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"Flameless" Combustion within Porous Radiant Burners Using Ceramic Fiber Mat as Burner Material

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Abstract

Experimental investigation of the combustion of premixed methane-air and propane-air in a ceramic fiber mat burner was conducted. The results revealed five distinct stages of combustion dependent on air ratio and mixture velocity exists. One of these is a stage where combustion is completed within the mat so that no flame is visible above the surface, and is called "flameless" combustion. The temperature profile, constant surface temperature map and profiles of the CO, CO_2 and NO_x concentrations above the surface were measured. It was found that the "flameless" stage offers promising application in the development of a clean, compact and highly efficient combustion technology. Porosity, thermal degradation and kind of fuel used affect the combustion characteristics of the burner.

1. Introduction

With the awareness that the energy resources of the world is limited, the increasing global demand for energy demands a more efficient utilization of existing energy resources. Likewise, it has prompted the expanded utilization of low grade fuel. However, the environmental impact of expanding energy production and utilization makes it imperative to extract as much energy per unit mass of fuel possible in a clean, environmentally benign way. Thus, research and development studies on combustion has increasingly focused on the development of clean, compact and highly efficient combustion systems.

One of the technologies under consideration is combustion within inert fibrous media. Although only a few studies have been done on this area so far, the results of those studies shows that the combustion of premixed gas in inert fibrous media is a promising technology [1-3], revealing the presence of of a uniform heating region [1] or radiative region [2] and absence of flashback [1, 2]. The material used in these two studies, however, was metal fiber. A theoretical study [3] showed that the performance of porous radiant burners will be largely improved when submicron sized fibers are used but no experimental study has been done to verify the results so far. For radiant burner application, the intrusion of the flame front into the burner material which causes the burner to become incandescent has the added

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advantage of converting a greater part of the energy released through combustion to radiant energy far exceeding that of ordinary radiant burners and at the same time offers the feasibility of more compact designs. Other studies on combustion within porous media have been done but most of these studies were done using ceramic foams and no ceramic fiber mats are utilized.

Thus, there is a need to expand the database concerning the technology and to refine existing models so as to provide clearer, and more comprehensive understanding of the basic mechanisms involved during the combustion process, specially within fibrous ceramic mats. The present work aims to do these.

A prerequisite to these is a clear description of the physical, chemical and thermal events that accompany combustion within inert porous media and the determination of important transport parameters affecting the phenomenon.

This report discusses the results of the study so far. Firstly, the distinct changes that combustion undergoes from the ignition of a rich mixture to the extinction of the combustion of a lean mixture is reported. One of these is a stage where combustion is completed within the porous media so that no flame is observed above the porous mat: a stage that may be termed "flameless". Then, the corresponding profiles of the temperature within the fibrous mat and of the combustion products above the mat are reported. Lastly, the implications of the findings concerning combustion within fibrous porous media is discussed.

2. Experimental Procedure

A schematic diagram of the experimental set-up is shown in Fig. 1. The set-up is composed of an air supply, a fuel line, a porous burner fixed with detachable fiber mats and a sampling line.

Air is supplied through a blower and the flow rate is controlled by a voltage regulator. Fuel gas is injected into the air supply line for mixing way ahead of the burner. The fuel flow rate is controlled by a needle valve. The flow rates are measured by orifice manometers. The air-fuel mixture is ignited above the burner and the flame is controlled by varying the air ratio. The combustion products are released to atmosphere.

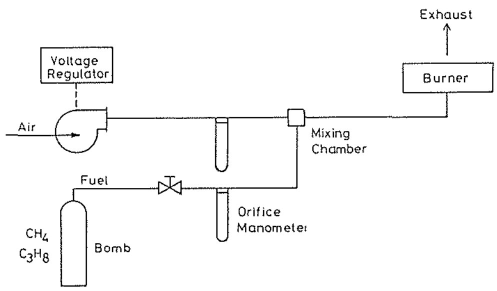


Fig. 1 Schematic Diagram of Experimental Set-up

Sampling of the gas products is done using a quartz probe. Carbon monoxide and carbon dioxide in the products of combustion are analyzed using an infrared spectrophotometer. NO_x is measured by the Saltzman method.

