

Method for lubricating large two-stroke engines using asymmetrical cavitation in the injector nozzle

FIELD OF THE INVENTION

5 The present invention relates to a method for lubricating a large combustion engine, for example a large two-stroke engine, and a method of lubricating such engine.

More specific the invention relates to a method of lubricating a large two-stroke engine comprising a cylinder with a reciprocal piston inside and with a number of lubricant injectors distributed along a perimeter of the cylinder for injection of lubricant into the
10 cylinder at various positions on the perimeter during injection phases; wherein each lubricant injector comprises a nozzle, the nozzle comprising sac hole, and a spray hole having a nozzle exit from which the lubricant leaves the nozzle into the cylinder; wherein the method comprises
-injection of lubricant into the cylinder as a spray directed to the liner of the cylinder
15 during operation of the engine,
-inducing lubricant cavitation in the nozzle during the injection and by the cavitation influencing characteristics of the spray.

20 BACKGROUND OF THE INVENTION

Due to the focus on environmental protection, efforts are on-going with respect to reduction of emissions from marine engines. This also involves the steady optimization of lubrication systems for such engines, especially due to increased competition. One
25 of the economic aspects gaining increased attention is a reduction of lubrication oil consumption, not only because of environmental protection but also because this is a significant part of the operational costs of ships. However, the longevity of engines should not be compromised by the reduction of oil consumption, as proper lubrication must be ensured at all times to minimize wear and provide longevity of the engine. Thus, there
30 is a need for steady improvements with respect to lubrication.

For lubrication of large slow-running two-stroke marine diesel engines, several different systems exist, including injection of lubrication oil directly onto the cylinder liner or injection of oil quills onto the piston rings.

5 An example of a lubricant injector for a marine engine is disclosed in EP1767751, in which a non-return valve is used to provide the lubricant access to the nozzle passage inside the cylinder liner. The non-return valve comprises a reciprocating spring-pressed ball in a valve seat just upstream of the nozzle passage, where the ball is displaced by pressurised lubricant. The ball valve is a traditional technical solution, based on a principle dating back to the start of the previous century, for example as disclosed in
10 GB214922 from 1923.

An alternative and relatively new lubrication method, compared to traditional lubrication, is commercially called Swirl Injection Principle (SIP). It is based on injection of a
15 spray of atomized droplets of lubrication oil into the scavenging air swirl inside the cylinder. The helically upwards directed swirl results in the lubricant being pulled towards the Top Dead Centre (TDC) of the cylinder and pressed outwards against the cylinder wall as a thin and even layer. This is explained in detail in international patent applications WO2010/149162 and WO2016/173601. The injectors comprise an injector
20 housing inside which a reciprocating valve member is provided, typically a valve needle. The valve member, for example with a needle tip, closes and opens the lubricant's access to a nozzle aperture according to a precise timing. In current SIP systems, a spray with atomized droplets is achieved at a pressure of 37 bar. In comparison, the oil pressure is less than 30 bar and often less than 10 bar in systems working with compact oil
25 jets that are introduced into the cylinder.

In such large marine engines, a number of injectors are arranged in the circumference of the cylinder, and each injector comprises one or more nozzle apertures at the tip for delivering lubricant jets or sprays into the cylinder from each injector. Examples of SIP
30 lubricant injector systems in marine engines are disclosed in international patent applications WO2002/35068, WO2004/038189, WO2005/124112, WO2010/149162, WO2012/126480, WO2012/126473, WO2014/048438, and WO2016/173601.

Optimization of the spray in SIP lubrication is undergoing steady development. Although, lubrication injectors have some similarities with fuel injectors, comparison also shows different behaviour and different effects. This is mainly attributed to the different working conditions for the injectors, which leads to different effects such as viscosity, surface tension and liquid pressure. Accordingly, results from studies of fuel injection are not automatically transferable to lubricant injection, and the difference in behaviour is in some cases surprising.

One of the important factors for spray formation is cavitation in the nozzle, which is formation of vapour cavities inside the liquid due to evaporation. Cavitation in the nozzle influences the atomization of the liquid because it introduces pronounced disturbances in the liquid stream, which destabilizes the jet. In the field of fuel injection, such cavitation in the nozzle has been intensively studied, however, there are also a few studies on cavitation in lubricant injectors. In the following, reference is made to a number of publications, which are mentioned at the end of this section in alphabetical order, and which are mentioned in the following by reference to the name of the first author.

Formation of vapour cavities in the nozzle, accordingly called cavitation, takes place when the local pressure of the liquid drops below its vapor pressure (Franc and Michel, 2006; Li, 2014). The most well-known type of cavitation in spray nozzles is geometrically induced cavitation (Dumouchel et al., 2013). This occurs when a change in geometry of the flow path, through which the liquid flows, leads to a pressure drop of a sufficient degree to evaporate the liquid.

Cavitation in the nozzle enhances the jet atomization, because it introduces large amplitudes of disturbances which result in a stochastic behavior of the liquid stream and destabilizes the jet (Bergwerk, 1959). Payri et al. (2004) investigated the influence of different nozzle geometries for diesel fuel injectors and showed that cavitation leads to increase in spray cone angle and in spray hole outlet velocity.

It had also been observed that, once the geometric cavitation reaches the exit of the nozzle, its structure transforms from a bubbly cloud into a smoothly curved lines film cavitation, which greatly influences the exiting spray structure (Mirshahi, 2015).

For example, a special fuel injection valve for providing cavitation during fuel injection is disclosed in US patent No. US 7,712,684.

5 For high-viscous liquids, Tamaki and Shimizu (2002) showed that shorter breakup-length and smaller Sauter mean diameter were obtained using low fluid pressure when bypassing the liquid through an intersection, which promotes cavitation. Sou et al. (2007) found that atomization is enhanced when the cavitation extends almost to the exit of the injector nozzle, but is suppressed if the cavitation extends to the nozzle exit. This is because the cavitation vanishes as downstream air moves upward into the nozzle.
10 This mechanism is known as hydraulic flip (He et al., 2016).

