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ABSTRACT

The surface combustor-heater is a combined combustion/heat-transfer device in which the heat-exchange surfaces are embedded in a stationary bed of refractory material where gaseous fuel is burned. Because of intensive heat radiation from the hot solid particles and enhanced heat convection from the gas flow to the heat-exchange tubes, heat transfer is significantly intensified. Removing heat simultaneously with the combustion process has the benefit of reducing the combustion temperature, which suppresses NO_x formation.

A basic experimental study was conducted on a 60-kW bench-scale surface combustor-heater with two rows of water-cooled tube coils to evaluate its performance and explore the mechanism of combined convective-radiative heat transfer and its interaction with combustion in the porous matrix. Combustion stability in the porous matrix, heat-transfer rates, emissions, and pressure drop through the unit have been investigated for the variable parameters of operation and unit configurations. Experimental results have demonstrated that high combustion intensity (up to 2.5 MW/m^2), high heat-transfer rates (up to 310 kW/m^2), high density of energy conversion (up to 8 MW/m^3), as well as ultra-low emissions (NO_x and CO as low as 15 vppm*) have been achieved.

The excellent performance of the test unit and the extensive data obtained from the present experimental study provide the basis for further development of high efficiency and ultra low-emission water heaters, boilers, and process heaters based on the surface combustor-heater concept.

INTRODUCTION

The major challenges for advanced utilization of fossil fuel energy via heat transfer from the combustion products to a heat exchanger are focused on environment, efficiency, and economics. To meet these requirements, the development of combustion/heat-exchange equipment is directed at high intensity, high efficiency, low emissions, and low capital and operating costs. The surface combustor-heater is such a device to convert energy from gas fuel combustion to the heat exchanger through which a working fluid circulates.

Enhancement of heat transfer is an important approach to improve energy utilization in many gas-fired devices. In a conventional system composed of a heat exchanger heated by the products of gas fuel combustion, convection is the dominant mode of heat transfer because heat radiation from the combustion products is negligible because of the low gas

* Unless otherwise specified, all pollutant emission data in this paper are corrected to 0% O_2

opacity. There are many techniques that have been applied to increase convective heat-transfer rates from the combustion products to the heat exchanger, such as surface modifications (for example, treated surfaces, rough surfaces, extended surfaces, etc.) and flow enhancement (for example, swirl flow, st rring flow, additives for liquid and gas, flow oscillation, etc.). Regardless of the technique, a basic approach for improving convection heat transfer of the gas flow across the heat-exchanger surfaces is to increase either velocity (or turbulence) or temperature, or both. However, an increase in gas velocity substantially increases the pressure drop that results in the reduction of the performance of the entire system, and an increase in the gas temperature requires higher flame temperatures that normally result in higher thermal NO_x emissions. Therefore, further improvement of heat transfer in conventional heat exchangers are restricted.

To reduce NO_x formation in a combustor, one of the most effective approaches is to remove heat from the combustion zone. This could be achieved by placing a heat sink or injecting a diluent in the flame zone. However, in a conventional combustor, the presence of cold heat-exchange surfaces within the combustion zone tends to quench the flame, thereby producing CO and total hydrocarbon (THC) emissions.

In the surface combustor-heater, however, the relatively cold heat-exchange surfaces are embedded in a stationary bed (porous matrix) where the fuel is burned, as shown in Figure 1. As the bed is heated by the combustion products, the heat is extracted from the bed by the embedded heat exchanger and is transferred to a working fluid circulating in the tubes. The overall heat-transfer rate to the heat-exchange surfaces is higher than that in a conventional heat exchanger because gas flow across the tubes is intensively mixed and turbulized by the solid particles in the bed, and the radiant heat transfer from the solid particles to the tubes accounts for the significant contribution to the total rate. Also, by removing heat simultaneously with the combustion process, the combustor-heater reduces NO_x formation by suppressing the combustion temperature. The problem with flame quenching can be avoided because combustion reaction takes place in a great number of the small pores between the particles as well as at the hot surfaces of the particles. Therefore, combustion intensity can be very high, which allows perfect completion of combustion.

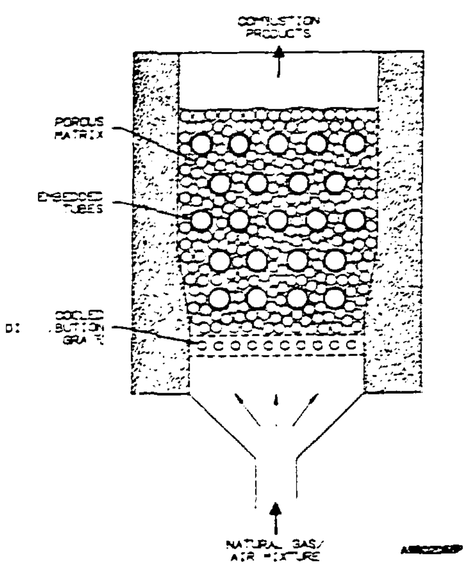

Figure 1. SCHEMATIC OF SURFACE COMBUSTOR-HEATER CONCEPT

Because the surface combustor-heater combines the combustor and the heat exchanger in a unit, the entire system can be compact and, therefore, low in cost. The overall energy conversion fro, , uel combustion to the working fluid can be accomplished in a very high density.

Preliminary proof-of-concept tests conducted in the U.S.S.R and the U.S.A. demonstrated excellent performance, such as high combustion intensity, high heat-transfer rates, and low combustion emissions.[1-4] However, the fundamental heat-transfer processes and the interaction with combustion in the surface combustor-heater system are not fully understood. In addition, the potential for further reduction of emissions, enhancement of heat transfer, and design optimization of this device for applications have not been investigated yet. A thorough theoretical analysis and parametric experimental study are being conducted to explore the mechanism of combined convective-radiative heat transfer in conjunction with combustion in the porous matrix combustor-heater, and these will develop extensive data and a computer program for optimizing the design and unit scale-up. This paper presents the experimental approach and some results obtained from the parametric study.

