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Inventor(s)	Shi; Junmei et al.

Injector for gaseous fuel

Abstract

A fuel injector for injecting gaseous fuels into a combustion chamber, comprising an injection nozzle including a nozzle cap, and an outward opening injection needle. The injection nozzle has a longitudinal injector axis and a tip region that is shaped to define a valve seat that extends about a central outlet opening for gaseous fuel. The outward opening injection needle is slidably received in the injection nozzle and is engageable with the valve seat to control a flow of gaseous fuel into a sac volume of the fuel injector. The nozzle cap is received over the tip region to define the sac volume, and is provided with a plurality of openings to enable the flow of gaseous fuel to pass from the sac volume into the combustion chamber when the injection needle is moved away from the valve seat.

Inventors:	Shi; Junmei (Trier, DE), Hoffman; Guy (Sandweiler, LU)
Applicant:	PHINIA DELPHI LUXEMBOURG SARL (Belvaux, LU)
Family ID:	1000008749941
Assignee:	PHINIA DELPHI LUXEMBOURG SARL (Belvaux, LU)
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Primary Examiner: Moubry; Grant

Attorney, Agent or Firm: WARNER NORCROSS + JUDD LLP

Background/Summary

CROSS-REFERENCE TO RELATED APPLICATIONS

(1) This application is the U.S. National Stage of International Application No.

PCT/EP2022/084240 filed on 2 Dec. 2022, which claims priority to and all advantages of United Kingdom Application No. 2117833.0 filed on 9 Dec. 2021, the contents of which are incorporated herein by reference.

TECHNICAL FIELD

(2) The present invention relates generally to a configuration of a fuel injector suitable for injecting a gaseous fuel such as hydrogen into a combustion chamber of an internal combustion engine. The injector may be suitable for injection of other fuels.

BACKGROUND

(3) Fuel injectors are used in combustion engines to inject fuel into a runner of an air intake manifold ahead of a cylinder intake valve or directly into the combustion chamber of an engine cylinder. Different types of fuel injectors for gaseous fuels are known. One approach is a so-called 'outward opening' fuel injector in which an injector valve needle (or pintle) is configured to lift away from a valve seat towards the combustion chamber in order to allow fuel to flow into the combustion chamber.

(4) One challenge associated with outward opening injectors is that of achieving efficient air-fuel mixing required for homogeneous combustion. It is particularly challenging to achieve such an efficient combustion at increasing engine loads and speeds. Typically, outward opening injectors create a spray or jet plume of fuel with a hollow cone shape which is susceptible to either inward or outward collapse. As a result, it can be difficult to target the delivery of fuel to optimal regions within the combustion chamber especially at high cylinder pressures which result from high engine loads and speeds. This is especially true for gas fuel injectors due to the low fuel density. Therefore, internal combustion systems that employ such fuel injectors experience poor engine efficiency at high cylinder pressures, the efficiency varying, and typically being improved with lowering engine loads and speeds. However, without optimal jet targeting, homogeneous combustion cannot be achieved, and engine efficiency suffers as a result.

(5) It is against this background that the invention has been devised.

SUMMARY OF THE INVENTION

(6) Against this background, a first aspect of the invention provides a fuel injector suitable for injecting gaseous fuels into a combustion chamber, the fuel injector comprising an injection nozzle having a longitudinal injector axis and a tip region that is shaped to define a valve seat that extends about a central outlet opening for gaseous fuel; and an outward opening injection needle slidably received in the injection nozzle and engageable with the valve seat to control a flow of gaseous fuel into a sac volume of the fuel injector. The injection nozzle further includes a nozzle cap that is received over the tip region to define the sac volume, the nozzle cap being provided with a plurality of openings to enable the flow of gaseous fuel to pass from the sac volume into the combustion chamber when the injection needle is moved away from the valve seat. The plurality of openings is comprised of at least (i) at least one first opening configured to direct a first flow portion of the flow of gaseous fuel into a first zone of the combustion chamber; and (ii) a second set of openings, configured to direct a second flow portion of the flow of gaseous fuel into a second zone of the combustion chamber.

(7) The second zone of the combustion chamber may be substantially different from the first zone of the combustion chamber and comprise regions within the combustion chamber which cannot be reached by the first flow portion of the flow of gaseous fuel. For example, the first zone may be defined as a lower portion of the combustion chamber and the second zone may be defined as an upper portion of the combustion chamber. In this way, the first and second flow portions of gaseous fuel achieve greater coverage within the combustion chamber thereby promoting greater air-fuel mixing and more efficient combustion.

