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Shuttle kiln exhaust configuration

Abstract

A shuttle kiln (**100**) according to certain aspects includes at least one flue channel (**124**) and multiple flue risers (**122**) in fluid communication with the flue channel (**124**), and at least one shuttle (**104**) defining multiple exhaust shafts (**140**) arranged above the multiple flue risers (**122**), wherein an aggregate volume of a first exhaust shaft/riser pair (**140-1, 122-1**) differs from an aggregate volume of a second exhaust shaft/riser pair (**140-2, 122-2**). Such configuration at least partially compensates for different backpressures that would otherwise be experienced by flue gas exiting a shuttle kiln cavity (**138**) through different exhaust shafts (**140**), thereby improving uniformity of flue gas flow and reducing temperature variability within a kiln cavity (**138**).

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Background/Summary

CROSS-REFERENCE TO RELATED APPLICATION (1) This is a national stage application under 35 U.S.C. § 371 of International Application No. PCT/US2020/039249, filed on Jun. 24, 2020, which claims the benefit of priority under 35 U.S.C § 120 of U.S. Provisional Application Ser. No. 62/870,231 filed on Jul. 3, 2019, the content of which is relied upon and incorporated herein by reference in their entireties.

BACKGROUND
(1) The disclosure relates to shuttle kilns for producing fired bodies, and more particularly to exhaust configurations providing enhanced temperature uniformity within shuttle kilns.
(2) Shuttle kilns are typically used for batch processing of products (e.g., ceramics) at elevated temperatures. A shuttle kiln may include a kiln housing and one or more shuttles that in combination form a kiln cavity. Temperature variations in a kiln cavity (e.g., from a center an edge of the kiln cavity) can produce significant differences in the specifications and quality of fired products, depending on where a fired product was located within the kiln cavity during a firing process. Batch processing for sensitive applications may require increased temperature control and uniformity within the kiln cavity to provide consistent results and higher yields. For example, in certain applications, fired products (e.g., porous ceramic products containing organic matter) within a batch may exhibit different significant dimensional variation due to experience non-uniform part shrinkages in the firing process, based on exposure of the products to different maximum temperatures depending on where the products were located within a kiln cavity.
(3) One such potential source of temperature variation within a kiln cavity is non-uniform flow of flue gas exiting the kiln cavity due to asymmetric location of an exhaust fan relative to flue risers and/or exhaust shafts of kiln cars. Need therefore exists in the art for shuttle kiln exhaust systems that address limitations associated with conventional systems.
SUMMARY
(4) A shuttle kiln according to certain aspects includes at least one flue channel and multiple flue risers in fluid communication with the flue channel, and at least one shuttle defining multiple exhaust shafts arranged above the multiple flue risers, wherein an aggregate volume of a first flue channel/riser pair differs from an aggregate volume of a second flue channel/riser pair. Such configuration at least partially compensates for different backpressures that would otherwise be experienced by flue gas exiting a shuttle kiln cavity through different exhaust shafts, thereby

improving uniformity of flue gas flow and reducing temperature variability within a kiln cavity.
(5) In one aspect, the present disclosure relates to a shuttle kiln including a kiln housing and at least one shuttle positioned within the kiln housing. The kiln housing includes a first flue channel and a first plurality of flue risers in fluid communication with the first flue channel. The first plurality of flue risers includes a first flue riser defining a first riser volume and a second flue riser defining a second riser volume. The at least one shuttle defines a first plurality of exhaust shafts including a first exhaust shaft defining a first shaft volume and a second exhaust shaft defining a second shaft volume. The first exhaust shaft is arranged above and in fluid communication with the first flue riser. The first exhaust shaft is separated from the first flue riser to define a first entrainment gap therebetween. The second exhaust shaft is arranged above and in fluid communication with the second flue riser. The second exhaust shaft being separated from the second flue riser to define a second entrainment gap therebetween. A sum of the first riser volume and the first shaft volume is less than a sum of the second riser volume and the second shaft volume.
(6) In certain embodiments, the kiln housing includes a floor, a door, sidewalls, and a ceiling bounding an interior. The first flue channel is arranged below a top surface of the floor. The first plurality of flue risers extend above the top surface of the floor. In certain embodiments, the kiln housing further includes a second flue channel and a second plurality of flue risers in fluid communication with the second flue channel. In certain embodiments, the kiln housing further includes an exhaust fan in fluid communication with the first flue channel, and the first flue riser is closer than the second flue riser to the exhaust fan.
(7) In certain embodiments, the at least one shuttle includes a plurality of shuttles. In certain embodiments, a first shuttle of the plurality of shuttles includes the first exhaust shaft, and a second shuttle of the plurality of shuttles includes the second exhaust shaft. In certain embodiments, the first plurality of flue risers further includes a third flue riser defining a third riser volume, and the first plurality of exhaust shafts further includes a third exhaust shaft defining a third shaft volume. The third exhaust shaft is arranged above and in fluid communication with the third flue riser. The third exhaust shaft separated from the third flue riser to define a third entrainment gap therebetween. A sum of the second riser volume and the second shaft volume is less than a sum of the third riser volume and the third shaft volume. In certain embodiments, at least a portion of the first exhaust shaft is vertically aligned with the first flue riser, and at least a portion of the second exhaust shaft is vertically aligned with the second flue riser. In certain embodiments, a cross-sectional area of the first flue riser is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2, and a cross-sectional area of the first exhaust shaft is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2.
(8) In certain embodiments, a height of the first flue riser is less than a height of the second flue riser. In certain embodiments, a height of the first exhaust shaft is less than a height of the second exhaust shaft. In certain embodiments, the height of the first flue riser is less than the height of the second flue riser, and the height of the first exhaust shaft is less than the height of the second exhaust shaft. In certain embodiments, the first entrainment gap is larger than the second entrainment gap. In certain embodiments, a cross-sectional area of the first flue riser is less than a cross-sectional area of the second flue riser. In certain embodiments, a cross-sectional area of the first exhaust shaft is less than a cross-sectional area of the second exhaust shaft. In certain embodiments, the cross-sectional area of the first flue riser is less than the cross-sectional area of the second flue riser, and the cross-sectional area of the first exhaust shaft is less than the cross-sectional area of the second exhaust shaft.
(9) In another aspect, the present disclosure relates to a shuttle kiln including a kiln housing. The kiln housing includes a flue channel and a plurality of flue risers in fluidic communication with the flue channel. The plurality of flue risers includes a first flue riser defining a first riser volume and a second flue riser defining a second riser volume that differs from the first riser volume. The first flue riser is configured to be arranged below a first exhaust shaft of a shuttle when the shuttle is positioned within the kiln housing. The second flue riser is configured to be arranged below a

