IMPROVEMENT OF OXYFUEL BURNER DESIGN AND OPERATIONS

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INTRODUCTION

Background

Conversion of a forehearth from air/natural gas to oxygen/natural gas firing has two principal advantages: (1) a substantial increase in energy efficiency, because of the reduction in waste heat loss, and (2) fewer burners are required, reducing capital and maintenance costs. In spite of these advantages, oxygen/natural gas-fired forehearths are relatively rare. Owens Corning and its partners Osram-Sylvania Inc., BOC Gases, and Combustion Tec/Eclipse have mounted a major effort to further develop the technology and conduct a demonstration at the Owens Corning Fiberglass plant in Jackson, TN. The project, entitled: "Development/Demonstration of an Advanced Oxy-Fuel-Fired Front-End System," is supported by the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, under its Industrial Technology Program (U.S. DOE, 2004; Greenman, 2004; Mighton, 2005a, 2005b, 2005c, 2005d). All reports indicate that the principal objectives: increased energy efficiency, reduced operating costs, improved environmental performance, and more uniform glass quality are all being met. U.S. patent and Patent Cooperation Treaty applications, entitled: "Oxygen-fired front end for glass forming operation," have been published (Baker, Adams, Jian, and Toth, 2003) and another U.S. patent application, "Low heat capacity gas oxy fired burner," is pending (Mighton, 2005a).

The project described in the present report was undertaken to complement the burner system development work being performed under the larger project described above. The work included design and testing of three burners and the incorporation of measurements of burner tip temperatures in the burner evaluation trials.

Previous Work on Oxygen/Natural-Gas-Fired Forehearth Burners

An early use of oxygen in forehearth burners is described by Desprez and Roux, (1987) of L'Air Liquide, who added a small tube at the center of premixed air/natural gas and air/propane burners to enrich the mixture with oxygen. The oxygen content of the mixture was kept below about 30 vol%. The authors reported that oxygen enrichment permitted significant reduction in the quantity of fuel consumed in the operation of a forehearth.

Following on the success of the conversion of a 400 ton/day container glass melter at Gallo Glass to oxygen/natural gas firing in 1991 (Moore and Brown, 1992), Corning Inc., Maxon Corp., BH-F (Engineering), Ltd., and Airco BH-F Systems, Inc. began a joint project to develop an oxygen/natural-gas-fired forehearth system. The rationale for oxygen/natural-gas-fired forehearths, design considerations, and results of initial testing of the system were described by Brown, Coppin, Stephens, and Marshall

(1993). These authors noted that, while oxygen/natural gas firing for glass melting is driven primarily by environmental regulations and capital cost, its advantages in glass conditioning are improved temperature control, increased pull rate, reduced volatilization, and extended forehearth life. Burner, combustion system, superstructure, and control system design considerations were all addressed in the paper by Brown and coworkers (1993). Three different burner designs had been tested at the time of their writing: (1) an over/under burner in which natural gas and oxygen are introduced through separate parallel tubes, (2) a variation on the over/under design, in which the oxygen tube surrounds the gas tube, but the oxygen and gas orifices are still separate from one another, and (3) a concentric tube-in-tube burner. The first and third designs remained as candidates at the time of the authors' presentation.

