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Figure 1

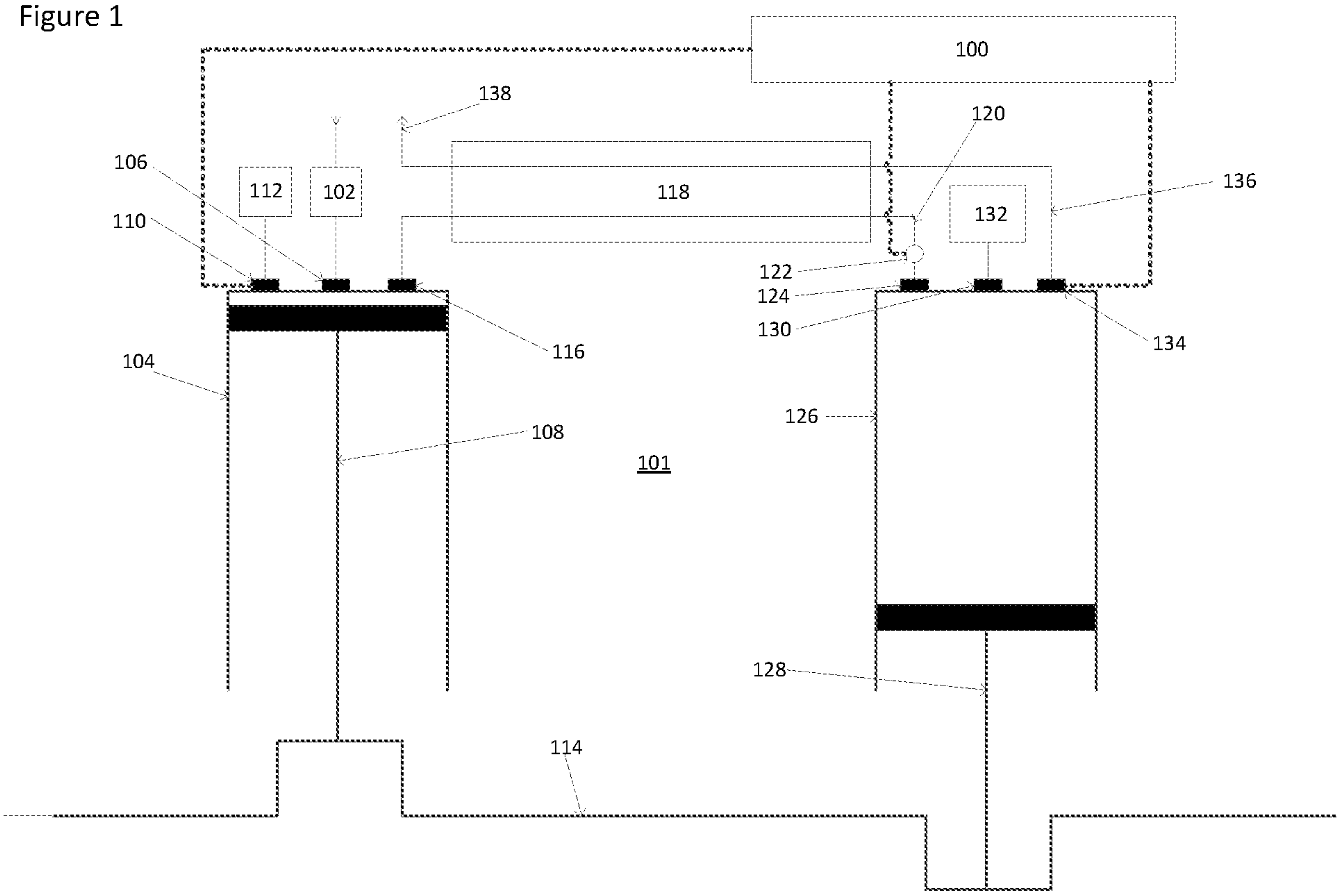

100
138
120
106
112
102
118
136
110
132
122
124
130
116
134
104
126
108
101
128
114

