



(51) International Patent Classification:

B22F 3/105 (2006.01) B33Y 80/00 (2015.01)

B22F 3/24 (2006.01) F23R 3/14 (2006.01)

B22F 5/00 (2006.01) F23R 3/28 (2006.01)

B33Y 10/00 (2015.01)

(21) International Application Number:

PCT/GB2020/051327

(22) International Filing Date:

02 June 2020 (02.06.2020)

(25) Filing Language:

English

(26) Publication Language:

English

(30) Priority Data:

1908055.5 06 June 2019 (06.06.2019) GB

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(81) Designated States (unless otherwise indicated, for every kind of national protection available): AE, AG, AL, AM, AO, AT, AU, AZ, BA, BB, BG, BH, BN, BR, BW, BY, BZ, CA, CH, CL, CN, CO, CR, CU, CZ, DE, DJ, DK, DM, DO, DZ, EC, EE, EG, ES, FI, GB, GD, GE, GH, GM, GT, HN, HR, HU, ID, IL, IN, IR, IS, JO, JP, KE, KG, KH, KN, KP, KR, KW, KZ, LA, LC, LK, LR, LS, LU, LY, MA, MD, ME, MG, MK, MN, MW, MX, MY, MZ, NA, NG, NI, NO, NZ,

OM, PA, PE, PG, PH, PL, PT, QA, RO, RS, RU, RW, SA, SC, SD, SE, SG, SK, SL, ST, SV, SY, TH, TJ, TM, TN, TR, TT, TZ, UA, UG, US, UZ, VC, VN, WS, ZA, ZM, ZW.

(84) Designated States (unless otherwise indicated, for every kind of regional protection available): ARIPO (BW, GH, GM, KE, LR, LS, MW, MZ, NA, RW, SD, SL, ST, SZ, TZ, UG, ZM, ZW), Eurasian (AM, AZ, BY, KG, KZ, RU, TJ, TM), European (AL, AT, BE, BG, CH, CY, CZ, DE, DK, EE, ES, FI, FR, GB, GR, HR, HU, IE, IS, IT, LT, LU, LV, MC, MK, MT, NL, NO, PL, PT, RO, RS, SE, SI, SK, SM, TR), OAPI (BF, BJ, CF, CG, CI, CM, GA, GN, GQ, GW, KM, ML, MR, NE, SN, TD, TG).

Published:

— with international search report (Art. 21(3))

(54) Title: COMBUSTION SYSTEM COMPONENT FORMED BY METALLIC ADDITIVE LAYER MANUFACTURE AND METHOD OF MANUFACTURING THEREOF

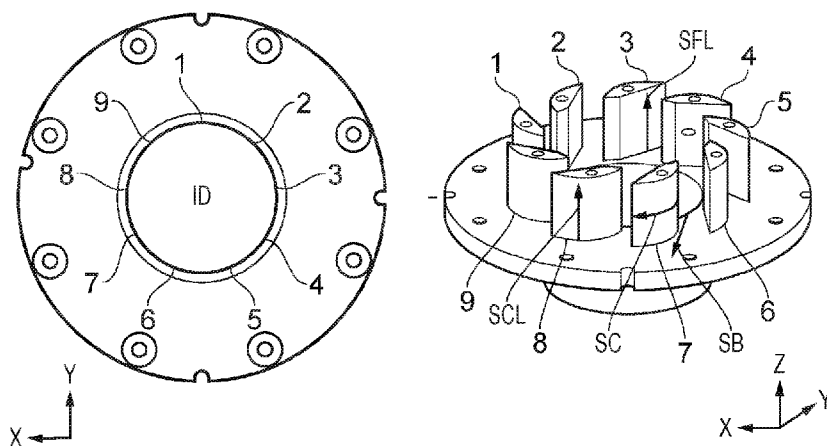


FIG. 5

(57) Abstract: A combustion system component formed by metallic additive layer manufacture wherein the component has a flow-developing surface (SC) having an arithmetic average surface roughness (R_a) of between 3 and 10 μm .

COMBUSTION SYSTEM COMPONENT FORMED BY METALLIC ADDITIVE LAYER MANUFACTURE AND METHOD OF MANUFACTURING THEREOF

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Field of Invention

The present invention relates to combustion system component formed by metallic additive layer manufacture and methods of forming such components. Particularly, but not exclusively the invention relates to combustion system components for gas
10 turbines.

Background

Additive manufacturing methods (which in some cases may be referred to as “3D printing”) typically form three-dimensional articles by building up material in a layer-
15 by-layer manner. One area of application for additive manufacturing is in combustion system components, particularly those for gas turbine engines. Combustion system components to which additive manufacture has been applied may, for example, include fuel nozzles, turbine blades, burners and guide vanes. Additive manufacture has potential for significant performance improvements in such applications for
20 example as an enabler of complex geometries, light-weighting, and multiple component integration.

Combustion components, particularly gas turbine components, are commonly made from “superalloy materials”, for example nickel-based superalloys such as Inconel (an
25 austenitic-nickel-chromium alloy), due to their performance at high temperatures. Such materials may be used in powder bed fusion additive manufacture, which is particularly applicable to high strength materials such as metal alloys (but may also be used for ceramic or polymer based materials). In powder bed fusion, a thin layer of

powder is provided on a base and is selectively exposed to an energy source to fuse sections of the layer. A further layer of powder is provided over the solidified layer, generally by lowering a platform supporting the powder, and the subsequent layer is selectively fused. This fuses the powder both within the new layer and to the fused regions of the previous layer. The process is repeated to build the full component on a layer-by-layer basis. Powder bed fusion includes, for example, Selective Laser Melting (in which the energy source is a Laser) and Electron Beam Melting (in which the energy source is an Electron Beam).

10 The use of additive manufacture introduces additional variables in the manufacture of combustion components. These variables may be particularly applicable to any flow-developing surfaces (i.e. surfaces which are designed to control or influence the flow of fluid through the combustion system). Thus, there is a desire to improve understanding of the impacts of additive manufacturing of components on, for example, the flow and flame stability of a combustion system.

Summary of Invention

According to a first aspect of the invention, there is provided a combustion system component formed by metallic additive layer manufacture wherein the component has a flow-developing surface having an arithmetic average surface roughness (R_a) of between 3 and 10 μ m.

In the context of the invention, a flow-developing surface may be a surface which is profiled to provide a specific fluid flow effect. The flow-developing surface may be considered to be a surface which directly provides a desired fluid flow characteristic. The flow developing surface may generally generate a boundary layer in the flow during use. For example, one flow developing surface would be the inner surface of a nozzle. The inner surface of a nozzle is profiled to control the direction and/or characteristics of the fluid flow passing out of the nozzle. For example, the nozzle may control one or more of the flow velocity, pressure, turbulence, and structure. In

combustion systems, flow-developing surfaces may also include profiled blade surfaces such as turbine blades or swirl blades, which may provide bulk flow directionality and swirl in addition to generating flow boundary layers as described previously.

5

This surface roughness is greater than the surface roughness that would be found in a component manufactured by traditional manufacturing methods (for example a component machined from stainless steel) which might have a typical surface roughness of less than 2 μ m. The applicants have found that the increased surface
10 roughness in accordance with embodiments of the invention result in changes in near-wall boundary layer thickness and turbulent fluctuations. These changes provide resultant differences in flame stability, for example when applied to a swirl nozzle, with the surface roughness of wetted surfaces positively influencing stability limits. This may provide a design variable to be considered in implementing additive
15 manufacture component design.

The component may be a superalloy, for example a nickel-based superalloy. In some embodiments the component may be formed from Inconel which is available as a powder for use in selective laser melting processes.

20

An arithmetic average surface roughness (R_a) between 8 to 10 μ m may be typical of a “raw” selective laser melted component. It will be appreciated that a “raw” surface would typically be a surface which has been subjected to minimal post processing. For example, the component may have had post processing, for example heat-treatment,
25 to remove residual stresses from the additive process and may have had any support structures removed but would not have had any additional processing to improve the surface roughness or finish. Accordingly, in some embodiments a “raw” additive manufactured surface may be used as a flow-developing service.

30 In some embodiments it may be preferable that the flow-developing surface has a lesser surface roughness (but a roughness which is still greater than that of a traditionally machined surface). It may be appreciated that the preferred surface

roughness for any particular flow-developing surface may be optimised during the design of the component. For example, the surface roughness may be optimised using CFD or by empirical methods. The flow-developing surface may for example have an arithmetic average surface roughness (R_a) of between 4.5 and 5.5 μm .

5

The orientation of a surface relative to the additive manufacture build direction may be a key determinate in the resulting surface roughness. For example, the surface orientation can impact the adherence of powder particles and the extent to which portions of the surface are re-melted during the build.

In particular, the applicants have noted a distinction between the surface roughness of a surface which is generally parallel to the additive layer manufacture build direction and a surface which is generally perpendicular to the additive layer manufacture. As such, in embodiments the flow-developing surface extends at least partially along a plane which is generally parallel to the additive layer manufacture build direction. Such an orientation provides resulting surface roughness properties on the surface which are distinct to a surface which is generally perpendicular to the build direction. It may be appreciated that in the present context a surface which is generally parallel to the additive manufacture build direction may be a surface which extends along a plane parallel to the build direction (or the z axis). Likewise, a surface which is generally perpendicular may be a surface which extends along a plane which is perpendicular to the build direction (or the z axis). In other words, a surface which is generally parallel to the additive manufacture build direction may be aligned primarily in an z-x or z-y plane, whereas a surface which is generally perpendicular to the build axis may be aligned primarily in an x-y plane (i.e. a plane corresponding to layers of the additive manufacture build).

The combustion system component may be a swirl burner, for example a gas turbine swirl burner. The flow-developing surface may be a surface of a swirl vane. The flow-developing surface may be a surface of a nozzle. The flow-developing surface may be all flow-developing surfaces of the swirl burner. The swirl burner may further

comprise a swirler base. In some embodiments the swirler base may have a different surface roughness. For example, the base may be generally aligned such that it is parallel with the build direction of the additive manufacturing process.

- 5 In some embodiments, at least the flow-developing surface of the component is a post-processed surface. The post processed surface may have an arithmetic average surface roughness (R_a) which is reduced relative to the average surface roughness (R_a) provided in the additive layer manufacturing process. For example, post processing may include abrasive blasting, such as grit and/or shot blasting. The arithmetic
- 10 average surface roughness (R_a) may for example be reduced by between 25 to 50% (for example approximately 40%) in comparison to the “raw” additive manufactured component. The reduction in arithmetic average surface roughness may be achieved by removing peak surface deviations.
- 15 In a further aspect of the invention there may be provided a method of manufacturing a combustion system component, the component having at least one flow developing surface, wherein the method comprises forming the flow developing surface of the component using a metallic additive layer manufacturing process in which at least one flow developing surface extends in a plane which is parallel to the additive layer build
- 20 direction.

In a further aspect of the invention, there is provided a method of forming combustion system components, the method comprising forming the component using a metallic additive layer manufacturing process; and post-processing the component using

25 abrasive blasting to reduced surface peak values and provide at least one flow-developing surface having a reduced average surface roughness (R_a).

The post-processing may use grit or bead blasting. In some embodiments grit and bead blasting may be carried out as sequential method steps. The post-processing

may for example comprise alumina grit blasting. The alumina grit blasting may for example be followed by stainless steel bead blasting.

- The post-processing may be carried out to reduce the average surface roughness (R_a)
- 5 by between 30 to 50% of the surface roughness provided by the additive layer process.

At least one flow developing surface may be non-parallel to the additive layer build direction during the additive layer manufacturing process.

- 10 At least one flow-developing surface is formed with an average surface roughness (R_a) of between 3 and 10 μ m.

