(19) Europäisches Patentamt
European Patent Office
Office européen des brevets

(11) EP 4 471 330 A1

(12) **EUROPEAN PATENT APPLICATION**

(43) Date of publication:
04.12.2024 Bulletin 2024/49

(21) Application number: **23176756.7**

(22) Date of filing: **01.06.2023**

(51) International Patent Classification (IPC):
F23C 15/00 *(2006.01)* ***F23D 14/02*** *(2006.01)*
F23D 14/64 *(2006.01)*

(52) Cooperative Patent Classification (CPC):
F23C 15/00; F23D 14/02; F23D 14/64;
F23C 2900/9901; F23D 2900/00015

(84) Designated Contracting States:
AL AT BE BG CH CY CZ DE DK EE ES FI FR GB GR HR HU IE IS IT LI LT LU LV MC ME MK MT NL NO PL PT RO RS SE SI SK SM TR
Designated Extension States:
BA
Designated Validation States:
KH MA MD TN

(71) Applicant: **P & P Industries AG**
8074 Raaba-Grambach (AT)

(72) Inventors:
- **Giuliani, Fabrice**
  8010 Graz (AT)
- **Paulitsch, Nina**
  9400 Wolfsberg (AT)

(74) Representative: **Schwarz & Partner Patentanwälte GmbH**
Patentanwälte
Wipplingerstraße 30
1010 Wien (AT)

(54) **RAPID MIXING DEVICE FOR MIXING AN AIR STREAM WITH A LIQUID OR GASEOUS HIGHLY REACTIVE FUEL AND PROCESS FOR MANUFACTURING THE SAME**

(57) 1. A mixing device (1) for mixing an air stream with a liquid or gaseous highly reactive fuel, such as hydrogen, comprises an elongated revolution body (10) having an air inlet end (11), an air outlet end (12), and a hollow central space (13) that extends through the revolution body (10) along its elongation. The mixing device (1) comprises multiple fuel channels (14) arranged at the revolution body (10) and distributed around the perimeter of the revolution body (10), wherein the fuel channels (14) extend between the air inlet end (11) and the air outlet end (12) of the revolution body (10), wherein the fuel channels (14) have fuel inlet openings (15) near or at the air inlet end (11) of the revolution body (10) and fuel injection orifices (16) at the air outlet end (12) of the revolution body (10).

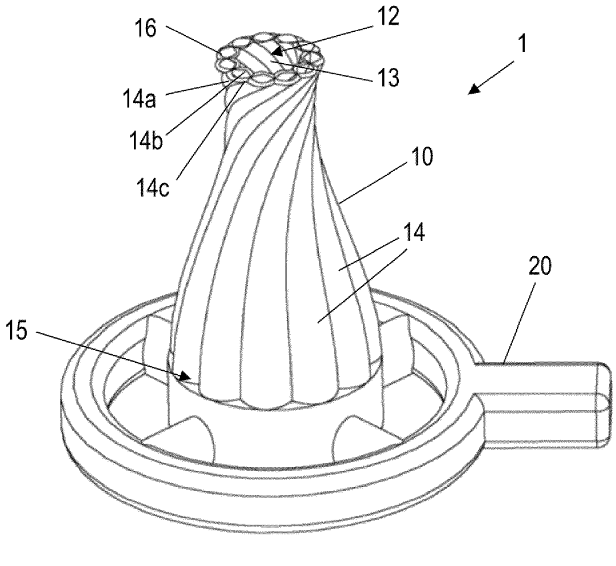

Fig. 2a

EP 4 471 330 A1

Description

[0001] The present invention generally relates to the field of complete and low-emission combustion of fuels. To achieve this goal burners may be used that can be excited thermo-acoustically. Austrian patent AT 516424 B1 discloses a device for operating of a flame, comprising a supply line for an oxidant and a conventional combustible fuel gas, a burner for the combustion of the same and a pulsation device, by means of which the oxidant can be set in oscillation. The burner has a control area for guiding the oscillating oxidant and the combustible gas to generate a pilot flame and a main region for a main flame, said control area being connected to the pulsation device. In the main area a further oxidant agent and a further combustible material are guidable.

[0002] The present invention aims at extending the technology for complete and low-emission combustion of fuels to carbon-free fuels, including H_2, NH_3 and H_2S. The general principle 100 of low-emission combustion of fuels is summarized in Fig. 1. An exciter 103 fed with pilot air 104 generates pulsations in the flow of the pilot air 104. The exciter 103 is a means for generating pulsations (such as an active device like a siren or loudspeaker, or a passive device like an acoustic resonator) and is mounted downstream from a premixer 101 feeding the pulsed pilot air 104 to the premixer 101. Fuel 105 is also fed to the premixer 101. The premixer 101 mixes the pilot air 104 and the fuel 105 and feeds the mixture to a burner 102, where it is combusted as a pilot flame 106, which is used as a driver to improve the performance of the main flame 107 generated in the burner 102 in terms of flammability limits, complete combustion and NOx levels. To generate and maintain the main flame 107 a mixture of main air 109 and fuel 108 is fed to the burner 102 as the source for generating and maintaining the main flame 107. The burner 102 is cooled by cooling and diluting air 110.

[0003] The main task of a premixer 101 is to generate a pilot flame 106, which always burns (as in gas boiler). This guarantees safe ignition of the main flame 107. The combustion staging (pilot flame 106 and main flame 107) reduces nitrogen oxides (NOx). The main flame 107 gets an excess of air, i.e. it is a lean mixture of fuel and air. More than 90% of the burning power comes from the main flame 107, less than 10% of the burning power comes from the pilot flame 106. The pilot flame 106 has a stoichiometric ratio of air to fuel, i.e. it is a richer mixture than in the main zone that produces a corresponding amount of NOx.

[0004] Premixed combustion, optionally operating in the lean domain (or with excess air regarding stoichiometry) has become a standard for efficient and low-emission combustion, see e.g. Arthur H. Lefebvre, Gas Turbine Combustion - Second Edition, Combustion: An International Series, Taylor & Francis, 1999, or Tim C Lieuwen and Vigor Yang, Gas turbine emissions, volume 38 of Cambridge Aerospace Series, Cambridge University Press, 2013.

[0005] To extend this technology to carbon-free fuels, including H_2, NH_3 and H_2S, it has turned out that the premixers presently used in low emission combustion devices are unusable for combusting carbon-free fuels, particularly when the fuels include hydrogen as combustion component.

[0006] To achieve efficient and low-emission combustion two staged burners, i.e. a pilot burner and a main burner, each of them combusting premixed fuels can be used. A promising configuration that guaranties a robust combustion is to use pure H_2 or H_2-enriched fuel in the pilot flame and any fuel in the main burner.

[0007] The two general disadvantages of premixed combustion are:

- the lean blow out extinction: This is the lower limit of operation, at which the flame tends to disappear. The fuel contents have become too low, or the air contents have become too high to self-sustain the combustion. This is typically situated around equivalence ratio $\phi = 0.6$ for conventional gases.
- the flashback: The flame leaves its average position and flies upstream, back into the mixer where the fuel is being injected. After that the flame settles as a diffusion flame in the volumes designed for mixture harmonization prior to the flame. This situation cannot last otherwise the burner is damaged. The two reasons leading to a flashback are a slow-down of the reactants, or a setting at the highest flame speeds (about stoichiometry for conventional fuels, and in the rich domain $\phi = 2$ for hydrogen).

[0008] In the specific case of hydrogen containing fuels the following applies:

- the lean blow out extinction is not a problem: Due to the extreme reactivity of hydrogen, it can burn down to equivalence ratios around 0.1, which are not very interesting from the thermal point of view. A flame operating down to phi = 0.25 is therefore no problem and behaves steadily and flashback free (flame temperature under atmospheric conditions about 1060K).
- the flashback is the major problem: Hydrogen flame speeds are approx. 10 times faster than flame speeds of conventional fuels. The mixture flow speed must therefore be kept high. Furthermore, its highest speed in the rich domain makes the flashback occur in case of poor mixing. This problem is the current show-stopper for many thermal applications of hydrogen.

[0009] The present invention generally aims at solving two tasks, namely enabling better combustion quality, and preventing flashbacks.