The surface temperature is measured by a Type R thermocouple. The temperature profile within the porous body is measured by Type R and Type K thermocouples. The burner and the placement of thermocouples are shown in Fig. 2.

Two types of ceramic fiber mats were used. The properties of these fiber mats are

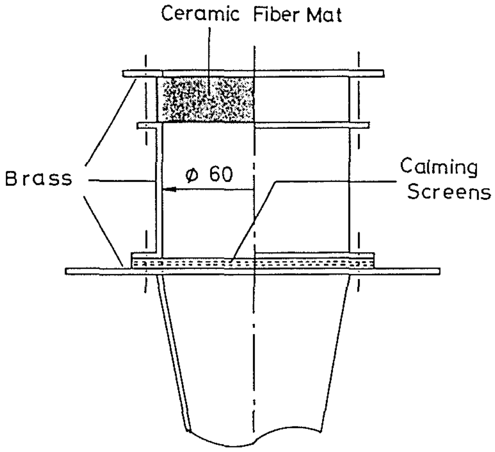


Fig. 2a Burner Diagram

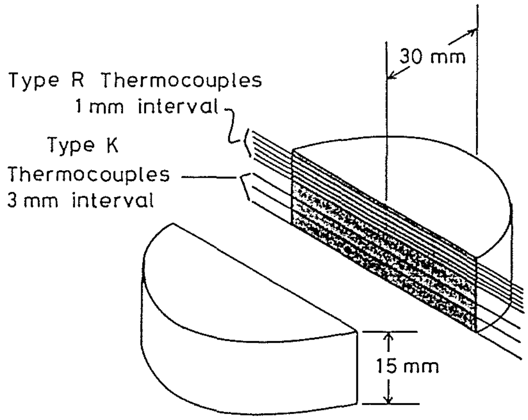


Fig. 2b Thermocouple Placement

described in Table 1. The fiber mats were provided by Nichiasu CeraTech Co., Ltd.

The following parameters were varied: mixture strength, mixture velocity, and porosity of the fiber burner mat. The thickness of the mat was also varied in some experiments. The fuels used were methane and propane.

Table 1 Fiber Mat Properties

	A	B
Fiber Material	Al_2O_3 49% SiO_2 51%	Al_2O_3 49% SiO_2 51%
Fiber diameter	≦ 3 μm	≦ 3 μm
Fiber Mat Thickness	15mm	15mm
Porosity	54.8%	48.6%

3. Results and Discussion

3.1 Stages of combustion

Starting from the ignition of a fuel rich mixture, increasing the air ratio or the mixture velocity leads to changes in flame characteristics. There are five stages that were observed as shown in Fig. 3.

Stage I. Combustion of a fuel rich mixture occurs above the burner with the flame no different from that of an ordinary fuel-rich premixed flame, consisting of a luminous blue inner cone and an outer diffusion flame as seen in Fig. 3a.

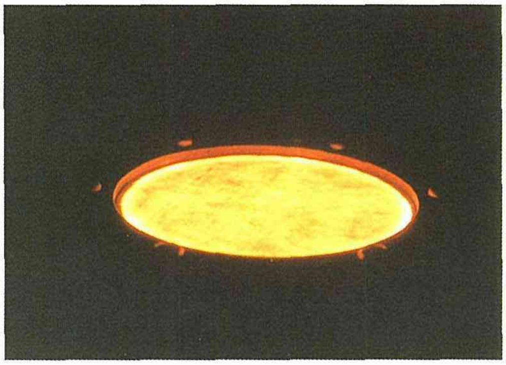
Stage II. Increasing the air ratio, the luminous blue inner cone slowly diminishes until it fully enters the fiber mat surface causing the surface to turn incandescent with a diffusion flame still observable above the burner as shown in Fig. 3b. This indicates that primary reactions occur inside the burner mat. Maximum brightness of the mat occurs at this stage.

