US 20140305355A1

(19) **United States**

(12) **Patent Application Publication**

(10) **Pub. No.: US 2014/0305355 A1**

(43) **Pub. Date: Oct. 16, 2014**

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(54) **OXY-SOLID FUEL BURNER**

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(21) Appl. No.: **14/224,554**

(22) Filed: **Mar. 25, 2014**

Related U.S. Application Data

(60) Provisional application No. 61/811,175, filed on Apr. 12, 2013.

Publication Classification

(51) **Int. Cl.**

F23D 1/00	(2006.01)
F23L 7/00	(2006.01)

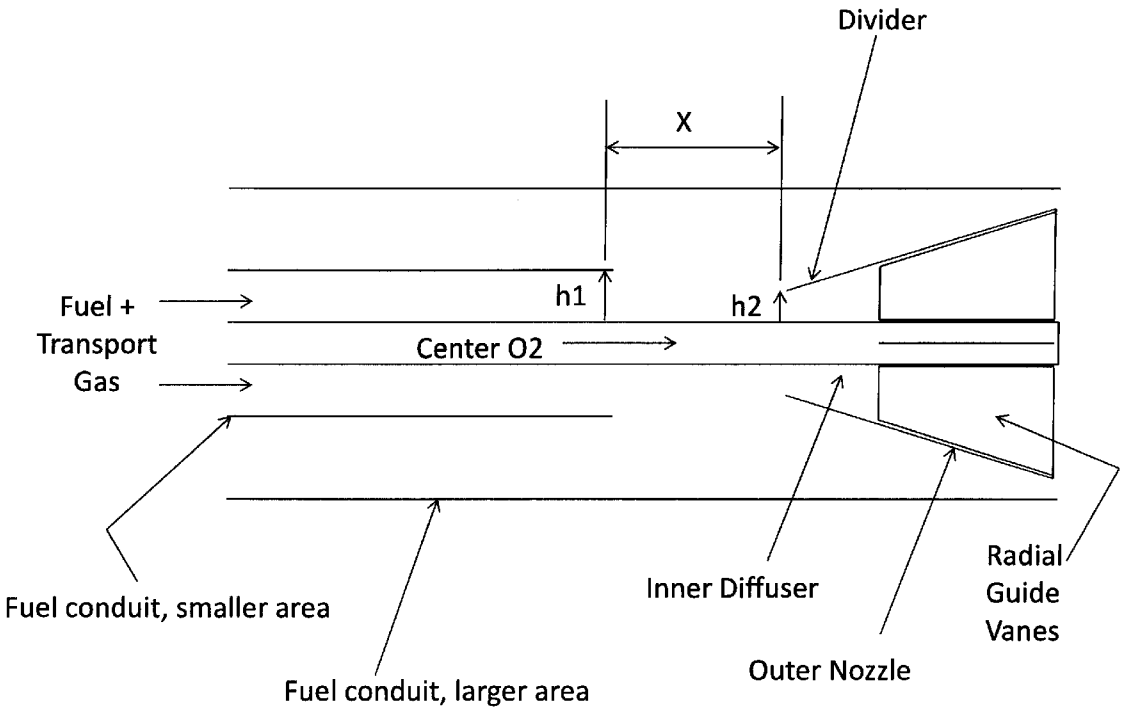
(52) **U.S. Cl.**

CPC ***F23D 1/005*** (2013.01); ***F23L 7/007*** (2013.01)

USPC **110/347**; 110/265

(57) **ABSTRACT**

A solid fuel/oxygen burner including a central oxygen conduit extending toward a tip end of the burner, an outer fuel conduit surrounding the oxygen conduit, an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit to form an inner annulus in conjunction with the oxygen conduit and an outer annulus in conjunction with the outer fuel conduit, the inner fuel conduit having an outlet end upstream of the tip end, a truncated conical divider within the outer fuel conduit surrounding the oxygen conduit downstream of the inner fuel conduit for dividing a fuel stream in the outer fuel conduit into an inner annular conical diffuser and an outer annular converging nozzle, and at least three radial guide vanes within the diffuser, wherein the outlet end of the inner fuel conduit is spaced apart from an inlet end of the divider by a distance, X.



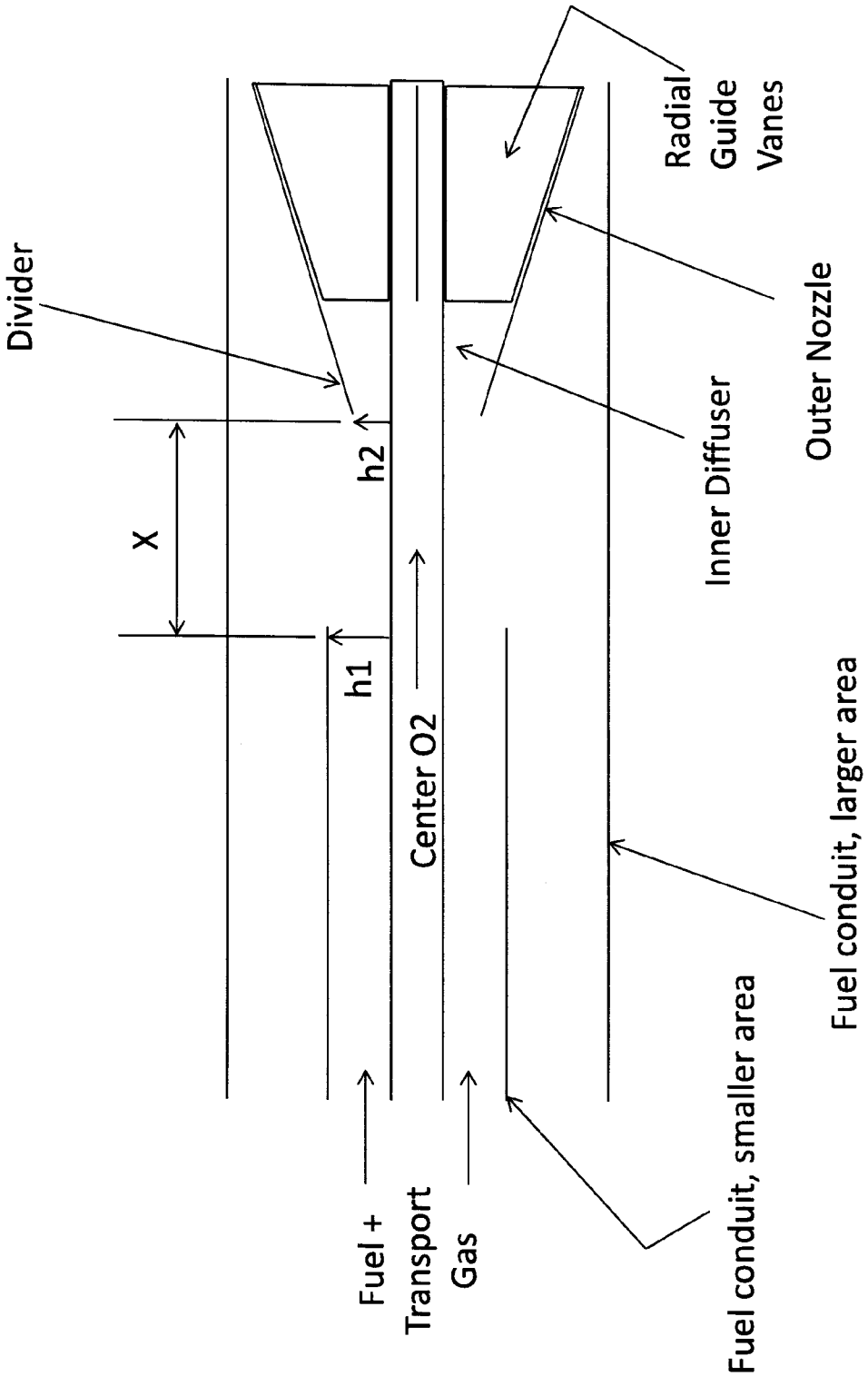

Radial Guide Vanes
Divider
Outer Nozzle
Inner Diffuser
h2
X
h1
Center O2
Fuel conduit, larger area
Fuel conduit, smaller area
Fuel + Transport Gas

Figure 1

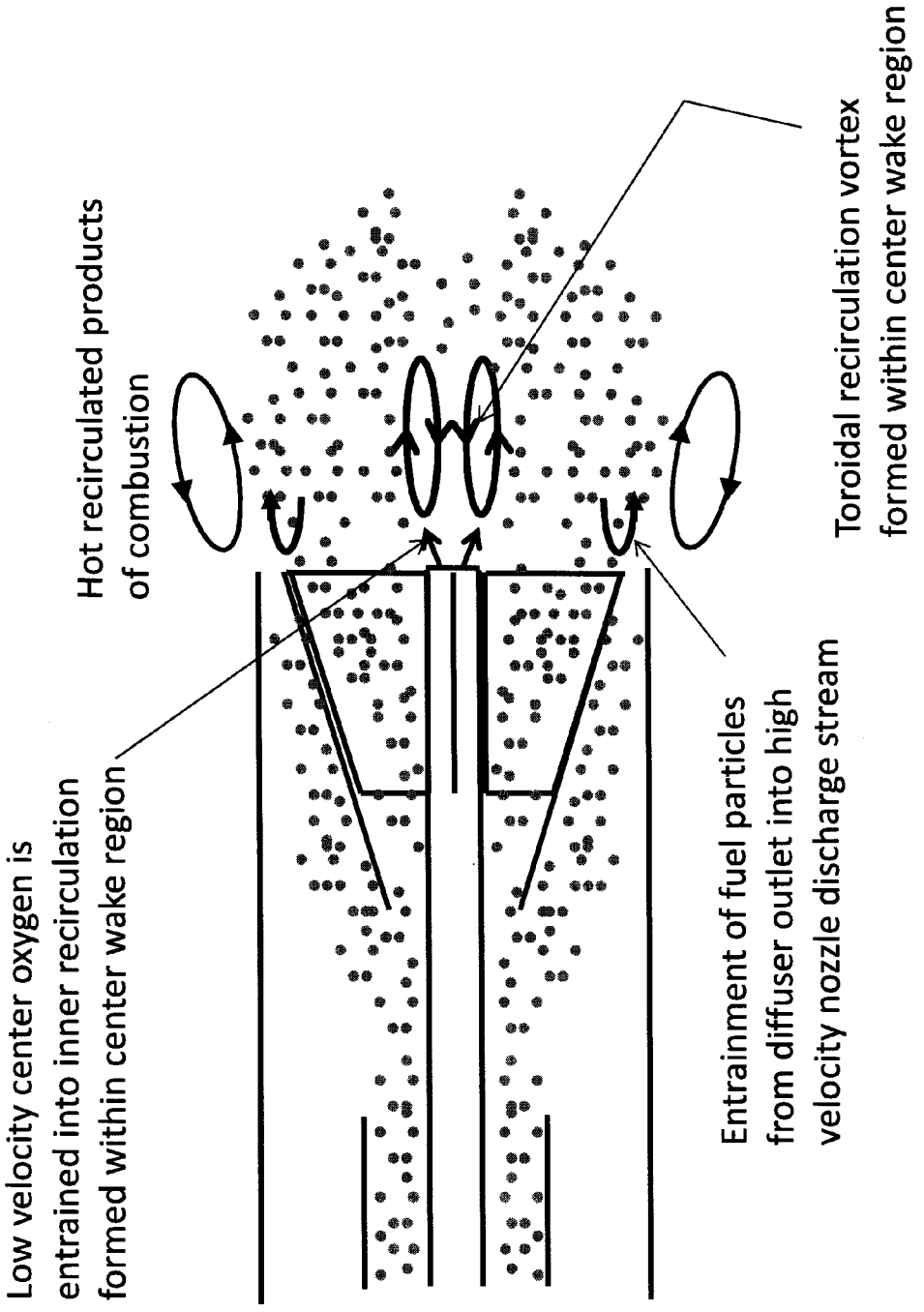

Low velocity center oxygen is entrained into inner recirculation formed within center wake region
Hot recirculated products of combustion
Toroidal recirculation vortex formed within center wake region
Entrainment of fuel particles from diffuser outlet into high velocity nozzle discharge stream