Corning Inc. introduced oxygen/natural-gas-fired forehearth burner and distribution channel designs in patents by Brown and Tinz (1995, 1996). The burner introduces oxygen and natural gas through straight (constant diameter) concentric tubes, with natural gas at the center and oxygen flowing through the annulus surrounding it. Its capacity ranges from 0.014 to 0.425 standard m^3/h of fuel (0.5 to 15 scfh or 150 to 4400 W for natural gas). The velocity of natural gas at the burner exit can be as high as 152 m/s (500 ft/s), but is preferably below about 76 m/s (250 ft/s). The ratio of the velocities of oxygen to natural gas is 1 to 3, but preferably approximately 1.5. The natural gas tip can lie in the same plane (same axial position) as the oxygen tip, or in front of, or behind it, but preferably in the same plane. Swirl is introduced into the flow by a spiral of wire in the oxygen annulus and by a spiral vane in the gas tube. In the burner used as the example in the patents, the outside and inside diameters of the oxygen tube are 6.26 and 4.76 mm (0.2465 and 0.1875 inch), respectively, and the outside and inside diameters of the natural gas tube are 3.19 and 1.78 mm (0.1255 and 0.070 inch), respectively. The ratio of oxygen to natural gas velocity in this configuration, with an oxygen-to-natural-gas ratio of 2.2 by volume and in the absence of any blockage of the orifices, is 0.56. Reynolds numbers for this burner are estimated to be in the range from 200 to 6000 for the specified range of flow rates from 0.014 to 0.425 standard m^3/h (0.5 to 15 scfh).

Combustion Tec, Inc., introduced its forehearth burner in a design by Joshi and Broadway (1996). These authors' burner is also a concentric tube-in-tube design, with natural gas at the center. Both the oxygen and natural gas tubes decrease in diameter near their exits, a feature that minimizes pressure drop through the burner and produces a somewhat flatter velocity profile at the exit than would be present in the fully-developed flow. The natural gas nozzle is recessed from the exit of the burner by one-half of the inside diameter of the oxygen nozzle. No swirl is present in either stream, other than that generated by the turns in piping leading to the burner. The optimum range of the ratio of the inside diameter of the oxygen nozzle to the inside diameter of the natural gas nozzle is specified as 2.5 to 3.0, corresponding to the range of values in which flame luminosity is greatest. Turndown ratios of 10 and 20 were achieved by burners designed for 0.41 and 0.66 m (16 and 26 inch) wide forehearth channels, respectively.

The BOC Group, Inc., (Travis, 1998) introduced a concentric tube-in-tube burner with natural gas introduced through the central tube, but having a tip markedly different from those of the designs described above. In the BOC Group's burner, the outer oxygen tube ends in a cone, converging to a relatively small single exit from the burner. Inside the cone is a conical plug attached to the end of the natural gas tube and blocking the end of the surrounding annular passage for oxygen. A hole through the center of the plug serves as the natural gas nozzle. The outer surface of the plug, which matches the inner surface of the end of the burner, is grooved to provide passages for oxygen from the annulus to a small cavity just inside the burner tip, where the oxygen and natural gas meet and mix. According to the patent (Travis, 1998), ignition and some combustion take place within the cavity, providing flame stabilization. The conical tip permits the burner block to be designed so that only a small area of the burner metal is exposed to radiation, and this feature, combined with cooling provided by the oxygen flowing inside the tip, make the burner resistant to formation of carbon deposits and damage from overheating. By not cutting the oxygen grooves straight down the surface of the conical plug parallel to its axis, but along slightly spiral paths around the cone, swirl is introduced into the oxygen flow. The range of flow rates is from 0.057 to 0.425 standard m^3/h (2 to 15 scfh) of natural gas, with a turndown ratio of up to 50.

Travis and Stephens (1997) describe the conversion of a forehearth for borosilicate glass conditioning to oxygen/natural gas firing, using a burner developed jointly by BOC Gases, BH-F (Engineering) Ltd., and Corning Inc. The burner is evidently closely related to the one described in the BOC Group, Inc., patent summarized in the previous paragraph. The capacity of the burner for the borosilicate glass conditioning application was from 600 to 3600 W (2000 to 12,000 Btu/h). Materials considerations, results of computational fluid dynamic modeling of the glass and combustion product flows in the channel, the performance of the forehearth system over an extended period, and refinements implemented during a repair of the melter were presented by Stephens, Clayton, Misra, Brown, and Cook (1998). The burners were fabricated using high nickel chromium alloys. The system met or exceeded all of its anticipated benefits, among which were: improved heat flux distribution and glass temperature uniformity, faster stabilization following pull change, lower fuel consumption, reduced volatilization from the glass, lower pressure in the combustion space, and slower refractory wear.

