



US 20160194256A1

(19) **United States**

(12) **Patent Application Publication**
Whitmore et al.

(10) **Pub. No.: US 2016/0194256 A1**

(43) **Pub. Date: Jul. 7, 2016**

(54) **SOLID GRAIN STRUCTURES, SYSTEMS, AND METHODS OF FORMING THE SAME**

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(21) Appl. No.: **14/807,667**

(22) Filed: **Jul. 23, 2015**

Related U.S. Application Data

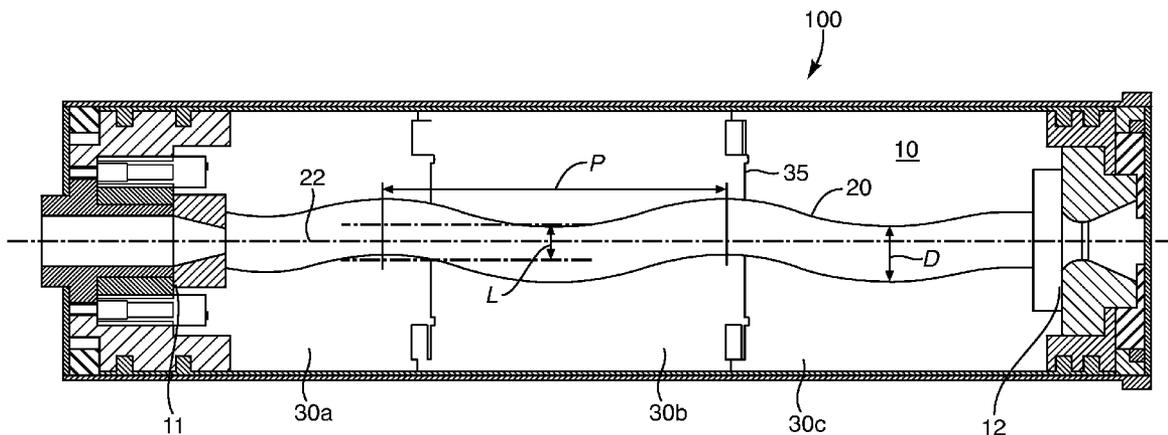
(63) Continuation-in-part of application No. 13/953,877, filed on Jul. 30, 2013.

(60) Provisional application No. 62/029,368, filed on Jul. 25, 2014, provisional application No. 61/677,254, filed on Jul. 30, 2012, provisional application No. 61/677,266, filed on Jul. 30, 2012, provisional application No. 61/677,418, filed on Jul. 30, 2012, provisional application No. 61/677,426, filed on Jul. 30, 2012, provisional application No. 61/677,298, filed on Jul. 30, 2012.

Publication Classification

(51) **Int. Cl.**
C06B 21/00 (2006.01)
C06B 45/00 (2006.01)
(52) **U.S. Cl.**
CPC **C06B 21/0033** (2013.01); **C06B 45/00** (2013.01)

(57) **ABSTRACT**
Devices, methods, and systems for providing a solid grain fuel for a hybrid rocket. In one embodiment, the solid grain fuel includes a housing having a length extending between a first side and a second side. The housing defines a central axis and a bore extending from the first side to the second side. The bore of the housing extends with a helical configuration along the length of the housing. Further, the housing includes multiple segments configured to interlock together to form the bore along the length of the housing.



