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A LOW NO_X POROUS CERAMICS BURNER PERFORMANCE STUDY

INDEPENDENT ASSESSMENT REPORT

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PREFACE

The Public Interest Energy Research (PIER) Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace.

PIER funding efforts focus on the following research, development, and demonstration (RD&D) program areas:

- Building End-Use Energy Efficiency
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Environmentally Preferred Advanced Generation
- Energy-Related Environmental Research
- Energy Systems Integration
- Transportation
- Energy Innovations Small Grant Program

The PIER Program, managed by the California Energy Commission (Energy Commission), annually awards up to $62 million, five percent of which is allocated to the Energy Innovation Small Grant (EISG) Program. The EISG Program is administered by the San Diego State University Foundation through the California State University, under contract with the California Energy Commission.

The EISG Program conducts up to six solicitations a year and awards grants for promising proof-of-concept energy research.

The EISG Program Administrator prepares an Independent Assessment Report (IAR) on all completed grant projects. The IAR provides a concise summary and independent assessment of the grant project to provide the California Energy Commission and the general public with information that would assist in making subsequent funding decisions. The IAR is organized into the following sections:

- Introduction
- Project Objectives
- Project Outcomes (relative to objectives)
- Conclusions
- Recommendations
- Benefits to California
- Overall Technology Assessment
- Appendices
    - Appendix A: Final Report (under separate cover)

- o Appendix B: Awardee Rebuttal to Independent Assessment (awardee option)

For more information on the EISG Program or to download a copy of the IAR, please visit the EISG program page on the California Energy Commission's website at: http://www.energy.ca.gov/research/innovations or contact the EISG Program Administrator at (619) 594-1049, or e-mail at: eisgp@energy.state.ca.us.

For more information on the overall PIER Program, please visit the California Energy Commission's website at http://www.energy.ca.gov/research/index.html.

Abstract

Air quality control is a major issue in the southern California metropolitan area. Pollutants (mainly nitrogen oxides, NOx) emissions from many industrial boilers and commercial heating equipment are major causes of the air quality problem. Reticulated ceramic burners have been found to be an effective combustion technology to reduce NOx emissions. In this project, the combustion performance of methane-air mixtures within a cylindrical shaped, dual-layer, porous ceramic burner was studied. The cylinder has an inner small pore sized layer and an outer large pore size layer and a center cavity that allows insertion of a fuel/air mixture distribution tube. The study found that the premixed flame can be stabilized inside the porous ceramics near the layer interface. The reticulated ceramic burners were able to operate at much higher temperatures (exceed $1665^{o}C$) than the fibrous burners (typically at $982^{o}C$) while at the same time produced the same low level of NOx and CO emissions as the fibrous burners. The radiation heat output efficiency of the reticulated ceramic burner was also found to be higher than the fibrous burner and much higher than the conventional free flame burner. However, due to the close proximity of the hot inner ceramic surface to the distribution tube, the tube melted during the experiment. The reticulated ceramics were susceptible to thermal shock. Although the reticulated ceramic burners show many benefits, more work is needed to improve the burner design and ceramic material to move the technology forward into the market and to address the air quality problem that is important to California.

Key words: Southern California, emissions, reticulated ceramic burners, radiation heat.

Introduction

Air quality is a major issue in California's agricultural areas. The California Legislature (AB 2283, Florez, 2000) required the state Air Resources Board (ARB) to investigate air-emission-abatement equipment required by the San Joaquin Valley Unified Air Pollution Control District. ARB prepared a one-time report to the Legislature describing its findings.[1] The report showed that sources in the food-processing industry account for 0.5 percent of the total NO_X emissions inventory in the Valley. However, the impact of these NO_X emissions on the region's air quality is disproportionately significant during the food-processing season, which occurs during July, August, and September. Typically, those are the months when the air quality is the worst. The ARB identified boilers and continuous dryers as the equipment generating the emissions in the food industry. The San Joaquin Valley has been reclassified to "severe" for non-attainment of the federal, health-based standards for ozone. This has caused the local district to seek further reductions in NO_X emissions, a precursor to ozone. These new reductions apply to the seasonal food-processing industry. Boilers used in other industries throughout California contribute to air pollution in metropolitan areas.

Significant reductions in pollutant emissions from several classes of equipment have not kept pace with the increasing use of energy in California. Thus, air basins such as the San Joaquin Valley are experiencing degraded air quality. The California Air Resources Board is identifying significant polluters and taking action to control those sources. Boilers, used extensively in the food industry, are noted contributors to air pollution. If boiler NO_X emissions were reduced from the current level of 30 ppmvd to 9 or 3 ppmvd, some of the air problems in the San Joaquin Valley would abate. This would lead to a healthier climate for all residents.

Porous radiant burners are in use in industrial and commercial applications because of their excellent performance characteristics, specifically, low pollutant emissions, high turn-down ratios, and more efficient radiation-heat output than the conventional free-flame burners. In this project, the researcher proposed development of porous ceramic burners for use in industrial and food industry boilers. The porous or reticulated ceramics can be characterized as rigid, porous, and sponge-like in appearance. The reticulated ceramic burners can operate at much higher temperatures (~ 1665^{o}C) than the fibrous burners currently used (~ 982^{o}C). However, the ceramic burners are susceptible to thermal shock and are not yet available in the market.

This project was to demonstrate that porous ceramic burners would provide greater heat release with lower emissions than porous radiant burners. When this project was started, only one-dimensional, flat, reticulated ceramic burners had been studied. Industrial boilers require more practical cylindrical burners. The researcher proposed developing a dual-layer, cylindrical, reticulated ceramic burner (Figure 1) with a stable flame to characterize its emissions and thermal characteristics. Earlier work by the researcher had shown that the dual-layer structure displayed favorable flame stability.[2]

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[1] *Implications of Future Oxides of Nitrogen Controls from Seasonal Sources in the San Joaquin Valley,* January 2002. Regulatory Assistance Section, Project Assessment Branch, Stationary Source Division, ARB.
[2] Hsu, P., Evans, W.D., and Howell, J.R., "Experimental and Numerical Study of Premixed Combustion Within Nonhomogeneous Porous Ceramics," *Combust. Sci. and Tech*., Vol. 90, pp. 149-172, 1993

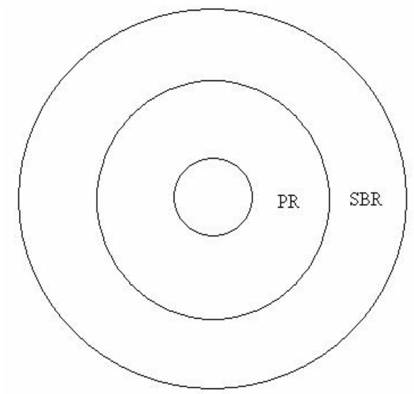

Figure 1: Cross section of a porous inert burner of the two-dimensional burner
The flow moves radially outward from the center. PR is a preheat region, while SBR is the stable burning region.

Objectives

This project was to determine the feasibility of multilayer, cylindrical-shaped, porous ceramic burners to reduce emissions while increasing heat release. The researcher established the following project objectives:

1. Fabricate and test prototype two-layer and three-layer cylindrical-shaped, porous ceramic burners.
2. Demonstrate NO_X emissions below the current, best-available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected to 3 percent oxygen). Current California regulations require NO_X levels below 0.07 lb/MW-hr by 2007.
3. Demonstrate porous ceramic burners with a radiant heat output 25 percent more efficient than that of free-flame burners.
4. Demonstrate that the prototype, multi-layer porous ceramic burners increase combustion stability resulting in extension of the lean flammability limit as compared to current ceramic fiber mat burners.

Outcomes

1. The researcher designed, fabricated, and tested a dual-layer cylindrical burner to determine its combustion performance. A stable flame was established inside the reticulated ceramic cylinder and low emissions were noted. However, the fuel/air-mixture-distribution tube inside the cylinder center cavity melted in the middle of the experiment due to high temperature. The researcher tested equivalence ratios of 0.7, 0.75, and 0.8. The flame speed ranged from 22.5 to 65 cm/s.
2. Higher flame speeds produced greater levels of NO_X and CO. At lower flame speeds, the dual-layer porous ceramic burners were capable of reducing NO_X emissions below the current, best-available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected at 3 percent O_2). At higher flame speeds or firing rates, the ceramic cylinder burner did not meet the 2007 California Air Resources Board emissions mandate for distributed-generation systems (approximately 9 to 12 ppmvd). NO_X emissions data are shown in Figure 2.

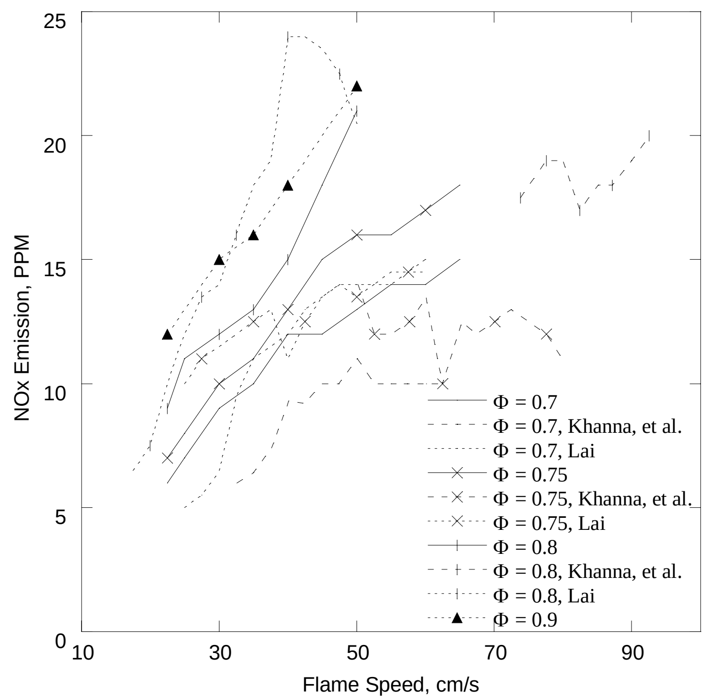

Figure 2: NO_X emissions as a function of flame speed
Data for various equivalence ratios are included in this figure.