Figure 2

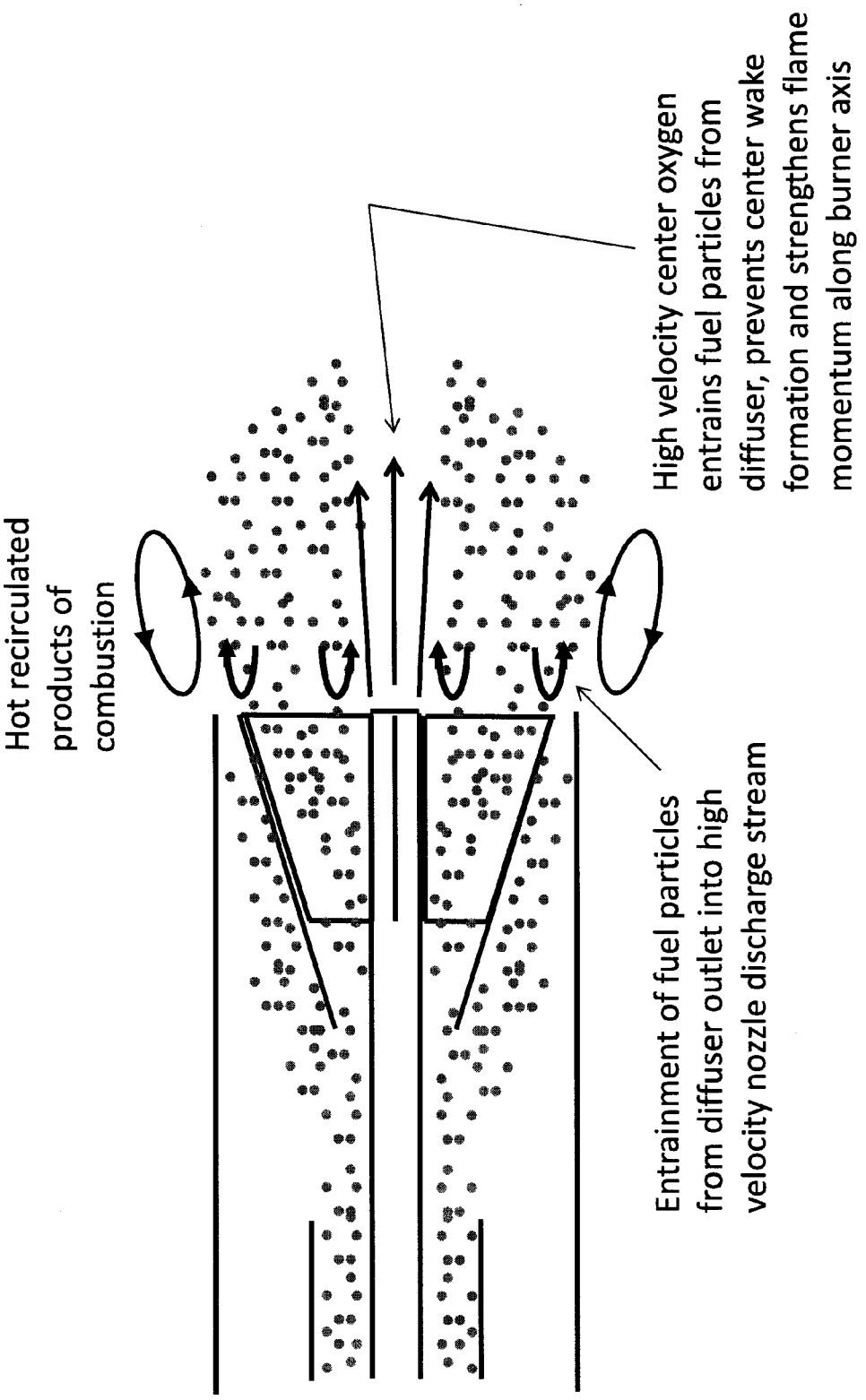

Hot recirculated products of combustion
High velocity center oxygen entrains fuel particles from diffuser, prevents center wake formation and strengthens flame momentum along burner axis
Entrainment of fuel particles from diffuser outlet into high velocity nozzle discharge stream

