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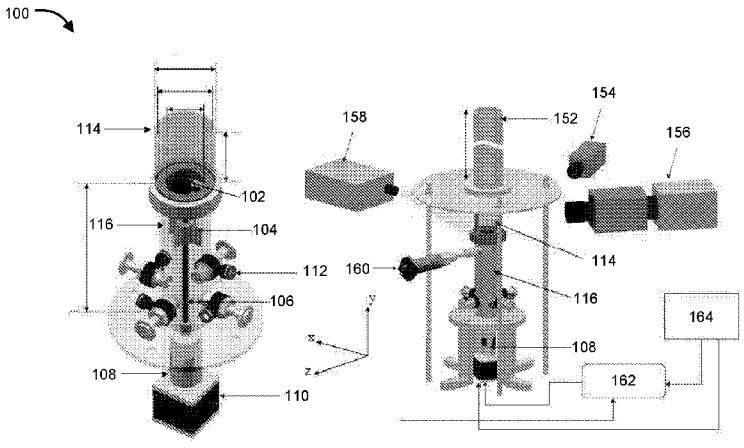


FIG. 1

(57) Abstract: The present disclosure relates to a method and apparatus to mitigate thermo-acoustic instabilities in combustor of gas turbine engines using a lean premixed flame; and provides a dynamic control strategy for mitigating thermo-acoustic instability in a swirl stabilized, lean premixed combustor by rotating the otherwise static swirler meant for stabilizing the lean premixed flame. The swirler is subjected to a controlled rotation for imparting increased turbulence intensity and higher tangential momentum to the premixed reactants towards mitigating thermo-acoustic instability. The rotating swirler induces vortex breakdown and increased turbulence intensity to decimate periodic interactions found during a particular phase of the instability cycle on account of periodic collision of diverging flame base with the flame segment above the dump plane in the combustor. This prevents flame-flame interactions and emergence of strongly positive Rayleigh indices which contribute as sources of acoustic energy to drive the self-excited instability.

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MITIGATING INSTABILITY BY ACTUATING THE SWIRLER IN A COMBUSTOR

FIELD OF THE INVENTION

[0001] The present disclosure relates generally to the field of gas turbines. In particular it relates to a method of reduction of thermo-acoustic instabilities in a lean premixed combustor of a gas turbine.

BACKGROUND

[0002] Background description includes information that may be useful in understanding the present invention. It is not an admission that any of the information provided herein is prior art or relevant to the presently claimed invention, or that any publication specifically or implicitly referenced is prior art.

[0003] Enhanced periodic pressure fluctuations that result from a positive feedback between the unsteady heat release rate and the acoustic pressure fluctuations in a confined combustion chamber is referred to as thermo-acoustic instability. In case of combustion chambers of gas turbines, high oscillation amplitudes can occur which lead to undesirable effects, such as, for example, a high mechanical/thermal load on the combustion chamber, flashback or the flame being extinguished. For this reason they have been a matter of prime concern among combustion researchers over decades.

[0004] Specifically, lean premixed gas turbine combustor operation is frequently plagued by intense thermo-acoustic oscillation at nearly discrete, narrow band frequencies leading to structural damage and possible failure of the engine parts. This is the major obstacle in using lean premixed combustion technology in gas turbine combustors despite its other remarkable benefits in terms of reduced pollutant emission, negligible soot production to name a few.

[0005] Systematic mitigation of thermo-acoustic instability is thus an important challenge. Thermo-acoustic instabilities in gas turbine engines can be suppressed in theory by disrupting the feedback loop between the unsteady heat release rate and acoustic pressure oscillations, but is yet to be satisfactorily addressed at either the design or working stages of an engine.

[0006] In practical combustors, two conceptually different approaches, namely passive and active control, are utilized for its mitigation. Passive control strategy involves permanent modification in the fuel injection system, alteration in combustor geometry and/or addition of

acoustic dampeners (Helmholtz resonators, quarter wave tubes, liners etc.) for suppressing these oscillations. However, instability mitigation using mechanisms like Helmholtz resonators are difficult to realize in realistic combustor systems mainly due to space and power constraints. Liquid-fuelled rockets and gas turbine combustors are often equipped with acoustic dampers like Helmholtz resonators, perforated liners, quarter and half-wave tubes and baffles; but the addition of such components affects the combustor performance, weight and heat loads.

[0007] On the other hand, active control methodology employs an externally excited auxiliary system for interrupting the heat release rate-acoustic pressure fluctuation feedback loop within the combustor. This control strategy typically involves real-time monitoring of chamber pressure oscillations by a sensor coupled with feedback control and actuator system for suppressing the thermo-acoustic instability.

[0008] Compared to the passive strategy, active control approach offers robust and better mitigating capability of thermo-acoustic instability over a wider operating range. Hence, development of new active control strategies is pursued by various combustion research groups.

[0009] Different active control strategies such as acoustic excitation of reactants, micro-jet injection, variable angle swirler are known to have been utilized for mitigating thermo-acoustic instability in lab scale combustors by various researchers. Paschereit et al. as disclosed in their paper "Coherent structures in swirling flows and their role in acoustic combustion control" (published in Physics of Fluids (1994-present), 1999. 11(9): p. 2667-2678) utilized acoustic excitation of air supply in a swirl stabilized flame combustor to alter the shear layer dynamics and suppress the unsteady pressure oscillations. Subsequently, Uhm and Acharya in their paper "Control of combustion instability with a high-momentum air jet." (published in Combustion and flame2004.139(1): p. 106-125) modulated the high momentum air jet in a swirl stabilized spray combustor using proportional drive valve for mitigating thermo-acoustic instability. Altay et al. in their paper "Mitigation of thermo-acoustic instability utilizing steady air injection near the flame anchoring zone" (published in Combustion and Flame, 2010. 157(4): p. 686-700) injected micro-jets close to the dump plane of a lean premixed swirl combustor for suppressing thermo-acoustic instability. Kim et al. in their paper "Plasma assisted combustor dynamics control" (published in Proceedings of the Combustion Institute, 2015. 35(3): p. 3479-3486) explored possibility of thermo-acoustic

mitigation of swirl stabilized combustor using Nano-Second Pulsed Plasma Discharge (NSPD).

[0010] Durox et al. in their paper "Flame dynamics of a variable swirl number system and instability control" (published in Combustion and Flame, 2013. 160(9): p. 1729-1742) disclosed design and testing of a variable angle swirler system for varying the swirl number in order to suppress thermo-acoustic instability in a lean premixed swirl combustor. Their results how that with an increase in the blade angle in a variable blade swirler, the swirl number does not increase rapidly as compared to the theoretical prediction, with the difference being more than a factor of 2 at higher blade angles.

[0011] It is important to note that the swirler with movable blades requires sophisticated and complex linkage mechanism for changing the blade angle. Furthermore, increasing blade angle for achieving higher swirl number introduces blockage in the flow path resulting in enhanced pressure drop. Therefore, a variable blade angle swirler offers limited change in swirl number at the cost of pressure drop.

[0012] Control techniques which utilize secondary/pilot fuel or air for suppressing thermo-acoustic instability modifies flow rate and/or the equivalence ratio within the combustor which could in turn unwantedly impact the heat release rate, flame stability, engine performance and exhaust emission levels.

[0013] To date, in all modern gas turbine combustors, flames are stabilized aerodynamically by static vane swirlers. In all these combustors, all solid wall (liners with cooling holes) boundaries enclosing the combustion process are almost static. This prevents any external actuation, active control or real time modification of the flow and flame pattern inside the combustor.

[0014] There is, therefore, a need in the art for a method for mitigating the problem of narrow band, low frequency thermo-acoustic oscillation in gas turbine combustors for which there is no systematic fool proof solution.

[0015] All publications herein are incorporated by reference to the same extent as if each individual publication or patent application were specifically and individually indicated to be incorporated by reference. Where a definition or use of a term in an incorporated reference is inconsistent or contrary to the definition of that term provided herein, the definition of that term provided herein applies and the definition of that term in the reference does not apply.

[0016] In some embodiments, the numbers expressing quantities of ingredients, properties such as concentration, reaction conditions, and so forth, used to describe and claim

certain embodiments of the invention are to be understood as being modified in some instances by the term "about." Accordingly, in some embodiments, the numerical parameters set forth in the written description and attached claims are approximations that can vary depending upon the desired properties sought to be obtained by a particular embodiment. In some embodiments, the numerical parameters should be construed in light of the number of reported significant digits and by applying ordinary rounding techniques. Notwithstanding that the numerical ranges and parameters setting forth the broad scope of some embodiments of the invention are approximations, the numerical values set forth in the specific examples are reported as precisely as practicable. The numerical values presented in some embodiments of the invention may contain certain errors necessarily resulting from the standard deviation found in their respective testing measurements.

[0017] As used in the description herein and throughout the claims that follow, the meaning of "a," "an," and "the" includes plural reference unless the context clearly dictates otherwise. Also, as used in the description herein, the meaning of "in" includes "in" and "on" unless the context clearly dictates otherwise.

[0018] The recitation of ranges of values herein is merely intended to serve as a shorthand method of referring individually to each separate value falling within the range. Unless otherwise indicated herein, each individual value is incorporated into the specification as if it were individually recited herein. All methods described herein can be performed in any suitable order unless otherwise indicated herein or otherwise clearly contradicted by context. The use of "any" and "all examples", or exemplary language (e.g. "such as") provided with respect to certain embodiments herein is intended merely to better illuminate the invention and does not pose a limitation on the scope of the invention otherwise claimed. No language in the specification should be construed as indicating any non-claimed element essential to the practice of the invention.

[0019] Groupings of alternative elements or embodiments of the invention disclosed herein are not to be construed as limitations. Each group member can be referred to and claimed individually or in any combination with other members of the group or other elements found herein. One or more members of a group can be included in, or deleted from, a group for reasons of convenience and/or patentability. When any such inclusion or deletion occurs, the specification is herein deemed to contain the group as modified thus fulfilling the written description of all Markush groups used in the appended claims.

OBJECTS OF THE INVENTION

[0020] A general objective of the present disclosure is to enable instability-freeimplementation of lean premixed combustion technology in gas turbine combustors.

[0021] An object of the present disclosure is to mitigate problem of narrow band, low frequency thermo-acoustic oscillation in gas turbine combustors so that the lean premixed combustion technology may be successfully implemented in gas turbine combustors.

[0022] An object of the present disclosure is to suppress thermo-acoustic instability without any addition or detraction in the combustor inlet air or fuel flow rates.

[0023] An object of the present disclosure is to provide a method for suppressing thermo-acoustic instability that does not incorporate an automated feedback loop.

[0024] Another object of the present disclosure is to dynamically control flow and flame structure towards achieving an instability-free combustor.

[0025] Yet another object of the present disclosure is to provide an externally actuated dynamic control for real time modification of the flow and flame pattern inside the combustor for mitigating thermo-acoustic instability.

SUMMARY

[0026] Aspects of the present disclosure relate to reduction of thermo-acoustic instabilities in combustor of a gas turbine. In particular, it discloses a method and apparatus to mitigate problem of narrow band, low frequency thermo-acoustic oscillation in gas turbine combustors so as to stabilize a lean premixed flame.

[0027] In an aspect, the disclosure provides a dynamic control strategy for mitigating thermo-acoustic instability in a swirl stabilized, lean premixed combustor by rotating the otherwise static swirler that is primarily meant for stabilizing the lean premixed flame. The otherwise static swirler is subjected to a controlled rotation for imparting increased turbulence intensity and higher tangential momentum to the premixed reactants towards mitigating thermo-acoustic instability. Thus the disclosed control technique does not suffer from unwanted impacts of the heat release rate, flame stability, engine performance and exhaust emission levels faced with other known control techniques which utilize secondary/pilot fuel or air modifying the equivalence ratio within the combustor for suppressing thermo-acoustic instability.

[0028] In an aspect, the rotating swirler induces vortex breakdown and increased turbulence intensity to decimate periodic interactions found during a particular phase of the

instability cycle on account of periodic collision of diverging flame base with the flame segment above the dump plane in the combustor. Thus the rotating swirler is able to avoid flame-flame interactions. The flame-flame interactions result in emergence of strongly positive Rayleigh indices contributing as sources of acoustic energy to drive the self-excited instability. The rotating swirler can, therefore, decimate the acoustic energy source, to render quiet, instability mitigated swirling flames.