- The method may be a method of forming a swirl burner, for example a a gas turbine swirl burner. The flow-developing surface of the swirl burner may include a surface
- 15 of at least one of a swirl vane and a nozzle. The swirl burner may include a nozzle surrounded by a plurality of swirl vanes. The flow developing surface may include multiple surfaces of the swirl vane and or nozzle. The flow-developing surface may for example include the surface defining the internal diameter of the nozzle. The flow-developing surfaces of the swirl vane may for example include the outer or inner
- 20 surface of the swirl vane (as defined relative to the nozzle). The swirl burner may also include a base which surrounds the nozzle and supports the swirl vanes. The surface of the base may be less critical to flow development so in embodiments the surface of the base may be considered a non-flow-developing surface in the context of the invention. As such, the base may be aligned perpendicular to the build direction of
- 25 the additive manufacture process (such that the surface roughness may be expected to be higher than that of the flow-developing surfaces).

The additive manufacturing process may be a powder bed fusion process, for example powder bed selective laser melting.

Whilst the invention has been described above, it extends to any inventive
5 combination of the features set out above or in the following description or drawings.

Description of the Drawings

Embodiments of the invention may be performed in various ways, and embodiments
10 thereof will now be described by way of example only, reference being made to the accompanying drawings, in which:

Figure 1 shows a schematic of a typical powder bed additive manufacturing system;

Figure 2 is a cutaway schematic of a high pressure generic swirl burner used in
15 evaluating embodiments of the invention;

Figures 3 (a) to 3(c) are images of swirl burner vanes used in the burner of figure 2;

Figure 4 is a schematic and cross-sectional view of the swirl burner of figure 3;

Figure 5 is a schematic showing surfaces on which surface roughness was
20 assessed on the swirl burners;

Figure 6 is a graph of the surface profile and roughness measured on swirl vane radii of the burner vanes of Figure 3;

Figure 7(a) and 7(b) are axial velocity profiles at equivalent air flow to (a) $\varphi = 0.55$ and (b) 0.80 with zero axial velocity shown as dashed line;

Figure 8(a) and 8(b) are turbulence intensity profiles at equivalent air flow to
25 (a) $\varphi = 0.55$ and (b) 0.80 with zero axial velocity shown as dashed line;

Figure 9 (a) to 9(c) are Abel transformed OH* chemiluminescence images for (a) 8R, (b) 8G, and (c) 8M at $\varphi = 0.55$, $\varphi = 0.75$ and $\varphi = 0.80$ (with colormap normalized to maximum OH* intensity at each φ);

Figure 10 is a plot showing OH* centroid location movement from $\varphi = 0.55$ (closed) to $\varphi = 0.75$ (hatched) to $\varphi = 0.80$ (open) with angles relative to burner axial centreline;

Figure 11 (a) and 11(b) are respectively plots of dynamic pressure (a) amplitude and (b) dominant frequency as a function of equivalence ratio for all swirlers;

Figure 12(a) to 12(b) are plots of first (open) and second (closed) mode frequencies and normalized amplitude (hashed) as a function of equivalence ratio for (a) 8R, (b) 8G, and (c) 8M;

Figure 13 are phase-averaged OH* chemiluminescence images of LBO instability at $\varphi = 0.515$ for the 8R swirler (in which identical false colormap is applied to all images);

Figure 14 is a plot of NO_x emissions as a function of AFT and swirler surface roughness; and

Figure 15 is a plot of NO_x emissions as a function of inverse swirler surface roughness.

Detail Description of Embodiments

A metallic powder bed laser fusion additive manufacture apparatus 10 for use in embodiments of the present invention is shown in Figure 1. The apparatus may for example be a commercially available apparatus, such as the applicant's commercially available "Renishaw AM" systems, but is not limited to any specific system. The apparatus comprises a process chamber 12 which encloses a powder bed 14. The powder bed 14 is supported on a platform 16 which, as is known in the art may also

support a substrate of the same metal as the powder. The platform 16 is moveable in the vertical axis such that it may be lowered as each successive layer of the additive manufacture process is carried out. A supply for providing powder to the bed 14 after the platform 16 is lowered and may include a roller (as shown in the present example) or scraper/wiper which travels across the powder bed 14 in the horizontal axis for distributing an even layer on the powder bed. It will be appreciated that the horizontal axis corresponds to the plane of the layers in the additive process (which may also be referred to as the X-Y plane) and the vertical axis is correspondingly aligned with the direction of movement of the platform in the build direction of the process (and may be referred to as the Z-plane).

A radiation source 20, typically a laser (although some embodiments could, for example, use an electron beam emitter), is provided for heating and fusing the powder in the bed 14. The radiation source is directed to the powder bed by a scanner 22, typically comprising a moveable mirror arrangement. A controller 30 is provided for controlling the radiation source 20, the scanner 22 and the process chamber 12 (including for example the platform 16, supply and environmental systems such as heating and gas supply). In use, the scanner 22 is used to move the energy beam across the surface of the powder bed 14.

20

The skilled person in the art will be aware of the general operation of a powder bed fusion additive manufacture processes. A component 50 to be built is first prepared using a file preparation software, such as the applicant's Quant AM software, to optimise the process and the component. The preparation stage requires the component geometry to be appropriately orientated and support structures added where required. Scan parameter may also be optimised, for example optimisation may include factors such as the layer thickness, beam size and dwell time of the beam. The component must then be divided into a series of slices (along the vertical axis of the additive manufacturing apparatus) and a scanning strategy for each slice prepared. The software then provides an output in the form of layer-by-layer

computer instructions for the additive manufacture machine. It will be understood that the methods of the present invention may include implementations in which the optimisation may also include taking into account the required or ideal surface roughness of flow-developing surfaces. For example, the orientation of surfaces with respect to the build direction may be adjusted depending upon the desired level of surface roughness.

The instructions from the preparation software are uploaded to the controller 30 so that the additive manufacture process can commence. An initial layer of powder is provided in the powder bed 14 supported by the platform 16 which will initially be in an upper position. The powder supply may pass a roller or the like across the powder to ensure it is evenly filled and suitably compacted. The chamber is evacuated by the outlet 24 before being filled with inert gas by the inlet 26. The laser 20 is then used to selectively scan the powder bed 14 in a two-dimensional scan pattern to melt powder so that it will solidify and form a first layer of the component 50 on the platform. In a powder bed fusion process, it is essential that the scan parameters (for example laser power, spot size and scan speed) are selected to achieve a full melt of the powder in each part of the component. This ensures that a fully dense part is formed with a homogenous mass and low porosity.

20

After the first layer of the powder has been fully selectively scanned, the platform 16 is moved downward and a subsequent layer of powder is added to the powder bed 14 by the supply. The scanning for the subsequent layer is then carried out with melted regions fusing not only with adjacent parts of the new layer but also with those of the immediately underlying layer. This process is then repeated until sufficient layers have been stacked in the vertical direction to form the full geometry of the part 50.

25

In order to verify the effectiveness of embodiments of the present invention, the applicants carried out experimental procedures to confirm the influence of surface

roughness to flow control in a swirl burner of the type which could be used in a gas turbine engine. The experiments will now be described by way of example to provide the skilled person with an understanding of the invention. The impact of surface roughness was evaluated based upon a variety of factors including the resulting swirl
5 flow boundary layers and turbulence, flame stability limits, and emissions (this being accomplished through the use of high-speed, time-resolved velocimetry, OH* chemiluminescence, and dynamic pressure measurements).

As seen in figure 2, experiments were performed based upon a radial-tangential gas turbine swirler 100. The swirler 100 includes an inlet 110 for premixed fuel and air, a radial/tangential swirler 120 and a burner exit nozzle 130. To allow optical access to the flame during experimental trials the burner exit nozzle 130 is positioned within a quartz tube 140. The swirler 100 selected for test purposes is part of a known 2nd generation high-pressure generic swirl burner ("HPGSB-2") and is useful for verifying
15 impacts of embodiments of the invention as it is well-characterized in terms of its stable operating limits (e.g. lean blowoff and flashback), fuel flexibility, and emissions. The HPGSB-2 is modular in that it can be operated with a variety of swirl numbers (S_g) and confinements, for the present examples study, S_g was held constant at 0.8.

20 The configuration of the swirler 120 can be further seen in the schematics of figure 4. The swirler 120 includes a base 122 which has a flange 123 on its rear face and supports a plurality of swirler vanes 125 on its opposing face. As can be seen the swirler 120 has nine circumferentially distributed swirl vanes 125. The vanes 125 surround a centrally located nozzle 126 in the base 122. The vanes 125 extend away
25 from the base 122 in the axial direction, are angled radially and each have a generally flat inner surface 127 and curved outer surface 128.

With reference to figure 3, embodiments of the invention were evaluated by comparing a "traditional" machined swirler 8M with two Additive Layer Manufactured

(“ALM”) swirlers, one “raw” swirler 8R and another “post-processed” swirler 8G. All three swirlers have the same bulk geometric features, as shown schematically in figure 4. The swirler geometry yields a geometric swirl number of $S_g = 0.8$. The traditional swirler 8M was formed from 304 stainless steel with machined surfaces. Both ALM swirlers were manufactured by using a Renishaw RenAM 500Q powder bed SLM machine, which utilizes four 500 W lasers and an argon inert atmosphere. The powder used for construction was Inconel 625 (commercially available from, for example, LPW Technology Ltd), selected due to its high strength characteristics at elevated temperature. Both swirlers were built in a common ALM process such that they were co-located on a single build plate along with 6 mm diameter tensile bars and a density block for post-build quality assurance. A post-build heat treatment was utilized to eliminate residual stresses induced during the build. Support structures were removed from all surfaces of the swirlers. The post-processed swirler 8G was subsequently post-processed using a manual grit blast (Guyson Saftigrit Brown 24, Rolls Royce CSS12 standard) and bead (Guyson Turbonox) application to improve the swirler surface finish.

All combustion studies were conducted under lean conditions (in which the equivalence ratio “ ϕ ” is $0.50 < \phi < 0.95$), with fully premixed methane-air at a fixed thermal power of 25 kW. The fuel flow rate was fixed to maintain the power density scaling (250 kW/MPa) required for future pressurized combustion experiments. The stable operating limits for each of the 3 swirlers were obtained by varying the equivalence ratio from Lean Blow Off (“LBO”) to a noted rich stability event or $\phi = 0.95$, whichever occurred first. The burner was ignited at a stable operating condition and ϕ was reduced towards LBO by increasing the air mass flow rate and then increased towards stoichiometry by reducing the air mass flow rate. LBO was categorized by abrupt flame transition into a low frequency, high amplitude limit cycle instability characterized by macro flame extinction and reignition events. The rich stability limit was characterized by one of two events, an abrupt change in the dynamic pressure amplitude into a limit cycle as ϕ was increased (as seen with swirler 8R) or $\phi = 0.95$

(as seen with swirlers 8G and 8M), at which high NO_x and CO emissions would make operation unfeasible.

With a fixed CH_4 flow rate of 0.5 g/s, the range of air flows achieved in the experiments
5 were 9.08 g/s to 17.14 g/s. This yields a Reynolds number range of approximately 10500 to 19100 and mean nozzle exit axial velocities, $\bar{u}$, of 11.9 m/s to 21.6 m/s, both based on premixed reactant volumetric flow through the 40 mm ID burner exit nozzle. For Laser Doppler Anemometry (“LDA”) measurements, isothermal air flows were utilized, ensuring that temperature, pressure, total mass flow, and Reynolds number
10 at the burner exit ($\pm 3\%$) were maintained with the equivalent combustion conditions. The air and fuel flows were measured using commercially available Coriolis mass flow meters allowing for flow accuracies of $\pm 0.5\%$. Premixed burner inlet temperature (T_2) and pressure (P_2) were measured at location 110 indicated in Figure 2 by a K-type thermocouple (± 2.2 K) and a pressure transducer ($\pm 0.04\%$), respectively. Burner
15 outlet temperature (T_3 , N-type, ± 1.1 K) was measured at the exit of the quartz cylinder. A dedicated swirler pressure drop measurement, ΔP , was made with a differential pressure transducer ($\pm 0.04\%$ full scale to 70 kPa). Finally, dynamic pressure measurements at the burner dump plane were sampled at 4000 Hz with a piezoelectric dynamic pressure transducer (DPT) with 14.5 mV/kPa sensitivity ($\pm 15\%$)
20 and 0-350 kPa range, with postprocessing conducted via Fast Fourier Transform to identify pressure fluctuation amplitude (p'_{RMS}) as well as dominant and secondary mode frequencies, f_1 and f_2 , and their individual amplitudes, M_{f1} and M_{f2} . All other rig operating conditions (e.g. flows, temperatures, pressures) were logged at 1 Hz by a dedicated data acquisition system.

