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(54) OPTICAL SENSORS FOR COMBUSTION CONTROL

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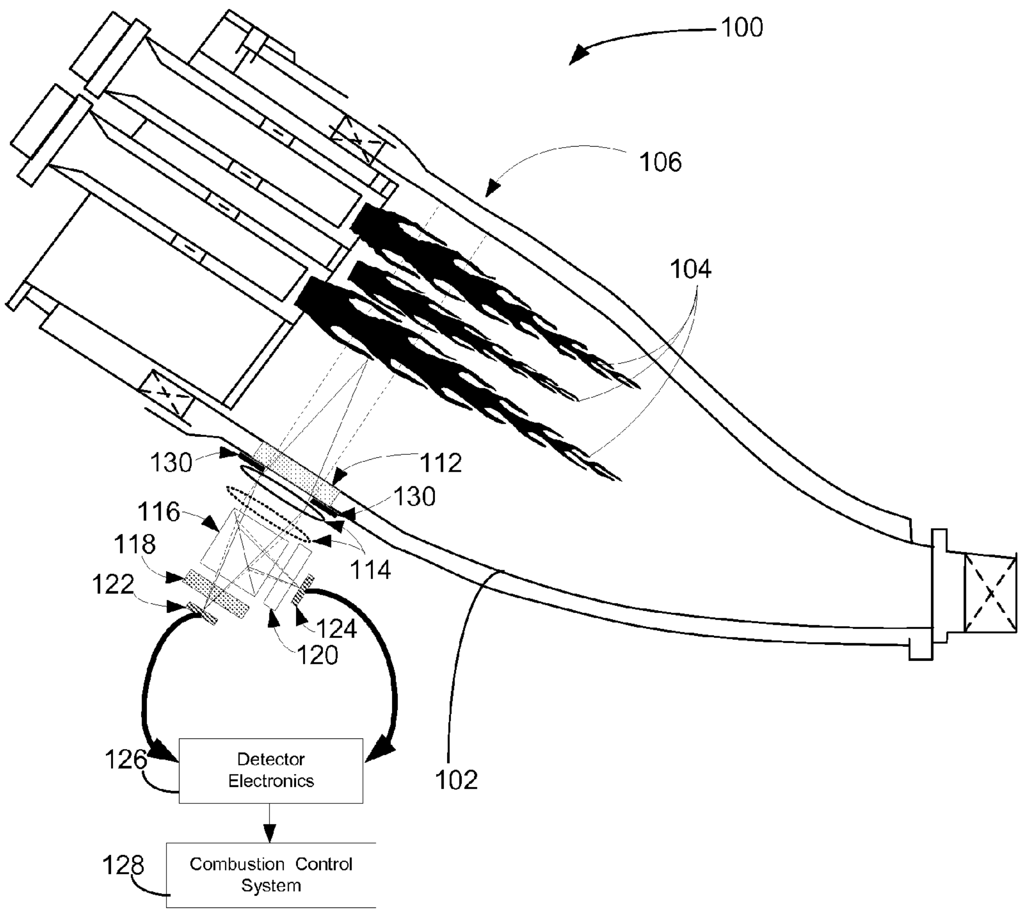
(57) **ABSTRACT**

Certain embodiments of the invention may include systems and methods for providing optical sensors for combustion control. According to an example embodiment of the invention, a method for controlling combustion parameters associated with a gas turbine combustor is provided. The method can include providing at least one optical path adjacent to a flame region in the combustor, detecting at least a portion of the light emission from the flame region within the at least one optical path, and controlling at least one of the combustion parameters based in part on the detected light emission.