3. The burner in this study displayed an average 45% radiation efficiency over a wide flame-speed range at the equivalence ratio (Φ) of 0.9. The radiation-heat output increased with firing rate.
4. Increased combustion stability could not be determined because of the severely limited life of the distribution tubes. There was no determination of increased lean limit on the reticulated ceramic burners.
5. The researcher compared the cost of reticulated ceramic burner material to the price of a commercially available fibrous burner of a typical size. For a commercial fibrous burner rated at a heating capacity of 400 boiler horsepower, the fibrous burner has a price of approximately $10,000 to $12,000. For the same heating capacity, the reticulated yttria-stabilized zirconia/alumina burner has a projected cost of $6,300.

Conclusions

1. The researcher speculated the burner geometry was responsible for the failures. The researcher first tried material substitution by fabricating distribution tubes from several high-temperature alloy materials, but that was not successful. It is possible that the distribution tube is failing from flashback. The cylindrical ceramic tube may be acting as a black body and radiating excessive thermal energy to the distribution tube.
2. Limited amounts of emission data were obtained in a stable flame situation. Results showed emissions lower than 2007 standards at some operating conditions. It is not clear if the range of low-emission operation is sufficient for commercial boiler burners. A possible solution is to reduce the combustion temperature to the level of the fibrous burners, or about 1000^oC, to reduce the thermal NO_X formation.

Reduction of combustion temperature would reduce emission at the cost of lowering the thermal radiation available from the burner.

3. The data from a commercial fibrous ceramic burner indicated that at 0.9 equivalence ratio and with the firing rate of 211.3 kW/m^2 the highest radiation efficiency was 38.4 percent. Therefore, the radiation efficiency of the ceramic burner is 17 percent higher than that of the fibrous burner. Both the reticulated and the fibrous burners have significantly higher radiation efficiency than that of the conventional free-flame burner. Thus the reticulated burner meets the goal of greater than 25 percent radiation efficiency than a free-flame burner.
4. This objective was not met.
5. While the cost estimate for the reticulated burner is significantly lower than the price mentioned for the fibrous burner, it may not include manufacturer margins for overhead costs and dealer markups. Considering that the reticulated ceramic burners have higher operating temperature, higher radiation efficiency, and about the same level of pollutants emissions as the fibrous burners, the reticulated ceramic burners may have a large market potential if the problem of thermal strength can be solved.
6. Both reticulated materials tested, partially stabilized zirconia and yttria-stabilized zirconia/alumina, could not sustain the high temperature cycling needed for industrial boilers. Ceramic manufacturers must solve the problem of thermal strength in porous ceramics before this burner concept can be a commercial success.

Recommendations

The researcher pursued an avenue of research that could lead to significant ratepayer benefits if the feasibility were proven and a commercial product produced. While the technical work in this project was competent, the feasibility is still questionable due to unforeseen material problems. Until reticulated ceramic materials with higher thermal strength are commercially available, the utility of this innovation is limited. Thus, it is difficult to recommend further research in cylindrical, reticulated ceramic burners until the new materials are developed. In addition, the repeated failure of the distribution tube must be addressed before to commercialization. The program administrator considers the distribution-tube failure resolvable through design without material innovation.

Benefits to California

Public benefits derived from PIER research and development are assessed within the following context:

- Reduced environmental impacts of the California electricity supply or transmission or distribution system.
- Increased public safety of the California electricity system.
- Increased reliability of the California electricity system.
- Increased affordability of electricity in California.

The primary benefit to the ratepayer from this research reduced environmental impacts of the California electricity supply. If the reticulated ceramic burner were available to California industries such as food processors, air emissions could decline. This is particularly important in the San Joaquin Valley, an area both of numerous food processors and of severe air emissions. Because it was difficult to fully characterize the cylindrical, reticulated ceramic burner, it is not possible to accurately assess the potential benefits of this innovation to California ratepayers.

Further work must be accomplished to determine if this innovation can operate at both high thermal efficiency and low NO_X emissions. Commercially available fibrous radiant burners can achieve NO_X emission levels of 9 ppmvd at 3 percent oxygen with reasonably high thermal efficiency. The innovation in this project holds the potential of increasing thermal efficiency further while achieving the same low emission levels.

Overall Technology Transition Assessment

As the basis for this assessment, the program administrator reviewed the researcher's overall development effort, which includes all activities related to a coordinated research effort, not just the work performed with EISG grant funds.

Marketing/Connection to the Market

The results of this project indicate that the reticulated ceramic burner is not yet ready for commercialization. Additional material development and engineering are required before marketing activities can begin. The researcher maintains market contact with developers of ceramic materials. In addition, the researcher's laboratory has published one thesis relating to this work (see below) and may publish technical papers on the results of this project.

Hyvonen, C.M., *Experimental Study of Premixed Combustion within a Cylindrical Dual-Layer Porous Inert Medium,* M.S. Thesis, Dept. of Mechanical and Aerospace Engineering, Florida Institute of Technology, Melbourne, FL, 2005.

Engineering/Technical

Reticulated ceramic materials with higher thermal strength are required to continue this work. Material development work is usually done by the manufacturer of ceramic materials. In addition, the researcher must solve the problem of distribution-tube failure.

Legal/Contractual

The researcher had not performed a patent search, nor had he received or applied for any patents relating to this project. The researcher planned to publish the results of this project in the public domain.

Environmental, Safety, Risk Assessments/ Quality Plans

Quality plans include reliability analysis, failure mode analysis, manufacturability, cost and maintainability analyses, hazard analysis, coordinated test plan, and product safety and environmental**.** Significant research and development is required before a true prototype burner can be demonstrated. While the researcher should be cognizant of the need for these plans during the development process, it is premature to require the development of them.

Production Readiness/Commercialization

The researcher states that the ceramics supplier should take any product into the marketplace. Since a ceramic material that meets program goals has not yet been identified and tested, it is premature to hold any negotiation with manufacturers. Thus, no commercialization plans are evident or needed at the time of this report.

Appendix A: Final Report (under separate cover)

Attachment A – Grantee Report

A LOW NO_X POROUS CERAMIC BURNER PERFORMANCE STUDY

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Inquires related to this final report should be directed to the Awardee (see contact information on cover page) or the EISG Program Administrator at (619) 594-1049 or email eisgp@energy.state.ca.us.

Acknowledgements

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Abstract

Air quality control is a major issue in the southern California metropolitan area. Pollutants (mainly nitrogen oxides, NOx) emissions from many industrial boilers and commercial heating equipment are major sources of the air quality problem. Reticulated ceramic burners have been found to be an effective combustion technology to reduce NOx emissions. In this project, the combustion performance of methane-air mixtures within a cylindrical shaped, dual-layer, porous ceramic burner was studied. The cylinder has an inner small pore sized layer and an outer large pore size layer and a center cavity that allows insertion of a fuel/air mixture distribution tube. The study found that the premixed flame can be stabilized inside the porous ceramics near the layer interface. The reticulated ceramic burners were able to operate at much higher temperatures (exceed 1665^{o}C) than the fibrous burners (typically at 982^{o}C) while at the same time produced the same low level of NOx and CO emissions as the fibrous burners. The radiation heat output efficiency of the reticulated ceramic burner was also found to be higher than the fibrous burner and much higher than the conventional free flame burner. However, due to the close proximity of the hot inner ceramic surface to the distribution tube, the tube melted during the experiment. The reticulated ceramics were susceptible to thermal shock. Although the reticulated ceramic burners show many benefits, more work is needed to improve the burner design and ceramic material to move the technology forward into the market and to address the air quality problem that is important to California.

Executive Summary

1. Introduction

The air quality control is a major issue in the southern California metropolitan area. It impacts many aspects of the society, from public health, transportation, to energy production and consumption. Pollutants (mainly nitrogen oxides, NOx) emissions from many industrial boilers and commercial heating equipment are major sources of air quality problem. Porous radiant burners have made their way into the industrial and commercial applications because of their excellent performance characteristics, specifically, low pollutant emissions, high turn down ratios, and higher radiation heat output efficiency than the conventional free flame burners. In this project, the combustion performance of methane-air mixture within porous ceramic burners was studied. The burners are different from the existing fibrous radiant burners used in the industry. The porous or reticulated ceramics can be characterized as rigid, porous, and sponge-like in appearance. The reticulated ceramic burners can operate at much higher temperatures (exceed 1665^{o}C) than the fibrous burners (typically at 982^{o}C); however, they are susceptible to thermal shock and not yet available in the market. Up to date, only one-dimensional, flat reticulated ceramic burners have been studied. A more practical geometry, i.e., cylindrical shape, that can be used in industrial boilers has not been studied. It is therefore important to examine carefully if a stable flame can be established inside a dual-layer reticulated ceramic burner and if so, to study its emissions and thermal characteristics. The dual-layer structure was used due to its favorable flame stability shown in earlier work.

2. Project Objectives

(1) Fabricate and test prototype two-layer and three-layer cylindrical shaped porous ceramic burners.
(2) Demonstrate that the prototype porous ceramic burners are capable of reducing NOx emissions below the current best available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected at 3% O_2) of premixed methane/air flame using ceramic fiber mat burners. The current California EPA Air Resources Board 2007 mandate for Distributed Generation systems is that NOx cannot exceed 0.07 lb/MW-hr generated.
(3) Demonstrate that the porous ceramic burners are capable of achieving a radiant heat output 25% more efficient than that of free flame burners.
(4) Demonstrate that the prototype multi-layer porous ceramic burners increase combustion stability resulting in extension of the lean flammability limit as compared to current ceramic fiber mat burners.

During the course of the study, objective (1) was revised and objective (4) was eliminated to allow time and to dedicate resources to study new problems that arose.

3. Project Outcomes

Two different reticulated ceramic foams were used as the burner material: partially stabilized zirconia (PSZ) and yttria-stabilized zirconia/alumina (YZA). The burners are made of two layers of porous ceramics with 10 pores per inch (PPI) placed at downstream of the flow direction and

65 PPI placed at upstream. The burner is either one-dimensional flat stacked layers geometry or two-dimensional concentric cylindrical shape. The major outcomes of the research:

(1) Establish a stable flame inside the dual-layer cylindrical burner – The dual-layer cylindrical burner was designed, fabricated, and tested to determine its combustion performance. It was found that a stable flame can be established inside the reticulated ceramics and low level of emissions was measured. However, the fuel/air mixture distribution tube inside the cylinder center cavity melted in the middle of experiment due to high temperature. It is believed that burner geometry was responsible for the shortcomings of the investigation. Several high temperature alloy tube materials were used but these still melted. Limited amounts of emission data were obtained with stable flame and the results were in agreement with those obtained in the flat, dual-layer burner.