Not only sharp inlet orifices promote cavitation but also parameters, such as needle lift, length to diameter ratio of the discharge orifice, curvature of the inlet edge, liquid properties, and system pressure (Dong et al., 2016; Jollet et al., 2014.; Pratama et al., 2015; Schmidt and Corradini, 2001).
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Andriotis et al. (2008) investigated non-axial injection conditions, and showed that the swirling liquid flow inside the nozzle leads to complex phenomena, as string cavitation or vortex cavitation.
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Cavitation can also be influenced by vibrations in nozzles at high frequencies, for example ultrasonic frequencies, optionally in the range of 20-200 kHz, for example 20-100 kHz. Ultrasonic excitation in nozzles is disclosed in the prior art (Khmelev 2006, Rajan 2001). An example of an ultrasonic nozzle is given in US patent No. 4,659,014
25 by Soth et al.

Special attention to cavitation in lubricant SIP injectors is found in the work by Gardhouse (2014) on the influence of cavitation on spray formation. A nozzle with a 4.8 mm sac hole and with an exit spray hole diameter of 0.3 mm was used for the study. Development of cavitation from the nozzle entrance to the nozzle exit was investigated with respect to its effect on the near and far field spray structure. The conclusion was that for such injectors, certain low viscosities would induce significant nozzle flow cavitation and lead to a splitting of the spray, and ultimately less controlled liner coverage.
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The conclusion from Gardhouse is that cavitation, especially near the nozzle tip, is disadvantageous for the spray stability and leads to a less controlled spray. This is largely in agreement with the work by Sou et al. (2007), as mentioned above, in which atomization was found to be suppressed if the cavitation extends to the nozzle exit. Accordingly, Gardhouse has missed the point of using the asymmetric cavitation to distribute the lubricant over a larger area. The skilled person reading Gardhouse is left with the teaching that an asymmetric cavitation is not useful for distribution of lubricant over larger areas.

As far as the conclusions of these findings can be applied to lubricant injection, which behaves differently from fuel injection due to different viscosities, cavitation at the nozzle exit is disadvantageous. In other words, parameters, such as nozzle dimensions, as well as pressure and viscosity of the lubricant, should be chosen such that cavitation, especially at the nozzle exit, is avoided. This is also in agreement with current commercial SIP injection systems for marine engines, which are operated at parameters that do not cause cavitation in the nozzle.

As there is a steady motivation for improvement of lubrication in large two-stroke gas and diesel engines, for example marine engines or engines for power plants, cavitation design advantageously is part of the considerations for optimising the spray, in particular for SIP injection.

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All of the above references are used as background for the invention described in WO 2018/215645 filed by the same applicant.

A further reference is:

- 5 **Ravendran**, Rathesan; Endelt, Benny; Christiansen, Jesper de Claville; Jensen, Peter; Theile, Martin; Najjar, Ibrahim., Coupling method for internal nozzle flow and the spray formation for viscous liquids, International Journal of Computational Methods and Experimental Measurements, DOI:10.2495/CMEM-V7-N2-130-141

10 DESCRIPTION / SUMMARY OF THE INVENTION

It is therefore the objective of the invention to provide an improvement in the art. A particular objective is to improve a method which comprises inducing lubricant cavitation in the nozzle during the injection and by the cavitation influencing characteristics of the spray in order to control where the lubricant spray ends up on the liner when injected by the injector. Especially, it is the objective to improve lubrication with SIP valves in a large two-stroke engine.

20 These objectives are achieved by a method for lubricating a large two-stroke engine as described in the following.

The large two-stroke engine comprises a cylinder with a reciprocal piston inside and with a number of lubricant injectors distributed along a perimeter of the cylinder for injection of lubricant into the cylinder as a spray directed to the liner of the cylinder at various positions on the perimeter during injection phases. For example, the engine is a marine engine or a large engine on a power plant. Typically, the engine is burning diesel or gas fuel.

30 The term injection phase is used for the time during which lubricant is injected into the cylinder by the injector. The term injection cycle is used for the time it takes to inject lubricant by the injector into the cylinder and until the next injection. This terminology is in line with the above-mentioned prior art.

The term injector is herein used for a lubricant injection valve system comprising a housing with a lubricant inlet and one single injection nozzle with a nozzle exit from which the lubricant leaves the nozzle into the cylinder as a spray, the nozzle exit having an exit aperture with an exit size S. For example, the exit aperture is circular with a diameter D, in which case the diameter D is a measure for the size S. If the exit aperture deviates from a circular shape, a potential measure for the size S is the aperture area or an averaged diameter; the latter being useful in case of slight oval or elliptical deviation from a circle. For example, for a noncircular exit aperture, the cross-sectional dimension is an equivalent diameter calculated as twice the square root of the ratio between the cross-sectional area and the number $\text{Pi} \approx 3.14$. The nozzle has one or more, typically not more than two, nozzle exits.

In SIP injectors, the nozzle comprises a spray hole, formed as a channel with a length L, for example between 0.5 and 1 mm, one end of which forms the nozzle exit. In typical injectors, nozzle comprises a sac hole for flow of lubricant to the spray hole that extends from the sac hole to the nozzle exit. Typically, the central longitudinal axis of the spray hole has an angle with a central longitudinal axis of the sac hole, for example in the range of 30 to 90 degrees. The cross-sectional area of the sac hole perpendicular to its central longitudinal axis is often larger than the cross-sectional area of the spray hole perpendicular to its central longitudinal axis.

Optionally, a controller is provided as an add-on system for upgrade the controller comprises a computer or is electronically or wirelessly connected to a computer. Advantageously, the computer is configured for monitoring parameters for the actual state and motion of the engine. In cooperation with the computer, on the basis of the parameters, the controller controls the amount and timing of the lubricant injection by the injectors during an injection phase. As will become more apparent in the following, the controller is configured to also control the lubricant pressure and optionally also the temperature of the lubricant.