25

A number of methods were used to provide experimental diagnostics. A high-speed OH^* chemiluminescence image capture system utilised a combination of commercially available high-speed camera, relay lens, highspeed image intensifier, UV lens, and 310 nm narrow bandpass filter. For averaged images (for example figure 9) each
30 instantaneous OH^* chemiluminescence image was filtered using a 3x3 pixel median

filter and corrected for background intensity before being temporally averaged from 2000 images ($t = 0.5s$). The temporally-averaged images were then processed using a modified Abel inversion algorithm to provide an axisymmetric planar representation of the localized areas of heat release within the field of view. For phase-averaged
5 images (for example figure 13), the number of images used is directly proportional to the number of phases presented and the period of the dominant instability frequency. Temporal variation of the OH^* chemiluminescence signal is also considered through the use of an instantaneous integral intensity, I''_{OH^*} .

10 A commercially available Laser Doppler Anemometry ("LDA") System was used for characterizing the influence of surface roughness on the mean flow field and turbulence characteristics of isothermal air flow conditions in each swirler. Two flow conditions were selected, equivalent to the $\phi = 0.55$ and $\phi = 0.80$ conditions, with mean nozzle exit axial velocities of $\bar{u} = 20.7$ m/s and 14.5 m/s, respectively. This
15 maintains Reynolds number ($\pm 3\%$) with the equivalent $\phi = 0.55$ and $\phi = 0.80$ conditions, with $Re \approx 17500$ and ~ 12000 , respectively. This backscatter system utilizes a 200 mW constant wave Nd:YAG laser (532 nm) split to produce two beams, one of which is frequency shifted by a Bragg cell operating at 40 MHz. Fibre optics carry the beams to a combined transmitting/receiver optic (beam separation 38 mm,
20 focal length 500 mm) together with the detected signal produced by particles traversing the control volume. The air flow was seeded with $1 \mu m$ nominal diameter Al_2O_3 . The burst signal was processed using a dedicated processor and flow analysis software (both commercially available, for example, from Dantec Dynamics A/S) to yield the mean and RMS velocities at the control volume location. In this study, the
25 mean and fluctuating axial velocity components, u and u'_{RMS} , were measured 5 mm downstream of the burner exit nozzle. The transmitting and receiving optics were mounted on a traverse system which allowed the control volume to be maneuvered throughout the flow field. Starting from the burner centreline ($r = 0$ mm), the control volume was moved radially to a final position outside the burner exit nozzle ($r = 30$
30 mm). Measurements were taken at 1 mm increments for the first 15 mm and last 5 mm covered, with 0.5 mm increments used for the area either side of the burner

nozzle ID wall (15 mm < ID wall < 25 mm), for a total of 41 measurements. To investigate the near-wall velocity and turbulence intensity at the burner exit, the isothermal flow measurements were conducted with the quartz confinement removed from the HPGSB-2. Data capture rates up to 40000 points or 25 s of capture
 5 time were achieved by controlling the seeding rate and density.

Exhaust gas sampling and analysis was conducted via an industry standard system (available, for example, from Signal Gas Analysers Ltd.). An equal area sample probe was placed 200 mm downstream of the exit of the cylindrical quartz confinement. The
 10 exhaust gas sample line, filter, and distribution manifolds were maintained at 433 K, while a heated pump was used to draw sample into the analyser setup. Total NO_x concentrations were measured using a heated vacuum chemiluminescence analyser (Signal Instruments 4000VM), calibrated in the range of 0-39 ppmV. Total NO_x concentrations were measured hot and wet to avoid any losses, with data presented
 15 at the equivalent dry conditions using a calculated equilibrium water molar fraction, X_{H2O}, and adiabatic flame temperature ("AFT"). NO_x emissions were then normalized to a reference value of 15% O₂ concentration per Equations 1 and 2, respectively. Exhaust molar O₂ measurements were made using a paramagnetic analyser (Signal Instruments 9000MGA), calibrated in the range 0 - 22.52 %vol O₂. Typical
 20 uncertainties of approximately 5% of measurement account for analyser specifications, linearization, and accuracy in span gas certification.

$$NO_{x,dry} = \frac{NO_{x,meas}}{(1-X_{H2O})} \quad (1)$$

$$NO_{x,dry,15\%O_2} = NO_{x,dry} * \left(\frac{20.9 - O_{2,ref}}{20.9 - O_{2,meas}} \right) \quad (2)$$

The form and surface roughness of 5 separate surfaces on each of the two ALM
 25 swirlers (8R and 8G) and the machined swirler (8M) were conducted using a commercially available profilometer, used extensively for tribology and SLM surface

roughness studies. A standard inductive pick-up stylus arm with a 90° conisphere diamond styli with 2 µm nominal radius was used with a 16 nm vertical resolution. This inductive gauge is calibrated over a 12.5 mm radius. As far as reasonably practicable, measurements and the corresponding surface roughness analysis were performed per the guidelines given in BS EN ISO 4287/4288. For example, the upper and lower cut-off lengths for the ALM components were 2.5 mm and 0.0025 mm, respectively due to anticipated mean surface roughness, R_a , values greater than 2 µm. The upper and lower cut-off lengths for the machined swirler were 0.8 mm and 0.0025 mm, respectively.

10

As shown in figure 5, for each swirler, five separate surfaces were characterized as detailed below. The axis of the ALM build is shown in the figure with the z axis being the build direction and the general orientation of the surface roughness measurement is noted for each surface:

15 1) Nozzle ID ("ID"): The inner diameter of the 40 mm swirler exit nozzle was measured at 9 locations, thus 40° intervals, in the direction from the swirler base plate to the edge of the nozzle (also the direction of air/fuel flow). The measurement length was 20 mm. This surface is parallel to the ALM build direction.

20 2) Swirl Base ("SB"): Each swirler consists of nine swirl vanes which stand perpendicular to a flat base plate. Between each swirler, this base was measured from near the exit nozzle ID to the OD of the swirler base plate. The measurement length was 20 mm. This surface is perpendicular to the build direction.

25 3) Swirl Curve ("SC"): On the centre of each swirl vane, the curved surface of the swirl vane was measured along the radius, providing a measure of the radius and the surface roughness. The measurement length was 7 mm, limited by the range of the inductive gauge. This surface is perpendicular to the build direction.

4) Swirl Curve Length ("SCL"): On the centre of each swirl vane, the length of the curved surface was measured in the direction from the base plate to the top of the swirl vane. The measurement length was 10 mm, limited by the length of the

swirl vane perpendicular to the swirl base plate. This surface is parallel to the build direction.

- 5) Swirl Flat Length ("SFL"): The flat on the trailing edge of the swirl vane surface was measured in the direction from the base plate to the top of the swirl vane.
- 5 The measurement length was 10 mm. This surface is parallel to the build direction.

Surface roughness and profile measurements were made on each swirler and are provided in Table 1. Several known surface roughness parameters are provided in which: R_a is the arithmetic average surface roughness; R_q is the Root Mean Square surface roughness; and R_z is the ten-point average surface roughness as a measure of

10 five highest peaks and five lowest valleys.

Swirler	Measurement	Measurement Location {{{ or L, relative to ALM build direction}}				
		Nozzle ID {{{}}	Swirler Base {L}	Swirler Curve {L}	Swirler Curve Length {{{}}	Swirler Flat Length {{{}}
8R	R_a (μm)	8.88	11.09	8.31	8.31	8.59
	R_q (μm)	10.97	14.92	10.29	10.14	10.64
	R_z (μm)	53.61	78.11	50.01	47.91	54.06
8G	R_a (μm)	5.48	8.12	5.13	4.73	4.92
	R_q (μm)	6.96	10.36	6.36	6.05	6.21
	R_z (μm)	35.50	49.57	31.15	31.06	33.54
8M	R_a (μm)	1.39	1.76	0.67	0.97	1.26
	R_q (μm)	1.88	3.31	1.04	1.24	1.75
	R_z (μm)	8.96	11.21	4.27	6.12	9.07

Table 1: Average Surface Roughness Measurements for Each Generic Swirler

- 5 The average overall R_a value for the “raw” ALM swirler, 8R, is approximately $8.5 \mu\text{m}$, if the swirler base is neglected due to its distinctly different finish. The swirler base shows higher surface roughness across both ALM components, as the result of partially-bonded powder particles on the surface perpendicular to the build direction, which does not undergo any further laser sintering during the build-up of the swirl
- 10 vanes. Each swirler was subjected to further sintering as each was built up from the base, resulting in an improved finish on its outer surfaces, including along the swirler curve direction, resulting in a difference in surface finish between the swirler base and swirler curve despite both being perpendicular to the build direction. These values of R_a are similar to those seen in the literature for “raw” unfinished ALM components
- 15 and were consistent with a further swirler built during the same ALM process.

The grit-blasted swirler, 8G, shows a reduction in all surface roughness values of approximately 40% compared to the unfinished ALM component. This difference appears to be primarily a result of a reduction in surface peak values.

20

The traditionally machined swirler, 8M, was found to have R_a values of approximately 15% of that for the “raw” swirler, 8R, and approximately 25% of that for the grit-blasted swirler, 8G.

In addition to the surface roughness measurement, a measure of the swirler radius was also made along the “SC” surface, a critical flow-developing surface. The nominal design value of this radius is 12 mm for all swirlers. The ALM swirl vanes were found
 5 to better replicate this curved profile than the machined swirl vanes, with an average value of 11.971 mm compared to 11.864 mm, respectively. These dimensional deviations fall within standard tolerance grades. Figure 6 graphically shows the radial profile measurement of the swirl vane and clearly illustrates the increased surface roughness of the ALM swirlers.

10

In order to characterise turbulent swirling flows temporally and spatially resolved measurements are required. It is desirable to characterise unique flow structures, such as the central recirculation zone (“CRZ”) or turbulent shear layer, which are developed as a result of pressure and velocity gradients in the flow field. LDA is one
 15 such measurement that provides simultaneous temporal and spatial measurements of both mean and fluctuating axial velocity components, with spatial resolution dictated by the laser control volume size and traverse increments. By combining the mean and fluctuating axial velocity components, u and u'_{RMS} , it is possible to obtain a measure of the turbulence intensity as given in Equation 3:

$$Turbulence (\%) = 100 * \left(\frac{u'_{RMS}}{u} \right) \quad (3)$$

20

The values used in Equation 3 were weighted by the transit time of seed particles through the control volume, so as not to bias regions of high velocity which would be expected to have higher seeding densities. Axial velocity and turbulence intensity profiles measured 5 mm above the burner exit are given in Figures 6 and 7,
 25 respectively. Two isothermal air flow conditions were investigated, with equivalent total mass flow to $\phi = 0.55$ (Figures 7a and 8a) and 0.80 (Figures 7b and 8b) combustion conditions, yielding bulk mean axial velocities of $\bar{u} = 20.7$ m/s and 14.5 m/s, respectively.