- (8) The first opening may form one of a set of first openings.
- (9) The or each opening of the first set may have a diameter that is different to the diameter of the or each opening of the second set. In some embodiments, the first opening may form one opening of a first set of openings. If there is only one opening in the first set, the opening may have a first flow axis which aligns with the longitudinal injector axis.
- (10) Additionally or alternatively, each opening of the second set may have a second central flow axis which defines a first angle to the longitudinal injector axis which is the same as for the other openings of the set. Further, each opening of the second set may have an inlet which opens into the sac volume which is located on a first plane perpendicular to the longitudinal injector axis. The inlets of each opening of the second set may be equiangularly spaced around the longitudinal injector axis in the first plane.
- (11) The plurality of openings may further include a third set of openings configured to direct a third flow portion of the flow of gaseous fuel into a third zone of the combustion chamber. The third zone may be substantially different to the first and second zones and comprises regions of the combustion chamber which cannot be reached by the first and second flow portions of the flow.
- (12) Each opening of the third set may have a third central flow axis which defines a second angle to the longitudinal injector axis which is different to the first angle defined by the second central flow axis to the longitudinal injector axis. Additionally or alternatively, each opening of the third set may have an inlet which opens into the sac volume which is located on a second plane perpendicular to the longitudinal axis. The second plane adopts a lower position along the longitudinal injector axis than the first plane—i.e. the second plane is lower than the first plane according to the orientation of the Figures which follow.
- (13) In some embodiments, each opening of the second set may have a diameter that is different to the diameter of each opening of the third set. Alternatively, each opening of the second set may have a diameter that is the same as the diameter of each opening of the third set.
- (14) In some embodiments, the second set of openings may include between two and five openings.
- (15) In some embodiments, the inlets of the second set of openings are angularly spaced apart from the inlets of the third set of openings around the nozzle cap in their respective planes perpendicular to the longitudinal injector axis/nozzle cap axis; and wherein the outlets of the second set of openings are angularly spaced apart from the outlets of the third set of openings around the nozzle cap in their respective planes perpendicular to the longitudinal injector axis/nozzle cap axis, such that the second central flow axis of the second set of openings is not axially aligned with the third central flow axis of the third set of openings.
- (16) In another aspect of the invention, there is provided a fuel injection system for gaseous fuel comprising a fuel injector and a combustion chamber into which the gaseous fuel is injected.
- (17) It will be appreciated that preferred or optional features of the first aspect of the invention may be incorporated in other aspects of the invention also, alone or in appropriate combination.
- (18) Further optional and advantageous features are referenced in the detailed description and the appended claims.
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Description

BRIEF DESCRIPTION OF THE DRAWINGS

- (1) So that the invention may be better understood, reference will now be made by way of example only to the following drawings in which:
- (2) FIG. 1 is an illustration of a centre-mounted injector on a combustion chamber;
- (3) FIG. 2 is an illustration of a side-mounted injector on a combustion chamber;
- (4) FIG. 3 is a cross section of an injection nozzle for use in the fuel injector in FIGS. 1 and 2;
- (5) FIG. 4(a) is a cross section, in a plane parallel to the longitudinal axis of the injection nozzle,

- through a nozzle cap for use with the injection nozzle in FIG. 3, to illustrate first and second rows of holes of the nozzle;
- (6) FIG. 4(b) is a schematic illustration to show the angles of the rows of holes in the nozzle cap in FIG. 4(a);
- (7) FIGS. 4(c) and 4(d) are cross section views, taken at different positions on the longitudinal axis of the nozzle cap, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show one example configuration for the rows of holes in the nozzle cap in FIGS. 4(a) and (b);
- (8) FIGS. 4(e) and 4(f) are cross section views, taken at different positions on the longitudinal axis of the nozzle cap, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show another example configuration for the holes in the nozzle cap in FIGS. 4(a) and (b);
- (9) FIG. 5(a) is a cross section view, in a plane parallel to the longitudinal axis of the injection nozzle, through a nozzle cap for use with the injection nozzle in FIG. 3, to illustrate an alternative arrangement of first and second rows of holes compared to FIG. 4;
- (10) FIG. 5(b) is a schematic illustration to show the angles of the rows of holes in the nozzle cap in FIG. 5(a);
- (11) FIGS. 5(c) and 5(d) are cross section views, taken at different positions on the longitudinal axis of the nozzle cap, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show one example configuration for the holes in the nozzle cap in FIGS. 5(a) and (b);
- (12) FIGS. 5(e) and 5(f) are cross section views, taken at different positions on the longitudinal axis of the nozzle cap, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show another example configuration for the holes in the nozzle cap in FIGS. 5(a) and (b);
- (13) FIG. 6(a) is a cross section view, in a plane parallel to the longitudinal axis of the injection nozzle, through a nozzle cap for use with the injection nozzle in FIG. 3, to illustrate an alternative arrangement of first and second rows of holes to those shown in FIGS. 4 and 5;
- (14) FIG. 6(b) is a cross section view, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show the configuration for the holes in the nozzle cap in FIG. 6(a);
- (15) FIG. 7(a) is a cross section view, in a plane parallel to the longitudinal axis of the injection nozzle, through a nozzle cap for use with the injection nozzle in FIG. 3, to illustrate an alternative arrangement of first and second rows of holes compared to FIGS. 4, 5 and 6;
- (16) FIG. 7(b) is a cross section view, through a plane perpendicular to the longitudinal axis of the injection nozzle, to show the configuration for the holes in the nozzle cap in FIG. 7(a);
- (17) FIGS. 8 to 11 are views from the bottom of various nozzle caps for use with the injection nozzle in FIG. 3; and
- (18) FIG. 12 is an example of an alternative nozzle cap to that shown in FIG. 11.

DETAILED DESCRIPTION OF THE EMBODIMENTS

- (19) To provide context for the invention, FIG. 1 schematically shows a cross-section view of part of an engine 2. The engine 2 comprises a cylinder or combustion chamber 4 with a cylinder axis 6 which, in this context, defines a vertical direction although this vertical direction may not coincide with the direction of gravity depending on the design of the engine 2. An air intake duct 8 and an air outlet duct 10 are connected to a head 12 of the cylinder 4 with an intake valve 14 and an outlet valve 16 disposed to alternately open and close the respective ducts 8, 10.
- (20) A fuel injector 18 (shown only in simplified form) is installed on the head 12 of the cylinder 4 in a central mounting configuration, meaning that the injector 18 is mounted in a centre region of the engine cylinder head 12 among the intake and outlet valves 14, 16. The injector 18 has a longitudinal injector axis 20 which is aligned with the cylinder axis 6. Alternatively, as shown in FIG. 2, the fuel injector 18 may be mounted to the side of the cylinder 4 where the intake valve 14 is installed. In this case, the injector axis 20 is tilted at an angle (e.g., of about 70°) with respect to the cylinder axis 6.
- (21) FIG. 3 shows an embodiment of the fuel injector 18 which is an outward opening type. As shown, the injector 18 comprises an injector body 22 and an elongated valve housing 24 (also

known as a 'nozzle') having the longitudinal injector axis **20**. The injector body **22** houses an actuator arrangement **26** that is configured to act on an injection valve needle **28** (or 'pintle') contained within the nozzle **24**. The injection nozzle **24** has a tip region that is shaped to define a valve seat **32** that extends about a central outlet opening for gaseous fuel. The valve needle **28** is biased against the valve seat **32** by means of a closure spring **34**.