In the prior art on lubricant injection detailed studies have surprisingly revealed that cavitation for lubricant in the nozzle can be used to provide stable, controlled injection of sprays, and uniform distribution of lubrication oil, which is a crucial factor for optimized SIP lubrication. This is discussed in WO 2018/215645. This was contrary to

earlier conclusion that cavitation, especially near the nozzle tip, is disadvantageous for the spray stability, distribution of lubrication oil, and leads to a less controlled spray.

Accordingly, in earlier days cavitation were not used in practice for lubricant injection in large marine engines, neither for jet injection nor for SIP injection. The parameters for spray injection, in particular SIP injection, have been outside the range where cavitation is achieved. This changed with the invention described in WO 2018/215645 as studies surprisingly revealed that cavitation for lubricant in the nozzle can be used to provide stable, controlled injection of sprays, and uniform distribution of lubrication oil, which is a crucial factor for optimized SIP lubrication. The technology described in WO 2018/215645 is based on lubrication where cavitation is beneficial for spray formation of lubricants, and where spray quality, control, and stability are improved when cavitation extends to the nozzle exit. The cavitation shows to play a key role in the lubricant injection and the spray breakup and liner impingement of the lubricant.

The different understanding in the prior art is believed to stem from conclusions drawn primarily from observations for low-viscous liquids, such as water and fuel (Sou 2007). However, even earlier reports on experiments using lubricants in injector nozzles (Guardhouse 2014) have drawn conclusions in line with the other prior art and have overlooked the advantageous effect of cavitation that reaches to the nozzle exit. Guardhouse writes that cavitation provides a "less controlled liner coverage". However, in further studies it has been realized that the asymmetric cavitation provides that a larger area may be covered with lubricant. This will reduce the need of the piston rings to distribute the lubricant on the liner and to provide for a better distribution of lubricant by the nozzle. The asymmetric cavitation can be used to direct the lubricant more towards the liner, to ensure the least possible loss and at the same time ensure that a larger area is covered.

Further studies leading to the present invention, not only the cavitation as such has been found beneficial but also it was found that inducing an asymmetric lubricant cavitation in the nozzle during the injection would influence characteristics of the spray whereby it was possible to establish a better control where the lubricant spray ends up on the liner when injected by the injector. In other words, it is found possible to obtain better lubrication as a derived effect of the finding that "fluid on the side of the spray

corresponding to the cavitation region is pulled outward” by controlling the side of the cavitation and thereby controlling the direction of the lubricant spray.

5 Accordingly, the method according to the present invention as presented herein comprises a step of inducing asymmetric cavitation in the lubricant in the nozzle during the injection.

10 Thus, according to the present invention it is possible to optimise the lubrication by controlling the cavitation in the injector nozzle and to establish an asymmetrical structure of the injected spray of lubricant oil into the cylinder of the large two-stroke engine.

The controlling of the establishing of the asymmetrical structure of the injected spray of lubricant oil into the cylinder of such combustion engine may be effected in more ways involving providing specific properties for the injectors nozzles.

15 The lubricant cavitation induced in the nozzle may be obtained according to the teaching of WO 2018/215645. Accordingly, the parameters described therein may be used for obtaining cavitation in the nozzle however modified for establishing the asymmetrical structure of the injected spray of lubricant oil for use in controlling the lubrication by
20 determining where the lubricant oil ends up on the liner of the cylinder.

The cavitation may extend to the nozzle exit to influence the characteristics of the spray by the disturbances introduced by cavitation. In some cases, it is possible, that cavitation extends to at least halfway through the spray hole, for example to at least half the distance between the sac hole and the nozzle exit.
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It is possible to provide the nozzle with the first cavitation pocket provided to a right side of the spray hole or with the first cavitation pocket provided to a left side of the spray hole. Hereby it is obtained that two nozzles may be provided which are identical
30 except for the position of the sac hole relative to the spray hole. This parameter will be controlling to which side the spray is drawn.

In a specific embodiment the method of lubricating a large two-stroke engine comprises the step of

-providing at least a first cavitation pocket at one side of the nozzle inside the nozzle.

- 5 Cavitation forms on the inside corner of the transition from the sac hole to the spray hole. This is called a cavitation pocket. It is known that as viscosity decreases, the extent of cavitation increases. It has shown that especially for low viscosity lubricants, the cavitation pocket may have different extensions and more than one cavitation pocket may be formed in the nozzle. The spray is clearly affected by the cavitation condition.
- 10 Lubricant oil on the side of the spray corresponding to the cavitating pocket is pulled outwards. This causes more atomization in the cavitation side of the spray in the later stages of the spray. Accordingly, the spray is pulled in a specific direction. This effect may be used in controlling where the lubricant spray ends up on the liner when injected by the injector.

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In a specific embodiment the method of lubricating a large two-stroke engine comprises the steps of

-providing a second cavitation pocket at a second side of the nozzle, and
-providing the first and second cavitation pocket with different sizes.

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Hereby it is possible to effect more atomization in the cavitation side of the spray in more than one direction in the later stages of the spray. Accordingly, the spray is pulled in specific directions.

- 25 The cavitation pockets may be arranged opposite each other with a mutual angle being 180° or with a mutual angle less than 180° .

The term cavitation pocket is herein used for a cavitation pocket which occupies more than 1% of the spray hole volume. If the cavitation pocket occupies less than 1% of the spray hole volume it is not considered as a cavitation pocket.

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In the situation with one cavitation pocket only on one side of the spray hole, then an asymmetric cavitation is provided.

In the situation with a cavitation pocket on both sides of the spray hole, then an asymmetric cavitation is provided if a first cavitation pocket is half as large, or smaller, compared to the second cavitation pocket.

- 5 For providing asymmetric cavitation different embodiments are possible for the nozzle.

10 In an example of the present invention the nozzle is provided with the first and second cavitation pocket in the two sides of the spray hole wherein there is a difference in size between the cavitation pockets so that the large cavitation pocket has a volume of 1%-50% of the volume of the spray hole, and the small cavitation pocket has a volume of 0%-25% of the volume of the spray hole and which cavitation pocket volumes are selected so that the small cavitation pocket is 50% or smaller than the large cavitation pocket.