(2) Achieve low pollutant emissions in the dual-layer flat burner – The equivalence ratios tested were 0.7, 0.75, 0.8 and the flame speed ranged from 22.5 to 65 cm/s. The larger the flame speed is, the more NOx and CO produced. The dual-layer porous ceramic burners are capable of reducing NOx emissions below the current best available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected at 3% O_2) at lower flame speeds. At higher flame speeds or firing rates, it can not meet the future California EPA Air Resources Board emissions mandate for distributed generation systems. A possible solution is to reduce the combustion temperature to the level of the fibrous burners, i.e., about 1000^{o}C, to reduce the thermal NOx formation.

(3) Obtain high radiation heat output – The radiation heat output from the reticulated ceramic burners is quite high. The burner in this study has an average 45% radiation efficiency over a wide flame speed range at the equivalence ratio (Φ) of 0.9. The radiation heat output increases with firing rate. The data from a commercial fibrous ceramic burner indicated that at $\Phi = 0.9$ and with the firing rate of 211.3 KW/m^2 the highest radiation efficiency was 38.4%. Therefore, the radiation efficiency is higher than the fibrous burner's. It is noted that both reticulated and fibrous burners have significantly higher radiation efficiency than that of the conventional free flame burner.

(4) Reduce burner material cost – The reticulated ceramic burner material cost was compared to a commercially available fibrous burner. Although only one burner size was compared, the result was a typical case. For a commercial fibrous burner rated at 400 boiler horse power heating capacity, the burner body costs about $10,000 to $12,000. For the same heating capacity, the reticulated YZA burner will only cost $6,300, which is nearly half of the fibrous burner cost. Considering that the reticulated ceramic burners have higher operating temperature, higher radiation efficiency, and about the same level of pollutants emissions as the fibrous burners, the reticulated ceramic burners have a great market potential.

4. Conclusions

Low pollutants emissions and high radiation efficiency are of prime importance for radiant burners used in industry. The experiment on the burner performance has showed that:

(1) A stable flame can be established inside the dual-layer cylindrical burner.

(2) The emissions of NOx or CO from either PSZ or YZA burners are about the same under the same operating condition.

(3) NOx and CO emissions increase with higher flame speed and larger equivalence ratio.

(4) The radiation heat output from the burner under various equivalence ratios and flame speeds is very high, compared to the fibrous burners.
(5) The radiation efficiency decreases when the flame speed increases. However, at high equivalence ratios of 0.8 and 0.9, the efficiency remains relatively constant when flame speed increases.
(6) The radiation heat output is proportional to the firing rate. At high equivalence ratios, the relationship between radiation heat output and firing rate is close to linear.

5. Recommendations

Although stable flame was observed in the cylindrical burner, the fuel/air mixture distribution tube inside the cylinder center cavity melted after the burner operated for a certain period of time. It is suspected either the intensive radiative emission from the inner ceramic surface to the tube or flame flashback occurred during the experiment. In the current burner design, the close proximity of the flame to the distribution tube is very noticeable. To avoid the melted tube problem in the future, the cylinder center cavity should be enlarged to keep the hot emitting inner surface not too close to the metal tube surface. By increasing preheat ceramic layer thickness, the flame is less likely to propagate through this region and reach a position too close to the distribution tube. This can prevent flame flashback. Another flashback prevention measure is to use a recuperative heat exchanger attached to the inner surface of the cylinder. Alternatively, a distribution tube made of high melting point solid ceramic can be used. An optimum way to reduce combustion temperature in the burner to further cut down NOx emissions is needed. More work is clearly needed to address these problems in order to move forward into the path of commercialization.

6. Public Benefits to California

The air quality problem requires aggressive approaches to reduce the emissions from the sources, e.g., boiler operations, heating equipments, and promote the scientifically-sound, environmentally-friendly combustion technologies. This study has established the design and performance knowledge base of a very practical cylindrical shape porous ceramic foam burner. The study will help address this critical problem important to the state of California. Specifically, the benefits to California residents are:
(1) A scientific study of a low-emission combustion technology that is commercially viable and feasible.
(2) A combustion technology that can be listed as one of the best available control technologies by the air-quality control regulating agencies.
(3) Reduced NOx emissions from many boilers and heating equipment to improve air quality, if the technology is widely adopted by the industry.

Introduction

1. Background

Porous radiant burners have made their way into the industrial and commercial applications because of their excellent performance characteristics, specifically, low pollutant emissions, high turn down ratios, and higher radiation heat output efficiency than the conventional free flame burners. To date, both metallic and ceramic radiant burners have been studied and implemented industrially. Two main categories of radiant burners exist, reticulated ceramic burners and fibrous metal alloy or ceramic burners. Reticulated ceramics can be characterized as rigid, porous, and sponge-like in appearance, whereas, fibrous burners can be characterized as mechanically softer and woven in appearance. The fibrous ceramic or metal burners operate at about 982^{o}C (or 1800^{o}F) are commercially available. On the other hand, the reticulated ceramic burners can operate at much higher temperatures (exceed 1665^{o}C, as will be shown in this study); however, they are susceptible to thermal shock and not yet available in the market.

The burner under investigation has been termed non-homogeneous due to the arrangement of the differing porous ceramic media along the fuel/air mixture flow direction. In particular, as viewed from the flow direction, there are two distinct regions, a preheat region (PR) and a stable burning region (SBR), each distinguished by their pore size. In all previous studies considered and the current investigation, the ceramic material is assumed to be inert, thus, these burner types are usually called porous inert media (PIM) burners.

Both the reticulated and fibrous ceramic burners take advantage of the excess enthalpy in the product gases, that is, using the ceramic media, energy is transported upstream of the flame through radiation and conduction heat transfer. However, one major operational difference between these two types of burners is: the fibrous burners have combustion occurs at the burner exterior surface but in the reticulated ceramic burners the combustion occurs in the open pores inside the solid matrix. The reticulated ceramic media typically have very high porosities, and consequently, large surface areas per unit volume, such that transported energy is used to convectively pre-heat the incoming fuel/air mixture resulting in higher flame temperatures than those in the free flames and the fibrous burners. Due to the higher surface emissivity of the solid matrix than that of the product gases, the radiation heat output form reticulated ceramic burners is not only much higher than the free flame burners, but also higher than the fibrous ceramic burners. Furthermore, because the flame speed of reticulated burner is very high (short residence time for product gases) and strong radiation heat release tends to bring down the post-flame temperature quickly, the nitrogen oxides (NOx) emission is very low (Howell, et al., 1996). The NOx emission is found to be comparable to that of the fibrous burners. However, the higher combustion temperature and stronger radiation output make reticulated ceramic burner a very desirable solution to the pollution emissions in many industrial heating and power boilers, which have been an air quality control problem, especially in the southern California.

Previous investigators have verified the positive aspects of the reticulated PIM burner. However, their findings have been limited to one-dimensional flat flame burners, that is, their flame sheets have been planar. As stated earlier, one of the major goals of this investigation to design and test a cylindrical dual-layer PIM radiant burner, that is, the flame sheet is cylindrical. This difference can be seen in Figure 1. The cylindrical burner is much more compact than the flat burner and can be easily fit into the typical industrial boilers, for example, the Scotch Marine type boilers. The cylindrical burners thus have very practical ramifications than the flat burners for retrofitting or use in new combustion systems.

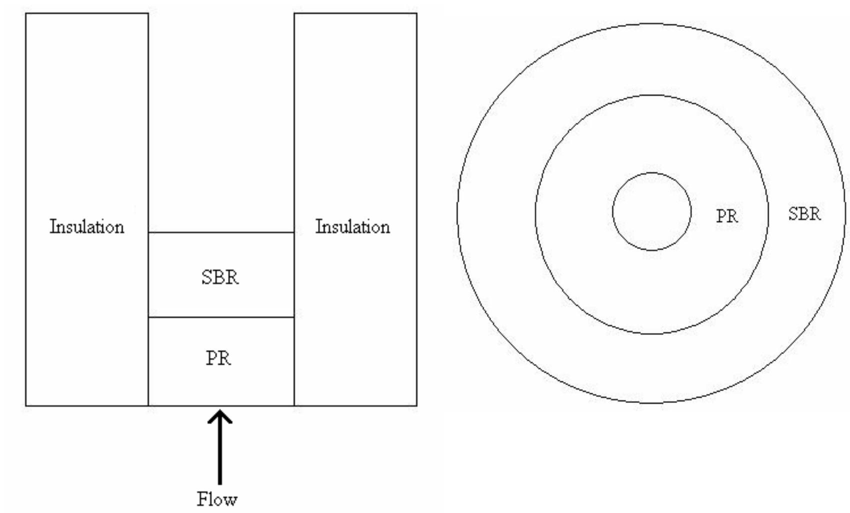

Figure 1. (a) (left diagram) One-dimensional burner used in previous and current investigations. (b) (right diagram) Cross section view, normal to axis, of the two-dimensional burner. The flow moves radially outward.

2. Literature Review

According to Lai (1995), the first investigation of an excess enthalpy flame was conducted by Shaulov in 1954, in which an accelerated flame speed was observed in a nozzle packed with a 40% porosity material. Another breakthrough occurred in the 1980's by Takeno (1981), in which the porous medium was created by the bundling of ceramic tubes. The significant findings of this experiment included higher flame temperatures when compared to free flame, an improved understanding of flame stability, and the reduction of CO and NOx.

Hsu et al. (1993) investigated premixed methane combustion within a non-homogeneous porous ceramic media; both experimental and numerical simulations were conducted. Four experiments were carried out in order to determine the effect of porosity on the SBR. Two cases utilized 10 PPI for the SBR, as in the current investigation, and the remaining cases used 30 and 45 PPI SBR. The significant findings of this work were:

- A numerical model could be used to reasonably predict combustion phenomena for the 10 PPI SBR cases. In particular, for a given equivalence ratio (Φ), burning rates were predicted to be greater than for an adiabatic free flame, which has been confirmed by experiment.
- A case with 65 PPI PR and 10 PPI SBR provided the greatest turndown ratio, while also extending the lean limit 23% lower than that of a free flame.
- Non-homogeneous PIM burners have an inherent quality to stabilize a flame near the interface of two differing porosities.
- Significant degradation of the PIM resulted in a tilted flame for two cases. The PIM used in this experiment is partially stabilized zirconia (PSZ).

