# STUDY OF THE EFFECTS OF AMBIENT CONDITIONS UPON THE PERFORMANCE OF FAN POWERED, INFRARED, NATURAL GAS BURNERS

Quarterly Technical Progress Report

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STUDY OF THE EFFECTS OF AMBIENT CONDITIONS UPON THE PERFORMANCE OF FAN POWERED, INFRARED, NATURAL GAS BURNERS

## INTRODUCTION

This quarterly technical progress report describes work performed under DOE Grant No. DE-FG22-94MT94011 during the period July 1, 1996 to September 30, 1996 which covers the eighth quarter of the project. The objective of this investigation is to characterize the operation of a fan powered infrared burner (IR burner) at various gas compositions and ambient conditions and develop design guidelines for appliances containing PIR burners for satisfactory performance.

The fan powered infrared burner is a technology introduced more recently in the residential and commercial markets. It is a surface combustor that elevates the temperature of the burner head to a radiant condition. A variety of metallic and ceramic materials are used for the burner heads. It has been demonstrated that infrared burners produce low CO and $NO_X$ emissions in a controlled geometric space [1]. As the environmental regulations become more stringent, infrared burners are receiving increasing interests.

The burner tested in this project is installed in a deep fat fryer. It consists of a pressurized air supply, an air/fuel mixing chamber, and a porous ceramic radiant tile. Combustion takes place on the surface of the perforated ceramic tile creating a radiant heat source. One main reason for the present interest in this type of burner is its low NOx emissions. This is attributed to the fact that a large proportion of the heat of combustion is given out as radiation from the burner surface. This results in relatively low gas temperature in the combustion zone compared to that of a conventional free-flame burner. As a consequence, such burners produce less NOx mainly by the so called prompt-NO mechanism[1]. Applications of radiant burners include boilers, air heaters, deep fat fryers, process heaters, and immersion heaters.

The performance of natural gas-fired heating and cooking equipment is strongly dependent on ambient conditions and natural gas composition. In the United States, ambient temperature, pressure, and relative humidity vary significantly by location and season. Also, natural gas compositions supplied by local gas distribution companies exhibit seasonal and regional variations. These variations can cause reliability and performance problems in gas-fired equipment. In service, IR burners have had reliability and performance problems, especially when exposed to various gas compositions, operating altitudes, and other ambient conditions like temperature and humidity. These parameters also effect the composition of the gaseous emissions from these burners.

Burning characteristics will differ in important respects, one of the most being speed of flame propagation. It is the responsibility of the manufacturers to design appliances capable of performing more satisfactorily under reasonably wide variations in gas composition while retaining desirable efficiencies and operation.

There have been very limited studies to investigate the effects of gas composition upon the performance of radiant burner. Due to the lack of data and fundamental understandings, the IR burner product development in the industry is empirical in nature, and is conducted with one gas composition. This project characterizes the operation of IR burner at various gas compositions and ambient conditions and develops a baseline theoretical analysis to predict the behavior of these burners to the change in fuel compositions.

## PROGRESS TO DATE

This project consists of both experimental research and numerical analysis. To conduct the experiments, an experimental setup has been developed and installed in the Combustion Laboratory at Clark Atlanta University. This setup consists of a commercial deep fat fryer that has been modified to allow in-situ radiation measurements on the surface of the infrared burner via a view port installed on the side wall of the oil vat. Proper instrumentation including fuel/air flow rate measurement, exhaust gas emission measurement, and radiation measurement has been developed. Since accurate IR radiation measurement plays a critical role for the success of this project, various instrumentation to measure the radiant output from the infrared burner have been evaluated. In the developed experimental setup, an FTIR, System 2000 from Perkin Elmer is used for in-situ measurements of the radiant output from the surface of the burner. A blackbody with temperature range of 50 to 1200 degree C (model IR-564 from Graseby Infrared) is used to calibrate the FTIR. A set of Horiba gas analyzers are used to measure the emissions from the burner. Experiments were conducted for an extensive test matrix of fuel gas mixtures that represent the complete range of gas compositions usually encountered in the United States. Methane is used as the baseline fuel. Mixtures of methane/propane, methane/hydrogen, and methane/nitrogen are tested to study the effect of fuel mixtures on the performance of the radiant burners. The performance of the burner are investigated in terms of its radiant efficiency (ratio of radiative flux generated by the burner to the total energy input by fuel) and gaseous emissions at various gas composition and air/fuel ratio.