(22) The nozzle **24** houses a supply of fuel in an annular chamber **30** that surrounds the needle **28**. The valve needle **28** is configured to be slidably actuated along the injector axis **20** in order to open and close the valve needle **28** against the valve seat **32** as required. When the valve needle **28** is in a closed position, an end of the needle **28** engages with the valve seat **32** defined at a tip region of the nozzle **24** so as to block the flow of fuel out of the nozzle **24**. When the valve needle **28** is actuated to move downwards (in the orientation of the Figures), the end of the valve needle **28** moves away from the valve seat **32** thereby allowing the fuel to flow out of the tip region of the nozzle **24** and into the combustion chamber **4**. In other words, the valve needle **28** is moved into an open position under the force of the actuator **26**.

(23) In the present embodiment, actuation of the valve needle **28** is achieved by way of an electromagnetic actuator. Other forms of actuation are acceptable, such as piezoelectric actuators.

(24) The nozzle **24** includes a nozzle cap **36**, which defines a sac volume **38** and is positioned over the tip region of the nozzle **24**. The nozzle cap **36** is hemispherical in shape, however, other embodiments in which the nozzle cap **36** is cylindrical in shape with a hemispherical end or taking other axisymmetric form are possible. As will be described in more detail below, the nozzle cap **36** comprises a plurality of holes or openings **40**, each opening **40** defining a flow passage through the wall of the nozzle cap **36** so as to enable the fuel to flow from the tip region of the nozzle **24** into the combustion chamber **4** via the sac volume **38** when the valve needle **28** is in the open position. That is to say, the injection needle **28** is configured to be slidably received in the injection nozzle **24** and engageable with the valve seat **32** so as to control the flow of fuel into the sac volume **38** of the fuel injector **18**. Accordingly, when the needle **28** is moved away from the valve seat **32**, gaseous fuel passes from the sac volume **38** and through the plurality of openings **40** into the combustion chamber **4**. The nozzle cap **36** has a central longitudinal axis **42** which aligns with the longitudinal axis of the injector **20**.

(25) Each opening **40** extends from an inlet **44** at an inner surface **46** of the nozzle cap **36** to an outlet **48** at an outer surface **50** of the nozzle cap **36** along an opening axis or central flow axis **52** which is a symmetrical axis of the respective opening. Each inlet **44** opens into the sac volume **38** while each outlet **48** opens into the combustion chamber **4**. Accordingly, the opening axis **52** corresponds to a general direction of fuel flow from the inside of the nozzle cap **36** (i.e. the sac volume **38**) to the outside of the nozzle cap **36** (i.e. the combustion chamber **4**), although the precise motion of the fuel is more complicated.

(26) The inlet **44** of each opening **40** is similarly shaped to the outlet **48** of the respective opening **40**. In this way, the walls of the opening **40** through the nozzle cap **36** are parallel to each other, thereby providing a cylindrical passage through which fuel can flow. In other words, the diameter of each opening **40** is constant along its length. Flow of fuel from cylindrical passages is advantageously robust and less susceptible to collapse. In instances where the opening axis **52** of an opening **40** is perpendicular to the inner and outer surfaces **46**, **50** of the nozzle cap **36**, the inlet and outlet **44**, **48** of the opening **40** have a circular cross section in a plane tangential to the outer surface **50** of the nozzle cap **36**. Conversely, embodiments are contemplated where the opening axis **52** is at a non-perpendicular angle to the inner and outer surfaces of **46**, **50** the nozzle cap **36**. In such instances, the inlet and outlet **44**, **48** are of elliptical cross section in a plane tangential to the outer surface **50** of the nozzle cap **36**.

(27) Generally, the plurality of openings **40** is configured to provide a controlled spray plume and may be optimised according to the requirements of the engine arrangement **2**. Specifically, the openings **40** are configured to direct fuel jets, or portions of the fuel flow, to various zones within

the combustion chamber **4** in order to achieve maximum flow separation and promote efficient air-fuel mixing. As will be explained in more detail below, the openings **40** are grouped in sets of openings according to the zones of the combustion chamber to which they direct fuel jets.

(28) The optimal spray plume, and thus the optimal configuration of openings **40**, for a particular engine **2** depends on the injector **18** mounting position as well as the type of air motion within the cylinder **4**. There are two general air motions which may be achieved depending on the arrangement of the air inlet and outlet ducts **8**, **10**. Swirl motion is defined by a rotational motion of the incoming air about the cylinder axis **6**, while tumble motion is defined by a rotational motion of the incoming air about an axis which is normal to the cylinder axis **6**. Therefore, several arrangements for the plurality of openings **40** in the nozzle cap **36** are contemplated and described with reference to the embodiments shown in FIGS. **4** to **9**.

(29) In each arrangement, the plurality of openings **40** is comprised of at least a first set of openings and a second set of openings. Generally, one or more sets of openings are configured to direct fuel so that it interacts with the tumbling or swirling air motion within the cylinder, thus actively mixing with the air as it circulates the cylinder. Inevitably, however, the circulating air and fuel does not effectively reach all regions within the cylinder when only one set of openings is used. Therefore, one or more further sets of openings are configured to direct fuel so that it flows to regions of the cylinder that is largely inaccessible by the fuel directed through the first set of openings, thereby improving the air-fuel mixing achieved. Accordingly, the first set of openings is configured to direct fuel into a first zone of the cylinder, which may be defined in a lower portion of the cylinder, while the second set of openings is configured to direct fuel into a second zone of the cylinder, which may be defined in an upper portion of the cylinder. The two zones preferably comprise different portions of the cylinder, but it is contemplated that they may overlap.