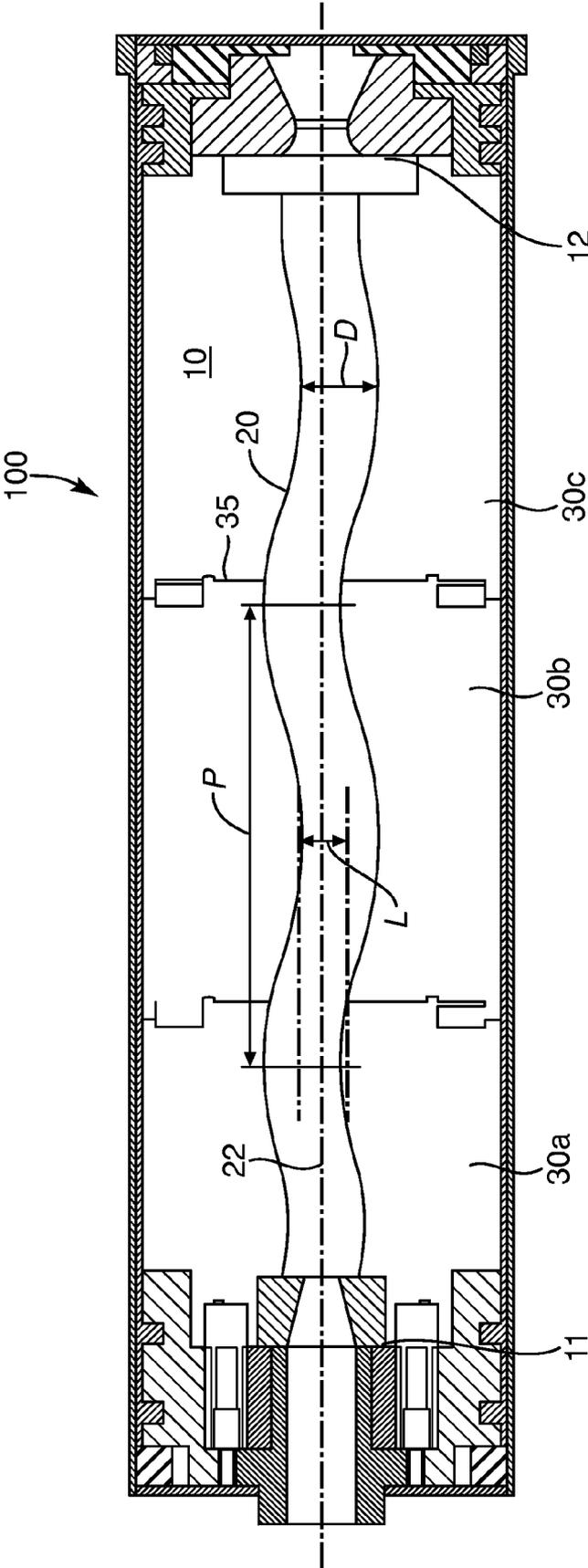
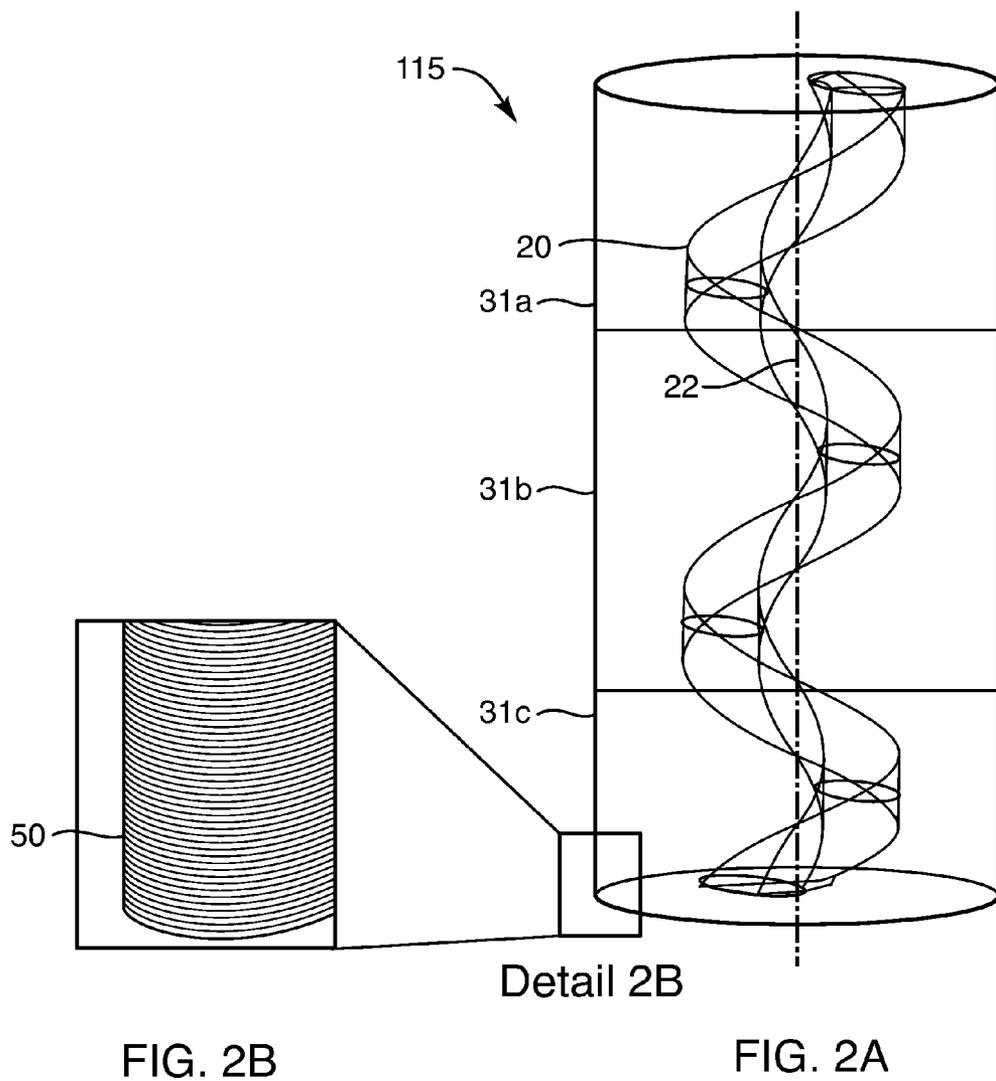