[0029] In an aspect, the disclosed concept has been tested over a wide range of lean equivalence ratios, bulk flow velocities and swirler rotation rates with advanced measurement and diagnostic techniques for validating its robustness. Prominent reduction of the fundamental acoustic mode amplitude: by about 25 dB is observed with this control technique for the cases that were studied. Furthermore, understanding of the physical mechanism responsible for dynamic instability mitigation by the disclosed strategy has been established through investigation of the transient flame dynamics and the reacting flow field. The distinct changes associated with the reacting flow field were observed using Particle Image Velocimetry (PIV). An attempt has been made to probe into the self-excited flame dynamics using high speed, intensified, chemiluminescence imaging and identify the instability driving, source locations from spatial Rayleigh indices map.

[0030] In an aspect, the disclosure provides a combustor to mitigate thermo-acoustic instability by a dynamic control strategy. The disclosed combustor can be a swirl stabilized, lean premixed combustor incorporating a vane swirler that is primarily meant for stabilizing the lean premixed flame. The swirler can be an axial swirler mounted on a shaft-bearing-coupling-motor arrangement configured to facilitate its rotation at different rpms. The combustor can further incorporate means for dynamic control of flow and flame structure towards achieving an instability free combustor.

[0031] In an aspect, the disclosed concept can be implemented along with a closed loop control mechanism based on detecting unstable flame condition using sensors, computing fastest route to achieve stable condition and actuating means to rotate swirler at desired speed. In an aspect, a combustor equipped with a swirler and closed loop mechanism to control the speed of swirler can serve as a smart combustor that can automatically maintain stable flame condition free from thermo-acoustic instability.

[0032] Various objects, features, aspects and advantages of the inventive subject matter will become more apparent from the following detailed description of preferred

embodiments, along with the accompanying drawing figures in which like numerals represent like components.

BRIEF DESCRIPTION OF THE DRAWINGS

[0033] The accompanying drawings are included to provide further understanding of the present disclosure, and are incorporated in and constitute a part of this specification. The drawings illustrate exemplary embodiments of the present disclosure and, together with the description, serve to explain the principles of the present disclosure.

[0034] FIG. 1 illustrates an exemplary perspective view of experimental setup and diagnostic tools in accordance with embodiments of the present disclosure.

[0035] FIGs. 2A, 2B and 2C illustrate exemplary images of the experimental setup of FIG. 1 along with close-up view of the lower section comprising of the main combustor and images of flame at different rotational speeds of the swirler in accordance with embodiments of the present disclosure.

[0036] FIGs. 3A and 3Billustrate exemplary plots of Fast Fourier Transform (FFT) of the unsteady pressure datafor one of the experimental conditions showing three distinct modes under conditions of stationary swirler and the rotating swirler respectively in accordance with embodiments of the present disclosure.

[0037] FIGs. 4A, 4B and 4C illustrate exemplary plots of variation of the three mode amplitudes for different swirler rotational speeds for three different experimental conditions in accordance with embodiments of the present disclosure.

[0038] FIGs. 5A, 5B and 5C illustrate exemplary plots of variation of frequencies of different FFT modes for three different experimental conditions in accordance with embodiments of the present disclosure.

[0039] FIG. 6 illustrates variation of mean chemiluminescence intensity with different swirler rotation rates for three different experimental conditions in accordance with embodiments of the present disclosure.

[0040] FIGs. 7A, 7B, 7C and 7D illustrate exemplary images of mean z-vorticity field superimposed with streamlines; and RMS of fluctuating velocity field without and with swirler rotation for one of the experimental conditions in accordance with embodiments of the present disclosure.

[0041] FIGs. 8A to 8F illustrate exemplary velocity and vorticity profiles at two different axial locations above the dump plane with and without swirler rotationin accordance with embodiments of the present disclosure.

[0042] FIGs. 9A and 9B illustrate exemplary flame image sequences for complete instability cycles without and with swirler rotation for one of the experimental conditions inaccordance with embodiments of the present disclosure.

[0043] FIGs. 10A and 10B illustrate exemplary phase averaged flame images without and with swirler rotation for one of the experimental conditions inaccordance with embodiments of the present disclosure.

[0044] FIG. 10C illustrates an exemplary plot of diverging flame base angle at different phases of instability cyclein accordance with embodiments of the present disclosure.

[0045] FIGs. 11A and 11B illustrate comparison of spatial Rayleigh Index (RI)without and with swirler rotation respectively for one of the experimental conditions in accordance with embodiments of the present disclosure.

[0046] FIG. 12 illustrates an exemplary instantaneous flame image sequence of thermo-acoustically unstable flame for one of the experimental conditions showing the interaction of diverging flame base with the flame segment above dump plane inaccordance with embodiments of the present disclosure.

[0047] FIG. 13 illustrates an exemplary instantaneous flame image sequence corresponding to the instability-free flame without Aluminium tube inaccordance with embodiments of the present disclosure.

[0048] FIG. 14 illustrates an exemplary block diagram indicating a closed loop feedback mechanism for maintaining thermo-acoustic instability-free flame condition in a smart combustor in accordance with embodiments of the present disclosure.

DETAILED DESCRIPTION

[0049] The following is a detailed description of embodiments of the disclosure depicted in the accompanying drawings. The embodiments are in such detail as to clearly communicate the disclosure. However, the amount of detail offered is not intended to limit the anticipated variations of embodiments; on the contrary, the intention is to cover all modifications, equivalents, and alternatives falling within the spirit and scope of the present disclosure as defined by the appended claims.

[0050] Each of the appended claims defines a separate invention, which for infringement purposes is recognized as including equivalents to the various elements or limitations specified in the claims. Depending on the context, all references below to the "invention" may in some cases refer to certain specific embodiments only. In other cases, it will be recognized that references to the "invention" will refer to subject matter recited in one or more, but not necessarily all, of the claims.

[0051] Various terms as used herein are shown below. To the extent a term used in a claim is not defined below, it should be given the broadest definition persons in the pertinent art have given that term as reflected in printed publications and issued patents at the time of filing.

[0052] The present disclosure relates to reduction of thermo-acoustic instabilities in combustor ofa gas turbine. In particular, it discloses a method and apparatus to mitigate problem of narrow band, low frequency thermo-acoustic oscillation in gas turbine combustors so as to stabilize a lean premixed flame.

[0053] In an aspect, the disclosure provides a dynamic control strategy for mitigating thermo-acoustic instability in a swirl stabilized, lean premixed combustor by rotating the otherwise static swirler that is primarily meant for stabilizing the lean premixed flame. The otherwise static swirler is subjected to a controlled rotation for imparting increased turbulence intensity and higher tangential momentum to the premixed reactants towards mitigating thermo-acoustic instability. Thus the disclosed control technique does not suffer from unwanted impacts of the heat release rate, flame stability, engine performance and exhaust emission levels faced with other known control techniques which utilize secondary/pilot fuel or air modifying the equivalence ratio within the combustor for suppressing thermo-acoustic instability.

[0054] Thermo-acoustic instability is a complex phenomenon influenced by several parameters including but not limited to swirl number, combustor acoustics, damping, mode of combustion, inlet velocity and density profiles, etc. An aero gas turbine engine operates over a wide range of the above parameters and during flight, these parameters could rapidly change and interact to render a particular operating condition stable or thermo-acoustically unstable. Hence instability-free stable regime for one particular flow or equivalence ratio may turn out to be highly unstable for a different flow condition. For e.g., in a high swirl number reacting flow, a prominent Processing Vortex Core (PVC) could be the source of instability. In such a scenario, it is possible that reducing swirl number might assist in the instability

mitigation which could also be easily achieved by rotating the static swirler in the opposite direction. Thus clearly, the flexibility to dynamically change the swirl number and inlet turbulence intensity that renders the rotating (spinning) swirler, a superior flame stabilization mechanism when compared to a static swirler.

[0055] In the present disclosure, a premixed flame is being stabilized downstream of high speed, rotating swirler blades, where the turbulence intensity could be varied and controlled. Increasing swirler rotation rate would lead to controlled increase of turbulent flame speed. With an increase in the turbulent flame speed, the flame stabilization location could be changed on average, accompanied by change in the flame structure. It is known that flame shape and location could be primary drivers that determine whether a given flame-combustor configuration would be thermo-acoustically unstable or not. Accordingly, the present disclosure provides a method and apparatus for changing the flame location by controlling the swirler rotational frequency and using it as a thermo-acoustic control strategy in a swirl stabilized flame configuration.

[0056] In an aspect, the present disclosure focuses on the effect of an actuated swirler on thermo-acoustics in an otherwise thermo-acoustically unstable combustor as against changing the flame dynamics with static swirlers.

[0057] Take off point for the current invention is variable angle swirler system designed and tested by Durox et al. (mentioned in the background section) for varying the swirl number in order to suppress thermo-acoustic instability in a lean premixed swirl combustor. As it is shown by Durox et al. that with an increase in the blade angle in a variable blade swirler, the swirl number does not increase rapidly as compared to the theoretical prediction, with the difference being more than a factor of 2 at higher blade angles. Moreover , a variable blade angle swirler offers limited change in swirl number at the cost of pressure drop. Besides this, swirler with movable blades requires sophisticated and complex linkage mechanism for changing the blade angles. Furthermore, increasing blade angle for achieving higher swirl number introduces blockage in the flow path resulting in enhanced pressure drop. The present disclosure aims to overcome disadvantage of an enhanced pressure drop and limited variation in swirl number in the case of variable blade angle swirler by rotating the static vane swirler thereby providing the additional work input to the flow by controlling the motor rpm. High rotation rates and effective design of the swirler blades could even lead to a net pressure gain in the combustor with an actuated swirler.

[0058] In an aspect, the rotating swirler induces vortex breakdown and increased turbulence intensity to decimate periodic interactions found during a particular phase of the instability cycle on account of periodic collision of diverging flame base with the flame segment above the dump plane in the combustor. Thus the rotating swirler is able to avoid flame-flame interaction locations which result in emergence of strongly positive Rayleigh indices contributing as sources of acoustic energy to drive the self-excited instability. The rotating swirler can, therefore, decimate the acoustic energy source, to render quiet, instability mitigated swirling flames.

[0059] In an aspect, the disclosed concept has been tested over a wide range of lean equivalence ratios, bulk flow velocities and swirler rotation rates with advanced measurement and diagnostic techniques for validating its robustness. Prominent reduction of the fundamental acoustic mode amplitude: by about 25 dB is observed with this control technique for the cases that were studied. Furthermore, understanding of the physical mechanism responsible for dynamic instability mitigation by the disclosed strategy has been established through investigation of the transient flame dynamics and the reacting flow field. The distinct changes associated with the reacting flow field were observed using Particle Image Velocimetry (PIV). An attempt has been made to probe into the self-excited flame dynamics using high speed, intensified, chemiluminescence imaging and identify the instability driving, source locations from spatial Rayleigh indices map.

[0060] FIG. 1 illustrates an exemplary perspective view 100 of experimental setup incorporating features of the disclosed combustor along with diagnostic tools to validate the proposed concept in accordance with embodiments of the present disclosure. The combustor can incorporate a swirler 102 mounted on a shaft-bearing-coupling-motor arrangement for facilitating its rotation at different speeds. The shaft-bearing arrangement 104 can be housed within a stainless steel circular pipe 116 of suitable inner diameter and height. In the exemplary embodiment shown in FIG. 1 the swirler diameter is 30 mm (with a hub diameter of 10 mm). The stainless steel circular pipe 116 housing the shaft-bearing arrangement 104 has inner diameter 31 mm and height 100 mm.