EXPERIMENTAL APPROACH

The purpose of the experimental study is to evaluate the performance of a bench-scale surface combustor-heater and to explore the mechanism of the interactive combustion/heat-transfer process within the porous matrix. The extensive data obtained from the parametric study will be used for verification and validation of the mathematical model as well as for optimizing the design of a commercial prototype.

Surface Combustor-Heater Test Unit

The firing capacity of the bench-scale surface combustor-heater test unit was determined to be 60 kW. The combustor-heater unit consists of six segments connected together by flanges:

- Natural gas/combustion air mixture plenum
- Water-cooled distribution grate
- Combustor-heater section
- Measuring section
- Exhaust plenum
- Exhaust stack.

The mixture of natural gas and combustion air is brought into the unit by a 1-1/4 inch pipe and mixture plenum. The distribution of the mixture is provided by the water-cooled grate equipped with specially designed distribution nozzles. The cooling water is channeled through the double-wall grate in such a way that the body of each nozzle is evenly cooled. In addition, each nozzle contains a cooling rod that is attached to the cap of the nozzle on one side and exposed to the cooling water on the other side. This arrangement assures additional cooling of the caps of the nozzles. The grate assembly is attached to the support frame in a way so that the distance between the first row of cooling tubes and the top of the distribution nozzles can be adjusted. The cooled grate sustains the flame above the grate and prevents the risk of flashback.

The combustor-heater chamber is a 6-inch by 6-inch square configuration. The chamber is lined with 8-inch-thick, high-temperature insulating block to minimize heat losses.

To conduct the parametric study, the combustor-heater segment is modularized into nine interchangeable sections. Each section consists of two rows of heat-exchanger tubes with selected spacing both vertically and horizontally. The individual sections can be combined to produce different configurations. The matrix bed is filled with ceramic particles within which the water-heater tubes are embedded. Silicon carbide- (SiC) and alumina- (Al_2O_3) based ceramic particles were used to construct the porous matrix.

Operation and Control System

The experimental system consists of the combustor-heater unit; water, fuel, and combustion air supply systems; the operation and control system; and the data acquisition and reduction system. A schematic diagram of the experimental system is shown in Figure 2.

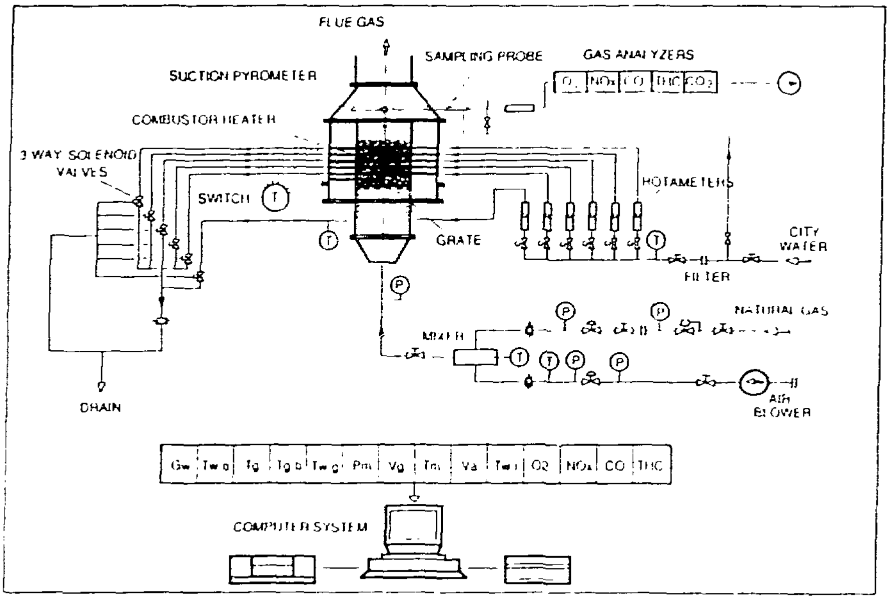

Figure 2. THE EXPERIMENTAL SYSTEM

Natural gas and ambient air are used in all tests. Natural gas and combustion air are premixed in a mixer as shown in Figure 2.

Water was selected as the working fluid of the heat exchanger embedded in the porous matrix bed. The water heater and the open water-flow system includes a total of five independent water tubes with a flow-rate control valve and a rotameter installed at the inlet of each tube.

Natural gas and combustion air flow rates, as well as water flow rates for each tube coil and the grate, are controlled by valves mounted on the control panel. All flow rates are measured by electronic mass-flow meters. Water flow rates through the tube coils and the grate can also be monitored by low-cost rotameters mounted on the control panel when the water flow is adjusted.

Data Acquisition System

A computer data acquisition and reduction system has been employed for parametric studies. This system collects, reduces, and analyzes the major data measured for operating control and analysis of overall combustion and heat-transfer characteristics.

Flow rates of natural gas, combustion air, and water are metered individually by electronic mass-flow meters and acquired by the computer system. The mass-flow meters for natural gas and combustion air were calibrated by two orifice flow meters. The water mass-flow meter was also calibrated by weighing the mass of water flow at operating conditions.

Several flue-gas analyzers, including those for oxygen (O_2), carbon monoxide (CO), carbon dioxide (CO_2), nitric oxide (NO), oxides of nitrogen (NO_x), and unburned total hydrocarbons (THC), are installed for combustion monitoring and evaluation of combustion emissions. The gas analyzers were calibrated for measuring ranges using cylinder span gases in every test.