Figure 3

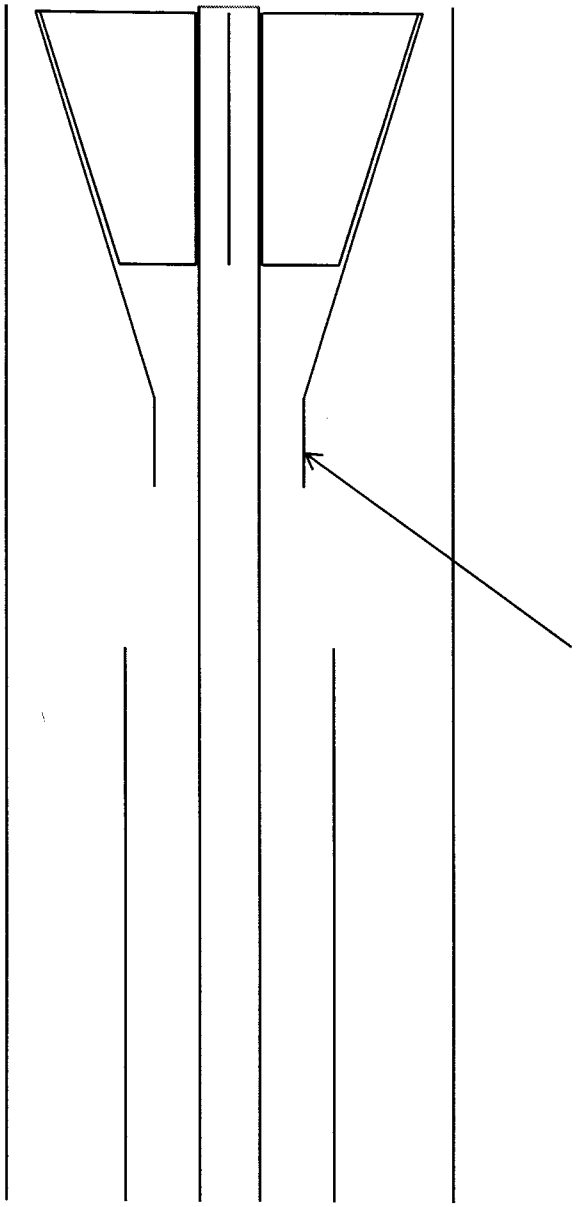


Figure 4

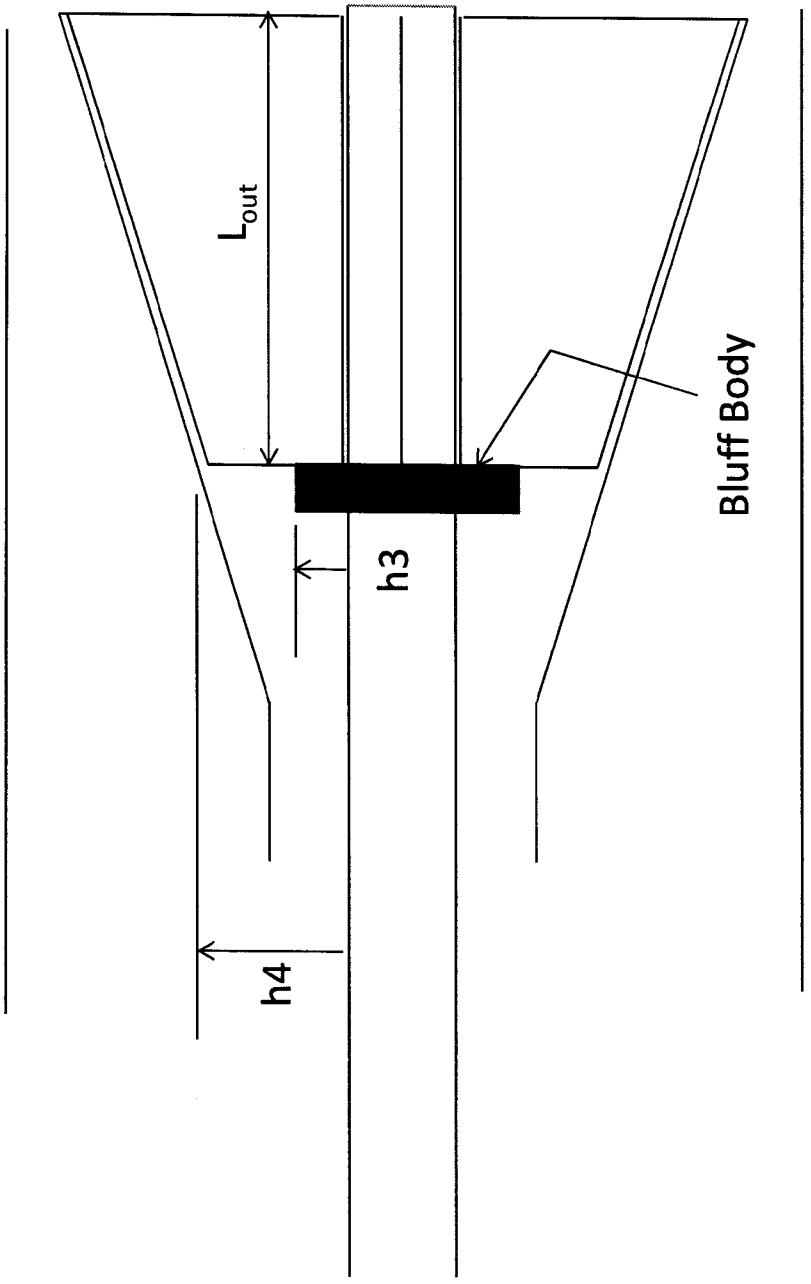


Figure 5

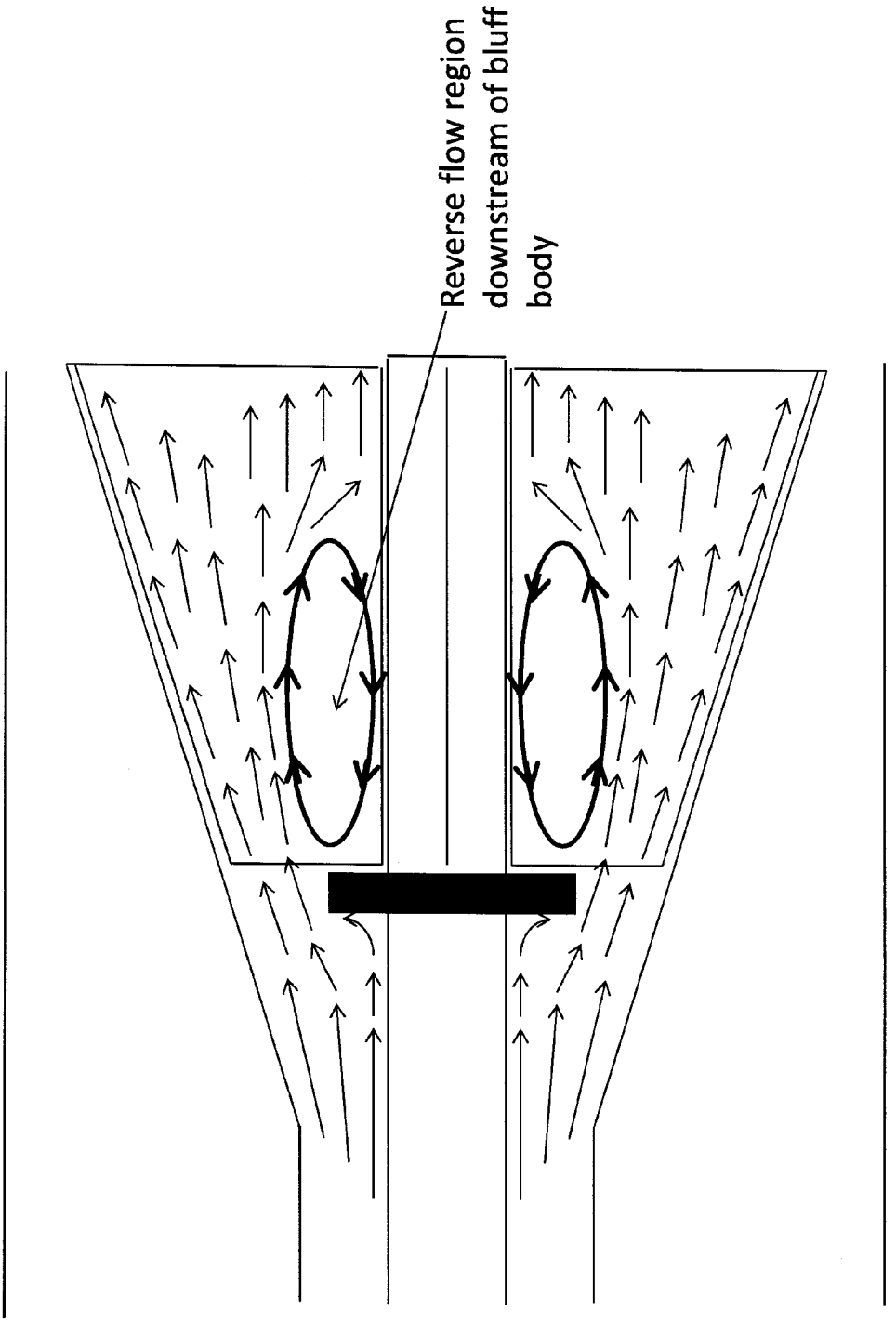


Figure 6

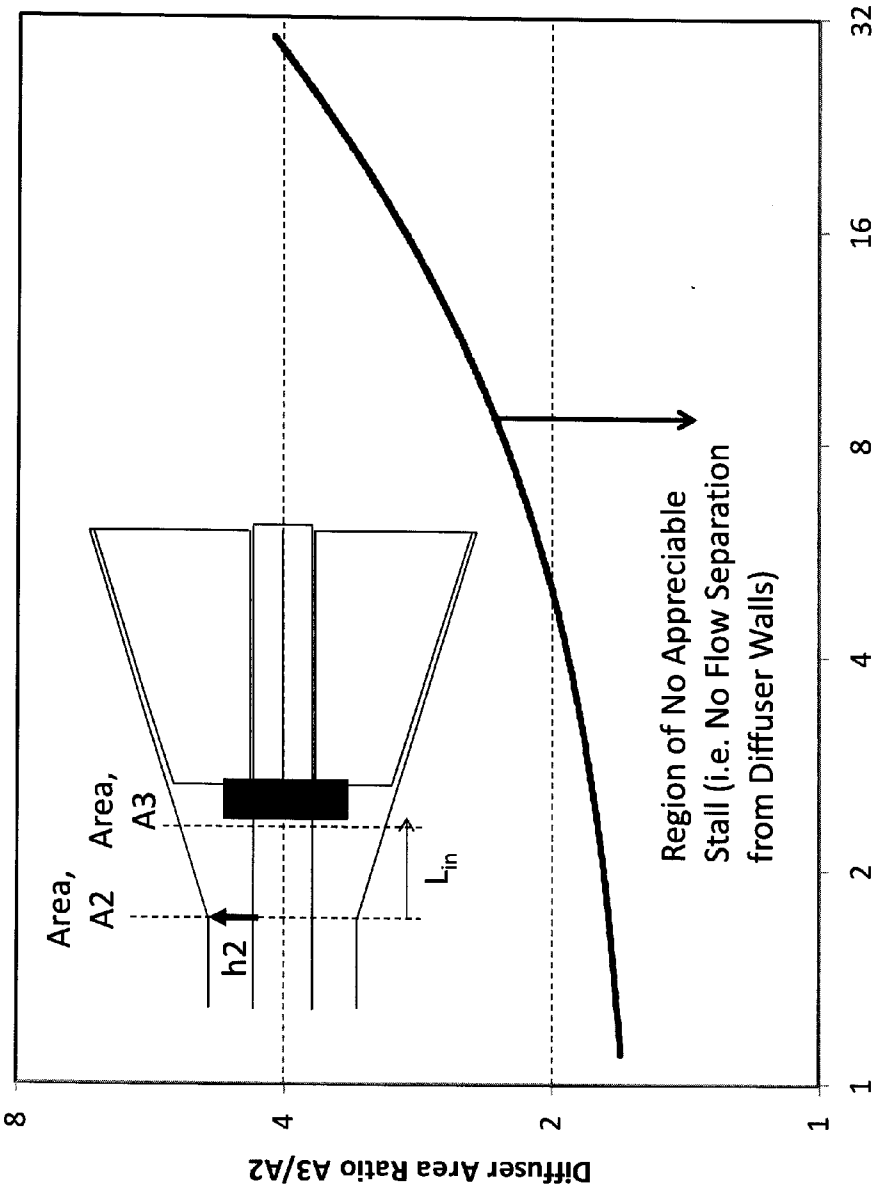

Diffuser Area Ratio A3/A2
8
4
2
1
1
2
4
8
16
32
$L_{in}/h2$
Region of No Appreciable Stall (i.e. No Flow Separation from Diffuser Walls)
Area, A2
Area, A3
h2
L_{in}