15 In a specific embodiment the method of lubricating a large two-stroke engine comprises the step of
-providing the second cavitation pocket with a size being less than or equal to 50% of the size of the first cavitation pocket.

20 Hereby it is possible to obtain an especially remarkable effect of the direction of the spray in the later stages of the spray.

25 In a specific embodiment the method of lubricating a large two-stroke engine comprises the step of
-providing the at least first cavitation pocket at the transition between the sac hole and the spray hole.

30 In a specific embodiment the method of lubricating a large two-stroke engine is peculiar in that, one end of the spray hole forms the nozzle exit, wherein the sac hole is arranged for flow of lubricant to the spray hole, which spray hole extends from the sac hole to the nozzle exit; wherein a central longitudinal axis of the spray hole has an angle with a central longitudinal axis of the sac hole, the angle being in the range of 30 to 90 degrees; wherein the cross sectional area of the sac hole perpendicular to its central

longitudinal axis is larger than the cross sectional area of the spray hole laterally to its central longitudinal axis; wherein the length of the spray hole is in the range of 0.5-1 mm.

- 5 In a specific embodiment the method of lubricating a large two-stroke engine is peculiar in that the Reynolds number for the lubricant in the nozzle aperture is above 450.

In a specific embodiment the method of lubricating a large two-stroke engine is peculiar in that D is at least 0.3 mm; and wherein the method comprises injecting the lubricant
10 into the cylinder through the nozzle exit at a pressure P above 20 bar and viscosity μ of less than 0.05 Pa·sec.

In a specific embodiment the method of lubricating a large two-stroke engine comprises the step of
15 -injecting the lubricant into the cylinder while cavitation in the nozzle is extending to the nozzle exit.

In a specific embodiment the method of lubricating a large two-stroke engine comprises the step of
20 -providing vibrations, preferably ultrasonic vibrations, in the nozzle with a frequency that promotes cavitation.

According to a practical method of the invention, lubricant is provided with a viscosity μ and a pressure P to the nozzle exit that has an exit aperture size S, for example a
25 diameter D of the exit aperture, such that cavitation is created in the nozzle during the injection phase, optionally the cavitation extending to the nozzle exit. For examples, the viscosity μ and/or the pressure P is/are adjusted such that cavitation in the nozzle, for example at the nozzle exit, is achieved merely due to the restricted flow of the lubricant through the nozzle and nozzle aperture.

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However, in order to promote cavitation in the nozzle, for example at the nozzle exit, it is also possible to mechanically influence the flow additionally in order to promote cavitation in the nozzle, for example at the nozzle exit. One option is to provide ultrasonic vibrations in the nozzle. An ultrasonic spray nozzle is disclosed in US patent No.

4,659,014 by Soth et al. For example, the injector comprises an ultrasonic transducer, optionally piezo transducer. Advantageously, the transducer is provided at or in the nozzle, optionally near or at the nozzle exit.

- 5 Selection of viscosity of the lubricant is done by selecting a specific lubricant. Viscosity can further be adjusted by varying the temperature, as lubricant has decreasing viscosity at increasing temperature. However, as investigations have revealed, for marine engines, typically used lubricants are very similar in viscosity, even over a wide range of temperatures.

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Pressure is selected by providing a certain lubricant pressure from the lubricant pump. For example, pressure can be adjusted by adjustment of the pump that is pressurizing the lubricant or by suitable pressure adjustment valves.

- 15 The most important factors determining cavitation are exit aperture size S , for example diameter D , in addition to lubricant viscosity and pressure. However, although to a lesser extent among commonly used SIP injectors, also nozzle geometry plays a role. Therefore, it is advised, prior to final operation, to perform a laboratory test for each type of injector that differs in geometry from already tested injectors. The term laboratory test is typically performed in a laboratory, but can in certain circumstances also be performed on site of the engine. In the latter case, the site takes the role of a laboratory.

- 20 The testing of a specific type of injector that has a nozzle with an exit aperture of size S , for example diameter D , involves selection of the viscosity μ and the pressure P of the lubricant, such that cavitation is provided in the nozzle, for example extending to the nozzle exit or at least halfway through the spray hole. For example, the viscosity μ is adjusted, as described above by temperature variation, or the pressure P is adjusted or both are adjusted, until cavitation occurs in the nozzle, for example until the cavitation extends to the nozzle exit or at least halfway through the nozzle hole. The parameters for viscosity and pressure are then recorded. Recorded are single values or range of values for the pressure P and the viscosity μ , or equivalently temperature for a specific type of lubricant. The values or ranges can be related to not only the aperture size S but also to other parameters, such as geometrical details of the nozzle.
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The recorded parameter values from a laboratory test for a specific type of injectors with a nozzle exit size S , for example diameter D , are then received and used when providing the same or similar type injectors in the engine. In practice, the viscosity μ and the pressure P of the lubricant as per the recorded parameter values are used when running the engine for causing injection of lubricant under cavitation conditions, where cavitation is provided in the nozzle, for example extending to the nozzle exit or at least halfway through the nozzle hole, during operation of the engine. In some embodiments, the viscosity is stated in the record, and the user would select a corresponding lubricant.

For example, experiments showed cavitation if D is at least 0.3 mm and the lubricant has a viscosity μ less than 0.05 Pa·sec and is injected into the cylinder through the nozzle exit at a pressure $P > 20$ bar. This was shown for a nozzle with a sac hole having a diameter of 1 mm, a spray hole that is 0.75 mm long and has an angle of 66° relative to the central longitudinal axis of the sac hole. However, the angle has only little influence on the cavitation, and the above parameters for viscosity and pressure to achieve cavitation are also valid if the spray hole lengths are varied within the range 0.5-1 mm.

The viscosity can be adjusted by changing the temperature of the lubricant. This is especially practical, as this gives a wide range of viscosities for adjustment. This is useful because, as mentioned above, typical lubricants used for injection into marine engines have similar viscosities.