American Air Liquide proposed an oxygen/natural gas fired forehearth burner built largely using standard, commercially available pipe and tube fittings (Joshi and Fournier, 2000, 2002). The design is concentric tube-in-tube, with natural gas at the center, but with some distinguishing features. A twist drill is placed at the center of the natural gas tube, blocking some of its area, increasing the gas velocity, and imparting some swirl to the flow. A helical spring is placed in the oxygen annulus, introducing swirl to the oxygen flow. In the particular version of the burner described in detail in the patent, the range of natural gas flow rates is from 0.057 to 0.340 standard m^3/h (2 to 12 scfh) with an oxygen/natural gas ratio of 2.0. The inside diameter of the natural gas passage is 1.5 mm (0.060 inch) and contains a twist drill 1.2 mm (0.047 inch) in diameter. The oxygen nozzle, natural gas nozzle, and the tip of the drill are all in the

same plane at the tip of the burner. Assuming that the web of the drill occupies 60% of the drill's cross section area, the range of natural gas velocities corresponding to the range of gas flows from 0.057 to 0.340 standard m^3/h (2 to 12 scfh) is approximately 14 to 82 m/s (45 to 270 ft/s). The inside diameter of the oxygen tube is 11.94 mm (0.47 inch) and the outside diameter of the natural gas tube is 6.35 mm (0.250 inch), so the annulus though which the oxygen arrives at the burner tip is relatively large. The range of the axial component of the oxygen velocity corresponding to the range of flow rates from 0.113 to 0.680 standard m^3/h (4 to 24 scfh) is 0.4 to 2.4 m/s (1.3 to 7.7 ft/s). The Reynolds number for the entire flow at the burner tip is estimated to be in the range from 300 to 1800.

Combustion Tec introduced an alternative to its earlier design incorporating internal mixing of fuel and oxygen (Anderson, Nitzman, and Mohr, 2001). The new design is also concentric tube-in-tube with natural gas at the center. The inside diameter of the oxygen tube decreases markedly before arriving at the burner tip. A tapered plug mounted on the end of the natural gas tube is matched to the taper of the constriction in the oxygen tube. By this arrangement, oxygen is directed through a conical annulus toward the tip of the natural gas tube where space is provided for mixing of the two streams. A passage having a length/diameter ratio between 0.5 and 8.0 carries the mixture to the burner tip. In various designs this passage may have a constant diameter all the way to the burner tip, may gradually increase in diameter over its entire length, may have a constant diameter section followed by a section of increasing diameter, or may have constant diameter over most of its length but flared just at the exit.

An entirely different approach was taken by Praxair Technology, Inc., Saint-Gobain Vidros, S.A., and the Instituto de Pesquisas Tecnologicas do Estado (Ibarlucea, Yokaichiya, and Sobrinho, 2004). These authors proposed an oxygen/gaseous-fuel-fired forehearth burner having a tee-shaped head providing two flames propagating in opposite directions, parallel to the glass surface and to the forehearth wall. Fuel gas and oxygen are externally mixed, outside the burner. In the diagrams shown in the patent, each of the two burners has a single fuel nozzle surrounded by five oxygen nozzles. Three of the oxygen nozzles are on the side of the burner closest to the wall of the forehearth and have their axes parallel to the fuel nozzle and to the wall. The other two oxygen nozzles are on the side of the burner toward the center of the forehearth channel and have their axes at an angle, directed inward toward the axis of the fuel nozzle, so their jets mix more rapidly with the fuel jet. Many other arrangements of the fuel and oxygen jets are possible. The burner head is protected from overheating by a refractory shroud that surrounds it completely, except for the two opposed faces of the burners.