Stage III. Further increasing the air ratio, the outer diffusion flame slowly diminishes until the flame is no longer visible above the burner as shown in Fig. 3c. Thus the stage could be called "flameless". Combustion proceeds to completion or very near completion within the mat.

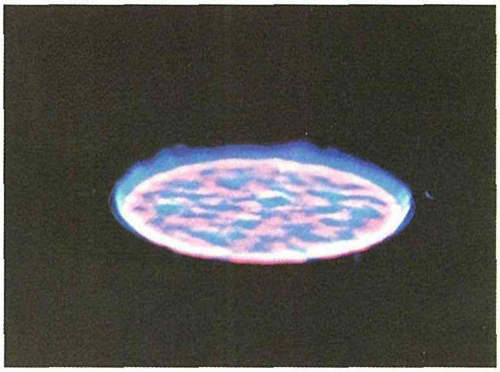
Stage IV. Upon further increase of the air ratio, a blue flame reappears over the burner

a. Stage I

b. Stage II



c. Stage III



d. Stage IV

e. Stage V

Fig. 3 Stages of Combustion

with the surface still incandescent. This blue flame consists of tiny blue flames over the surface as seen in Fig. 3d, which grow bigger and merge to form a larger flame with the increasing air ratio.

Stage V. Only blue flame appears above the burner, which, at first, is flat but later forms a cellular like flame as seen in Fig. 3e. The surface is no longer incandescent. Extinction occurs when the flame is blown off.

Obviously, stage III defines the conditions of practical significance to burner application

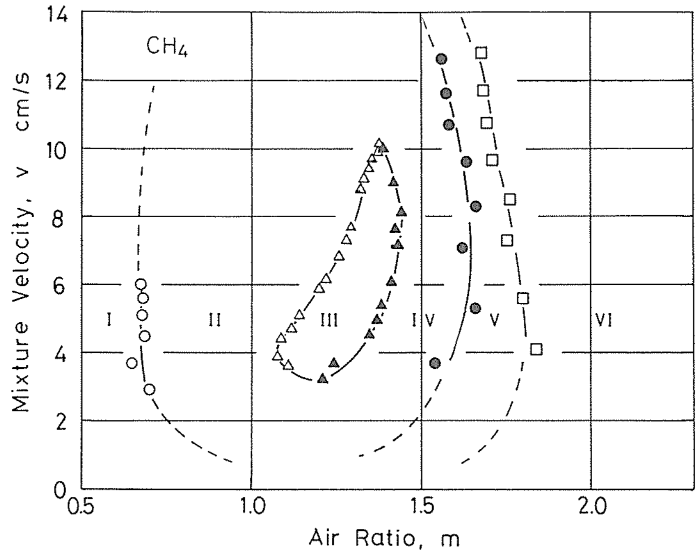


Fig. 4a Stages of Combustion

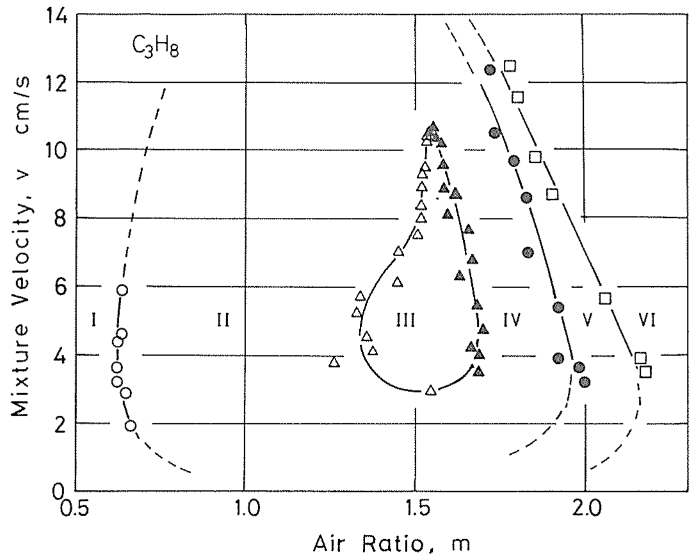


Fig. 4b Stages of Combustion

because the absence of flame enables a more compact design, and as discussed in later sections, it is a region of high combustion efficiency, minimal pollution and high burner radiative output.