[0010] Due to premixing, the flame temperature is lower. In principle, an H2 flame has a flame temperature about 100°C higher than conventional fuels. Pre-mixing lowers the temperature of the flame and thus also lowers the nitrogen oxide levels. I.e. premixed H2 flames have reduced NOx emissions and a temperature that is about the same as the flame temperature of conventional fuels.

[0011] To solve the above-mentioned tasks of the invention a rapid mixing device (premixer) is needed for mixing a highly reactive fuel, such as H2, with air that can produce as fast as possible a well-stirred mixture under elevated flow speeds.

[0012] The present invention solves this task by providing a mixing device for mixing an air stream with a liquid or gaseous highly reactive fuel according to claim 1. Preferred embodiments of the invention are defined in the dependent claims, the description, and the drawings.

[0013] The present invention suggests a mixing device for mixing an air stream with a liquid or gaseous highly reactive fuel, such as hydrogen, wherein the mixing device comprises an elongated revolution body having an air inlet end, an air outlet end, and a hollow central space that extends through the revolution body along its elongation. The mixing device comprises multiple fuel channels arranged at the revolution body and distributed around the perimeter of the revolution body, wherein the fuel channels extend between the air inlet end and the air outlet end of the revolution body, wherein the fuel channels have fuel inlet openings near or at the air inlet end of the revolution body and fuel injection orifices at the air outlet end of the revolution body.

[0014] The invention applies the principle of multi-jet injection, which guarantees the homogeneity of the fuel-air-mixture. The revolution body profile allows fast moving air and fuel flows under low pressure loss conditions. Furthermore, the mixing device according to the invention avoids regions of flow detachment, where a flashbacked flame could settle. Jets of fuel and air are in co-flow, meaning that their flow directions have the same orientation. The fuel jet is taken in sandwich by two streams of air instead of one, which increases mixing efficiency. The fuel flows through the walls of the mixing device and gets ejected at the air outlet end of the revolution body, offering low flame anchoring surface, thereby greatly reducing the risk of generating flashbacks. The fuel (liquid or gaseous, pure or mixture) is distributed over many internal channels, as many as there are injection points to the top (multipoint fuel distribution). Once emitted, the multiple fuel jets are taken in sandwich by the inner and outer air flows, leading to a rapid mixing. The shape of the revolution body eases the heat exchange, to harmonize the reactants' temperatures, which in turn leads to a homogeneous mixture.

[0015] Before, it has been regarded as best way to mix homogeneously air and fuel (liquid or gas) by injecting the fuel in a crossflow jet into the air stream, which means that a point injection of fuel is performed perpendicular to the air stream. The resulting fuel jet is bended by the momentum of the main air flow, and the fuel diffusion starts. Document AT 522614 B1 describes such homogenous, well-distributed and well-thermalized crossflow air-fuel mixture. However, applying the principle of cross-flow jets to combusting highly-reactive fuels is not recommended, since the penetration of the fuel jet in the flow offers an easy anchor to a diffusion flame, with its zero-axial-flow speed. This is why the invention replaces jets in cross-flow by jets in co-flow: the flow directions have the same orientation. Although it is less efficient than the cross-flow regarding mixing efficiency, it offers less chance for flame anchoring. Furthermore, the jet is taken in sandwich by two streams of air instead of one, which compensates a bit the loss in mixing efficiency.

[0016] EP 2 221 541 A2 discloses a coaxial fuel and air premixer for a gas turbine combustor, comprising a peripheral wall defining a mixing chamber, a nozzle disposed within the peripheral wall comprising an outer annular wall spaced from the peripheral wall so as to define an outer air passage between the peripheral wall and the outer annular wall, an inner annular wall disposed within and spaced from the outer annular wall, so as to define an inner air passage, and a fuel gas annulus between the outer annular wall and the inner annular wall. The fuel gas annulus defines a fuel gas passage, an air inlet for introducing air through the inner air passage and the outer air passage to the mixing chamber, and a fuel inlet for injecting fuel through the fuel gas passage to the mixing chamber to form an air/fuel mixture.

[0017] US 7,406,827 B2 describes an apparatus for injecting a fuel-air mixture into a combustion chamber. The apparatus comprises a fuel lance for injecting fuels, via at least two separate passages, into a combustion chamber alternately or simultaneously at an injection location arranged substantially at the lance tip. The risk of flashbacks is reduced in that the fuel lance, in addition to fuel, also passes purge air to the injection location, and that the purge air, at the injection location, is routed between the two fuel systems, in such a manner that these systems are shielded from one another by the purge air.

[0018] One embodiment of the mixing device according to the invention is characterized in that the walls of the fuel channels compose the revolution body. This embodiment has the advantage that walls of the fuel channels being embedded in the revolution body are excellent for building up the body by means of additive manufacturing. The path lines of the fuel channels are used to define the skeleton of the wall-structure.

[0019] When the fuel channels are tangentially twisted in relation to the elongation of the revolution body in an end region of the revolution body at its air outlet end a spinning - or swirling - injection is realized that generates a tangential momentum to fuel jets thereby shortening the dilution length and enhancing the mixing of fuel and air. Preferably, a twist angle of the fuel channels in relation to the elongation of the revolution body continuously increases towards the air outlet end. It is further preferred that the maximum value of the twist angle is less than 170°.

[0020] In an alternative embodiment of the mixing device according to the invention the fuel channels are straight and arranged under the shape of a hyperboloid. Aerodynamics of this embodiment allow elevated flow speeds at the lowest possible pressure drop (function of the flow speed to the square). The path lines of the fuel channels are used to define the skeleton of the wall structure of the revolution body. This representation is important to capture the velocity vectors of the fuel as it comes in contact to the air, at the outlet of the body. This orientation generates a swirling of the surrounding air through an entrainment effect. This drag and swirl effect is even stronger if the channels are not straight but show a spiral trajectory as described in the previous paragraph. These drag and swirl effect also contribute to the rapid mixing.

[0021] An embodiment of the mixing device according to the invention is characterized in that the fuel channels comprise at least one section with continuously decreasing cross section in direction to the injection orifice. This embodiment provides the advantage that the fuel channels function as a nozzle and chokes the fuel flow. By avoiding steps or jumps in cross section of the fuel channels generation of turbulences and pressure drops is avoided.

[0022] When the fuel channels of the mixing device comprise a section with continuously widening cross section towards the injection orifice steps or jumps in cross section are avoided that would cause turbulences and pressure drops. This embodiment allows elevated flow speeds at the lowest possible pressure drop (function of the flow speed to the square).

[0023] A preferred embodiment of the mixing device according to the invention is characterized in that the hollow central space has a radius which varies continuously at least in sections along the elongation of the revolution body, wherein a radius to elongation ratio is less than 1, preferably less than 0.5. The small ratio of elongation to radius promotes the heat exchange. Ideally, the temperature of the fuel jets is even at the injection point, and as near as possible to the temperature of the ambient.

[0024] In another preferred embodiment of the mixing device according to the invention the fuel channels are formed by two opposing walls corrugated in cross-section, wherein intersections of the walls separate the fuel channels from each other. This embodiment provides a very stiff construction and yields stretched surfaces to promote heat exchange.

[0025] Another embodiment of the mixing device according to the invention is characterized in that it comprises a, preferably ring-shaped, fuel manifold connected to the fuel inlet openings of the fuel channels. This embodiment provides even fuel supply to all fuel channels. The supplied fuel can be pure, or a mixture with other products, such as inert gases. The fuel can be liquid or gas.

[0026] Preferably, the interior and exterior surface of the revolution body is configured to avoid causing turbulences of air streams passing along the interior and exterior surface. Aerodynamics inside the burner is of great importance. They must allow elevated flow speeds at the lowest possible pressure drop (function of the flow speed to the square). According to the invention the fuel jet is "sandwiched" between inner and outer air stream. Profiling to minimize drag and air vortices or air shadows. In air shadows, the flame can burn back, i.e. there is flashback, which can cause the material of the mixing device to melt. By profiling, the mixer body is flowed around with high air velocity and a better mixing with air is still achieved.