Owens Corning (Baker, Adams, Jian, and Toth, 2003) proposed marked departures from the traditional parallel, closely spaced, side-by-side arrangement of air/gaseous-fuel-fired forehearth burners. Their designs are intended to maximize the advantages to be derived from the unique characteristics of oxygen/gas flames. These authors place the burners in a variety of locations and angles with respect to the axis of the channel, both in the crown and the sidewalls of the forehearth, to reduce the number of burners required per unit length of channel, while maintaining good uniformity of

temperature in the glass delivered to the forming process and long life of the superstructure refractory.

The great variety of burner and forehearth proposals found in the literature reviewed above shows that no consensus has yet been reached in the glass industry regarding the optimum design and placement of oxygen/natural-gas-fired forehearth burners, suggesting that further improvements in the performance of the technology will be possible.

BURNER DESIGN AND TESTING

The first objective of the work was to evaluate alternative design concepts for burners that would be applicable as retrofits to existing air/natural-gas-fired forehearths, and the new types of forehearth burner arrangements proposed by Baker, Adams, Jian, and Toth (2003). Burners having maximum output in the range from 6 to 18 kW (20,000 to 60,000 Btu/h) were of interest.

The second objective was to place the comparison of alternative burner designs on a more quantitative basis, by making provision for direct measurements of burner tip temperatures. This was accomplished by threading fine wire sheathed thermocouples through compression fittings at the oxygen and gas connections at the back of each burner and placing the bead ends of the thermocouples in contact with the tube walls close to the burner tip. This permitted a direct observation of the condition of the burner tip and its behavior with change in fuel heat input or position in the burner block, to determine what orientation and which operating conditions provided most effective cooling of the metal.

The burners were fabricated at Owens Corning and the tests were conducted in the forehearth simulator at the Owens Corning Science & Technology Center in Granville, OH.

Venturi Burner

The motivation behind this design was to prevent the buildup of deposits sometimes formed on the tip of the natural gas tube, a phenomenon noted in several of the works reviewed in the previous section. The idea was to direct the oxygen flow at high velocity across the tip of the natural gas tube to prevent particles from reaching the tip and to scour any deposit that formed there. The configuration and dimensions of this burner are shown in Figure 1. Natural gas was introduced through the center tube and oxygen through the annulus surrounding it. Inside the tip of the burner, near the end of the oxygen tube, is a converging/diverging nozzle intended to increase the oxygen velocity with minimum increase in pressure drop. The natural gas tip was moveable, so it could be placed at any location from the throat of the nozzle to the end of the burner or beyond. When the gas tip is at the location shown in Figure 1, the areas available to natural gas and oxygen at the throat are proportional to their volumetric flow rates, so the velocities of the two streams are the same, 85.7 m/s (281 ft/s). The Reynolds number, based on the throat diameter and average velocity, is 33,000.

Computational fluid dynamic (CFD) calculations of the natural gas flame formed by the burner were performed using FLUENT flow modeling software (Fluent Inc., Lebanon, NH). The calculated distribution of temperatures is shown in Figure 2. The