Figure 7

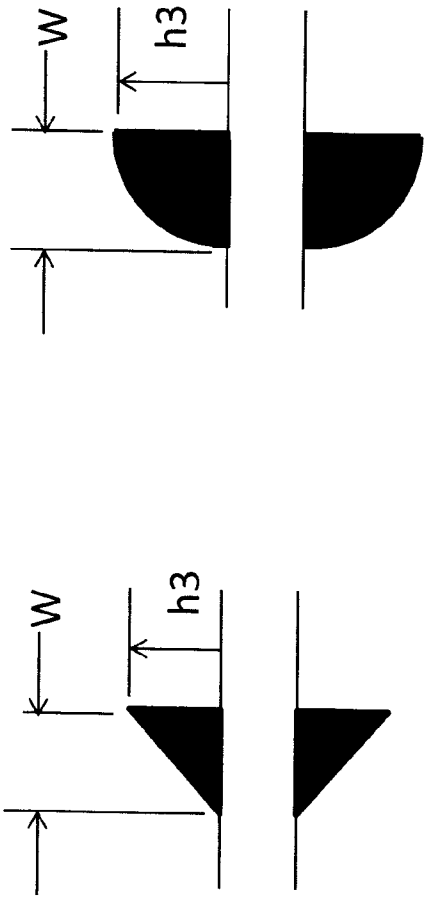


Figure 8

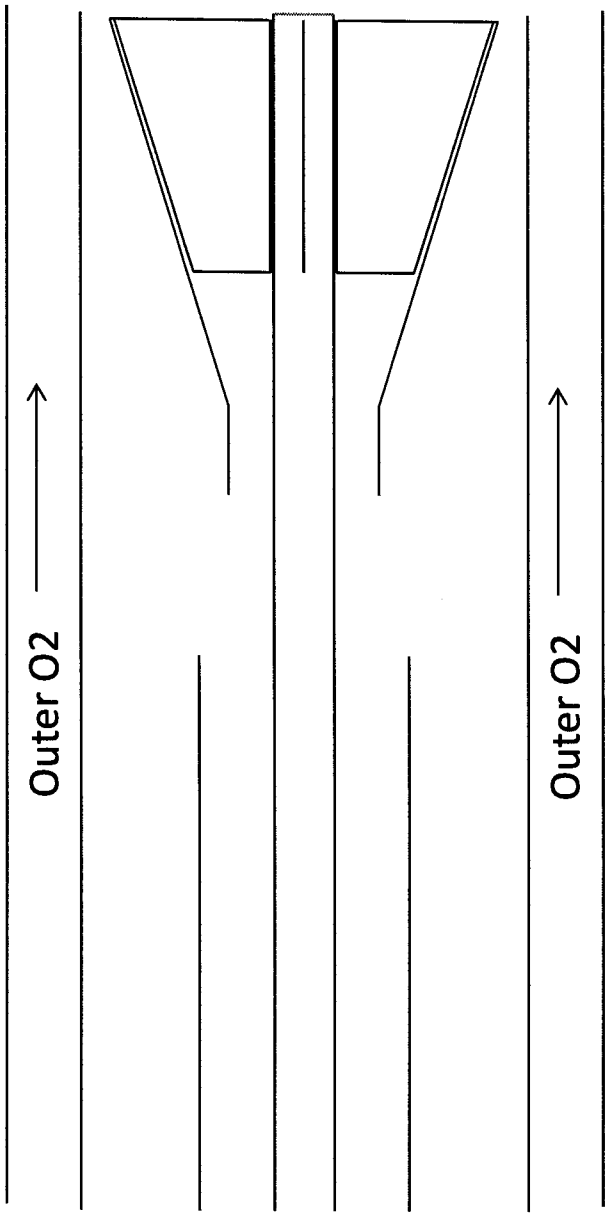


Figure 9

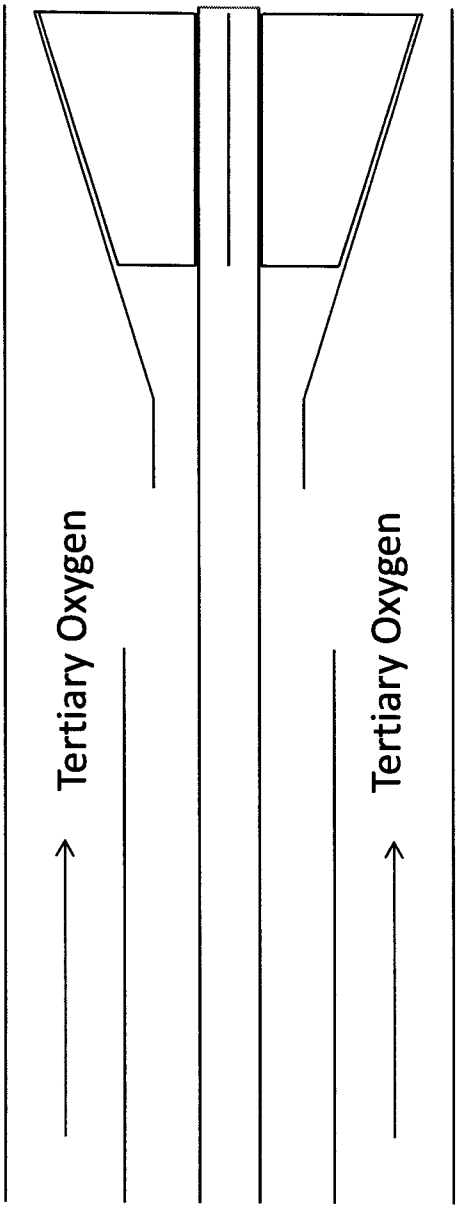


Figure 10

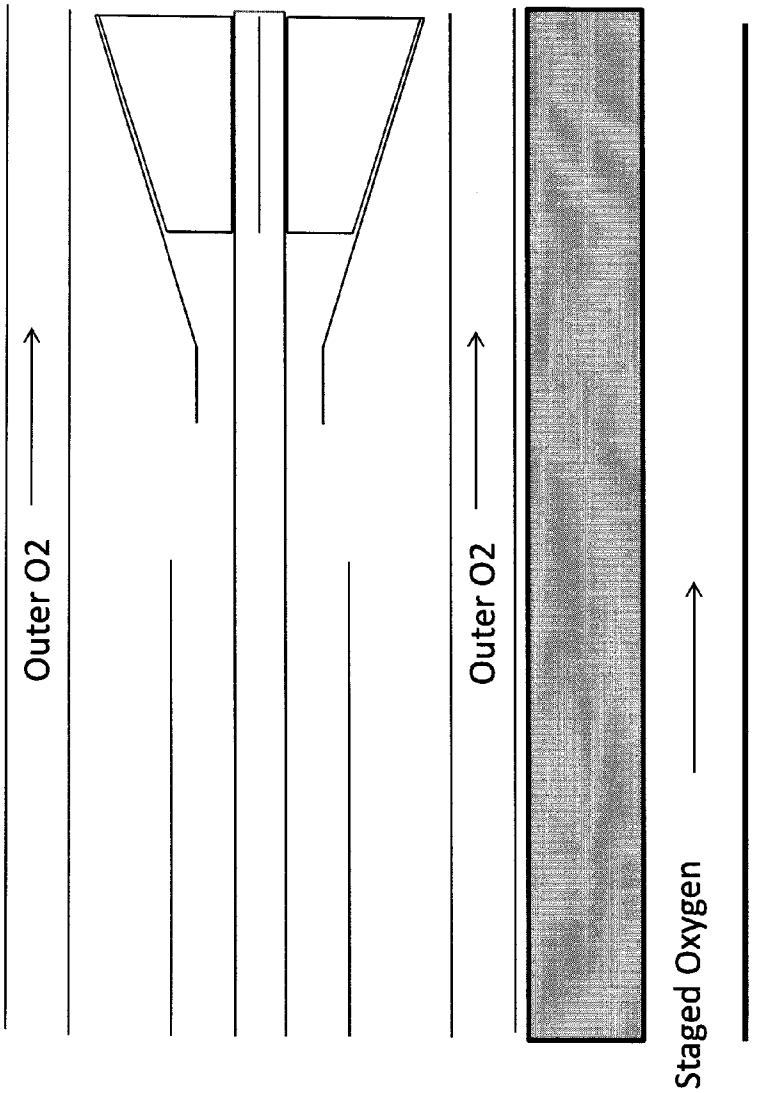


Figure 11

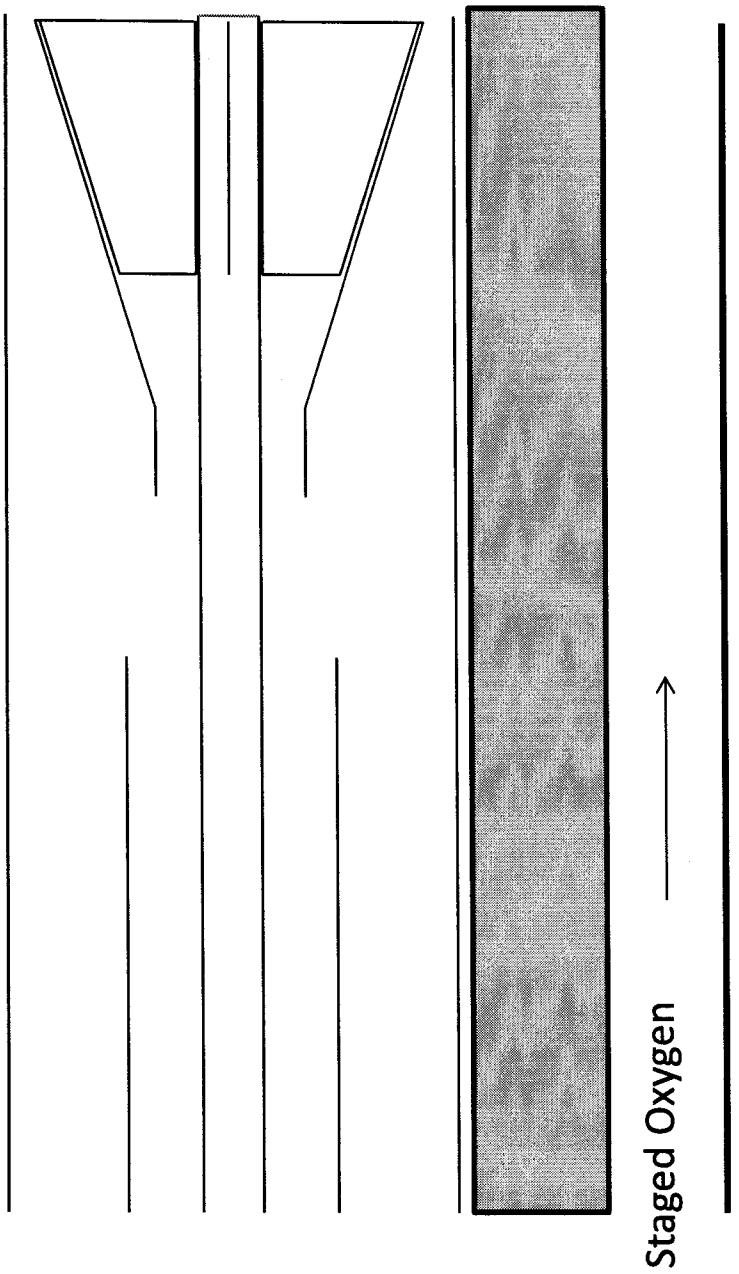


Figure 12

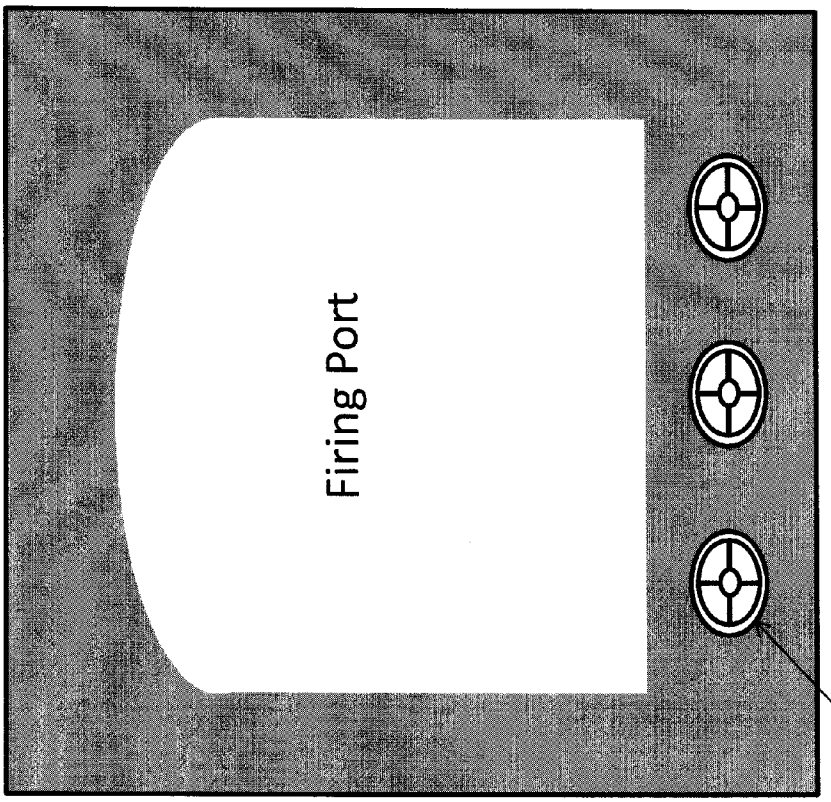


Figure 13

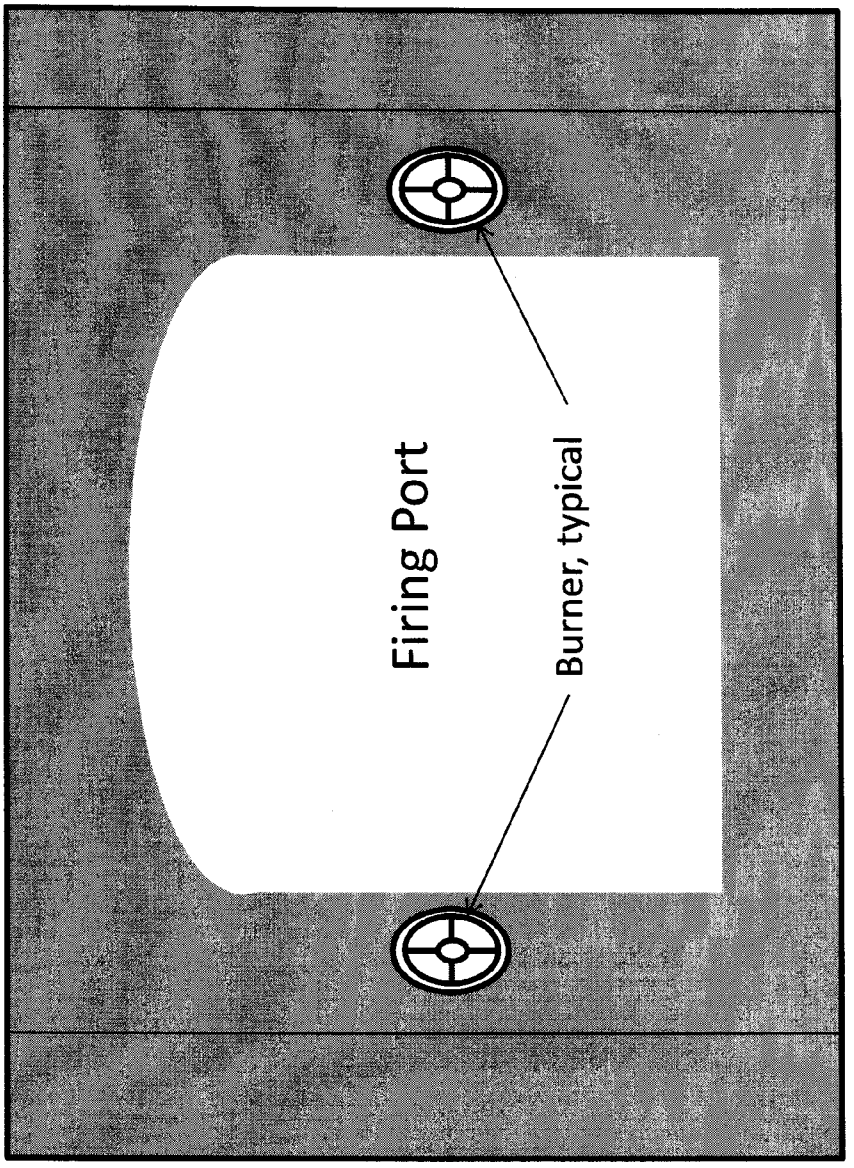