second exhaust shaft of the shuttle when the shuttle is positioned within the kiln housing.
(10) In another aspect, the present disclosure relates to a shuttle kiln including at least one shuttle. The at least one shuttle is configured to be removably positioned within a kiln housing. The at least one shuttle defining a plurality of exhaust shafts including a first exhaust shaft defining a first shaft volume and a second exhaust shaft defining a second shaft volume that differs from the first shaft volume. The first exhaust shaft is configured to be arranged above a first flue riser of the kiln housing when the at least one shuttle is positioned within the kiln housing. The second exhaust shaft is configured to be arranged above a second flue riser of the kiln housing when the at least one shuttle is positioned within the kiln housing.
(11) In another aspect, the present disclosure relates to a method of fabricating at least one fired body. The method includes moving at least one shuttle carrying at least one unfired body into a kiln housing of a shuttle kiln, the kiln housing including a first flue riser and a second flue riser. The method further includes arranging a first exhaust shaft of the at least one shuttle above the first flue riser and arranging a second exhaust shaft of the at least one shuttle above the second flue riser, wherein a sum of a first riser volume of the first flue riser and a first shaft volume of the first exhaust shaft is less than a sum of a second riser volume of the second flue riser and a second shaft volume of the second exhaust shaft. The method further includes heating a kiln cavity bounded by the at least one shuttle and the kiln housing to alter the at least one unfired body. The method further includes exhausting gas from the kiln cavity through a first flow path and a second flow path, wherein the first flow path extends through the first exhaust shaft, across a first entrainment gap, and through the first flue riser to a first flue channel, and wherein the second flow path extends through the second exhaust shaft, across a second entrainment gap, and through the second flue riser to the first flue channel.
(12) In certain embodiments, the present disclosure relates to a fired body is produced by the foregoing method.
(13) Additional features and advantages will be set forth in the detailed description which follows, and in part will be readily apparent to those skilled in the art from that description or recognized by practicing the embodiments as described herein, including the detailed description which follows, the claims, as well as the appended drawings.
(14) It is to be understood that both the foregoing general description and the following detailed description are merely exemplary, and are intended to provide an overview or framework to understanding the nature and character of the claims. The accompanying drawings are included to provide a further understanding, and are incorporated in and constitute a part of this specification. The drawings illustrate one or more embodiment(s), and together with the description serve to explain principles and operation of the various embodiments.

Description

BRIEF DESCRIPTION OF THE DRAWINGS
(1) FIG. **1**A is a perspective view of a shuttle kiln including a kiln housing and multiple shuttles positioned therein;
(2) FIG. **1**B is a perspective view of an interior of the kiln housing of FIG. **1**A;
(3) FIG. **1**C is a schematic top view of an exhaust system of the shuttle kiln of FIG. **1**A including flue channels and an exhaust fan;
(4) FIG. **1**D is a schematic side view of the shuttle kiln of FIG. **1**A including exhaust ports of the shuttle in fluid communication with flue risers of the kiln housing;
(5) FIG. **2**A is a schematic side view of one embodiment of the shuttle kiln with different flue risers of the kiln housing of FIG. **1**A having different heights;
(6) FIG. **2**B is a schematic side view of one embodiment of the shuttle kiln with different flue risers

of the kiln housing of FIG. **1**A having different widths;
(7) FIG. **2**C is a schematic side view of one embodiment of the shuttle kiln with different exhaust shafts of the shuttle of FIG. **1**A having different widths;
(8) FIG. **3**A is a chart illustrating the effect on undercar dilution fraction by increasing the size of an entrainment gap between exhaust shafts of the shuttle and flue risers of the kiln housing;
(9) FIG. **3**B is a chart illustrating the effect on temperature by increasing the size of an entrainment gap between exhaust shafts of the shuttle and flue risers of the kiln housing;
(10) FIG. **3**C is a chart illustrating the effect on flow distribution through shuttle exhaust shafts by increasing the size of an entrainment gap between exhaust shafts of the shuttle and flue risers of the kiln housing;
(11) FIG. **3**D is a chart illustrating the effects of increasing the size of an entrainment gap between exhaust shafts of the shuttle and flue risers of the kiln housing on max non-uniformity through the exhaust shafts, flue tunnel temperature, and flue tunnel oxygen concentration;
(12) FIG. **4** is a chart depicting flow distribution through offtakes as a function of offtake number, illustrating increased flow uniformity through shuttle exhaust shafts with differently-sized entrainment gaps; and
(13) FIG. **5** is a flowchart identifying steps of a method of fabricating at least one fired body.