Fig. 4 plots the conditions defining the five stages: 4a for methane and 4b for propane. The figure shows that the transition between stages is sensitive to the air ratio of the mixture. The lean flammability limit of the burner occurs at about an air ratio of 1.90 for methane. Comparing 4a and 4b, the influence of fuel type is seen. Transition conditions differ, occuring at leaner conditions for propane than for methane. The lean flammability limit occurs at a leaner value of 2.16 for propane.

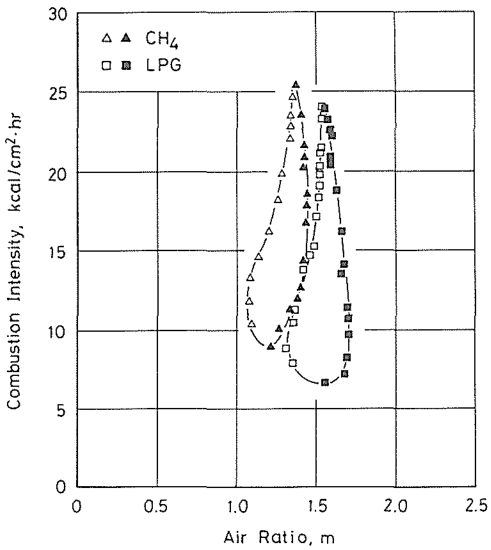


Fig. 5 Flameless Stage

Fig. 5 focuses on the flameless stage and compares the plot of stage III for methane and propane. For propane, the transitions between stages occur at leaner conditions but the width of the plots are almost the same for both fuel.

3.2 Temperature profile within the fiber mat

Before the axial temperature profile within the fiber mat was measured, the radial temperature profile of the burner surface was verified. For an air ratio of 1.0 and a superficial velocity of 5.89 cm/s, although the radial profile was not constant, the profile can be considered uniform within 15 ℃ of a mean temperature of 1220 ℃.

The temperature profile within the fiber mat for the different stages for constant combustion load of 22 W/cm² is shown in Fig. 6. From the figure, at m = 0.47, stage I, the temperature inside the mat is low. As the air ratio increases, the internal temperature also rises. At m = 0.74, stage II, a temperature peak appears with the location of the maximum temperature within the burner deeper in the fiber mat. At m = 1.31, the temperature is high for the given air ratio. Although it is not shown in the figure, the temperature outside the mat is lower than the surface temperature at this point. The highest internal termperature is determined by the balance of the mixture velocity and combustion velocity while completeness of combustion is determined by air ratio, hence, the figure shows that the deepest penetration of the flame inside the mat occurs at stage II and not at the flameless stage.

Some evidence of thermal degradation of the material is shown in Fig. 7. The combustion characteristics of the system changed after the burner was exposed to high temperatures after a week of intermittent use. The figure shows the temperature profile for a newly used fiber mat and the temperature profile of the same mat after being used for some time. The profiles for the mat show that after long use, the temperature is lower than the temperature