Lai (1995) experimentally investigated premixed methane/air combustion within a non-homogeneous porous ceramic medium. Similar to Howell et al. (1996), Lai stacked ceramic cylindrical ceramic inserts of differing porosities to establish the preheat region, stable burning region, and in two of the five configurations, a third insert (called radiation reflecting region) was stacked to prevent flame blow-off. The study demonstrated the multi-layer reticulated ceramic burners can achieve: 1) compact burner size, 2) the ability to burn fuels of lower quality, 3) a broader range of flame speeds at a given equivalence ratio, 4) an extended lean limit for a given fuel, and 5) a reduction in CO and NOx emissions.

Mital et al. (1997) measured temperature and species distributions within the submerged reaction zone stabilized inside of a stacked radiant burner. Reticulated cordierite was used for both the PR and SBR. The thickness of the PR was held constant at 19 mm, while the SBR or flame support layer had a thickness ranging from 3.2 mm to 9.6 mm. The burners were tested through a range of 150 kW/m^2 to 650 kW/m^2 and $\Phi = 0.6$ to 1.0. Conclusions of their work are:

- Radiation efficiencies for reticulated ceramic burners are between 20 and 30%, and are dependent upon firing rate, equivalence ratio, porosity of the reticulated material, and SBR thickness.
- CO and unburned hydrocarbon emission indices are relatively low, CO: 0.1-3.6 g/kg-fuel, HC: 0.1-1.2 g/kg-fuel, and are directly proportional to equivalence ratio and inversely proportional to firing rate.
- NOx emission index is also very low, 0.1-0.35 g/kg-fuel and are directly proportional to equivalence ratio and firing rate.
- As also confirmed later by Mathis and Ellzey (2003), temperature profiles reveal that beyond a certain firing rate, the reaction zone moves upstream as firing rate increases, to the point of flashback at high enough rates.

Mathis and Ellzey (2003) studied flame stabilization, operating range, and emissions for a non-homogeneous methane/air porous burner. Two material types were tested, yttria-stabilized zirconia/alumina (YZA) and zirconia-toughened mullite (ZTM). The porosities for the PR and SBR were 60 PPI and 10 PPI and initially the length of both the PR and SBR were 5.1 cm (~2 in). Post experiment temperature profiles showed that the length of the initial PR was excessive; therefore, a third burner was constructed from YZA that used a PR length of 2.54 cm. One major peculiarity reported was that the YZA burner stabilized the flame at the PR SBR interface, however, the ZTM burner allowed the flame to travel upstream of the interface (a flash back), at which the point the test was terminated. The burners were run at equivalence ratios 0.6 to 0.75, and up to a maximum firing rate of 4000 kW/m^2. Relevant findings include:

- For any equivalence ratio, all stable conditions existed at flame speeds higher than corresponding laminar flame speed.
- HC emissions were elevated at low firing rates, but were lower at higher firing rates.
- CO emissions remained below 15 ppm for firing rates less than 2000 kW/m^2, and NOx emissions were below 10 ppm for all cases.

3. Environmentally Friendly Combustion with Reticulated Ceramic Burners

There exists a great demand for porous radiant burner technology. Especially the advancement in the reticulated ceramic burners is strongly needed to bring the technology to the market place.

The technology has been shown to be beneficial in many ways. This section describes some of the current and potentially new applications of reticulated ceramic burners.

The typical applications are residential burners for air and water heating systems, industrial heating/power boilers, air-heating drying systems, gas turbine combustion chambers, car engine pre-heaters and car heaters, steam generation, and waste incineration (Mößbauer et al., 2002). In these applications, the maximum power densities (kW/m^2) can be ten times greater through the use of porous radiant burner technology. The use of porous radiant burners in industrial power generation is advantageous because of low pollutants emissions and much higher turndown ratio. Dryers are required for many industrial processes. Thus far, these dryers attain thermal energy through free, pre-mixed, and diffusion flames. The natures of the aforementioned flame types require large combustion chambers, which is undesirable. In this case, reticulated ceramic burners have the potential to have combustion chambers an order of magnitude smaller in size.

With the current push towards hydrogen powered vehicles and the inherently high specific energies of hydrocarbon fuels, one application in particular - hydrogen production from rich combustion in porous media (Pedersen-Mjaanes et al., 2005) - is very interesting and relevant to the current work. Their reforming study was conducted using fuel rich mixtures. Combustion of methanol, methane, octane, and automotive grade petroleum inside of a dual-layer porous alumina foam burner was examined. The general findings were that the porous burner had high reforming conversion efficiencies, quick start up times, and compact size. Furthermore, no catalyst is necessary (inert media).

State-of-the-art gas turbines achieve very low NOx emissions utilizing premixed combustion. However, if power decreases below 50% of nominal maximum power, the combustion inside of the gas turbine burners becomes unstable. To combat this instability, burners must operate using diffusion combustion, which yields high NOx and CO emissions. Since reticulated ceramic burners display stability over large turndown ratios, they have the potential to be very useful in turbine power generation.

4. Goals of the Research

Because of the many advantages of the reticulated ceramic burners over the conventional burners and fibrous burners and the great potential of mitigating the pollutants emissions, it is important to move the technology toward the commercialization path. Since many fundamental studies have been done on reticulated burners, the main goals of this study are to demonstrate the feasibility of a cylindrical shape burner and measure radiation heat output and pollutants emissions. The cylindrical geometry, although is the most practical shape, has not been studied and its performance and potential problem are not known. It is therefore important to investigate this geometry. Although emission and radiation have been measured in earlier studies on flat burners, these measurements were either conducted separately or using indirect measurement, for example, an infrared camera (Khanna et al., 1994), to measure the radiation heat flux. This study will measure pollutant emissions and radiation heat output on a flat burner simultaneously. The radiation heat output measurement was performed with a low cost thermopile detector that can be easily calibrated to obtain high accuracy.

Finally the relative cost of reticulated ceramic and fibrous ceramic cylinders will be compared. It demonstrates the commercial viability of the reticulated ceramic burner and the potential to be listed as a best available control technology (BACT) by state or regional regulating agencies.

The rest of the report will describe the specific objectives of the research, the experimental methods to measure the burner performance, and important results. At the end, conclusions of the work will be drawn and recommendations of future work are given.

Project Objectives

(1) Fabricate and test prototype two-layer and three-layer cylindrical shaped porous ceramic burners.
(2) Demonstrate that the prototype porous ceramic burners are capable of reducing NOx emissions below the current best available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected at 3% O_2) of premixed methane/air flame using ceramic fiber mat burners. The current California EPA Air Resources Board 2007 mandate for Distributed Generation systems is that NOx cannot exceed 0.07 lb/MW-hr generated.
(3) Demonstrate that the porous ceramic burners are capable of achieving a radiant heat output 25% more efficient than that of free flame burners.
(4) Demonstrate that the prototype multi-layer porous ceramic burners increase combustion stability resulting in extension of the lean flammability limit as compared to current ceramic fiber mat burners.

During the course of the study, the Objective 1 was revised and Objective 4 was eliminated to allow time and to dedicate resources to study new problems that arose. These changes are explained in the next section.

Project Approach

The main tasks are the experimental testing of two different burner geometries: dual-layer flat burner (Fig. 1(a)) for emissions and radiation heat flux measurements and dual-layer cylindrical burner (Fig. 1(b)) to determine cylindrical flame sheet stability and emissions. A three-layer cylindrical burner was considered but not pursued. Although adding a third, outer layer of small pore size ceramic will help stabilize the flame in the mid-layer, it would have drastically cut down the radiation heat output. Since one of the objectives is to determine the maximum radiation output from the burner, the three-layer configuration serves no purpose to achieve this goal. It should be pointed out that there is no technical difficulty to manufacture three-layer burner by the vendor and to conduct the performance testing in our laboratory. Based on these considerations and to best utilize the funding for the most critical tasks, the three-layer burner was thus not pursued in this study. The emissions measurements are mainly conducted on the flat burner. Limited emission measurements were also preformed on the cylindrical burner which was mainly used to demonstrate its capability to achieve a stable flame within the ceramic foam. Radiation heat flux measurements were conducted on the flat burner only since it is easier to set up optical path from burner to detector.

In the performance testing of the cylindrical burner, the original plan was to reuse the 1D flat burner table and the existing fuel and air pipelines. It was quickly found that is not possible due to the much larger flow rate required to support the much larger flame area of the 2D cylindrical burner. Therefore, an extensive amount of design work was needed to develop the new burner support table with new fuel/air mixing chamber and flashback arrestor (these parts are designed and made in-house and shown in the sub-section 2 "Two-Dimensional Dual-Layer Cylindrical Burner"). The lab compressed air supply was also found inadequate. Additional changes had to be made to the supply air pipeline to provide the required air flow rate. During the testing of the cylindrical burner, due to the intensive high temperature in the cylinder center cavity, the fuel/air distribution tube (located in the cavity) melted several times. Each time, a new tube material was selected and tube was re-made. These additional efforts necessitated the extension of the original project duration from 12 months to 27 months to ensure the completion of this study's main objectives.

Regarding the Project Objective 4 described in the previous section, it has been demonstrated by several previous studies on the one-dimensional flat burners that the lean flammability limit can be extended. The extended lean flammability limit can also be established in cylindrical burner as the heat transfer mechanism remains the same as in the one-dimensional burner. However, during the course of measuring the radiation efficiency, it was found that it serves little practical purpose to operate burners at lean fuel condition. It was therefore decided that it would be best to utilize the research resources and time to handle the unexpected problems occurred in the cylindrical burner testing and not allocating time in testing the lean limit of the cylindrical burner. The Objective 4 was therefore not pursued.

The project was conducted in two chronicle stages. The first stage on one-dimensional flat burner concentrated on achieving Project Objectives 2 and 3. The second stage examined the combustion performance of a dual-layer cylindrical burner (Project Objective 1).