DETAILED DESCRIPTION

(14) The embodiments set forth below represent the necessary information to enable those skilled in the art to practice the embodiments and illustrate the best mode of practicing the embodiments. Upon reading the following description in light of the accompanying drawing figures, those skilled in the art will understand the concepts of the disclosure and will recognize applications of these concepts not particularly addressed herein. It should be understood that these concepts and applications fall within the scope of the disclosure and the accompanying claims.
(15) It will be understood that, although the terms first, second, etc. may be used herein to describe various elements, these elements should not be limited by these terms. These terms are only used to distinguish one element from another. For example, a first element could be termed a second element, and, similarly, a second element could be termed a first element, without departing from the scope of the present disclosure. As used herein, the term “and/or” includes any and all combinations of one or more of the associated listed items.
(16) Relative terms such as “below” or “above” or “upper” or “lower” or “horizontal” or “vertical” may be used herein to describe a relationship of one element, layer, or region to another element, layer, or region as illustrated in the drawing figures. It will be understood that these terms and those discussed above are intended to encompass different orientations of the device in addition to the orientation depicted in the drawing figures.
(17) The terminology used herein is for the purpose of describing particular embodiments only and is not intended to be limiting of the disclosure. As used herein, the singular forms “a,” “an,” and “the” are intended to include the plural forms as well, unless the context clearly indicates otherwise. It will be further understood that the terms “comprises,” “comprising,” “includes,” and/or “including” when used herein specify the presence of stated features, integers, steps, operations, elements, and/or components, but do not preclude the presence or addition of one or more other features, integers, steps, operations, elements, components, and/or groups thereof.
(18) Unless otherwise defined, all terms (including technical and scientific terms) used herein have the same meaning as commonly understood by one of ordinary skill in the art to which this disclosure belongs. It will be further understood that terms used herein should be interpreted as having a meaning that is consistent with their meaning in the context of this specification and the relevant art and will not be interpreted in an idealized or overly formal sense unless expressly so defined herein.
(19) FIGS. **1**A-**1**D are views of a shuttle kiln **100** including a kiln housing **102** and a first shuttle **104**A, a second shuttle **104**B, and a third shuttle **104**C (referred to generally herein as shuttles **104**)

positioned therein. In certain embodiments, more or fewer shuttles **104** (may also be referred to herein as shuttle cars, kiln cars, kiln carts, etc.) may be used. A shuttle kiln **100** is a type of periodic kiln configured to uniformly heat a kiln cavity **138** bounded in part by the kiln housing **102** to a kiln peak temperature (may also be referred to as a maximum temperature, peak temperature, etc.). The features described herein and below may be applied to other types of periodic kilns.

(20) Referring to FIGS. **1**A and **1**B, the kiln housing **102** includes a floor **106**, a front door **108**, a left sidewall **110**A, a right sidewall **110**B (opposite the left sidewall **110**A), a back sidewall **110**C (wherein the foregoing left, right, and back sidewalls **110**A-**110**C may be referred to generally herein as sidewalls **110**), and a ceiling **112**, which bound and define an interior **114** of the kiln housing **102**. As shown in FIG. **1**A, each shuttle **104**A-**104**C includes a top **128** and a bottom **130** (opposite the top **128**). When the shuttles **104** are positioned within the kiln housing **102** and the front door **108** is in the closed position, a kiln cavity **138** is defined between the front door **108**, the sidewalls **110**, and the ceiling **112** of the kiln housing **102** as well as the top **128** of the shuttle **104**. The top **128** of the shuttle **104** serves as a moveable refractory floor that is used as a hearth of the shuttle kiln **100**.

(21) The front door **108** of the kiln housing **102** is moveable from a closed position enclosing the interior **114** to an open position allowing insertion of shuttles **104** into, and/or removal of the shuttles **104** from, the interior **114** of the kiln housing **102**. The shuttles **104** are configured to carry unfired bodies into the interior **114** of the kiln housing **102** and carry fired bodies out of the interior **114** of the kiln housing **102** (e.g., through the front door **108**). In certain embodiments, the kiln housing **102** includes a back door (as well as a front door **108**).

(22) The shuttle kiln **100** includes a firing system **116** to heat the kiln cavity **138**. The firing system **116** includes a plurality of burners **118** that extend through the left sidewall **110**A and right sidewall **110**B to heat the kiln cavity **138**. In certain embodiments, the plurality of burners **118** may additionally, or alternatively, extend through the ceiling **112**. The front door **108**, sidewalls **110**, and ceiling **112** each include refractory interior surfaces to retain heat produced by the plurality of burners **118** within the kiln cavity **138**. The plurality of burners **118** produce hot gas (which may also be referred to herein as flue gas) in the kiln cavity **138**.