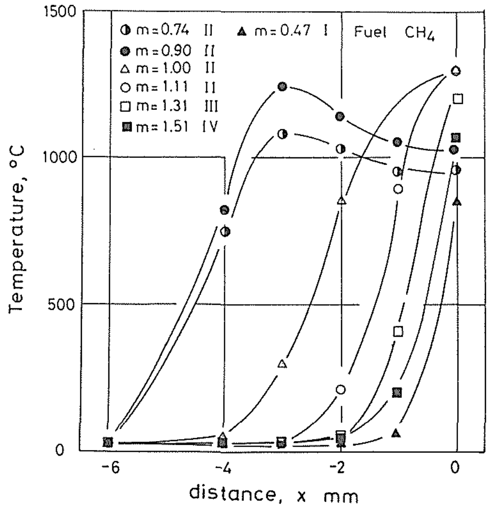


Fig. 6 Temprature Distribution

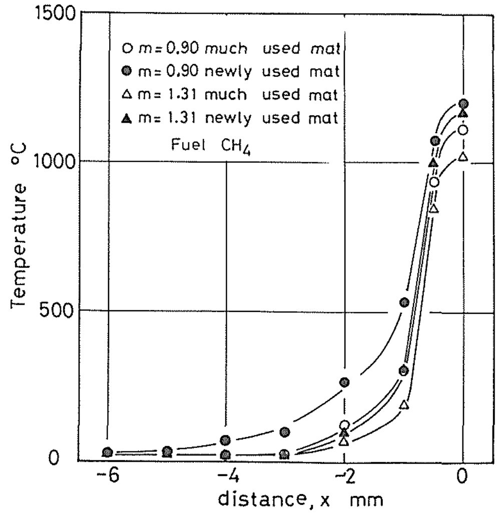


Fig. 7 Temperature Profile After Long Use

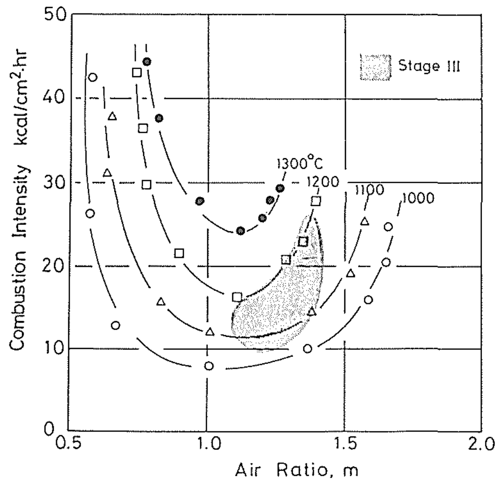


Fig. 8 Constant Surface Temperature

for corresponding points inside a newly used mat. This is considered to be caused by changes in the transport property of the part of the burner material which has been exposed to high temperatures after long use.

Constant surface temperature curves are shown in Fig. 8, where the shaded area represents "flameless" stage III. Although the actual maximum temperature that the burner surface attains was not measured to comply with the temperature limit of about 1300 ℃ suggested by the manufacturer, the figure shows that the maximum surface temperature occurs at stage II, which is reasonable because considerable reaction still occurs very near the surface at this stage. The temperature for stage III ranges from 1000 to 1200 °C. It also shows that for a given load, starting from a very rich mixture and moving towards leaner mixture, the surface temperature rises until it reaches a peak temperature and then it starts to decrease.

3.3 Products of Combustion

Measurements of the products of combustion had been conducted above the burner for the different stages. Carbon dioxide, carbon monoxide and nitric oxides concentration profiles above the mat were measured. The results for a combustion load of 22 W/cm² with methane as fuel are shown in Fig. 9 & 10.

Fig. 9 shows that combustion has proceeded substantially within the fiber mat for an air

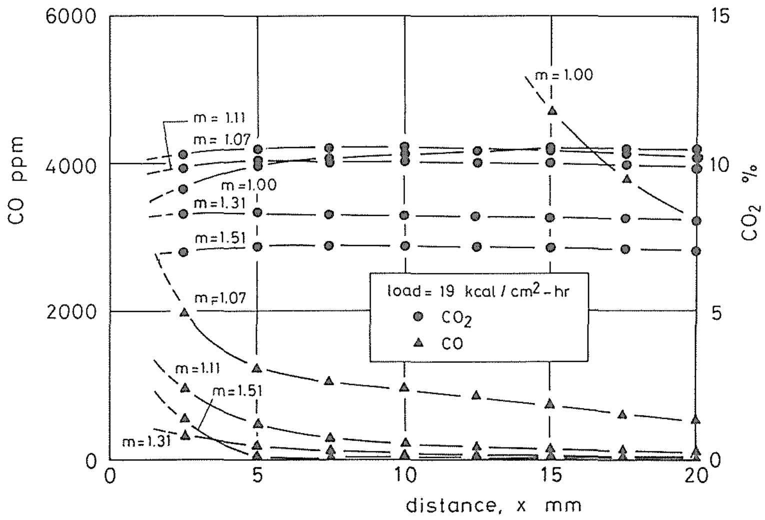


Fig. 9 CO and CO_2 Emission

ratio of 1.31, within stage III. CO was reduced to 10 ppm at a distance of 20 mm. from the surface. The CO emission for stage II is higher, while that for stage IV is almost the same as for stage III.