Figure 14

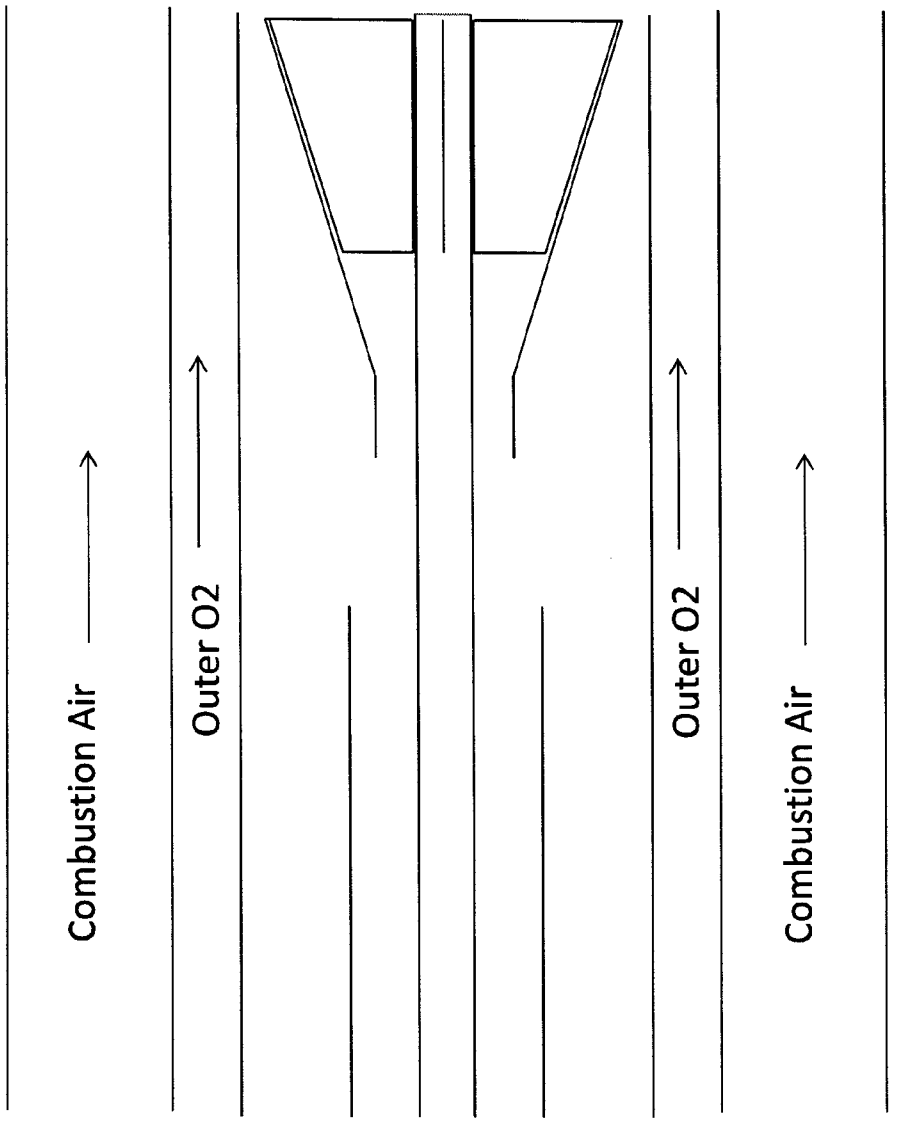


Figure 15

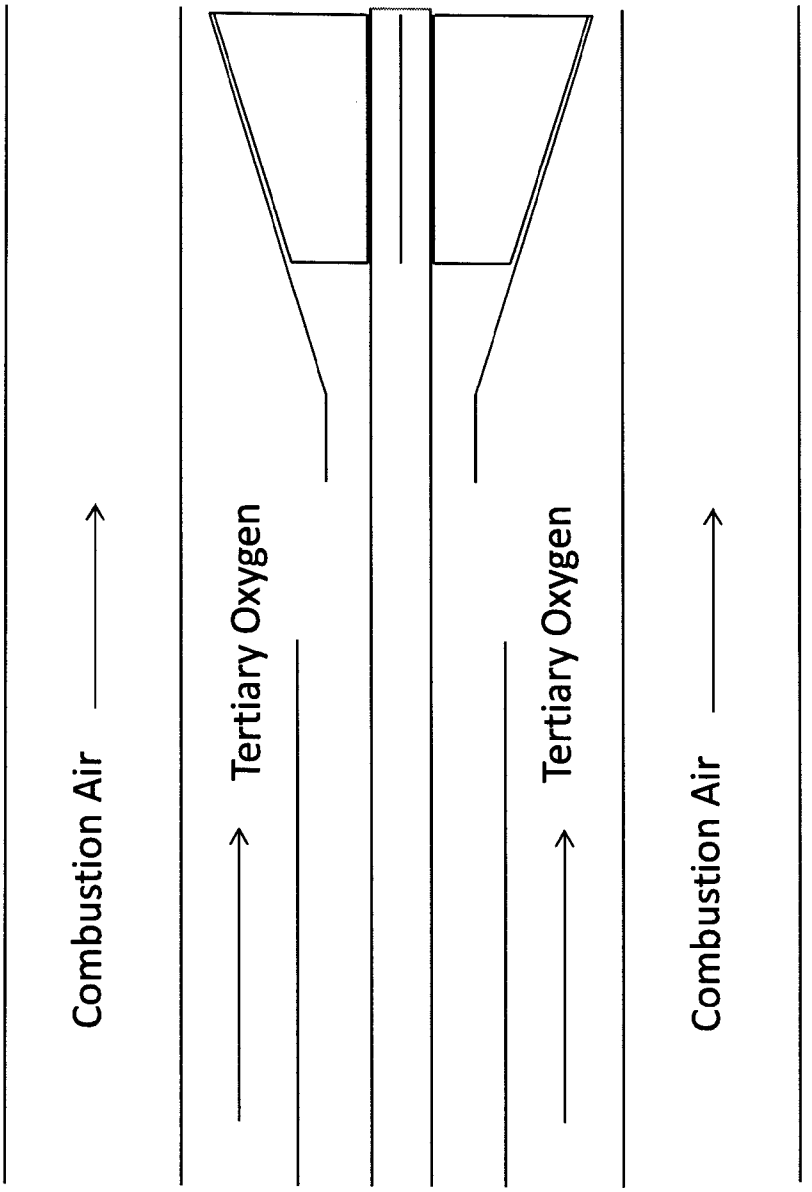

Combustion Air
Tertiary Oxygen
Tertiary Oxygen
Combustion Air

Figure 16

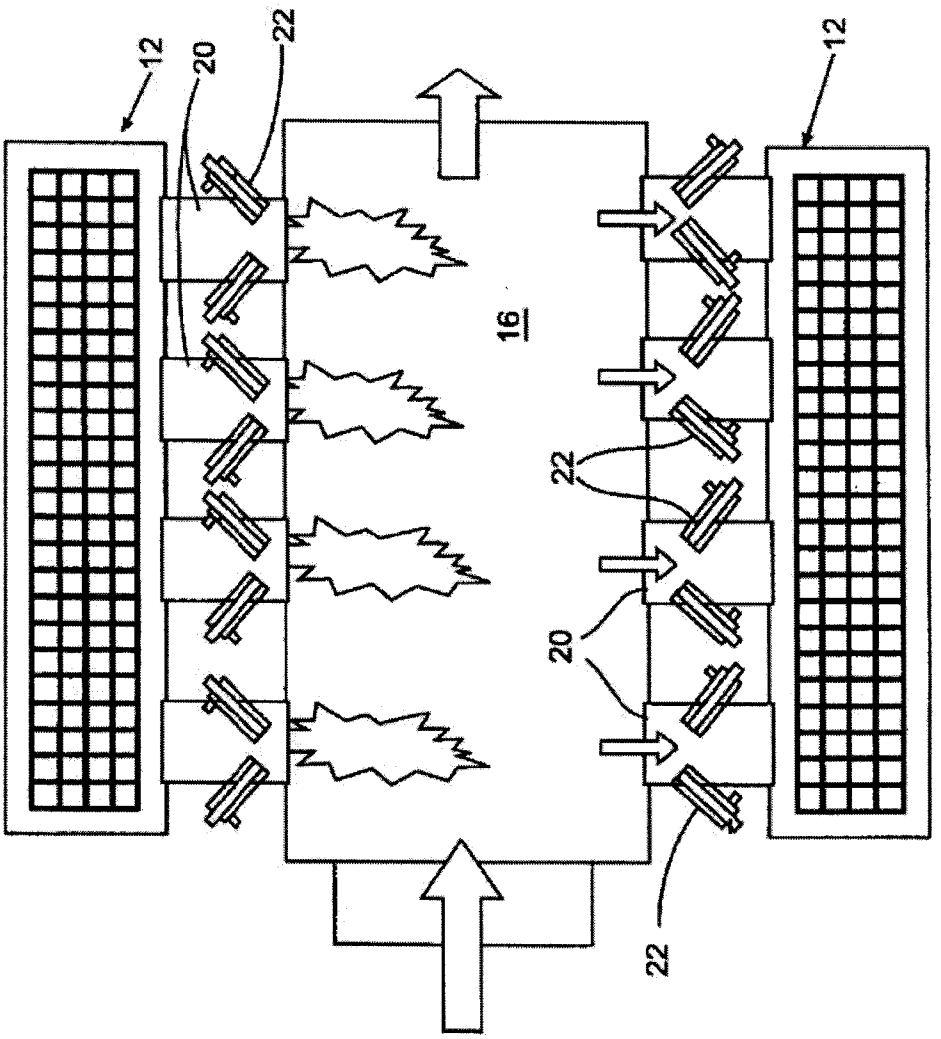


Fig. 17

OXY-SOLID FUEL BURNER

BACKGROUND

[0001] This application relates to a burner for combustion of solid fuel with oxygen.