(23) Referring to FIGS. **1**B and **1**C, the shuttle kiln **100** includes an exhaust system **120** to exhaust the hot gas (e.g., flue gas) from the kiln cavity **138**. The exhaust system **120** includes a plurality of flue risers **122** extending upward from a top surface of the floor **106** of the kiln housing **102**, with the plurality of flue risers **122** being in fluid communication with a plurality of flue channels **124** arranged below a top surface of the floor **106**. The flue risers **122** include a first plurality of flue risers **122**A in fluid communication with a first flue channel **124**A (proximate the left sidewall **110**A), a second plurality of flue risers **122**B in fluid communication with a second flue channel **124**B, and a third plurality of flue risers **122**C in fluid communication with a third flue channel **124**C (proximate the right sidewall **110**B). The second plurality of flue risers **122**B and the second flue channel **124**B are laterally positioned between the first and third plurality of flue risers **122**A, **122**C and the first and third flue channels **124**A, **124**C. In certain embodiments, fewer or more flue risers **122** and/or flue channels **124** may be used. As shown in FIG. **1**C, the flue channels **124** each lead to a header duct **127** that is arranged to collect fluid gas and supply the flue gas to a fan inlet duct **125**.

(24) An exhaust fan **126** associated with the kiln housing **102** receives flue gas supplied from the flue channels **124** to the fan inlet duct **125**. The exhaust fan **126** pulls flue gas from the kiln cavity **138** through the flue risers **122**, the flue channels **124**, the header duct **127**, and the fan inlet duct **125**. As illustrated, the exhaust fan **126** may be positioned proximate to the second flue channel **124**B and proximate to the back sidewall **110**C. In certain embodiments, additional exhaust fans **126** may be used. Further, in certain embodiments, one or more exhaust fans may be positioned proximate to the first flue channel **124**A and/or the third flue channel **124**C. In each flue channel **124**A-**124**C, individual flue risers **122** are arranged at different distances relative to the exhaust fan

126. For example, in each flue channel **124**A-**124**C the respective first flue riser **122**A-**1**, **122**B-**1**, **122**C-**1** is closer to the exhaust fan **126** than the respective second flue riser **122**A-**2**, **122**B-**2**, **122**C-**2**, etc.
(25) Referring to FIGS. **1**A and **1**D, each shuttle **104** is configured to carry furniture **132** positioned on the shuttle **104**. In certain embodiments, the first shuttle **104**A carries first furniture **132**A, the second shuttle **104**B carries second furniture **132**B, and the third shuttle **104**C carries third furniture **132**C. The furniture **132** defines a plurality of support surfaces **134** configured to support a plurality of bodies **136** (e.g., unfired bodies prior to firing, fired bodies after firing, etc.). In certain embodiments, the furniture **132** may resemble shelving units, with upstanding columns or posts supporting multiple shelf-like support surfaces **134** arranged at different heights.
(26) Each shuttle **104** includes a plurality of exhaust shafts **140** (which may also be referred to herein as offtakes) that extend from the top **128** to the bottom **130** of the shuttles **104**. The exhaust shafts **140** extend through the shuttle **104** to exhaust hot gas from the kiln cavity **138** above the shuttle **104** to the flue risers **122** below the shuttle **104**. When the shuttle **104** is positioned within the interior **114** of the kiln housing **102**, each exhaust shaft **140** is arranged above and in fluid communication with a respective one of the plurality of flue risers **122**, and each exhaust shaft **140** is vertically aligned with at least a portion of one of the plurality of flue risers **122**. In other words, when the shuttle **104** is positioned within the interior **114** of the kiln housing **102**, at least a portion of each flue riser **122** is arranged below a respective exhaust shaft of the shuttle **104**. In certain embodiments, the first shuttle **104**A includes a first plurality of exhaust shafts **140** that align with the first plurality of flue risers **122**A (which are in fluid communication with the first flue channel **124**A), the second shuttle **104**B includes a second plurality of exhaust shafts **140** that align with the second plurality of flue risers **122**B (which are in fluid communication with the second flue channel **124**B), and the third shuttle **104**C includes a third plurality of exhaust shafts **140** that align with the third plurality of flue risers **122**C (which are in fluid communication with the third flue channel **124**C). In certain embodiments, exhaust shafts of multiple shuttles **104** (with the shuttles arrange front to back) may be aligned with flue risers **122** associated with one flue channel **124**. For example, in certain embodiments, an exhaust shaft **140** of a first shuttle **104** may be aligned with a first flue riser **122**A-**1** of the first flue channel **124**A and an exhaust shaft **140** of a second shuttle **104** may be aligned with a seventh flue riser **122**A-**7** of the first flue channel **124**A.
(27) The exhaust shafts **140** are vertically aligned with at least portions of the flue risers **122** to place the exhaust shafts **140** in fluid communication with the flue risers **122**. Restated, at least a portion of each exhaust shaft **140** may be vertically aligned with a respective one of the flue risers **122**. As the shuttle **104** is movable relative to the floor **106** of the kiln housing **102** (and relative to the flue risers **122**), the exhaust shafts **140** are not directly attached to the flue risers **122**. The exhaust shafts **140** each include an inlet port **143** at the top **128** of the shuttle **104**, and an outlet port **144** at the bottom **130** of the shuttle **104**. In each instance, the outlet port **144** is arranged below the inlet port **143**. Entrainment gaps **142** are defined between outlet ports **144** of the exhaust shafts **140** (at a bottom of each exhaust shaft **140**) and inlet ports **146** of the flue risers **122** (at a top of each flue riser **122**). In other words, each exhaust shaft **140** is configured to be separated from a corresponding flue riser **122** with an entrainment gap **142** arranged therebetween. As the top **128** of the shuttle **104** has a refractory surface configured to reflect heat upward, cooler gas (e.g., undercar gas or undercar air) in the undercar space **148** beneath the shuttle **104** and above the floor **106** is cooler than the hot gas in the kiln cavity **138** above the shuttle **104**. As flue gas exhausts from the exhaust shaft **140** to the flue riser **122**, cooler gas is drawn through the entrainment gap **142** into the flue riser **122**, due to suction generated by the exhaust fan **126**. The cooler gas in the undercar space **148** mixes with and cools the hot gas entering the flue channel **124**. In certain embodiments, the exhaust fan **126** is configured to handle gas at a maximum operating temperature, and the cooler gas pulled through the entrainment gap **142** is used to cool the hot gas from the exhaust shaft **140** to a temperature below the maximum operating temperature. The temperature of the gas inside