A water-cooled probe is used to sample the combustion products. The probe at the cold end is equipped with a section of externally heated stainless steel tubing to maintain a sample temperature of about 190°F so that moisture would not condense. The warm sample is passed through a millipore filter to remove any solid particles and a Permapure dryer to remove moisture. The dried sample is supplied to the analyzers through Teflon tubing.

A water-cooled suction pyrometer is used to measure the temperature of the exhaust gas for overall energy balance in the combustor-heater unit. To measure gas temperatures in the porous matrix bed, two thermocouple probes are installed between the grate and the first row of tubes and between the two rows of tubes.

All the major data are acquired and reduced by the computer to provide real-time monitoring of operating conditions and combustion/heat-transfer characteristics of the test system.

EXPERIMENTAL RESULTS

The purpose of the experimental study is to explore effects of major configurations of the combustor-heater and the materials of the porous matrix on the performance of the test surface combustor-heater. The data will be used for the further study on the interactive combustion/heat-transfer as well as to guide and validate the mathematical model for optimization of the combustor-heater design.

The experiments were performed for the variable parameters, including air/fuel ratio, firing rate, horizontal spacing (S/D) and vertical spacing (H/D) of the heater tubes, as well as bed materials. The performance of the test combustor-heater was evaluated for combustion stability within the porous matrix, combustion intensity and turndown operation, heat-transfer rate for each row of tubes, thermal efficiency or energy conversion rate of the unit, combustion emissions (CO, NO/NO_x, and THC), and pressure drop across the unit.

To ensure accuracy of the experimental results, the natural gas used in the tests was sampled and analyzed. Temperatures on the outer surface of the combustor-heater were measured at a total of 52 points by a surface temperature probe to estimate heat loss from the walls. Heat loss from the walls is approximately 3% of the total heat input. Flue-gas temperature was also measured by a suction pyrometer for calculation of exhaust heat. Heat balance for the combustor-heater unit is calculated based on all measured data. The overall discrepancy between heat input and output is around 5% of the total heat input. In each test, the data were acquired by the computer system at a certain firing rate, while excess air was controlled at different levels.

The experimental results are presented as follows.

Effect of Excess Air

Because air/fuel stoichiometric ratio is the key parameter to govern combustion stability in the porous matrix, all tests were conducted at a fixed firing rate, but with variable excess air. Although direct monitoring for flame stabilization was not performed, flame stability can be evaluated based on heat-transfer characteristics. To maximize the overall thermal efficiency of the combustor-heater, the flame is desired to be stabilized between the grate and the first row of tubes. Heat transfer to each row of tubes as well as gas temperature measured within the bed can indicate a tendency for flame movement.

The effect of excess air on the heat-transfer rate to the grate and each row of tubes at a 45-kW firing rate is shown in Figure 3. The highest heat-transfer rate occurs at the first row of tubes over most of the range of excess air, while the lowest heat-transfer rate occurs at the grate. However, as excess air increases, the heat-transfer rates to the grate and the first row of tubes are decreased, while the rates are increased for the second row of tubes. That indicates move up of the flame with an increase in excess air. At higher excess air, for instance, 40% in this typical condition, heat extraction by the first row of tubes is dramatically decreased because the flame is almost moved away from that row of tubes. Therefore, the range of operating parameters for stable flame that is desired below the first row of tubes can be defined, depending upon the configuration of the combustor-heater and the bed material.

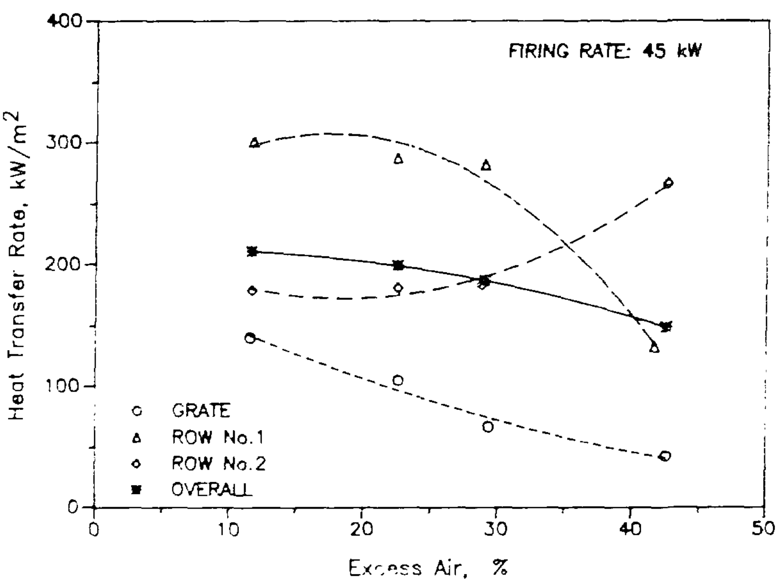

Figure 3. EFFECT OF EXCESS AIR ON HEAT-TRANSFER RATES

The data shown in Figure 3 also show that a heat-transfer rate as high as 300 kW/m^2 was achieved for the first row of tubes. The overall average heat-transfer rate for this configuration of the water heater is 215 kW/m^2 at low excess air operation.

Flame stabilization in the porous matrix is also indicated by gas temperatures measured in the flue gas and the porous bed, as shown in Figure 4. As the excess air increases, the gas temperature in the porous bed measured below the first row of tubes steadily decreases because of the decrease in flame temperature as well as the movement of the flame. However, the flue-gas temperature increases because of the upward movement of the flame, resulting in a steady decrease of the overall heat-transfer rate, as shown in Figure 3.