1. One-Dimensional Dual-Layer Flat Burner

The burner consists of two porous ceramic disks with a circumferential insulation. The 65 PPI ceramic disk is laid in the upstream section (lower position in Fig. 2) to preheat the methane and air mixture, while the 10 PPI disk is in the downstream section to stabilize the flame. Figure 1 is the overview of the burner with insulation. The ceramic disks are 50.8 mm in diameter and 25.4 mm in thickness. The circumferential insulation was made of a material called ALC by the manufacturer Zircar. It was a mixture of Al_2O_3 and SiO_2. Before use, ALC was soaked in alumina rigidizer to increase the mechanical strength at high temperatures up to 1650°C. After igniting the burner, a radiant shield made of a 10 PPI ceramic plate was immediately placed on the top of the insulation to stabilize the flame. The thermocouple junctions were in contact with the circumferences of the ceramic disks. A total of four columns of R-type thermocouples were places around the disks and each column had five thermocouples evenly spaced in vertical direction as shown in Fig. 2. The thermocouple signals were fed into data acquisition board and the instantaneous temperature information were displayed in a computer screen. An axisymmetric temperature profile could be identified by examining the displayed temperatures during the measurement.

This experiment is divided into three parts. The detailed discussions about the instrumentation operation, accuracy, and calibration are given in Li and Hsu (2005) and in a MS thesis by Li (2005). Due to the scope of the final report, these details will not be repeated here.

Emission measurement

The following steps were taken to measure the emissions.

1) Turn on the flow controller and set the equivalence ratio at around 0.9.
2) Ignite the burner from the downstream and place a 10 PPI radiant shield on the top of the burner. The equivalence ratio was held constantly for at least 30 minutes to allow the burner to warm up and the flame to be stabilized. When an ideal temperature distribution (an axis-symmetrical temperature distribution) and flame stabilization in the 10 PPI section were observed, the equivalence ratio was adjusted to the value of interest. The highest temperature recorded during the experiment was around 1700 K, which was at the circumference of the ceramic disks. It is expected the flame temperature inside the pore would have been higher but the amount of temperature difference between disk center and edge was not known. Figures 3 and 4 show the burner at the warm-up and stable combustion stages, respectively.
3) Set the flow controllers to lock-in at the desired equivalence ratio and adjust the mixture flow rate to obtain different flame speeds. The flame speeds were increased at an interval of 5 cm/s from 22.5 cm/s to 65 cm/s.
4) At each stabilized flame speed, a quartz sampling tube is then inserted to the exit plane of the burner to extract the combustion product gases into the CO, HC, and NOx analyzers.
5) Repeat the procedure for different flame speeds and equivalence ratios.

Radiation Output Measurement

1) Blackbody calibration of the heat flux detector
   a. Arrange the calibration optical path to be the same as in Fig. 5 on a optical bench, set the blackbody temperature to 400°C, chopper frequency to 16 Hz and wait around 30

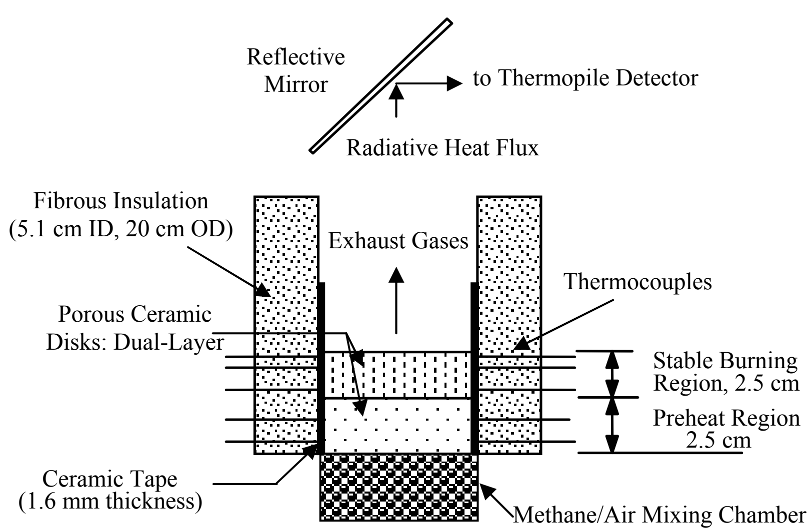

Figure 2. One-dimensional dual-layer flat burner construction. A burner support table is underneath the fibrous insulation and integrated with the mixing chamber.

Figure 3. Warm-up stage.

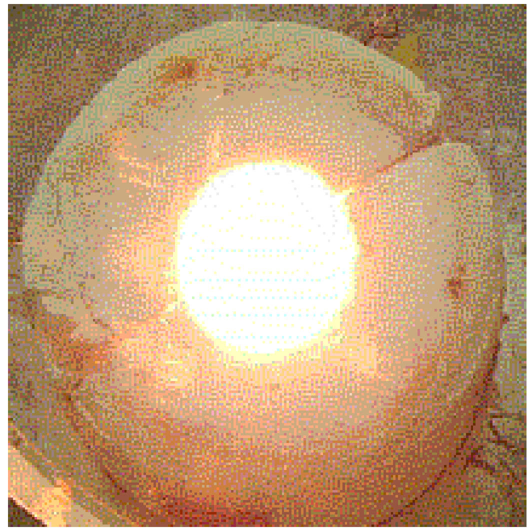

Figure 4. Stable combustion stage.

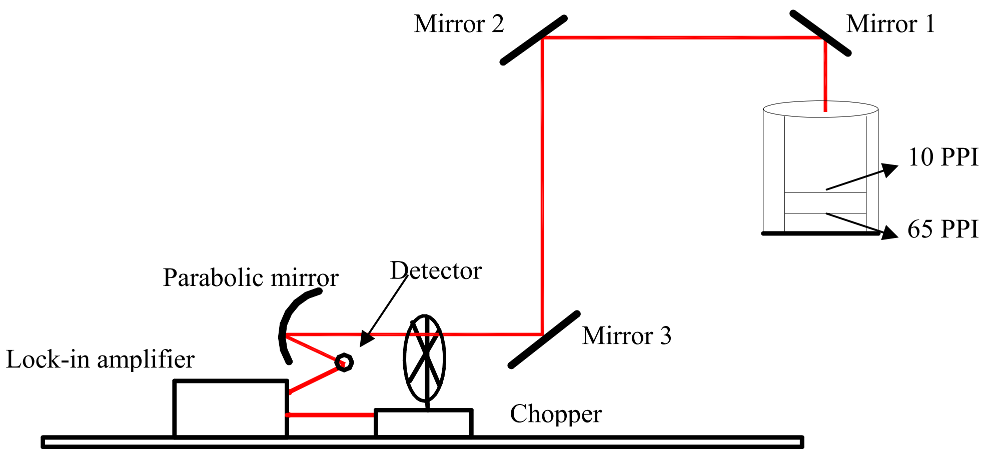

Figure 5. Optical path from burner to thermopile detector.

minutes for the blackbody temperature to stabilize, then record the detector output voltage from the lock-in amplifier.

b. Adjust the blackbody temperature by an increment of 100°C until it reaches 1100°C and record the corresponding detector output. It takes about 40 minutes for the temperature of the blackbody to be stable after each adjustment.

2) Measuring radiation output from the burner
Set the chopper frequency to 16 Hz. Repeat the step of emissions measurement part to reach a stabilized flame at a desired equivalence ration and record the output voltage of the detector in the optical path of Fig. 5. Repeat the procedure for different combinations of flame speeds and equivalence ratios as discussed before.

Reflectivity Measurement
During the experiment, the surface of metal mirror 1 (Fig. 5) was oxidized by the high temperature product gases. The actual reflectivity has to be determined. A FTLA2000 series

(Model MB154S) spectrometer from ABB Bomem is used for the mirror reflectivity measurement. A VeeMAX II ATR reflectometer from Pike Technologies supplied a collimated beam onto mirror 1 at an incidence angle of 45°. It provided exceptionally high throughput to minimize sampling time. Motorized control of angle of incidence via personal computer for automated data collection of specular reflectance was also available but not used.

The FTLA2000 uses a cube-corner design with two moveable mirrors, which allows for permanent alignment, rather than a stationary and moveable mirror. A He-Ne laser measures the position of the mirrors using the interferometer fringes from the laser's monochromatic light. The instrument has a wave number range of 500 cm^{-1} to 12000 cm^{-1} and a maximum resolution of 1 cm^{-1}. The spectrometer uses a ceramic globar mid-IR source and a deuterated triglycine sulfate pyroelectric detector. The opening on the sample holder, which is 6 mm in diameter, limits the beam spot size on the sample. The reflectance spectra were measured at room temperature in the wave number range from 500 cm^{-1} to 5000 cm^{-1} (2 $\mu m \le \lambda \le 20$ μm).

The reading from the spectrometer indicated that the total hemispherical reflectivity within the wavelength range from 1.5 μm to 3 μm is pretty constant, which covered the wavelength of the radiant infra-red energy from the burner. The mirror surface reflectivity (around 11%) within the above wavelength range is used in the radiation heat flux calculation. As the reflectivity of mirror 1 (Fig. 3) changed, the energy reflected from mirror 1 to mirror 2 became diffusive. Commercial CFD/CHT software (Fluent 6.1) was used to determine the fraction of the energy from the burner that was received by mirror 2 with the built-in surface radiation heat exchange solver. The fraction is important in determining the exact amount of radiation heat output from the burner.

2. Two-Dimensional Dual-Layer Cylindrical Burner

The burner was constructed from two concentric porous ceramic annuli of differing porosity. The thickness of the PR was decided to be 18 mm. Downstream of the PR, in the radial outward direction, lies the SBR. The ideal thickness of this region was found to be 25 mm. Both of these region thicknesses were based on the first stage one-dimensional burner investigations. The length of the cylinder is 178 mm and the diameter is 108 mm (Fig. 6(a)). It was confirmed by the data from the ceramic manufacturer, Selee Corp., that YZA was in fact mechanically superior to PSZ (Olson, 2004). Previous investigations using PSZ have been hindered by the material's inferior thermal shock resistant strength. Elverum et al. (2005) found that YZA has much better thermal shock properties. Very similar reticulated YZA burner performance, as compared to PSZ burner, was reported (Mathis and Ellzey, 2003). Therefore, in the second stage of the experiment the reticulated YZA ceramics was used instead of the PSZ in the first stage.

Figure 6(b) shows the major components used in the burner table for cylindrical burner. The flame flashback arrestor, a rectangular piece right below the cylinder, has to be designed and manufactured in-house as there was no off-the-shelf part that will fit in the flow range of the burner and the one used in the flat burner has too low flow capacity. Another critical piece of equipment is the fuel air mixing chamber. Again, due to the larger flow rate requirement, the steel balls filled mixing chamber used in the flat burner (Fig. 2) is not suitable. A new one was designed and made in-house as well. The details of design calculations for flashback arrestor and mixing chamber were given in another MS thesis (Hyvonen, 2005). The constructions of these two pieces are shown in Fig. 7.

