An oxy-fuel furnace and method of heating material in an oxy-fuel furnace are disclosed. The method includes combusting oxygen and fuel with an oxy-fuel burner arrangement in the oxy-fuel furnace forming combustion gases, and maintaining a vortex including the combustion gases within a central region of an enclosure of the oxy-fuel furnace. The oxy-fuel burner arrangement includes a plurality of high momentum oxy-fuel burners arranged at an angle to generate the vortex, the angle being greater than 15 degrees but less than 75 degrees with respect to the furnace wall boundary of the enclosure, an angular velocity of greater than 0.07 radians per second, or a combination thereof. The furnace includes an oxy-fuel burner arrangement including at least two high momentum oxy-fuel burners having high shape factor nozzle geometries, and an enclosure. The vortex increases convective heating within the enclosure and uniformity of heating within the enclosure.
OXY-FUEL FURNACE AND METHOD OF HEATING MATERIAL IN AN OXY-FUEL FURNACE

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application claims priority to and benefit of U.S. Provisional Patent Application No. 61/471,900, filed Apr. 5, 2011, which is hereby incorporated by reference in its entirety.

BACKGROUND OF THE INVENTION

[0002] The present invention is directed to systems and methods of heating materials. More specifically, the present invention is directed to oxy-fuel furnaces and methods of heating material by using oxy-fuel furnaces.

[0003] Nitrogen oxides (NOx) are among the primary air pollutants emitted by combustion processes. Because NOx promotes the formation of harmful atmospheric reaction products that cause smog, air quality standards have been imposed by various government agencies to limit the amount of NOx that can be emitted into the atmosphere. As a result of the increasing environmental legislation in many countries and increasing global awareness of atmospheric pollution, modern combustion technology has been improved to reduce NOx emissions from many types of combustion equipment.

[0004] The secondary metals industry is generally considered to be a major source of NOx pollution and therefore is subject to stringent regulations on NOx emissions. The reduction of NOx production in combustion processes becomes more important in this industry as the demand for metals increases while environmental regulations on NOx become increasingly stringent. Full oxy-fuel combustion theoretically can produce very low NOx emissions due to the lack of nitrogen in the oxidant.

[0005] The secondary metals industry has had innovation that reduces NOx emissions. Such a known system is described in U.S. Pat. App. Pub. No. 2007/0254251, which is hereby incorporated by reference in its entirety. The known system achieves spacial combustion by entraining furnace gases into a flame zone. Such a system reduces NOx emissions. However, further reductions are desirable, especially if the further combustion NOx reductions are balanced with heat energy consumption concerns, for example, by balancing radiative and convective heat transfer components.

[0006] Traditional low-momentum oxy-fuel combustion is dominated by radiative mode heat transfer but lacks a convective component of heating. The lack of convective component is due to the low gas volumes and can increase the potential for inconsistent or uneven heating, hot spots, and the generation of NOx. In contrast, air fuel combustion lacks efficiency of radiative heating because of N₂ dilution. However, air fuel combustion can have a strong convective heat transfer component because of higher flu gas volumes that can be useful in heating a product when combined with radiation. However, the radiation from an air-fuel flame is much lower than the radiation from an oxy-fuel flame.

[0007] An oxy-fuel furnace and method of heating material in an oxy-fuel furnace that do not suffer from one or more of the above drawbacks would be desirable in the art.

BRIEF SUMMARY OF THE INVENTION

[0008] In an exemplary embodiment, a method for heating material in an oxy-fuel furnace includes combusting oxygen and fuel with an oxy-fuel burner arrangement in the oxy-fuel furnace forming combustion gases, and maintaining a vortex including the combustion gases within a central region of an enclosure of the oxy-fuel furnace. The oxy-fuel burner arrangement includes a plurality of high momentum oxy-fuel burners arranged at an angle to generate the vortex, the angle being greater than 15 degrees but less than 75 degrees with respect to a furnace wall boundary of the enclosure.