A significant effect of excess air on combustion emissions was demonstrated. Figure 5 shows the major pollutant emissions from the combustion process – CO, NO_x, and THC – versus excess air at a constant firing rate operation. NO_x emissions decreased with an increase in excess air because of a decrease in combustion temperature, as expected. As low as 15 vppm of NO_x emissions was demonstrated over a practical operating range. CO emissions below 20 vppm were also achieved in this typical testing. At higher excess air, however, CO increases dramatically with excess air because not only is the combustion temperature lower, but the flame also moves up closer to the first row of tubes. This results in an overcooling of the combustion gases, within which CO is (normally) continuously burnt out. Even so, ultra-low emissions of unburnt total hydrocarbons (THC) were achieved (less than 3 vppm). Therefore, almost 100% combustion efficiency was achieved. There was no flame quenching found in the test combustor-heater.

Therefore, combustion has to be stabilized below the first row of tubes to achieve high heat-transfer rate and low combustion emissions. The range of operating parameters for stable combustion in the porous matrix depends upon configurations of the combustor-heater and bed material as well

Effect of Firing Rate (Turndown Operation)

Testing was conducted for each configuration at firing rates from 12.5 to 56 kW for evaluating turndown performance of the combustor-heater. A further reduction of firing rate may cause flame quenching on the grate because the flame is so close to the grate surface. A further increase in firing rate above 56 kW was restricted because the flame was gradually moving up, resulting in reduction of the overall heat extraction. Figure 6 shows that the overall heat-transfer rate increased with firing rate until the maximum heat-transfer rate was reached. For the present configuration, the maximum overall heat-transfer rate is approximately 220 kW/m^2 at a 50-kW firing rate when the flame starts to move up. Heat transfer from combustion gases to the tubes is achieved by the combined heat radiation and heat convection. Heat radiation is mostly dependent upon temperature of the solid particles and much less dependent on firing rate, whereas heat convection is basically dependent on firing rate approximately to the 0.8 exponential power. Therefore, the overall thermal efficiency, which is defined as a ratio of total heat transmission to the total heat input (firing rate), decreases with increasing firing rate. For the present operating conditions, the thermal efficiency of the test unit consisting of two rows of tubes decreased from 70% to 35% over a turndown ratio from 4.5 to 1.

The effect of firing rate on combustion emissions at 30% excess air is shown in Figure 7. With an increase in firing rate, CO emissions significantly decreased to as low as 15 vppm because combustion intensity in the porous matrix is enhanced at a higher firing rate. At very low firing intensity, however, CO emissions decreased, as demonstrated in some tests. This is a result of the interaction of combustion and heat transfer. Gas temperatures measured in the bed indicated the flame moved upstream at the lower firing rate; that resulted in longer residence times for combustion completion.