FIG. 1



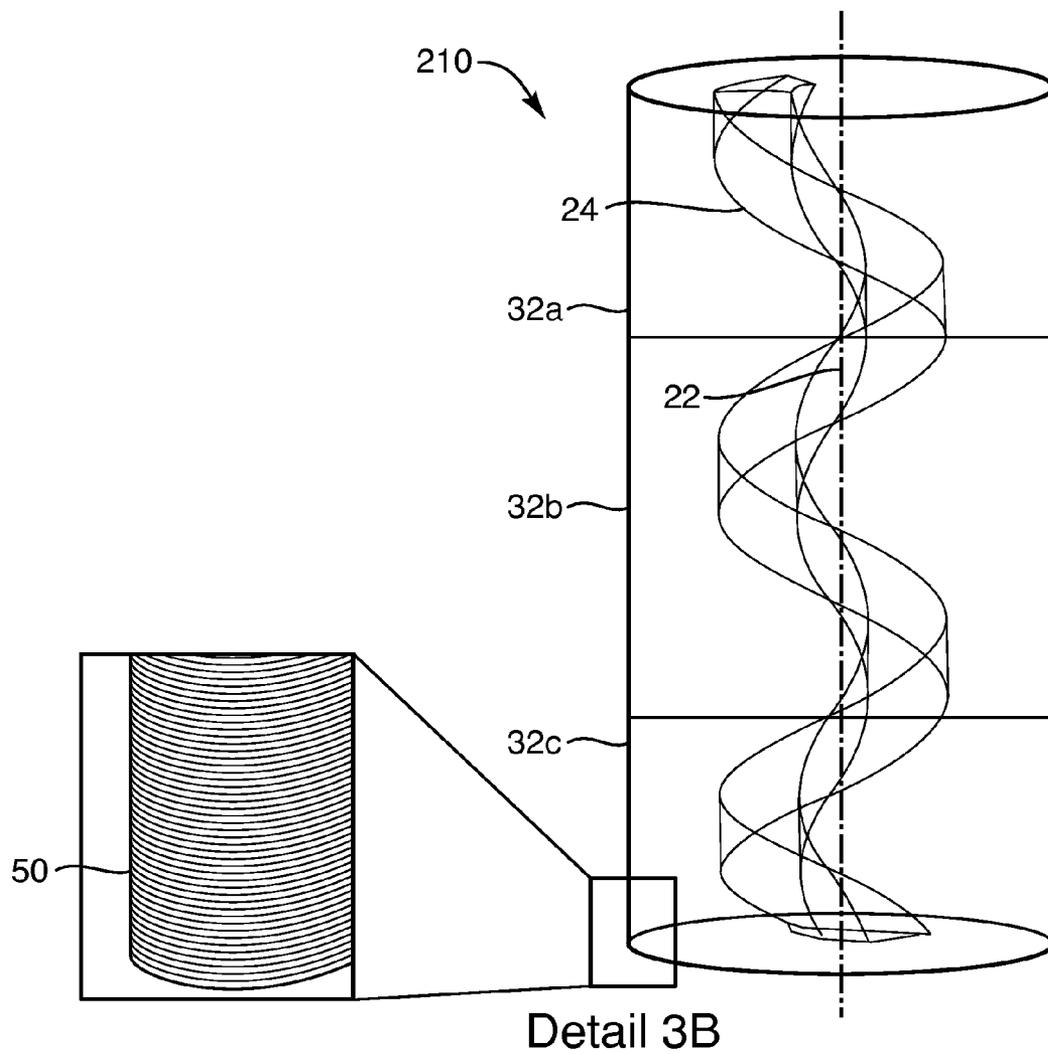


FIG. 3B

FIG. 3A

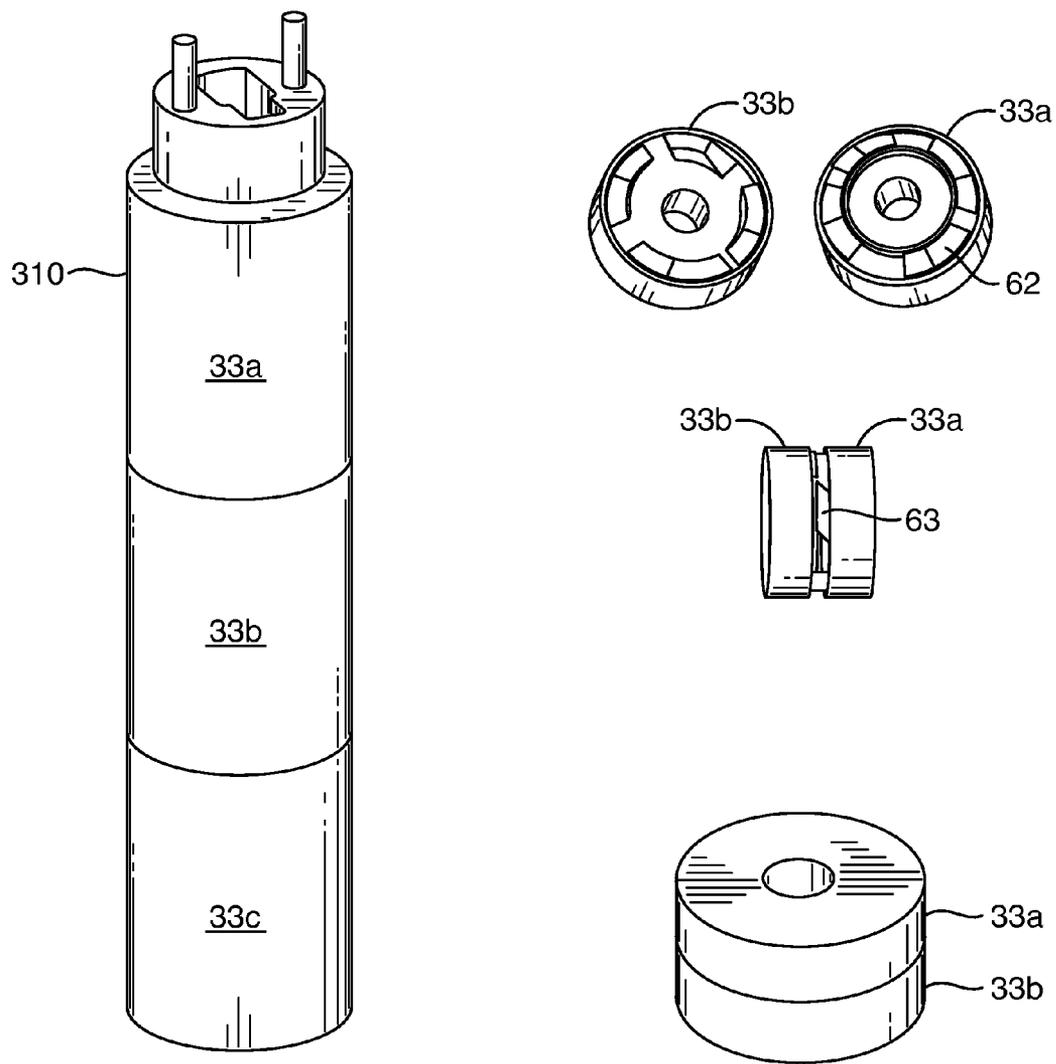


FIG. 4

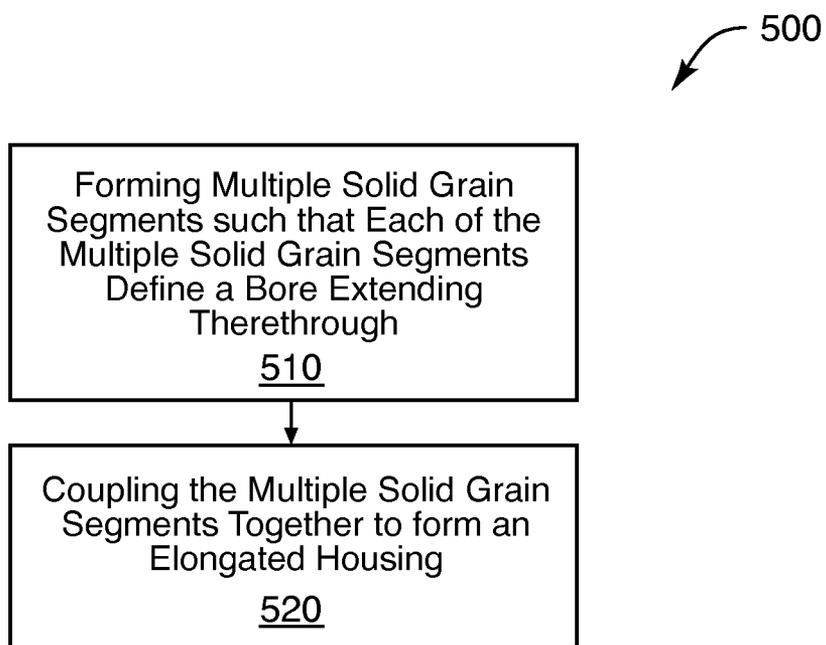


FIG. 5

SOLID GRAIN STRUCTURES, SYSTEMS, AND METHODS OF FORMING THE SAME

CROSS-REFERENCE TO RELATED APPLICATIONS

[0001] This application is a continuation-in-part application to U.S. Non-provisional application Ser. No. 13/953,877, filed on Jul. 30, 2013 and entitled "Multiple Use Hybrid Rocket Motor," which is hereby incorporated by reference in its entirety and which claims the benefit under 35 U.S.C. §119(e) of U.S. Provisional Application Nos. 61/677,254; 61/677,266; 61/677,418; 61/677,426; and 61/677,298; all filed Jul. 30, 2012, and all of which are hereby incorporated by reference in their entirety.

[0002] This application also claims priority to U.S. Provisional Application No. 62/029,368, filed on Jul. 25, 2014, and entitled "Solid Grain Structures, Systems, and Methods of Forming the Same," which is herein incorporated by this reference in its entirety.

GOVERNMENT SPONSORED RESEARCH

[0003] This invention was made with government support under contracts NNX09AW08A and NNX12AN12G awarded by NASA. The government has certain rights in the invention.

TECHNICAL FIELD

[0004] The present invention relates generally to hybrid rocket systems and, more specifically, to devices, systems and methods of forming a solid grain structure for a hybrid rocket system.

BACKGROUND