the flue channel **124** is lower than the temperature of the hot gas in the exhaust shafts **140** due to the addition of cooler gas through the entrainment gap **142**.

(28) Referring to FIG. **1**C, the position of the exhaust fan **126** relative to the flue risers **122** and/or relative to the flue channels **124** is asymmetric. The exhaust fan **126** is closer to the first flue riser **122**A-**1** than the second flue riser **122**A-**2**. Additionally, the exhaust fan **126** is closer to the second flue channel **124**B than to each of the first flue channel **124**A and the third flue channel **124**C. If the exhaust shafts **140** and/or flue risers **122** all have the same volume (e.g., height and width) relative to one another, this can create non-uniform flow of flue gas through the exhaust shafts **140**. In other words, the first flue riser **122**A-**1** is closer to the exhaust fan **126** than the second flue riser **122**A-**2**. As a result, backpressure at the first exhaust shaft **140-1** (in communication with the first flue riser **122**A-**1**) is lower than the second exhaust shaft **140-2** (in communication with the second flue riser **122**A-**2**). Differences in backpressure create non-uniform flow of the cooler gas into the flue risers **122**. As the cooler gas beneath the shuttle **104** is colder than the hot gas above the shuttle **104**, this can create non-uniform temperatures within the kiln cavity **138**. In certain embodiments, multiple exhaust fans **126** may be used (e.g., one for each flue channel **124**), which may help reduce (but not eliminate) the flow asymmetry. However, multiple exhaust fans **126** may not be practical, due to increased cost in producing and/or operating the shuttle kiln **100**.

(29) FIGS. **2**A-**2**C are views of embodiments of the shuttle kiln **100** with flue risers **122** of the kiln housing **102** and/or exhaust shafts **140** of the shuttle **104** including different volumes (e.g., height and/or cross-sectional area, etc.) and/or different entrainment gaps **142**. A sum of a first riser volume of a first flue riser **122-1** (closer to the exhaust fan **126**) and a first shaft volume of a first exhaust shaft **140-1** (closer to the exhaust fan **126**) is less than a sum of a second flue riser volume **122-2** (farther from the exhaust fan **126**) and a second shaft volume of the second exhaust shaft **140-2** (farther from the exhaust fan **126**). Providing exhausts (i.e., flue risers **122** and/or exhaust shafts **140**) with different characteristics (e.g., sizes) may at least partially mitigate backpressure differences through different exhaust flow paths, thereby providing more uniform flow from the exhaust shafts **140** and concomitantly provide more uniform temperature within the kiln cavity **138**. In certain embodiments, the volume of each flue riser **122** increases from the first flue riser **122-1** to the seventh flue riser **122-7**, the size of the entrainment gap **142** decreases from the first entrainment gap **142-1** to the seventh entrainment gap **142-7**, and/or the volume of each exhaust shaft **140** increases from the first exhaust shaft **140-1** to the seventh exhaust shaft **140-7**. As flue gas exhausts from each exhaust shaft **140** to a corresponding flue riser **122**, cooler gas is pulled through the entrainment gap **142**. The amount of cooler gas supplied to each flue riser **122** may depend on the size of the entrainment gaps **142** and/or size of the volumes (e.g., height and/or cross-sectional area, etc.) of the exhaust shafts **140** and/or flue risers **122**.

(30) The amount of cooler gas (e.g., undercar gas, undercar air) drawn through the entrainment gaps **142** from the undercar space **148** beneath the shuttle **104** that is mixed with the hot gas from the kiln cavity **138** above the shuttle **104** affects the temperature and flammability of flue gas in the flue channel **124**. The shuttle kiln **100** disclosed herein may provide more control over exhaust flow uniformity, gas temperature in the flue channel **124**, gas flammability in the flue channel **124**, and/or scavenging efficiency of the gas from the kiln housing **102**. In certain embodiments, an exhaust configuration disclosed herein may be achieved solely by adjusting dimensions (e.g., height, width, volume, etc.) of flue risers **122** of a shuttle kiln **100**, thereby enabling the benefits described herein to be achieved with interchangeable (e.g., identical) shuttles **104** placed at any position within a kiln housing **102**. In certain embodiments, an existing shuttle kiln may be retrofitted with minimal hardware changes to include one or more exhaust configurations as disclosed herein.