Fig. 10 shows that the NO_x emission characteristics of the burner is very sensitive to changes in the air ratio, decreasing with increasing air ratio. The sensitivity, however, diminishes with increasing air ratio, so that at an air ratio of about 1.3 and over, the slope of the curve is almost flat. The values, however, are very low. For stage III, the NO_x emission is a mere 3.6 ppm. For stage II, the values are considerably higher, while for stage II, the emission was only slightly lower than stage III which was measured at 2.61 ppm.

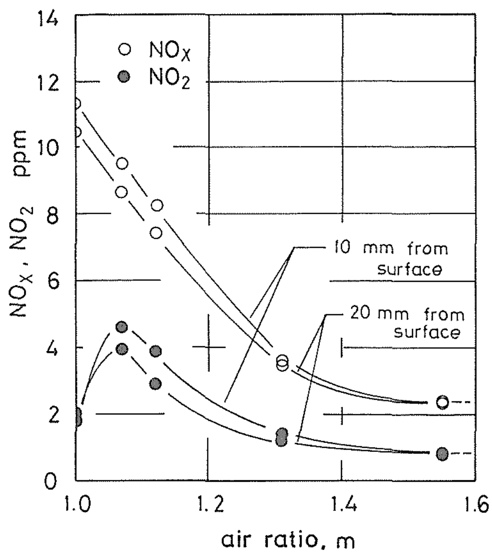


Fig. 10 NO_x, NO_2 Emission

These values are within the standards set for environmentally acceptable emissions. Further, these are relatively low compared with ordinary fan heater using methanol or kerosene as fuel [4] and is also comparatively low compared with thermally stabilized burners using ethane [5].

4. Implications to Burner Design

For the purposes of developing clean and compact combustion systems, it may be misconstrued that the optimum conditions for operating the burner lie in stage II where the highest temperatures are observed. However, the optimum conditions does not only require high temperature but also require high combustion efficiency, high percentage of conversion of the energy released via combustion to radiant energy, and low levels of pollutant emission. It appears then that the optimum conditions to operate a porous fibrous burner occurs within stage III. At this sstage, no flame is formed above the burner making a compact design feasible and the surface temperature can be limited to the range 1000 ℃−1200℃ which is low enough to limit NO_x emissions to very low levels but is still sufficiently high for significant radiant heating, combustion is completed within the fibrous mat burner, which signifies that substantial conversion of the energy released through combustion to radiant heat exists, and CO emission is nil.

5. Conclusions

The study was conducted to characterize the combustion of a premixed gas within inert fibrous mat. The study revealed the following observations:

1. There are five distinct stages of combustion characterized by the visibility of flame above the burner. One of these is a so called "flameless" stage where combustion is completed within the fibrous mat, thus, no flame is visible above the surface.
2. The conditions defining the combustion stages are sensitive to the air ratio and mixture velocity and are affected by the fuel, fiber porosity and thermal degradation of the fiber mat.
3. Combustion is completed within stage III as evidenced by minimal CO concentration just above the surface and the absence of flame.
4. NO_x emission is greatly influenced by the air ratio but is kept at very low levels, specially at stage III.
5. The surface temperature reaches its maximum in stage II. However, for the purposes of developing a clean, compact and highly efficient combustion system, stage III defines the optimal conditons to be considered: completeness of combustion, low pollutant emission, significant conversion of heat released through combustion to radiant energy, and the absence of flame that allows compact designs.

Acknowledgement

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