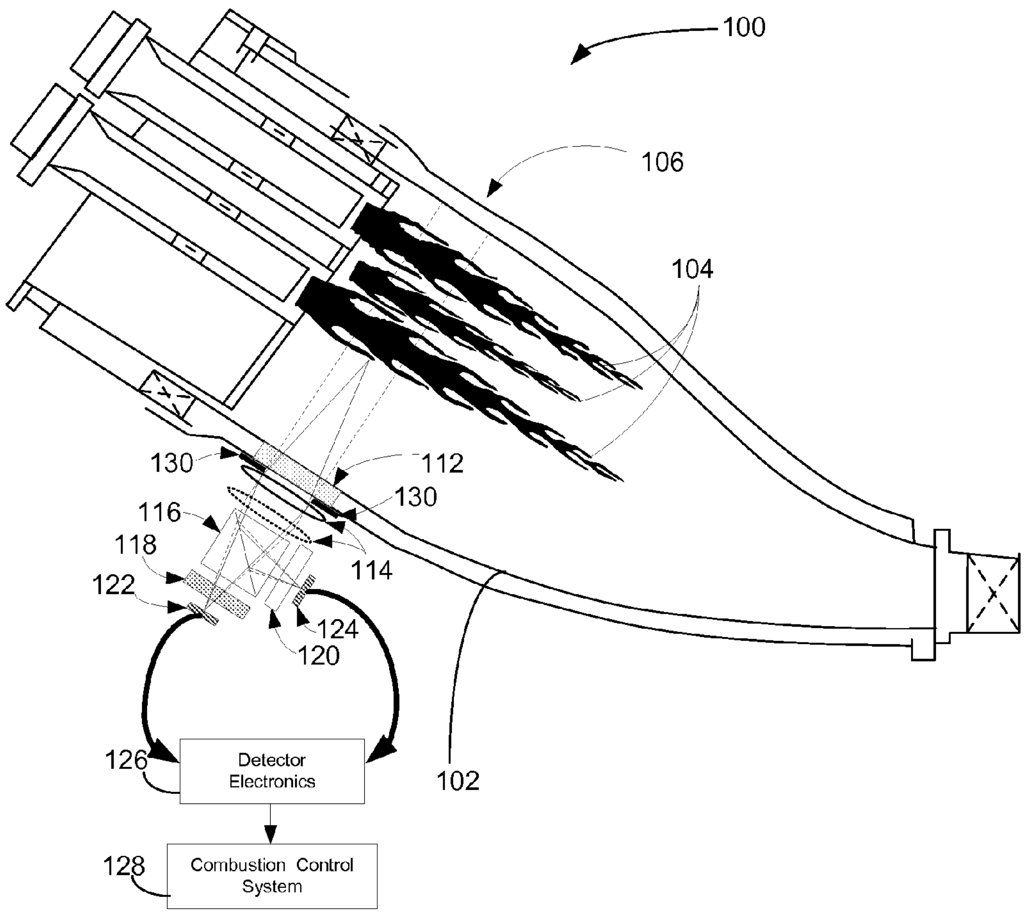

100
106
104
130
112
130
116
118
114
122
124
120
126
Detector Electronics
102
128
Combustion Control System

FIG. 1

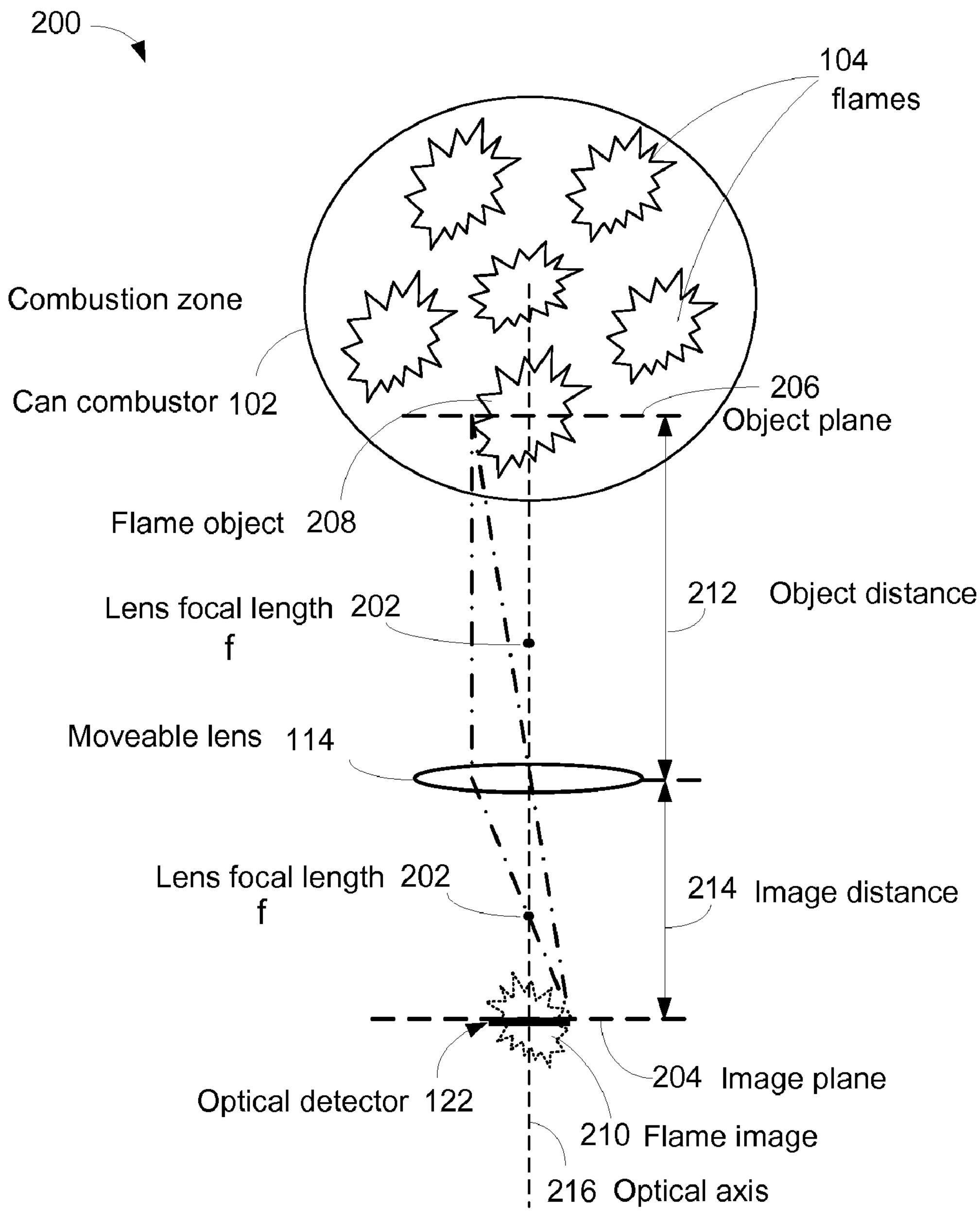

200
104
flames
Combustion zone
Can combustor 102
206
Object plane
Flame object 208
212 Object distance
Lens focal length 202
f
Moveable lens 114
Lens focal length 202
f
214 Image distance
Optical detector 122
204 Image plane
210 Flame image
216 Optical axis