Figure 7 details the axial velocity component along the radial direction, providing indication of the flow structures mentioned previously, with a CRZ identified by negative magnitude velocities from $0 < r < \sim 10$ mm, a shear layer with $u = 0$ m/s velocity, positive outward flow from ~ 10 mm $< r < 30$ mm and an outer recirculation zone causing reduced velocities after the swirl nozzle ID wall located at $r = 20$ mm. At both flow rates, the maximum positive axial velocity is seen to reduce with increasing surface roughness. For example, in figure 7(a) maximum positive axial velocity decreases by 6.6% from 28.2 m/s (8M) to 26.3 m/s (8R) for the same volumetric flow.

This is due to an increase in the pressure drop across the swirler with increasing surface roughness, with ΔP increasing from 0.96 kPa (8M) to 1.11 kPa (8R) for the $\phi = 0.55$ flow condition. An increase in the CRZ strength is also noted, with higher magnitude negative axial velocities for the 8M swirler compared with the ALM swirlers. This corresponds to the observed outward radial shift of the velocity peak with reduced surface roughness. The velocity profiles are notably more variable at the reduced flow rates (Figure 7b), influenced by higher turbulence fluctuations, as shown in Figure 8b, particularly near the nozzle ID wall at $r = 20$ mm.

At the high flow conditions (see figure 8(a)), the turbulence intensity near the nozzle ID wall is shown to increase with increasing surface roughness. At the low flow condition (see figure 8(b)), the results are more variable with a notable response from the 8R swirler at $\phi = 0.80$ conditions. The reduction in axial velocity magnitude near the nozzle ID wall and corresponding increase in turbulence intensity suggests increased vortex formation in this region, interpreted by the LDA system as contributing a negative axial velocity component to the flow. This increasing turbulence intensity serves to spread the region of maximum velocity gradient seen in the profiles in figure 7. By fitting a high-order polynomial function to the velocity profiles in Figure 7 and evaluating its first derivative to locate maxima and minima on either side of the peak positive axial velocity position, the width of the maximum velocity gradient could be evaluated. The width of this region increases by 9.6% from 8M to 8R (11.5 mm to 12.6 mm) at $\phi = 0.55$ conditions and by 14.6% from 8M to 8R

(12.6 mm to 14.5 mm) at $\phi = 0.80$ conditions. Such a response is considered to correspond to a reduced boundary layer thickness at the burner exit nozzle with increasing surface roughness of the nozzle ID wall.

- 5 Further combustion experiments were conducted at fixed thermal power of 25 kW and a range of equivalence ratios to evaluate the influence of varying surface roughness on the flame location and stable operating range. While a wide operating range was investigated, the results presented herein focus first on the same flow conditions as presented in the isothermal velocimetry measurements discussed
10 above, namely $\phi = 0.55$ and 0.80 . Figure 9 provides Abel-transformed OH^* chemiluminescence images for these two equivalence ratios along with $\phi = 0.75$ for swirlers 8R (figure 9(a)), 8G (figure 9(b)), and 8M (figure 8(c)). The field of view expands axially downstream from the burner exit nozzle ($y = 0$ mm) and radially outward from the burner centreline ($r = 0$ mm). Images for each fixed ϕ are presented
15 with a false colormap normalized to the maximum OH^* intensity value in each set.

As expected for this burner configuration and conditions, each swirler generates a V-shape flame with the flame lying on the outward expanding shear layer of near-zero axial velocity between the CRZ and the outward positive flow. The flame is also
20 observed to transition towards the burner exit nozzle along the shear layer as ϕ is increased, resulting from a combination of reduced axial velocity and increased burning rate. For the $\phi = 0.55$ condition, the area of increased heat release is observed to initiate at a location ($r = 10$ mm, $y = 5$ mm) similar to that identified as the shear layer in the corresponding isothermal flows (figure 7a), with the shear layer (and
25 flame) shifting radially outward with a reduction in surface roughness. A similar response can be seen for the $\phi = 0.75$ and $\phi = 0.80$ conditions. The applicants consider this to be indicative that, in addition to influencing the axial velocity component, the surface roughness may also have an effect on the tangential velocity component (and thus, local swirl number) at the burner exit nozzle.

Also of interest is the change in OH* chemiluminescence intensity and location of maximum intensity. For both $\varphi = 0.55$ and $\varphi = 0.80$, the maximum OH* intensity is measured in the 8R swirler flame, and decreases with decreasing surface roughness. The applicants attribute this to enhanced heat release along the shear layer induced
5 by the increased turbulence intensity noted in figure 8. This acts to increase localized flame consumption speed.

At $\varphi = 0.75$, the maximum OH* intensity is nominally constant between the 8R and 8G swirlers, with the 8G swirler shown to exhibit bimodal stability at this condition, as
10 discussed further below. However, this is only a localized effect as the exhaust temperatures for all three swirlers are $T_3 = 1204 \pm 6$ K, 1270 ± 5 K, and 1282 ± 4 K for $\varphi = 0.55$, $\varphi = 0.75$, and $\varphi = 0.80$, respectively. As the swirler surface roughness is decreased (left to right for fixed φ in figure 9), the flame is observed to transition axially upstream and radially outward. This is in agreement with the change in the
15 velocity profiles for the similar isothermal flow conditions presented in figure 7 and is further confirmed by the plot in figure 10 of the OH* chemiluminescence intensity centroid location. Figure 10 provides a measure of the movement of the heat release zone with change in surface roughness and burner operating conditions from $\varphi = 0.55$ (closed symbols) to $\varphi = 0.75$ (hatched symbols) to $\varphi = 0.80$ (open symbols). An
20 increase in flame angle relative to the burner centreline is also quantified for a reduction in surface roughness, particularly at $\varphi = 0.55$.

The applicants have recognised that it is notable that as the surface roughness increases, the flame stabilization location shifts towards the radial position of the
25 nozzle ID wall at $r = 20$ mm, indicative of the increased influence that this feature imparts on the flow field.

The dynamic behaviour of the 25 kW flame with varying swirler surface roughness was also considered across the entire operating range using high-speed dynamic pressure

and OH* chemiluminescence. A measure of the dynamic response of the system is given in figure 11, which plots the dynamic pressure amplitude, p'_{RMS} (figure 11(a)) and dominant mode frequency, f_1 (figure 11(b)), against equivalence ratio. In general, the operating range is bounded by limits marked by LBO at approximately $\phi = 0.50$ and a rich operating limit, either $\phi = 0.81$ (8R) or $\phi = 0.95$ (8G and 8M). The 8M swirler has distinct stable operating regimes between $0.50 < \phi < 0.60$ and $0.65 < \phi < 0.90$. Increasing the surface roughness from 8M to 8R is shown to reduce the instability amplitude observed at $\phi = 0.60$. However, increased surface roughness in the 8R swirler introduces a potential thermoacoustic instability at $\phi = 0.81$ at approximately 400 Hz. This is also suggested in figure 12(a), where the secondary mode frequency, f_2 , is observed to be equal to $2f_1$ (i.e. second harmonic) for the 8R swirler at $\phi = 0.81$ (Note the value of f_2 is off-scale in this plot). The applicants attribute this to the unique near-wall turbulence profile seen for the 8R swirler at near identical flow conditions in figure 8(b), which would serve to modulate the flame surface, imposing heat release fluctuations which are in phase with the dynamic pressure fluctuation, leading to a limit cycle instability. Of the three swirlers, the grit-blasted 8G swirler shows the widest stable operating range of all three swirlers, with p'_{RMS} below 0.4 kPa for the range $0.52 < \phi < 0.90$. The applicants consider this to support that a level of surface finish for ALM radial-tangential swirlers could yield an advantage to stable operation across a wide range of flow conditions.

As discussed above, Figure 12 provides insight into the dynamic behaviour of each individual swirler, with 8R (Figure 12(a)), 8G (figure 12(b)), and 8M (Figure 12(c)). The frequencies of both the first (f_1 , open symbols) and second (f_2 , closed symbols) dominant dynamic pressure fluctuation modes are plotted against equivalence ratio along with the normalized amplitude of the second mode to the first mode (M_{f2}/M_{f1} , hashed symbols). Dashed lines are imposed for clarity only. The applicants believe that when M_{f1}/M_{f2} is near unity that the system could be considered bimodal. The applicants identified conditions where lean stability mode switching could occur (indicated in figure 12 by arrows). Bimodal stability was first identified in swirler 8G at $\phi = 0.75$, where $M_{f2}/M_{f1} = 0.89$. The applicants consider it of note that it is at this

ϕ in Figs. 8 and 9, where the 8G and 8R swirler OH^* chemiluminescence intensity and centroid location are nearly identical, providing indication of the increasing influence of the bimodal stability on flame heat release with increasing reactivity. Figure 12(a) provides evidence of a mode switch from a ~ 250 Hz dominant frequency to ~ 400 Hz dominant frequency near $\phi = 0.55$ in the 8R swirler with increasing ϕ . A similar mode switch shifts to higher equivalence ratio ($\phi = \sim 0.64$) for the 8G swirler in figure 12(b). Both a lean ($\phi = \sim 0.57$) and near-stoichiometric ($\phi = \sim 0.92$) mode switch were observed in the 8M swirler (Figure 11.c). This behaviour was further confirmed by evaluation of the time varying II'_{OH^*} signal at conditions where $M_{f1}/M_{f2} = \sim 1$.

10

It can also be seen in Figures 11 and 12 that all swirlers experience a similar LBO instability, with identical low frequency of $f_{\text{LBO}} = 7.18$ Hz (shown in figure 11(b)), confirmed by both dynamic pressure measurement and instantaneous OH^* chemiluminescence measurement. For example, in the 8R LBO case shown in figure 13, the phase difference between time varying II'_{OH^*} and p' signals was measured as 37° , satisfying the Rayleigh criterion for instability. Phase-averaged imaging in figure 13 of this low frequency, high-amplitude instability from the 8R swirler at $\phi = 0.515$ is produced using 64 images for each phase, for a total time between images of $t = 0.016$ s.

20

This instability is characterized by bulk flame extinction and reignition events, with flame detachment from the burner exit nozzle, downstream axial motion and reduction in heat release, and then reignition of the fresh incoming premixed fuel/air through the CRZ, and finally reattachment to the burner exit nozzle. A similar LBO instability was observed for the 8M swirler at ambient temperature conditions. The instability frequency appears to be independent of the swirler surface roughness; however, there is a slight lean shift in LBO equivalence ratio with decreased surface roughness. This suggests that the 8M swirl flame, with its stronger CRZ, is able to maintain stable combustion under highly turbulent conditions, as local temperatures

in the flow field would be increased at the root of the flame, resulting in increased reactivity.

Exhaust NO_x measurements were taken at each experimental condition with each
5 swirler to identify any potential contribution or reduction from the change in surface
roughness. NO_x production in these lean premixed flames is expected to be
dominated by the thermal NO_x pathway. However, given that swirler surface
roughness has been shown to influence the flow field, turbulence intensity, and flame
stabilization location, the applicants anticipated a measurable influence on NO_x
10 emissions. By maintaining near identical volumetric flow through each swirler for a
fixed equivalence ratio, AFT could be isolated as a contributing factor to thermal NO_x
production. This can be observed in figure 14, which shows the exponential response
in measured NO_x formation with increasing AFT (thus, increasing ϕ). NO_x emissions
below 35 ppmv could be achieved across a wide range of AFT. Within the
15 measurement error of the gas analysis system, NO_x emissions at AFT $\leq$ 2000 K are
nominally similar for all swirlers, with sub-5 ppmv NO_x achievable under stable
operating conditions. Above 2000 K, however, there is an observable offset between
the machined swirler, 8M, and the ALM swirlers, 8R and 8G. This behaviour is more
apparent in Figure 15, which plots measured NO_x emissions against the inverse of a
20 representative swirler surface roughness value taken as Ra of the swirler nozzle ID
(surface roughness decreasing from left to right). Note that dotted lines are
superimposed for clarity. Under lean conditions below $\phi = 0.65$, NO_x formation
appears to be independent of the swirler surface roughness. Above $\phi = 0.65$, NO_x
formation is seen to increase with decreasing surface roughness, with over 18%
25 increase at $\phi = 0.80$.