The numerical analysis is conducted through modification of an existing infrared burner code, which is chosen after extensive review of research papers in this area. The physical mechanism and theoretical analysis of the combustion process of the infrared burner has been formulated.. In the past quarter, the code has been obtained from the original developer, and has been installed and compiled. Preliminary results have been obtained through test run. Modifications of the code is now underway. Recently, the task force for the numerical analysis and modeling has been strengthen through collaboration with engineers at AGAR and Energy International, Inc. Their work has also yielded some preliminary results.

**Progress in Experimental Studies**

Measurement of Radiant Output

Sathe et al. [1] used a pyroelectric detector (Oriel Model) connected to an Oriel radiometer to measure the radiation from the porous radiant burner. Sheridan [2] used a thermopile (Eppley Model) connected to a radiometer to measure the radiant output from a tube heater. Williams et al. [3] employed an optical pyrometer to measure the total radiation output from surface burners. Though these techniques are inexpensive, they do not provide a detailed spectrum of intensity versus wavelengths. Such a spectrum will indicate at which wavelength a load best absorbs heat and how much energy is available at various wavelengths. Also, it will help to match the burner emission to load absorption for optimum process efficiency.

The System 2000 FT-IR from Perkin Elmer provides spectrum measurement capability. Solomon et al.[4] demonstrated the use of FT-IR technique in the measurement of emission output and concentration of gaseous species in their coal combustion experiments. They validated the FT-IR measurements with independent thermocouple measurements made at the same point. It should be noted that Kawaguchi et al. [5] employed a monochrometer (SR-5000 made by CI Co) to measure the emissive power from a heated mat. But the wavelength range employed in this monochrometer is only from 1.3 to 14.5 micrometer. System 2000 with a KBr detector provides a wavelength range of about 1 to 25 micrometer.

Test Matrix

The test matrix of fuel gas mixtures has been selected to represent the complete range of gas compositions found in the United States. These test gas compositions are specifically selected to characterize the burner's performance in terms of sooting, flashback and flame lift off. Specifically, methane is used as the reference gas, the baseline fuel. Mixtures of methane/propane are used to test the burner's performance on sooting. Methane/hydrogen is for flashback, and methane/nitrogen for flame lift off. The matrix covers a wide range of air/fuel ratios under each test gas composition. The nondimentional air/fuel ratio is designed to vary between 90% - 170% for each fuel mixture, which covers an aeration range from slightly fuel-rich to very fuel-lean operating conditions.

Test Results

Test results for methane/propane sooting gas were obtained for nondimentional air/fuel ratio from 0.8 to 1.7. Experiments were performed for various methane/propane mixture, in which the propane content increased from 3% to 18%. It is found from the test results that, in general, radiant efficiency and NOx emissions increase steadily up to stoichiometric and decrease through air/fuel ratio of 1.7, while unburned hydrocarbon emission continued to increase as air/fuel ratio decreases from 1.

It is noted that the NOx emissions from the burner are very low. This is attributed to the fact that a large proportion of the heat of combustion is given out as radiation from the burner surface. This results in relatively low gas temperature in the combustion zone compared to that of a conventional free-flame burner. As a consequence, such burners produce less NOx mainly by the so called prompt-NO mechanism [3].

Test results for methane/hydrogen flashback gas and methane/nitrogen flame lift off gas were obtained for similar range of the nondimentional air/fuel ratio. These results are still under analysis and will be reported in next quarterly report.