[0009] In another exemplary embodiment, a method for heating material in an oxy-fuel furnace includes combusting oxygen and fuel with an oxy-fuel burner arrangement in the oxy-fuel furnace forming combustion gases, and maintaining a vortex including the combustion gases within a central region of an enclosure of the oxy-fuel furnace. The vortex has an angular velocity of greater than 0.07 radians per second.

[0010] In another exemplary embodiment, an oxy-fuel furnace includes an oxy-fuel burner arrangement including at least two high momentum oxy-fuel burners having high shape factor nozzles, and an enclosure. The oxy-fuel burner arrangement includes a plurality of high momentum oxy-fuel burners arranged at an angle to generate a vortex, the angle being greater than 15 degrees but less than 75 degrees with respect to a furnace wall boundary of the enclosure. The vortex increases convective heating within the enclosure and uniformity of heating within the enclosure.

BRIEF DESCRIPTION OF SEVERAL VIEWS OF THE DRAWINGS

[0012] FIGS. 1 through 4 are schematic drawings of oxy-fuel furnaces according to embodiments of the disclosure.

[0013] FIG. 5 is a three-dimensional schematic drawing of an oxy-fuel furnace according to an embodiment of the disclosure.

[0014] FIG. 6 is a graphical comparison of an exemplary method of heating material in an oxy-fuel furnace according to the disclosure and other methods of heating material.

[0015] FIG. 7 is a graphical illustration of surface temperature as a function of time for an exemplary oxy-fuel furnace according to the disclosure.

[0016] FIG. 8 is a comparative graphical illustration of surface temperatures of furnace walls and material due to operation of an oxy-fuel furnace without forming a vortex.

[0017] FIG. 9 is a graphical illustration of surface temperatures of furnace walls and material due to operation of an oxy-fuel furnace forming a vortex according to the disclosure.

[0018] Wherever possible, the same reference numbers will be used throughout the drawings to represent the same parts.

DETAILED DESCRIPTION OF THE INVENTION

[0019] Provided is an exemplary oxy-fuel furnace and method of heating material in an oxy-fuel furnace. Embodiments of the present disclosure increase the convective contribution of heat transfer in an oxy-fuel heating process,
Referring to FIGS. 1 through 5, according to an embodiment, an oxy-fuel furnace 100 includes at least two high-momentum oxy-fuel burners 102 and an enclosure 104 generally defining a combustion zone within the oxy-fuel furnace 100. The enclosure 104 is any suitable geometry and is defined by a furnace wall boundary 108. For example, in one embodiment, the enclosure 104 is a cuboid or generally cuboid geometry. In another embodiment, the enclosure 104 is a cylindrical or generally cylindrical geometry. The enclosure includes a central region, for example, defined by the burner axis of each of the burners 102, the burner axis being a line extending from the middle of the burner. The oxy-fuel furnace 100 includes other suitable features as are necessary to maintain combustion, heating, other operational conditions, or combinations thereof.

The enclosure 104 is configured for containing at least a portion of a vortex 106 of combustion gases, such as a furnace-scale vortex. The vortex 106 is formed by offset firing of the burners 102 that entrains surrounding combustion gases into a flame zone within the enclosure 104, thereby resulting in a churning (or equilibration of gases) that forms the vortex 106, for example, by transporting the combustion gases. In one embodiment, the vortex 106 is used with spurious combustion, combustion achieved by entrainment of furnace gases in a flame zone. In one embodiment, the burners 102 form two different furnace gas recirculation currents, for example, a horizontal component and a vertical component that construct the vortex 106 due to differential pressure within the enclosure 104.

The burners 102 are arranged and disposed for forming the vortex 106. The oxy-fuel furnace 100 includes two of the burners 102 (see FIGS. 1 and 2), three of the burners 102, four of the burners 102 (see FIG. 3), or more than four of the burners 102. As shown in FIG. 1, in one embodiment, the burners 102 are positioned on opposite sides of the enclosure 104 on the furnace wall boundary 108, in a staggered orientation. As shown in FIG. 2, in one embodiment, two of the burners 102 are positioned on the furnace wall boundary 108 in an angular configuration. As shown in FIG. 3, in one embodiment, four of the burners 102 are positioned on the furnace wall boundary 108 in an angular configuration. Other embodiments include combinations of these embodiments.