[0005] Hybrid rocket motors, in spite of their well-known safety and handling advantages, have not seen widespread commercial use due to internal motor ballistics that produce fuel regression rates typically 25-30% lower than solid fuel motors in the same thrust and impulse class. These lowered fuel regression rates tend to produce unacceptably high oxidizer-to-fuel (O/F) ratios. These high O/F ratios lead to grain and nozzle erosion and reduced motor duty cycles. To achieve O/F ratios that produce acceptable combustion characteristics, traditional cylindrical fuel ports have been fabricated to have a longer length-to-diameter ratio. This high aspect ratio results in poor volumetric efficiency and presents the potential for lateral structural loading issues in the motor during high thrust burns.

SUMMARY

[0006] Applicants of the present disclosure have identified that it would be advantageous to provide a hybrid rocket system that provides acceptable fuel regression rates and O/F ratios similar or better than solid fuel motors without the deficiencies of poor volumetric efficiency and lateral structural loading.

[0007] Embodiments of the present invention are directed to various devices, systems and methods of forming a solid grain fuel for a hybrid rocket. For example, in one embodiment, the solid grain fuel includes a housing having a length extending between a first side and a second side. The housing defines a central axis and a bore extending from the first side to the second side. The bore of the housing extends with a

helical configuration along the length of the housing. Further, the housing includes multiple segments configured to interlock together to form the bore along the length of the housing.

[0008] In one embodiment, each of the multiple segments includes multiple flat layers. Such flat layers may be formed by fused deposition modeling or three dimensional printing, or the like. In another embodiment, each of the multiple flat layers define a plane that is transverse relative to the central axis of the housing. In still another embodiment, the bore extends through each of the multiple flat layers.

[0009] In another embodiment, the housing is formed of acrylonitrile butadiene styrene (ABS). In another embodiment, the bore includes a circular cross-section. In still another embodiment, the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the coupled multiple segments.

[0010] In accordance with another embodiment of the present invention, a solid grain fuel for a hybrid rocket is provided. In one embodiment, the solid grain fuel includes a housing having a length extending between a first side and a second side. Such housing defines a central axis and a bore extending from the first side to the second side such that the bore extends with a helical configuration along the length of the housing. The housing in this embodiment includes an acrylonitrile butadiene styrene (ABS) material.

[0011] In another embodiment, the housing includes multiple segments configured to interlock together to form the bore along the length of the housing. In another embodiment, the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the coupled multiple segments. In another embodiment, each of the multiple segments includes multiple flat layers. In yet another embodiment, the bore includes a circular cross-section.