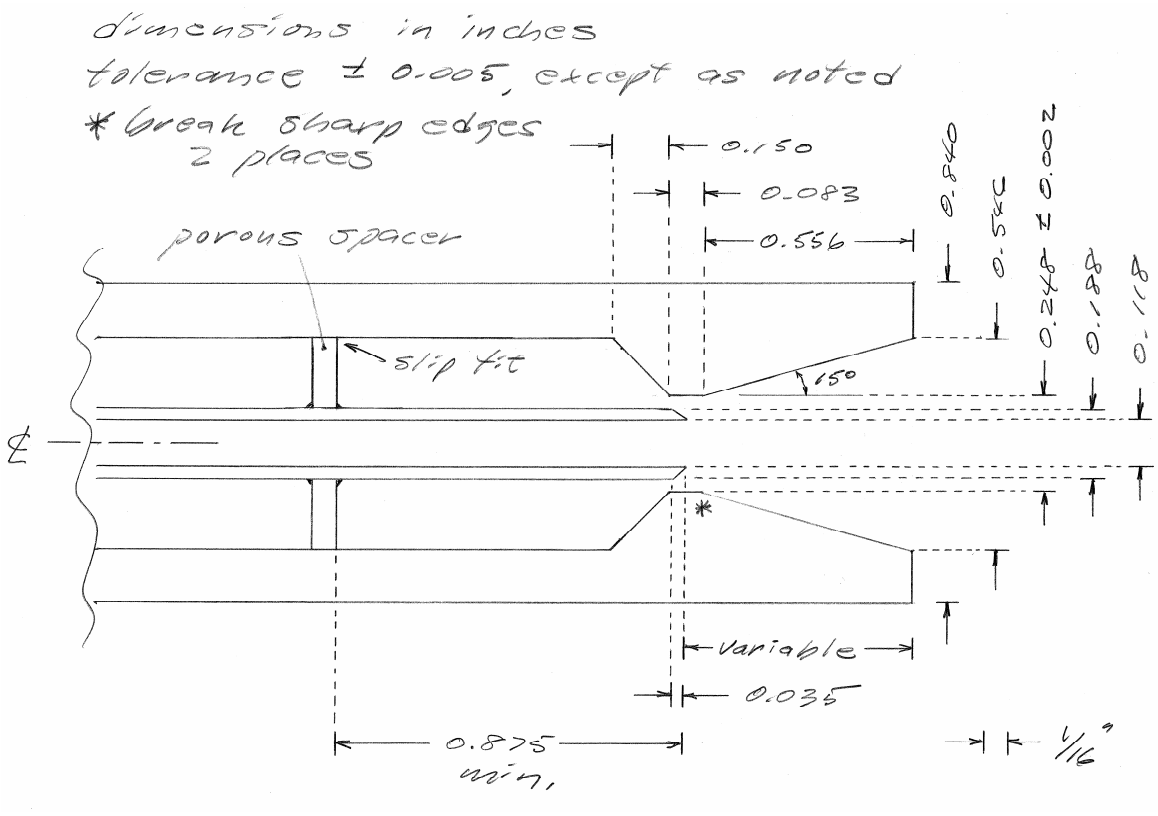

Figure 1. Burner having a converging/diverging nozzle with natural gas introduced through the central tube and oxygen through the annular passage surrounding it.