As mentioned above, in typical lubricant injectors, the nozzle comprises a spray hole, one end of which forms the nozzle exit and the opposite end of which is flow-communicating with a sac hole. In typical SIP injectors, a central longitudinal axis of the spray hole is angled relative to the central longitudinal axis of the sac hole, the angle being in the range of 30 to 90 degrees, and the cross-sectional area of the sac hole perpendicular to its central longitudinal axis is larger than the cross-sectional area of the spray hole perpendicular to its central longitudinal axis. A typical length of the spray hole is in the range of 0.5-1 mm. It will be possible to use a nozzle disclosed by Gardhouse or Rathesan.

For such range of nozzles, a good criterion for cavitation is $C > 0.1$, as it expresses a substantial extension of the cavitation towards the nozzle, for example to at least half the distance between the sac hole and the nozzle exit.

5 It appears that the described method for obtaining the asymmetric cavitation is useful for SIP injection. In order to provide a proper SIP lubrication during running of the engine, sprays with atomized droplets of lubrication oil are repeatedly injected into scavenging air in the cylinder by the injectors prior to the piston passing the injectors in its movement towards the TDC. In the scavenging air, the atomized droplets are diffused
10 and distributed onto the cylinder wall, as they are transported in a direction towards the TDC due to a swirling motion of the scavenging air towards the TDC.

For example, the injectors comprise a spray nozzle having exit apertures of between 0.1 and 1 mm in diameter, for example between 0.2 and 0.5 mm, for ejecting the spray or
15 atomized droplets, also called mist of oil. In the performed experiment, a nozzle exit diameter $D=0.3$ mm was used.

SHORT DESCRIPTION OF THE DRAWINGS

20

The invention will be explained in more detail with reference to the drawing, where
FIG. 1 illustrates one half of a cylinder 1 of a large two-stroke engine, for example a marine diesel engine;

FIG. 2 shows the experimental setup used to detect the internal nozzle cavitation;

25 FIG. 3 illustrates an internal geometry of the HJ-SIP spray injection nozzle used in the experiment;

FIG. 4 are high speed shadow-graphic images of the internal nozzle flow. The images are taken after 0.13 ms. after injection;

FIG. 5 are high speed shadow-graphic images of the spray. The images are taken after
30 0.13 ms. after injection;

FIG. 6 illustrates edge cavitation and vortex cavitation

FIG. 7 shows a comparison where in the right image cavitation extends to the nozzle exit;

FIG. 8 shows a near-nozzle comparison where in the right image cavitation extends to the nozzle exit;

FIG. 9 shows examples of cavitation pockets and the lubricant sprays for a high viscosity lubricant and a low viscosity lubricant,

5 FIG. 10 shows an example of spray structure seen from the side and the front of a nozzle,

FIG. 11 shows spray pattern under different conditions as seen from the side of a nozzle and

FIG. 12 shows spray pattern of FIG. 11 as seen from the front of the nozzle.

10

DETAILED DESCRIPTION / PREFERRED EMBODIMENT

FIG. 1 illustrates one half of a cylinder 1 of a large two-stroke engine, for example
15 marine diesel engine. The cylinder 1 comprises a cylinder liner 2 on the inner side of the cylinder wall 3. Inside the cylinder wall 3 and extending through the cylinder wall 3, there are provided a plurality of injectors 4 for injection of lubricant into the cylinder 1. As illustrated, the injectors 4 are distributed along the perimeter on a circle with the same angular distance between adjacent injectors 4, although this is not strictly necessary. Also, the arrangement along a circle is not necessary, seeing that an arrangement with axially shifted injectors is also possible, for example every second injector shifted
20 relatively to a neighbouring injector.

As an example among alternatives, the injectors 4 receive lubrication oil from a controller 11 through a common feed conduit 9, also called “common rail”. Alternatively,
25 the injectors 4 are arranged in groups where each group receives lubrication oil from the controller 11 through a common feed conduit 9 for each group. For example, there are two groups of injectors 4, such that neighbouring injectors along the perimeter alternately belong to one or the other group. As a further alternative, a controller 11 is provided for each single injector and a feed conduit 9 is provided for each injector. As
30 an even further alternative, a controller 11 is provided with a plurality of feed conduits 9 with one feed conduit 9 for each single injector 4.

Each of the injectors 4 has a nozzle 5 with a nozzle aperture 5' from which a fine atomized spray 8 with miniature droplets 7 is ejected under high pressure into the cylinder 1, which is in contrast to a compact jet of lubricant. The swirl 14 of the scavenging air in the cylinder 1 transports and presses the spray 8 against the cylinder liner 2 such that an even distribution of lubrication oil on the cylinder liner 2 is achieved. This lubrication system is known in the field as Swirl Injection Principle, SIP. Optionally, the cylinder liner 2 is provided with free cuts 6 for providing adequate space for the spray 8 or jet from the injector 4.

Optionally, the injectors 4 are connected to the controller 11 by a control line 10. Several possibilities exist for such a control line 10. In some embodiments, the control line 10 is a hydraulic pipe which is controlling a hydraulic injection valve inside the injector 4 such that pressurising the hydraulic pipe opens or closes the hydraulic injection valve. Alternatively, the control line 10 is an electrical wire that delivers electrical power to an electrical valve in the injector 4, for example a solenoid valve. These examples are not exhaustive, as other possibilities for control of injection exist.

The controller 11 is connected to a supply conduit 12 for receiving lubricant from a lubricant supply 16, including an oil pump, and a return conduit 13 for return of lubricant, typically to an oil reservoir, typically for recirculation of lubricant. The lubricant pressure in the supply conduit 12 is higher than the pressure in the return conduit 13, for example at least two times higher. Typically, the lubricant pressure in the return conduit 13 is in the range of 1-15 bar, for example in the range of 5-15 bar.