[0002] Due in part to its variable volatile matter content, solid fuel can be a very difficult fuel to ignite in a flowing stream. Hence, typically the solid fuel undergoes a significant ignition delay that results in a flame front which is substantially detached from the fuel nozzle. This is an inherently unstable situation that can lead to high levels of unburned carbon, unstable process heating conditions (heat transfer, melting, etc.) and, potentially, blow-off of the flame that can lead to a very rapid and unsafe degradation in combustion.

[0003] It is desirable to have a burner capable of forming of a solid fuel flame front that is attached to the burner tip. This is an inherently desirable condition that maximizes heat transfer, carbon burnout and flame stability.

SUMMARY

[0004] Described herein is a burner having a center oxygen conduit surrounded by an outer fuel (pulverized solid fuel/transport gas) conduit. The outer fuel conduit may, in turn, be surrounded by an outer oxygen conduit. The outer fuel conduit includes an upstream section in which an inner annular flow passage terminates prior to the tip end of the burner and abruptly discharges into a larger, intermediate annular section between the outer fuel conduit and the center oxygen conduit. The intermediate section is followed by a downstream annular section that includes an inner annular diffuser and an outer annular nozzle on either side of a truncated conical divider (diffuser/nozzle combination). The intake to the diffuser/nozzle combination is separated from the discharge of the inner annular flow passage by a distance, X, that influences the flow distribution entering said diffuser/nozzle combination. The distance X must be greater than 0. The diffuser a plurality of radial guide vanes distributed around its periphery for the purpose of controlling flow separation within the diffuser.

[0005] Divergence of the diffuser lowers the velocity of a first fraction of the solid fuel stream in a controlled manner without appreciable flow separation. A second fraction of the solid fuel stream in the converging annular nozzle to a relatively high velocity. The combination of relatively high velocity and low velocity streams flowing adjacent to one another creates a large flow recirculation pattern that substantially aids in sustaining stable combustion at the fuel nozzle tip.

[0006] The diffuser may also include a bluff body (static mixing device) positioned immediately upstream of the radial guide vanes.

[0007] Center oxygen may flow through the central oxygen conduit, while outer oxygen may flow through the outer oxygen conduit. The solid fuel/transport gas stream, having flowed through the outer fuel conduit, discharges from the diffuser/nozzle combination having a velocity distribution characterized by a low inner velocity (generated in the diffuser) and a high outer velocity (generated in the annular converging nozzle). The combination of oxygen, fuel and transport gas produces a stable solid fuel flame of nominally circular cross-section.

[0008] The various aspects of the system disclosed herein can be used alone or in combinations with each other.

[0009] Aspect 1: A solid fuel/oxygen burner comprising: a central oxygen conduit extending toward a tip end of the burner; an outer fuel conduit surrounding the oxygen conduit and extending toward the tip end of the burner; an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit to form an inner annulus between the oxygen conduit and the inner fuel conduit and an outer annulus between the inner fuel conduit and the outer fuel conduit, the inner fuel conduit having an outlet end upstream of the tip end of the burner; a truncated conical divider positioned within the outer fuel conduit and surrounding the oxygen conduit downstream of the inner fuel conduit, the divider being configured to divide a fuel stream in the outer fuel conduit into an inner annular conical diffuser and an outer annular converging nozzle; and at least three radial guide vanes positioned within the diffuser; wherein the outlet end of the inner fuel conduit is spaced apart from an inlet end of the divider by a distance, X.

[0010] Aspect 2: The burner of Aspect 1, wherein the outlet end of the inner annulus has a height, h**1**; wherein the inlet end of the annular conical diffuser has a height, h**2**; and wherein h**1** is greater than h**2**.

[0011] Aspect 3: The burner of Aspect 1 or 2, further comprising: a bluff body positioned within the diffuser, the bluff body having a leading edge and a trailing end adjacent to an upstream end of the radial guide vanes.

[0012] Aspect 4: The burner of Aspect 3, wherein the bluff body has a height, h**3**, perpendicular to the flow direction as measured from the oxygen conduit; wherein the height of the inner annular conical diffuser at a perpendicular plane coincident with the leading edge of the bluff body has a height, h**4**; and wherein the ratio of h**3**/h**4** is from about 0.2 to about 0.5.

[0013] Aspect 5: The burner of Aspect 4, wherein the radial guide vanes have an axial length, Lout, from the bluff body to a trailing end of the diffuser; and wherein the ratio Lout/h**3** is from about 3 to about 25.

[0014] Aspect 6: The burner of Aspect 5, wherein the ratio of Lout/h**3** is from about 5 to about 15.

[0015] Aspect 7: The burner of any one of Aspects 3 to 6, wherein the bluff body is positioned with a leading end of the bluff body a distance, Lin, from the inlet end of the diffuser; wherein the diffuser has an inlet flow area, A**2**, and a flow area immediately upstream of the bluff body, A**3**; and wherein the relationship between the ratio A**3**/A**2** and the normalized position of the bluff body, Lin/h**2**, is set to substantially prevent flow separation in the diffuser.

[0016] Aspect 8: The burner of any one of Aspects 1 to 7, wherein the divider includes a leading edge oriented substantially parallel to the outer fuel conduit.

[0017] Aspect 9: The burner of any one of Aspects 1 to 8, further comprising: an outer oxygen conduit surrounding the outer fuel conduit and extending toward the tip end of the burner.

[0018] Aspect 10: The burner of Aspect 9, further comprising: a secondary oxygen conduit spaced apart from the outer oxygen conduit and extending toward the tip end of the burner.

[0019] Aspect 11: The burner of any one of Aspects 1 to 8, further comprising: the outer annulus forming a tertiary oxygen conduit.

[0020] Aspect 12: The burner of Aspect 11, further comprising: a secondary oxygen conduit spaced apart from the outer fuel conduit and extending toward the tip end of the burner.

[0021] Aspect 13: A method of combusting a pulverized solid fuel with oxygen, the method comprising: flowing a center oxygen stream through a central conduit extending toward a tip end of a burner, the central oxygen conduit being surrounded by an outer fuel conduit extending toward the tip end of the burner; flowing a fuel stream of pulverized fuel in a transport gas through an inner annulus formed by an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit; causing the fuel stream to exit the inner annulus at an outlet end of the inner fuel conduit positioned upstream of the tip end of the burner; dividing the fuel stream into two streams including an inner annular conical diffuser stream formed by a truncated conical divider having an inlet end positioned at a distance, X, downstream of the outlet end of the inner fuel conduit, and an outer annular converging nozzle stream formed between the divider and the outer fuel conduit, wherein the inner diffuser stream decelerates and the outer nozzle stream accelerates; and flowing the inner diffuser stream across at least three radial guide vanes positioned within the divider.

[0022] Aspect 14: The method of Aspect 13, wherein the outlet end of the inner annulus has a height, h**1**; wherein the inlet end of the annular conical diffuser has a height, h**2**; and wherein h**1** is greater than h**2**.

[0023] Aspect 15: The method of Aspect 13 or 14, further comprising: flowing the inner diffuser stream across a bluff body positioned with a trailing end of the bluff body adjacent to an upstream end of the radial guide vanes.

[0024] Aspect 16: The method of Aspect 15, wherein the bluff body has a height, h**3**, perpendicular to the flow direction as measured from the oxygen conduit.

[0025] Aspect 17: The method of Aspect 16, wherein the radial guide vanes have an axial length, Lout, from the bluff body to a trailing end of the diffuser; and wherein the ratio Lout/h**3** is from about 3 to about 25.

[0026] Aspect 18: The method of Aspect 17, wherein the ratio of Lout/h**3** is from about 5 to about 15.

[0027] Aspect 19: The method of any one of Aspects 14 to 17, wherein the bluff body is positioned with a leading end of the bluff body a distance, Lin, from the inlet end of the diffuser; wherein the diffuser has an inlet flow area, A**2**, and a flow area immediately upstream of the bluff body, A**3**; and wherein the relationship between the ratio A**3**/A**2** and the normalized position of the bluff body, Lin/h**2**, is set to substantially prevent flow separation in the diffuser.

[0028] Aspect 20: The method of any one of Aspects 13 to 19, wherein the divider includes a leading edge oriented substantially parallel to the outer fuel conduit.

[0029] Aspect 21: The method of any one of Aspects 13 to 20, further comprising: flowing a stream of outer oxygen through an annular oxygen passage bounded by an outer oxygen conduit surrounding the outer fuel conduit and extending toward the tip end of the burner.

[0030] Aspect 22: The method of Aspect 21, further comprising: flowing a stream of secondary oxygen through a secondary oxygen conduit spaced apart from the outer oxygen conduit and extending to the tip end of the burner.

[0031] Aspect 23: The method of any one of Aspects 13 to 20, further comprising: flowing a stream of tertiary oxygen through the outer annulus between the inner fuel conduit and the outer fuel conduit.

[0032] Aspect 24: The method of Aspect 23, further comprising: flowing a stream of secondary oxygen through a secondary oxygen conduit spaced apart from the outer fuel conduit and extending toward the tip end of the burner.

[0033] Aspect 25: The method of any of Aspects 13 to 24, further comprising: flowing the center oxygen stream at a velocity of less than about 20 to about 30 ft/sec.

[0034] Aspect 26: The method of any of Aspects 13 to 24, further comprising: flowing the center oxygen stream at a velocity of greater than about 20 to about 30 ft/sec.