(30) In the arrangements of FIGS. **4** to **6**, the first set of openings consists of only one opening **154'** which is arranged in the nozzle cap **36** to have an opening axis **52** which aligns with the longitudinal injector axis **20**. That is to say, the one opening is arranged to extend from a circular inlet **44** at the centre of the inner surface **46** of the nozzle cap **36** to a circular outlet **48** at the centre of the outer surface **50** of the nozzle cap **36** in a cylindrical manner. The diameter of the inlet and outlet **44**, **48** are substantially the same and the internal diameter of the one opening is constant along its length.

(31) Additionally, each aperture or opening of the second set of openings is offset from the centre of the nozzle cap **36** and arranged to extend from the inner surface **46** of the nozzle cap **36** to the outer surface **50** of the nozzle cap **36** in a cylindrical manner. The internal diameter of each second set opening is different to, and preferably smaller than, the internal diameter of the first set opening so that the fuel flow rate through the first set opening is different to, and preferably greater than, the fuel flow rate through each second set opening.

(32) These arrangements further comprise a third set of openings, similar to the second set of openings in that each aperture or opening of the third set is offset from the centre of the nozzle cap **36** and arranged to extend from the inner surface **46** of the nozzle cap **36** to the outer surface **50** of the nozzle cap **36** in a cylindrical manner. In the embodiments shown, the internal diameter of each third set opening is the same as the internal diameter of the second set openings, but it is contemplated that they could be different.

(33) More specifically, FIGS. **4a** to **4f** show embodiments of a centre-mounted injector **18** with a nozzle cap **136** optimised for a tumble motion cylinder **4**. FIGS. **4a** and **4b** depict the nozzle cap as seen from the side, while FIGS. **4c** and **4d** provide cross-sectional plan views of one embodiment and FIGS. **4e** and **4f** provide cross-sectional plan views of another embodiment. In both embodiments, the nozzle cap **136** comprises a first opening **154'** and second and third sets of openings, **156a**, **156b** respectively, as described above.

(34) The second set of openings **156a** includes four apertures or openings **156'**, each of which has a respective inlet **144a** and a respective outlet **148a**. The inlets **144a** of the openings of the second set

156a are equiangularly spaced on the inner surface of the nozzle cap **136** around an axis **142** of the nozzle cap (the longitudinal nozzle cap axis) which is aligned with the injector axis **20**. The inlets **144a** are defined in a plane perpendicular to the longitudinal injector axis **20**/nozzle cap axis **142**. The third set of openings **156b** also includes four apertures or openings **156''**, each of which has a respective inlet **144b** and a respective outlet **148b**. The inlets **144b** of the openings of the third set **156b** are equiangularly spaced on the inner surface **146** of the nozzle cap **136** around the longitudinal nozzle cap axis **142** and are defined in a plane perpendicular to the longitudinal injector axis **20**/nozzle cap axis **142**.

(35) Likewise, the outlets **148a** of the openings of the second set **156a** are equiangularly spaced on the outer surface of the nozzle cap **136** (i.e. around the longitudinal nozzle cap axis **142**) and are defined in a plane perpendicular to the longitudinal injector axis **20**, and the outlets **148b** of the openings of the third set **156b** are equiangularly spaced on the outer surface of the nozzle cap **136** around the longitudinal nozzle cap axis **142** and are defined in a plane perpendicular to the longitudinal injector axis **20**.

(36) The opening axis **152** of each opening **156'** of the second set **156a** defines an angle to the longitudinal nozzle cap axis **142** which is the same as for the other openings in the second set **156a**. Likewise, the opening axis **152** of each opening **156''** of the third set **156b** defines an angle to the longitudinal nozzle cap axis **142** which is the same as for the other openings in the third set **156b**. Further, the centre of the inlet **144a** of each of the openings **156'** of the second set **156a** lies on the same plane perpendicular to the longitudinal injector axis **20** as for the inlets **144a** of the other openings in the same set, and the centre of the inlet **144b** of each of the openings **156''** of the third set **156b** lies on the same plane (i.e. the inlet plane) perpendicular to the longitudinal injector axis **20** as for the inlets **144b** of the other openings in the third set **156b**. Likewise, the centre of the outlet **148a** of each opening of the second set **156a** lies on the same plane (i.e. the outlet plane) perpendicular to the longitudinal injector axis **20** as for the outlets **148a** of the other openings **156'** of the second set, and the centre of the outlet **148b** of each opening of the third set **156b** lies on the same plane (i.e. the outlet plane) perpendicular to the longitudinal injector axis **20** as for the outlets **148b** of the other openings **156''** of the third set **156b**. That is to say, the fluid path through each opening **156'** **156''** in a set **156a**, **156b** is of the same length.

(37) The second and third sets of openings **156a**, **156b** are arranged relative to each other about the longitudinal injector axis **20** such that the inlet and outlet planes of the second set **156a** are further away from the cylinder **4** (i.e. axially higher in the orientation of the Figures) than the inlet and outlet planes of the third set of openings **156b**. In other words, the inlet and outlet planes of the third set **156b** of openings **156''** adopt a lower position along the longitudinal injector axis **20** than the inlet and outlet planes of the second set **156a** of openings **156'**. Further, as shown in FIG. **4b**, the angle $\alpha_{\text{sub.1}}$ of the opening axis **152** relative to the longitudinal injector axis **20** defined for the second set **156a** is different to, and preferably larger than, the angle $\alpha_{\text{sub.2}}$ of the opening axis **152** relative to the longitudinal nozzle cap axis **142** defined for the third set **156b**.