Figure 2a

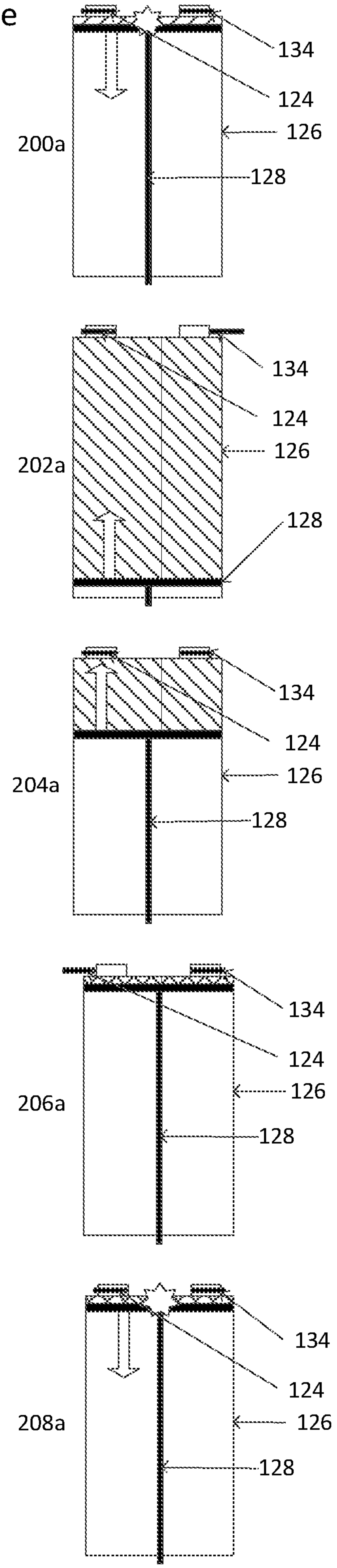


Figure 2b

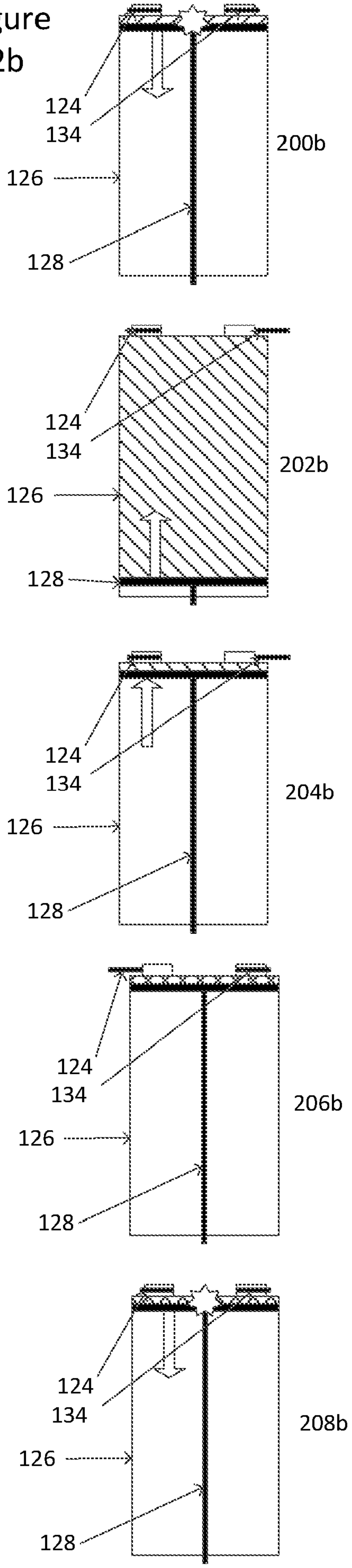


Figure 3

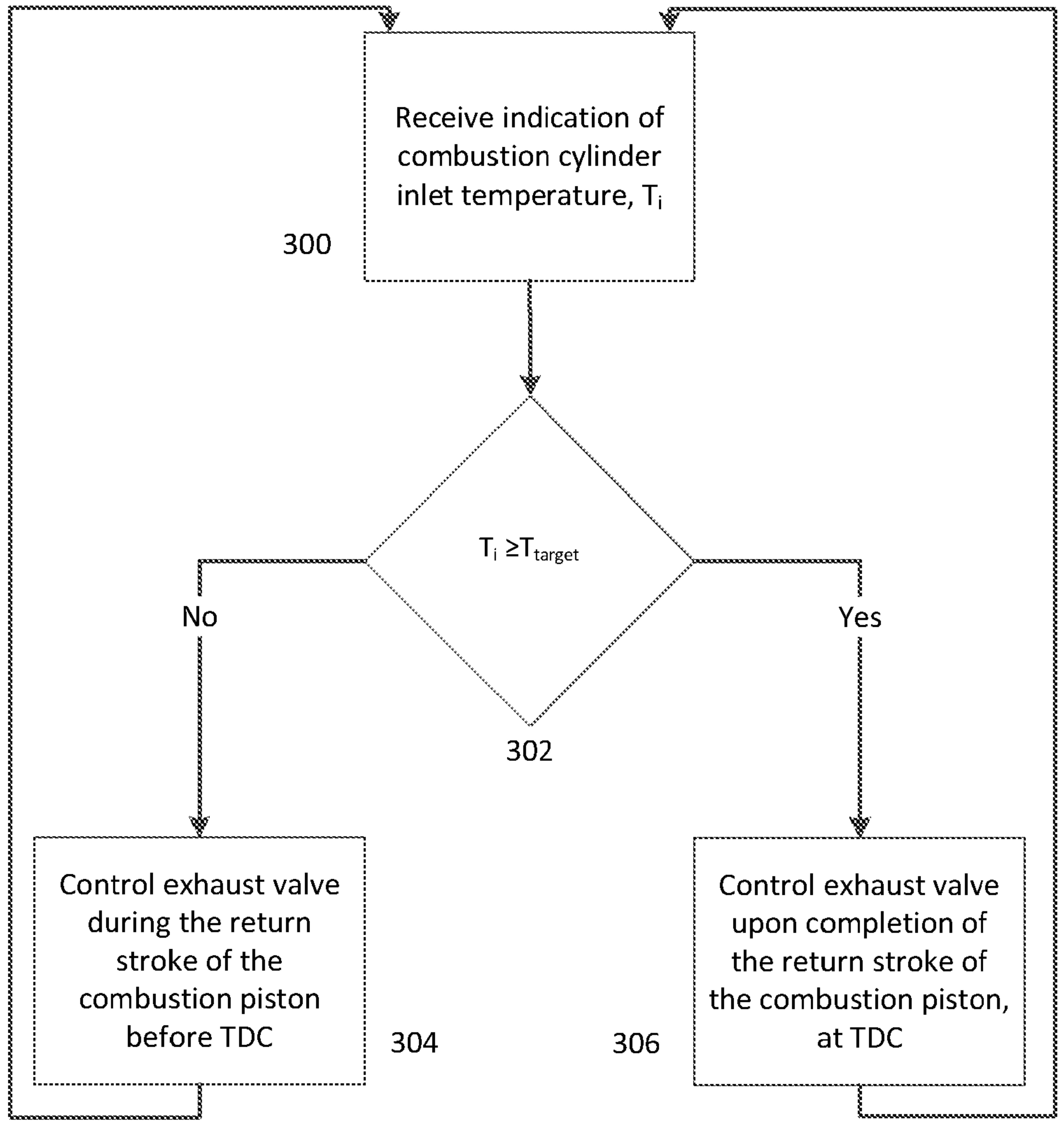

Receive indication of combustion cylinder inlet temperature, T_i
300
$T_i \geq T_{target}$
No
Yes
302
Control exhaust valve during the return stroke of the combustion piston before TDC
304
306
Control exhaust valve upon completion of the return stroke of the combustion piston, at TDC