[0027] In a preferred embodiment of the invention the mixing device is equipped with a pulsation device arranged near the air inlet end of the revolution body. This embodiment improves mixing. Laminar flow is bad for mixing of H2 and air, but good for high velocity, which in turn prevents flashback. Providing a pulsation device results in air flow that is not completely laminar, but predominantly laminar, which leads to much higher performance. At the same time turbulence is avoided which could lead to flashback. Without pulsation the mixing device is in a fail-safe mode, which offers lower performance but ensures safety. H2 flames are much faster than flames with conventional fuel, therefore they do not mix as well with air or need a longer mixing distance.

[0028] The invention further comprises a process of manufacturing a revolution body of a mixing device according to the invention. This process is characterized in that the revolution body is manufactured additively, preferably by powder bed fusion. This manufacturing process is optimal for the industrial production of the complicated mixer geometry and channel guidance.

[0029] In an embodiment of the manufacturing process the revolution body is manufactured additively by a mathematics-to-shape process, based on a parametric equation. The advantage of this embodiment is that geometrical parameters of the revolution body can quickly and easily be adapted. This accelerates up the process of finding an optimized dimensioning and prototype construction.

[0030] The invention will now be further explained by way of exemplary embodiments with reference to the drawings.

Fig. 1 is a schematic drawing showing the principle of an apparatus for complete and low-emission combustion of fuels.

Figs. 2a, 2b, 2c show a mixing device in accordance with the invention in a perspective side view, a top view, and a bottom view.

Fig. 3 schematically shows another embodiment of the revolution body of the mixing device having straight fuel channels.

Fig. 4a and Fig. 4b show the differences of mixing speed and length when a pulsation device is used.

Fig. 5 shows a parametric curve defining the walls of the revolution body.

Fig. 6 is a diagram explaining realizing the revolution based on a mathematics-to-shape approach, and using additive manufacturing.

Figs. 7 and 8 are diagrams showing the form factor and the twist angle of chosen profiles of the revolution body.

Figs. 9 und 10 show a "flower" profile of the revolution body and its extrusion using a variable form factor.

Fig. 11 shows a revolution body with twisted configuration.

Fig. 12 shows a bottom view of the revolution body of Fig. 11 with thickened walls.

[0031] Figs. 2a to 2c show a first embodiment of a mixing device 1 for mixing an air stream with a liquid or gaseous highly reactive fuel, such as hydrogen, wherein the mixing device 1 comprises an elongated revolution body 10 having an air inlet end 11, an air outlet end 12, and a hollow central space 13 that extends through the revolution body 10 along its elongation. The mixing device 1 is made by 3D printing, e.g. realized by powder bed fusion, in titanium 64. The mixing device comprises multiple fuel channels 14 arranged at the revolution body 10 and distributed around the perimeter of the revolution body 10, wherein the fuel channels 14 extend between the air inlet end 11 and the air outlet end 12 of the revolution body 10. The fuel channels 14 have fuel inlet openings 15 near or at the air inlet end 11 of the revolution body 10 and fuel injection orifices 16 at the air outlet end 12 of the revolution body 10. The mixing device 1 comprises a fuel manifold 20 connected to the fuel inlet openings 15 of the fuel channels 14. It is an essential function of the revolution body 10 to distribute fuel over the many internal fuel channels 14 to the air outlet end 12.

[0032] The walls of the fuel channels 14 compose the revolution body 10. The fuel channels 14 are tangentially twisted in relation to the elongation of the revolution body 10 in an end region of the revolution body 10 at its air outlet end 12. A twist angle α of the fuel channels 14 in relation to the elongation of the revolution body 10 continuously increases towards the air outlet end 12, wherein preferably the maximum value of the twist angle α is less than about Pi radians (half a turn). The twist angle α is shown in Fig. 12.

[0033] The fuel channels 14 have continuously decreasing cross sections in direction to the injection orifice 16. Alternatively, or additionally, the fuel channels 14 can comprise sections with continuously widening cross section towards the injection orifice 16.

[0034] The hollow central space13 has a radius r which varies continuously at least in sections along the elongation of the revolution body 10, wherein a radius to elongation ratio is less than 1, preferably less than 0.5.

[0035] The fuel channels 14 are formed by two opposing walls 14a, 14b corrugated in cross-section, wherein intersections 14c of the walls 14a, 14b separate the fuel channels 14 from each other. See also Fig. 5. The interior and exterior surface of the revolution body 10 is profiled to avoid causing turbulences of air streams passing along the interior and exterior surface. Forming the walls 14a, 14b with corrugated cross-sections perfectly meets this requirement.

[0036] Fig. 3 schematically shows another embodiment of the revolution body 10, represented by the path lines of its fuel channels 14. In this embodiment, the fuel channels 14 are straight and arranged under the shape of a hyperboloid.

[0037] In a preferred embodiment the mixing device 1 comprises a pulsation device 103 arranged near the air inlet end 11 of the revolution body 10. Fig. 4a and Fig. 4b show the differences of mixing speed and length when such a pulsation device 103 is used. Fig. 4a shows the mixing device 1 without a pulsation device 103 and Fig. 4b shows the mixing device 1 having the pulsation device 103. The pulsation device 103 is used for generating a pulsed stream of pilot air 104. In both embodiments the fuel 105 moves through the multiple fuel channels 14 and emerges at the fuel injection orifices 16, where mixing with the pilot air 104 begins. It is apparent from the drawings that the dilution length and characteristic time (represented by vertical and horizontal double-arrows) is shorter when the pulsation device 103 is used. On the other hand, without using the pulsation device 103 the mixing device runs in a fail-safe mode. The main air 109 is not pulsed by the pulsation device 103.

[0038] The revolution body can be manufactured additively, preferably by powder bed fusion. Advantageously, the revolution body is manufactured additively by a mathematics-to-shape process, based on a parametric equation. Examples of 3D additive manufacturing of the revolution body 10 will now be explained.

[0039] The revolution body 10 can be designed using conventional CAD methods, e.g. designing the shape of the walls of the revolution body 10, defining the trajectory and cross-sections of the fuel channels 14, multiply and distribute these regularly, and subtract these from the volume of the walls.

[0040] However, another preferred method is hereby described, relying on mathematics to shape. It has the advantage to fit the 3D printing method very well, and it is rather elegant as it relies on analytical geometry, and more specifically on parametric curves, such as those shown in Fig 5, which curves define the walls 14a, 14b, and intersections 14c, whereby the fuel channels 14 are formed in the revolution body 10. If well-chosen, one single curve suffices to define the fuel and air passages.

[0041] While approximative numerical methods are used in CAD to estimate specific passage cross-sections, wall widths, surfaces and volumes, the mathematic approach offers the advantage to determine the same values first analytically, then using calculus. This is of advantage during the dimensioning phase, before the equation's parameters are frozen.

[0042] A "flower" profile serves the purpose of designing the revolution body 10 of the mixing device 1 well. The "petals of the flower" shape the multiple fuel channels 14, while the flower's core defines the hollow central space13 dedicated to pilot air. A fine tuning on the coefficients discussed above offer the ideal distribution for the rapid mixing at the air outlet end 12 of the revolution body 10.

[0043] In the case of the mixing device 1 shown in Figs. 2a to 2c, the chosen parametric curve expressed under polar or cylindric coordinates has the form:

$$\rho(\theta) = r\left(1 + \alpha\cos\left(\frac{n\theta}{2}\right)\right) \qquad (1.1)$$

where:

r [m] is the radius of the lower section
α [-] is the amplitude of the waves forming the petals of the flower
n [-] is the number of petals, provided n is an odd number
θ [rad] is the polar angle

[0044] Fig. 5 shows this parametric curve using equation 1.1 defined over $\theta \in [0,2\pi]$. It will be understood that two rounds are needed to close the curve.

[0045] This equation 1.1 is particularly convenient to shape a "flower", while any odd value of n greater than 1, n petals appear on a closed curve for any angle interval $[\theta, \theta + 4\pi]$. Once shaped and extruded, the flower consists only in one single closed surface.