The experimental investigations described above were found to characterize the
influence of varying surface roughness and swirl number on the resulting flow field,
flame stability, and NO_x emissions. Stable operating regimes between a well-defined
30 LBO instability and two rich stability limits were identified for a fixed thermal power

of 25 kW by varying the air mass flow rate to adjust the exit velocity and equivalence ratio. Thus, the applicants have identified potential benefits of surface features generated during ALM component fabrication. The skilled person would be able to consider these features during the design process and CFD modelling.

5

More specifically, the applicants have identified the following factors which could be utilised in embodiments of the invention:

1) Radial-tangential gas turbine swirler geometry can be achieved using ALM with high-strength, high-temperature materials. Also, a 40% reduction in Ra of “raw”
10 ALM components was achieved using a post-build grit blast. The resulting Ra remains approximately twice that of a machined part.

2) The magnitude of isothermal positive and negative axial velocities is observed to decrease with increasing surface roughness while also shifting the shear layer towards the burner centreline. The maximum axial velocity gradient width is
15 shown to increase up to 15% with increasing surface roughness, corresponding to an increase in turbulence.

3) Despite maintaining similar bulk axial velocities, OH* chemiluminescence distribution was observed to shift upstream with reduced surface roughness. Mean OH* chemiluminescence intensities were seen to increase with increasing surface
20 roughness, indicative of enhanced heat release due to an increase in turbulence and therefore flame consumption speed near the burner exit.

4) All swirlers were observed to experience a similar LBO instability with a frequency of 7.18 Hz, characterized by bulk extinction and reignition events. Transition to higher frequency modes is observed with increasing ϕ , with increasing
25 surface roughness shown to dampen lean instabilities due to enhanced turbulence, but potentially promote rich instabilities due to increased heat release fluctuations.

5) The combustion system exhibits bimodal stability, with dominant frequencies of ~250 Hz and 400 Hz across all swirlers, with surface roughness shown to influence the operating condition at which the mode switching occurs. It is posited

that high turbulence fluctuations near the nozzle internal diameter of swirler 8R contribute to the onset of a limit cycle instability near $\varphi = 0.8$, which was not observed in the other swirlers.

6.) Corrected NO_x emissions follow a thermal NO_x production trend with increasing AFT. At $\varphi > 0.65$, increasing surface roughness was observed to reduce NO_x emissions for nominally similar AFT and exhaust gas temperature due to residence time effects.

Although the invention has been described above with reference to preferred embodiments, it will be appreciated that various changes or modification may be made without departing from the scope of the invention as defined in the appended claims.

For example, the skilled person will appreciate that the teaching of the disclosure may be applied to a specific component in a manner which is optimised for that component. For example, in some applications the flow-developing surface to which embodiments of the invention are applied may be only the parts of the surface having the most influence on the required flow. For example, in some embodiments the flow-developing surface may be a leading or trailing edge of a feature such as a swirl vane or nozzle.

Further, it may be appreciated that whilst some embodiments of the invention may utilise differences in build direction as a means of effecting the surface roughness there may be other ways to distinguish between such surfaces. For example, whether or not a surface has any subsequent laser passes to fuse residual powder particles (e.g. in the build direction) may be significant. As such, the flow-developing surfaces in embodiments may be considered “completed” surfaces (e.g. surfaces which have further layers built onto them in the “z” direction). In contrast, it may be acceptable for other non-critical surfaces such as the swirler base may have a different surface

roughness as they may be considered “incomplete” surfaces (e.g. surfaces which only have a single laser pass after powder lay down, thus no more build in the “z” direction.

The skilled person may further appreciate that due to complex geometries the measurement of the R_a may be difficult for some additive manufactured components. As such, it may be necessary to determine the R_a value of a surface by building an equivalent cube using the same additive process with all parameters and material identical so as to measure the R_a value of the cube as an equivalent value. Such an approach may be applied when implementing embodiments of the invention – for example if modelling or optimising a component.

Claims

1. A combustion system component formed by metallic additive layer manufacture wherein the component has a flow-developing surface having an arithmetic average surface roughness (R_a) of between 3 and 10 μm .
5
2. The combustion system component of claim 1, wherein the flow developing surface has an arithmetic average surface roughness (R_a) of between 4.5 and 5.5 μm .
- 10 3. The combustion system component of claim 1 or 2, wherein the component is a nickel-based superalloy.
4. A combustion system component as claimed in any preceding claim, wherein the flow-developing surface extends along at least one plane which is
15 generally parallel to a build direction of the additive layer manufacture process.
5. The combustion system component of any preceding claim wherein the component is a gas turbine swirl burner and the flow-developing surface
20 includes a surface of at least one of a swirl vane and a nozzle.
6. The combustion system component as claimed in claim 5, further comprising a swirler base.
- 25 7. The combustion system component as claimed in any of claims 1 to 6, wherein at least the flow-developing surface of the component is a post-processed surface such that the arithmetic average surface roughness (R_a) is

reduced relative to the average surface roughness (R_a) provided in the additive layer manufacturing process.

8. A method of manufacturing a combustion system component, the component having at least one flow developing surface, wherein the method comprising

forming the at least one flow developing surface using a metallic additive layer manufacturing process in which the at least one flow developing surface extends along a plane which is parallel to the additive layer build direction.

9. A method of forming combustion system components, the method comprising

forming the component using a metallic additive layer manufacturing process; and

post-processing the component using abrasive blasting to reduce surface peak values and provide at least one flow-developing surface having a reduced average surface roughness (R_a).

10. The method of claim 9, wherein the post-processing comprises alumina grit blasting followed by stainless steel bead blasting.

11. The method of claim 9 or 10, wherein the post processing reduces the average surface roughness (R_a) by between 30 to 50% of the surface roughness provided by the additive layer process.

12. The method of any of claims 9 to 11, wherein the at least one flow developing surface is non-parallel to the additive layer build direction during the additive layer manufacturing process.
- 5 13. The method of any of claims 8 to 12, wherein the at least one flow-developing surface is formed with an average surface roughness (R_a) of between 3 and 10 μ m.
- 10 14. The method of any of claims 8 to 13, wherein the component is a gas turbine swirl burner and the flow-developing surface includes a surface of at least one of a swirl vane and a nozzle.
- 15 15. The method of any of claims 8 to 14, wherein the additive layer manufacturing process comprises powder bed selective laser melting.

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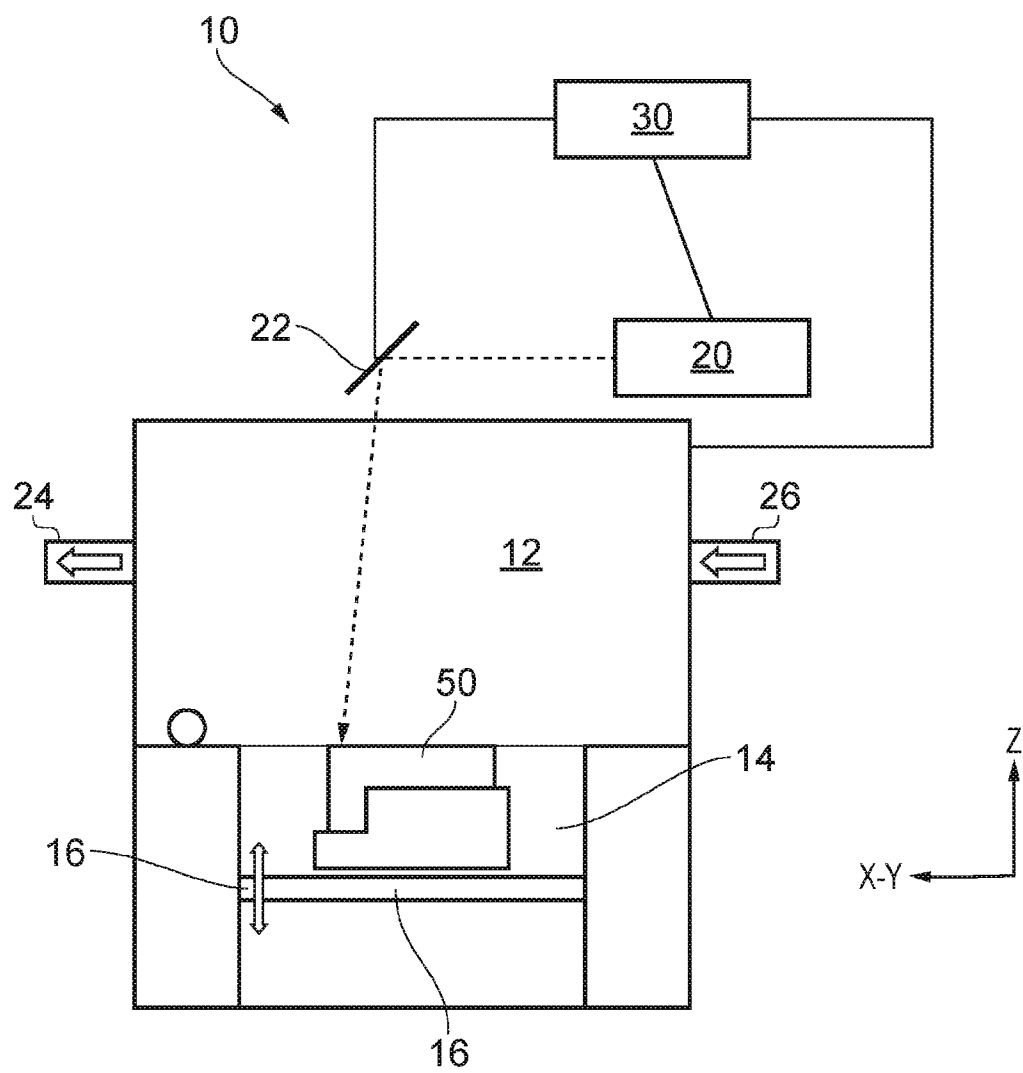


FIG. 1

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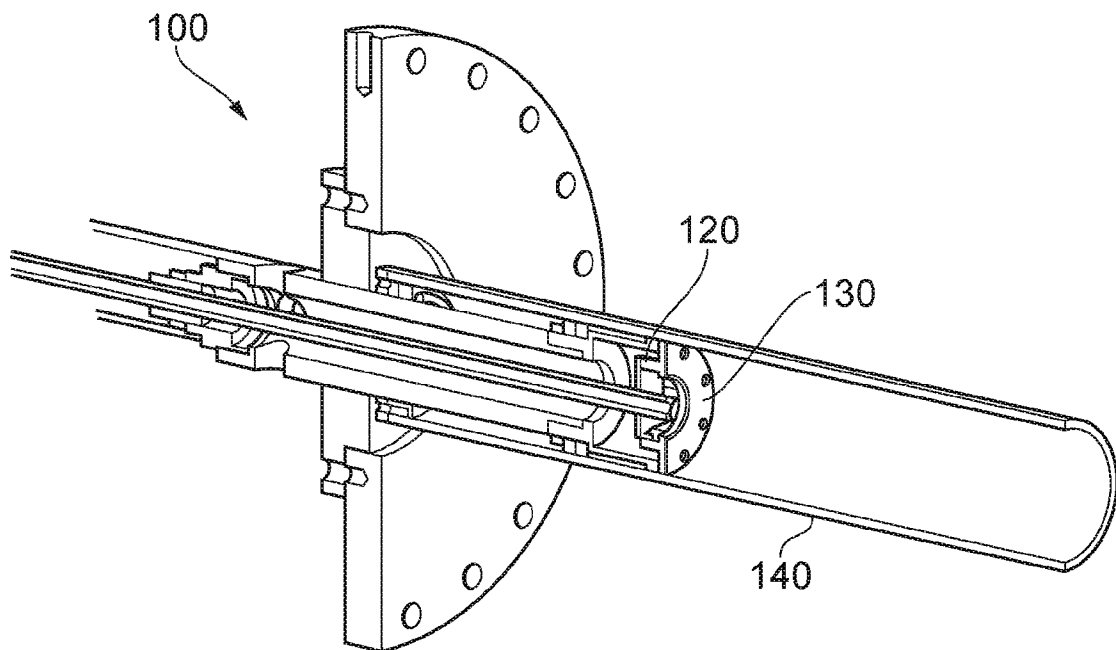