[0061] The swirler 102 can be recessed from the exit of the pipe 116 by a distance of 3 mm. One end of the shaft 106 of the shaft-bearing arrangement 104 can be attached to the swirler 102 andits other end can be connected to a motor such as stepper motor 110 through a coupling such as love-joy coupling 108. The stepper motor 110can have adequate power/torque rating depending on size of the swirler 102. In the exemplary set up shown in

FIG. 1 the stepper motor 110 has torque rating of 1.7 kgf-cm. The stepper motor 110 can be powered by a transformer 164 and its rotational speed can be controlled by stepper driver circuit which in the exemplary set-up uses sine pulses from a waveform generator integrated with oscilloscope 162 (Agilent InfiniiVision DSO-X-2002A). Air and Methane in appropriate ratio can enter into a perforated plate fitted plenum chamber where they are premixed. Air and methane can be separately metered by mass flow controllers. In the exemplary set-up of FIG. 1 air flow supplied by an external screw compressor and Methane (99% purity) is controlled by calibrated AlicatMass Flow Controllers (Air- 0-500 SLPM range; Methane 0-50 SLPM range). Uncertainty in mass flow controllers (MFC) is given by ±0.8% of displayed reading in the MFC + 0.2% of full scale range of the MFC.

[0062] The air-fuel mixture can be delivered into the combustor through four inlets 112 placed at the bottom portion of the stainless steel circular pipe 116. The swirl stabilized premixed flame is confined within a tube such as cylindrical quartz tube 114 in FIG. 1 having inner diameter 46 mm and height 60 mm. Besides this, another tube such as aluminium tube 152 having inner diameter 44 mm and length 2 m can be mounted above the quartz test section to generate the self-excited thermo-acoustic instability. The cylindrical quartz tube 114 and aluminium tube 152 can be connected by a threaded cap(not shown here)which has a provision for igniting the reactants.

[0063] Transient pressure data from the combustor in the experimental set up of FIG. 1 can be acquired at a rate of 10 kS/s using a pressure sensor such as Kistler piezo-resistive pressure sensor 160 (Model no: 4260A045BIBA07D1; range: 0-3 bar absolute pressure) placed just upstream of the swirler 102. The uncertainty in the pressure sensor 160 used in the set-up is ± 0.2% of full scale range. The unsteady pressure time series can be monitored and recorded for a span of 3 sec. through an oscilloscope 162.

[0064] In order to capture data to validate the disclosed concept, a camera such as high speed camera 156 (Photron FASTCAM SA5) equipped with intensified relay optics-IRO (LaVision) and UV lens is utilized for observing the line of sight integrated, unfiltered, flame chemiluminescence dynamics associated with the thermo-acoustic instability and its transition with swirler rotation. The flame videos are captured for 2 seconds at 5000 fps with a resolution of 1024×1024 pixel^2. Besides this, distinct changes in the reacting flow field, with and without swirler 102 rotation are analysed quantitatively using PIV. The PIV measurements can be performed at the symmetry x-y plane of quartz tube shown in FIG. 1 which is illuminated by a 532 nm Nd:YAG laser 158 (Litron Nano SPIV) sheet of sub-

millimeter (~ 0.5 mm) thickness. The reacting flow field is seeded uniformly by 1-5 micron sized alumina particles. The PIV images are captured using high resolution CCD camera 154 (LaVision Imager Intense) at a frame rate of 4 Hz and processed using DAVIS 8 software. The swirler rotation rates are varied from 0 to 1800 rpm in steps of 200 for all three cases.

[0065] FIGs. 2A, 2B and 2C illustrate exemplary images200, 225 and 250 respectively of the experimental setup of FIG. 1 along with zoomed view (in image 225) of the lower section comprising of the main combustor 202, and close up images 250 of the flame in the combustion chamber at different swirler speed in accordance with embodiments of the present disclosure. The 2m long Aluminium pipe 152 shown in the image 200 has been used as a duct for exciting for generating self-excited thermo-acoustic instability. Image 225 shows the combustor comprising the quartz test section (tube) 114, fuel-air mixture inlets 112, stepper motor 110 and love-joy coupling 108 etc. The image 250 shows an exemplary flame emission images when the swirler 102 is stationary i.e. at 0 rpm and rotating at three different rpms.

[0066] In an embodiment, the 2 m long Aluminium pipe 152 has been used as a duct for exciting narrow band thermo-acoustical longitudinal modes at about 75 Hz. Rotation of swirler within 1350-1800 rpm could significantly mitigate these excited thermo-acoustic longitudinal modes over different bulk flow Reynolds number (~ 4000 - ~10000) and equivalence ratios (0.676 – 0.732).In another embodiment, test was carried out in the above described set-up on a model combustor that stabilizes a premixed flame using 30 degree vane angle swirlers. When the swirler 102 was static, the flame could thermo-acoustically self-excite at a frequency of around 75 Hz due to 2m long tube downstream of the quartz test section.

[0067] It was found, both from pressure transducer signals and phase averaged flame images obtained by image processing of high speed flame chemiluminescence videos, that on rotating swirler 102 within the range of 1200-1800 rpm, the amplitude of the 75 Hz mode and large scale longitudinal motion of the flame and flame base angle were greatly diminished. The mitigation of the dominant instability mode is shown in FIG.3. This clearly suggests successful mitigation of the self-excited thermo-acoustic instability using rotation of swirler. Results of the experiments carried out with the experimental set-up of FIG. 1 and 2A under different operating conditions i.e. bulk flow conditions have been discussed further in succeeding paragraphs.

[0068] The disclosed method highlights utilization of rotation/actuation of swirlers in combustors that stabilize flame(s) in propulsion or power generation gas turbine engines towards i) instability mitigation ii) dynamic and systematic augmentation or reduction of swirl number iii) enhanced turbulence iv) better atomization of liquid sprays v) better mixing of fuel and air vi) easier implementation in practical combustors with relatively easier mechanical arrangement, among other possible uses in this field to a person having ordinary skill in the art.

[0069] In an embodiment, in order to establish efficacy of the disclosed concept, above described experimental setup was used to carry our experiments under bulk flow conditions corresponding to three different experimental cases are presented in Table 1 below:

Table 1:*Experimental Conditions*

Experimental Conditions Case	Bulk Reynolds number (Re)	Equivalence Ratio (ϕ)	Swirler rotation rates (rpm)
I	4085	0.676	0-1800 in steps of 200
II	7274	0.705	0-1800 in steps of 200
III	10269	0.732	0-1800 in steps of 200

[0070] As shown in the table 1 above, swirler rotational speed was varied from 0 to 1800 rpm in steps of 200 for all three cases namely Case I, II and III. For Case I, Bulk Reynolds number (Re) is 4085 and equivalence ratio (ϕ) is 0.676. Likewise for Case II, Bulk Reynolds number (Re)is 7274 and equivalence ratio (ϕ) is 0.705. And for Case III, Bulk Reynolds number (Re) is 10269 and equivalence ratio (ϕ) is 0.732.

A. Pressure Measurements

[0071] In an embodiment, the experiments were used to quantitatively establish efficacy of the rotating swirler in mitigating thermo-acoustic instability from the pressure amplitudes at discrete frequencies. Initially, when the swirler 102 was stationary (i.e. 0 rpm), three distinct modes were observed from the Fast Fourier Transform (FFT) of the unsteady pressure data corresponding to case II, as shown in graph 300 of FIG. 3. Here the first

longitudinal mode exhibits a sharp distinct peak at 76 Hz. In addition, the second and third modes occur at 206 and 342 Hz respectively with much weaker amplitudes. Plot350 of FIG. 3shows the FFT of unsteady pressure data when the swirler 102 is rotated at 1800 rpm where significant attenuation in the amplitude of the first mode is evident.

[0072] FIGs. 4A, 4B and 4C illustrate exemplary plots 400, 430 and 460 respectively depicting the variation of three mode amplitudes for different swirler speeds corresponding to three cases in accordance with embodiments of the present disclosure. It can be seen from the plot 400 where variation in the ensemble averaged first mode amplitude (in dBSPL) with swirler rotation rate is shown, that for all the three cases, with an increase in swirler rpm, the amplitude of the first mode decreases monotonically from about 150 dB observed with stationary swirler. A reduction in the first mode amplitude by about 25 dB is observed with a maximum swirler rotation rate of 1800 rpm for these cases which explicitly demonstrates effectiveness of the proposed mitigating strategy.

[0073] In an aspect, electrical power expended in rotating the swirler at 1800 rpm is less than 1% of the thermal power output from the combustor, and therefore, the proposed strategy does not result in any significant drain on the power output of the turbine where the combustor may be used, thereby establishing basic feasibility of the proposed dynamic control concept.

[0074] The influence of swirler rotation rate on the second and third mode amplitudes of pressure data is shown in plots 430 and 460 respectively. The plot 430indicates that the second mode amplitude exhibits a slightly increasing trend beyond 900 rpm for the three cases. On the other hand, as evident from plot 460, third mode amplitude does not reveal any prominent trend with swirler rotation rate for these cases. However, on comparing plot 430 and 460 with plot 400, it is clearly evident that the amplitude of second and third acoustic modes are comparable with that of the first mode at higher swirler rotation rates where the mitigation of the first mode is significant. To summarize, an increase in the swirler rotation rate does not energize the amplitudes of second and third acoustic modes appreciably, though mitigation of the first dominant mode is significant.

[0075] FIG. 5A, 5B and 5C illustrate exemplary plots 500, 530 and 560 respectively of variation of frequencies of different FFT modes for the three different experimental conditions in accordance with embodiments of the present disclosure. The plot 500 shows effect of swirler speed on frequency of the first mode and it can be noticed that the first mode frequency increases with swirler rotation rate. An increase in the swirler rpm enhances the

turbulence intensity at the burner exit close to the dump plane. This observation is also confirmed by the PIV measurements which will be discussed in subsequent paragraphs. Increased turbulence intensity can augment turbulent flame speed through increased flame surface area, especially near the wall boundary layers. On the other hand, it can be noticed from plots 530 and 560 that the frequencies of second and third acoustic modes exhibit negligible variation with swirler rotation rate for the three cases.

B. Flow Field Measurements with PIV

[0076] The investigation of reacting flow velocity field with swirler actuation is expected to shed more light into the underlying physical mechanism responsible for the mitigation of thermo-acoustic instability by the proposed concept. In this regard, vorticity ω_z superimposed with streamlines and u'_{rms}, associated with the reacting flow field are analyzed in detail. The statistics of the velocity field are realized from an ensemble average of 200 individual PIV scans along the symmetry (x-y) plane of the quartz section spanning the flame region.

[0077] The mean z-vorticity field of the reacting flow superimposed with streamlines is shown in FIG. 7A for Case II without swirler rotation. The streamlines exhibit an elongated vortex tube residing above the dump plane in the Outer Recirculation Zone (ORZ). Furthermore, the Inner Recirculation Zone (IRZ) has not evolved for this case owing to a low geometric swirl number of about 0.4. Interestingly in FIG. 7B, when the swirler is rotated at 1800 rpm, the formation of IRZ with two counter-rotating vortices, as in a Vortex Breakdown Bubble (VBB) can be observed from the streamlines close to the burner exit. The swirler rotation increases the swirl number thereby facilitating vortex breakdown leading to the formation of a coherent IRZ. Furthermore, size of corner vortices and its vorticity strength in the ORZ diminishes with swirler rotation, which can be observed from the comparison of FIG. 7A and FIG. 7B. In addition to this, enhanced turbulence intensity with swirler rotation is also evident close to the ORZ and shear layers. This can be noted from the comparison of FIG. 7C and FIG. 7D.

[0078] A comparison of y-component of mean velocity (U_y), $u'_{rms,}$ and ω_z profiles at the axial locations of 1mm and 3mm above the dump plane are shown in FIGs. 8A to 8F for the swirler rotation rates of 0 and 1800 rpm. From FIGs. 8A and 8B, it can be observed that U_y slightly reduces close to the dump plane region with the actuation of swirler at 1800 rpm. However, in contrast to the static swirler case, U_y is enhanced close to the IRZ with swirler actuation due to the formation of vortex bubble breakdown. The swirler rotation also enforces

a pronounced enhancement in u'_{rms} near the ORZ and in the shear layer as compared to the static swirler case (see FIGs. 8C and 8D). In addition, an overall reduction in corresponding values near the ORZ, with swirler actuation, can be noted from FIGs. 8E and 8F.

C. High Speed Chemiluminescence Imaging

[0079] The instantaneous flame image sequences for complete instability cycles, corresponding to Case II for the static and actuated swirler (0 and 1800 rpm respectively), are shown in FIGs. 9A and 9B respectively. The sinusoidal variation in the mean spatial heat release rate during one instability cycle can be observed clearly from FIG. 9A. Large scale longitudinal motion of the self-excited flame is also evident without swirler rotation. FIG. 9B depicts the instantaneous flame image sequence during one dampened instability cycle with the swirler rotation rate of 1800 rpm. Here, an increase in mean spatial heat release rate and corresponding reduction in its peak to peak amplitude during one cycle can be noticed with swirler rotation as compared to the static swirler.