FIG. 2

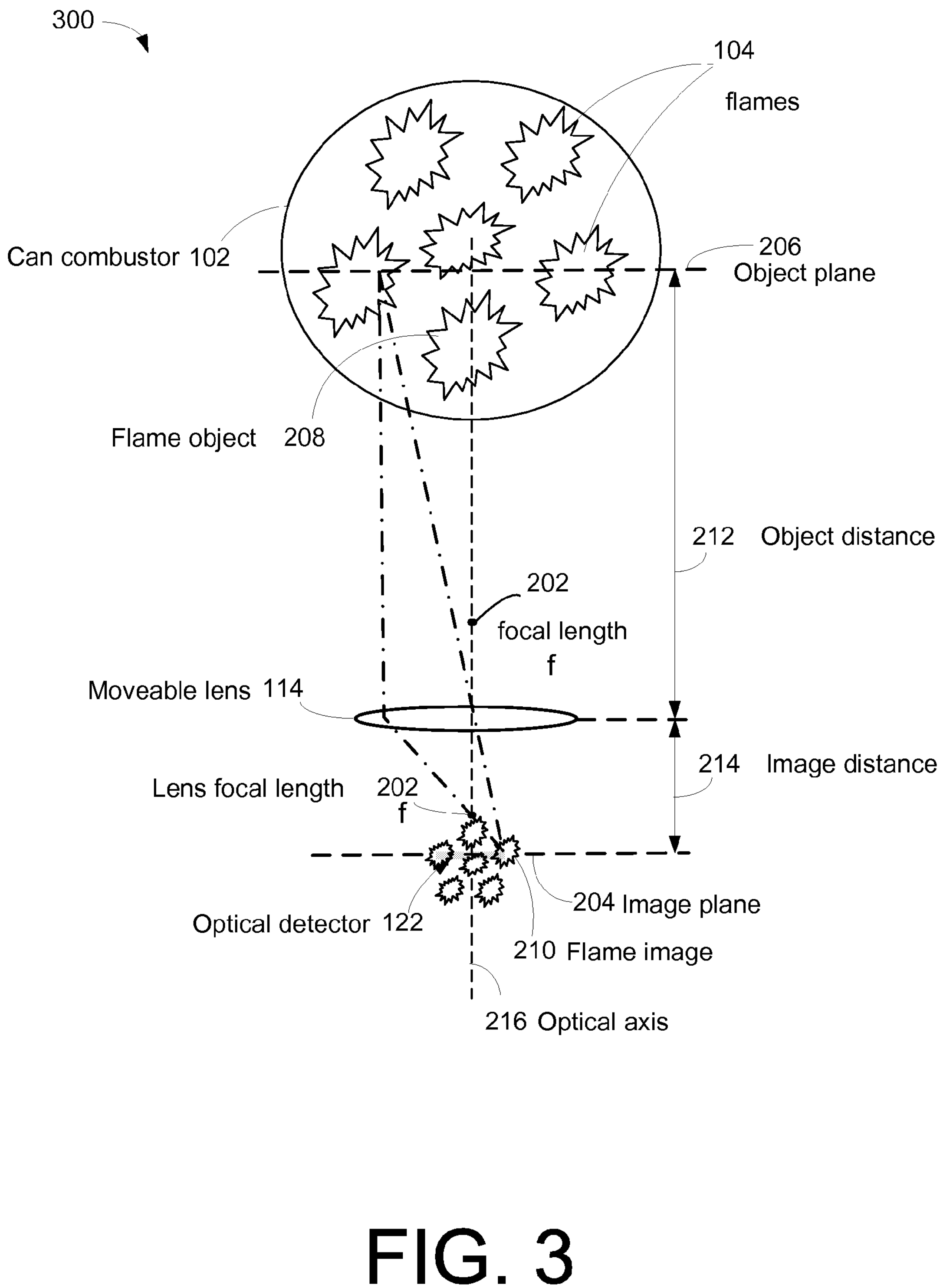

300
104
flames
Can combustor 102
206
Object plane
Flame object 208
212 Object distance
202
focal length
f
Moveable lens 114
214 Image distance
Lens focal length 202
f
204 Image plane
Optical detector 122
210 Flame image
216 Optical axis

