/hr
Min burner input	11,000 Btu/hr

Table C2. Burner operating times, fuel flow, and firing rate for experiments with on-demand water heater ECOH200DVLN.

Trial	Approximate Water Draw (GPM)	Burn Time	Fuel Flow[3] (ft^3 h^{-1})	Firing Rate[3] (kBTU/h)	Fox Fuel Flow[4] (ft^3 h^{-1})	Fox Firing Rate[4] (kBTU/h)
1	1	17:45:42-17:53:42	31.0	32.2	30.3	31.4
	2	18:03:47-18:11:45	53.0	55.0	51.1	53.0
	4	18:21:48-18:29:47	78.3	81.2	102.0	105.8
2	1	19:21:44-19:29:44	31.3	32.4	30.5	31.6
	2	19:39:46-19:47:46	55.6	57.6	54.0	56.0
	4	19:57:47-20:05:46	103.3	107.1	100.2	103.9

Table C3. Combustion air conditions and measured water flow[1] for experiments with on-demand water heater ECOH200DVLN.

Trial	Air Temp (°C)			Water Draw (GPM)[2]			Vent Temp 1 (°C)			Vent Temp 2 (°C)		
1	19.7	±	<0.1	1.1	±	<0.1	36.2	±	0.3	34.4	±	0.2
	19.7	±	<0.1	2.0	±	0.1	36.7	±	0.1	35.1	±	0.1
	19.6	±	<0.1	4.0	±	<0.25	39.7	±	0.1	38.7	±	0.1
2	19.6	±	0.1	1.1	±	<0.1	37.2	±	0.2	35.4	±	0.3
	19.4	±	<0.1	2.1	±	0.1	37.0	±	<0.1	35.5	±	0.1
	19.3	±	<0.1	4.0	±	<0.25	40.0	±	0.1	38.6	±	0.1

[1] Mean ± standard deviation measured over period of two sampling burns, measured in basement nearby to water heater, but not directly at air intake.
[2] The 4GPM for experiment 1 required a bypass valve to reach the desired water flow so flow rate was verified manually rather than through the omega flow sensor

Table C4. Calculated air-free concentrations over last 5 min of each burn, water heater ECOH200DVLN.

Trial	Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	1	151.5	1.4	35.2	9.2	44.4
	2	116.1	2.8	30.0	6.9	36.9
	4	85.0	5.6	14.9	4.4	19.3
2	1	148.0	1.4	34.9	9.1	44.0
	2	119.7	2.9	30.9	7.3	38.2
	4	83.0	5.6	14.5	4.4	18.9

Table C5. Calculated concentrations at 3% O_2 over last 5 min of each burn, water heater ECOH200DVLN.

Trial	Approximate Water Draw (GPM)	CO (ppm)	CO_2 (%)	NO (ppm)	NO_2 (ppm)	NO_X (ppm)
1	1	130	1	30	8	38
	2	99	3	26	6	32
	4	73	6	13	4	17
2	1	127	1	30	8	38
	2	103	3	26	6	33
	4	71	6	12	4	16

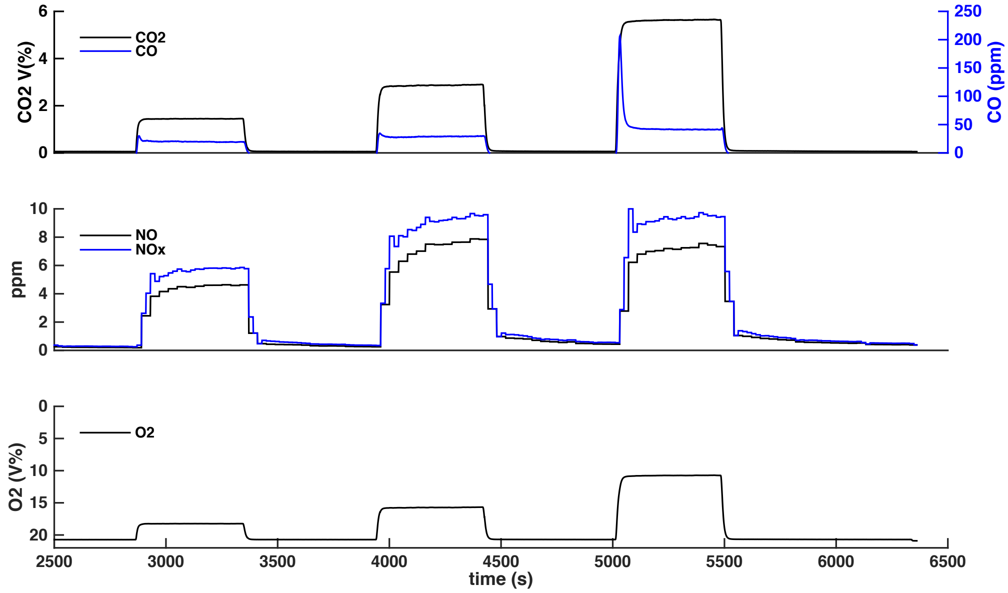

Figure C2: Measured analyte concentrations for on-demand water heater ECOH200DVLN (Trial 1)

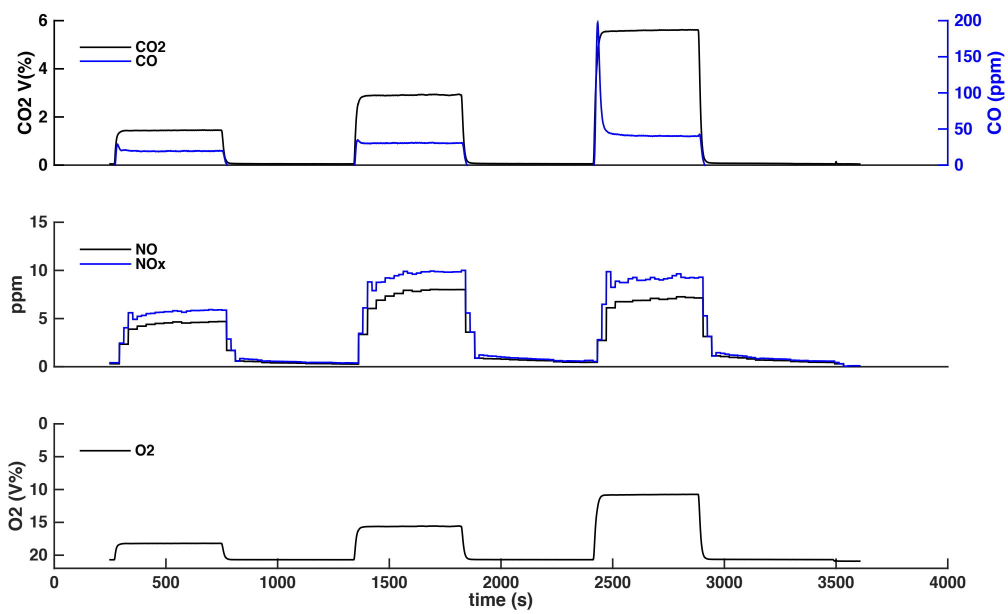

Figure C3: Measured analyte concentrations for on-demand water heater ECOH200DVLN (Trial 2)