In the prior art, it has been described that the pressure for injection by the SIP principle is in the range of 20-100 bar, and the prior art lubricant pressure in the supply conduit 12 is correspondingly in the range of 20-100 bar, as the high pressure for the injectors is achieved by the lubricant from the supply conduit 12. However, in practice, when SIP injectors have been installed in marine engines under normal operation with SIP injection, the pressure has been at 37 bar and the temperature about 55°C. In the present invention, as will become more apparent in the following, in order to achieve cavitation in the nozzle for the same nozzle, the same lubricant, and the same temperature, a higher pressure of at least 60 bar is necessary, for example in the range 60-300 bar.

The controller 11 supplies lubrication oil to the injectors 4 in precisely timed pulses which are synchronised with the piston motion in the cylinder 1 of the engine. For the synchronisation, the controller system 11 is electronically connected to a computer 11' which monitors parameters for the actual state and motion of the engine, for example speed, load, and position of the crankshaft, as the latter reveals the position of the pistons in the cylinders. Potentially, the computer 11' is part of the controller 11.

The temperature of the lubricant in the feed conduit 9 is optionally determined by the lubricant supply in the supply conduit 12 or, alternatively, regulated by or in the controller 11.

The injectors 4 can be of various types, for examples as disclosed in international patent applications WO2002/35068, WO2004/038189, WO2005/124112, WO2010/149162, WO2012/126480, WO2012/126473, WO2014/048438, and WO2016/173601 or in Danish patent DK178427.

FIG. 2 illustrates an example of an experimental setup for testing various types of injectors and adjusting parameters in a laboratory prior to insertion of injectors 4, for example of the same type, into an engine. In the laboratory, the conditions for cavitation are tested, and parameters adjusted in order to provide a parameter set for controlled and stable cavitation as a method for optimizing the lubrication in the engine.

The exemplified experimental laboratory setup was used for testing cavitation conditions for optimising sprays. The setup comprised a HJ Lubtronic system (a) from Hans Jensen Lubricators A/S, which delivers 85 mg lubrication oil per injection to a heated HJ-SIP injection valve (b). The opening pressure of the injection valve is 3.7 MPa. The lubrication oil is injected into ambient atmospheric conditions. The lubricator is supplied with 6 MPa in hydraulic pressure from a pump station (c) and fresh lubrication oil from a heated reservoir (d). The high-speed camera (e) used in this study is a Photron Fastcam SA5. Images are taken with a frame rate of 1000 frames per seconds (fps) with a shutter speed of 1/161000 seconds. A 1000W halogen lamp is used as illumination source (f). Both the high-speed camera and the lubricator are controlled by a computer (g). The lubrication oil used is Mobilgaard 570™, which is a commercial lubrication oil from ExxonMobil®. The properties of the lubrication oil are shown in Table 1, where

the temperature T is in degrees Celcius, however, the approximation being valid for $T > 20^\circ\text{C}$.

Table 1

Oil property	Value
Vapor Pressure	$P_v = 13 \text{ MPa}$
Liquid Density	$\rho_l(T) = -0.6087 \cdot T + 943.97$
Liquid Viscosity	$\mu(T) = 0.00610 \cdot e^{1246/(8.31 \cdot T)}$

5

Cavitation inside the spray nozzle is captured using a shadow-graphic imaging technique. The high-speed camera and illumination source is placed on either side of the spray nozzle, which is manufactured in a transparent poly(methyl methacrylate) (PMMA) material. It was found that the refractive index of lubrication oil and PMMA material matched, and therefore refraction appears only at the phase interface between the liquid and vapor. This means that phase interfaces will appear as a dark shadow on the image.

10 The internal geometry of the spray nozzle is shown in FIG. 3. This geometry corresponds to nozzles in injectors that are currently used for SIP injection of lubricant into cylinders of marine engines.

15 The experiments are conducted at various Reynolds numbers Re and cavitation parameter σ , which are described in equation 1 and 2, respectively, below and of which both are related to the degree of cavitation.

$$Re = \frac{\rho_l \cdot U_n \cdot D}{\mu} \quad (1)$$

$$\sigma = \frac{P_a - P_v}{0.5 \cdot \rho_l \cdot U_n^2} \quad (2)$$

25 In the equations, P_a is the atmospheric pressure, P_v is the lubricant vapor pressure, ρ_l the lubricant density, U_n the mean lubricant velocity in the nozzle, μ is the liquid viscosity, and D is the diameter of the spray hole. The Reynolds number Re and cavitation parameter σ are controlled by changing the temperature of the lubricant. The change in

temperature has the highest impact on the Reynolds number, as an increase of the lubricant temperature reduces the lubricant viscosity and vice versa. The Reynolds number for the experiments is between 200 and 800.

- 5 It is pointed out that the mean liquid velocity in the nozzle U_n can be expressed by the pressure of the lubricant as delivered from the supply line 12 (see FIG. 1) into the injector and at the nozzle.

$$U_n = \sqrt{\frac{2 \cdot P}{\rho_l}} \quad (3)$$

- 10 When inserted into the above expression (1), the Reynolds number becomes the following

$$Re = \sqrt{\frac{2 \cdot P}{\rho_l}} \cdot \frac{\rho_l \cdot D}{\mu} \quad (4)$$

- 15 This is a simple expression where the Reynolds number is determined by the delivery pressure P , the lubricant density ρ_l , the nozzle exit diameter D , and the lubricant viscosity μ , which in turn is dependent on the temperature.

- FIG.4 shows high-speed shadow-graphic images of the internal nozzle flow at different Reynolds and cavitation parameter σ , which is only controlled by the liquid temperature, as the temperature changes the viscosity of the lubricant, while the pressure in the experiments was 40 bar. In the experiments, the temperature has been chosen as the variable instead of the viscosity, as the temperature is a parameter that is illustrative and also easily adjustable in practice when operating an engine. When using a different lubricant, the viscosity/temperature relationship is easily adjusted, as the viscosity is usually known for the product.
- 25

- In FIG. 4, it is shown that cavitation is not present, when the liquid temperature is 60°C, which is slightly higher than the lubricant temperature of $T=55^\circ\text{C}$ in SIP injectors in use in marine diesel engines in the prior art and currently in use. This shows that SIP injection in practice has been performed with sprays where no cavitation was present in the nozzle. It is pointed out that the temperature of the lubricant for injection in
- 30

commercially available lubricants is 55°C, which is lower than the temperature of around 100°C of the cylinder liner.