FIG. 3

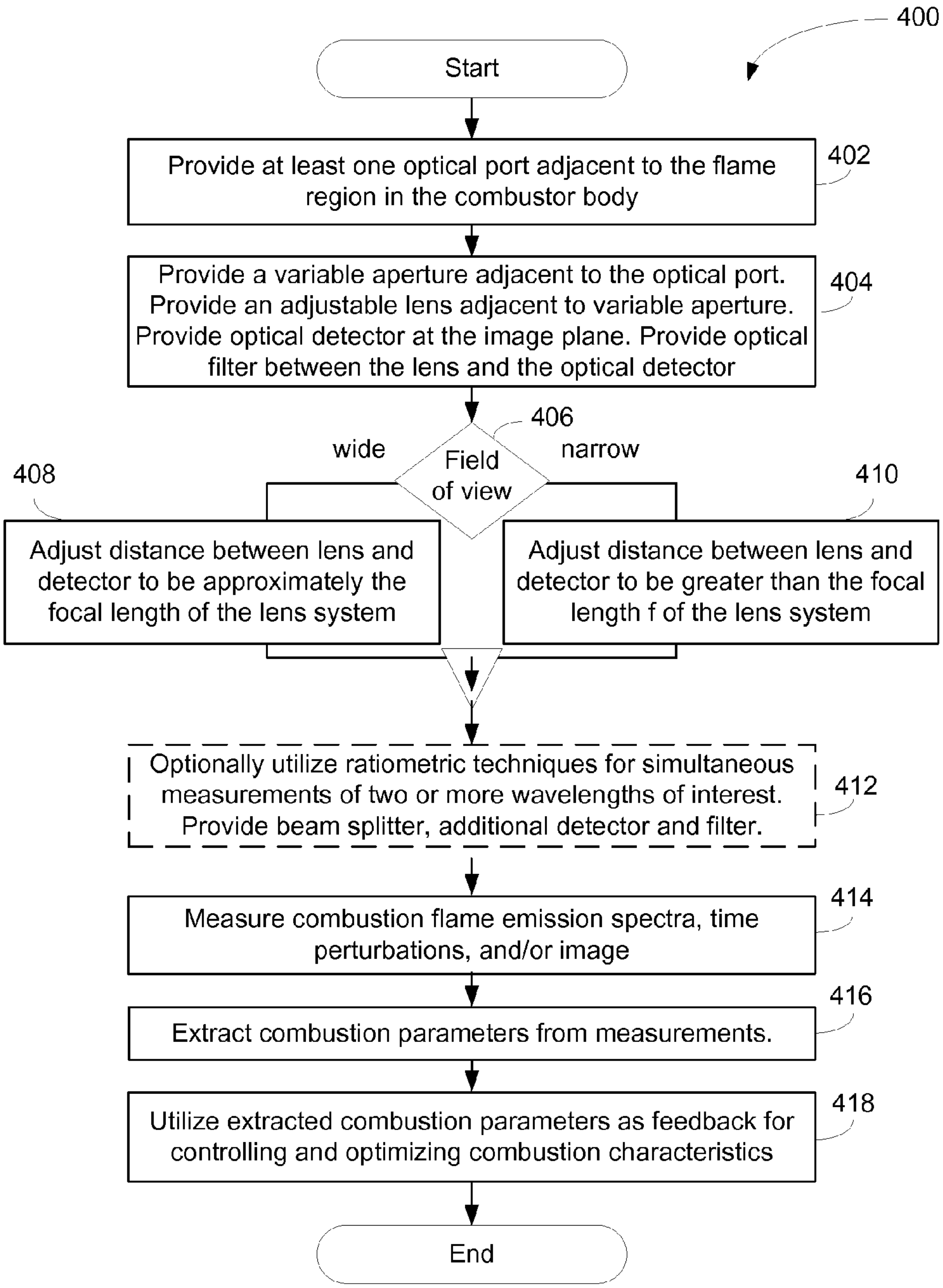

400
Start
Provide at least one optical port adjacent to the flame region in the combustor body
402
Provide a variable aperture adjacent to the optical port. Provide an adjustable lens adjacent to variable aperture. Provide optical detector at the image plane. Provide optical filter between the lens and the optical detector
404
406
Field of view
wide
narrow
408
Adjust distance between lens and detector to be approximately the focal length of the lens system
410
Adjust distance between lens and detector to be greater than the focal length f of the lens system
Optionally utilize ratiometric techniques for simultaneous measurements of two or more wavelengths of interest. Provide beam splitter, additional detector and filter.
412
Measure combustion flame emission spectra, time perturbations, and/or image
414
Extract combustion parameters from measurements.
416
Utilize extracted combustion parameters as feedback for controlling and optimizing combustion characteristics
418
End

FIG. 4

OPTICAL SENSORS FOR COMBUSTION CONTROL

FIELD OF THE INVENTION

[0001] This invention generally relates to sensors, and more particularly relates to optical sensors for combustion control.

BACKGROUND OF THE INVENTION

[0002] Modern industrial gas turbines are required to convert energy at a high efficiency while producing minimum polluting emissions. But these two requirements are at odds with each other since higher efficiencies are generally achieved by increasing overall gas temperature in the combustion chambers, while pollutants such as nitrogen oxide are typically reduced by lowering the maximum gas temperature. The maximum gas temperature can be reduced by maintaining a lean fuel-to-air ratio in the combustion chamber, but if the fuel/air mixture is too lean, incomplete fuel combustion can produce excessive carbon monoxide and unburned hydrocarbons. Therefore, the temperature in the reaction zone must be adequate to support complete combustion.

[0003] To balance the conflicting needs for increased efficiency and reduced emissions, extremely precise control is required to adjust the fuel/air mixture in the reaction zones of the combustors. Systems have been proposed for controlling the fuel/air mixture by monitoring various combustion parameters, and using the measured parameters as input to control the fuel system. For example, one conventional system includes a control system where fuel flow rates, pressure levels, and discharge exhaust temperature distributions are utilized as input for setting fuel trim control valves.