The burners 102 are any suitable burners capable of being used under high-momentum conditions, such as, the burners disclosed in U.S. Pat. App. Pub. No. 2007/0254251, which is incorporated by reference in its entirety, and/or a high shape factor burner. As used herein, the term “high-momentum” refers to flow of gases through at least one channel of passageway of the burner 102 that is greater than about 5 lb-ft/s². In some embodiments, flow of gases through at least one channel of passageway of the burner 102 is greater than about 10 lb-ft/s², for example, as with natural gas having a flow rate between about 10 lb-ft/s² and 70 lb-ft/s², enabling firing at higher rates, improving cycle times, reducing localized overheating (such as overheating of thermocouples), or combinations thereof. As used herein, the term “high shape factor burner” refers to a burner having a nozzle perimeter or multiple perimeters that is are greater than a perimeter of a circular nozzle. For example, a relative perimeter ratio (Pₓᵧ) is a ratio of the perimeter of nozzle(s) of a high shape factor burner (such as, a non-circular burner) in comparison to the perimeter of a circular nozzle. For nozzles having areas of 1.0 in², a circular nozzle has a perimeter of 3.54 inches. Thus, a high shape factor burner having a nozzle with a 1.0 in² has a perimeter that is greater than 3.54 inches. In one embodiment, the high shape factor burner has a relative perimeter ratio of 1.96.

Referring to FIGS. 4 and 5, in one embodiment, two or more of the burners 102 form the vortex 106 by being angled at angle 0, with respect to the furnace wall boundary 108. The angle 0 corresponds with the specific configuration of the oxy-fuel furnace 100 (for example, the geometry, the size, or combinations thereof), the materials to be heated (for example, metal or metallic materials, such as, ingots, sheets, cast materials, forged materials, aluminum, iron, steel, ferrous materials, non-ferrous materials, or combinations thereof), other suitable operational considerations (for example, flow rates, compositions of oxy-fuel, enclosure pressure, enclosure material, etc.), or a combination thereof. The material heated is positioned at any suitable portion within the enclosure 104, for example, on the bottom of the enclosure 104. In one embodiment, the oxy-fuel includes a composition of at least 50 mol % oxygen in the oxidizer (for example, from an oxidizer flow of 95 mol % oxygen) and fuel (for example, natural gas, propane, syngas, low Btu fuels, etc.).

In one embodiment, the angle 0 is greater than 15 degrees, greater than 30 degrees, greater than 45 degrees, greater than 60 degrees, less than 75 degrees, less than 60 degrees, less than 45 degrees, less than 30 degrees, or any suitable range sub-range, combination, or sub-combination thereof.

In one embodiment, the oxy-fuel furnace 100 enhances mixing and furnace gas entrainment that reduces the peak flame temperature and thermal NOx generation. The enhanced mixing is caused by the burners 102 creating a lower pressure region having a first pressure within the vortex 106 and a higher pressure region having a second pressure that is proximal to the furnace wall boundary 108 of the enclosure 104.

The force (Fₜₒ) brought into the enclosure 104 of the furnace 100 by the flow of combustion gases through the burner 102 can be represented as shown in Equation 1:

\[ F_{tot} = \rho_{out} Q_{out} u_{out} \]  
(Eq. 1)

As used in Equation 1, \( \rho_{out} \) refers to the density of combustion flow entering the enclosure 104 (for example, as measured in lb/ft³, dependent upon flame temperature). \( u_{out} \) refers to the velocity of inlet flows entering the enclosure 104 (for example, as measured in ft/s). \( Q_{out} \) refers to the total inlet flow rate into the enclosure 104 (for example, as measured in ft³/s).