FIG. 2

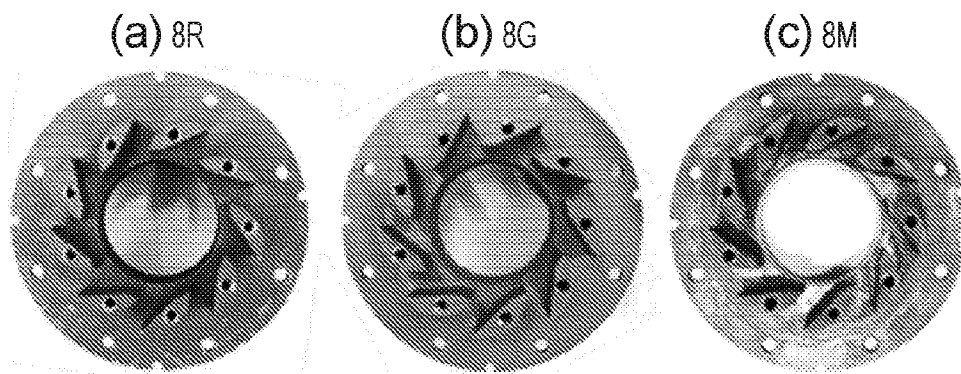


FIG. 3

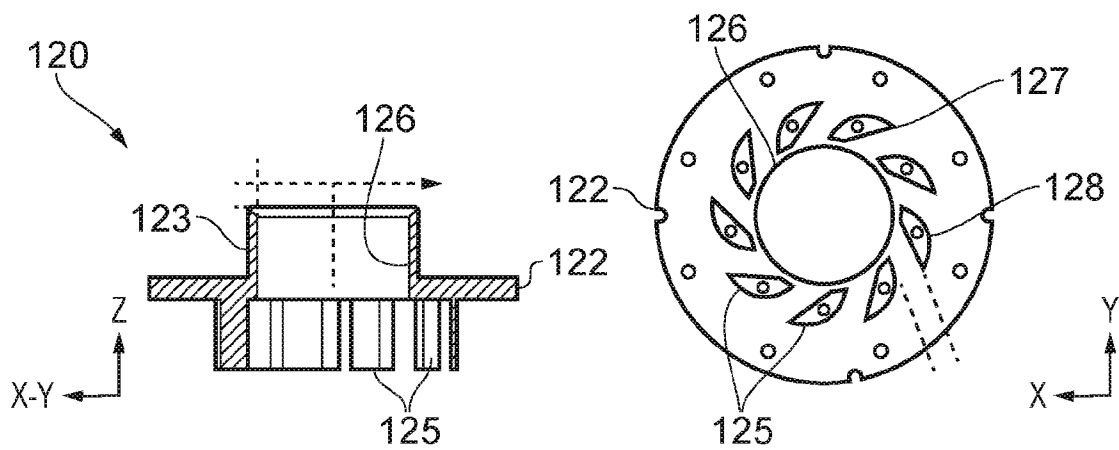


FIG. 4

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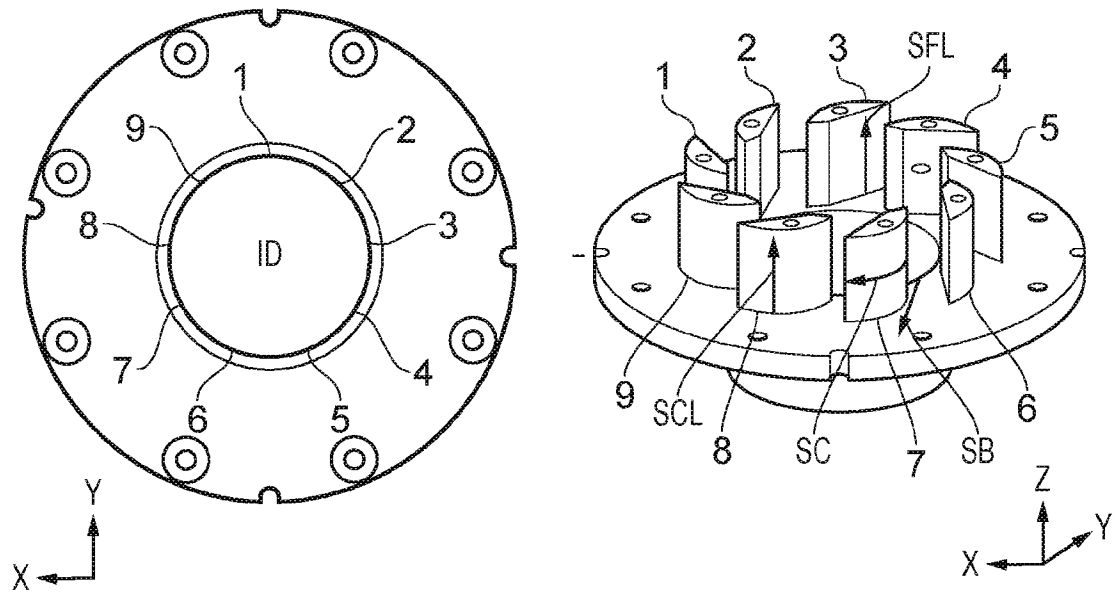


FIG. 5

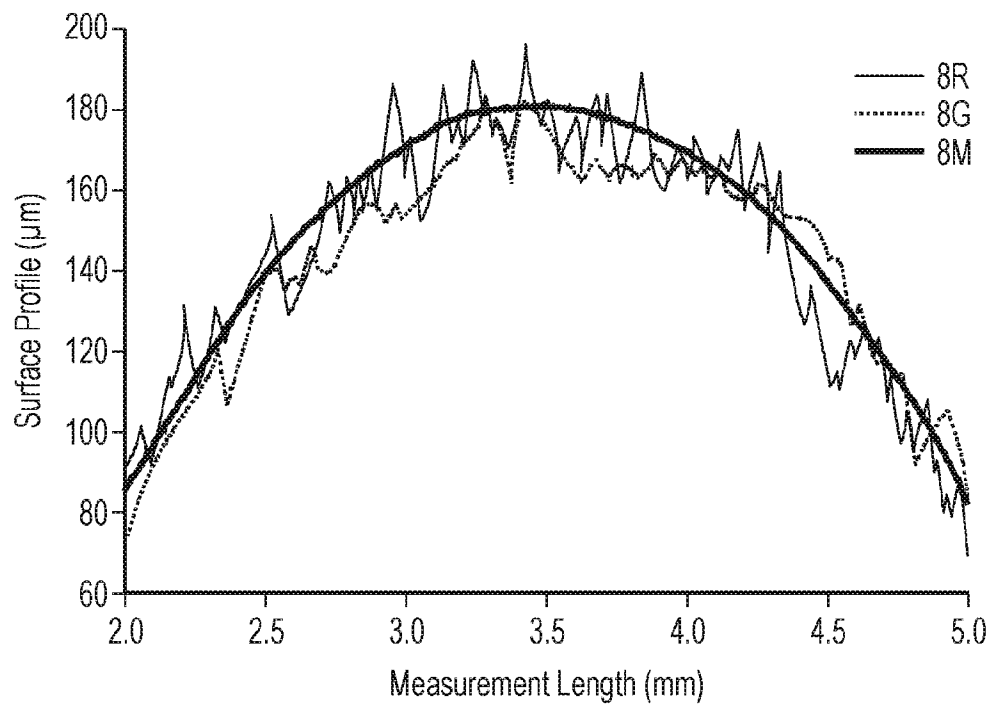


FIG. 6

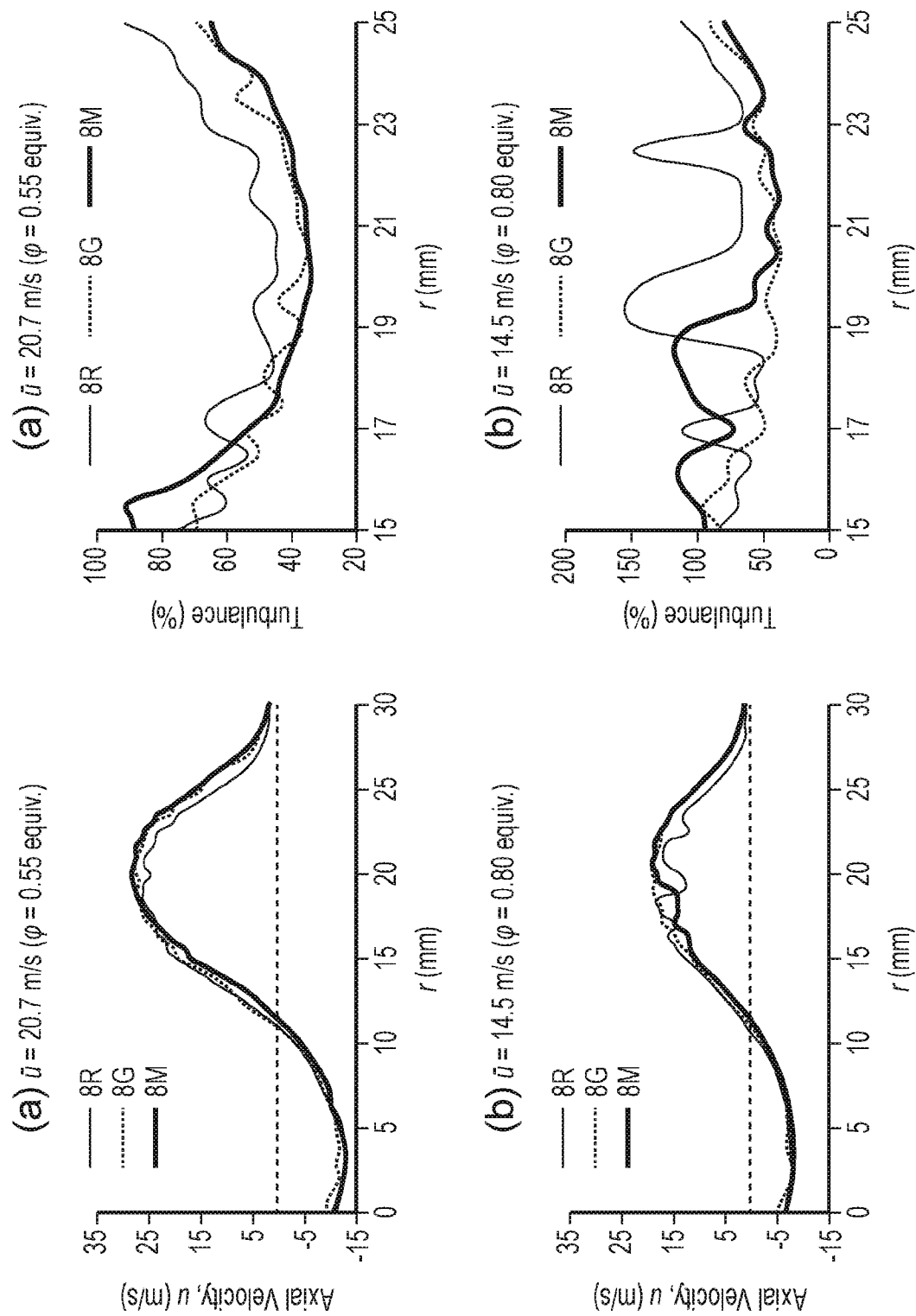
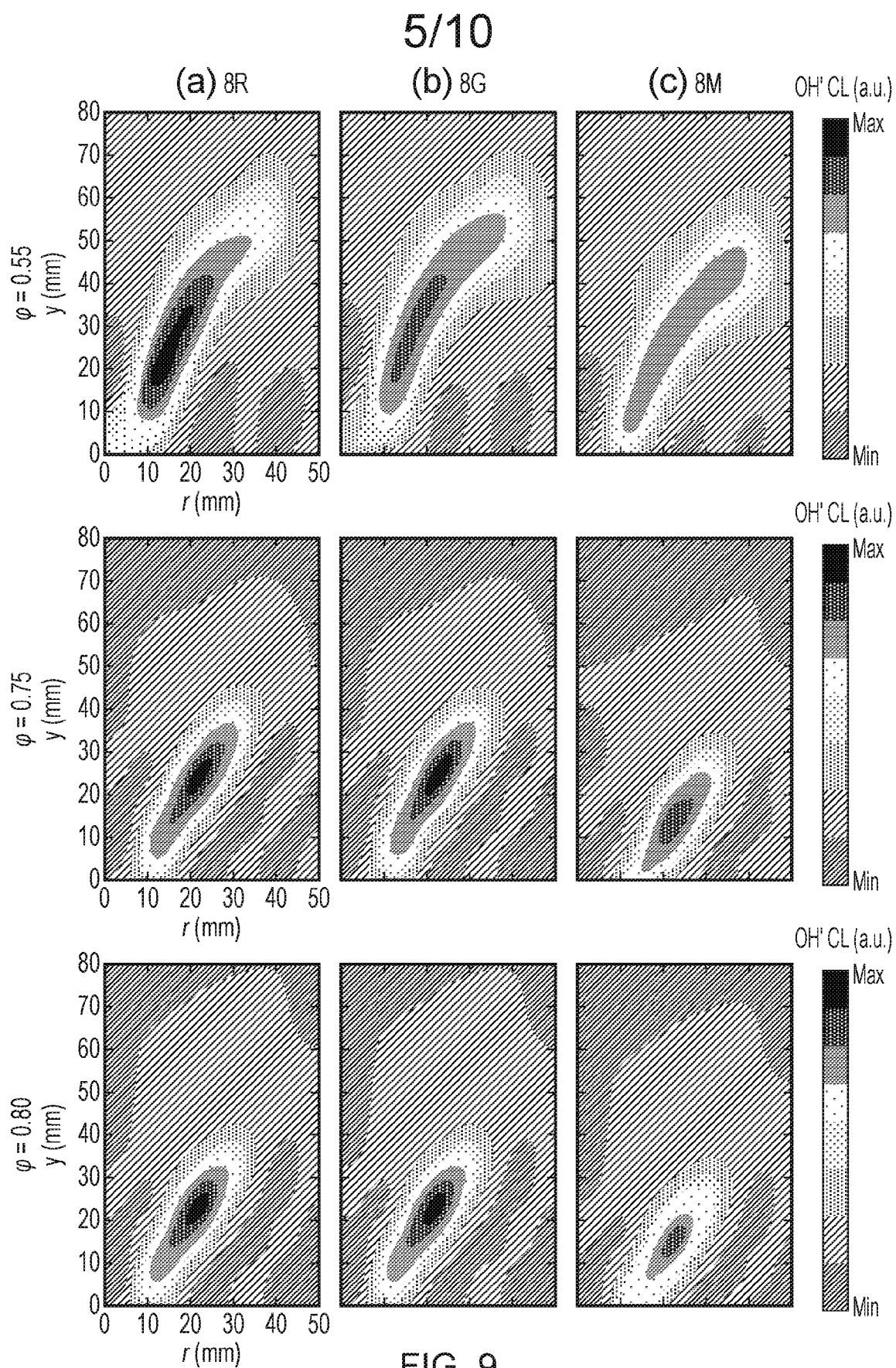