(38) Furthermore, the respective inlets **144a**, **144b** of the second and third set openings **156'**, **156''** are angularly spaced apart around the inner surface of the nozzle cap **136** (in their planes perpendicular to the nozzle cap axis **142**) so that they are not axially aligned with one another in their respective planes. Similarly, the respective outlets **148a** of the second set of openings **156a** are equiangularly spaced around the outer surface of the nozzle cap **136** are alternately and equiangularly spaced around the inner surface of the nozzle cap **136** (in their plane perpendicular to the nozzle cap axis **142**) so that they are not axially aligned with the respective outlets **148b** of the third set of openings **156b**. This provides an alternating configuration of the inlets **144a**, **144b**, equiangularly spaced around the longitudinal nozzle cap axis **142** whereby the inlets **144a** of the second set of openings **156a** are interspersed between the inlets **144b** of the third set of openings **156b** and a similar configuration of the outlets **148a**, **148b** which are arranged in the same alternating manner. This is especially clear when looking at the plan views of the openings. The

opening axes **152** of the second and third sets of openings **156a**, **156b** are therefore not axially aligned with one another.

(39) FIGS. **4(e)** and **4(f)** show a similar embodiment to that described with reference to FIGS. **4(c)** and **4(d)**, except that there are only three openings **156'**, **156''** in each of the second and third sets. As before, the inlets **144a** and outlets **148a** of the openings of the second set **156a** and the inlets **144b** and outlets **148b** of the openings of the third set **156b** are arranged such that the opening axes of the second and third sets of openings are not axially aligned. The inlets **144a** of the second set of openings **156a** and the inlets **144b** of the third set of openings **156b** are alternately and equiangularly spaced around the inner surface of the nozzle cap **136** (in their respective planes perpendicular to the nozzle cap axis **142**) so that the inlets **144a** of the second set of openings **156a** are interposed between the inlets **144b** of the third set of openings **156b** (this is especially clear when looking at the plan views of the openings). Likewise, the outlets **148a** of the second set of openings **156a** and the outlets **148b** of the third set of openings **156b** are alternately and equiangularly spaced relative to one another around the outer surface of the nozzle cap **136** so that the outlets **148a** of the second set of openings **156a** are interposed between the outlets **148b** of the third set of openings **156b** (this is especially clear when looking at the plan views of the openings).

(40) In the embodiment of FIGS. **4(c)** and **4(d)**, the second and third sets of openings **156a**, **156b** each comprise four openings, **156'**, **156''**, respectively, while in the embodiment of FIGS. **4e** and **4f**, the second and third set of openings **156a**, **156b** each comprise only three openings **156'**, **156''**, respectively. It is further contemplated that each set of openings **156a**, **156b** may comprise up to eight openings, for example.

(41) In each case, the third set **156b** of openings is arranged relative to the second set **156a** of openings such that the nozzle cap **136** has at least one plane of symmetry in the vertical direction. It should be noted, however, that any arrangement of openings which gives the nozzle cap **136** at least one plane of symmetry in the vertical direction is particularly suitable for a centre mounted injector **18** of a tumble motion cylinder **4**. Such an arrangement of second and third sets of openings **156'**, **156''**, in combination with the single opening **154'** as described above, will produce an unbiased spray pattern which evenly distributes the fuel within the compression chamber **4**. Specifically, the first opening **154'**, being aligned with the longitudinal injector axis **20** and thus being parallel with the cylinder axis **6**, targets fuel into a lower portion of the cylinder so that it interacts with the tumble motion of air in the cylinder **4**. The second and third set openings **156'**, **156''** being angled away from the longitudinal injector axis, target fuel to an upper portion of the cylinder where fuel targeted through the first set opening cannot effectively reach. By virtue of this opening arrangement, the injection of fuel is less likely to disrupt the tumble motion initiated by the air intake **8**. Thus, the tumble motion of air can be exploited to promote better air-fuel mixing.

(42) FIGS. **5a** to **5f** show embodiments of a centre mounted injector **18** with a nozzle cap **236** optimised for a swirl motion cylinder **4**. The injection nozzle cap **236** includes a first opening **254'** and second and third sets of openings, **256a**, **256b** respectively, having second and third set openings, **256'**, **256''** respectively. More specifically, FIGS. **5a** and **5b** depict the nozzle cap **236** as seen from the side, while FIGS. **5c** and **5d** provide cross-sectional plan views of one embodiment and FIGS. **5e** and **5f** provide cross-sectional plan views of another embodiment. These embodiments differ from those described above with reference to FIGS. **4a** to **4f** in that the inlet **244a**, **244b** of each second and third set of openings **256'**, **256''** is angularly offset from each respective outlet **248a**, **248b** such that each opening axis **252** defines an angle $\theta_{sub.1}$ between the inner and outer surfaces **246**, **250** of the nozzle cap **236**. Accordingly, the inlets **244a**, **244b** and outlets **248a**, **248b** of each of the second and third set openings **256'**, **256''** are elliptical in shape. The angle $\theta_{sub.1}$ defined for each second and third sets of openings **256'**, **256''** is the same as for all other second and third sets of openings **256'**, **256''** in the arrangement.

(43) Although the nozzle cap according to these embodiments does not have a plane of symmetry in the vertical direction, the nozzle cap does have rotational symmetry. The embodiment of FIGS.

5c and 5d comprise four openings 256', 256'', respectively, in each of the second and third sets and so the openings are arranged to provide rotational symmetry to the order of four. Similarly, in the embodiment of FIGS. 5e and 5f each of the second and third sets comprise three openings 256', 256'', and so the openings are arranged to provide rotational symmetry to the order of three. Other embodiments are contemplated in which each of the second and third sets comprise up to eight openings being arranged such the rotational symmetry order increases correspondingly. By virtue of this rotational symmetry, the arrangement of openings will produce an unbiased spray pattern which evenly distributes the fuel within the compression chamber 4.