[0012] In accordance with another embodiment of the present invention, a solid grain fuel for a hybrid rocket is provided. In one embodiment, the solid grain fuel includes a modular housing including multiple segments each configured to be coupled together to form the modular housing. The modular housing includes a length extending between a first side and a second side. Such modular housing defines a helical extending bore extending along the length and between the first side to the second side of the modular housing. Further, the modular housing includes an acrylonitrile butadiene styrene (ABS) material.

[0013] In another embodiment, each of the multiple segments includes multiple flat layers. In another embodiment, the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that a bore in each of the multiple segments of the modular housing collectively defines the helically extending bore.

[0014] In accordance with another embodiment of the present invention, a method of forming a solid grain fuel for a hybrid rocket is provided. The method includes: forming multiple solid grain segments such that each of the multiple solid grain segments define a bore extending therethrough; and coupling the multiple solid grain segments together to form an elongated housing such that the bore extending

through each of the solid grain segments collectively defines a helically extending bore that extends along a length of the elongated housing between opposite first and second sides.

[0015] In another embodiment, the forming step includes the step of forming each of the multiple solid grain segments with multiple flat layers. In another embodiment, the forming step includes the step of forming the multiple solid grain segments with fused deposition modeling. In still another embodiment, the forming step includes the step of forming the multiple solid grain segments with an acrylonitrile butadiene styrene (ABS) material. In yet another embodiment, the forming step includes the step of forming the multiple solid grain segments with additive layering with an acrylonitrile butadiene styrene (ABS) material.

[0016] In another embodiment, the forming step includes the method step of forming the multiple solid grain segments with inter-locking features to inter-lock the multiple solid grain segments together to form the elongated housing. In another embodiment, the forming step includes the method step of forming the multiple solid grain segments with an orientation feature or keying feature on at least one of the oppositely facing sides of the multiple solid grain segments. In still another embodiment, the coupling step includes the step of orienting each one of the multiple solid grain segments relative to another one of the multiple solid grain segments with the orientation feature to form the helically extending bore of the elongated housing.

[0017] In accordance with another embodiment of the present invention, a hybrid rocket system is provided. In one embodiment, the hybrid rocket system includes a container, a solid grain portion, and a nozzle. The container is sized to contain liquid or gaseous fuel. The solid grain portion includes a length extending between a first side and a second side such that the first side is configured to receive fuel from the container. The solid grain portion defines a central axis and a bore extending between the first side and the second side such that the bore extends with a helical configuration along the length of the solid grain portion. The nozzle is coupled to the second side of the solid grain portion such that the nozzle is configured to manipulate thrust to the rocket system.

[0018] In another embodiment, the solid grain portion includes multiple segments configured to interlock together to form the bore along the length of the housing. In another embodiment, each of the multiple segments includes multiple flat layers. In still another embodiment, the bore extends through each of the multiple flat layers. In another embodiment, the solid grain portion is formed of an acrylonitrile butadiene styrene (ABS) material. In another embodiment, the bore includes a circular cross-section. In yet another embodiment, the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the multiple segments.

BRIEF DESCRIPTION OF THE DRAWINGS

[0019] The foregoing features of embodiments of the present disclosure will become more fully apparent from the following description and appended claims, taken in conjunction with the accompanying drawings. Understanding that these drawings depict only typical embodiments of the invention and are, therefore, not to be considered limiting of its

scope, the invention will be described with additional specificity and detail through use of the accompanying drawings in which:

- [0020] FIG. 1 is a plan view of a hybrid rocket;
- [0021] FIG. 2A is an elevation view of a solid grain fuel with a circular cross-sectional helical bore;
- [0022] FIG. 2B is a detail view of the solid grain fuel of FIG. 2A illustrating multiple flat layers;
- [0023] FIG. 3A is an elevation view of a solid grain fuel with a square cross-sectional helical bore;
- [0024] FIG. 3B is a detail view of the solid grain fuel of FIG. 3A illustrating multiple flat layers;
- [0025] FIG. 4 illustrates a solid grain fuel and multiple segments of a solid grain fuel configured to couple together; and
- [0026] FIG. 5 is a method of forming a solid grain fuel.

DETAILED DESCRIPTION

[0027] The present disclosure covers various devices, systems and methods of forming a solid grain fuel for a hybrid rocket. In the following description, numerous specific details are provided for a thorough understanding of specific preferred embodiments. However, those skilled in the art will recognize that embodiments can be practiced without one or more of the specific details, or with other methods, components, materials, etc. In some cases, well-known structures, materials, or operations are not shown or described in detail in order to avoid obscuring aspects of the preferred embodiments. Furthermore, the described features, structures, or characteristics may be combined in any suitable manner in a variety of alternative embodiments. Thus, the following more detailed description of the embodiments of the present invention, as illustrated in some aspects in the drawings, is not intended to limit the scope of the invention, but is merely representative of the various embodiments of the invention.