[0080] To better observe the statistical nature of the self-excited flame dynamics, the phase averaged images at 0°, 90°, 180°, 270° corresponding to Case II, without swirler rotation is depicted in FIG. 10A. The phase averaging is performed over 79 cycles. A periodic change in the spatial chemiluminescence intensity along with fluctuation (expansion and contraction) in diverging flame base angle at different phases can be observed for the static swirler case from FIGs. 10A and 10B. The periodic fluctuation in the diverging flame base angle can be attributed to the instability in the absence of vortex bubble breakdown and IRZ, which is evident from FIG. 7A.

[0081] The phase averaged flame chemiluminescence images at (0°, 90°, 180°, 270°) with swirler rotation rate of 1800 rpm are shown in FIG. 10B. Here, the phase averaging is performed over 80 cycles. With swirler rotation, increase in the diverging flame base angle can be observed. Earlier reported LES numerical study by Stone and Menon (*Proceedings of the Combustion Institute,* Vol. 29, No. 1, 2002, pp. 155-160) made similar observation on the flame shape with an increase in swirl number in a dump combustor configuration. Besides this, fluctuation in the diverging flame base angle, over different phases, is however diminished which can be confirmed from FIGs. 10B and 10C. Increased diverging flame base angle is attributed to VBB and formation of coherent IRZ due to an increased swirl number, as confirmed earlier by PIV measurements in FIG. 7B. Significant reduction in the flame heat release rate unsteadiness can also be inferred indirectly from the spatial chemiluminescence intensity of the phase averaged images in FIG. 10B as compared to 10A. The phase averaged

images clearly reveal significant suppression in the periodic longitudinal motion of the flame with swirler rotation, indicating a prominent mitigation in the thermo-acoustic instability. This can be attributed to the overall change in the mean flame topology with swirler rotation due to the formation of stable IRZ and enhanced turbulence intensity in the flame stabilization region.

D. Driving Regions of Thermo-acoustic Instability – Analysis of Rayleigh Index Map

[0082] Probing the spatial distribution of the local Rayleigh Index (RI) of the thermo-acoustically unstable flame can help in identifying the locations which drive the instability in a given combustor configuration. In order to compute the spatial RI, pressure and high speed chemiluminescence representative of heat release rate, must be simultaneously obtained. This is accomplished by simultaneously triggering the data acquisition from the pressure transducer and high speed IRO camera at a common sampling rate of 5 kS/s. The spatial RI is computed for the flame corresponding to case II for the swirler rotation rates of 0 and 1800 rpm.

[0083] The Rayleigh Index is given by Equation. (1) below:

$$\mathrm{RI} = \frac{1}{T}\int_0^T p'q'dt \qquad (1)$$

Here, T corresponds to the time period of one cycle. p' denotes fluctuating component of pressure (N/m^2) and q' denotes fluctuating component of heat release rate (W/m^2).

In the present work, spatial RI map is computed by integrating $p'q'$over 91 cycles for the thermo-acoustically unstable flame. The equation for computing RI integrated over n cycles is given by Equation (2) below:

$$\mathrm{RI} = \frac{1}{nT}\int_0^{nT} p'q'dt \qquad (2)$$

[0084] FIGs. 11A and 11B illustrate comparison of spatial RI without and with swirler rotation respectively for one of the experimental conditions inaccordance with embodiments of the present disclosure. The region which drives the instability corresponds to the zone where the diverging flame base interacts with the flame segment above the dump plane as can be seen in FIG. 11A. A comparison of spatial Rayleigh indices in FIG.11A and 11B clearly reveals a prominent reduction of the intensity of the instability sources in the flow, with swirler rotation. In order to understand the origin of the instability driving source in RI map of FIG. 11A without swirler rotation, the dynamics of self-excited flame is further

investigated. The time sequence of instantaneous images of the thermo-acoustically unstable flame corresponding to case II without swirler rotation is shown in FIG. 12. At particular phases (0°, 90° in FIG 10A) of the instability cycle, the diverging flame base and the flame segment above the dump plane approach each other due to opposing directions of the tangential velocity of IRZ and ORZ vortices which is evident from FIG. 12. These two flame regions eventually collide and merge, resulting in the annihilation of flame surface area. During second half of the instability cycle at certain phases, diverging flame base and the flame segment retreat away from each other thereby generating new flame surfaces (refer phase averaged images corresponding to 180°, 270° in FIG. 10A). In an earlier study, Lee et al. (in their paper titled "An experimental estimation of mean reaction rate and flame structure during combustion instability in a lean premixed gas turbine combustor," published in *Proceedings of the Combustion Institute*, Vol. 28, No. 1, 2000, pp. 775-782.) utilized mean reaction rate computed from OH-PLIF images for estimating the spatial RI in the case of swirl stabilized natural gas premixed flame in a dump combustor. During the instability cycle, they noticed that periodic interaction of IRZ and ORZ and found that IRZ and ORZ act as driving regions for instability whereas shear layer region damps the same.

[0085] It is important to note that the variation in diverging flame base angle in the case of static swirler (due to the absence of a continuous VBB and IRZ) is the main factor which contributes to this flame-flame interaction. The periodic annihilation and generation of flame surface area due to the interaction of diverging flame base with the flame segment above the dump plane ultimately leads to the unsteadiness in the heat release rate. This, when coupled with pressure fluctuations, feeds energy to the acoustic oscillations thereby driving the thermo-acoustic instability.

E. Thermo-acoustic Instability Triggering Precursors

[0086] In an aspect, an attempt has also been made to investigate the origin or precursor of the flame-flame interaction discussed in the previous section by probing the dynamics of swirl flame without the presence of Aluminium tube. The flame thus stabilized in the absence of Aluminium tube is always instability-free but otherwise is conditioned to the same experimental parameters as case II. The experimental conditions corresponding to this instability-free flame is denoted by case II(b) and shown in Table 2 below:

Table 2. *Details of Experimental Conditions for Case II and Case II(b)*

Case	Bulk Reynolds number (Re)	Equivalence Ratio (ϕ)	Presence of tube above quartz test section	State at 0 rpm (Static swirler)
II	7274	0.705	Yes	Thermo-acoustically unstable
II(b)	7274	0.705	no	Instability-free

[0087] Investigation of case II(b) is critical as it provides an unambiguous reference for identifying the inherent features of the flow and understanding the mechanism that could trigger the transition from an instability-free state to thermo-acoustically unstable state under suitable conditions.

[0088] The instantaneous image sequence showing the dynamics of instability-free flame corresponding to case II(b) is shown in FIG. 13. In the case of instability-free flame, corner vortex interact with the flame segment above the dump plane, which leads to its stretching by roll-up into the ORZ as observed from FIG. 13. There is no large scale fluctuation in the diverging flame base angle in case II(b) as compared to case II due to the absence of instability. This flame-vortex interaction dynamics observed in the instability-free flame assists the flame segment above the dump plane to interact strongly with the periodically fluctuating diverging flame base in case II. Hence, this flame segment roll-up into the ORZ can be considered as a possible precursor which leads to the flame-flame interaction for sustaining instability under favourable conditions.

F. Mitigating Mechanism of Thermo-Acoustic Instability with the Rotating Swirler

[0089] As discussed in earlier paragraphs, rotation of the static swirler enhances swirl number resulting in vortex bubble breakdown. This creates a stable IRZ which was absent when the swirler remained static. Consequently, a stable but increased diverging flame base angle is also realized accompanied by the suppression in its periodic fluctuation. This prevents the periodic annihilation and generation of flame surfaces due to the interaction between the diverging flame base and the flame segment above the dump plane at particular phases during an instability cycle. Thus, the strong driving source (positive RI) for sustaining thermo-acoustic instability is progressively decimated with swirler rotation.

[0090] Along with the formation of IRZ, the swirler rotation also enhances the turbulence intensity in the flame stabilization region. The well-known effect of enhanced turbulent intensity is increased turbulent flame speed which shifts the mean flame position to an upstream location near the swirler. The increased turbulent flame speed also assists the flame segment above the dump plane to move closer towards the ORZ. As a result, the continuous, augmented heat release in the dump corner region weakens the strength of the vortices residing in the ORZ due to enhanced dilatation and kinematic viscosity. Sustenance of increased diverging flame base angle due to the formation of stable IRZ accompanied by the upstream propagation of flame segment above the dump plane due to enhanced turbulence intensity reduce the size and strength of ORZ vortices, eventually disrupting their interaction with the ORZ flame. Thus, these two mechanisms: formation of stable IRZ due to enhanced swirl number together with enhanced turbulence intensity, interact to render a much more stable flame topology at higher rotation rates: the favourable outcome of this methodology of mitigating instability by actuating the swirler in a combustor.

[0091] In an aspect, based on proof of concept resulting from the experimental set-up of FIG. 1, 2A and 2B, the proposed rotating swirler such as 102 can be implemented in combustors for gas turbine engines to mitigatethermo-acoustic instabilities and lead to introduction of lean premixed combustion technology in gas turbines with its resultant benefits such as reduced pollutant emission, negligible soot production to name a few.

[0092] In an aspect, the disclosure provides a combustor to mitigate thermo-acoustic instability by a dynamic control strategy. The disclosed combustor can be a swirl stabilized, lean premixed combustor incorporating a vane swirler that is primarily meant for stabilizing the lean premixed flame. The swirler can be an axial swirler mounted on a shaft-bearing-coupling-motor arrangement configured to facilitate its rotation at different rpms. The combustor can further incorporatemeans for dynamic control of flow and flame structure towards achieving a instability free combustor.

[0093] In an aspect, the disclosure provides a gas turbine engine incorporating at least one combustor; the at least one combustor incorporating at least one vane swirler and means to rotate the at least one swirler at varying rotational speeds, wherein rotating the swirler mitigates thermo-acoustic instabilities. The at least one combustor can further incorporate means to detect thermo-acoustic instabilities such as comprising pressure sensors to sense pressure in the combustion chamber and processors to process the sensed pressure to identify

occurrence of thermo-acoustic instabilities; and control means to change rotational speed of the swirler based on detected occurrence of thermo-acoustic instabilities.

[0094] FIG. 14 illustrates an exemplary block diagram 1400 indicating a closed loop feedback mechanism for maintaining thermo-acoustic instability free flame condition in a smart combustor in accordance with embodiments of the present disclosure. As shown in the block diagram 1400, a combustor that may be operating under stable conditions can become unstable due to change in any of the operating conditions as shown at 1402. The resultant unstable condition as exemplified by increased amplitude of pressure transducer signal shown at 1412 of the combustor can be detected by sensors as shown at 1404. Based on detected condition the closed loop feedback mechanism can, as shown at 1406, compute fastest route to a stable condition. Using a control mechanism the computed route can be implemented as shown at 1408, by actuating flame holder of the combustor towards a target frequency. Change in frequency can result in restoration of stable condition for the changed operating parameters as shown at 1410 and exemplified by reduced amplitude of pressure transducer signal 1414. The combustor can remain stable as long as operating condition are maintained, and any future change in the parameters can be handled by the closed loop feedback mechanism to keep the combustor in stable condition.

[0095] Thus the disclosed method and apparatus overcomes limitation of known method and apparatus having a variable blade angle swirler. The variable blade angle swirler offers limited change in swirl number at the cost of pressure drop. Besides this, it also requires a complicated mechanism to control the swirl angle. The disclosure provides a concept that does not suffer from the above stated disadvantages i.e. an enhanced pressure drop and limited variation in swirl number can be overcome in a rotating swirler. In an aspect, the disclosed method and apparatus overcomes these deficiencies by an additional work input to the flow through controlling the motor rpm, respectively. High rotation rates and effective design of the swirler blades could even lead to a net pressure gain in the combustor with an actuated swirler. In another aspect, and as stated earlier power expended in rotating the swirler even at its maximum speed is insignificant (less than 1%) compared to the thermal power output from the combustor, and therefore the proposed strategy does not result in any significant drain on the power output of the turbine where the combustor may be used, thereby establishing basic feasibility of the proposed dynamic control concept.