[0004] Other techniques for controlling combustion dynamics include measuring light emission from the combustion burner flame, and using the measured signal to control certain combustion parameters. For example, one conventional system uses a closed loop feedback system employing a silicon carbide photodiode to sense the combustion flame temperature via the measurement of ultraviolet radiation intensity. The sensed ultraviolet radiation is utilized to control the fuel/air ratio of the fuel mixture to keep the temperature of the flame below a predetermined level associated with a desired low level of nitrogen oxides.

[0005] Other conventional systems can use optical fibers for gathering and transmitting light from a combustion region to detectors. Yet other conventional systems can use a video camera to capture images of the flame primarily for monitoring the presence or absence of a flame.

[0006] A need remains for improved systems and methods for providing optical sensors.

BRIEF SUMMARY OF THE INVENTION

[0007] Some or all of the above needs may be addressed by certain embodiments of the invention. Certain embodiments of the invention may include systems and methods for providing optical sensors for combustion control.

[0008] According to an example embodiment of the invention, a method for controlling combustion parameters associated with a gas turbine combustor is provided. The method can include providing at least one optical path adjacent to a flame region in the combustor, detecting at least a portion of the light emission from the flame region within the at least one optical path, and controlling at least one of the combustion parameters based in part on the detected light emission.

[0009] According to another example embodiment, a system for controlling combustion parameters associated with a gas turbine combustor is provided. The system can include at least one optical port adjacent to a flame region in the combustor, one or more photodetectors in communication with the at least one optical port operable to detect at least a portion of light emission from the flame region, and at least one control device operable to control one or more combustion parameters based at least in part on one or more signals from the one or more photo detectors.

[0010] According to another example embodiment, a gas turbine is provided. The gas turbine can include a combustor, at least one optical port adjacent to a flame region in the combustor, one or more photodetectors in communication with the at least one optical port, and operable to detect at least a portion of light emission from the flame region, and at least one control device operable to control one or more combustion parameters based at least in part on one or more signals from the one or more photodetectors.

[0011] Other embodiments and aspects of the invention are described in detail herein and are considered a part of the claimed invention. Other embodiments and aspects can be understood with reference to the description and to the drawings.

BRIEF DESCRIPTION OF THE FIGURES

[0012] Reference will now be made to the accompanying drawings, which are not necessarily drawn to scale, and wherein:

[0013] FIG. **1** depicts an illustrative optical sensor in communication with the flame region of a turbine combustor, according to an example embodiment of the invention.

[0014] FIG. **2** illustrates the optical sensor imaging system, in accordance with a narrow field-of-view example embodiment of the invention, where the lens is positioned to collect light primarily from one flame region of the combustor.

[0015] FIG. **3** illustrates the optical sensor imaging system, in accordance with a wide field-of-view example embodiment of the invention, where the lens is positioned to collect light from multiple flame regions of the combustor.

[0016] FIG. **4** is an example method flowchart for measuring flame combustion parameters, according to an example embodiment of the invention.

DETAILED DESCRIPTION OF THE INVENTION

[0017] Embodiments of the invention will be described more fully hereinafter with reference to the accompanying drawings, in which embodiments of the invention are shown. This invention may, however, be embodied in many different forms and should not be construed as limited to the embodiments set forth herein; rather, these embodiments are provided so that this disclosure will be thorough and complete, and will fully convey the scope of the invention to those skilled in the art. Like numbers refer to like elements throughout.

[0018] An embodiment of the invention may enable combustion parameters to be measured in a turbine combustor by selectively detecting spatial, temporal, and/or spectral light emissions from combustor burner flames. According to embodiments of the invention, the measured combustion parameters may in turn be utilized to control various parameters of the combustor, including, but not limited to fuel flow rates, fuel/air ratios, and fuel flow distributions to optimize nitrous oxide emissions, dynamic pressure oscillations, and fuel efficiencies.

[0019] According to example embodiments of the invention, chemiluminescence emissions from one or more flames in a combustor may be monitored using optical detectors. The light energy emissions may be spectrally filtered to identify the partial contribution of the total light emission from specific excited-state species such as OH*, CH*, C2* and CO2*. Ratios of these measured signals may be correlated to the fuel-to-air ratio, heat release rate, and temperature. According to example embodiments, the time-resolved output from optical detectors may be analyzed to reveal unsteady phenomena associated with the combustion, and may be used to indicate combustion-acoustic oscillations (combustion dynamics), incipient flame blowout, and flame extinction. In addition, the output signals may be used as feedback for use in a closed-loop combustion control system. Various sensor options and configurations for combustion control applications, according to embodiments of the invention, will now be described with reference to the accompanying figures.

[0020] FIG. **1** illustrates an example can combustor with a flame sensor and control system **100** for controlling combustion parameters associated with a gas turbine combustor, according to an example embodiment of the invention. The flame sensor components may be placed or mounted adjacent to the can combustor **102** and may selectively detect light emission from the flames **104** within the can combustor **102** near the flame region **106** of the can combustor **102**. The light emission from at least a portion of the burner flames **104** may pass through an optical port **112** in the side wall of the can combustor **102** and may be focused, imaged, or transformed by one or more lenses **114**. According to example embodiments of the invention, the one or more lenses **114** may be moveable in order to vary the optical system field of view, as will be discussed in reference to FIGS. **2** and **3** below.