5 In FIG. 4, it is also shown that cavitation emerges at the left side of the spray hole as temperature increases above 60°C. The size of cavitation is highly dependent on the liquid temperature, as both length and width of the cavitation volume increases with increasing temperature. When the liquid temperature is above 90°C, for example at 100°C, the cavitation extends to the nozzle exit. As the cavitation is not fully attached at one side of the nozzle wall and due to the asymmetrical geometry of the internal
10 cavity, it is assumed that the liquid is exposed to a swirling flow which is responsible for vortex cavitation. Vortex cavitation or string cavitation is created in the core of strong recirculation zones in the liquid, where the liquid pressure drops below its vapor pressure. This is a different situation than the hydraulic flip, as reported in the prior art (Sou 2007) which would suppress liquid atomization.

15 From numerical simulations, the cavitation could be reproduced, and the following conclusion could be drawn, with reference to the illustration in FIG. 6. At the beginning of the spray hole, a high degree of cavitation is attached at one side of the wall. This mechanism is known as edge cavitation and is created by the pressure drop in the liquid at
20 the wall. Furthermore, two circular cavitation zones are observed at the exit and near the exit of the spray hole. These zones are caused by the swirling motion of the liquid, where cavitation is created in the core of liquid vortices. The vortices in the nozzle become more prominent as the temperature increases. In addition to disturbances from cavitation, the ratio between the velocity components is important for the break-up of
25 liquid jets. Cavitation with vortices is advantageous in that it prevents collapse of the cavitation, which is in contrast to the discussion in the introduction of cavitation flip and spray collapse for experiments with low viscous fuel (Sou et al., 2007).

30 It is observed in Figure 4, that the cavitation parameter σ is largely constant, whereas the Reynolds number varies substantially. The change in the cavitation conditions can be attributed to the change in the Reynolds number.

Having identified the mechanisms leading to the cavitation structures and their dependence on liquid temperature, it is considered important to investigate the effects on the

subsequent spray. FIG. 5 shows shadow-graphic images of the liquid stream injected into the atmosphere. The images show that the liquid is undisturbed and jet shaped at temperatures up to 90 °C. At 100 °C and 110 °C, the liquid stream is more disrupted, and the spray angle is increased. Furthermore, this also leads to shorter breakup-length and enhanced degree of liquid atomization.

Comparing the observations made from the internal flow in FIG. 4 and subsequent spray in FIG. 5, both made at a pressure of 40 bar, it is obvious that the degree of atomization increases significantly if the cavitation extends to end of the spray hole. This is in contrast to cases where the cavitation collapses in the nozzle volume, which results in a jet-shaped liquid stream. It is assumed, that the different behavior is due to viscoelastic damping of the liquid. If the cavitation collapses inside the nozzle volume, the liquid will stabilize the stochastic disturbances introduced, and when the cavitation extends to the exit, the disturbances are directly transferred to the spray.

As a conclusion, despite certain similarities between cavitation of low viscous liquids, such as liquid fuel, and cavitation of highly viscous liquids, such as lubricant, the results show that there are different effects achieved with respect to lubricant sprays. These results are utmost surprising. Whereas cavitation at the nozzle exit for diesel fuel was reported to lead to collapse of sprays, improved spray characteristics were found for lubricant sprays when cavitation extends to the nozzle exit. This is illustrated in more detail in FIGS. 7 and 8.

In FIG. 7, the right image is a situation with cavitation extending to the nozzle exit and the left image is for a low degree of cavitation. The right spray turns out to have smaller droplets, which results in better distribution of the lubrication.

In FIG. 8 it is shown in the right image that the breakup of the spray occurs immediately at the nozzle exit if the cavitation extends to the nozzle exit. This spray was achieved with a pressure of 60 bar at a temperature of $T=100^{\circ}\text{C}$. Without cavitation, the pressure would have to be multiple times larger for achieving the same breakup outside the nozzle.

In practice, once, parameters for pressure and viscosity, including temperature, have been established in the laboratory for stable, controlled cavitation, lubricant injectors of the same or similar type are provided in the engine and run with such parameters.

- 5 By controlling and adjusting the degree of cavitation in the lubricant nozzle, for example by changing the injection pressure, the lubricant spray can be adjusted to more or less atomization in dependence on the engine parameters. Instead, or in addition to pressure variation, the viscosity of the lubricant can be adjusted by changing its temperature.
- 10 Mainly, the cavitation is determined by the nozzle exit aperture, the lubricant pressure and the lubricant viscosity. To some degree, also the internal nozzle geometry plays a role. Therefore, it is advantageous to run experiments with varying parameters in the laboratory and thereby characterising a specific nozzle type with respect to cavitation. Once, the useful and characterising parameters for cavitation has been found, these parameters are then used in operation, for example standard operation, in an engine of the
- 15 type as discussed above.

- It is pointed out that optimised spray is achieved when cavitation extends to the nozzle exit. However, cavitation extending to at least halfway through the spray hole has been
- 20 found as a good alternative optimization, as cavitation moves quickly towards the nozzle exit with only slight increase of temperature. But already a minor degree of cavitation is an improvement.

- In FIG. 9, it is shown in the left-hand image cavitation pockets and in the right-hand
- 25 image the resultant spray for a high(a) and low(b) viscosity lubricant oil in a lubricant injection nozzle. The internal geometry of the nozzle consists of a 4.8 mm hole which guides a needle, prolonged by 1 mm sac hole. The exit orifice consists of a 0.3 mm spray hole coming out at a sharp angle near the end of the 1 mm sac hole.

- 30 FIG. 9 is still images of the internal flow of the nozzle. The nozzle images show the inside of the nozzle on the left-hand side, with the resultant spray on the right-hand side. Despite the blur of the images, the general character of the spray is discernible. It shows that, for the high viscosity oil, cavitation is just developing at the intersection of the 1 mm and 0.3 mm holes. This has little effect on the spray, which appears

laminar. FIG. 9 shows that for the low viscosity oil, the cavitation pocket extends the length of the nozzle. The spray is clearly affected by this condition.