(31) FIG. **2**A illustrates flue risers **122** including different volumes defined at least partly by different heights and entrainment gaps **142**. The height A of each exhaust shaft **140** is uniform. However, the height B differs for different flue risers **122** and/or the depth C for different

entrainment gaps **142** are different. The first flue riser **122-1** closest to the exhaust fan **126** has a first volume defined in part by a first height B**1**, which is the smallest height of the flue risers **122**. Similarly, a depth C**1** of the first entrainment gap **142-1** between the first flue riser **122-1** and the first exhaust shaft **140-1** is the largest among the multiple entrainment gaps **142**. The seventh flue riser **122-7** farthest from the exhaust fan **126** has a seventh volume defined in part by a seventh height B**7**, which is the largest height of the flue risers **122**. Similarly, a depth C**7** of the seventh entrainment gap **142-7** between the seventh flue riser **122-7** and the seventh exhaust shaft **140-7** is the smallest among the multiple entrainment gaps **142**. Accordingly, the height of each flue riser **122** increases from the first flue riser **122-1** to the seventh flue riser **122-7**, and/or the size of the entrainment gap **142** decreases from the first entrainment gap **142-1** to the seventh entrainment gap **142-7**.

(32) In such a configuration, the shuttles **104** do not require modification. As a result, the design can easily be retrofitted to existing shuttles kilns **100** without major modifications. Although the heights A of the exhaust shafts **140** are uniform, in certain embodiments, the heights A of the exhaust shafts **140** could be different in addition to, or instead of, providing flue risers **122** of different heights B. In this case, the heights A of the exhaust shafts **140** would increase from the first exhaust shaft **140-1** to the seventh exhaust shaft **140-7**.

(33) FIG. **2**B illustrates flue risers **122** including different volumes defined at least partly by different cross-sectional areas (e.g., as a function of differing width). The width D of each exhaust shaft **140** (and/or each outlet port **144**) is uniform. However, the width E of each flue riser **122** (and/or each inlet port **146**) differs relative to one another. The first flue riser **122-1** closest to the exhaust fan **126** has a first volume defined in part by a first width E**1**, which is the smallest width of the flue risers **122**. The seventh flue riser **122-7** farthest from the exhaust fan **126** has a seventh volume defined in part by a seventh width E**7**, which is the largest width of the flue risers **122**. Accordingly, the size of each flue riser **122** increases from the first flue riser **122-1** to the seventh flue riser **122-7**.

(34) FIG. **2**C illustrates the exhaust shafts **140** include different volumes defined at least partly by different sized cross-sectional areas (as a function of differing width). The width E′ of the flue risers **122** (and/or inlet port **146**) are uniform. The width D′ (and/or outlet port **144**) of the exhaust shafts **140** are different. The first exhaust shaft **140-1** closest to the exhaust fan **126** has a first volume defined in part by a first width D**1**, which is the smallest width of the exhaust shafts **140**. The seventh exhaust shaft **140-7** farthest from the exhaust fan **126** has a seventh volume defined in part by a seventh width D**7**′, which is the largest width of the exhaust shafts **140**. Accordingly, the size of each exhaust shaft **140** increases from the first exhaust shaft **140-1** to the seventh exhaust shaft **140-7**.

(35) It is noted that the volume of the exhaust shafts **140** and/or the flue risers **122** can be varied as a function of height, cross-sectional area (e.g., width), and/or depth of the entrainment gap **142**, individually or in combination. In other words, the features of FIGS. **2**A-**2**C are compatible with and may be combined with one another. In certain embodiments, the cross-sectional area of each flue riser **122** is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2 and/or the cross-sectional area of each exhaust shaft **140** is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2.

(36) FIGS. **3**A-**3**D and FIG. **4** illustrate the effects of increasing the size of the entrainment gaps **142** between exhaust shafts **140** of the shuttle **104** and flue risers of the kiln housing **102**. In certain embodiments, extreme scenarios were considered, in which the kiln cavity **138** had a temperature of 1400° C., 5 Pa, and/or 3% oxygen concentration, an undercar space **148** had a temperature of 50° C., 0 Pa, and/or 23% oxygen concentration, and/or a flue channel **124** pressure of −100 Pa.

(37) FIG. **3**A is a chart illustrating the effect on undercar dilution fraction by increasing the size of an entrainment gap **142** between exhaust shafts **140** of the shuttle **104** and flue risers **122** of the kiln housing **102**. The undercar dilution fraction is the ratio of hot gas (from within the kiln cavity **138**) to cool gas (from undercar space **148**). As shown, as the entrainment gap **142** increases, the

undercar dilution fraction increases for every exhaust shaft **140** (i.e., offtake). A greater entrainment gap **142** means that more cool gas is pulled into the flue risers **122** and flue channel **124**. It is further noted that increasing the entrainment gap **142** also increases the overall flow through the flue channel **124**, which thereby increases the operating load on the exhaust fan **126**.