Figure 4

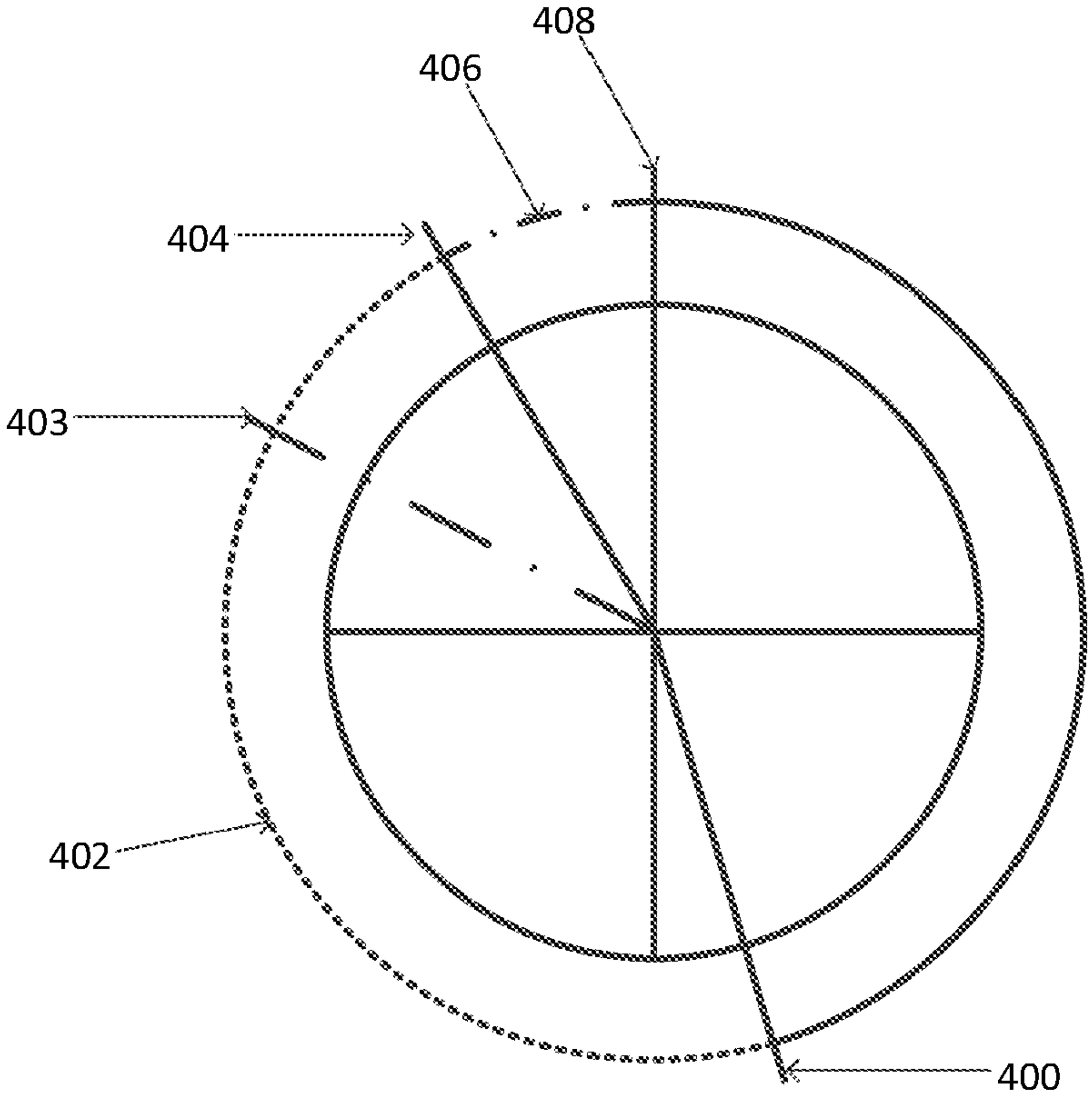


Figure 5a

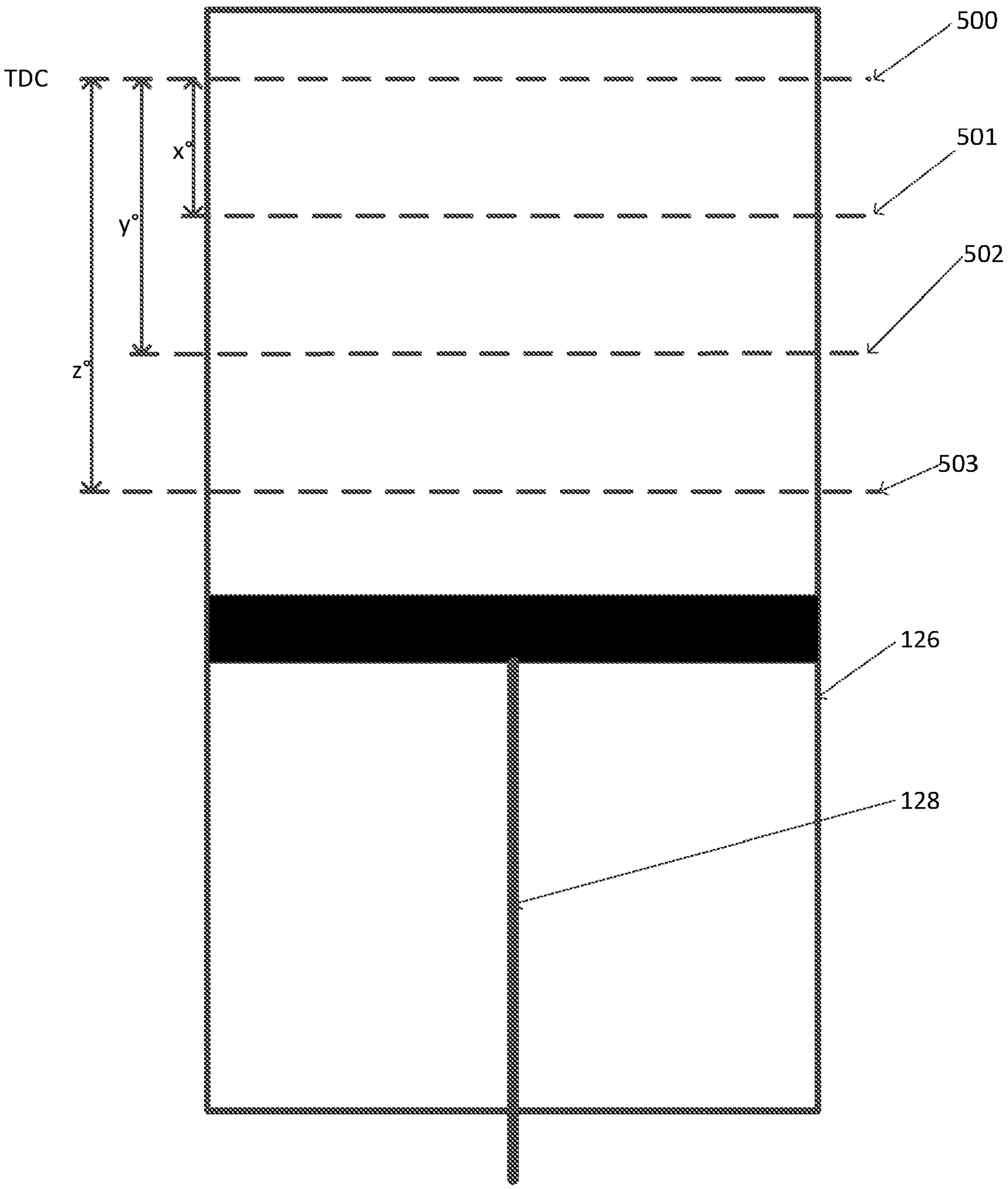


Figure 5b

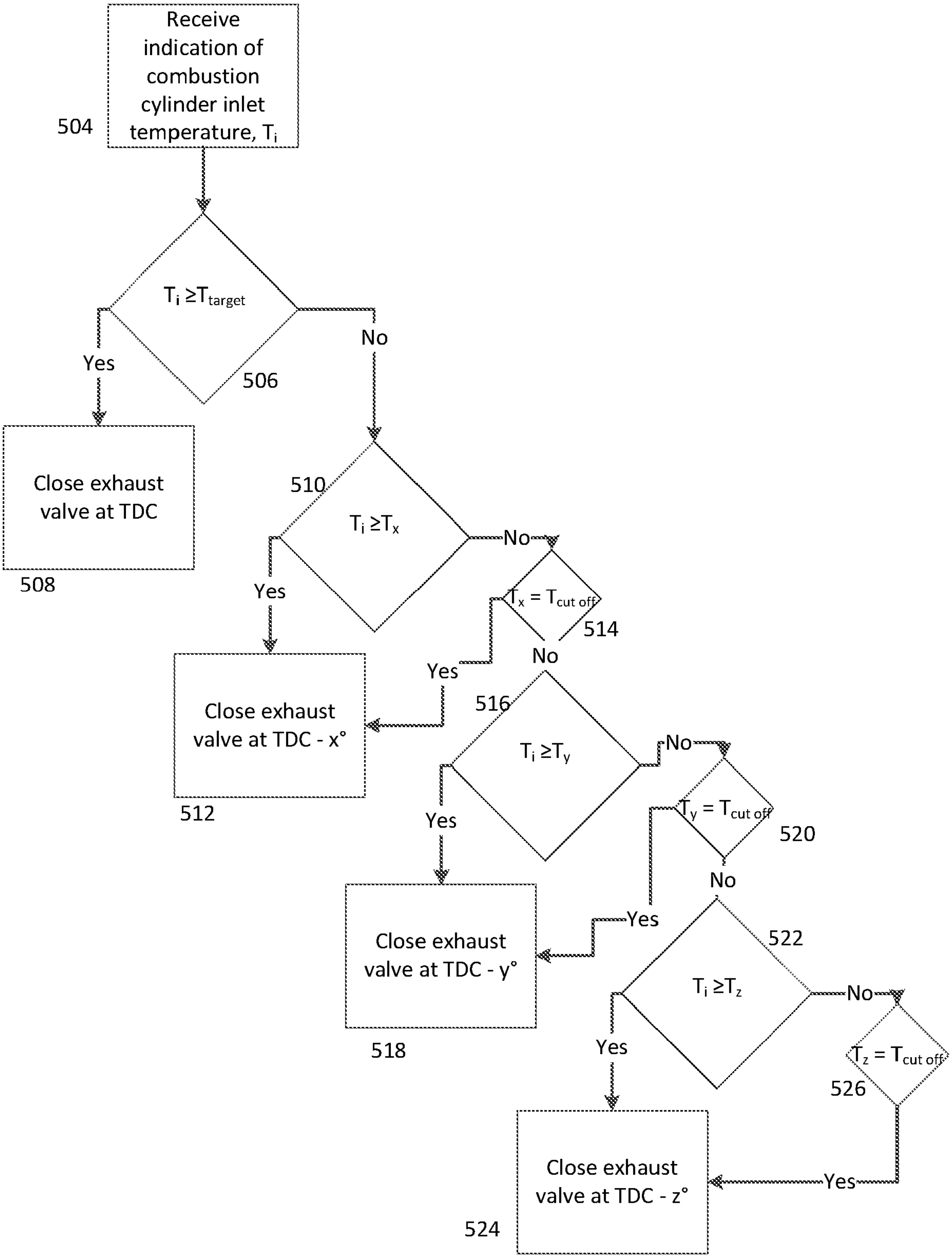

Receive indication of combustion cylinder inlet temperature, T_i
504
$T_i \geq T_{target}$
506
Yes
No
Close exhaust valve at TDC
508
510
$T_i \geq T_x$
Yes
No
$T_x = T_{cut\ off}$
514
Yes
No
Close exhaust valve at TDC - x°
512
516
$T_i \geq T_y$
Yes
No
$T_y = T_{cut\ off}$
520
No
Yes
Close exhaust valve at TDC - y°
518
522
$T_i \geq T_z$
Yes
No
$T_z = T_{cut\ off}$
526
Yes
Close exhaust valve at TDC - z°
524

Figure 5c

528

Temperature increment	**Value**	**Exhaust valve closure position**
T_{target}	Target combustion temperature, e.g 700°C	TDC
T_x	E.g. 550°C	TDC - x° E.g. 40°
T_y	E.g. 400°C	TDC - y° E.g. 80°
T_z	E.g. 250°C	TDC - z° E.g. 120°