[0096] While the foregoing describes various embodiments of the invention, other and further embodiments of the invention may be devised without departing from the basic scope

thereof. The scope of the invention is determined by the claims that follow. The invention is not limited to the described embodiments, versions or examples, which are included to enable a person having ordinary skill in the art to make and use the invention when combined with information and knowledge available to the person having ordinary skill in the art.

ADVANTAGES OF THE INVENTION

[0097] The present disclosure can enable instability-free implementation of lean premixed combustion technology in gas turbine combustors.

[0098] The method and apparatus of the present disclosure mitigate problem of narrow band, low frequency thermo-acoustic oscillation in a lean premixed combustor. This can enable successful implementation of the lean premixed combustion technology in gas turbine combustors.

[0099] The method and apparatus of the present disclosure suppress thermo-acoustic instability without any addition or detraction in the combustor inlet air or fuel flow rates.

[00100] The present disclosure provides a method for suppressing thermo-acoustic instability that does not incorporate an automated feedback loop.

[00101] The method and apparatus of the present disclosure dynamically controls flow and flame structure towards achieving an instability-free combustor.

[00102] The method and apparatus of the present disclosure provide an externally actuated dynamic control for real time modification of the flow and flame pattern inside the combustor.

CLAIMS

We Claim:

1. A combustor configured to receive fuel and air, and burn the fuel-air mixture, the combustor comprising:
    (a) at least one swirler in feeding path of the fuel-air mixture and configured to create turbulence by swirling of the air; and
    (b) means to rotate the at least one swirler at different rotational speeds;
    wherein rotation of the at least one swirler at different rotational speeds results in mitigating thermo-acoustic instabilities.
2. The combustor of claim 1, wherein the combustor is configured to receive air pre-mixed with fuel and burn the fuel-air mixture; and the at least one swirler is in feeding path of the air pre-mixed with fuel.
3. The combustor of claim 1, wherein the at least one swirler is a vane swirler.
4. The combustor of claim 1, wherein the combustor further comprises means to detect thermo-acoustic instabilities.
5. The combustor of claim 4, wherein the means to detect thermo-acoustic instabilities includes one or more pressure sensors for sensing pressure in the combustor and a processor to process sensed pressure signals to detect occurrences of thermo-acoustic instabilities.
6. The combustor of claim 5, wherein the combustor further comprises controller to actuate the means to rotate the at least one swirler at a desired rotational speed based on detection of occurrence of thermo-acoustic instability.
7. The combustor of claim 1, wherein the means to rotate the at least one swirler at different rotational speeds is at least one motor operatively coupled to the at least one swirler through at least one shaft.
8. The combustor of claim 7, wherein the at least one motor is a variable speed motor to facilitate rotation of the at least one swirler at different rotational speeds.
9. A method for mitigating thermo-acoustic instabilities in a combustor, the method comprising steps of:
    (a) providing at least one swirler in feeding path of fuel-air mixture to stabilize the premixed flame in the combustor.

(b) providing means to rotate the at least one swirler at different rotational speeds;

(c) providing means to detect the occurrence of thermo-acoustic instability; and

(d) rotating the at least one swirler, on detection of thermo-acoustic instability, at a desired rotational speed;

(e) wherein rotation of the at least one swirler at different rotational speeds results in a change in swirl number and change in turbulence intensity by further swirling the fuel-air mixture thereby mitigating thermo-acoustic instabilities.

10. The method of claim 9, wherein the air is pre-mixed with fuel.

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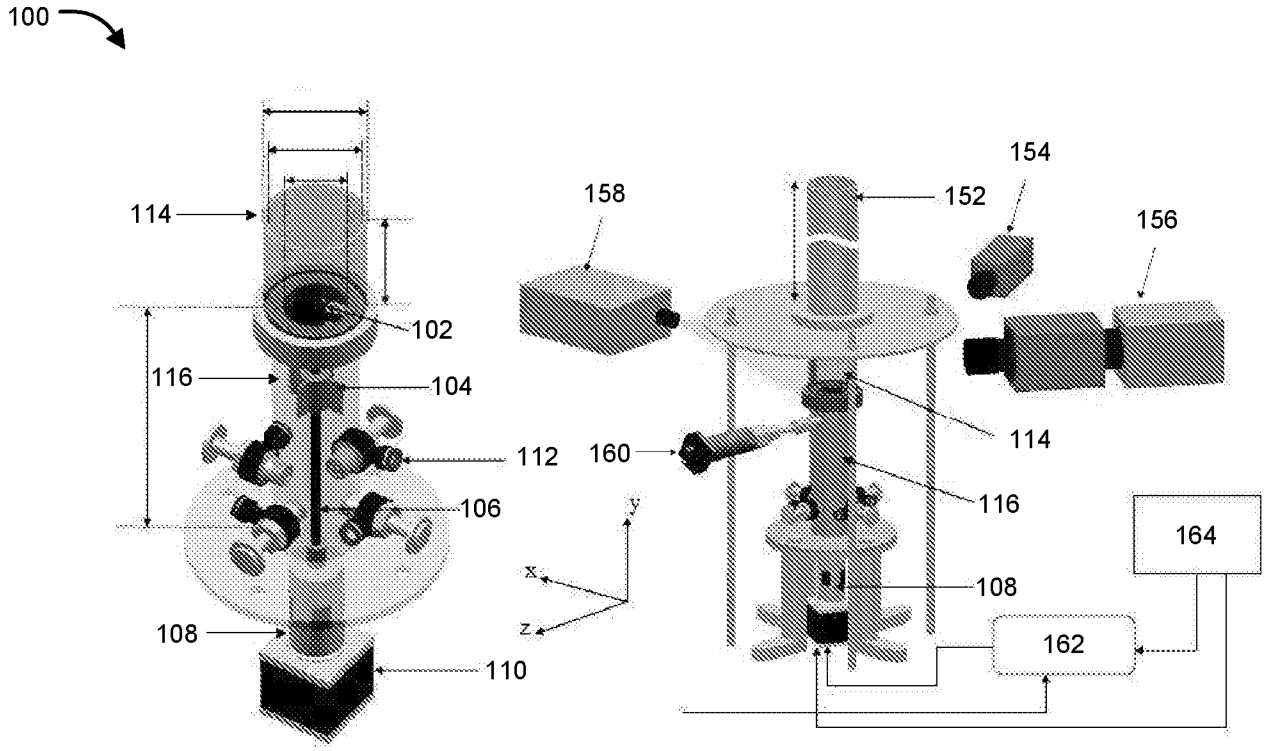


FIG. 1

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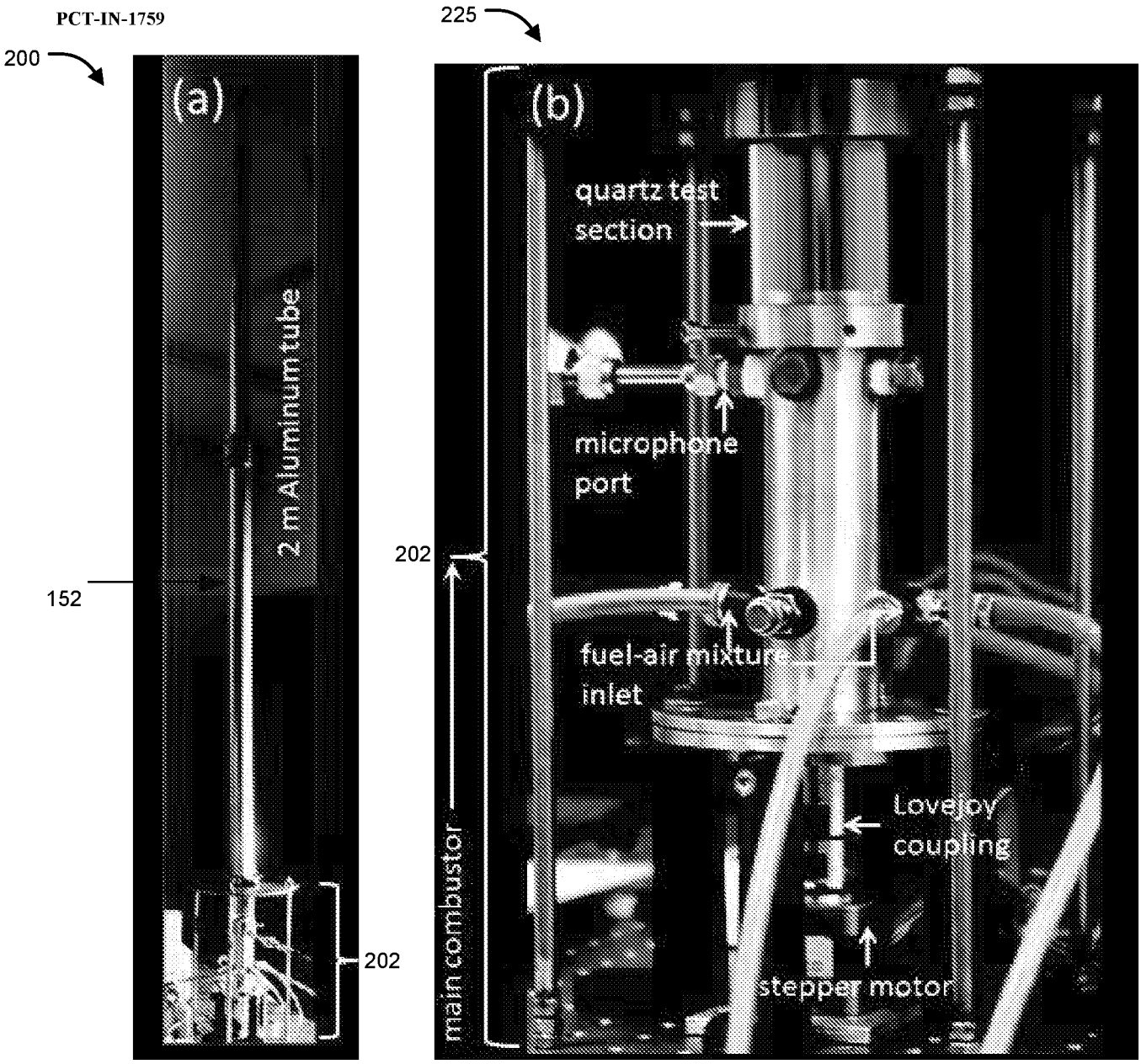