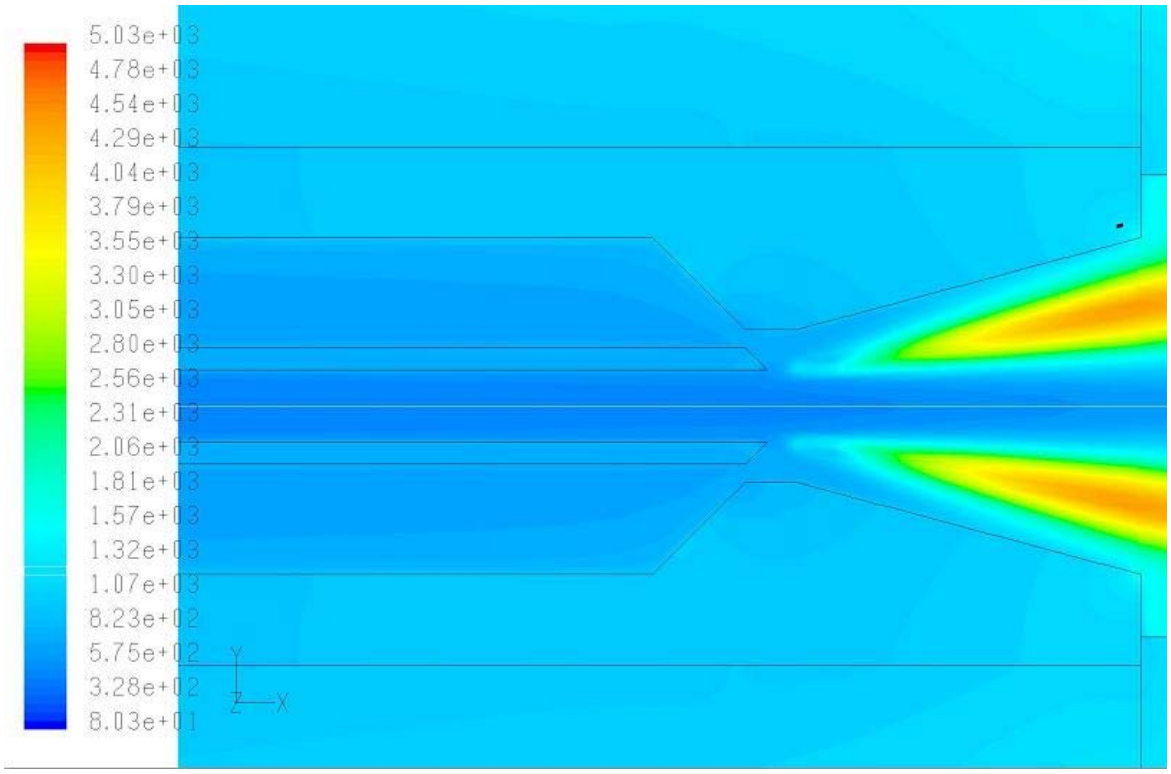

Figure 2. Computational fluid dynamic simulation, using FLUENT (Fluent Inc.), of the temperature distribution in the flame formed by a burner having the dimensions shown in Figure 1. The scale, at the left, indicates the temperatures in degrees Fahrenheit. Simulation by Christopher Q. Jian.

contour plot shows that the flame front originates very close to the gas tip and that combustion products at approximately 1500 ^{o}F (800 ^{o}C) come in contact with the inside wall of the diverging section of the burner just upstream from the burner exit.

A photograph of the natural gas flame formed by the burner in open air is shown in Figure 3. In this configuration the flame did not appear to approach too closely to the wall of the diverging section of the burner. However, the properties of a flame can change markedly when the burner is placed in its tuyere, the configuration for which the calculation shown in Figure 2 was done. When it is enclosed, the jet issuing from the burner is no longer able to entrain fluid (air in the case of Figure 3) from its surroundings. The flow then either attaches itself to the wall of the enclosure or gives rise to secondary flows that bring fluid from slower-moving, higher temperature, downstream regions of the jet back toward the burner. Either situation increases heat transfer between the jet and the surrounding wall.

The thermocouples to monitor tip temperature were fed through fittings at the back of the burner down the natural gas tube to the tip and through the oxygen annulus to the beginning of the converging section. Both thermocouples were slightly bent to place their tips in contact with the inside walls of the two tubes.

Upon insertion into the burner block in the forehearth simulator, the burner shown in Figures 1 to 3 overheated almost immediately. So much so that the tip of the burner completely melted down. As more than one burner of this type had been fabricated, the test was repeated with the natural gas tip placed flush with the exit of the burner. In this configuration the natural gas velocity at its tip remains the same as before, but the average oxygen velocity at the exit from the burner is reduced to 9 m/s (30 ft/s). The Reynolds number of the flow, based upon the exit diameter of the burner and total flow rate, is then 10,000. This change did not substantially alter the performance of the burner, which overheated and melted down almost as quickly as before.

Equal Velocity Straight Tube Burner

Because high combustion intensity appeared to be the characteristic that caused overheating of the burner described above, a straight tube design was formulated in which mixing would be retarded by adjusting the sizes of the natural gas and oxygen nozzles to match their axial velocities at the burner exit. By scaling the sizes of both nozzles up or down, still keeping the natural gas and oxygen velocities equal, the intensity of mixing and length of a flame could be continuously adjusted to match a given application. Two burners, having relatively high and low velocities, were fabricated according to this criterion.