[0021] According to an example embodiment of the invention, and with continued reference to FIG. **1**, an aperture **130** may be placed adjacent to the lens **114** in order to control the intensity of the light from the flames **104**. The aperture **130** may also be utilized for adjusting the optical system depth of field. According to an example embodiment of the invention, a portion of the spectrum of the light from the burner flames **104** may be filtered before reaching the first optical detector **122** by a first optical filter **118** to aid in identifying the partial contribution of the total light emission from specific excited-state species that produce optical radiation in narrow-band portions of the optical spectrum. According to example embodiments of the invention, the optical detector **122** may be selected for its response within wavelength spectra windows of interest. For example, a silicon carbide (SiC) photo detector may be selected because of its sensitivity to the ultra violet portion of the wavelength spectrum, and therefore, may be suitable for sensing the emission from the excited state OH* radical in the 300 nm wavelength range. The OH* emission can be a primary indicator of chemical reaction intensity (heat release) and therefore, wavelengths in the 300 nm region may be used to determine gas temperature. According to another embodiment, a silicon (Si) photo detector may be utilized for monitoring the emission from chemical species in the 400 to 1000 nm spectrum including CH* (about 430 nm) and C2* (about 514 nm). These flame radicals have been found to be proportional to heat release and local fuel-to-air ratio in pre-mixed flames.

[0022] According to an example embodiment of the invention, a beam splitter **116** may be utilized to redirect a portion of the light emission through a second optical filter **120** to a second optical detector **124**. The spectral transmission characteristics of the first optical filter **118** and the second optical filter **120** may be selected such that specific excited-state species ratios may be measured with increased accuracy while partially eliminating interfering background emissions from excited-state species that may be of less interest. According to an example embodiment, the first optical filter **118** and the second optical filter **120** may be interchangeable, fixed, or tunable. According to an example embodiment, the optical filters **118 120** may be narrowband filters. Fabry-Perot or dichroic optical filters are examples of the types of filters that may be utilized for transmitting certain wavelength bands while attenuating or reflecting out-of-band wavelengths.

[0023] Also shown in FIG. **1** are blocks representing the detector electronics **126** and the combustion control system **128**. According to an example embodiment, the detector electronics **126** may be operable to condition, amplify, filter, and process the signals from the optical detectors **122**, **124**. The detector electronics **126** may also provide control for adjusting the diameter of the aperture **130** and/or for positioning the lens **114**. The output signal from the detector electronics may be used as a control signal for the combustion control system **128**. For example, according to an embodiment of the invention, the measured ratio of CH to OH chemiluminescence (CH*/OH*) may be utilized as feedback in the combustion control system **128**, and may provide a control to dynamically adjust the fuel/air ratio.

[0024] FIG. **2** depicts an end view of combustion zone and a narrow field-of-view flame imaging and sensor system **200**, according to an example embodiment of the invention. For clarity, the beam splitter **116**, second optical detector **124**, and the first and second optical filters **118**, **120** are omitted from this figure. According to an example embodiment, a portion of the light emission from the burner flames **104** may be imaged onto the surface of the optical detector **122**. In an example embodiment, the flame object **208** may be imaged at the image plane **204** to produce a flame image **210**. In an example embodiment, the optical detector **122** at the image plane **204** may comprise a single sensing element having a finite sensing area, and therefore, the optical radiation that is imaged onto the sensor area may produce an output signal proportional to the integrated sum of the total optical energy incident on the detector. According to optical imaging theory for thin lenses, the field of view may be determined by a combination of factors including the placement of the lens **114**, the width of the optical detector **122**, the focal length f **202** of the lens **114**, the object distance **212**, and the image distance **214**. The approximate relationship between the object distance d_o **212**, the image distance d_i **214**, and the focal length f of the lens may be expressed as $1/d_o + 1/d_i = 1/f$. The image magnification can be expressed as $M = -d_i/d_o$, where the minus sign indicates that the image is reversed with respect to the optical axis **216**.

[0025] FIG. **2** shows an example narrow field-of-view embodiment where a lens **114**, having a focal length f **202**, is placed in an example first position at an image distance **214** from the image plane **204**, where the image plane **204** is coincident with the surface of the optical detector **122**. In this example configuration, the flame object **208** located at the object plane **206** produces a flame image **210** at the image plane **204**. The example configuration shown will also allow a small portion of the light from the non-imaged burner flames **104** to be incident on the optical detector **122**, but the majority of the output signal produced by the detector will be related to the portion of the imaged flame **210** that falls on the active area of the detector. In an example embodiment of the invention, the detector may be adjustable such that it is able to move along the image plane to enable different burner flame **104** regions to be selected for detecting.

[0026] According to an example embodiment of the invention, a fixed or adjustable aperture (not shown) may be placed adjacent to the detector to limit unwanted portions of the flame image **210** that may otherwise be incident on the optical detector **122**. The fixed or adjustable aperture may move parallel to the image plane **204** to selectively transmit regions of the burner flame image **210** for sensing with the detector, thereby, providing an alternative to moving the detector to enable different burner flame **104** regions to be selected for detecting. According to an example embodiment of the invention, multiple detectors may be utilized in the image plane **204** to simultaneously detect or monitor spatially separated regions of the burner flames **104**.