(44) The second and third set openings 256', 256'', being angled between the inner and outer surfaces of the nozzle cap, direct fuel such that it enters the cylinder with rotational momentum in the direction of the swirl motion induced by the air intake. Accordingly, the fuel flow from the second and third set openings 256', 256'' is encouraged to interact with the swirl motion in an upper portion of the cylinder. Meanwhile, the first set opening 254', being aligned with the longitudinal injector axis 20 and thus being parallel with the cylinder axis 6, targets fuel into a lower portion of the cylinder so that it induces a tumble motion of air in the cylinder which compliments the swirl motion induced by the air intake. This leads to greater circulation within the cylinder and thus greater air-fuel mixing.

(45) Referring to FIG. 5b, the angle $\alpha_{\text{sub.1}}$ of the opening axis 252 relative to the longitudinal nozzle cap axis 242 defined for the second set of openings 256a is different to, and preferably larger than, the angle $\alpha_{\text{sub.2}}$ of the opening axis 252 relative to the longitudinal nozzle cap axis 242 defined for the third set of openings 256b. For example, the angle $\alpha_{\text{sub.1}}$ may range between 60 to 75 degrees relative to the longitudinal nozzle cap axis 242, and preferably between 65 to 70 degrees relative to the longitudinal nozzle cap axis 242. Additionally, the angle $\alpha_{\text{sub.2}}$ may range between 40 to 60 degrees relative to the longitudinal nozzle cap axis 242, more preferably between 45 to 50 degrees relative to the longitudinal nozzle cap axis 242.

(46) The configurations of the openings in FIGS. 5(c) and 5(d) and FIGS. 5(e) and (f) are similar to those shown in FIGS. 4(c) and 4(d) and FIGS. 4(e) and 4(f), respectively, in that the inlets 244a, 248a to the openings are equiangularly spaced around the inner surface of the nozzle cap 236, relative to one another and in their respective axial planes, so that they form an alternating arrangement of inlets between the sets (this is especially clear when looking at the plan views of the openings). Likewise, the outlets 244b, 248b from the openings are angularly spaced around the outer surface of the nozzle cap 236, relative to one another and in their respective axial planes, so that they form an alternating arrangement of outlets between the sets (this is especially clear when looking at the plan views of the openings).

(47) FIGS. 6a and 6b show an embodiment of a side mounted injector 18 with a nozzle cap 336 optimised for a tumble motion cylinder 4. More specifically, FIG. 6a depicts the nozzle cap 336 as seen from the side, while FIG. 6b provides a cross-sectional plan view of the nozzle cap 336. As can be seen, the nozzle cap 336 comprises a first set opening 354' as described above and further second and third sets of openings 356a, 356b, with each of the second and third sets of openings 356a, 356b comprising only two openings 356', 356'' respectively. As in the previously described embodiments, and as shown in FIG. 6a, the second and third sets of openings 356a, 356b are arranged relative to each other about the longitudinal injection axis 20 such that the inlet and outlet planes of the first set 356a are further away from the cylinder 4 (i.e. higher in the orientation of the Figures) than the inlet and outlet planes of the second set 356b.

(48) Also as above, the opening axis 352 of each opening 356', 356'' in the second and third sets 356a, 356b defines an angle to the longitudinal injector axis 20 which is the same as for the other openings 356', 356'' in the associated set 356a, 356b. The angle $\alpha_{\text{sub.1}}$ to the longitudinal axis 20 defined for the first set 356a is different to, and preferably larger than, the angle $\alpha_{\text{sub.2}}$ to the longitudinal axis 20 defined for the second set 356b.

(49) However, unlike the previously described embodiments, the second and third set openings

356', **356''** are not necessarily arranged equiangularly about the longitudinal nozzle cap axis **342**, but they are arranged symmetrically about an axis **358** perpendicular to the longitudinal nozzle cap axis **342** (i.e. a lateral axis).

(50) More specifically, and as shown in FIG. **6b**, the outlet **348** of each second set opening **356'** is offset from each respective inlet **344** such that each respective opening axis **352** defines an angle β to the lateral axis **358** which is the same as for the other minor opening **356'** in the set **356b**. That is to say, the second set openings **356'** are arranged either side of the lateral axis **358** such that the inlet **344** and outlet **348** of one opening **356'** are arranged symmetrically to the inlet **344** and outlet **348** of the other opening **356'** about the lateral axis **358**. The same is true for the third set openings **356''**—i.e. the opening axis **352** of each third set opening **356''** defines an angle $\beta_{sub.2}$ to the lateral axis **358** which is the same as for the other opening **356''** in the set **356b**. The angle $\beta_{sub.2}$ defined by the opening axes **352** of the third set **356b** openings **356'** is different to and preferably smaller than the angle $\beta_{sub.1}$ defined by the opening axes **352** of the second set **356a** openings **356'**. Accordingly, the arrangement of all the second and third set openings **356'**, **356''** is symmetric about the lateral axis **358** and biased such that all the opening axes **352** are angled towards one side of the nozzle cap **336**, with the opening axes **352** of the third set **356b** being angled more towards that side than the opening axes **352** of the second set **356a**.

(51) Since the opening axes **352** of the second and third set openings **356'**, **356''** are not normal to the inner and outer surfaces **342**, **350** of the nozzle cap **336**, the inlet and outlet **344**, **348** of each opening **356'**, **356''** is elliptical in shape so as to maintain parallelism of the opening walls through the nozzle cap **336**. The embodiment of FIG. **6** is particularly advantageous for use with an injector side mounted to a tumble motion engine cylinder **4** because the first set opening targets fuel to interact with the tumbling air motion, while the second and third set openings **356'**, **356''** target fuel to the regions either side of the main tumble motion. In this way, the second and third set openings **356'**, **356''** direct fuel to a second zone of the cylinder, that is, one which the fuel from the first set opening does not reach effectively.