[0046] The method for shaping the walls of the revolution body 10 under cylindrical coordinates is shown in Fig 6, where one location of the wall is defined by a polar equation of type $\rho(\theta, z)$:

1. An ad-hoc parametric curve is chosen. Such curves can be found in references D.G. Wells. The Penguin Dictionary of Curious and Interesting Geometry. Penguin books : Mathematics reference. Penguin Books, 1991; Stephen Wolfram. http://mathworld.wolfram.com; and Diana Estévez Schwarz. Wellen und Blumen - eine anschauliche Darstellung der Fourier-Transformation, Berichte aus der Mathematik, Physik und Chemie, BEUTH Hochschule für Technik Berlin, 2018.
2. The shape is extruded upwards, which is a specific of most of the 3D printing methods.
3. For aerodynamic flow optimization, and provided the section changes are smooth, the section for factor is fine-tuned step-by-step. A growth factor depending on the height z, e.g. as a polynomial.
4. In order to shorten the depth of penetration of the fuel jets in the ambient, and in order to sustain the presence of a swirled flow, a twist is brought into the fuel channels, itself being a function of the height z. This operation is applied right after the previous.
5. The process loops until the height of the object is achieved.

[0047] Now, examples of specific geometries of the 3D-printed revolution body 10 are explained.

[0048] We suggest two different approaches of "mathematics to shape" design.

[0049] The first approach is the analytic approach:

Let us consider equation 1.1, the result of which is shown in Fig. 5. This shape is homothetic all along the body, we study just a section. We are interested in the surface of the petals - where the fuel is going to flow, and the surface of the core - where the pilot air is going to flow. More exactly, we are interested in the ratio of both. Assuming we want these streams to be isokinetic and near to stoichiometry, the ratio of these areas should correspond to the ratio of the volume flows (or molar ratio between the reactants). When using an hydrogen-air mix at stoichiometry, the molar fraction of hydrogen is 29.5% of the mixture, and the fuel-to-air volume flows ratio $FAR_{\dot{V}}$ defined as

$$FAR_{\dot{V}} = \frac{\dot{V}_{H2}}{\dot{V}_{air}}$$

is 41.5%.

[0050] Fig. 6 is a diagram showing the method called mathematics to shape, which is ideal for the realization of the revolution body 10 according to the invention.

[0051] For any parametric curve describing under polar coordinates ρ (θ) as the distance from the the section's center to the wall for a given angle θ, the sector surfaces s from angle θ_1 to θ_2 can be computed as $\mathrm{s} = \int_{\theta_1}^{\theta_2} \frac{1}{2}\rho^2 \, \mathrm{d}\theta$

$$s = \int_{\theta_1}^{\theta_2} \frac{1}{2}\rho^2 d\theta$$

[0052] In the particular case of equation 1.1, and calculating the surface section-wise, the total surface of the flower S_{tot} (petals + core) is:

$$S_{tot} = \pi\, r^2 \left(1 + \frac{\alpha^2}{2} + 4\frac{\alpha}{\pi}\right) \qquad (1.2)$$

[0053] Having *n* as an odd number only, the surface of the core S_{core} is:

$$S_{core} = \pi\, r^2 \left(1 + \frac{\alpha^2}{2} - 4\frac{\alpha}{\pi}\right) \qquad (1.3)$$

[0054] The total petal surface results therefore from the subtraction of equation 1.3 from equation 1.2. Interestingly, all these latest formulas are independent of the number of petals n:

$$S_{petals} = 8\,\alpha\, r^2 \qquad (1.4)$$

[0055] The surface ratio between petals and core becomes that corresponds to $^{\cdot}FAR_{\dot{V}}$ is therefore:

$$\frac{S_{petals}}{S_{core}} = \frac{16\,\alpha}{2\pi + \pi\alpha^2 - 8\alpha} \qquad (1.5)$$

[0056] The desired flower amplitude α can therefore be computed from the desired fuel-to-air volume flows ratio $FAR_{\dot{V}}$ by solving the second order equation:

$$\pi\alpha^2 - \frac{8\alpha\left(2 + FAR_{\dot{V}}\right)}{FAR_{\dot{V}}} + 2\pi = 0 \qquad (1.6)$$

[0057] When computing for a $FAR_{\dot{V}}$ value of 41.5% specific to air-hydrogen mixture, a recommended value α = 13.8% comes out. In the following, considering the effective area loss due to the wall thickening, this value is set to 20%.

[0058] The second approach is the numeric approach:

A few calculations similar to previous show that a bottom radius r(0) of 20mm, a number of n = 11 "petals", an amplitude α near 20% and an extrusion over 40mm are a good start. The profiles for the form factor and the twist angle are tested on chosen polynomials, as shown in Figs. 7 and 8. The diagrams in Fig. 7 and 8 show the chosen profiles for the form factor and the twist angle as a function of the elevation z, using a set of chosen points and a polynomial best fit method.

[0059] The system of equations needed to achieve the "straight" extruded flower profile is:

$$\begin{cases} \rho(\theta, z) & = & r(z)\left(1 + 0.2\cos\left(\frac{11}{2}\theta\right)\right) \\ r(z) & = & 3.5417\ 10^{-4}\ z^3 - 0.0173\ z^2 + 10 \\ & & \forall z\ \in [0, 40] \end{cases}$$

$$(1.7)$$

[0060] The flower profile at z = 0, the chosen polynomials and the resulting "straight" flower are shown in Fig. 9 and Fig. 10.

[0061] The next operation is the twist of the resulting profile, to induce a swirl in the fuel injection. The chosen polynomial for the twist angle is:

$$\theta_{twist}(z) = 1.6541\ 10^{-6}\ z^4 - 2.2412\ 10^{-5}\ z^3 + 7.1054\ \ 10^{-16} \qquad \forall z\ \in\ [0, 40] \quad (1.8)$$

[0062] Expressed under polar coordinates, the twisting function becomes:

$$\theta\ (z) \longrightarrow \theta\ (z) + \theta\ \text{twist}(z) \quad \forall\ z \in [0, 40] \quad (1.9)$$

[0063] When applied to the straight extrusion of Fig. 10, a twisted revolution body 10 is created, as shown in Fig. 11.

[0064] The last operation performed is a grid thickening, to transform a flat surface into a 3D body. In this case, a 0.5mm thickness is applied in outward direction. The resulting revolution body is shown in Fig. 12 in a bottom view.

Claims

1. A mixing device (1) for mixing an air stream with a liquid or gaseous highly reactive fuel, such as hydrogen, wherein the mixing device (1) comprises an elongated revolution body (10) having an air inlet end (11), an air outlet end (12), and a hollow central space (13) that extends through the revolution body (10) along its elongation, **characterized in that** the mixing device (1) comprises multiple fuel channels (14) arranged at the revolution body (10) and distributed around the perimeter of the revolution body (10), wherein the fuel channels (14) extend between the air inlet end (11) and the air outlet end (12) of the revolution body (10), wherein the fuel channels (14) have fuel inlet openings (15) near or at the air inlet end (11) of the revolution body (10) and fuel injection orifices (16) at the air outlet end (12) of the revolution body (10).

2. The mixing device according to claim 1, **characterized in that** the walls of the fuel channels (14) compose the revolution body (10).

3. The mixing device according to claim 1 or 2, **characterized in that** the fuel channels (14) are tangentially twisted in relation to the elongation of the revolution body (10) in an end region of the revolution body (10) at its air outlet end (12).

4. The mixing device according to claim 3, **characterized in that** a twist angle (α) of the fuel channels (14) in relation to the elongation of the revolution body (10) continuously increases towards the air outlet end (12), wherein preferably the maximum value of the twist angle (α) is less than about Pi radians.

5. The mixing device according to claim 1 or 2, **characterized in that** the fuel channels (14) are straight and arranged under the shape of a hyperboloid.

6. The mixing device according any one of the preceding claims, **characterized in that** the fuel channels (14) comprise at least one section with continuously decreasing cross section in direction to the injection orifice (16).

7. The mixing device according to any one of the preceding claims, **characterized in that** the fuel channels (14) comprise a section with continuously widening cross section towards the injection orifice (16).

8. The mixing device according to any one of the preceding claims, **characterized in that** the hollow central space

(13) has a radius which varies continuously at least in sections along the elongation of the revolution body (10), wherein a radius to elongation ratio is less than 1, preferably less than 0.5.

9. The mixing device according to any one of the preceding claims, **characterized in that** the fuel channels (14) are formed by two opposing walls (14a, 14b) corrugated in cross-section, wherein intersections (14c) of the walls (14a, 14b) separate the fuel channels (14) from each other.