[0035] Aspect 27: A regenerative furnace comprising: a burner block having at least one firing port mounted in a sidewall of the furnace; and one or more solid fuel/oxygen burners positioned near an edge of the at least one firing port, the burner comprising: a central oxygen conduit extending toward a tip end of the burner; an outer fuel conduit surrounding the oxygen conduit and extending toward the tip end of the burner; an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit to form an inner annulus between the oxygen conduit and the inner fuel conduit and an outer annulus between the inner fuel conduit and the outer fuel conduit, the inner fuel conduit having an outlet end upstream of the tip end of the burner; a truncated conical divider positioned within the outer fuel conduit and surrounding the oxygen conduit downstream of the inner fuel conduit, the divider being configured to divide a fuel stream in the outer fuel conduit into an inner annular conical diffuser and an outer annular converging nozzle; and at least three radial guide vanes positioned within the diffuser; wherein the outlet end of the inner fuel conduit is spaced apart from an inlet end of the divider by a distance, X; wherein in an under-port arrangement, the one or more burners are positioned beneath the at least one firing port in an under-port arrangement; and wherein in a side-port arrangement, the one or more burners are positioned along a side of the at least one firing port.

[0036] Aspect 28: The furnace of Aspect 27, wherein the one or more burners are positioned adjacent to an edge of the port and outside the port.

[0037] Aspect 29: The furnace of Aspect 27, wherein the one or more burners are positioned adjacent to an edge of the port and within the port.

[0038] Aspect 30: A method of combusting a pulverized solid fuel with oxygen in a regenerative furnace, the method comprising: flowing hot combustion air through a regenerator firing port; providing a solid fuel/oxygen burner positioned adjacent to an edge of the firing port; flowing a center oxygen stream through a central conduit extending toward a tip end of a burner, the central oxygen conduit being surrounded by an outer fuel conduit extending toward the tip end of the burner; flowing a fuel stream of pulverized fuel in a transport gas through an inner annulus formed by an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit; causing the fuel stream to exit the inner annulus at an outlet end of the inner fuel conduit positioned upstream of the tip end of the burner; dividing the fuel stream into two streams including an inner annular conical diffuser stream formed by a truncated conical divider having an inlet end positioned at a distance, X, downstream of the outlet end of the inner fuel conduit, and an outer annular converging nozzle stream formed between the divider and the outer fuel conduit, wherein the inner diffuser stream decelerates and the outer nozzle stream accelerates; and flowing the inner diffuser stream across at least three radial guide vanes positioned within the divider.

[0039] Aspect 31: The method of Aspect 30, further comprising flowing a stream of tertiary oxygen through the outer fuel conduit.

[0040] Aspect 32: The method of Aspect 30, further comprising flowing a stream of outer oxygen through an outer oxygen annulus.

[0041] Aspect 33: The method of any of Aspects 30 to 32, wherein the fuel and oxygen streams discharging from the burner are mixed with air as it exits the adjacent regenerator firing port.

[0042] Aspect 34: The method of Aspect 33, wherein the burner is operated with less than the stoichiometric amount of oxygen, with a stoichiometric ratio from about 0.05 to about 0.5.

BRIEF DESCRIPTION OF THE DRAWINGS

[0043] FIG. **1** is a schematic side cross-sectional view of an exemplary solid fuel/oxygen burner in which a central oxygen conduit is surrounded by an outer fuel conduit, an inner fuel conduit surrounding the central oxygen conduit discharges into the outer fuel conduit upstream of the tip end of the burner, and fuel exiting the inner fuel conduit is divided between an inner annular diffuser and an outer annular converging nozzle by a divider positioned within the outer fuel conduit and having an inlet end spaced apart from an outlet end of the inner fuel conduit. Radial guide vanes are positioned within the diffuser and being at a point downstream of the diffuser inlet.

[0044] FIG. **2** is a schematic depiction of flow patterns in the burner of FIG. **1** when the central oxygen stream velocity is less than the velocity of the fuel stream exiting the diffuser.

[0045] FIG. **3** is a schematic depiction of flow patterns in the burner of FIG. **1** when the central oxygen stream velocity is greater than the velocity of the fuel stream exiting the diffuser.

[0046] FIG. **4** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **1**, wherein the divider includes a straight, parallel leading edge.

[0047] FIG. **5** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **4**, wherein the burner further includes a bluff body positioned within the diffuser at an upstream end of the guide vanes.

[0048] FIG. **6** is a schematic depiction of the flow pattern within the diffuser of FIG. **5**.

[0049] FIG. **7** is a schematic and graphical depiction indicating a geometric relationship of the diffuser as in FIG. **5** to prevent flow separation from the diffuser walls.

[0050] FIG. **8** is a series of schematic representations of alternate shapes and forms of bluff bodies for use in the burner as in FIG. **5**.

[0051] FIG. **9** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **4**, further including an outer annular oxygen conduit.

[0052] FIG. **10** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **4**, in which tertiary oxygen is flowed in an outer annulus between the outer fuel conduit and the inner fuel conduit.

[0053] FIG. **11** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **9**, further including a secondary oxygen conduit spaced apart from the outer annular oxygen conduit.

[0054] FIG. **12** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **10**, further including a secondary oxygen conduit spaced apart from the outer fuel conduit.

[0055] FIG. **13** is a schematic end view of a regenerative glass melting furnace firing port in which a plurality of burners, for example as any of the embodiments described herein, in an under-port arrangement. wherein the burners are positioned below the regenerator firing port. The end view is taken from the furnace chamber look toward the furnace sidewall.

[0056] FIG. **14** is a schematic end view of a regenerative glass melting furnace firing port in which a plurality of burners, for example as any of the embodiments described herein, in a side-port arrangement. wherein the burners are positioned along one or both sides of the regenerator firing port. The end view is taken from the furnace chamber look toward the furnace sidewall.

[0057] FIG. **15** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **9**, further including a combustion air conduit surrounding the outer oxygen conduit.

[0058] FIG. **16** is a schematic side cross-sectional view of an embodiment of a burner as in FIG. **10**, further including a combustion air conduit surrounding the outer fuel conduit.

[0059] FIG. **17** is a schematic plan view of a regenerative furnace into which one or more burners as described herein may be installed.

DETAILED DESCRIPTION

[0060] For the purposes of the description herein, the following definitions are provided. Transport gas is a gaseous fluid used to carry or transport solid fuel particles, and may comprise air, oxygen-enriched air, nitrogen, carbon dioxide, recycled flue gas, and combinations thereof. Oxygen is a gas containing oxygen molecules at a concentration greater than or equal to 28 mol % O2, preferably greater than or equal to 60 mol % O2, and more preferably greater than or equal to 85 mol % O2. Solid fuel is a hydrocarbon fuel in solid form and may comprise petroleum coke; all varieties of coal including anthracite, bituminous, sub-bituminous, and lignite; peat, wood, grass, and other so-called biomass materials; municipal solid waste; and combinations thereof.

[0061] Several embodiments and variations of an oxygen/pulverized solid fuel burner are described herein. One embodiment of a burner is illustrated in FIG. **1**. A central oxygen conduit is surrounded by an outer fuel conduit, both the oxygen conduit and the outer fuel conduit extending toward a tip end of the burner. An inner fuel conduit, having a smaller diameter than the outer fuel conduit, is positioned between the oxygen conduit and the outer fuel conduit, and terminates at a location upstream of the tip end of the burner. A truncated conical flow divider is positioned within the outer fuel conduit and surrounding the oxygen conduit at a location downstream of the inner fuel conduit. The divider may extend to the tip end of the burner or may terminate upstream of the tip end of the burner. In some embodiments, one or both of the oxygen conduit and the outer fuel conduit extend to the tip of the burner.

[0062] Pulverized solid fuel plus a transport gas flows downstream through the inner fuel conduit, while center oxygen flows through the central oxygen conduit. The outlet (trailing) edge of the inner fuel conduit has an annular opening of height, h**1**, from the oxygen conduit. The outlet of the inner fuel conduit is separated from the divider in the axial

direction by a length, X. The inlet (upstream) edge of the divider has an annular opening of height, h**2**, where h**2** is smaller than h**1**. The divider gives rise to two co-annular flow sections: an annular diffuser located between the oxygen conduit and the divider, whose flow cross-sectional area increases in the direction of flow; and an annular converging nozzle located between the divider and the outer fuel conduit, whose cross-sectional area decreases in the direction of flow.

[0063] In one embodiment, the annular diffuser contains at least three radial guide vanes spaced around the circumference of the diffuser passage. The guide vanes provide controlled separation of the flow emanating from the corners formed at the intersection of each guide vane with the surface of the center oxygen conduit. The controlled separation at the inner corners in turn promotes attachment of the flow at the outer surface of the diffuser, thus improving diffuser stability relative to annular diffusers without the radial guide vanes. The radial guide vanes need not extend the entire axial length of the diffuser. For example, as illustrated in FIG. **1**, the radial guide vanes begin downstream of the inlet end of the diffuser.

[0064] The fuel and transport gas stream exits the inner fuel conduit and spreads radially as it flows axially downstream toward the divider. Based on the velocity of the fuel and transport gas stream, the magnitude of the distance, X, and the relative magnitudes of the annular openings h**1** and h**2**, a certain portion of the fuel stream enters the diffuser while the remainder enters the converging nozzle. The portion flowing through the diffuser experiences a decrease in axial velocity, while the portion flowing through the nozzle experiences an increase in axial velocity. The low velocity portion at the outlet of the diffuser is essential toward attaining a stable, attached flame region, while the high velocity portion at the outlet of the nozzle helps to create a large scale, torroidal, streamwise vortex between the low and high velocity regions, improving mixing therein, while also inducing recirculation of hot products of combustion from the surrounding, thereby assisting fuel ignition.

[0065] Two distinct flow regimes may be associated with the burner configuration of FIG. **1**. First, if the center oxygen stream is flowing at relatively low velocity, e.g., below about 20-30 ft/sec, then upon exiting from the center oxygen conduit, the flow pattern immediately downstream of the burner is that which is qualitatively illustrated in FIG. **2**. That is, a wake region is formed along the burner axis due to the weak center momentum and strong outer momentum of the burner. Second, if the velocity of the center oxygen stream is relatively high, e.g., greater than about 20-30 ft/sec, then the momentum of the center oxygen jet largely prevents the formation of an axial wake region, and instead induces the flow of fuel toward the axis, and the overall flow pattern immediately downstream of the burner is qualitatively as illustrated in FIG. **3**.

[0066] A related embodiment, shown in FIG. **4**, includes a leading edge on the divider that is largely straight and substantially parallel to the burner axis. The purpose of the straight and parallel leading edge is to minimize flow disturbances at the inlet of the diffuser by reducing the angle of attack between the oncoming flow and the divergent diffuser wall.

[0067] Another embodiment of the burner includes a bluff body positioned adjacent to the leading edge of the radial guide vanes within the diffuser, for example as depicted in

[0068] FIG. **5**. The function of the bluff body is to "trip" the flow entering the diffuser, facilitating more reliable downstream attachment of the flow to the outer diffuser wall (i.e., the divider), while creating intense mixing that acts to reduce high velocity peaks in the flow field exiting the diffuser. The bluff body has a height, h**3**, perpendicular to the flow direction, and the radial guide vanes have a length, Lout, from the trailing edge of the bluff body to the diffuser exit.