[0027] FIG. **3** depicts an end view of combustion zone wide field-of-view flame imaging and sensor system **300**, according to an example embodiment of the invention. The beam splitter **116**, second optical detector **124**, and the first and second optical filters **118**, **120** are omitted from this figure for clarity. In this example depiction, the movable lens **114** is positioned closer to the optical detector **122** and image plane **204** as compared to the depiction shown in FIG. **2**. One consequence of moving the lens **114** closer to the optical detector **122** is that the distance between the image plane **204** and the object plane **206** may increase approximately according to the thin lens formula $1/d_o+1/d_i=1/f$. Another consequence of moving the lens **114** closer to the optical detector **122** is that size of the flame image **210** may decrease approximately according to the magnification $M=-d_i/d_o$. Therefore, depending on the geometry of the imaging system, the position of the lens **114**, and the area of the optical detector **122**, the flame image **210** incident on the optical detector **122** may comprise the image of multiple burner flame objects **208**. Thus, by adjusting the position of the moveable lens **114** towards the detector, the imaging system may selectively collect and image light emission from multiple combustor flames **104** (i.e., the wide-field-of-view embodiment as shown in FIG. **3**). Conversely, by adjusting the position of the moveable lens **114** away from the detector, the imaging system may selectively collect and image light emission primarily from a single combustor flame **104** (i.e., the narrow-field-of-view embodiment as shown in FIG. **2**).

[0028] According to example embodiments, the optical detectors **122**, **124** may be selected to measure one- or two-dimensional representations of the primary combustion parameters. For example, optical detectors **122**, **124** may comprise an array, rather than a single sensitive element. Therefore, the arrays may capture flame images over a two-dimensional grid, similar to a digital camera system. Examples of such arrays can include, but are not limited to, charged coupled devices (CCD), complementary metal-oxide semiconductor (CMOS) arrays, and indium gallium arsenide (InGaAs) arrays.

[0029] An example method for measuring flame parameters for use in controlling combustion characteristics will now be described with reference to the flowchart **400** of FIG. **4**. Beginning in block **402** and according to an example embodiment of the invention, at least one optical port such as **112** may be provided in the body of the turbine can combustor such as **102** adjacent to the flame region such as **106**. The optical port may be constructed from high temperature resistant, optically transparent material such as quartz, sapphire, or other suitable materials with low loss and a transmission bandwidth appropriate for the wavelengths of interest. Light emissions from the burner flames such as **104** may be transmitted through the optical port **112** to the remaining optical system, which may reside outside of the can combustor **102** where thermal isolation, cooling, etc., can be used to protect the optics, detectors, and associated electronics and hardware.

[0030] In block **404**, according to an example embodiment of the invention, the optical system may comprise a variable aperture such as **130** adjacent to the optical port such as **112**. The variable aperture **130** may be manually adjusted, or it may be motorized so that the diameter of the aperture opening may be electronically controlled to adjust the total influx of light reaching the optical detectors such as **122**, **124**. The variable aperture **130** may also be used to provide a depth-of-field control for the optical imaging system. According to one example embodiment, the variable aperture **130** may be mounted adjacent to the optical port **112**. The optical imaging system may additionally comprise an adjustable or moveable lens such as **114** or lens system adjacent to the variable aperture **130**, at least one optical detector **122** responsive to at least the portion of the burner flame such as **104** emission spectrum of interest, and at least one optical filter such as **118** in the optical path before the optical detector **122** and operable to selectively transmit a portion of the burner flame **104** emission spectrum to the optical detector **122**.

[0031] Decision block **406** depicts two settings available for the optical imaging system: wide and narrow field-of-view. According to an example embodiment, the binary (wide or narrow) settings may be accomplished by selectively inserting or removing fixed lenses into the appropriate position along the optical path. However, according to another example embodiment, the lens such as **114** may be moveable, and therefore, the field-of-view may also be variable, and may be set as desired at any intermediate setting between the extreme wide and narrow field-of-view settings.

[0032] In block **408**, the optical imaging system may be set to comprise a wide field-of-view, for example, by adjusting the distance between the lens such as **114** and the optical detector such as **122** to be approximately the focal length f **202** of the lens **114** (as depicted in FIG. **3**).

[0033] In block **410**, the optical imaging system may be set to comprise a narrow field-of-view, for example, by adjusting the distance between the lens **114** and the optical detector **122** to be approximately twice the focal length f **202** of the lens **114** (as depicted in FIG. **2**). Physical constraints may limit the actual movement of the lens **114**, therefore, it is to be understood that the invention is not to be limited to the specific embodiments disclosed, and that additional lens methods can be utilized in accordance with embodiments of the invention.

[0034] Block **412** indicates that an optional ratiometric technique may be utilized for simultaneously measuring and relating two or more wavelengths of interest. According to an example embodiment, the ratiometric measurement technique may be achieved by providing a beam splitter **116**, a first optical filter **118**, a first optical detector **122**, a second optical filter **120**, and a second optical detector **124**, as shown in FIG. **1**. In one example embodiment, the ratiometric measurement may be achieved by utilizing the first optical filter **118** and the first optical detector **122** to selectively measure the emission response from one excited species (for example CH* near 425 nm) and simultaneously measuring the response of another excited species (for example, OH* near 310 nm) using the second optical filter **120** and second optical detector **124**. The ratiometric measurement may be achieved, for example, by dividing the response of the CH* by the response of the OH*. The ratio CH*/OH* has been shown to relate to the equivalence ratio (ϕ), which is a universal function related to many combustion characteristics. One other aspect of the ratiometric measurement technique is that background radiation common to each detector may be eliminated, thereby increasing the signal to noise ratio.