In one embodiment, the entrainment of furnace gases into the flame is enhanced by using nozzles in one or more of the burners 102 that have a high shape factor. The actual flow achieved by strong interaction of the nozzles with the furnace gases can be represented as shown in Equation 2:

\[ F_{tot} = \rho_{inlet} (Q_{inlet} P_{inlet}) u_{inlet} \]  
(Eq. 2)

As used in Equation 2, \( \rho_{inlet} \) refers to the relative perimeter ration and \( Q_{inlet} / P_{inlet} \) refers to the total actual inlet flow rate (for example, as measured in ft³/s).

The vortex is generated by the balance of forces brought into the furnace and viscous dissipation (\( F_{visc} \)) of these flows in the furnace, given by Equation 3:

\[ F_{visc} = \frac{\rho_{inlet} V_{inlet} (u_{inlet}^2/2)}{D} \]  
(Eq. 3)
As used in Equation 3, \( p_{\text{furn}} \) refers to the density of furnace gases within the enclosure 104 (for example, as measured in lb/ft\(^3\), dependent upon flame temperature). \( V_{\text{furn}} \) refers to the volume of the enclosure 104 in the oxy-fuel furnace 100 (for example, as measured in ft\(^3\)). \( u \) refers to the tangential velocity of the Vortex at diameter \( d_1 \) inside the enclosure 104 (for example, as measured in ft/s). \( d_1 \) refers to a characteristic dimension of the Vortex 106 (for example, an equivalent diameter measured in ft).

In one embodiment, the angular velocity \( (u_\text{m}) \) of the vortex 106 is defined using Equation 4, which is based upon consolidation of equations 2 and 3:

\[
u_\text{m} = \sqrt{\frac{(Q_{\text{air}} V_{\text{furn}})}{\pi d_1}} \quad \text{(Eq. 4)}
\]

As used in Equation 4, \( \rho_{\text{furn}} \) refers to a density ratio of inlet flows (\( \rho_{\text{furn}} \)) to furnace gases (\( \rho_{\text{furn}} \)). The density ratio is between 0.8 for air-fuel combustion and 0.6 for oxy-fuel combustion due to the difference in flame temperature.

In one embodiment, the burners 102 enhance a convective heat transfer component (in addition to a radiative heat transfer component) to increase uniformity and/or efficiency of heating. For example, in one embodiment, a vortex-induced component of the convective heat transfer component increases uniformity and efficiency by using the burners 102. The vortex-induced component is achieved by arranging and/or orienting the burners 102 such that the vortex 106 is formed and maintained within the enclosure 104. In one embodiment, the convective heat transfer reduces or eliminates direct impact of a flame on the material to be heated.

In one embodiment, the vortex-induced component of the convective heat transfer component impacts between 15% and 75% of the plan-view area of the enclosure 104. In further embodiments, the convective heat transfer component impacts between 30% and 60%, between 30% and 45%, between 45% and 60%, about 15%, about 30%, about 45% about 60% about 75%, or any suitable range, sub-range, combination, or sub-combination thereof. In one embodiment, the vortex-induced component is increased by increasing the angular velocity \( (u_\text{m}) \) of the vortex 106.

Referring to FIG. 6, the uniformity and efficiency of the overheated with the burners 102 forming the vortex 106 is improved in comparison to one-sided firing and opposed (but not staggered) burning. FIG. 6 shows profiles of heating steel ingots with the enclosure 104 being in a pit furnace under different configurations. A vortex-induced heating profile 602 is based upon using the burners 102 to form the vortex 106 as described herein. A one-sided-burner heating profile 604 is based upon using one-sided firing, positioning the steel ingots at an end distal from a burner and moving the steel ingots toward an end proximal to the burner. An opposing-burner heating profile 606 is based upon having two burners on opposing walls of a furnace. The jets collide and have the tendency to heat the steel ingots at the center of the pit furnace. The opposing-burner heating profile 606 also creates large heat flux gradients in comparison to the other configurations.