The first, higher velocity, burner had the same central natural gas tube as the venturi burner shown in Figures 1 to 3, with outside and inside diameters of 4.8 mm (0.188 inch) and 3.0 mm (0.118 inch), respectively. A straight sleeve pressed into the outer tube reduced the outer diameter of the oxygen annulus to 6.6 mm (0.261 inch), as

Figure 3. Firing test of the burner having the dimensions shown in Figure 1. Photograph by Steve Mighton.

can be seen in Figure 4. The velocities of natural gas and oxygen leaving the burner were 72.5 m/s (238 ft/s) and 72.8 m/s (239 ft/s), respectively, and the Reynolds number for the flow was 30,000. Figure 4 shows the short, intense, rapidly mixed flame produced by this burner. In its tuyere in the forehearth simulator this burner ran too hot and, though the burner itself suffered no damage during the short test, the burner block was overheated and partially melted.

In the second, lower velocity, burner, the size of the natural gas tube was doubled, to 9.5 mm (0.375 inch) o.d. and 7.0 mm (0.275 inch) i.d. The oxygen nozzle diameter was increased to 14.3 mm (0.563 inch), slightly larger than that of the burner shown in Figures 1 to 3, and it had a straight bore without any insert or converging/diverging nozzle. The velocities of natural gas and oxygen were 13.4 m/s (44 ft/s) and 13.7 m/s (45 ft/s), respectively, and the Reynolds number for the flow at the burner exit was 12,000. The long, low intensity, slowly mixed flame produced by this burner is shown in Figure 5. When installed in the forehearth simulator, and at the full firing rate, the temperatures of both burner tubes and the burner block stabilized at satisfactory levels. The temperatures were: natural gas tube, 236 ^{o}C (456 ^{o}F); oxygen tube, 428 ^{o}C (803 ^{o}F); and burner block, < 932 ^{o}C (< 1710 ^{o}F). The temperatures increased somewhat at 50% of the full firing rate to: natural gas tube, 388 ^{o}C (730 ^{o}F); oxygen tube 595 ^{o}C (1103 ^{o}F); and burner block, 948 ^{o}C (1738 ^{o}F).

By varying the sizes of the oxygen and natural gas nozzles, keeping their exit velocities equal, burners exhibiting a continuous transition in flame length and combustion intensity can be obtained, between the extreme flame types illustrated in Figures 4 and 5. In this way, a burner and flame can be adapted to the particular requirements and dimensions of the burner blocks and forehearth in which they are to be housed. Although the flames are compared here, for purposes of discussion, by their appearances in open air, the only comparison having any relevance to performance in a forehearth is with the flames enclosed in the tuyeres in which they will be placed in practice, because an enclosure changes the properties of a flame dramatically. Installation of thermocouples at the tips of the gas and oxygen tubes greatly facilitates quantitative comparison of burner performance in place in the forehearth simulator, where visual access to the flames is limited.

Figure 4. Burner having constant tube diameters and equal oxygen and gas velocities at their tips. The central natural gas tube is the same size as in the burner shown in Figures 1 to 3 [4.8 mm (0.188 inch) o.d.; 3.0 mm (0.118 inch) i.d.]. A sleeve in the oxygen tip reduced its area to make the oxygen and natural gas velocities the same. Photograph by Steve Mighton.