FIG. 2A

FIG. 2B

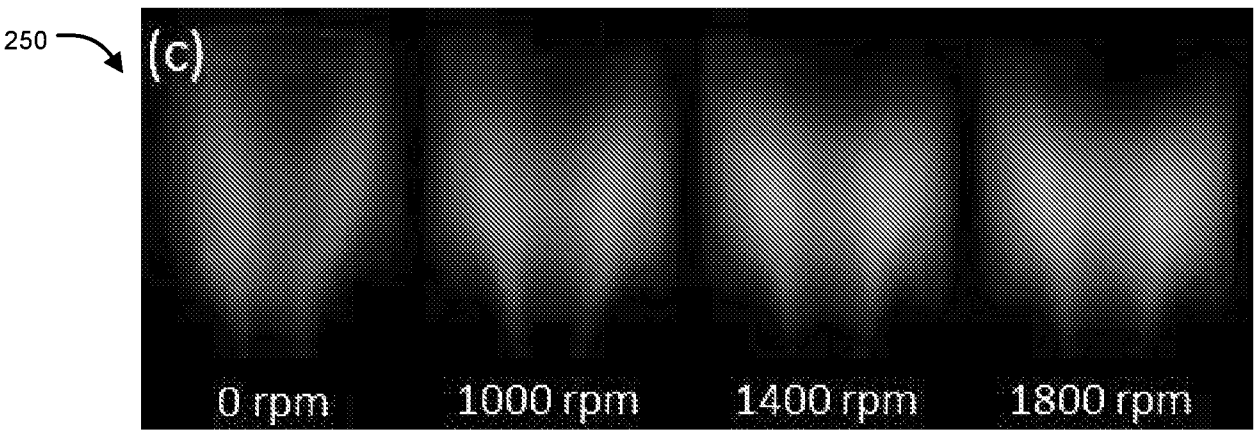


FIG. 2C

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300

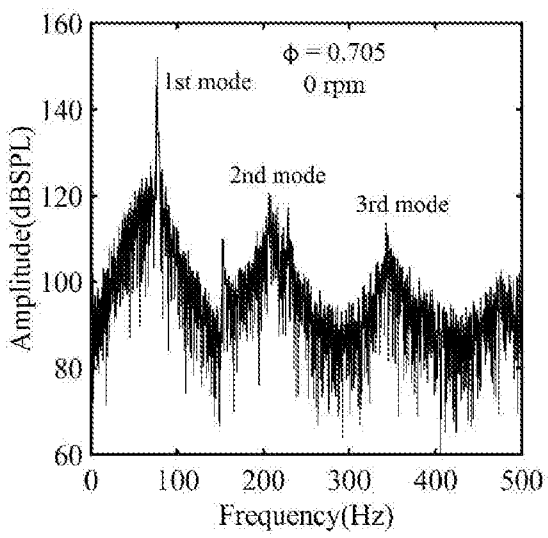


FIG. 3A

350

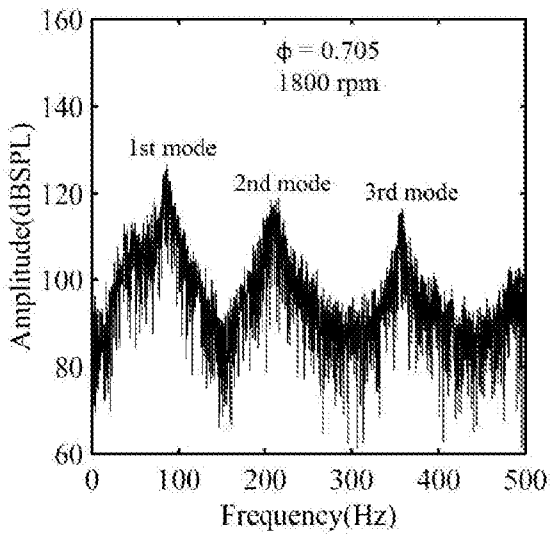


FIG. 3B

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400

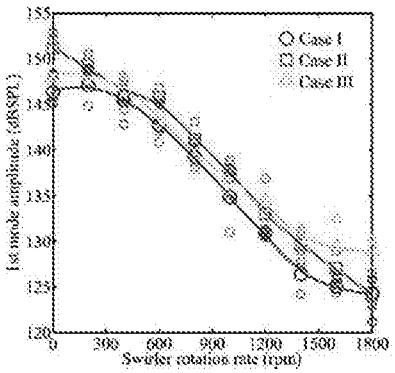


FIG. 4A

430

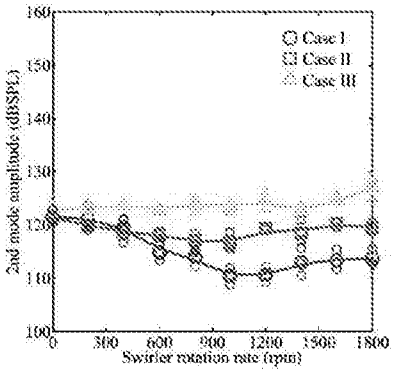


FIG. 4B

460

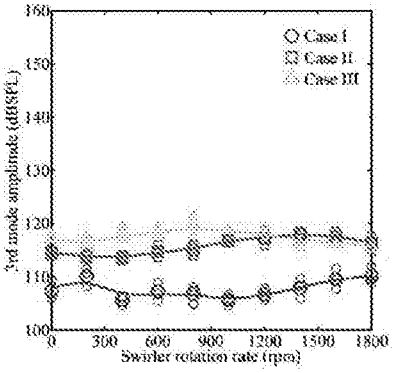


FIG. 4C

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500

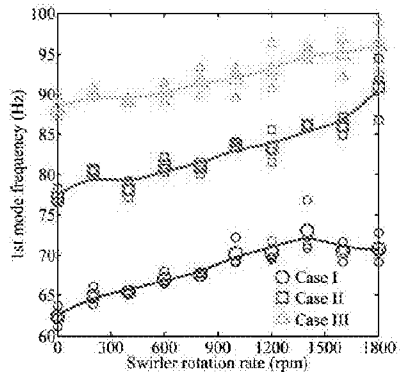


FIG. 5A

530

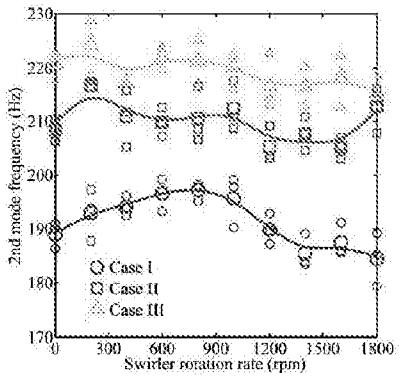


FIG. 5B

560

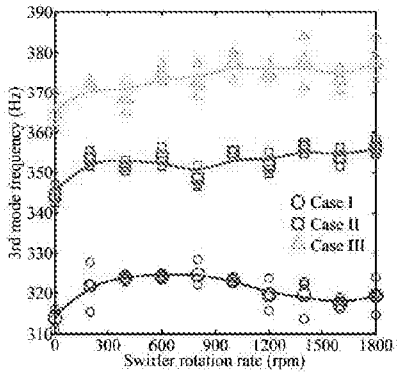


FIG. 5C

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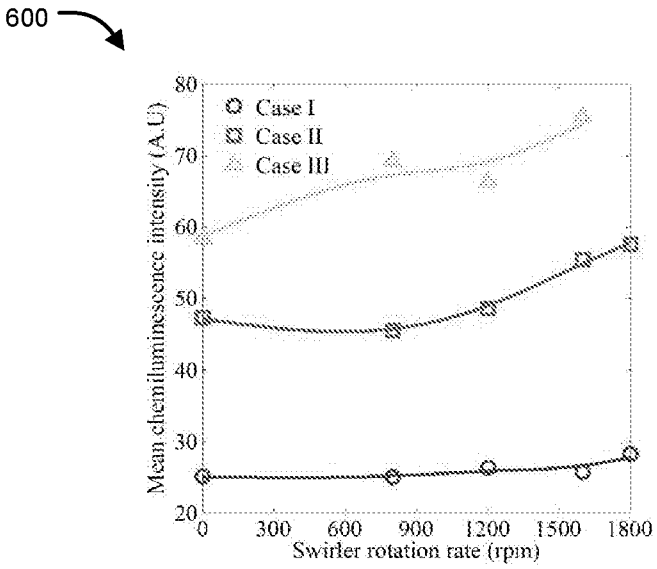