As shown in FIG. 6, the vortex-induced heating profile 602, including the vortex-induced component, is maintained within a temperature range of less than 25°F. In further embodiments, the vortex-induced heating profile 602 including the vortex-induced component is maintained within a temperature range of less than 10°F, less than 5°F, or is substantially constant. In contrast, the one-sided-burner heating profile 604 and the opposing-burner heating profile 606 exceed the temperature range of 25°F.

Referring to FIG. 7, the surface temperature of material heated under the vortex-induced heat profile 602 and the opposing-burner heat profile 606 described above are shown over time. Each profile corresponds with a maximum surface face temperature profile 702 and an average face temperature profile 704. The maximum surface face temperature profile 702 is substantially consistent over time for the vortex-induced heat profile 602 and the opposing-burner heating profile 606. The average face temperature profile 704 bifurcates above time permitting a decrease in cycle time for achieving a predetermined average face temperature under the vortex-induced heat profile 602 in comparison to the opposing-burner heating profile 606. In one embodiment, the decrease in cycle time is at least 10%, between 10% and 20%, about 15%, or any suitable range, sub-range, combination, or sub-combination thereof.

FIGS. 8 and 9 comparatively illustrate the heating of the material within the enclosure 104 according to the vortex-induced heat profile 602 (see FIG. 8) in contrast to the opposing-burner heating profile 606 (see FIG. 8). Specifically, FIG. 8 illustrates the temperature of walls within an enclosure heated by the opposing-burner heating profile 606 and FIG. 9 illustrates the temperature of the furnace wall boundary 108 heated by the vortex-induced heat profile 602. FIG. 8 shows that the opposing-burner heating profile 606 forms a hot spot 802. FIG. 9 shows that the vortex-induced heat profile 602 forms a more uniform temperature gradient, for example, having no regions of the furnace wall boundary 108 that exceed the temperature of the furnace wall boundary 108 proximal to the burner 102, thereby allowing increased amounts of energy input into the oxy-fuel furnace 100 and/or reducing cycle times for achieving a predetermined temperature.

In one embodiment, the enclosure 104 has dimensions of 24 ft x 9 ft x 14 ft. In a heating process achieved in the enclosure 104, the heating process uses an average of about 10 MMBTU/hr of air-fuel firing rate and about 6 MMBTU/hr of oxy-fuel firing rate (assuming 45% and 75% available heat in the enclosure 104, respectively) to form the vortex 106. The angular velocity \( (u_\text{m}) \) of the vortex 106 is calculated, for example, based upon Equations 1 through 4 above, and depends upon the fuel used and the burner used. For example, air fuel combustion with a staggered burner configuration (see FIG. 1) results in an angular velocity \( (u_\text{m}) \) of 0.099 rad/s and an angled burner configuration (see FIG. 2) results in an angular velocity \( (u_\text{m}) \) of 0.087 rad/s. Low-momentum oxy-fuel combustion with a staggered burner configuration (see FIG. 1) results in an angular velocity \( (u_\text{m}) \) of 0.035 rad/s and an angled burner configuration (see FIG. 2) results in an angular velocity \( (u_\text{m}) \) of 0.031 rad/s. High-momentum oxy-fuel combustion with a staggered burner configuration (see FIG. 1) and circular nozzles results in an angular velocity \( (u_\text{m}) \) of 0.079 rad/s and an angled burner configuration (see FIG. 2) results in an angular velocity \( (u_\text{m}) \) of 0.070 rad/s. High-momentum oxy-fuel combustion with a staggered burner configuration (see FIG. 1) and non-circular nozzles results in an angular velocity \( (u_\text{m}) \) of 0.111 rad/s and an angled burner configuration (see FIG. 2) results in an angular velocity \( (u_\text{m}) \) of 0.077 rad/s.