10. The mixing device according to any one of the preceding claims, **characterized in that** it comprises a, preferably ring-shaped, fuel manifold (20) connected to the fuel inlet openings (15) of the fuel channels (14).

11. The mixing device according to any one of the preceding claims, **characterized in that** the interior and exterior surface of the revolution body (14) is configured, preferably profiled, to avoid causing turbulences of air streams passing along the interior and exterior surface.

12. The mixing device according to any one of the preceding claims, **characterized in that** it comprises a pulsation device (103) arranged near the air inlet end (11) of the revolution body (103).

13. A process of manufacturing a revolution body of a mixing device according to any one of the preceding claims, **characterized in that** the revolution body is manufactured additively, preferably by powder bed fusion.

14. The process according to claim 13, **characterized in that** the revolution body is manufactured additively by a mathematics-to-shape process, based on a parametric equation.

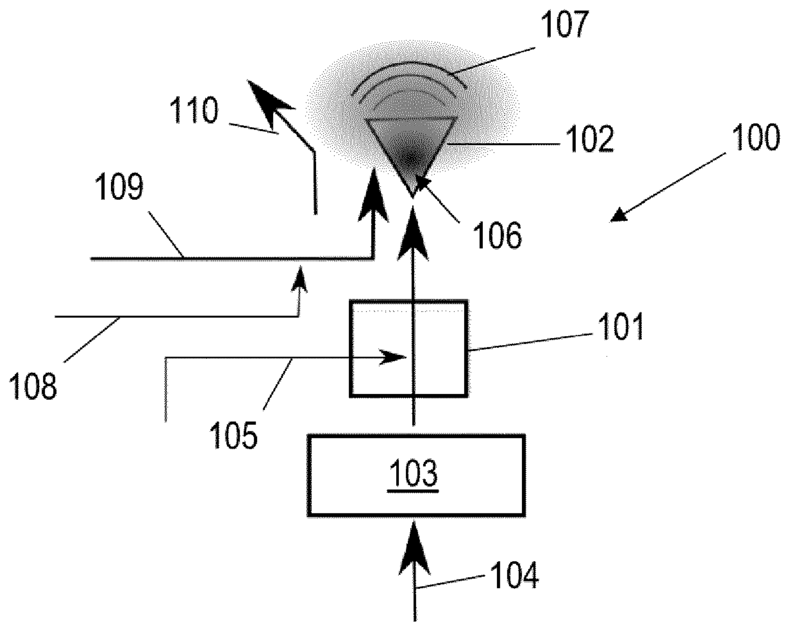
107
110
102
100
109
106
101
108
105
103
104