(38) FIG. **3**B is a chart illustrating the effect on temperature by increasing the size of an entrainment gap **142** between exhaust shafts **140** of the shuttle **104** and flue risers **122** of the kiln housing **102**. As shown, as the entrainment gap **142** increases, the temperature decreases for every exhaust shaft **140** (i.e., offtake). A greater entrainment gap **142** means that more cool gas is pulled into the flue risers **122** and flue channel **124**. As noted above, in certain embodiments, these cooler gas temperatures may be necessary for reliable operation of the exhaust fan **126**.

(39) FIG. **3**C is a chart illustrating the effect on flow distribution through shuttle exhaust shafts **140** by increasing the size of an entrainment gap **142** between exhaust shafts **140** of the shuttle **104** and flue risers **122** of the kiln housing **102**. In this chart, flow is normalized such that in an ideal scenario the flow through each exhaust shaft **140** is 1. In this way, a value of 1.1 means 10% more exhaust shaft flow than the expected flow rate. As an example, for a 2″ gap, the flow is 20% lower for exhaust shaft #1, and 20% higher for exhaust shaft #10 (with gradual increases therebetween).

(40) As shown, as the entrainment gap **142** increases, the flow distribution from each of the exhaust shafts **140** (i.e., offtakes) becomes more uniform. Increasing the entrainment gap **142** reduces the transfer of exhaust fan pressure to the exhaust shafts **140**, thereby increasing the uniformity through the exhaust shafts **140**. As a result, for a 4″ gap, the flow rates are 12% lower for exhaust shaft #1 and 12% higher for exhaust shaft #10.

(41) FIG. **3**D is a chart illustrating the effects of increasing the size of an entrainment gap **142** between exhaust shafts **140** of the shuttle **104** and flue risers **122** of the kiln housing **102** on maximum non-uniformity of exhaust shaft **140** gas flow, flue tunnel temperature, and flue tunnel oxygen concentration. As shown, increasing the entrainment gap **142** decreases maximum non-uniformity **300** of gas flow through exhaust shafts **140** and temperature **302** in flue channel **124**, but increases oxygen concentration **304** in flue channel **124**. In certain embodiments, the operating temperature **302** of the exhaust fan **126** must not be above 800° C., which means that the entrainment gap must be at least 2″. In certain embodiments, the oxygen concentration **304** must be below 18% to maintain solvent concentrations within safe lower flammable limits, which means that the entrainment gap must be less than 4″. As a result, a maximum entrainment gap **142** of 4″ may be used to maximize flow uniformity through the flue risers **122** and within the flue channel **124**, or a minimum gap of 2″ may be used to minimize the load on the exhaust fan **126**. However, varying the volume of the exhaust shafts **140**, varying the volume of the flue risers **122** (e.g., as a function of height, cross-sectional area (e.g., width), and/or varying the depth of the entrainment gap **142**, individually or in combination), enables attainment of an optimized solution to provide flow uniformity without undue load on the exhaust fan **126**.

(42) FIG. **4** is a chart depicting flow distribution through offtakes (i.e., exhaust shafts **140**) as a function of offtake number, illustrating increased flow uniformity through shuttle exhaust shafts **140** with entrainment gaps **142** of different sizes. As shown, the presence of differently-sized entrainment gaps **142** provides more uniform flow in comparison to a uniform 3″ entrainment gap **142**. Further, providing differently-sized entrainment gaps **142** increases efficiency while operating within safety limits.

(43) FIG. **5** is a flowchart identifying steps of a method of fabricating at least one fired body **136**. According to step **500**, at least one shuttle **104** carrying at least one unfired body **136** is moved into a kiln housing **102** of a shuttle kiln **100**. The kiln housing **102** includes a first flue riser **122-1** and a second flue riser **122-2**. According to step **502**, a first exhaust shaft **140-1** of the at least one shuttle **104** is arranged above the first flue riser **122-1** and a second exhaust shaft **140-2** of the at least one shuttle **104** is arranged above the second flue riser **122-2**. A sum of a first riser volume of the first flue riser **122-1** and a first shaft volume of the first exhaust shaft **140-1** is greater than a sum of a

second riser volume of the second flue riser **122-2** and a second shaft volume of the second exhaust shaft **140-2**.

(44) According to step **504**, a kiln cavity **138** bounded by the at least one shuttle **104** and the kiln housing **102** is heated to alter the at least one unfired body **136**. According to step **506**, gas from the kiln cavity **138** is exhausted through a first flow path and a second flow path. The first flow path extends through the first exhaust shaft **140-1**, across a first entrainment gap **142-1**, and through the first flue riser **122-1** to a first flue channel **124**. The second flow path extends through the second exhaust shaft **140-2**, across a second entrainment gap **142-2**, and through the second flue riser **122-2** to the first flue channel **124**.

(45) It will be apparent to those skilled in the art that various modifications and variations can be made without departing from the spirit or scope of the invention.