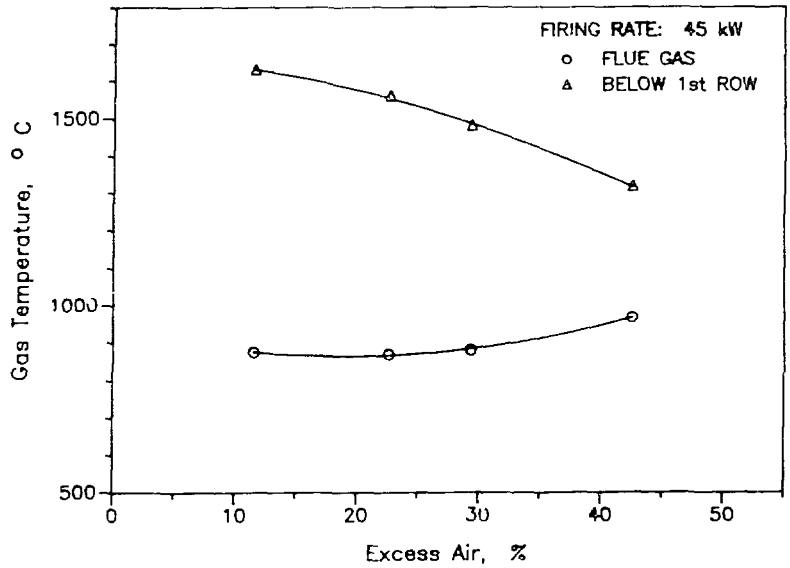

Figure 4. EFFECT OF EXCESS AIR ON GAS TEMPERATURE

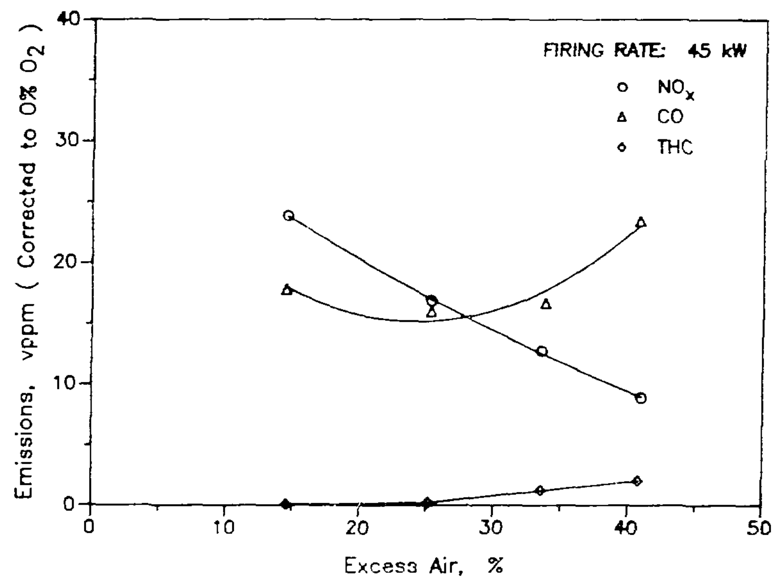

Figure 5. EFFECT OF EXCESS AIR ON COMBUSTION EMISSIONS

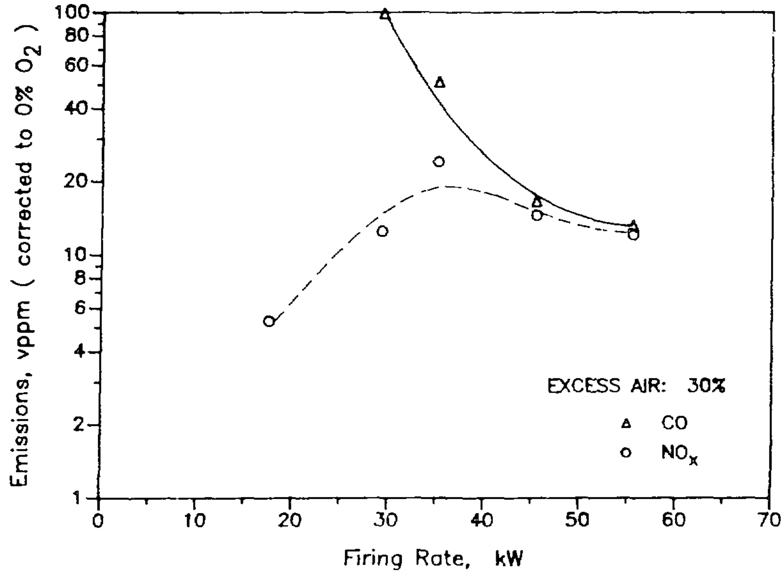

Figure 6. EFFECT OF FIRING RATE ON COMBUSTION EMISSIONS

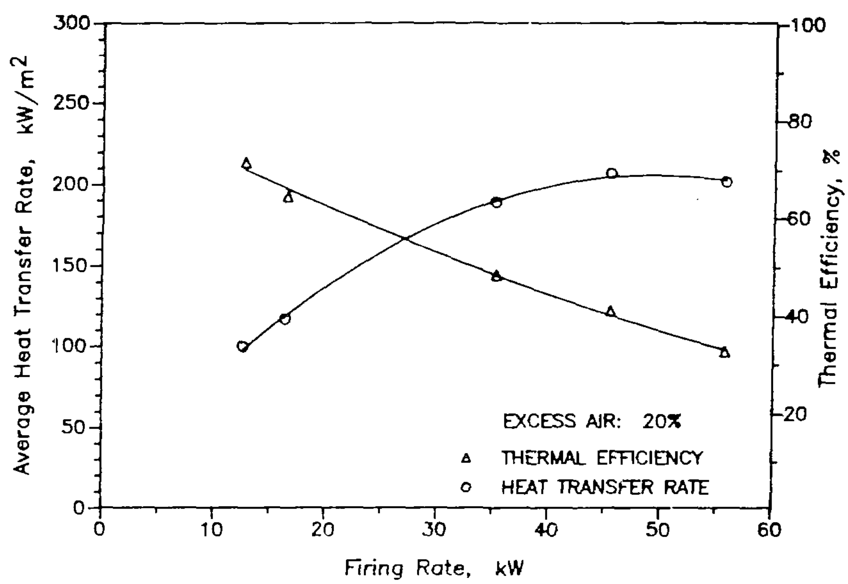

Figure 7. EFFECT OF FIRING RATE ON OVERALL HEAT TRANSFER

NO_x emissions below 20 vppm were demonstrated over a large range of firing rates, as shown in Figure 7. Especially notable, as low as 10 vppm NO_x emissions were achieved at lower and higher firing rates. This is the result of the interaction of combustion and heat transfer in the combustion zone. Greater heat removal from the grate at lower firing rates and from the first row of tubes at higher firing rates results in further reduction of NO_x emissions.

In summary, the experimental data have demonstrated high combustion intensity and high heat-transfer rate achieved in the test surface combustor-heater. Particularly, because the combustor and heat exchanger are combined in a single unit, density of energy conversion – defined as amount of energy transferred from fuel combustion to working media within a unit of volume – is extremely high, up to 8 MW/m^3 in the present test unit. The data also demonstrate that combustion emissions of both NO_x and CO less than 15 vppm and THC less than 3 vppm have been achieved over a large range of operating parameters. The experimental data show a strong interaction between combustion and heat transfer. Combustion stability and emissions are strongly affected by heat extraction by the embedded tubes. Simultaneously, the combined convective-radiative heat-transfer mode and its intensities are also affected by combustion characteristics.

Effect of Vertical Spacing of Tubes (H/D)

To evaluate the effect of heater configuration on performance, three combustor-heater sections with different vertical spacings of the two rows of tubes have been tested at the same operating conditions. The relative ratios of the vertical spacing of tubes are 1.0 (as the base configuration), 1.33, and 2.0. Figure 8 shows overall thermal efficiency of the three combustor-heater configurations versus excess air at a 30-kW firing rate. For the configuration with closest tube coils, the heat-exchange surface of the second row of tubes is less effectively used. The overall thermal efficiency is therefore relatively low, as shown in Figure 8. For the heater section with the tube coils quite far apart, however, the heat-transfer rate is also decreased. An apparent reason is that enhancement of flow turbulence by the tube array is depressed. For the combustor-heater with a medium vertical spacing of tubes, the overall heat transfer can increase by 10% to 15%.