Figure 6

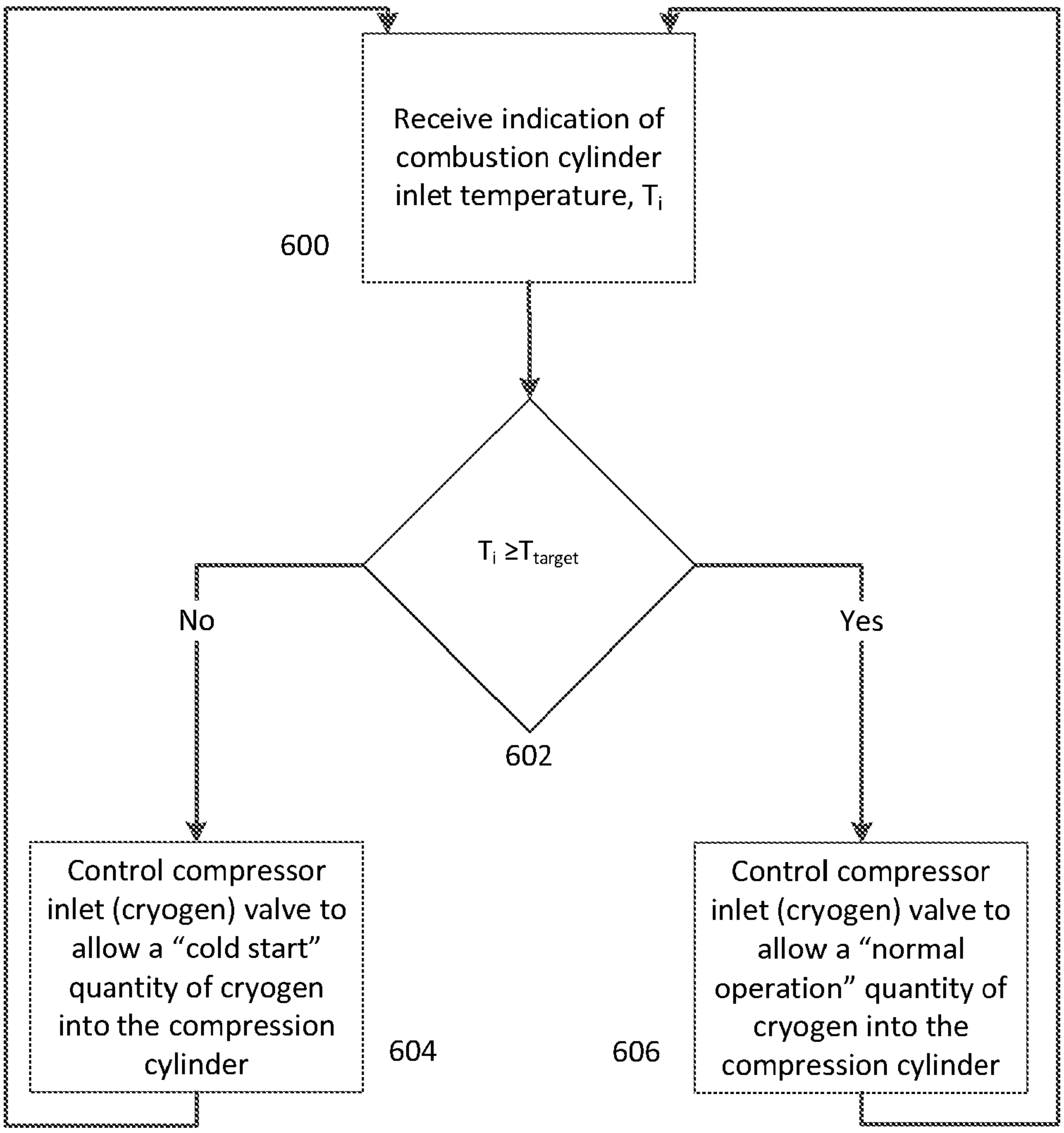
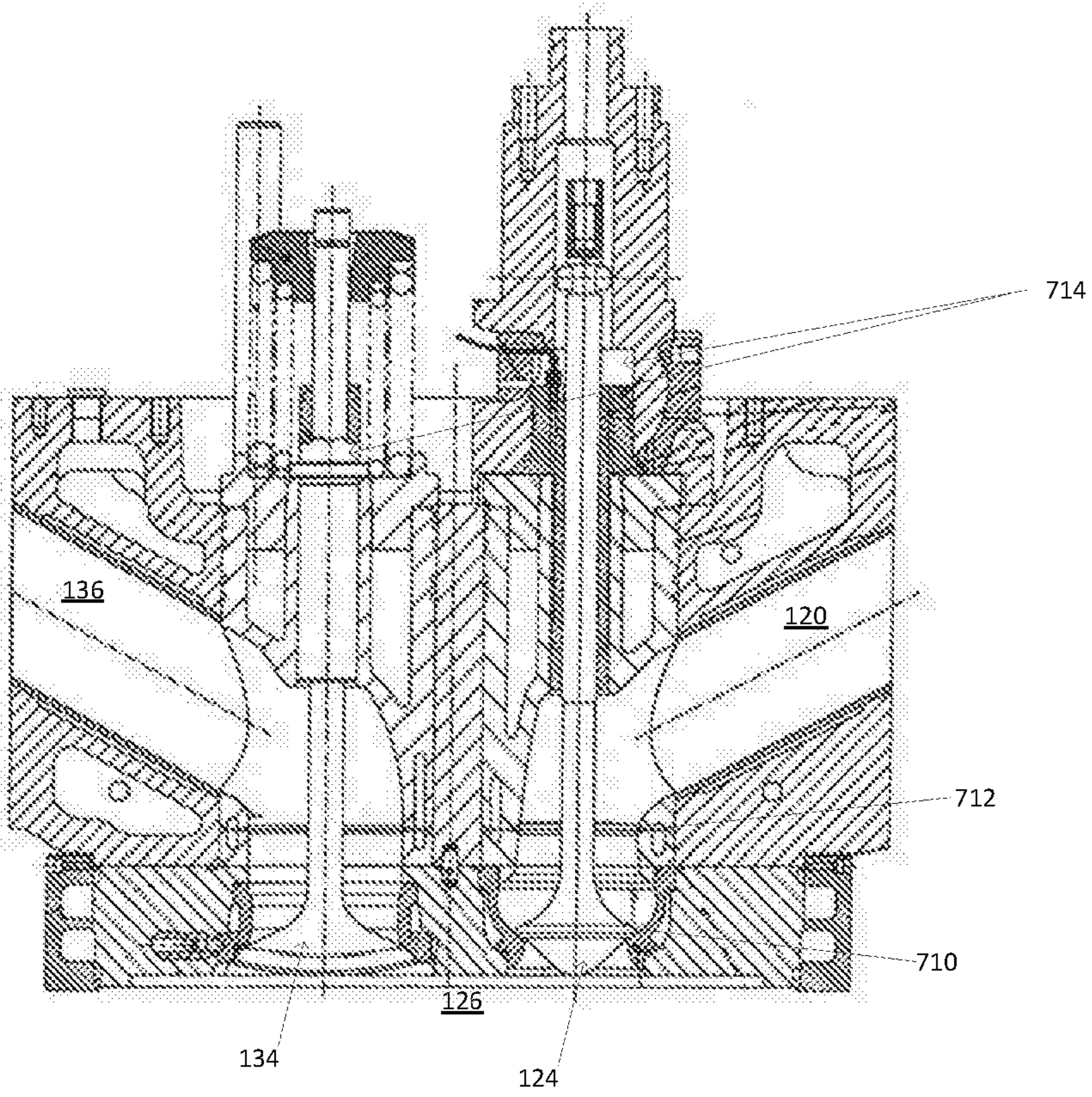