FIG. 6

PCT-IN-1759

700

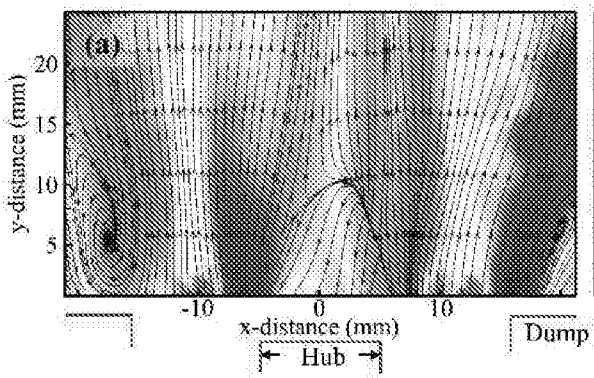


FIG. 7A

725

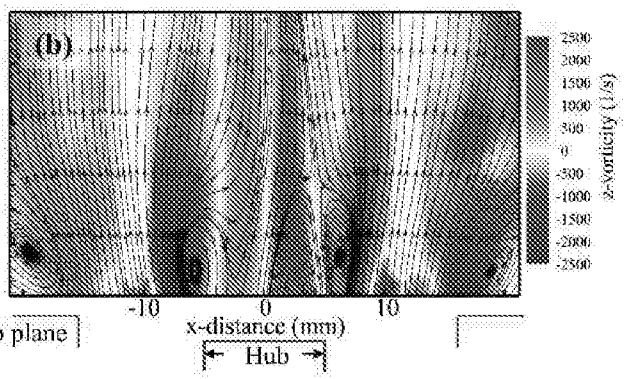


FIG. 7B

750

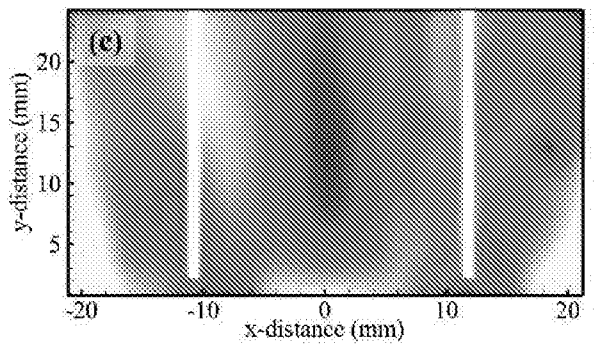


FIG. 7C

775

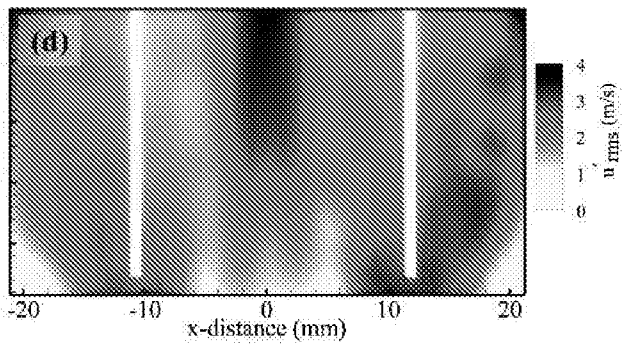


FIG. 7D

800

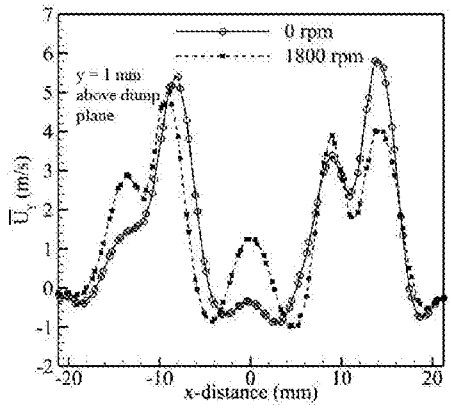


FIG. 8A

810

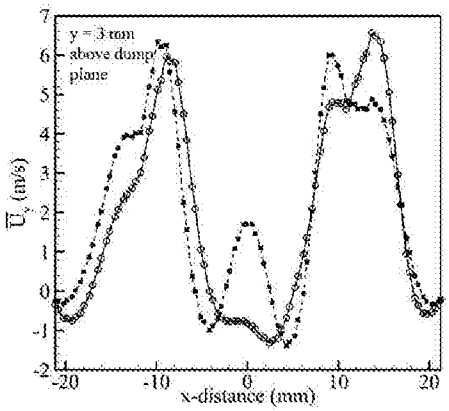


FIG. 8B

820

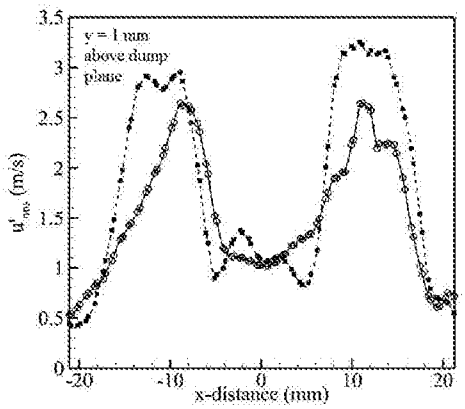


FIG. 8C

830

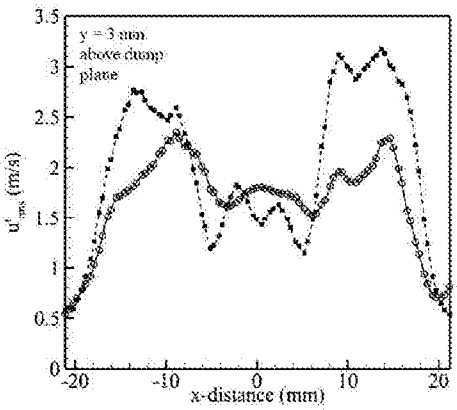


FIG. 8D

840

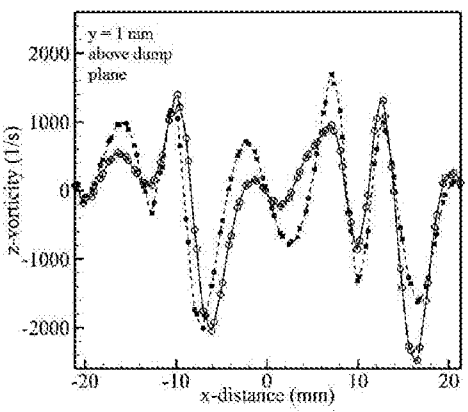


FIG. 8E

850

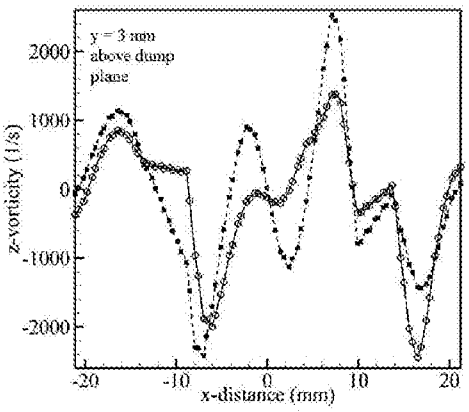


FIG. 8F

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900

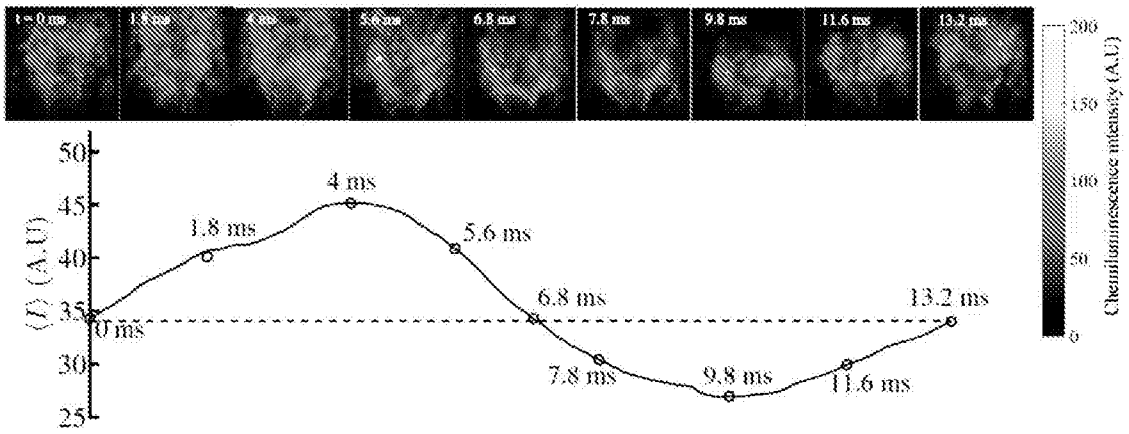


FIG. 9A

950

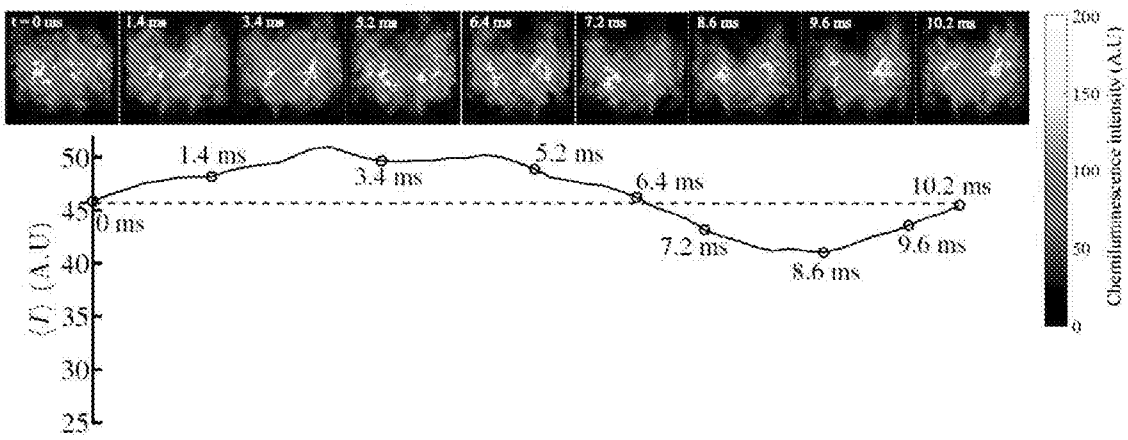


FIG. 9B

PCT-IN-1759

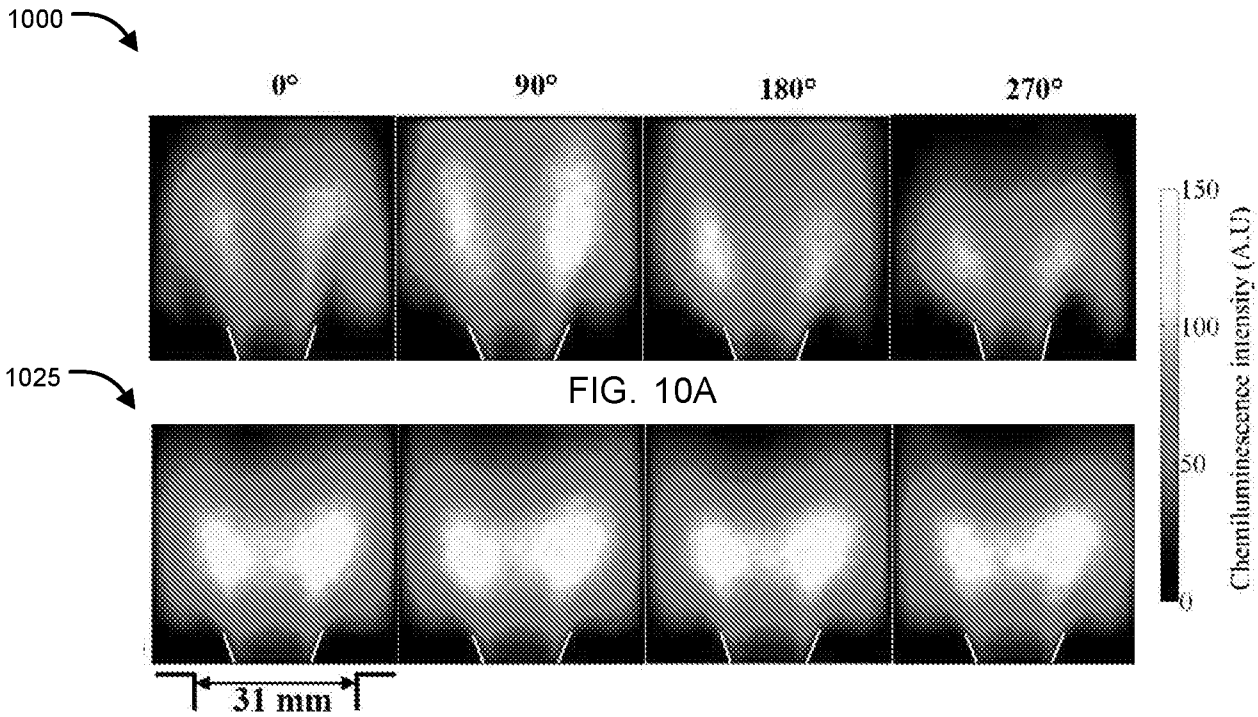


FIG. 10A

FIG. 10B

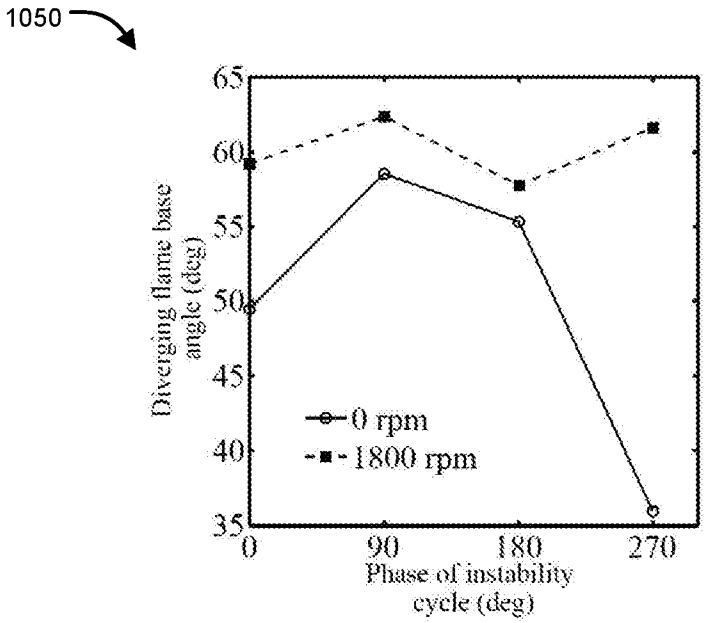


FIG. 10C

PCT-IN-1759

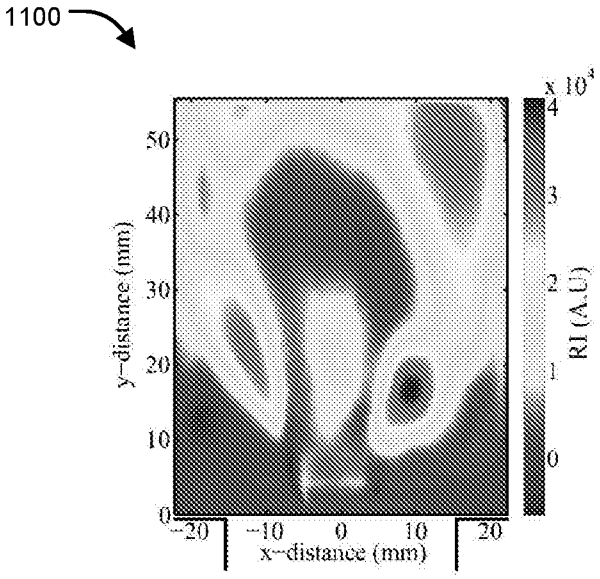


FIG. 11A

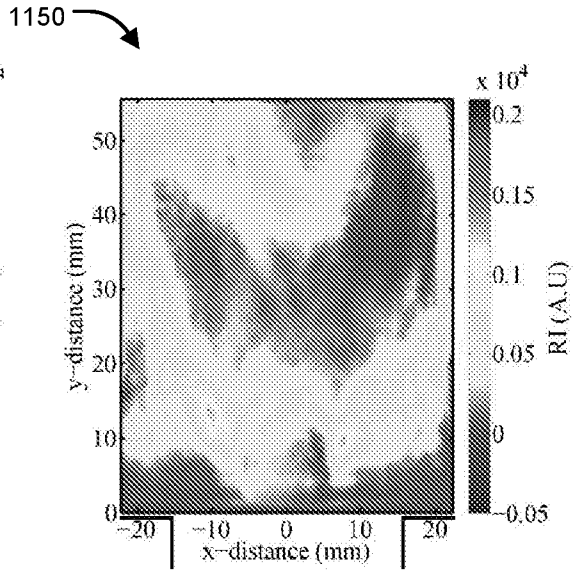


FIG. 11B

PCT-IN-1759

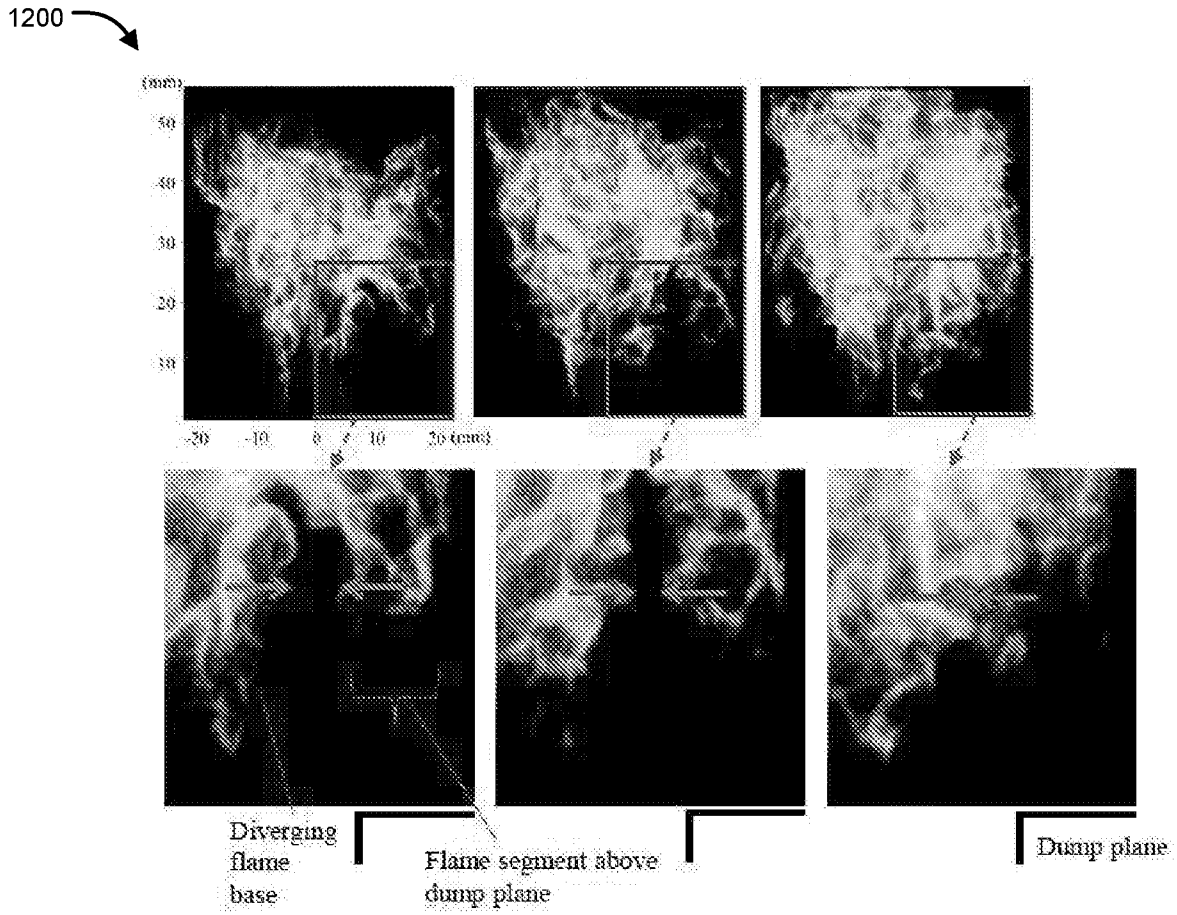


FIG. 12

PCT-IN-1759

1300

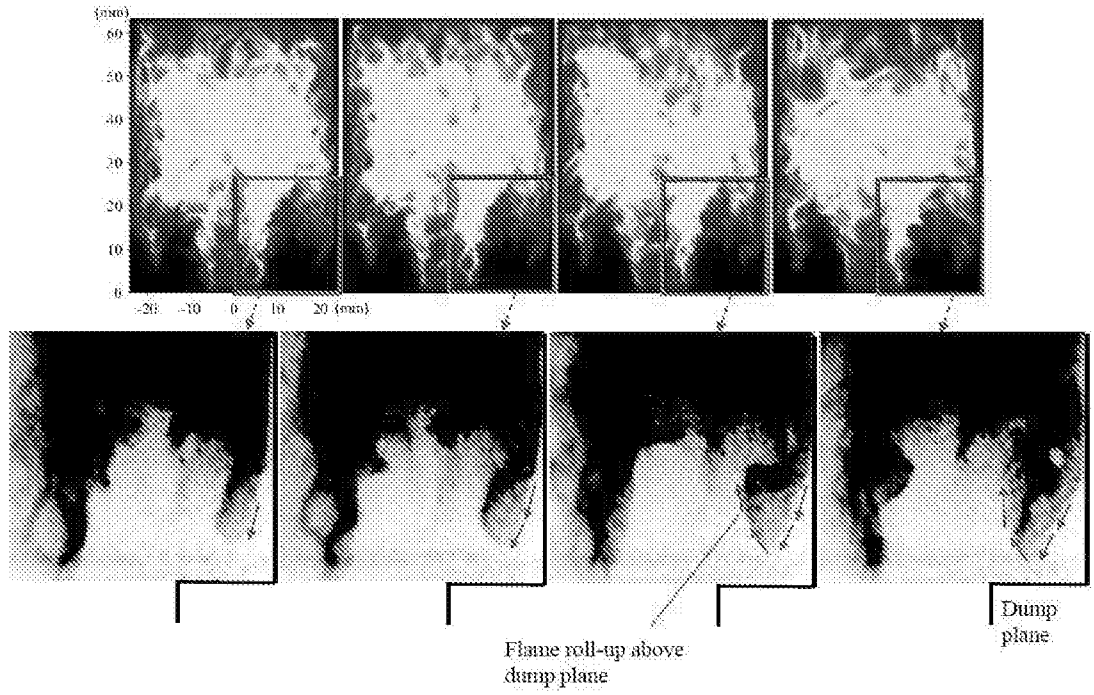


FIG. 13

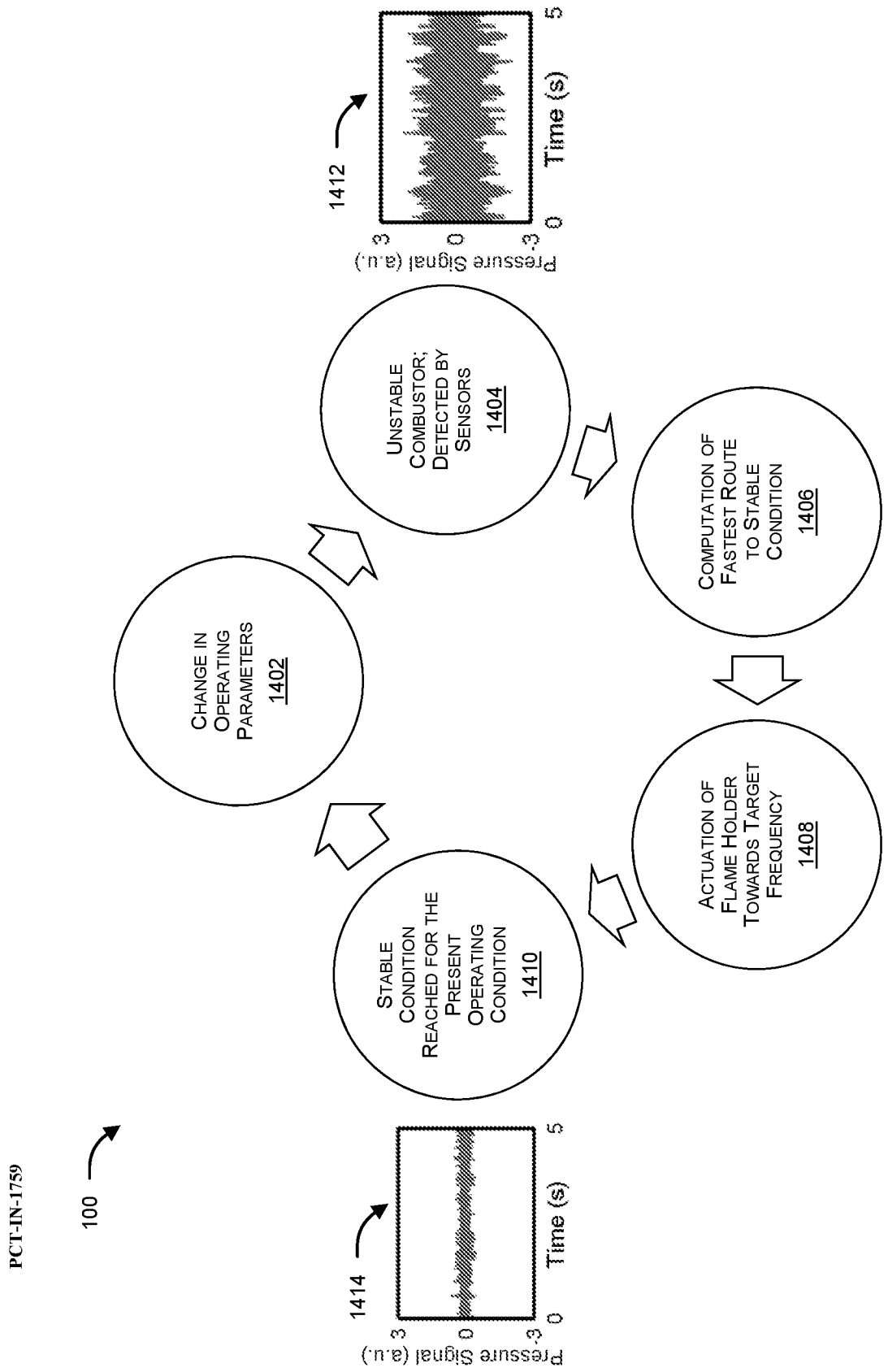

PCT-IN-1759
100
1414
Pressure Signal (a.u.)
3
0
-3
0
Time (s)
5
1412
Pressure Signal (a.u.)
3
0
-3
0
Time (s)
5
CHANGE IN OPERATING PARAMETERS 1402
UNSTABLE COMBUSTOR; DETECTED BY SENSORS 1404
COMPUTATION OF FASTEST ROUTE TO STABLE CONDITION 1406
ACTUATION OF FLAME HOLDER TOWARDS TARGET FREQUENCY 1408
STABLE CONDITION REACHED FOR THE PRESENT OPERATING CONDITION 1410

FIG. 14

INTERNATIONAL SEARCH REPORT

International application No.
PCT/IB 16/55940

A. CLASSIFICATION OF SUBJECT MATTER
IPC(8) - F23R 3/14 (2016.01)
CPC - F23R 2900/00013
According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC(8): F23R 3/14 (2016.01)
CPC: F23R 2900/00013

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
IPC(8): F23R 3/14, F23R 3/22, F23R 3/16, F23R 3/26 (2016.01); USPC: 60/725, 431/114, 431/354, 123/306, 123/592