FIG. 8

FIG. 7



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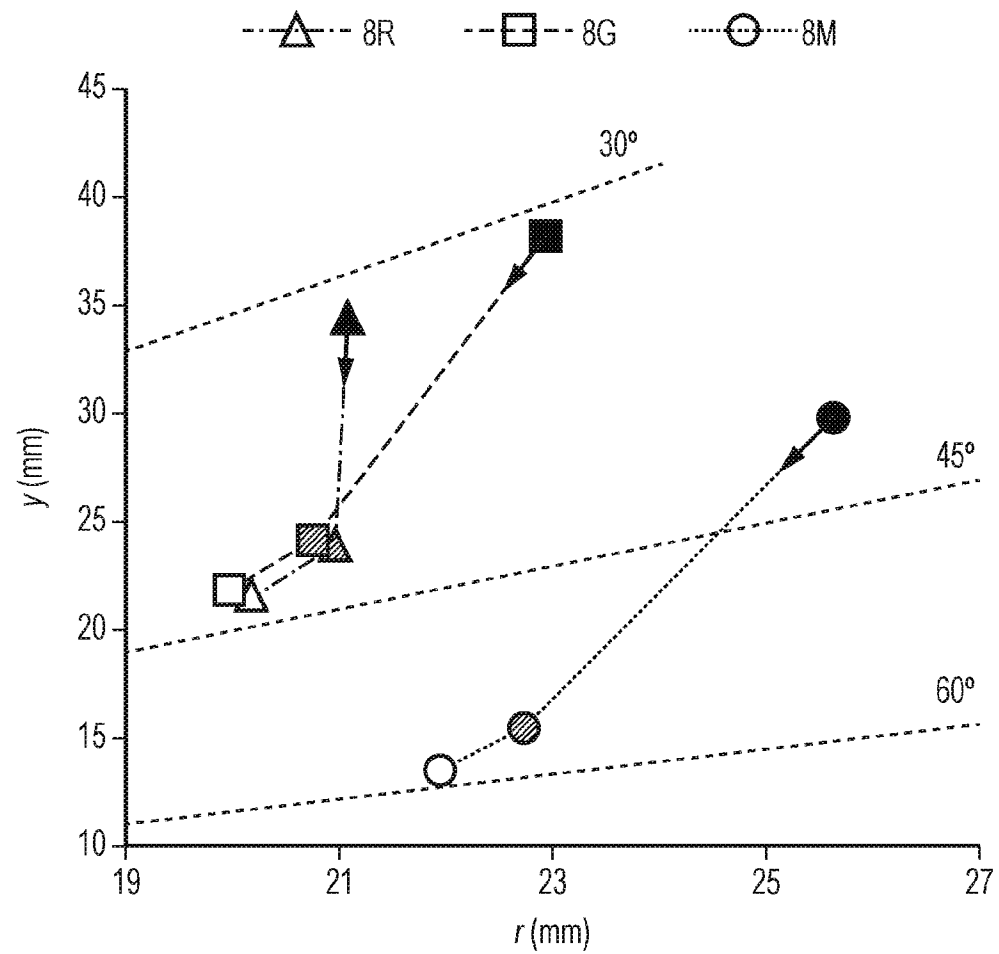


FIG. 10

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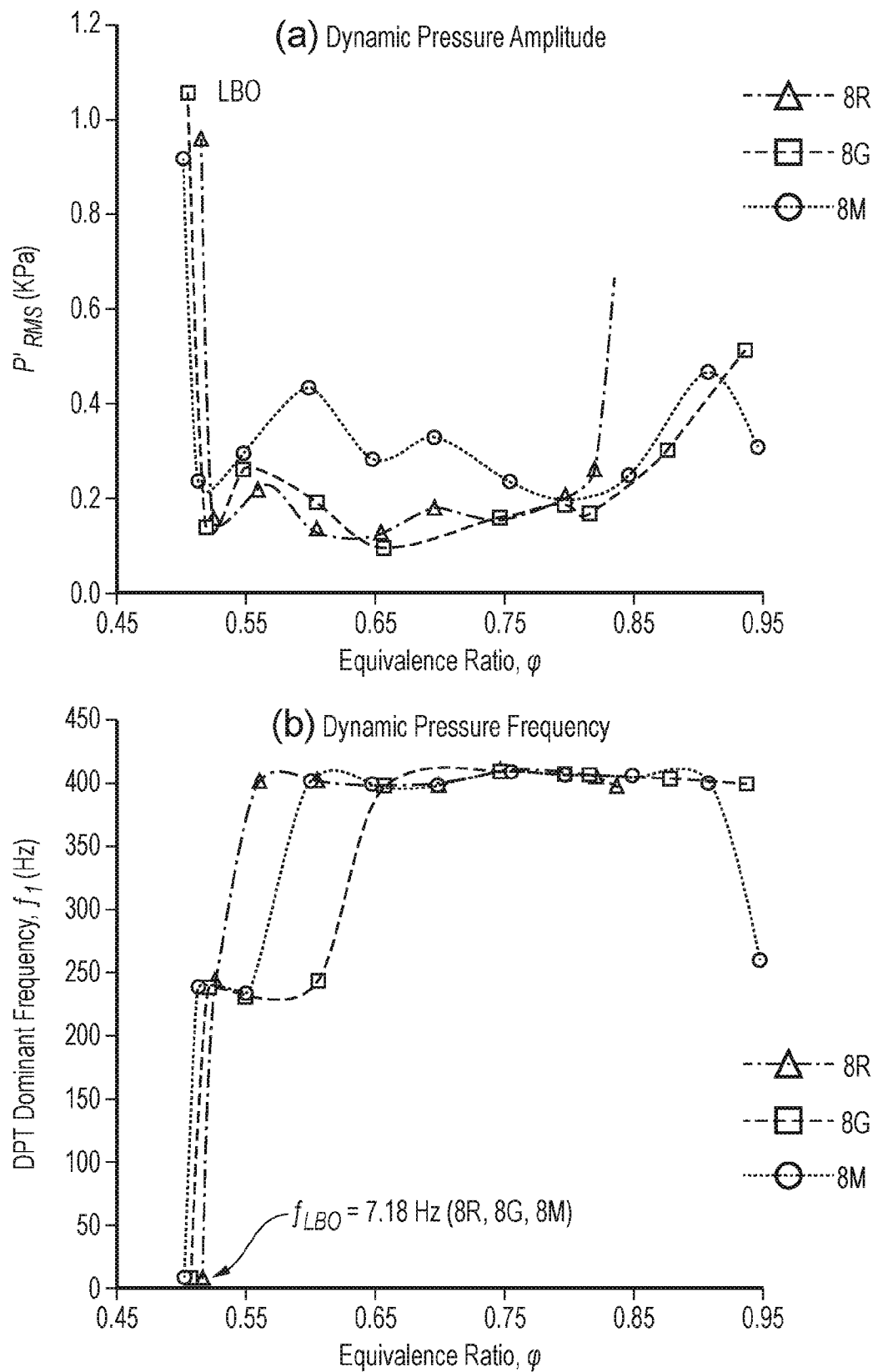
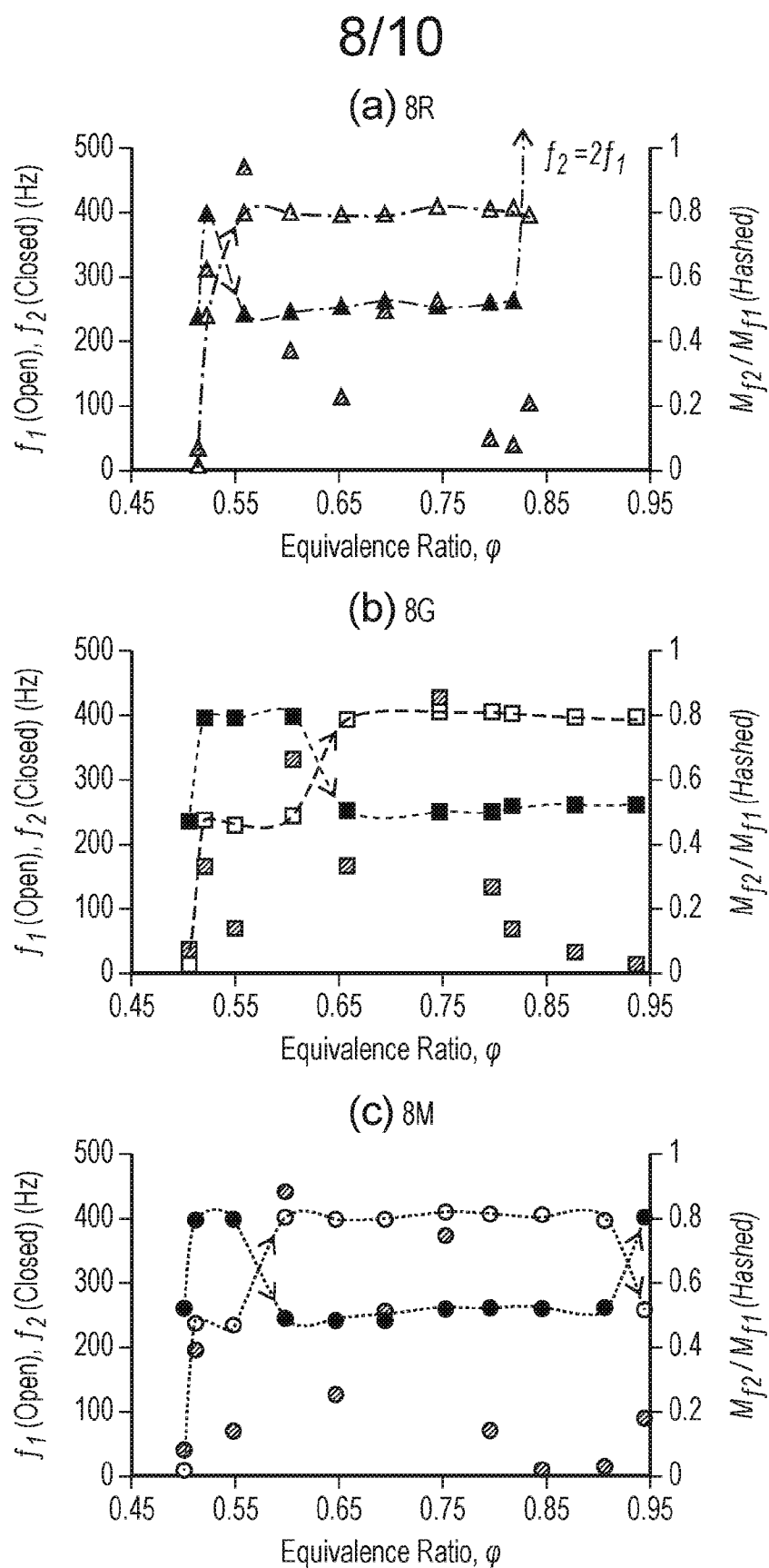