Receive indication of combustion cylinder inlet temperature, T_i
600
$T_i \geq T_{target}$
No
Yes
602
Control compressor inlet (cryogen) valve to allow a “cold start” quantity of cryogen into the compression cylinder
604
606
Control compressor inlet (cryogen) valve to allow a “normal operation” quantity of cryogen into the compression cylinder

Figure 7



Split Cycle Engine

Field of Invention

The present disclosure relates to a split cycle internal combustion engine and method of operating the same.

Background

In a split cycle internal combustion engine, a working fluid comprising air is compressed in a first, compression, cylinder and provided to a second, combustion, cylinder, where fuel is injected and the mixture of the fuel and the high pressure fluid combusts to produce drive. Thermodynamic benefits may be derived from separating the compression and the expansion/combustion processes in this manner. WO 2010/067080 describes a split cycle engine and associated thermodynamic advantages.

In a split cycle engine, further thermodynamic benefits may be achieved by injecting a cryogenic fluid into the compression cylinder during the compression stroke. Such a system and method is described in WO 2016/016664.

In particular in engines in which a cryogen is used, a recuperator may be provided, having a first fluid path carrying compressed fluid from the compression cylinder to the expansion cylinder, and a second fluid path carrying exhaust gases from an outlet of the combustion cylinder, in order to heat the compressed fluid on its way to the combustion cylinder. This may help to ensure that the compressed fluid arriving at the combustion cylinder is sufficiently hot that combustion may occur when the fuel is injected.

Summary of invention

The inventor in the present case has appreciated that difficulties in achieving efficient combustion may be encountered during start-up of the engine (“cold start”), when there is little or no exhaust heat in the recuperator, leading to the compressed fluid arriving at the combustion cylinder at a sub-optimal temperature for combustion.

Embodiments described herein address these difficulties.

The invention is set out in the claims appended hereto.

In the following description, the term “cryogenic” fluid or liquid is used to refer to a fluid which has been condensed into its liquid phase via a refrigeration process.

Embodiments described herein relate to a split cycle engine in which a cryogenic fluid is injected during the compression stroke. In other examples, the methods described herein could be implemented without the injection of a cryogen. Additionally, other fluids, water as an example, may be added to the recuperator to control terminal temperature at the exit from the recuperator.