[0069] A qualitative illustration of the effect of the bluff body on the diffuser flow is shown in FIG. **6**. Note that a localized zone of reverse flow forms downstream of the bluff body adjacent the central oxygen conduit. In order to limit the extent of deposited solid particulate within the diffuser passage due to the reverse flow, yet still provide sufficient mixing length for adjustment of flow momentum, the non-dimensional length, Lout/h**3**, of the diffuser section from the trailing edge of the bluff body to the diffuser exit (i.e., normalized by the bluff body height) should be from about 3 to about 25, and is preferably from about 5 to about 15.

[0070] Another factor in the placement of the bluff body is the relationship between the ratio of the diffuser cross-sectional area just upstream of the bluff body to that at the diffuser inlet (A**3**/A**2** as denoted in FIG. **7**), and the non-dimensional inlet length, Lin/h**2**, from the inlet of the diffuser to the leading edge of the bluff body (i.e., normalized by the opening height of the diffuser).

[0071] It known that, for a fixed angle annular diffuser, increasing the diffuser length will eventually result in flow separation (also known as stall), which can generate flow instabilities and distort the velocity profile within the diffuser. Flow instabilities and a distorted velocity profile at the inlet to the radial guide vanes would cause sub-standard performance of the diffuser section downstream of the bluff body. Hence, for optimal operation of the burner, upstream stall can be avoided by keeping the non-dimensional length, Lin/h**2**, as a function of the area ratio, A**3**/A**2**, within the region below the curve shown in FIG. **7**.

[0072] It is contemplated that a similarly effective bluff body may assume other forms and shapes beyond the representative disk of FIG. **5**. These alternative shapes include, but are not limited to, curved and triangular as depicted in FIG. **8**. Regardless the shape of the bluff body, its height, h**3**, should be greater than nominally half of its streamwise thickness, W.

[0073] In a further embodiment of the present burner, an outer oxygen annulus is positioned to introduce a stream of outer oxygen around the outer periphery of the fuel stream exiting the burner, as illustrated in FIG. **9**. Mixing of the outer oxygen and fuel streams facilitates rapid ignition of the fuel stream and increases flame radiative heat transfer. From an operational perspective, the outer oxygen can be utilized with or without central oxygen. In the latter case, the end of the central oxygen passage may be blocked to prevent the ingress of partially burned fuel and hot products of partial combustion.

[0074] Yet another embodiment of the present burner eliminates the outer oxygen annulus, but introduces tertiary oxygen into the annulus between the outer fuel conduit and the inner fuel conduit, as illustrated in FIG. **10**. The tertiary oxygen has a similar beneficial effect on ignition and heat transfer as the outer oxygen, but accomplishes it within a smaller diameter device.

[0075] Still another embodiment of the present burner incorporates a "staged" oxygen stream that is introduced adjacent to and beneath the burner body as depicted in FIGS. **11** and **12**. FIG. **11** corresponds to the burner embodiment with outer oxygen (FIG. **9**), while FIG. **12** corresponds to the

burner embodiment with tertiary oxygen (FIG. **10**). The principal advantages of the so-called staged oxygen is that it affords a means of controlling the flame length and burner NOx emissions. In particular, by introducing less than the stoichiometric amount of oxygen to the main body of the burner and the balance to the staged oxygen port, an increase in flame length and reduction of NOx can be obtained. The practical upper limit to the amount of staged oxygen, as a percent of the stoichiometric value, is reached when degradation in combustion occurs (e.g., the flame becomes unstable, CO emissions and unburned carbon increase), or the flame becomes too long relative to the process furnace dimensions. This limit must be determined on a case-by-case basis.

[0076] In another configuration, the burner can be surrounded by combustion air. In this way, the burner can provide enhancement of air-fuel combustion. For example, FIGS. **15** and **16** illustrate burner embodiments as in FIGS. **9** and **10** with an additional outer annulus of air. Air may also be introduced around the burner in a duct of arbitrary cross-section.

[0077] A burner as described herein can be used in a system as a device for heating and/or melting operations. In particular, the burner can be utilized in a regenerative glass melting furnace, for example as shown in FIG. **17**. In known regenerative furnaces burner blocks having one or more firing ports are positioned on opposite sides or ends of the furnace combustion chamber. Each of the firing ports typically contains one or more burners for delivery of fuel into the combustion chamber. The firing ports also provide a combustion air supply around the burners. During furnace operation, the burners on opposite sides of the combustion chamber are operated alternately in a cyclic fashion. While the burners on one side of the combustion chamber are fired, hot combustion products exit the opposite side of the combustion chamber. Regenerators or refractory checkers on either side of the furnace provide a heat transfer medium to transfer heat from the hot combustion gases exiting the combustion chamber to the cold combustion air which is delivered to the furnace. The combustion air and exhaust gas flows are reversed typically every 20 minutes so that each side checker can be alternately heated and used for preheating of combustion air. FIG. **17** shows a regenerative furnace **10** having regenerator checkers **12** on opposite sides. During firing of the burners **22**, combustion air is delivered from the regenerator checkers **12** through the firing ports **20**, into the combustion chamber **16** of the furnace **10**.

[0078] There are many ways in which the presently disclsoed burner can be configured to operate in a regenerative glass melting furnace. One configuration of particular utility is in tandem with hot combustion air. FIGS. **13** and **14**, for example, illustrate exemplary embodiments wherein one or more burners are installed near a hot combustion air port (i.e., firing port) in a regenerative glass melting furnace, wherein near means that the burner can be either adjacent to and outside the edge of the port or adjacent to the end and within the port. In these embodiments, solid fuel is injected into the hot air stream as it discharges from the firing port. FIG. **13** illustrates an exemplary under-port firing arrangement, while FIG. **14** illustrates an exemplary side-port firing arrangement. In these embodiments, the burners can be operated with less than stoichiometric oxygen as a means to enhance the solid fuel combustion with hot combustion air from the regenerator port. For example, the burners can be operated with a stoichiometric ratio between about 0.05 and about 0.5.

[0079] The present invention is not to be limited in scope by the specific aspects or embodiments disclosed in the examples which are intended as illustrations of a few aspects of the invention and any embodiments that are functionally equivalent are within the scope of this invention. Various modifications of the invention in addition to those shown and described herein will become apparent to those skilled in the art and are intended to fall within the scope of the appended claims.

1. A solid fuel/oxygen burner comprising:

a central oxygen conduit extending toward a tip end of the burner;

an outer fuel conduit surrounding the oxygen conduit and extending toward the tip end of the burner;

an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit to form an inner annulus between the oxygen conduit and the inner fuel conduit and an outer annulus between the inner fuel conduit and the outer fuel conduit, the inner fuel conduit having an outlet end upstream of the tip end of the burner;

a truncated conical divider positioned within the outer fuel conduit and surrounding the oxygen conduit downstream of the inner fuel conduit, the divider being configured to divide a fuel stream in the outer fuel conduit into an inner annular conical diffuser and an outer annular converging nozzle; and

at least three radial guide vanes positioned within the diffuser;

wherein the outlet end of the inner fuel conduit is spaced apart from an inlet end of the divider by a distance, X.

2. The burner of claim **1**,

wherein the outlet end of the inner annulus has a height, h**1**;

wherein the inlet end of the annular conical diffuser has a height, h**2**; and

wherein h**1** is greater than h**2**.

3. The burner of claim **1**, further comprising:

a bluff body positioned within the diffuser, the bluff body having a leading edge and a trailing end adjacent to an upstream end of the radial guide vanes.

4. The burner of claim **1**,

wherein the divider includes a leading edge oriented substantially parallel to the outer fuel conduit.

5. The burner of claim **1**, further comprising:

an outer oxygen conduit surrounding the outer fuel conduit and extending toward the tip end of the burner.

6. The burner of claim **5**, further comprising

a secondary oxygen conduit spaced apart from the outer fuel conduit and extending toward the tip end of the burner.

7. The burner of claim **1**, further comprising:

the outer annulus forming a tertiary oxygen conduit.

8. The burner of claim **7**, further comprising

a secondary oxygen conduit spaced apart from the outer fuel conduit and extending toward the tip end of the burner.

9. A method of combusting a pulverized solid fuel with oxygen, the method comprising:

flowing a center oxygen stream through a central conduit extending toward a tip end of a burner, the central oxygen conduit being surrounded by an outer fuel conduit extending toward the tip end of the burner;

flowing a fuel stream of pulverized fuel in a transport gas through an inner annulus formed by an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit;

causing the fuel stream to exit the inner annulus at an outlet end of the inner fuel conduit positioned upstream of the tip end of the burner;

dividing the fuel stream into two streams including an inner annular conical diffuser stream formed by a truncated conical divider having an inlet end positioned at a distance, X, downstream of the outlet end of the inner fuel conduit, and an outer annular converging nozzle stream formed between the divider and the outer fuel conduit, wherein the inner diffuser stream decelerates and the outer nozzle stream accelerates; and

flowing the inner diffuser stream across at least three radial guide vanes positioned within the divider.

10. The method of claim **9**,

wherein the outlet end of the inner annulus has a height, h**1**;

wherein the inlet end of the annular conical diffuser has a height, h**2**; and

wherein h**1** is greater than h**2**.

11. The method of claim **9**, further comprising:

flowing the inner diffuser stream across a bluff body positioned with a trailing end of the bluff body adjacent to an upstream end of the radial guide vanes.

12. The method of claim **9**,

wherein the divider includes a leading edge oriented substantially parallel to the outer fuel conduit.

13. The method of claim **9**, further comprising:

flowing a stream of outer oxygen through an annular oxygen passage bounded by an outer oxygen conduit surrounding the outer fuel conduit and extending toward the tip end of the burner.

14. The method of claim **13**, further comprising:

flowing a stream of secondary oxygen through a secondary oxygen conduit spaced apart from the outer oxygen conduit and extending to the tip end of the burner.

15. The method of claim **9**, wherein the burner is operated with less than the stoichiometric amount of oxygen, with a stoichiometric ratio from about 0.05 to about 0.5.

16. A regenerative furnace comprising:

a burner block having at least one firing port mounted in a sidewall of the furnace; and

one or more solid fuel/oxygen burners positioned near an edge of the at least one firing port, the burner comprising:

a central oxygen conduit extending toward a tip end of the burner;

an outer fuel conduit surrounding the oxygen conduit and extending toward the tip end of the burner;

an inner fuel conduit positioned between the oxygen conduit and the outer fuel conduit to form an inner annulus between the oxygen conduit and the inner fuel conduit and an outer annulus between the inner fuel conduit and the outer fuel conduit, the inner fuel conduit having an outlet end upstream of the tip end of the burner;

a truncated conical divider positioned within the outer fuel conduit and surrounding the oxygen conduit downstream of the inner fuel conduit, the divider being configured to divide a fuel stream in the outer fuel conduit into an inner annular conical diffuser and an outer annular converging nozzle; and

at least three radial guide vanes positioned within the diffuser;

wherein the outlet end of the inner fuel conduit is spaced apart from an inlet end of the divider by a distance, X;

wherein in an under-port arrangement, the one or more burners are positioned beneath the at least one firing port in an under-port arrangement; and

wherein in a side-port arrangement, the one or more burners are positioned along a side of the at least one firing port.

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