**Progress in Numerical Analysis**

A physical model of the infrared burner can be described as follows: the mixture of air and fuel enter the perforated ceramic tile of approximately 13 mm thick, the mixture is gradually heated and combusted while it is flowing through the tile. The combustion starts within the tile at some 5 mm from its surface. The enthalpy of combustion released in the gas phase heats the ceramic tile which then emits thermal radiation to a heat load.

Infrared burners have been modeled by numerous researchers using conduction, convection, radiation, combustion (heat generation), and premixed flame model for one or more outputs such as surface temperature, gas temperature, temperature within the porous layer, flame speeds/flame locations, radiant output, efficiency, and emissivity [1,5-9].

Research collaboration with Energy International (EI) to successfully complete the modeling effort in this project has been initiated during this quarter. As of July 1, 1996, AGA Research is now a division of EI. Engineers at EI conducted a separate literature review on the radiant burner modeling and came to the same conclusion CAU made previously; i.e., the most sophisticated model reported in the literature was developed by Sathe et. al. [1] at Arizona State University (ASU). The model developed at ASU incorporates the effects of convection, conduction, radiation, and combustion on the performance of radiant burners. The flow is assumed to be one-dimensional, steady, and laminar. The solid matrix is assumed to be gray and to emit, absorb, and scatter radiant energy. Gaseous radiation is neglected compared to solid radiation. Non-local thermal equilibrium between the gas and the solid phase is accounted for by considering separate energy equations for the two phases. The PRB model developed and tested by Sathe et al. was based on a modified version of the PREM code developed at Sandia National Laboratory in the early 1980's. PREMIX is a subset of the CHEMKIN solution routines, and solves the governing equations for a one-dimensional, laminar premixed flame. Sathe et al. added the solid energy conservation equation and the radiative transfer equation to the PREM solution algorithm as well as added a term in the PREMIX gas phase energy equation to account for the thermal conduction heat transfer from the gas to the solid burner. Details of the governing equations and solution algorithm can be found in the paper by Sathe et al.

Sathe et al. used a simple single step methane oxidation mechanism for predicting the combustion of methane into carbon dioxide and water. It is unclear from the published results if this simple mechanism was used to reduce computational time, or if fundamental modifications to PREMIX were made which eliminated its capability of incorporating multi-step kinetics. Reasonable agreement between the predicted and measured radiant output, flame speed, and radiant efficiency are reported by the ASU team.

In the current investigation, the model developed by Sathe et al. has been acquired from ASU. The model is being reviewed to determine its current capabilities and limitations. It is anticipated that the ASU model will have to be modified to account for variable fuel composition, aeration effects, and operation at altitude. It is also anticipated that coupling the model with the most recent version of CHEMKIN (currently known as CHEMKIN-II) will provide the necessary capabilities for the model to account fuel composition, aeration, and altitude, as well as improve solution convergence. Since CHEMKIN-II is capable of incorporating pressure sensitive reaction rates, unlike the original version of CHEMKIN, which will be necessary for determining PRB performance at altitude. The updated version of PREMIX also provides improved convergence over the original version used in the ASU code. This improved convergence and stability provided by the updated PREMIX can significantly decrease the computational cost associated with obtaining a converged solution.

## SUMMARY AND CONCLUSIONS

In summary, the project is progressing well. The scheduled tasks for this period of time were conducted smoothly. Specifically:

1. Baseline experimental study at CAU has completed. The data are now under detailed analysis and will be reported in next quarterly report.
2. Theoretical formulation and analysis of the PIR burner performance model are continued. Preliminary results have been obtained.
3. An abstract of a paper has been submitted for presentation at the Fifth Annual HBCU/Private Sector/Fossil Energy Research and Development Technology Transfer Symposium, 1997.

## PLANS FOR THE NEXT QUARTER

The major task remaining is to complete the numerical analysis and modeling of the burner. This part of research has been initiated and will continue. It is expected that significant progress will be obtained in next quarter. In addition, AGAR is planning to conduct high altitude tests with the help from a gas company. These tests were originally planned to be conducted in an environmental chamber to be built at AGAR. Since it will not be available for this project, the test plan has been modified.

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