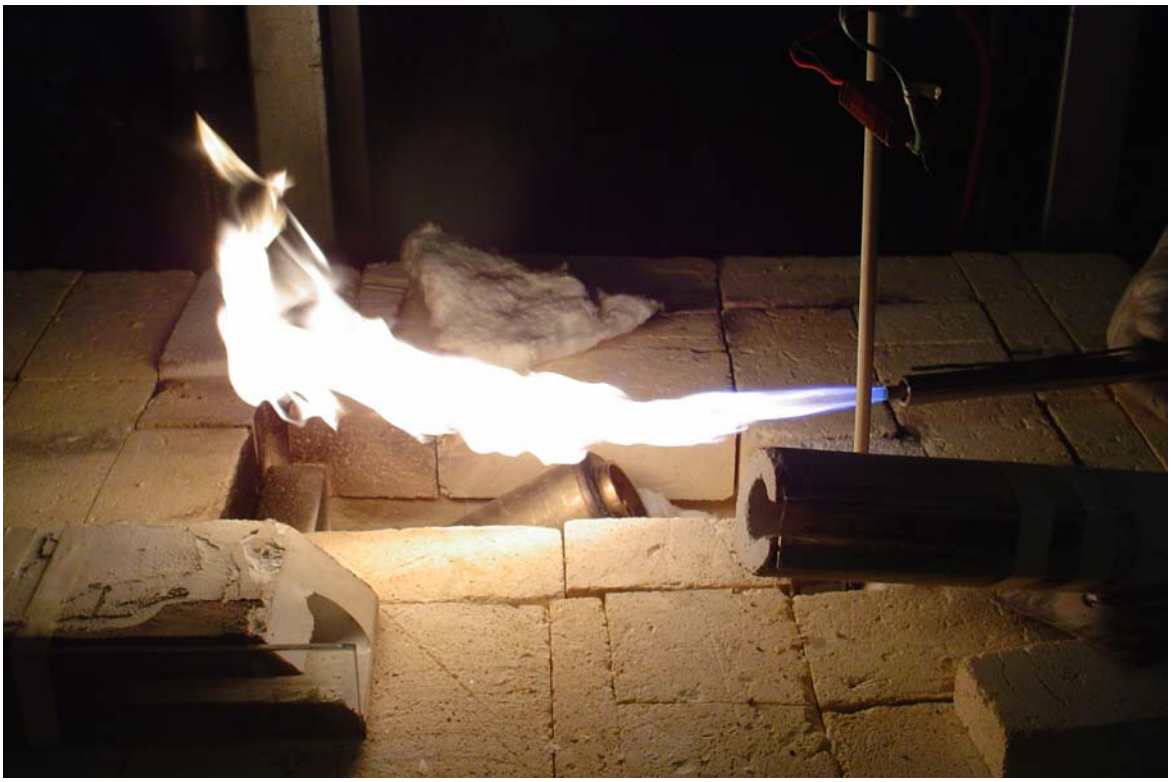

Figure 5. Burner having equal oxygen and natural gas velocities, but with a natural gas tube twice the diameter [9.5 mm (0.375 inch) o.d.; 7.0 mm (0.275 inch) i.d.] of those in the burners shown in Figures 1 to 4. The oxygen tip diameter [14.3 mm (0.563 inch)] is similar to that in the burner shown in Figures 1 to 3, but without the converging/diverging nozzle. Photograph by Steve Mighton.

CONCLUSIONS

A venturi burner containing a converging/diverging nozzle, internally mixing oxygen with natural gas, produced satisfactory flames in open air, but was rapidly destroyed by overheating when placed in a tuyere in the forehearth simulator. The marked changes in flow and heat transfer on placing a flame in an enclosure, especially one as restricted as a forehearth burner block, make observations of the behavior of forehearth burner candidates in open air of little value in assessing the likely performance of the burners in practice.

Instrumenting the burners with thermocouples placed at the oxygen and natural gas tips provides quantitative comparison of the performance of the burners and is especially useful for evaluating the effects of operating conditions on burner performance *in situ*, where the ability to observe flames, burners, and burner blocks visually is severely limited.

A straight concentric tube-in-tube burner having equal oxygen and natural gas velocities is capable of producing, with increasing tube diameters, a range of flames from short, with high combustion intensity, to long, with low combustion intensity. A burner of the latter type performed satisfactorily in a short-term test in the forehearth simulator. Because the spatial distributions of the properties of jet flames are dominated by their nozzle diameters and initial velocities, adjustment of orifice diameters is a useful approach to the adaptation of a basic burner design to the requirements of particular applications.

A review of the burner designs described in U.S. patents and publications related to oxygen/natural-gas-fired forehearth burners indicates that wide ranges of opinion exist regarding the optimum velocities of oxygen and fuel, internal versus external mixing, and desirability of flame luminosity. This shows that no consensus on the design of forehearths and forehearth burners has yet been reached and suggests that continued research and development work can lead to further improvements in performance.

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