In view of such differences, in one embodiment of the disclosure, the burners 102 of the furnace 100 are arranged and operated such that the vortex has an angular velocity that...
is greater than a corresponding angular velocity for an air-fuel combustion vortex that would be formed by air-fuel combustion, for example, being at least 0.07 radians per second. In one embodiment, the vortex 106 formed by combusting the oxy-fuel with the burners 102 having non-circular nozzles has an angular velocity that is 10% greater than a vortex that would be formed by air-fuel combustion, 40% greater than the vortex 106 formed by the burners 102 having the circular nozzles, 200% greater than a vortex that would be formed by low-momentum oxy-fuel combustion, or a combination thereof.

While the invention has been described with reference to a preferred embodiment, it will be understood by those skilled in the art that various changes may be made and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention not be limited to the particular embodiment disclosed as the best mode contemplated for carrying out this invention, but that the invention will include all embodiments falling within the scope of the appended claims.

1. A method for heating material in an oxy-fuel furnace, the method comprising:
   - combusting oxygen and fuel with an oxy-fuel burner arrangement in the oxy-fuel furnace forming combustion gases;
   - maintaining a vortex including the combustion gases within a central region of an enclosure of the oxy-fuel furnace;
   - wherein the oxy-fuel burner arrangement comprises a plurality of high momentum oxy-fuel burners arranged at an angle to generate the vortex, the angle being greater than 15 degrees but less than 75 degrees with respect to a furnace wall boundary of the enclosure.

2. The method of claim 1, wherein at least one of the plurality of high momentum oxy-fuel burners includes a high shape factor nozzle.

3. The method of claim 1, wherein the plurality of high momentum oxy-fuel burners includes two burners.

4. The method of claim 1, wherein the plurality of high momentum oxy-fuel burners includes two burners.

5. The method of claim 1, wherein the plurality of high momentum oxy-fuel burners includes four burners.

6. The method of claim 1, wherein the plurality of high momentum oxy-fuel burners includes more than four burners.

7. The method of claim 1, wherein the vortex has an angular velocity that is greater than 0.07 radians per second.

8. The method of claim 1, wherein the angle is between about 30 degrees and about 60 degrees.

9. The method of claim 1, wherein the vortex induces convective heat in an area of the enclosure, the area being between about 15% and about 75% of the enclosure.

10. The method of claim 1, wherein the vortex induces convective heat in an area of the enclosure, the area being between about 30% and about 60% of the enclosure.

11. The method of claim 1, wherein the enclosure has a first pressure within the vortex that is less than a second pressure that is proximal to the furnace wall boundary of the enclosure.

12. The method of claim 1, further comprising heating metal within the enclosure.

13. The method of claim 1, further comprising heating aluminum within the enclosure.

14. The method of claim 1, wherein the vortex increases convective heating within the enclosure.

15. The method of claim 1, wherein the vortex increases uniformity of heating within the enclosure.

16. A method for heating material in an oxy-fuel furnace, the method comprising:
   - combusting oxygen and fuel with an oxy-fuel burner arrangement in the oxy-fuel furnace forming combustion gases; and
   - maintaining a vortex including the combustion gases within a central region of an enclosure of the oxy-fuel furnace;
   - wherein the vortex has an angular velocity of greater than 0.07 radians per second.

17. The method of claim 16, wherein at least one of the plurality of high momentum oxy-fuel burners includes a non-circular nozzle geometry.

18. The method of claim 16, wherein the plurality of high momentum oxy-fuel burners includes staggered burners.

19. The method of claim 16, wherein the angle is greater than 15 degrees but less than 75 degrees with respect to a furnace wall boundary of the enclosure.

20. An oxy-fuel furnace, comprising:
   - an oxy-fuel burner arrangement including at least two high momentum oxy-fuel burners having high shape factor nozzles; and
   - an enclosure;
   - wherein the oxy-fuel burner arrangement comprises a plurality of high momentum oxy-fuel burners arranged at an angle to generate a vortex, the angle being greater than 15 degrees but less than 75 degrees with respect to a furnace wall boundary of the enclosure;
   - wherein the vortex increases convective heating within the enclosure and uniformity of heating within the enclosure.

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