Fig. 1

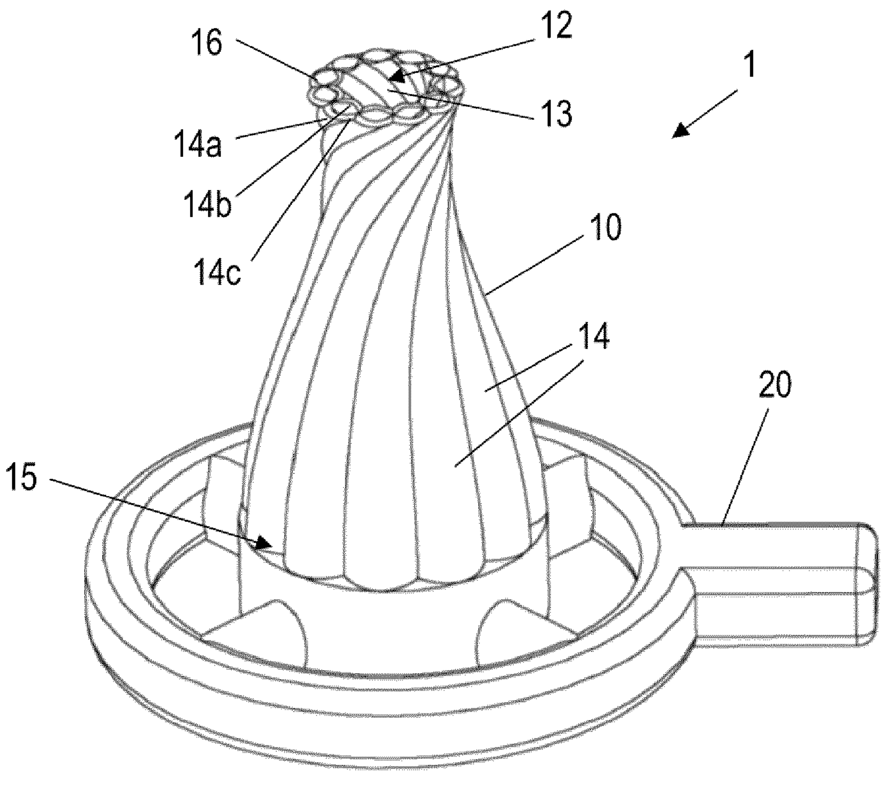
16
12
1
13
14a
14b
14c
10
14
20
15

Fig. 2a

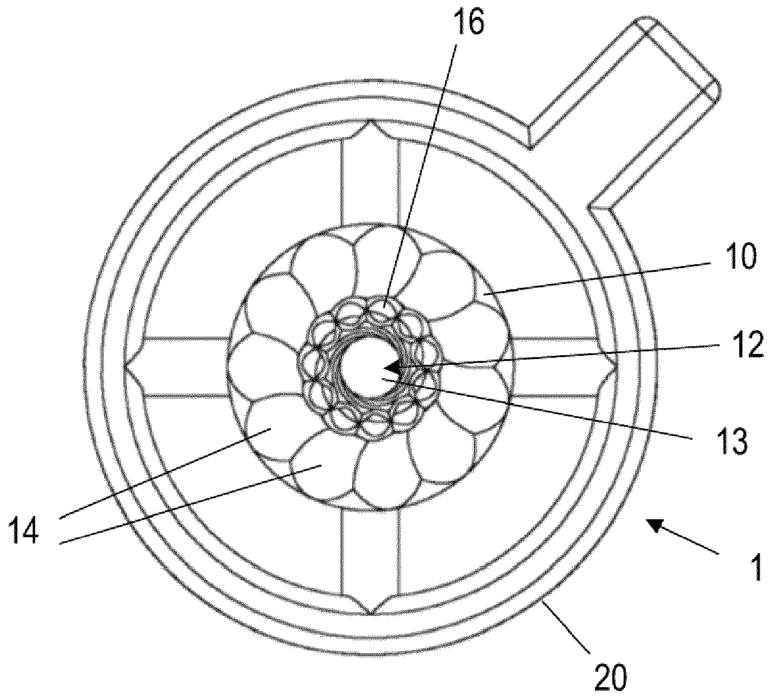

Fig. 2b

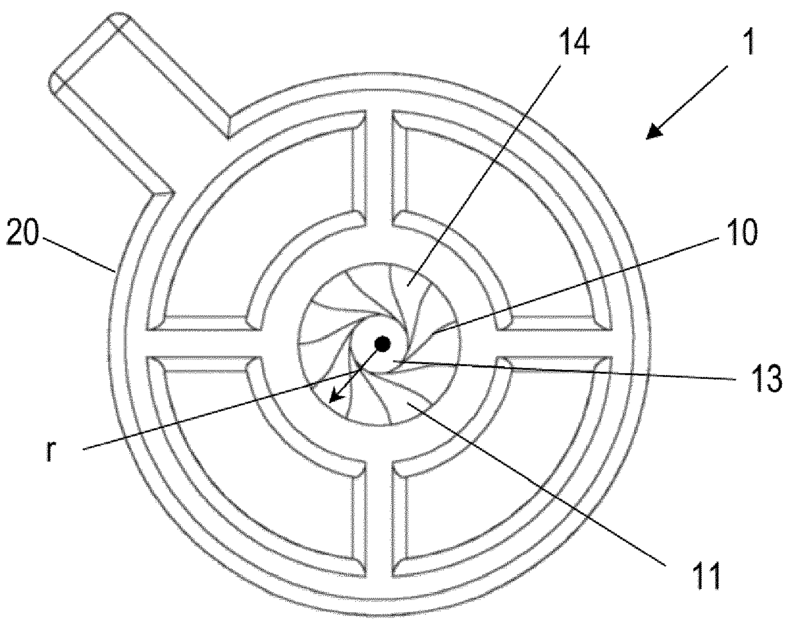

Fig. 2c

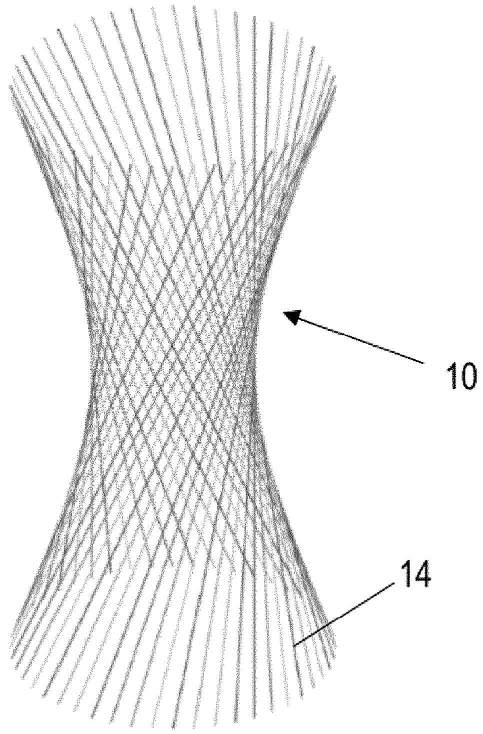

Fig. 3

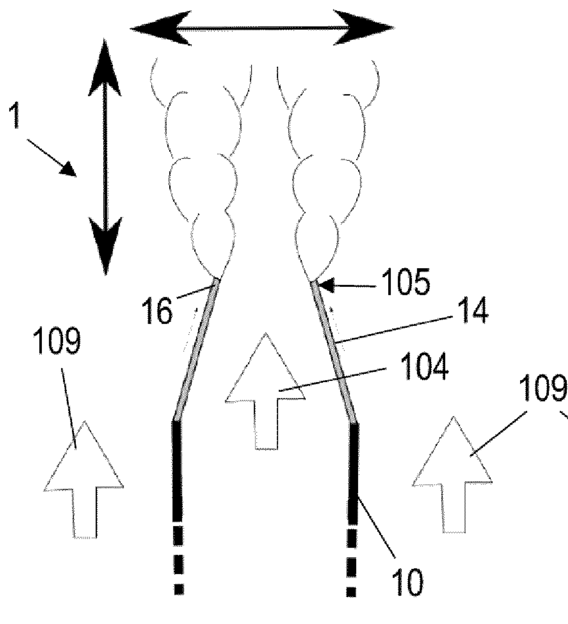

Fig. 4a

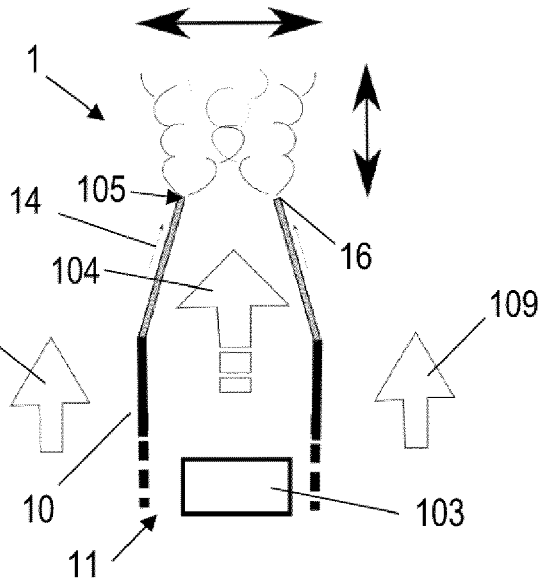

Fig. 4b

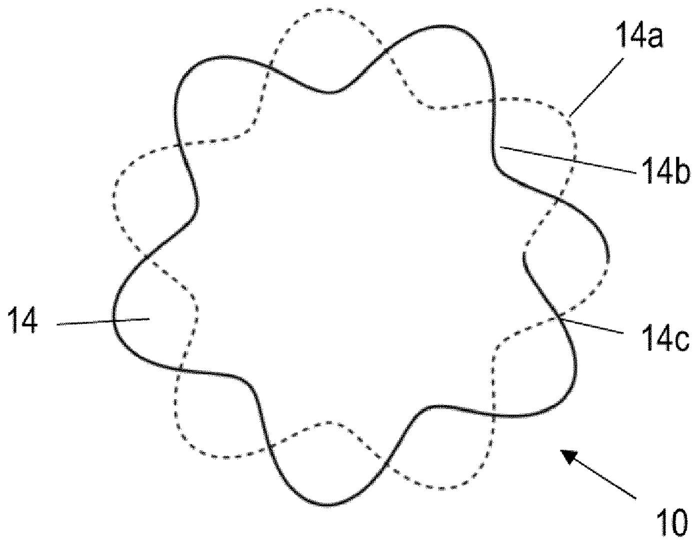
14a
14b
14
14c
10

Fig. 5

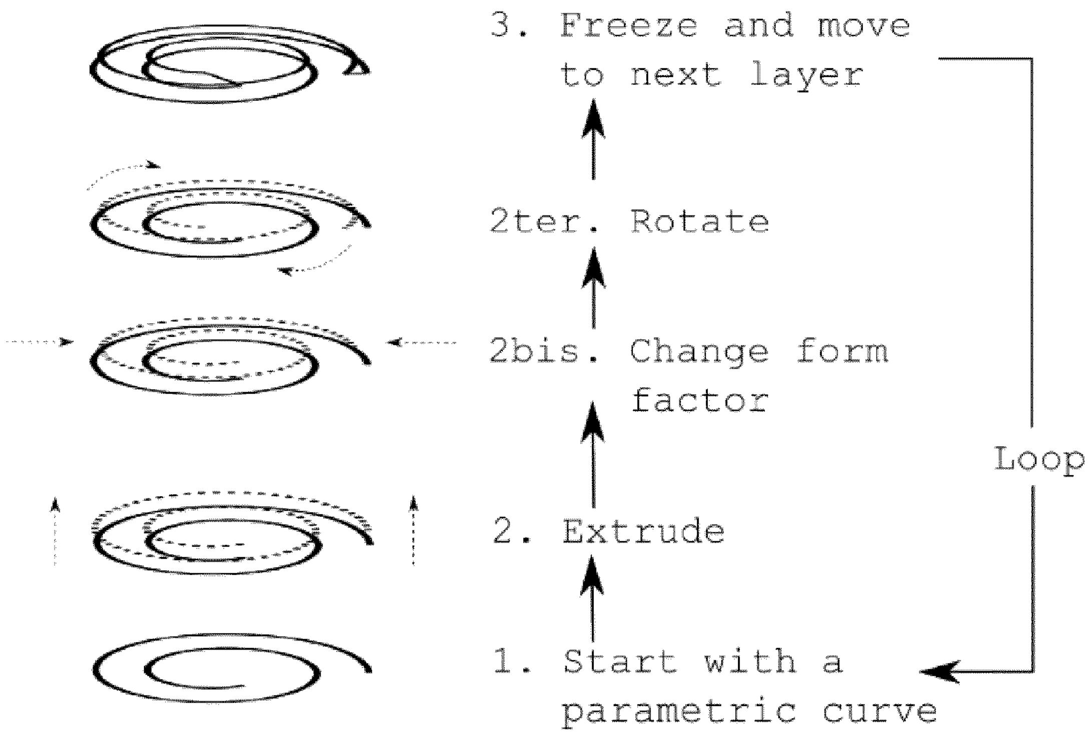
3. Freeze and move to next layer
2ter. Rotate
2bis. Change form factor
Loop
2. Extrude
1. Start with a parametric curve