The effect of vertical spacing of tube coils on NO_x emissions is shown in Figure 9. NO_x emissions are constantly decreased with an increase in excess air, as expected. It is also noted that NO_x emissions are significantly decreased with an increase in vertical spacing of tubes. However, CO emissions from the burner with the largest H/D are much higher than others, particularly at higher excess air, as shown in Figure 10. This is evidence that flame stability and location are strongly affected by vertical configuration of the combustor-heater. In the combustor-heater with largest H/D, the flame is relatively closer to the grate. That results in lower NO_x but higher CO emissions.

Effect of Horizontal Spacing of Tubes (S/D)

Three combustor-heater sections with different horizontal spacings of the first row of tubes were tested to evaluate the effect of the combustor-heater configuration on its performance. Figure 11 shows the overall thermal efficiency of the unit obtained from the three different configurations at different excess air, but at the same firing rate, which was 45 kW. It is obvious that the heat-transfer rate from the tubes with the largest S/D is lowest because of the least number of tubes installed. Heat transfer to the tubes with the smallest S/D is highest at low excess air operation, as expected, but significantly decreased at relatively high excess air, as shown in Figure 11. This is because combustion is partially completed above the first row of tubes which are too closely arranged. The effects of horizontal spacing of tubes on combustion emissions were also evaluated. It has been found that NO_x emissions do not significantly depend on horizontal spacing, but CO emissions do. As shown in Figure 12, CO