5 In FIG. 9 the upper of the two pictures illustrates that the cavitation pocket is approximately 1% of the volume of the spray hole, and the lower of the two pictures illustrates that the cavitation pocket is approximately 35-40% of the volume of the spray hole.

10 FIGS. 10-12 show a spray viewed from the side and the front of the nozzle and is a result of studies effected by Lionel Christopher Ganippa, Göran Bark, Sven Andersson and Jerzy Chomiak;. *The Structure of Cavitation and its Effect on the Spray Pattern in a Single-Hole Diesel Nozzle*,. *SAE Transactions*, Vol. 110, Section 4: JOURNAL OF FUELS AND LUBRICANTS (2001), pp. 1435-1444.

15 The global structure of the spray, both the near-nozzle and the far-field spray dispersion under different cavitating conditions is discussed.

FIG.10 Shows a spray visualization viewed from the side and the front of the nozzle.

20 FIGS. 11 and 12 show spray pattern under different conditions and seen from the side in FIG. 11 and from the front in FIG. 12.

FIGS. 11 and 12 show: non-cavitating (a), incipient cavitation (b), developing cloud (c) developed coherent cavitation (d), developed coherent cavitation on both sides (e) and a cavitation pocket cavitation stage (f).
25

The spray patterns issuing from the nozzle under different cavitating conditions when viewed from the side are shown in Figure 11. Under the conditions (a) to (e), the spray was observed to be symmetric.
30

In the cavitation pocket cavitation stage (f) there is a clear asymmetry in the spray as seen from the front in FIG. 11. This asymmetry was not due to imperfect or partial hydraulic flip. In this condition of asymmetric spray, the cavitation pocket was

attached to the right side of the nozzle wall throughout the spray hole. On the other hand, a cavitation pocket was also seen on the other side of the spray hole, but the cavitation pocket did not extend to the spray hole exit.

- 5 In general, cavitation was distributed more to the right side of the nozzle compared to the left side of the nozzle. This unsymmetrical flow inside the nozzle is one of the reasons for the creation of the asymmetric spray in form of an atomizing spray on the right side and non-atomizing spray on the left side. When the spray was viewed from the front, the spray appeared to be symmetric under all conditions. This effect can be
10 used to establish a better control where the lubricant spray ends up on the liner when injected by the injector.

- As a conclusion, cavitation for lubricant injection is beneficial, as it results in a better breakup of the lubricant into droplets, especially when the cavitation extends to the
15 nozzle exit, and moreover the lubricant spray formed may advantageously be controlled to establish a better control where the lubricant spray ends up on the liner when injected by the injector.

CLAIMS

1. A method of lubricating a large two-stroke engine comprising a cylinder (1) with a reciprocal piston inside and with a number of lubricant injectors (4) distributed along a perimeter of the cylinder (1) for injection of lubricant into the cylinder (1) at various positions on the perimeter during injection phases; wherein each lubricant injector (4) comprises a nozzle (5), the nozzle (5) comprising sac hole, and a spray hole having a nozzle exit from which the lubricant leaves the nozzle into the cylinder; wherein the method comprises
- 5 -injection of lubricant into the cylinder (1) as a spray directed to the liner of the cylinder during operation of the engine,
- inducing lubricant cavitation in the nozzle during the injection and by the cavitation influencing characteristics of the spray, **characterized in that** the method further comprises a step of inducing asymmetric cavitation in the lubricant in the nozzle during the injection.
- 15
2. The method according to claim 1, wherein the method comprises the steps of
- providing at least a first cavitation pocket at one side of the nozzle inside the nozzle.
- 20
3. The method according to claim 2, wherein the method comprises the steps of
- providing a cavitation pocket which occupies more than 1% of volume of the spray hole.
- 25
4. The method according to claim 2 or 3, wherein the method comprises the steps of
- providing a second cavitation pocket at a second side of the nozzle, and
- providing the first and second cavitation pocket with different sizes.
- 30
5. The method according to claim 4, wherein the method comprises the steps of
- providing the second cavitation pocket with a size being less than or equal to 50% of the size of the first cavitation pocket.
6. The method according to claim 4 or 5, wherein the method comprises the steps of

-providing a difference in size between the cavitation pockets so that the large cavitation pocket has a volume of 1%-50% of the volume of the spray hole, and the small cavitation pocket has a volume of 0%-25% of the volume of the spray hole.

- 5 7. The method according to any of the preceding claims, wherein the method comprises the steps of
- providing the at least first cavitation pocket at the transition between the sac hole and the spray hole.
- 10 8. The method according to any of the preceding claims, wherein one end of the spray hole forms the nozzle exit, wherein the sac hole is arranged for flow of lubricant to the spray hole, which spray hole extends from the sac hole to the nozzle exit; wherein a central longitudinal axis of the spray hole has an angle with a central longitudinal axis of the sac hole, the angle being in the range of 30 to 90 degrees; wherein the cross
- 15 sectional area of the sac hole perpendicular to its central longitudinal axis is larger than the cross sectional area of the spray hole laterally to its central longitudinal axis; wherein the length of the spray hole is in the range of 0.5-1 mm.
- 20 9. The method according to any of the preceding claims, wherein the Reynolds number for the lubricant in the nozzle aperture is above 450.
- 25 10. The method according to any of the preceding claims, wherein D is at least 0.3 mm; and wherein the method comprises injecting the lubricant into the cylinder through the nozzle exit at a pressure P above 20 bar and viscosity μ of less than 0.05 Pa·sec.
- 30 11. The method according to any of the preceding claims, wherein the method comprises injecting the lubricant into the cylinder while cavitation in the nozzle is extending to the nozzle exit.
12. The method according to any of the preceding claims, wherein the method comprises providing vibrations, preferably ultrasonic vibrations, in the nozzle with a frequency that promotes cavitation.