CPC: F23R 2900/00013, F23R 2900/00, F23R 3/14, F23R 3/22, F23R 3/16, F23R 3/26

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
PatBase, Google Patents, Google Scholar; Search terms used: gas, turbine, engine, swirl, swirler, rotate, active, control, combustor, thermo, acoustic, instability, pressure, sensor, actuator, motor, injector, speed, velocity, variable, variation, difference, number, vibration.

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 2012/0312890 A1 (ROMIG) 13 December 2012 (13.12.2012), entire document, especially Figs 1-3; para [0016], [0017], [0021], [0023], [0024], [0027]	1-10
A	US 2009/0183511 A1 (DINU) 23 July 2009 (23.07.2009), entire document, especially Figs 1-2; para [0012]-[0013]	1-10
A	US 8,099,960 B2 (ELKADY et al.) 24 January 2012 (24.01.2012), entire document, especially Fig 4; col 5, ln 36-50, 56-68	1-10
A	WO 2013/042049 A1 (ANSALDO ENERGIA S.P.A.) 28 March 2013 (28.03.2013), entire document, especially Figs 1, 3; pg 4, ln 25-28; pg 5, ln 2-9	1-10
A	US 2007/0137171 A1 (CHAPIN et al.) 21 June 2007 (21.06.2007), entire document	1-10

☐ Further documents are listed in the continuation of Box C. ☐

* Special categories of cited documents:
"A" document defining the general state of the art which is not considered to be of particular relevance
"E" earlier application or patent but published on or after the international filing date
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)
"O" document referring to an oral disclosure, use, exhibition or other means
"P" document published prior to the international filing date but later than the priority date claimed
"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
28 December 2016	26 JAN 2017

Name and mailing address of the ISA/US	Authorized officer:
Mail Stop PCT, Attn: ISA/US, Commissioner for Patents P.O. Box 1450, Alexandria, Virginia 22313-1450 Facsimile No. 571-273-8300	Lee W. Young PCT Helpdesk: 571-272-4300 PCT OSP: 571-272-7774