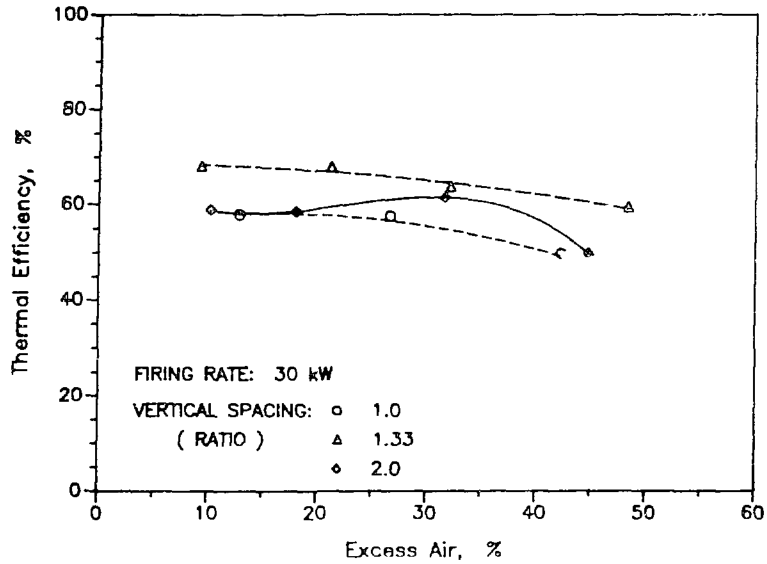

Figure 8. EFFECT OF VERTICAL SPACING OF TUBES ON THERMAL EFFICIENCY

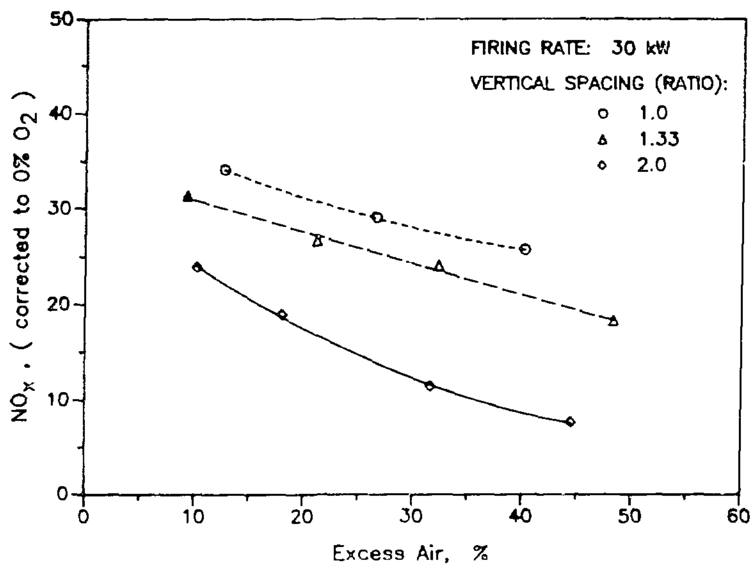

Figure 9. EFFECT OF VERTICAL SPACING OF TUBES ON NO_x EMISSIONS

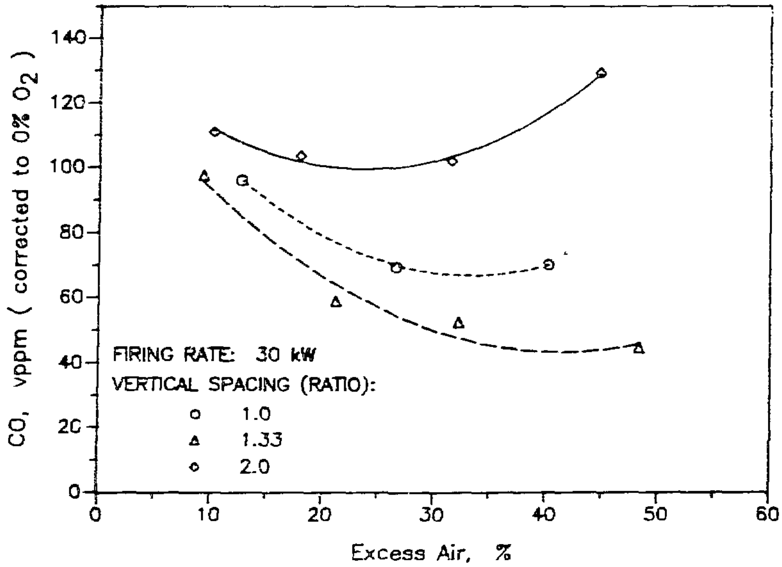

Figure 10. EFFECT OF VERTICAL SPACING OF TUBES ON CO EMISSIONS

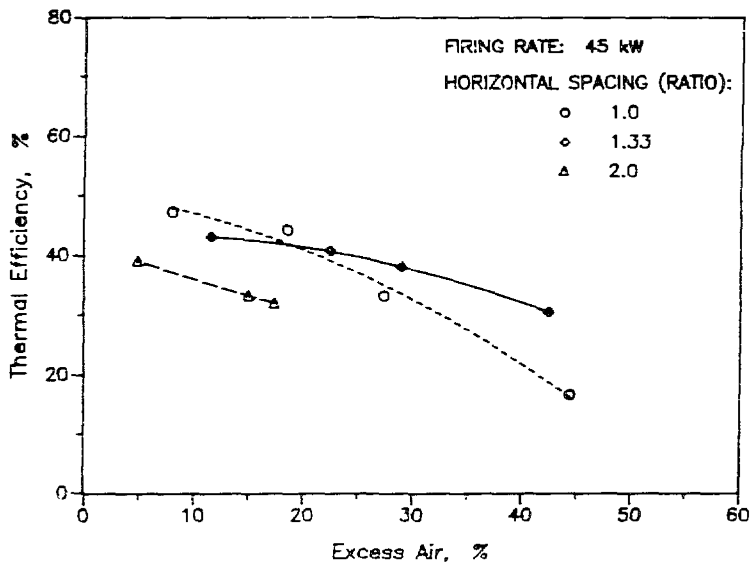

Figure 11. EFFECT OF HORIZONTAL SPACING OF TUBES ON THERMAL EFFICIENCY

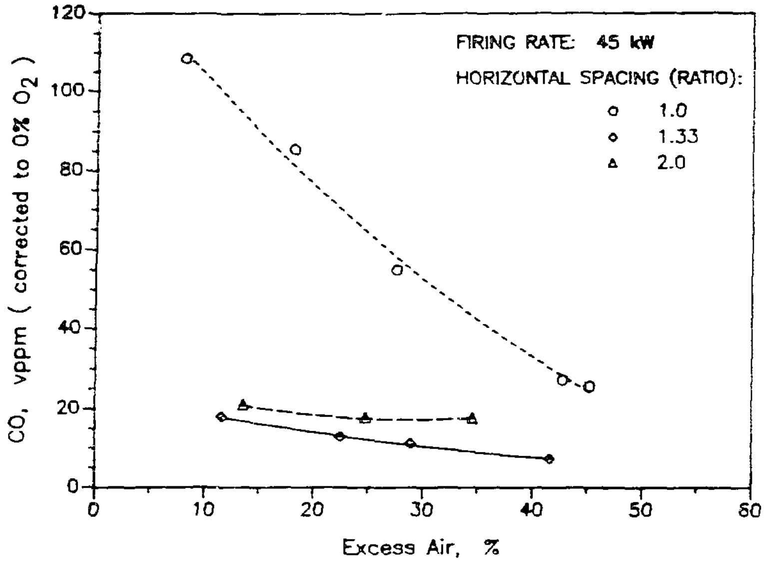

Figure 12. EFFECT OF HORIZONTAL SPACING OF TUBES ON CO EMISSIONS

emission produced from the combustor-heater with smallest S/D is much higher than that from the unit with larger tube spacing because combustion gases suffered from overcooling by the closely spaced water tubes. The effect of overcooling the combustion gases on CO formation is more severe at lower excess air because of the lower amount of combustion gases. Provided that the horizontal spacing of tubes is large enough, CO emission can be dramatically reduced down below 20 vppm, as shown in Figure 12. The experimental data show the strong effects of heat-exchanger configurations on the thermal performance as well as combustion characteristics and emissions.

Effect of Bed Materials

Because of strong interaction of combustion and the combined convective-radiative heat transfer in the surface combustor-heater. it is expected that material contained in the porous matrix has a significant effect on performances of the combustor-heater.

Figures 13 through 16 show the effects of bed material on the performances of the combustor-heater with the same configuration. Silicon carbide (SiC) particles and alumina (Al_2O_3) spheres were used in the testing. Thermal efficiency of the unit using SiC is obviously higher than that using Al_2O_3. particularly at higher excess air operation as shown in Figure 13 This is because the inherent higher radiation emissivity of SiC can enhance radiative heat transfer from the hot particles to the tube surfaces. It was also observed that the flame in the SiC matrix bed can be stabilized over a larger range of excess air. compared to that in the Al_2O_3 bed Therefore the overall heat extraction by the tubes in SiC bed is greater at high excess air operation. However, in the combustor-heater containing the Al_2O_3 spheres. the flame starts to move up at higher excess air. resulting in reduction of the overall heat extraction.