FIG. 11



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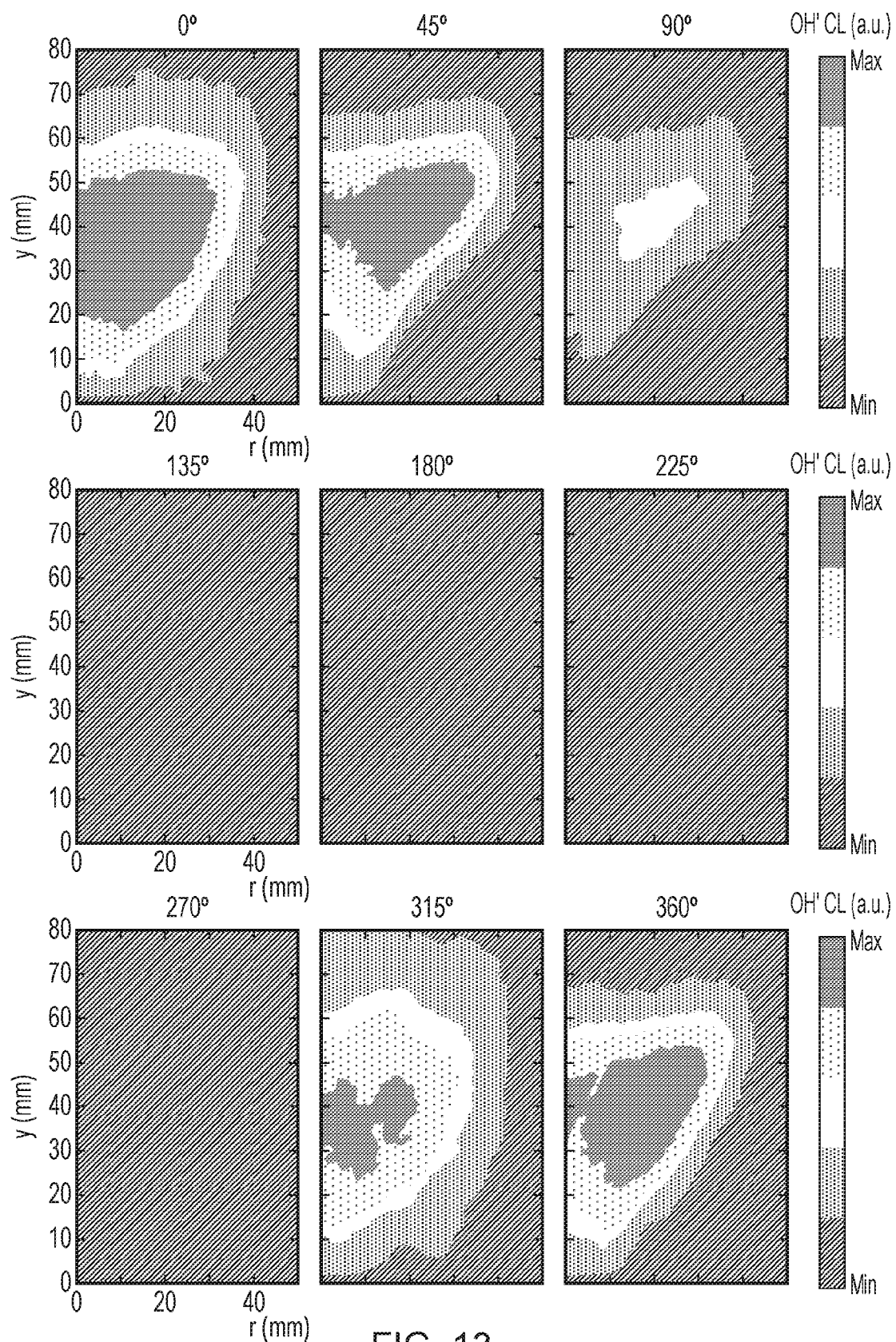


FIG. 13

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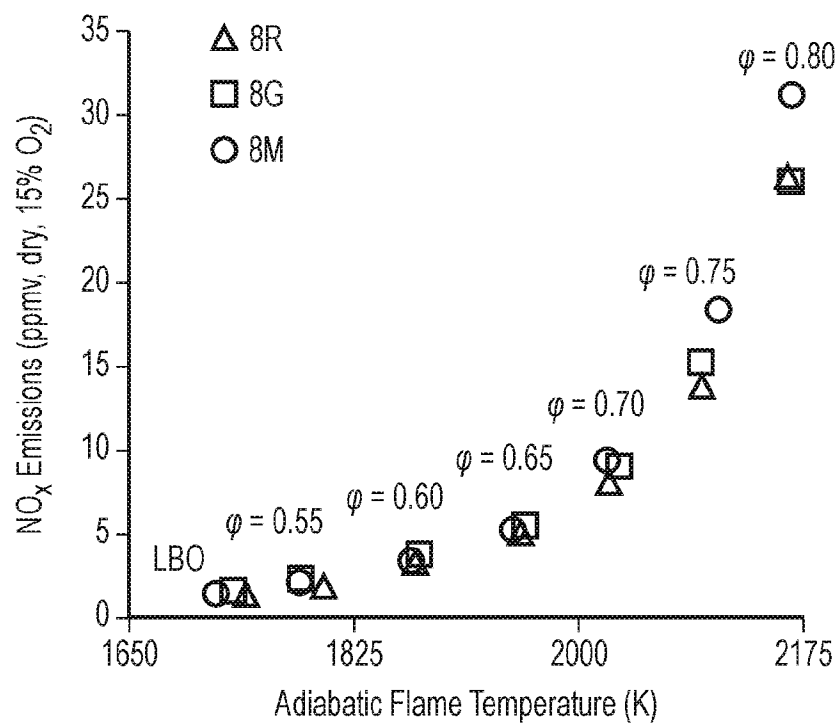


FIG. 14

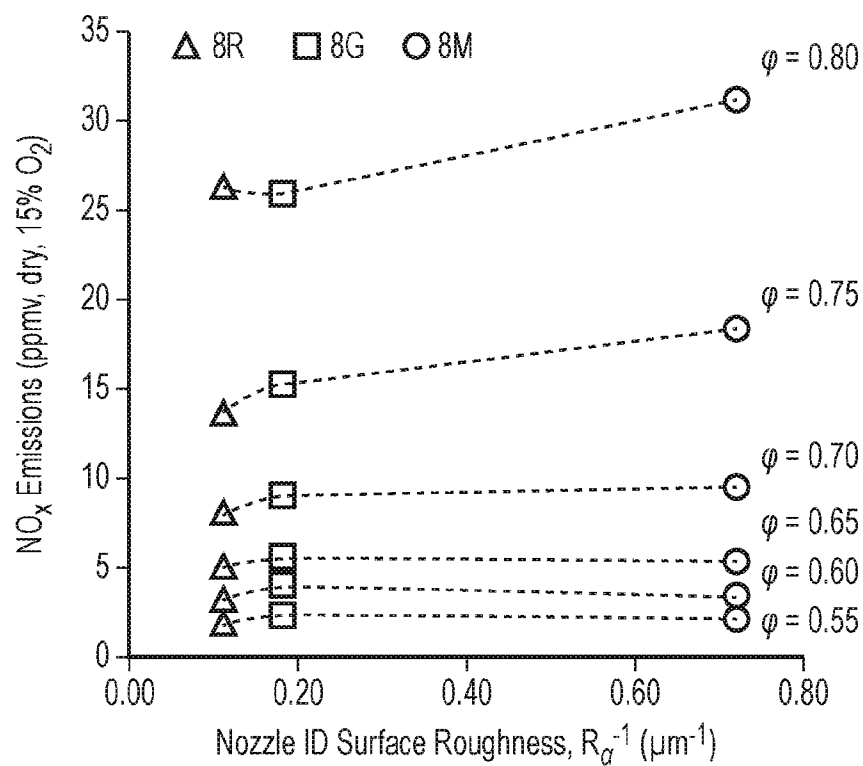


FIG. 15

INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/051327

A. CLASSIFICATION OF SUBJECT MATTER

INV. B22F3/105 B22F3/24 B22F5/00 B33Y10/00 B33Y80/00
F23R3/14 F23R3/28

ADD.

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)

B22F F23R B33Y

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

EP0-Internal, WPI Data

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X	EP 3 105 364 A1 (GEN ELECTRIC [US]) 21 December 2016 (2016-12-21)	1-4,7,8, 13,15
Y	paragraph [0001] - paragraph [0004] paragraph [0016] - paragraph [0019] figure 1 claims 1-15	1,3-7,14
X	----- W0 2017/106029 A1 (EXXONMOBIL RES & ENG CO [US]) 22 June 2017 (2017-06-22)	1-4,7
Y	paragraph [0001] - paragraph [0003] paragraph [0195] - paragraph [0204] claims 1-15	1-7
	----- -/--	



Further documents are listed in the continuation of Box C.



See patent family annex.

* Special categories of cited documents :

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"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

30 June 2020

Date of mailing of the international search report

09/07/2020

Name and mailing address of the ISA/

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INTERNATIONAL SEARCH REPORT

International application No
PCT/GB2020/051327

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