[0035] In block **414**, and according to an example embodiment, the combustion flame properties may be measured. The properties may comprise the emission spectra, time perturbations, flame images, or a combination of these properties. A measurement may include both spectral and time varying information. For example, portions of the flame emission spectra may be selected by filtering, and the filtered emission may be incident upon one or more optical detectors **122**, **124** to produce a time varying signal that can be utilized in block **416** to extract combustion parameters from the measurements. The extracted combustion parameters may be used in block **418** to control and optimize the combustion characteristics using other methods in accordance with embodiments of the invention. For example, the extracted combustion parameters may be utilized in a feedback control loop for adjusting the fuel flow, fuel-to-air ratio, fuel distribution among the burners, etc.

[0036] Many modifications and other embodiments of the invention will come to mind to one skilled in the art to which this invention pertains having the benefit of the teachings presented in the foregoing descriptions and the associated drawings. Therefore, it is to be understood that the invention is 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. Although specific terms are employed herein, they are used in a generic and descriptive sense only and not for purposes of limitation.

1. A method for controlling combustion parameters associated with a gas turbine combustor, the method comprising:
- providing at least one optical path adjacent to a flame region in the combustor;
- detecting within the at least one optical path at least a portion of light emission from the flame region; and
- controlling at least one of the combustion parameters based in part on the detected light emission.

2. The method of claim **1**, wherein detecting within the at least one optical path at least a portion of light emission from the flame region comprises selectively filtering the light emission to isolate spectral information associated with the light emission.

3. The method of claim **1**, wherein providing at least one optical path adjacent to a flame region in the combustor comprises providing a lens operable to image at least a portion of the light emission from the flame region.

4. The method of claim **3**, wherein providing at least one optical path adjacent to a flame region in the combustor comprises providing a moveable lens operable to variably adjust at least a field of view associated with the optical path.

5. The method of claim **1**, wherein detecting within the at least one optical path at least a portion of light emission from the flame region comprises filtering least a portion of the light with a first filter and detecting at least a portion of the first filtered light with at least one first photodetector.

6. The method of claim **5**, wherein detecting within the at least one optical path at least a portion of light emission from the flame region comprises filtering least a portion of the light with a second filter and detecting at least a portion of the second filtered light with at least one second photodetector, wherein the second filter differs from the first filter.

7. The method of claim **6**, wherein controlling at least one of the combustion parameters is based in part on signals from the at least one first photodetector and the at least one second photodetector.

8. The method of claim **1**, wherein controlling at least one of the combustion parameters based in part on the detected light emission comprises controlling at least one of fuel flow rate, fuel flow distribution, air/fuel ratio, combustion flame oscillations, combustion flame extinction, heat release ratio, or flame temperature.

9. The method of claim **1**, wherein providing at least one optical path adjacent to a flame region in the combustor comprises providing a beam splitter to spatially separate optical paths.

10. A system for controlling combustion parameters associated with a gas turbine combustor, the system comprising:
- at least one optical port adjacent to a flame region in the combustor;
- one or more photodetectors in communication with the at least one optical port operable to detect at least a portion of light emission from the flame region; and
- at least one control device operable to control one or more combustion parameters based at least in part on one or more signals from the one or more photodetectors.

11. The system of claim **10**, further comprising:
- one or more optical filters operable to isolate spectral information associated with the light emission.

12. The system of claim **10**, further comprising:
- at least one lens operable to image at least a portion of light emission from the flame region.

13. The system of claim **12**, wherein the at least one lens comprises moveable lens operable to variably adjust at least a field of view associated with the optical path.

14. The system of claim **10**, further comprising:
- at least one first optical filter, wherein the at least one first optical filter is in communication with at least one first photodetector.

15. The system of claim **14**, further comprising:
- at least one second optical filter, wherein the at least one second optical filter is in communication with at least one second photodetector.

16. The system of claim **15**, wherein the at least one control device is operable to control the one or more combustion parameters based at least in part on signals from the at least one first photodetector and the at least one second photodetector.

17. The system of claim **10**, wherein the at least one control device operable to control one or more combustion parameters is operable to control at least one of fuel flow rate, fuel flow distribution, air/fuel ratio, combustion flame oscillations, combustion flame extinction, heat release ratio, or flame temperature.

18. The system of claim **10**, further comprising:

at least one beam splitter operable to spatially separate light emission from the flame region.

19. The system of claim **10**, wherein the one or more photodetectors are responsive to at least a portion of the ultraviolet spectrum.

20. A gas turbine comprising:

a combustor;

at least one optical port adjacent to a flame region in the combustor;

one or more photodetectors in communication with the at least one optical port, and operable to detect at least a portion of light emission from the flame region; and

at least one control device operable to control one or more combustion parameters based at least in part on one or more signals from the one or more photodetectors.

* * * * *