(52) FIG. **7** shows an embodiment of a side mounted injector **18** with a nozzle cap **436** optimised for a swirl motion cylinder **4**. As can be seen in FIG. **7a** (which shows the nozzle cap **436** as seen from the side), the first opening **454'** is similar to that of the previously described embodiments in that it is arranged to extend from an inlet **444** at the centre of the inner surface **446** of the nozzle cap **436** to an outlet **448** at the outer surface **450** of the nozzle cap **436** in a cylindrical manner such that the walls of the opening **454'** are parallel to each other. While the inlet **444** is aligned with the centre of the inner surface **446** of the nozzle cap **436**, the outlet **448** is offset from the centre of the outer surface **450** of the nozzle cap **436** such that the opening axis **452** defines an angle γ to the longitudinal axis **20** of the injector **18**. Specifically, the outlet **448** is offset from the longitudinal injector axis **20** so that the opening axis **452** is angled towards a lining **60** of the cylinder **4** associated with the injector **18**. In this way, the first opening **454'** directs fuel downwards and towards the cylinder lining **60**, thereby inducing a swirl motion of fuel within the lower portion (or a first zone) of the cylinder.

(53) Also shown is a second set **456'** of openings comprising five openings **456'** arranged around the longitudinal nozzle cap axis **442** and with each opening **456'** extending cylindrically from respective inlets **444** on the inner surface **446** of the nozzle cap **436** to respective outlets **448** on the outer surface **450** of the nozzle cap **436**. The five second set openings **456'** are equiangularly spaced around one half of the nozzle cap **436**, and specifically around the half of the nozzle cap **436** furthest from the cylinder lining **60**. Accordingly, the second set openings **456'** direct fuel into the upper portion (or a second zone) of the combustion chamber **4** where the fuel from the first opening **454'** does not reach effectively.

(54) It is contemplated that the nozzle cap **436** may comprise additional sets of openings, each similarly arranged about the longitudinal nozzle cap axis **442** as the second set openings **456'**, but with differing inlet and outlet planes perpendicular to the injector axis **20**. Although FIG. **7b**

indicates five minor openings **456'** for the second set **456**, any number between two and five per set **456** is considered.

(55) Generally, for a swirl motion side mounting injector as shown in FIG. 7, it is recommended to include between 1 and 3 openings in the nozzle cap **136**. One major opening (for example, opening **454'**) should have at least 60% of the fuel mass or higher. As mentioned, the major jet should be targeted in a way of impinging on the cylinder lining **60** of the wall opposite the injector location.

(56) In any embodiment of the invention for a swirl engine, the first set openings **254'**, **454'** may comprise one opening **254'**, **454'**, whilst the second set openings **256'**, **456'** may comprise between one to three openings (for example, for injection of fuel up to 60 bar, in an outward opening injector). There is also a minimum spray momentum requirement for the spray jet to propagate into the combustion chamber, and it has been found that high spray momentum gives better mixing.

(57) In embodiments, the first opening **454'** may be at an angle γ relative to the longitudinal axis **20** such that the fuel flow through the first opening **454'** impinges the cylinder lining **60**.

Advantageously, the fuel to flow through the opening **454'** should be directed so as not to impinge on the spark plug or the air intake port. In this way, the fuel may flow directly into the combustion chamber **4** such that no fuel flow is sucked back into the intake port of the engine **2**.

(58) FIGS. **8** to **10** depict other possible nozzle cap embodiments **536**, **636**, **736** as seen from the bottom when viewed along the longitudinal nozzle cap axis. As can be seen, the plurality of openings **40** is comprised of at least a first set of openings and a second set of openings. Unlike the previously described embodiments, the first set of openings comprise more than one opening—there are three first set openings **554'**, **654'** in the embodiments of FIGS. **8** and **9**, and four first set openings **754'** in the embodiment of FIG. **10**. The second set of openings also comprise more than one opening **556'**, **656'**, **756'**—three in the embodiments of FIGS. **8** and **9**, and four in the embodiment of FIG. **10**. In each of these embodiments all of the openings **554'**, **556'**, **654'**, **656'**, **754'**, **756'** are arranged such that the opening axis is normal to the inner and outer surfaces of the nozzle cap **536**, **636**, **736**. The first and second sets of openings are arranged relative to reach other about the longitudinal nozzle cap axis such that the inlet and outlet planes of the first set are closer to the bottom of the nozzle cap **536**, **636**, **736** than the inlet and outlet planes of the second set of openings. In the embodiments of FIGS. **8** and **10**, the first set openings **554'**, **654'** are larger (in diameter) than the second set openings **556'**, **656'**, whereas, in the embodiment of FIG. **9**, all the openings **754'**, **756'** have the same diameter.

(59) Also, the first set openings **554'**, **654'**, **754'** are equiangularly arranged around the longitudinal nozzle cap axis (which aligns with the injector axis **20**). Similarly, the second set openings **556'**, **656'**, **756'** are equiangularly arranged around the longitudinal nozzle cap axis. The first set of openings and the second set of openings are rotated about the longitudinal nozzle cap axis relative to each other such that symmetry in the overall arrangement of both first and second set openings **554'**, **556'**, **654'**, **656'**, **754'**, **756'** is maintained. More specifically, in the embodiments of FIGS. **8** and **9**, the second set of openings is rotationally offset (about the longitudinal nozzle cap axis) from the first set of openings by 120° so that the nozzle cap **536**, **636**, **736** has three planes of symmetry and a rotational order of symmetry of three about the longitudinal nozzle cap axis. Similarly, in the embodiment of FIG. **10**, the second set of openings is rotationally offset (about the longitudinal nozzle cap axis) from the first set of openings by 90° so that the nozzle cap **536**, **636**, **736** has four planes of symmetry and a rotational order of symmetry of four about the longitudinal nozzle cap axis.