The fuel/air mixture distribution tube is another important piece of the device to ensure flow coverage over the entire length of the ceramic. Figure 8 illustrates the hole pattern used. The tube diameter must be smaller than the diameter of the cavity which runs axially through the burner. The burner had certain limitations on physical size. Keeping the cylindrical flame area at an appropriate size is essential given the laboratory infrastructure limitations. Brass was initially chosen for the tube material because it is readily available, soft enough to machine easily, yet stiffer than copper, and thought to have a sufficient melting point. The first tube created had an outer diameter of 13 mm, a length of 178 mm, equally spaced holes along its length, and 6 holes around the circumference (Fig. 8).

(a)

(b)

Figure 6. (a) 2D cylindrical porous ceramic - the 10 PPI SBR is visible in the photo, and (b) burner table set up.

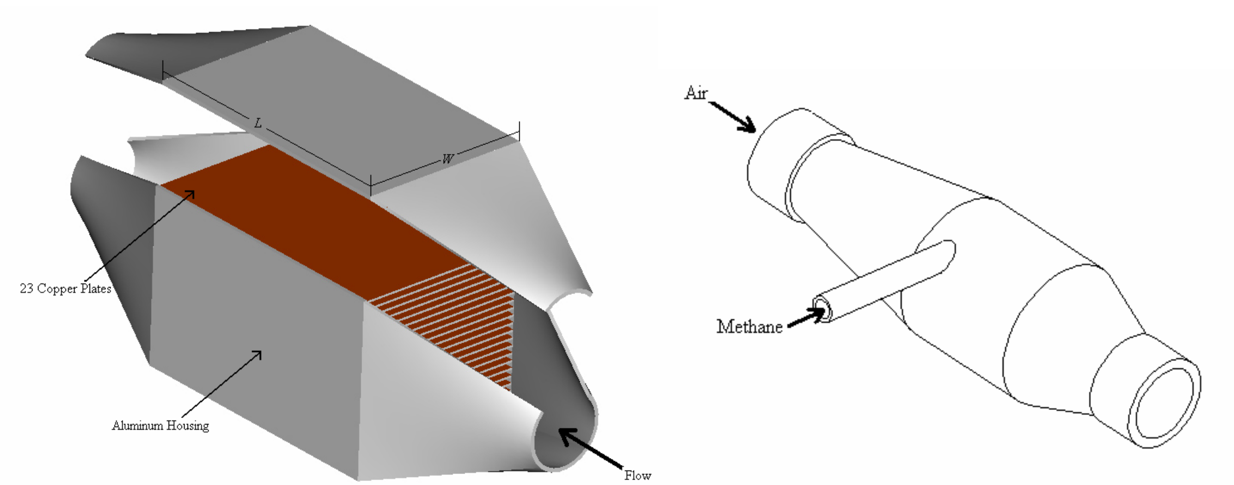

Figure 7. Flame flashback arrestor (left) and fuel/air mixing chamber (right).

The objective in the mixture distribution tube design was to insure equal mass flow in the radial direction, along the length of the burner. Consequently, the velocity of fluid flow was measured along one column of holes (lengthwise) using a digital manometer (Hyvonen, 2005), which provided pressure measurements. Using Bernoulli's principle, pressure measurements were converted to velocity values. It was found that velocity did not vary significantly along the tube length. The most undesirable velocity spread (100% down to 82%) occurred for a flow rate of 300 SLPM. This was tolerable due to the boundary conditions encountered by the flow upon exiting the tube, that is, upon exiting the tube, it was thought that the flow would stagnate somewhat and become more uniform as it encountered the inner boundary of the porous PR.

Emission measurement

The emissions measurement in the cylindrical burner followed identical procedure as in the 1D flat burner in the first stage. The measurements were only taken for a limited number of equivalence ratios and flame speeds. Since the main purposes are (1) to see if flame can be stabilized inside the reticulated YZA foam and (2) to determine if similar emissions levels as measured in flat burner also exist in cylindrical burner, it was therefore not necessary to conduct measurement over a wide range of equivalence ratios and flame speeds. The measurement confirmed that the NOx and CO emission levels are similar to those in 1D flat burner.

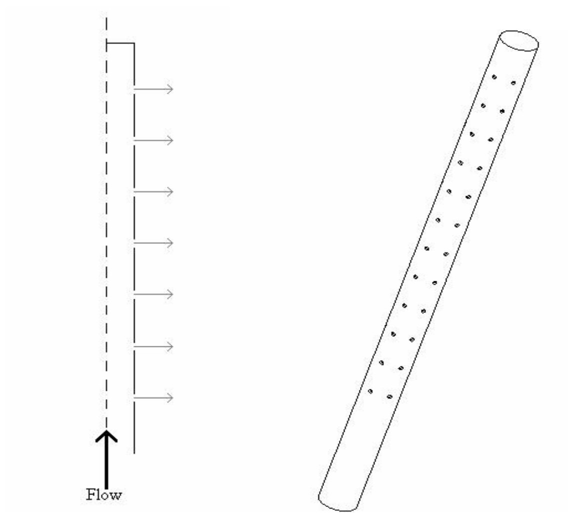

Figure 8. Axisymmetric sectional view and 3D view of fuel/air mixture distribution tube.

Project Outcomes

1. Establish Stable Flame inside the Dual-Layer Cylindrical Burner

The dual-layer cylindrical burner was designed, fabricated, and tested to determine its combustion performance. Both qualitative and quantitative results are obtained. Flame distribution is summarized qualitatively; emissions data are measured. It was found that a stable flame can be established inside the reticulated ceramics and low level of emissions was measured. However, the fuel/air mixture distribution tube inside the cylinder center cavity melted in the middle of experiment due to high temperature. It is believed that burner geometry was responsible for shortcomings of the investigation. In short, the proximity of the flame to the distribution tube caused the tube to melt, and therefore, a uniform radial flow could not be established along the length of the burner once the tube was melted. The major ramification of this is the inability to calculate flame speed because a flame sheet area cannot be exactly determined. As a result, emissions data are correlated with equivalence ratios only and the measurement were taken without the distribution tube. For the range of equivalence ratios tested in this burner, the CO and NOx emissions level is consistent with those in the flat burner measurement. As mentioned previously, since more extensive emissions measurement was done in the flat burner and as long as the emissions performances of the two burners are similar, only the flat burner emission results will be reported (see the next subsection). The limited amount of cylindrical burner emission data is given in Appendix A.

Pictures are used to show flame locations and distributions within the cylindrical burner. Three flame distributions were encountered in experimentation (Fig. 9): (1) a uniform and stable flame that covered the entire length of the burner (prior to tube melt down); (2) a somewhat uniform flame that enveloped 1/3 of the burner (no distribution tube); and (3) an irregular flame structure (no distribution tube). The distribution tubes used in the experiment are shown in Figure 10. Respective melting temperatures increase from left to right and are as follows, brass, 900^{o}C, stainless steel, 1400^{o}C, and titanium 1665^{o}C. Two ceramic cylinder burners were used in this experiment. The first distribution tube used was brass. Within 10 minutes of startup, exhaust gases appeared greenish blue, indicating an unwanted chemical reaction. Immediately, it was thought that the tube had melted. In fact, upon disassembling of the experiment, a melted tube was confirmed. Figure 10 shows what remained of the tube. This experimental run permanently discolored the first burner. From that point forward, that particular burner was considered unusable because of residue left on the porous ceramic material. However, the burner was used to test further distribution tubes, i.e. whether or not other tube materials would melt. The distribution tube was considered to be necessary for this experiment, therefore, two more tubes were created, one from stainless steel and one from titanium. In addition, the outside diameter of the tubes was changed from 13 mm to 6 mm to increase the distance between the flame and the tube. Ultimately, both of the tubes melt. This indicates that the temperature within the central cavity of the burner exceeded 1665^{o}C.

The melted tubes indicate the cylinder center cavity has to be enlarged so the flame front won't be too close to the tube. Additionally, the flame flashback could be the culprit that caused the extremely high temperature in the center. Two possible solutions are: (1) to increase SBR thickness and/or (2) to add a cooling heat exchanger attached to the inside surface of the cylinder. More work to develop an effective strategy to prevent flame flashback is clearly needed.

2. Achieve Low Pollutant Emissions in the Dual-Layer Flat Burner

The two independent variables in this experiment are the equivalence ratios, Φ, and the total volume flow rate of the methane and air mixture, $\dot{V}$. For each equivalent ratio, there was a range of volume flow rates to be adjusted to obtain various flame speeds. The flame speed, *S*, is defined as $\dot{V}/A$, where *A* is the flat burner cross section area.

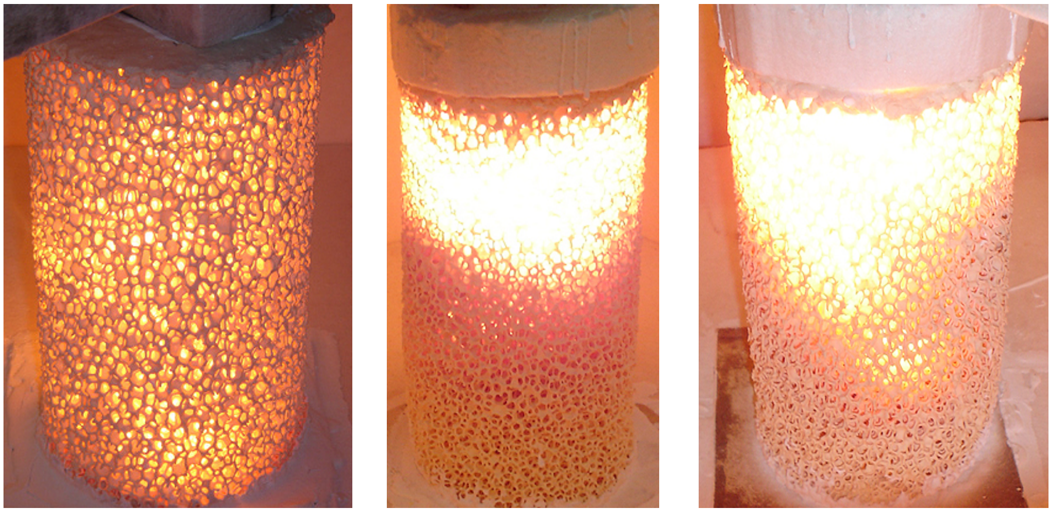

Figure 9. From left to right, full flame, 1/3 flame, and irregular flame.