(46) Many modifications and other embodiments of the embodiments set forth herein will come to mind to one skilled in the art to which the embodiments pertain having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the description and claims are not to be limited to the specific embodiments disclosed and that modifications and other embodiments are intended to be included within the scope of the appended claims. It is intended that the embodiments cover the modifications and variations of the embodiments provided they come within the scope of the appended claims and their equivalents. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

Claims

1. A shuttle kiln, comprising: a kiln housing comprising a first flue channel and a first plurality of flue risers in fluid communication with the first flue channel, the first plurality of flue risers comprising a first flue riser defining a first riser volume and a second flue riser defining a second riser volume; at least one shuttle positioned within the kiln housing and defining a first plurality of exhaust shafts comprising a first exhaust shaft defining a first shaft volume and a second exhaust shaft defining a second shaft volume, the first exhaust shaft arranged above and in fluid communication with the first flue riser and separated therefrom by a first entrainment gap, the second exhaust shaft arranged above and in fluid communication with the second flue riser and separated therefrom by a second entrainment gap; and wherein a sum of the first riser volume and the first shaft volume is less than a sum of the second riser volume and the second shaft volume and the first entrainment gap is larger than the second entrainment gap.
2. The shuttle kiln of claim 1, wherein: the kiln housing comprises a floor, a door, sidewalls, and a ceiling bounding an interior; the first flue channel is arranged below a top surface of the floor; and the first plurality of flue risers extend above the top surface of the floor.
3. The shuttle kiln of claim 2, wherein: the kiln housing further comprises a second flue channel and a second plurality of flue risers in fluid communication with the second flue channel.
4. The shuttle kiln of claim 1, wherein: the kiln housing further comprises an exhaust fan in fluid communication with the first flue channel; and the first flue riser is closer than the second flue riser to the exhaust fan.
5. The shuttle kiln of claim 1, wherein the at least one shuttle comprises a plurality of shuttles.
6. The shuttle kiln of claim 5, wherein a first shuttle of the plurality of shuttles comprises the first exhaust shaft, and a second shuttle of the plurality of shuttles comprises the second exhaust shaft.
7. The shuttle kiln of claim 1, wherein: the first plurality of flue risers further comprises a third flue riser defining a third riser volume; the first plurality of exhaust shafts further comprises a third exhaust shaft defining a third shaft volume; the third exhaust shaft is arranged above and in fluid communication with the third flue riser and separated from the third flue riser by a third entrainment gap; and a sum of the second riser volume and the second shaft volume is less than a

sum of the third riser volume and the third shaft volume.
8. The shuttle kiln of claim 7, wherein the kiln housing further comprises an exhaust fan in fluid communication with the first flue channel, the first flue riser is closer than the second flue riser to the exhaust fan, and the second flue riser is positioned between the first flue riser and the third flue riser.
9. The shuttle kiln of claim 8, wherein the second entrainment gap is larger than the third entrainment gap.
10. The shuttle kiln of claim 1, wherein: at least a portion of the first exhaust shaft is vertically aligned with the first flue riser; and at least a portion of the second exhaust shaft is vertically aligned with the second flue riser.
11. The shuttle kiln of claim 1, wherein: a cross-sectional area of the first flue riser is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2; and a cross-sectional area of the first exhaust shaft is in a range of from 0.09 m.sup.2 to 0.21 m.sup.2.
12. The shuttle kiln of claim 1, wherein a height of the first flue riser is less than a height of the second flue riser.
13. The shuttle kiln of claim 1, wherein a height of the first exhaust shaft is less than a height of the second exhaust shaft.
14. The shuttle kiln of claim 1, wherein: a height of the first flue riser is less than a height of the second flue riser; and a height of the first exhaust shaft is less than a height of the second exhaust shaft.
15. The shuttle kiln of claim 1, wherein a cross-sectional area of the first flue riser is less than a cross-sectional area of the second flue riser.
16. The shuttle kiln of claim 1, wherein a cross-sectional area of the first exhaust shaft is less than a cross-sectional area of the second exhaust shaft.
17. The shuttle kiln of claim 1, wherein a cross-sectional area of the first flue riser is less than a cross-sectional area of the second flue riser and a cross-sectional area of the first exhaust shaft is less than a cross-sectional area of the second exhaust shaft.
18. A shuttle kiln, comprising: a kiln housing comprising a flue channel and a plurality of flue risers in fluidic communication with the flue channel, the plurality of flue risers comprising a first flue riser defining a first riser volume and configured to be arranged below a first exhaust shaft of a shuttle when the shuttle is positioned within the kiln housing, and a second flue riser defining a second riser volume that differs from the first riser volume, the second flue riser configured to be arranged below a second exhaust shaft of the shuttle when the shuttle is positioned within the kiln housing; and when the shuttle is positioned within the kiln housing, the first flue riser is separated from the first exhaust shaft by a first entrainment gap and the second flue riser is separated from the second exhaust shaft by a second entrainment gap that differs in size from the first entrainment gap.
19. A shuttle kiln, comprising: at least one shuttle configured to be removably positioned within a kiln housing, the at least one shuttle defining a plurality of exhaust shafts comprising a first exhaust shaft defining a first shaft volume and a second exhaust shaft defining a second shaft volume that differs from the first shaft volume, the first exhaust shaft configured to be arranged above a first flue riser of the kiln housing and separated therefrom by a first entrainment gap when the at least one shuttle is positioned within the kiln housing, the second exhaust shaft configured to be arranged above a second flue riser of the kiln housing and separated therefrom by a second entrainment gap that differs in size from the first entrainment gap when the at least one shuttle is positioned within the kiln housing.