[0028] In this specification and the claims that follow, singular forms such as “a,” “an,” and “the” include plural forms unless the content clearly dictates otherwise. All ranges disclosed herein include, unless specifically indicated, all endpoints and intermediate values. In addition, “optional,” “optionally,” or “or” refer, for example, to instances in which subsequently described circumstance may or may not occur, and include instances in which the circumstance occurs and instances in which the circumstance does not occur. The terms “one or more” and “at least one” refer, for example, to instances in which one of the subsequently described circumstances occurs, and to instances in which more than one of the subsequently described circumstances occurs.

[0029] FIG. 1 illustrates an example hybrid rocket **100** that includes a housing **10** having a length extending between a first side **11** and a second side **12**. In this example, the housing or fuel grain **10** defines a central axis **22** and a bore or helical fuel port **20** extending from the first side **11** to the second side **12** inside the fuel grain **10**. The bore **20** extends with a helical configuration along the length of the housing **10**. The housing **10** also includes multiple modular housing segments **30a**, **30b**, and **30c**, configured to interlock together through matching interlocking features **35** to form the bore **20** along the length of the housing **10**. The housing **10** or multiple modular housing segments **30a**, **30b**, and **30c** may be manufactured by fused deposition modeling (FDM) with acrylonitrile butadiene styrene (ABS).

[0030] In FIG. 1, the helical fuel port **20** is further defined by a pitch rotation P , a bore diameter D , and a mean diameter

L. These dimensions may be adjusted to achieve different initial fuel port areas and different oxidizer-to-fuel (O/F) ratios in operation.

[0031] ABS is a thermoplastic that melts before vaporizing when subjected to heat. This property makes ABS one of the materials of choice for fused deposition modeling (FDM) rapid prototyping machines. Because ABS can be formed into a wide variety of shapes using modern additive manufacturing and rapid prototyping techniques, it is possible to embed complex high-surface area flow paths within the fuel grain. These internal flow paths allow for motor aspect ratios that are significantly shorter than can be achieved using conventional solid, hybrid, or mono-propellant technologies. These flow paths cannot be achieved with thermo-setting materials that are cast using tooling that must be removed once the material is set.

[0032] The embedded helical port or bore 20 provides an extended length flow path and a large surface area contact in a short form factor. Centrifugal forces created by combustion gases and oxidizer rotating in and flowing through the helical fuel port or bore 20 significantly increases the fuel regression rates and propellant mass flow from the fuel grain or housing 10.

[0033] In order to significantly increase the regression rate, a helical port or bore 20 fuel design feature increases the nominal surface skin friction while also minimizing the effects of radial surface blowing. A helical pipe flow with cylindrical ports shows significantly increased end-to-end pressure losses when compared to flows through straight pipes with identical cross sections. Thus, helical flows have the effect of significantly increasing the local skin friction coefficient. Helical flows also introduce a centrifugal component into the flow field. In hybrid rocket applications such as hybrid rocket 100, this centrifugal component will have the effect of thinning the wall boundary layer—bringing the flame zone closer to the wall surface and increasing the flame diffusion efficiency. An increased flame diffusion efficiency increases O/F ratios. Helical fuel ports in a wide variety of cross sectional areas can be easily manufactured using ABS fuel materials manufactured by FDM techniques.

[0034] FIG. 2A illustrates the housing 115 with similar features to housing 10 illustrated in FIG. 1. Housing 115 includes multiple modular housing segments 31a, 31b, and 31c, configured to interlock together to form the bore 20 along the length of the housing 115. More segments may be used to extend the overall length of the housing 115. Segments such as 31a, 31b, and 31c may couple or “snap” together with matching interlocking features and then further secured using ABS pipe joint cement.

[0035] FIG. 2B is a detail view of multiple flat layers 50 of the housing 115. In this example, each of the multiple flat layers 50 defines a plane that is transvers relative to the central axis 22 of the housing 115.

[0036] FIGS. 3A and 3B similarly illustrate a housing 210 with a square bore 24 extending in a helical configuration along the length of the housing 210.

[0037] FIG. 4 illustrates a modular housing 310 that includes multiple segments 33a, 33b, and 33c. The segments 33a, 33b, and 33c are configured to couple together through matching interlocking features 62 to form the modular housing 310. If made of ABS, the segments 33a, 33b, and 33c may be further secured together to form an air-tight connection with ABS pipe joint cement. Although not shown, a helical bore extends through the segments 33a, 33b, and 33c.