Fig. 6

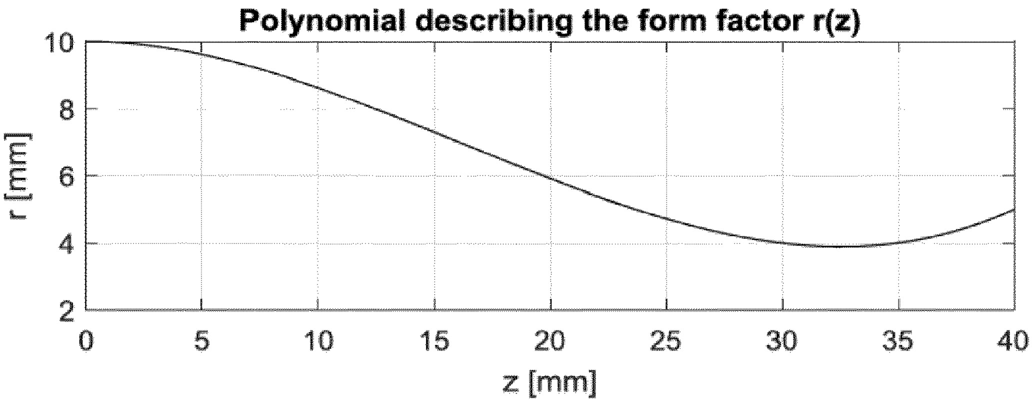
Polynomial describing the form factor r(z)
10
8
6
4
2
r [mm]
0
5
10
15
20
25
30
35
40
z [mm]

Fig. 7

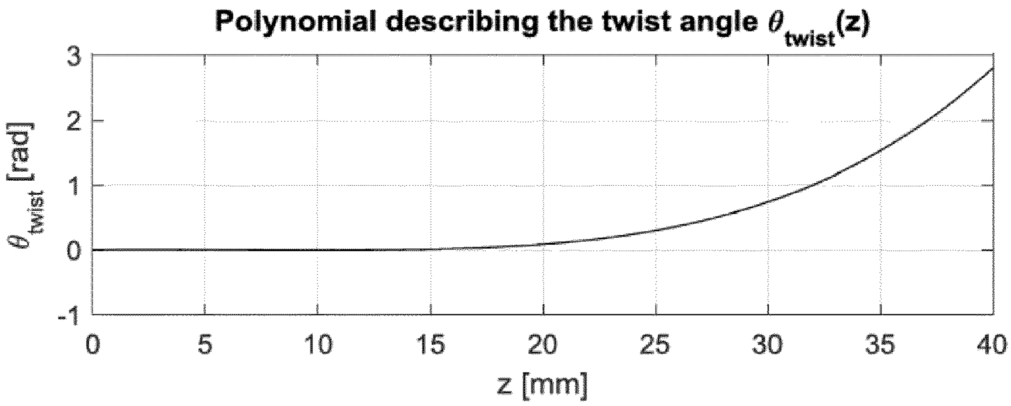
Polynomial describing the twist angle $\theta_{twist}(z)$
3
2
1
0
-1
θ_{twist} [rad]
0
5
10
15
20
25
30
35
40
z [mm]

Fig. 8

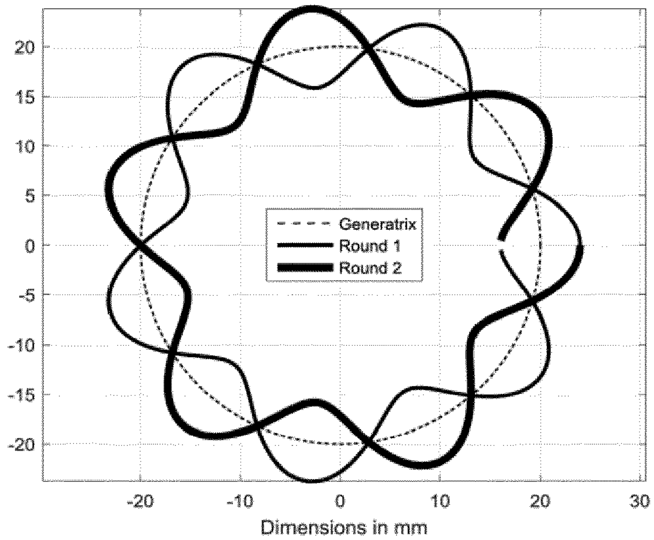
20
15
10
5
0
-5
-10
-15
-20
-20
-10
0
10
20
30
Dimensions in mm
Generatrix
Round 1
Round 2