Figure 10. Distribution tubes, from left to right, brass, stainless steel, and titanium.

Figures 11 and 12 show the plots of the NOx and CO emissions as a function of flame speed compared with the data of Lai (1995) and Khanna et al. (1994). These data are corrected at 3% O_2. The equivalence ratios tested were 0.7, 0.75, 0.8 and the flame speed ranged from 22.5 to 65 cm/s. The larger the flame speed is, the more NOx and CO produce. The flame speed of 65 cm/s is significantly higher than the laminar flame speed of free flame at the same equivalence ratio. Both of the CO and NOx measurement results are in general agreement with those reported by Lai (1995). However, CO emission data from Khanna et al. (1994) is higher than this study. The maximum concentration of NOx measured in the experiment is far below the conventional burners.

The dual-layer porous ceramic burners are capable of reducing NOx emissions below the current best available control technology of 0.076 lb/MW-hr (or 9-12 ppmvd corrected at 3% O_2) at lower flame speeds. However, it should be pointed out that at higher flame speeds or firing rates, it is not able to meet the California EPA Air Resources Board 2007 mandate for distributed generation systems emission requirement: NOx cannot exceed 0.07 lb/MW-hr generated. Since the dual-layer burners tested in this study operate at a much higher temperature than those fibrous radiant burners, a possible approach is to bring down the combustion temperature to reduce the thermal NOx formation. There are ways to achieve this, for example, reducing the pre-heating effect though the controls of thermal transport in the PR region. More work is clearly needed in this area and is beyond the scope of this study.

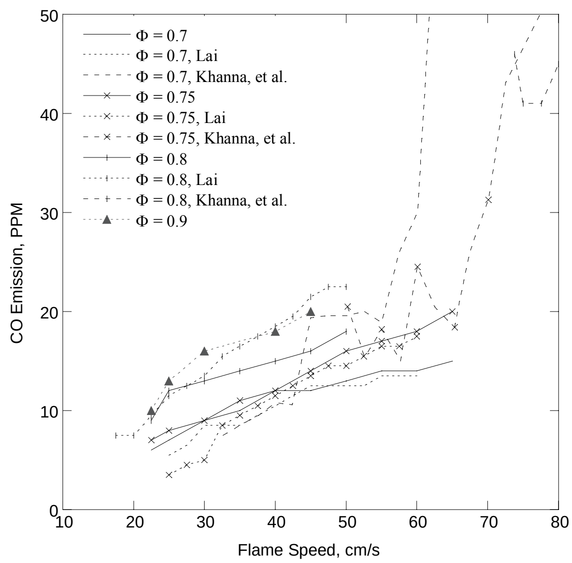

Figure 11. CO emission vs. flame speed.

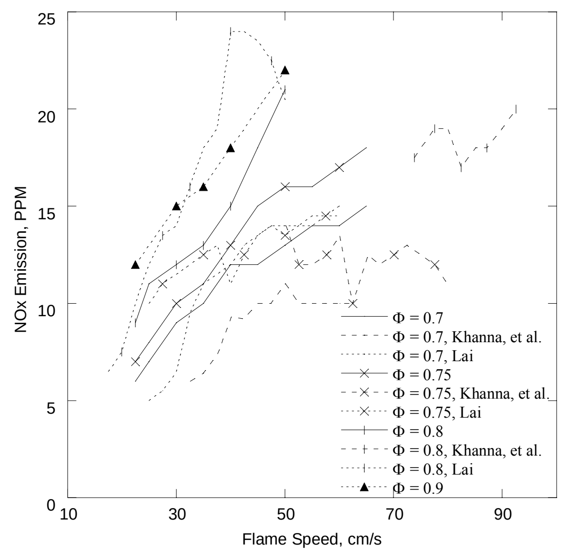

Figure 12. NOx emissions vs. flame speed.

3. Obtain High Radiation Heat Output

Detailed calculation procedure to compute the radiation heat transfer rate from the burner is given in Appendix B. Only the important results are given here.

Figure 13 depicts the thermal radiation efficiency versus the flame speeds. The uncertainty of the efficiency measurement is estimated to be ±2.7%. The radiation efficiency, η, is defined as

$$\eta = P_f / \dot{Q}_{in} \tag{1}$$

where P_f is the radiation power from the burner and $\dot{Q}_{in}$ is the incoming energy rate. $\dot{Q}_{in}$ is defined as

$$\dot{Q}_{in} = \dot{m}_f \Delta h_c \tag{2}$$

where $\dot{m}_f$ is the mass flow rate of methane and Δh_c is the lower heating value of methane, which equals to 50016 kJ/kg.

From Fig. 13, it is obvious that the radiation efficiency decreases when the flame speed increases. This is resulted from the faster increase of $\dot{Q}_{in}$ than P_f when the flame speed increases. At higher equivalence ratios, the overall radiation efficiency is higher. However, at high equivalence ratios (e.g., 0.8 and 0.9), the radiation efficiency remained more or less constant when flame speed increased. This suggests a practical way to run the burner which allows large turn down ratio with little change in radiation efficiency.

Figure 14 depicts the radiation heat output P_f versus the firing rate. The firing rate is defined as $\dot{Q}_{in}/A$, where A is the burner crossing section area. One can see that P_f is proportional to the firing rate. At higher equivalence ratio, the relationship is close to linear.

Figure 15 is the comparison of the radiation efficiency from Khanna et al. (1994) and the current study. Both studies used the same burner material, geometry, and size. However, the measurement method is different. They used an infrared camera to measure the exit temperature of the burner and assumed the burner exit plane is a blackbody to calculate its radiation output by Stefan-Boltzman law. In this study, the radiant flux is measured directly by an infrared thermopile detector, which is direct and straightforward without assuming the emissivity of the burner exit surface. The thermal efficiency obtained in this study is at least 5% higher than that by Khanna et al. (1994) and Mital et al. (1997) but the overall trend is similar, i.e., the thermal efficiency decreases with the flame speed.

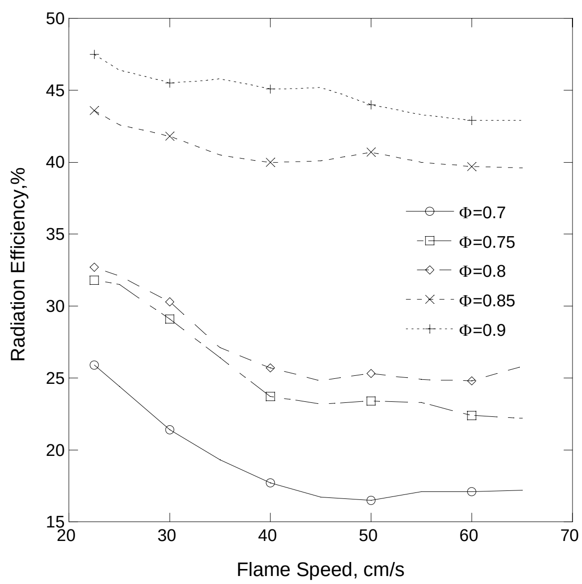

Figure 13. Radiation efficiency.

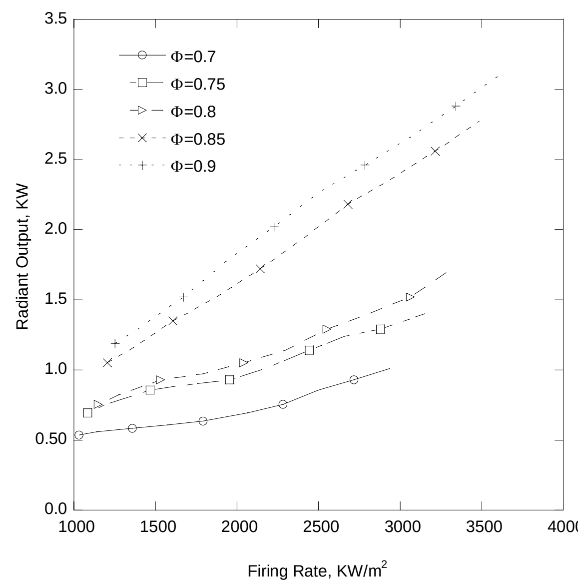

Figure 14. Radiant heat flux output.

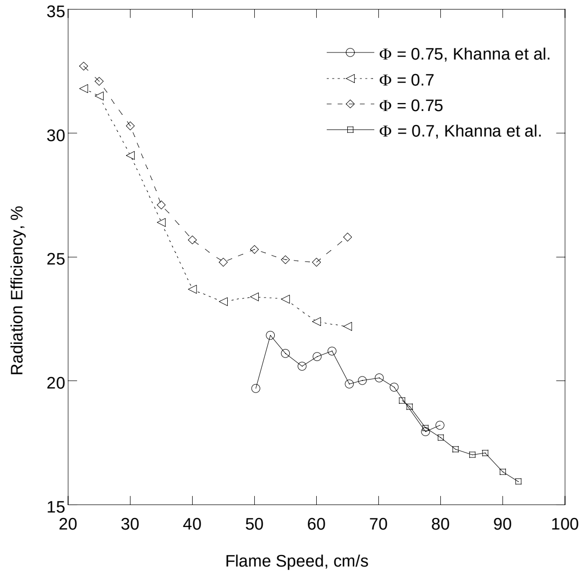

Figure 15. Radiation efficiency comparison.

The data from a commercial fibrous ceramic burner indicated that at the equivalence ratio of 0.9 and with the firing rate of 211.3 KW/m^2 the highest radiation efficiency was 38.4% (Tidball et al., 1989). The dual-layer burner in this study has an average 45% radiation efficiency over a wide flame speed range at $\Phi = 0.9$. The radiation heat output increases with firing rate. Therefore, the radiation efficiency is significantly higher than the fibrous burner's. Another notable difference between the two types of burners is the operating temperature: the typical commercial fibrous ceramic burner temperature is much lower than that has been achieved in the dual-layer ceramic foam burners used in this study. It should be noted that the measured radiation efficiency of the current burners is much higher than that is achievable in a conventional free flame burner.

4. Reduce Burner Material Cost

The reticulated ceramic burner material cost was compared to a commercially available fibrous burner. Although only one burner size was compared, the result was a typical case.