[0038] FIG. 4 further illustrates how the multiple segments 33a, 33b, and 33c have opposite ends that include an orientation feature 63 configured to couple one segment to another segment such that the bore in each of the multiple segments of the modular housing collectively defines a helical extending bore.

[0039] FIG. 5 illustrates a method 500 for forming an elongated housing of a solid grain fuel structure. A method includes a step 510 of forming multiple solid grain segments such that each of the multiple solid grain segments define a bore extending therethrough and an additional step 520 of coupling the multiple solid grain segments together to form an elongated housing.

What is claimed is:

1. A solid grain fuel for a hybrid rocket, comprising:
 - a housing having a length extending between a first side and a second side, the housing defining a central axis and a bore extending from the first side to the second side, the bore extending with a helical configuration along the length of the housing, the housing including multiple segments configured to interlock together to form the bore along the length of the housing.
2. The solid grain fuel of claim 1, wherein:
 - each of the multiple segments comprises multiple flat layers and each flat layer defines a plane that is transverse relative to the central axis of the housing, and the bore extends through each of the multiple flat layers
3. The solid grain fuel of claim 1, wherein the housing is formed of acrylonitrile butadiene styrene (ABS).
4. The solid grain fuel of claim 1, wherein the bore comprises a circular cross-section.
5. The solid grain fuel of claim 1, wherein the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the coupled multiple segments.
6. A solid grain fuel for a hybrid rocket, comprising:
 - a housing having a length extending between a first side and a second side, the housing defining a central axis and a bore extending from the first side to the second side, the bore extending with a helical configuration along the length of the housing, the housing including acrylonitrile butadiene styrene (ABS).
7. The solid grain fuel of claim 6, wherein the housing comprises multiple segments configured to interlock together to form the bore along the length of the housing.
8. The solid grain fuel of claim 7, wherein the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the coupled multiple segments.
9. The solid grain fuel of claim 7, wherein each of the multiple segments comprises multiple flat layers.
10. The solid grain fuel of claim 7, wherein the bore comprises a circular cross-section.
11. A method of forming a solid grain fuel for a hybrid rocket, the method comprising:
 - forming multiple solid grain segments with additive layering with acrylonitrile butadiene styrene (ABS) wherein each of the multiple solid grain segments define a bore extending therethrough; and

coupling the multiple solid grain segments together to form an elongated housing such that the bore extending through each of the solid grain segments collectively defines a helically extending bore that extends along a length of the elongated housing between opposite first and second sides.

12. The method according to claim **11**, wherein the forming comprises:

forming each of the multiple solid grain segments with multiple flat layers with fused deposition modeling.

13. The method according to claim **12**, wherein the forming comprises forming the multiple solid grain segments with acrylonitrile butadiene styrene (ABS).

14. The method according to claim **11**, wherein the forming comprises forming the multiple solid grain segments with inter-locking features to inter-lock the multiple solid grain segments together to form the elongated housing.

15. The method according to claim **11**, wherein:

the forming comprises forming the multiple solid grain segments with a keying feature on at least one of the oppositely facing sides of the multiple solid grain segments, and

the coupling comprises orienting each one of the multiple solid grain segments relative to another one of the multiple solid grain segments with the keying feature to form the helically extending bore of the elongated housing.

16. A hybrid rocket system, comprising:
a container sized to contain liquid or gaseous fuel;
a solid grain portion having a length extending between a first side and a second side, the first side configured to receive fuel from the container, wherein:
the solid grain portion defines a central axis and a bore extending between the first side and the second side;
the bore extends with a helical configuration along the length of the solid grain portion; and
the solid grain portion comprises multiple segments configured to interlock together to form the bore along the length of the housing; and
a nozzle coupled to the second side of the solid grain portion, the nozzle configured to manipulate thrust to the rocket system.

17. The hybrid rocket system of claim **16**, wherein each of the multiple segments comprises multiple flat layers and the bore extends through each of the multiple flat layers.

18. The hybrid rocket system of claim **16**, wherein the solid grain portion is formed of acrylonitrile butadiene styrene (ABS).

19. The hybrid rocket system of claim **16**, wherein the bore comprises a circular cross-section.

20. The hybrid rocket system of claim **16**, wherein the multiple segments include opposite ends, at least one of the opposite ends including an orientation feature configured to couple to an end of another one of the multiple segments so that the bore in each of the multiple segments collectively defines the helical configuration within the multiple segments.

* * * * *