(60) FIG. **11** shows yet another nozzle cap embodiment **836** as seen from the bottom when viewed along the longitudinal nozzle cap axis. As can be seen, the plurality of openings **40** comprises a first set of openings and a second set of openings, each set comprising two openings **854'**, **856'** arranged opposite each other. The second set of openings is arranged rotationally offset from the first set of openings by 90° about the longitudinal nozzle cap axis so that the nozzle cap **836** has two planes of symmetry and a rotational order of symmetry of two.

(61) The first and second sets are arranged relative to each other about the longitudinal injector axis such that the inlet and outlet planes of the first set are closer to the bottom of the nozzle cap **836** than the inlet and outlet planes of the second set of openings. Accordingly, first set of openings direct fuel to a lower portion (or a first zone) of the cylinder, while the second set of openings direct fuel to an upper (or second) zone of the cylinder **4**. Finally, FIG. **12** shows an example of a nozzle cap **936** which is identical to FIG. **11** but in which the second set of openings is removed. This may be useful for some cylinder configurations, where effectively the nozzle cap openings are grouped into first and second sets of openings which each direct gaseous fuel into a different region or zone of the combustion space.

(62) Further investigations into the performance of the fuel injector **18** have concluded that high chamber pressures as a result of high load and high engine speed operating conditions result in poorer air-fuel mixing and, therefore, lower engine combustion efficiency overall. Generally, the higher chamber pressures require the fuel injector **18** to operate at higher injection pressures to provide the jet momentum required to achieve performance requirements. Therefore, generally, gaseous fuel injectors with high fuel flow rates provide better flow separation and better performance in high chamber pressures than gas fuel injectors with lower fuel flow rates.

(63) Therefore, the nozzle cap has been designed with an appropriate number of holes with respective diameters to provide optimum jet targeting such that the minimum performance requirements are met for the various engine operating conditions.

(64) It will be appreciated that various modifications may be made to the aforementioned embodiments without departing from the scope of the appended claims.

Claims

1. A fuel injector for injecting gaseous fuels into a combustion chamber, the fuel injector comprising: an injection nozzle having a longitudinal injector axis and a tip region that is shaped to define a valve seat that extends about a central outlet opening for gaseous fuel; and an outward opening injection needle slidably received in the injection nozzle and engageable with the valve seat to control a flow of gaseous fuel into a sac volume of the fuel injector, wherein the injection nozzle further includes a nozzle cap having a nozzle cap axis, aligned with the longitudinal injector axis, the nozzle cap being received over the tip region of the nozzle to define the sac volume and being provided with a plurality of openings to enable the flow of gaseous fuel to pass from the sac volume into the combustion chamber when the injection needle is moved away from the valve seat, the plurality of openings being comprised of at least: a first opening configured to direct a first flow portion of the flow of gaseous fuel into a first zone of the combustion chamber, wherein the first zone is defined by a lower portion of the combustion chamber; a second set of openings, configured to direct a second flow portion of the flow of gaseous fuel into a second zone of the combustion chamber, wherein the second zone is defined by an upper portion of the combustion chamber, and wherein each opening of the second set has a second central flow axis which defines a first angle to the longitudinal injector axis which is the same as for the other openings of the second set, wherein the first angle is between 60 to 75 degrees relative to the longitudinal injector axis; and a third set of openings, wherein each opening of the third set has a third central flow axis which defines a second angle to the longitudinal injector axis which is different from the first angle defined by the second central flow axis to the longitudinal injector axis, and wherein the second angle is between 40 to 60 degrees relative to the longitudinal injector axis.
2. The fuel injector as claimed in claim 1, wherein the first opening forms one of a first set of openings.
3. The fuel injector of claim 2, wherein the first opening, or each opening of the first set of openings, has a diameter that is different from a diameter of each opening of the second set.
4. The fuel injector as claimed in claim 2, wherein the first opening of the first set of openings has a

first central flow axis which aligns with the longitudinal injector axis.

5. The fuel injector as claimed in claim 1, wherein each opening of the second set has an inlet which opens into the sac volume and an outlet which opens into the combustion chamber, wherein a center of the outlet of each opening of the second set lies on a first plane perpendicular to the longitudinal injector axis.

6. The fuel injector as claimed in claim 5, wherein the inlets of each opening of the second set are equiangularly spaced around the nozzle cap axis in the first plane.

7. The fuel injector as claimed in claim 5, wherein each opening of the third set has an inlet which opens into the sac volume and an outlet which opens into the combustion chamber, wherein a center of the outlet of each opening of the third set lies on a second plane perpendicular to the longitudinal injector axis, wherein the second plane adopts a lower position along the longitudinal injector axis than the first plane.

8. The fuel injector as claimed in claim 7, wherein the inlets of each opening of the third set are equiangularly spaced around the longitudinal injector axis in the second plane.

9. The fuel injector as claimed in claim 7, wherein the inlets of the second set of openings are angularly spaced apart from the inlets of the third set of openings around the nozzle cap in their respective planes perpendicular to the longitudinal injector axis; and wherein the outlets of the second set of openings are angularly spaced apart from the outlets of the third set of openings around the nozzle cap in their respective planes perpendicular to the longitudinal injector axis, such that the second central flow axis of the second set of openings is not axially aligned with the third central flow axis of the third set of openings.

10. The fuel injector as claimed in claim 1, wherein each opening of the second set has a diameter that is different from a diameter of each opening of the third set.

11. The fuel injector as claimed in claim 1, wherein the second set of openings includes between two and five openings.

12. A fuel injection system for gaseous fuel comprising the fuel injector of claim 1 and the combustion chamber into which the gaseous fuel is injected.