According to the ceramic manufacturer, the large scale production cost of the dual-layer YZA cylinder shown in Fig. 6(a) is about $100 (Olson, 2004). An industrial fibrous ceramic burner from Alzeta Corp., Santa Clara, CA, was selected for cost comparison. The model selected from Alzeta's is the CSB burner model CSB168 (http://www.alzeta.com/products/csb.asp), the burner body itself costs about $10,000 to $12,000. CSB168 has a nominal heating capacity of 400 Bhp (boiler horse power) or 3901 kW. For an YZA cylinder burner, assuming a flame speed of 40 cm/s and equivalence ratio of 0.9, the firing rate is 2228 kW/m^2. For the same heating capacity as the CSB168, the flame sheet area needed in the reticulated YZA burner is 3901/2228 = 1.75 m^2. This will require an YZA cylinder of the size of 0.3 m in diameter and 1.86 m in length. The manufacturing cost of YZA cylinder with this size will be $6300, which is nearly half of the list price of the Alzeta's CSB168 burner.

As mentioned earlier, the reticulated ceramic burners operate at a much higher temperature that exceeds titanium melting point of 1665^{o}C than the typical fibrous burners operating temperature of 982^{o}C. The radiation efficiency of reticulated ceramic burner is also higher, even though the NOx emission level is about the same as the fibrous burners. Based on the cost and thermal performance, it is reasonable to expect the dual-layer reticulated ceramic burners will be very competitive relative to the existing fibrous burners.

Conclusions

Low pollutants emissions and high radiation efficiency are of prime importance for radiant burners used in industry. In this study, premixed combustion of a methane-air mixture within porous ceramic burners was studied. Two different reticulated ceramic foams were used: partially stabilized zirconia and yttria-stabilized zirconia/alumina. The burners are made of two layers of porous ceramics with 10 PPI placed at downstream of the flow direction and 65 PPI placed at upstream. The burner is either one-dimensional flat stacked layers geometry or two-dimensional concentric cylindrical shape. The experiment has showed that:

1) A stable flame can be established inside the dual-layer cylindrical burner.
2) The emissions of NOx or CO from either PSZ or YZA burners are about the same under the same operating condition.
3) NOx and CO emissions increase with higher flame speed and larger equivalence ratio.
4) The radiation heat output from the burner under various equivalence ratios and flame speeds is very high.
5) The radiation efficiency decreases when the flame speed increases. However, at high equivalence ratios of 0.8 and 0.9, the efficiency remains relatively constant when flame speed increases.
6) The radiation heat output (P_f) is proportional to the firing rate. At high equivalence ratios, the relationship between P_f and firing rate is close to linear.

The results indicate that the combustion within porous ceramic burners produces low emissions of CO and NOx while operating at relatively high and constant radiation efficiency. It is more efficient to run the burner at high equivalence ratios. In the entire experiment process, no flashback and blow off was observed in the flat burner. The overall CO concentration over the range of stable flame speed studied was within the range of 5 to 18 ppm. The overall NOx concentration over the range of stable flame speed studied was within the range of 7 to 21 ppm.

A more effective radiation heat transfer rate measurement procedure was used in this study. The radiation heat transfer rate from the burner was measured by an infrared thermopile detector. Maximum radiation efficiency reported in this study is around 47% at the equivalence ratio of 0.9. The measured radiation efficiency is at least 5% higher than that of a previous work using infrared camera, but the general trend of decreasing radiation efficiency with increasing flame speed is the same. Since at high equivalence ratios ($\Phi = 0.8$ and 0.9) the efficiency remains relatively constant at various flame speeds, this suggests an optimal way of operating the burner in practice is to keep the equivalence ratio above 0.8.

The stable combustion within a dual-layer cylindrical PIM burner has been demonstrated and the geometry can be easily scaled up for large capacity applications. There is still room for improvement, both in the burner design and the methodology of the performance testing. Due to the extremely high temperature inside the burner core region, three different burner distribution tubes melted. This leaves a tremendous gap for improvement. It also implies that the current burner was too "tight," i.e., does not have sufficient space in the core region for fuel/air mixture distribution and to avoid flame flashback.

On the other hand, the intensive heating and extremely high temperature in the cylinder center (much higher than that can be achieved with the typical gaseous fuel flames) indicate that the reticulated cylinder can be used in the gaseous or liquid wastes incineration, for example, volatile organic compounds (VOC). It can eliminate the wastes with high destruction efficiency. The burner will have great potential in such applications.

The manufacturing cost of the cylindrical ceramic burner is quite competitive with the existing fibrous ceramic burners that are commercially available. It should be noted that the major advantage of the porous ceramic foam burner is stronger radiation efficiency and much higher combustions temperature while maintaining the same level of pollutants emissions as the fibrous ceramic burners. Although the thermal shock strength remains a concern, the reticulated ceramic foam composition can be improved over time to provide better thermal shock resistance. Considering the cost and combustion performance, the dual-layer, cylindrical shape, porous ceramic foam burner demonstrates that it is an environmentally friendly, clean combustion technology and a very viable solution to the air quality control problem.

Recommendations

To avoid the melted tube problem in the future research, the cylinder center cavity should be enlarged to keep the hot emitting inner ceramic surface not too close to the metal tube surface. The current and future burner geometries are depicted in Fig. 16. When compared to the future burner design, the relative proximity of the flame to the distribution tube is very noticeable. Both burners are drawn to the same scale in the figure. The internal core region cavity seen in the future burner is larger for two reasons: 1) to maintain the flame farther from the distribution tube, and 2) high flow rates experience a choking effect when they encounter small flow channels, .i.e. the current burner distribution tube. Another argument for increasing the radius of the burner is that in all potential industrial applications, the PR diameter D becomes very large (when compared to that in the current investigation), and therefore, the ratio of D to the thickness of the preheating region and stable burning region (which remain constant, regardless of D) becomes larger than the current experiment. For example, the current burner has D approximately equal to 50.8 mm (2 inches). Also, both of the current PR and SBR length scales are on the order of 1 inch or 25.4 mm, therefore, the ratio is about 2:1. In an industrial application, D will most likely be an order of magnitude larger, i.e., 300 to 600 mm, making the diameter to thickness ratio very large, i.e., greater than 10:1.

It is also possible to increase PR thickness so the flame is less likely to propagate through this region and reach a position too close to the distribution tube. This is related to the flashback prevention and perhaps a recuperative heat exchanger attached to the inside surface of the cylinder can be incorporated in the design. Alternatively, a distribution tube made of high melting point solid ceramic can be used. There are options to be explored to maintain the integrity of the mixture distribution tube. There is also a need to determine the best approach to reduce combustion temperature to cut down thermal NOx formation to meet future emission regulatory mandate. More work is clearly needed to address these problems.

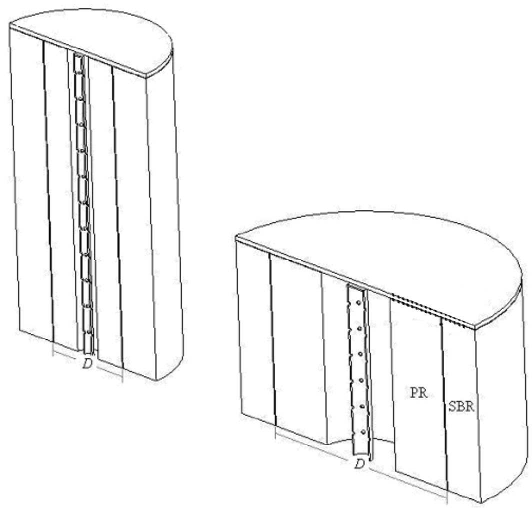

Figure 16 Sectional views of current (left) and future design (right) burners.

From this study, it is found that the reticulated YZA has a much better thermal shock resistance than PSZ. Nevertheless, the thermal shock strength of YZA ceramic needs improvement before it can be used as a durable burner material. It is expected the material improvement will be carried out by the ceramic manufacturer.

Public Benefits to California

The air quality control is a major issue in the southern California metropolitan area. The main pollution sources are the internal combustion engines in the transportation sector and industrial/commercial boilers and heating equipment. The problem requires aggressive approaches to reduce the emissions from the sources, e.g., boiler operations, heating equipments, and promote the scientifically-sound, environmentally-friendly combustion technologies. This study has established the design and performance knowledge base of a very practical cylindrical shape porous ceramic foam burner. The study will help address this critical problem important to the state of California. Specifically, the benefits to California residents are:

(1) A scientific study of a low-emission combustion technology that is commercially viable and feasible.
(2) A combustion technology that can be listed as one of the best available control technologies by the air-quality control regulating agencies.
(3) Reduced NOx emissions from many boilers and heating equipment to improve air quality, if the technology is widely adopted by the industry.

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Glossary and Symbols

A	the burner section area; [m^2]
A_b	the area of the blackbody aperture; [m^2]
$d_{m\text{-}d}$	the distance from the 2nd mirror to the detector; [m]
$d_{b\text{-}d}$	the distance from the blackbody to the detector; [m]
Δh_c	lower heating value of methane, which equals to 50016 kJ/kg;
$\dot{m}_f$	the mass flow rate of methane; [kg/s]
P_b	radiation power of the blackbody at temperature T_b; [W]
P_f	radiation power of the burner flame; [W]
P_m	radiation power reflected from the mirror 2 (Fig. 5); [W]
PPI	pore per inch
PR	pre-heat region
PSZ	partially stabilized zirconia
S	flame speed; [cm/s]
SBR	stable burning region
T_b	temperature of the blackbody; [K]
$\dot{V}$	volumetric flow rate of fuel and air; [m^3/s]
V	detector output voltage; [μV]
$V_{det,m}$	output voltage of the detector, which resulted from the radiation power reflected from mirror 2 (Fig. 5); [V]
$V_{det,b}$	output voltage of the detector (Fig. 5); [V]
YZA	yttria-stabilized zirconia/alumina
ZTM	zirconia-toughened mullite
λ	wavelength; [μm];
Φ	equivalence ratio;
ω	solid angle of the blackbody viewed by the detector; [sr]
α	fraction of the radiation energy received by the mirror 2 (Fig. 5) from the burner;
σ	Stefan-Boltzman constant, $5.67 \cdot 10^{-8}$ $W/m^2 \cdot sr$.

Appendix A & B

Please contact the awardee for a copy of these appendices.