Because of a greater heat removal from the combustion process in the SiC-filled combustor-heater. NO_x emissions from the unit are lower compared to the Al_2O_3-filled combustor-heater. as shown in Figure 14. However. CO emission from the burner with SiC matrix bed is higher than that with Al_2O_3-sphere bed because the flame within the SiC bed is

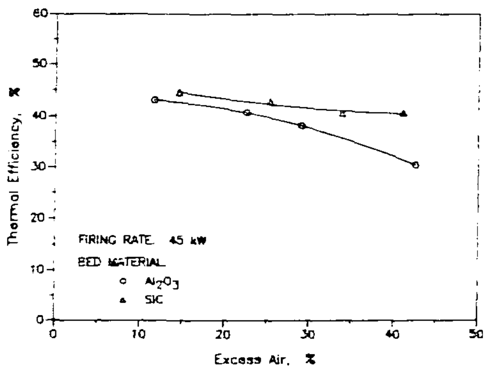

Figure 13. EFFECT OF BED MATERIAL ON THERMAL EFFICIENCY

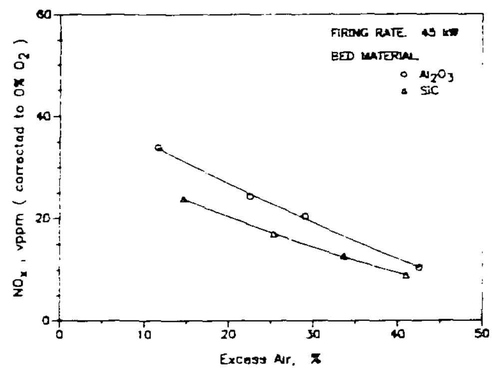

Figure 14. EFFECT OF BED MATERIAL ON NO_x EMISSIONS

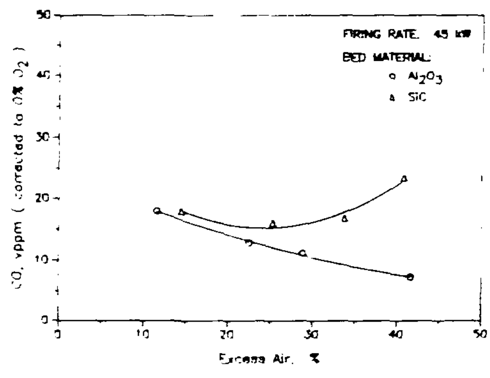

Figure 15. EFFECT OF BED MATERIAL ON CO EMISSIONS

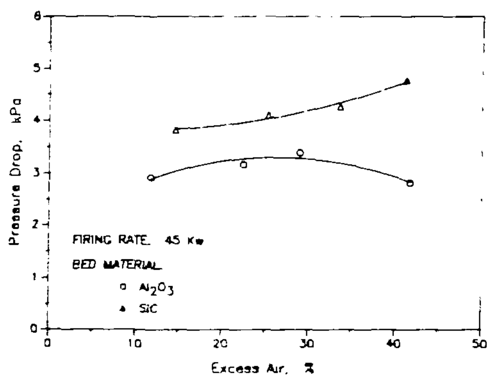

Figure 16. EFFECT OF BED MATERIAL ON PRESSURE DROP

greatly cooled, as shown in Figure 15. Moreover, at relatively high excess air, CO emission from the test burner using SiC is increased, in contrast with that using Al_2O_3 spheres. Even so, CO emissions from the present test units are still less than 20 vppm over a practical operating range of excess air.

Figure 16 shows pressure drop across the combustor-heater unit versus excess air measured in the SiC-filled burner and the Al_2O_3-filled burner. Because the SiC particles are of irregular shape, flow resistance is higher. It was also noted that at higher excess air, pressure drop for the Al_2O_3-filled combustor-heater is even decreased. This is evidence that the flame is moving up. Therefore, the high-temperature zone in the unit is reduced and results in decreasing pressure drop across the matrix bed.

It is obvious that the effects of bed materials on the performance of the surface combustor-heater are very complex. Fluid dynamics and the combined convective-radiative heat transfer are directly affected by combustion, while the combustion process is also influenced by fluid dynamics and heat transfer. An integration of experimental data and analytical results will allow a thorough exploration of the effect of bed materials. Determination of the physical properties of the bed materials will play an important role in identifying quantitative regularities in terms of material effect.

SUMMARY AND CONCLUSIONS

A basic experimental study was conducted on a bench-scale surface combustor-heater. Combustion stability in the porous matrix, combustion emissions, heat transfer to the embedded tubes, and pressure drop across the test unit have been investigated for the variable parameters of operation and unit configurations. Experimental data obtained at different combustor-heater configurations over a large range of operating parameters have demonstrated the excellent performance of the test surface combustor-heater:

- Ultra-low combustion emissions with NO_x and CO less than 15 vppm, and THC less than 3 vppm
- High combustion intensity up to 2.5 MW/m^2
- High heat-transfer rate up to 310 kW/m^2
- High density of energy conversion up to 8 MW/m^3
- 4.5 to 1 turndown ratio
- Relatively low pressure drop across the combustor-heater unit.

The data show a strong interaction between combustion, the combined convective-radiative heat transfer, and fluid dynamics within the combustor-heater.

Conceptionally, the following points are revealed based on the experimental results.

- Heat-transfer performance, combustion emissions, and fluid dynamics are strongly dependent upon the location of the flame in the combustor-heater.
- The location of the flame is dependent upon operating parameters and the configuration of the combustor-heater as well as bed material. Therefore, flame location should be an outcome of calculation, instead of as assigned.

- In practice, it is desired to stabilize the flame below the first row of heater tubes. Operating ranges of the parameters are therefore defined based on the desired location of the combustion zone.

- A significant effect of bed material on heat transfer shows an important contribution of heat radiation from the solid particles to the tube surfaces to the overall heat transfer. A quantitative assessment of the combined convective-radiative heat transfer requires an extensive experimental study as well as a further analysis.

The data provide a basis to guide and validate the mathematical model that is being developed.

As a result of the parametric study, an optimized design of the surface combustor-heater and selection of the bed materials can be preliminary defined. The extensive data can provide a basis for the further development of high-efficiency and ultra low-emission water heaters, boilers, and process heaters for industrial and commercial applications.

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