Fig. 9

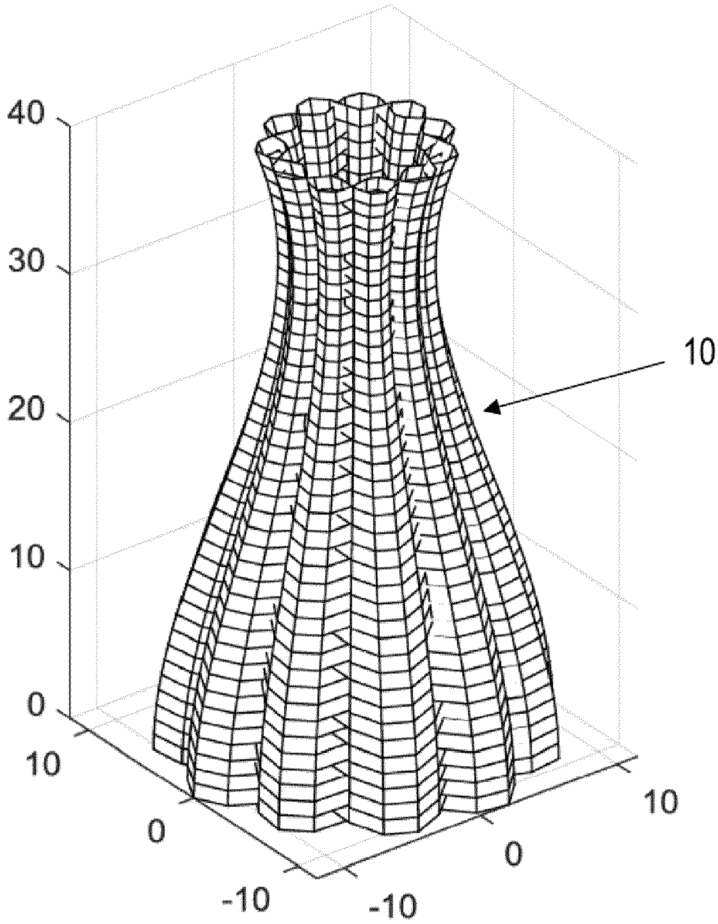
40
30
20
10
0
10
0
-10
10
0
-10
10

Fig. 10

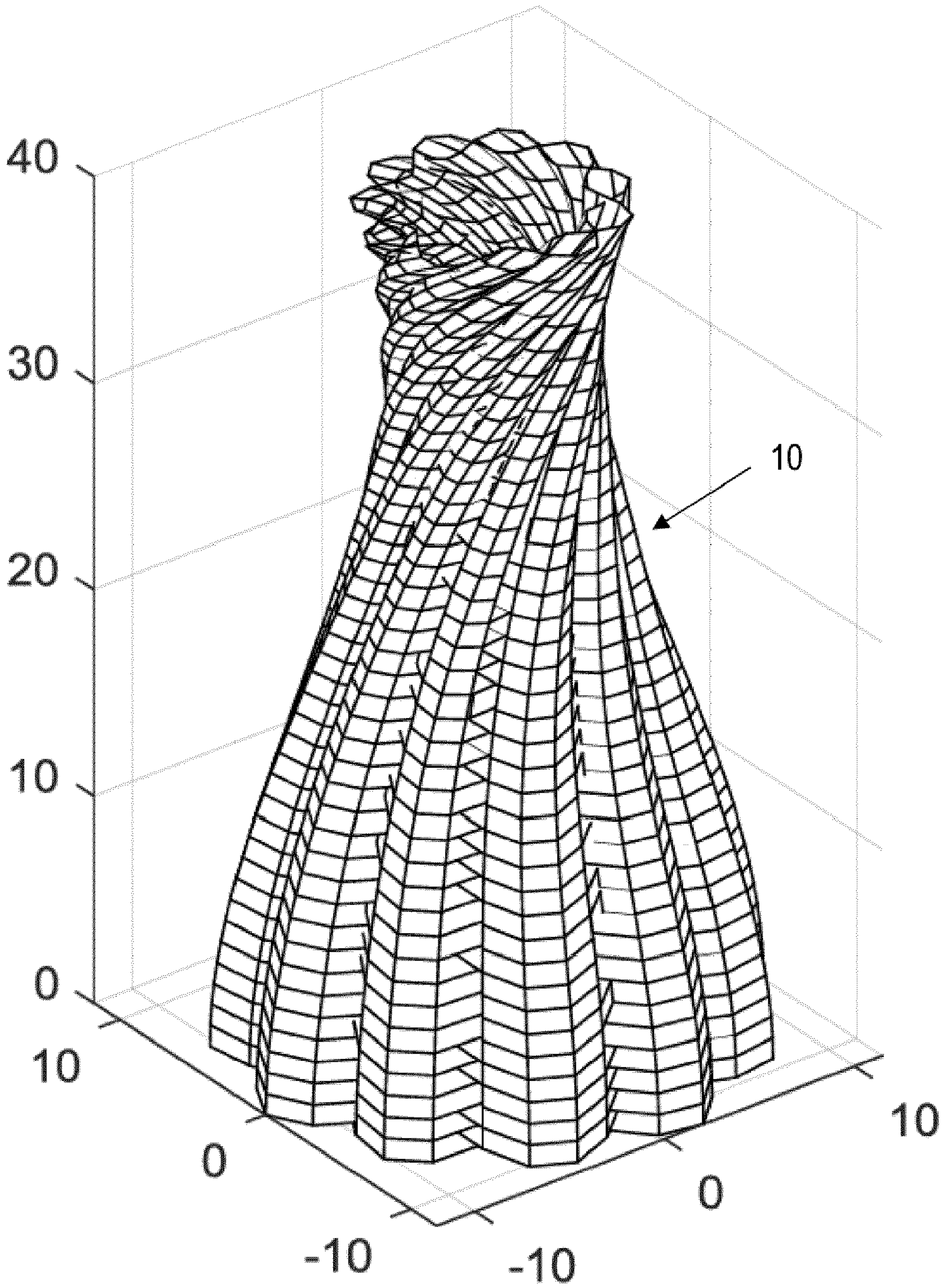

Fig. 11

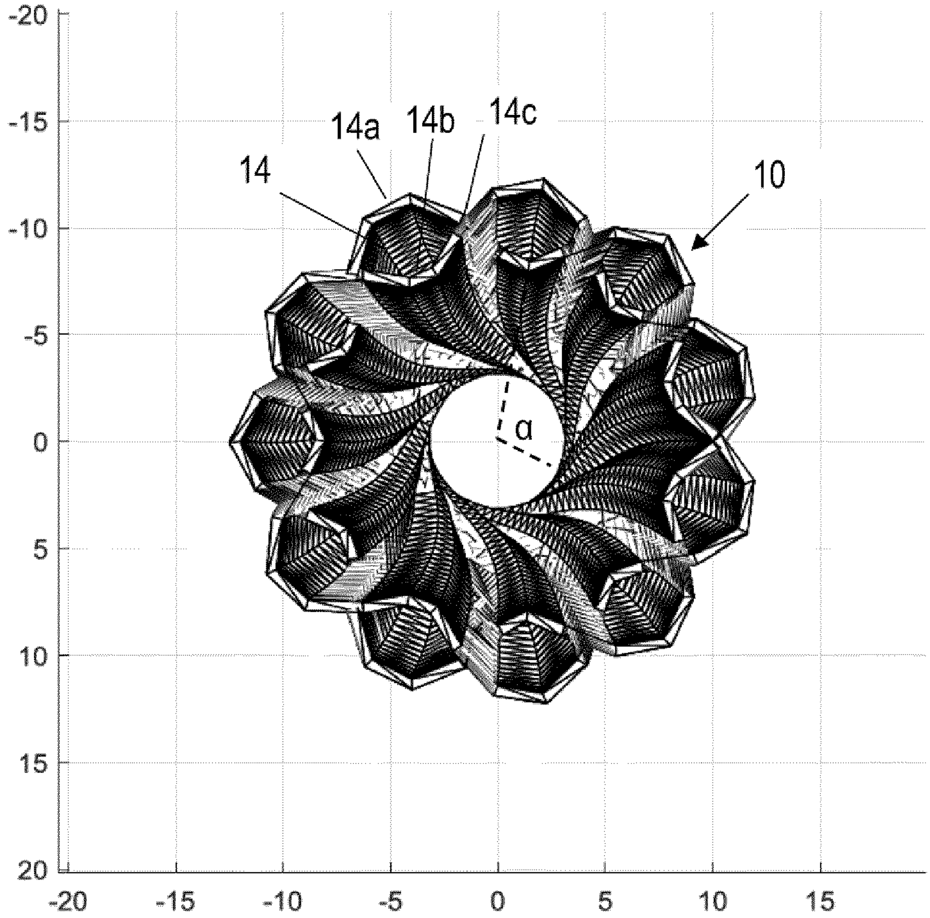

Fig. 12

Europäisches Patentamt
European Patent Office
Office européen des brevets

EUROPEAN SEARCH REPORT

Application Number
EP 23 17 6756

DOCUMENTS CONSIDERED TO BE RELEVANT

Category	Citation of document with indication, where appropriate, of relevant passages	Relevant to claim	CLASSIFICATION OF THE APPLICATION (IPC)
A	US 2019/011122 A1 (CHANDRAN RAVI [US] ET AL) 10 January 2019 (2019-01-10) * paragraphs [0002], [0009] - [0013]; figures 3,4,22 * * paragraph [0173] - paragraph [0177] * * paragraph [0181] - paragraph [0185] * -----	1-14	INV. F23C15/00 F23D14/02 F23D14/64

TECHNICAL FIELDS SEARCHED (IPC)

F23C
F23D

The present search report has been drawn up for all claims

1

Place of search	Date of completion of the search	Examiner
Munich	8 November 2023	Hauck, Gunther

CATEGORY OF CITED DOCUMENTS

X : particularly relevant if taken alone
Y : particularly relevant if combined with another document of the same category
A : technological background
O : non-written disclosure
P : intermediate document

T : theory or principle underlying the invention
E : earlier patent document, but published on, or after the filing date
D : document cited in the application
L : document cited for other reasons
& : member of the same patent family, corresponding document

EPO FORM 1503 03.82 (P04C01)

ANNEX TO THE EUROPEAN SEARCH REPORT ON EUROPEAN PATENT APPLICATION NO.

EP 23 17 6756

This annex lists the patent family members relating to the patent documents cited in the above-mentioned European search report. The members are as contained in the European Patent Office EDP file on
The European Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

08-11-2023

Patent document cited in search report	Publication date	Patent family member(s)	Publication date
US 2019011122 A1	10-01-2019	CA 3069675 A1	17-01-2019
		EP 3622218 A1	18-03-2020
		US 9920926 B1	20-03-2018
		US 2019011122 A1	10-01-2019
		WO 2019014226 A1	17-01-2019

For more details about this annex : see Official Journal of the European Patent Office, No. 12/82

REFERENCES CITED IN THE DESCRIPTION

This list of references cited by the applicant is for the reader's convenience only. It does not form part of the European patent document. Even though great care has been taken in compiling the references, errors or omissions cannot be excluded and the EPO disclaims all liability in this regard.

Patent documents cited in the description

- AT 516424 B1 **[0001]**
- AT 522614 B1 **[0015]**
- EP 2221541 A2 **[0016]**
- US 7406827 B2 **[0017]**

Non-patent literature cited in the description

- Combustion: An International Series. **ARTHUR H. LEFEBVRE.** Gas Turbine Combustion. Taylor & Francis, 1999 **[0004]**
- Cambridge Aerospace Series. **TIM C LIEUWEN ; VIGOR YANG.** Gas turbine emissions. Cambridge University Press, 2013, vol. 38 **[0004]**
- The Penguin Dictionary of Curious and Interesting Geometry. **D.G. WELLS ; STEPHEN WOLFRAM.** Penguin books : Mathematics reference. Penguin Books, 1991 **[0046]**
- Wellen und Blumen - eine anschauliche Darstellung der Fourier-Transformation. **DIANA ESTÉVEZ SCHWARZ.** Berichte aus der Mathematik, Physik und Chemie. BEUTH Hochschule für Technik, 2018 **[0046]**