As described herein, the split cycle engine has a controller which is arranged to receive an indication of a parameter associated with the combustion cylinder and/or a fluid associated therewith and to control a feature of the engine in dependence on the indicated parameter.

The parameter may be one or more of a temperature, pressure and oxygen concentration, therefore an indication of a parameter may comprise one or more of temperature data, pressure data and oxygen concentration data.

The controller may receive temperature and pressure data, temperature and oxygen concentration data, pressure and oxygen concentration data or temperature, pressure and oxygen concentration data and use this date to control one or more of the cryogen injection, exhaust valve timing and recuperator water injection, individually or in combination.

In the case where the parameter is a temperature, the indicated temperature could be at least one of a temperature inside the combustion cylinder, a temperature inside the recuperator of the engine, in particular a surface of the recuperator which is coated with a catalyst, a temperature of the compressed fluid in the recuperator, a temperature of the compressed fluid at the inlet of the combustion cylinder or a temperature of the exhaust gas.

In the case where the parameter is a pressure, the indicated pressure could be at least one of a pressure inside the combustion cylinder, a pressure inside the recuperator of the engine, a pressure of the compressed fluid in the recuperator, a pressure of the compressed fluid at the inlet of the combustion cylinder or a pressure of the exhaust gas.

In the case where the parameter is an oxygen concentration, the indicated oxygen concentration could be at least one of an oxygen concentration inside the combustion cylinder, an oxygen concentration inside the recuperator of the engine, an oxygen concentration of the compressed fluid in the recuperator, an oxygen concentration of the compressed fluid at the inlet of the combustion cylinder or an oxygen concentration of the exhaust gas.

The feature of the engine which is controlled may be one or more of the timing of closure of the exhaust valve, the quantity or rate of cryogen injection during the compression stroke and rate, quantity or timing of fuel injection into the combustion cylinder.

In embodiments, the feature of the engine is controlled based on a comparison between the indication of the parameter and a target value for the parameter.

In embodiments, the feature of the engine is controlled based on a difference between the indication of the parameter and a target value for the parameter.

In embodiments, the controller is arranged to receive an indication of a temperature of the compressed fluid at the inlet of the combustion cylinder and to control the closure of the exhaust valve of the combustion cylinder based on a comparison between the indicated temperature and a target temperature for the compressed fluid at the combustion cylinder inlet. The target temperature may be defined based on a desired temperature for combustion in the cylinder. As described herein, the controller is arranged to cause the exhaust valve to close during the return stroke of the combustion piston (108, 128), before the combustion piston has reached its top dead centre position (TDC), when the indicated temperature is less than a temperature; and to close on completion of the return stroke of the combustion piston, as the combustion piston reaches its top dead centre position (TDC), when the indicated temperature is equal to or greater than the target temperature.

Closing the exhaust valve before the combustion piston has reached its top dead centre position (TDC), when the indicated temperature is less than a temperature, may be described as a “cold start” mode of operation. This corresponds to the indicated temperature being sub-optimal for combustion, which may be due to the lack of heat available for collection in the recuperator. By closing the exhaust valve before the combustion piston reaches TDC, a portion of the hot exhaust gases of combustion may be retained inside the combustion cylinder and compressed to raise the temperature of the cylinder to assist combustion on the next engine cycle.

Closing the exhaust on completion of the return stroke of the combustion piston, as the combustion piston reaches its top dead centre position (TDC), may be described as a “normal mode” of operation, which corresponds to the indicated temperature being acceptable for combustion. This condition would usually be expected to be reached after the recuperator, and thereby the temperature of the compressed fluid supplied to the combustion cylinder inlet, has warmed up as hot exhaust gases flow through the recuperator. The exhaust valve may, in this condition, be closed as the combustion piston completes its return stroke, expelling all exhaust gases from the combustion cylinder and into the recuperator pathway.

In other examples, the valve timing control is based on the measurement of a pressure and/or an oxygen concentration, optionally in addition to a temperature measurement.

In embodiments, the controller is arranged to receive an indication of a temperature of the compressed fluid at the inlet of the combustion cylinder and to control the amount of cryogenic fluid provided to the compression cylinder during the compression stroke. This reduces the limitation on the temperature rise of the compressed fluid during “cold” cycles in which there is insufficient heat in the recuperator to raise the compressed fluid to a target combustion temperature at the combustion cylinder inlet.

The control may be based on a comparison between the indicated temperature and a target temperature for the compressed fluid at the combustion cylinder inlet. The target temperature may be defined based on a desired temperature for combustion in the cylinder. As described herein, the controller may be arranged to control the quantity of cryogenic fluid injected into the compression cylinder such that a “normal mode” quantity of cryogenic liquid is provided to the compression cylinder when the indicated temperature is equal to or greater than a target temperature, and a “cold mode” quantity of cryogenic liquid is provided to the compression cylinder when the indicated temperature is less than the target temperature, wherein the “cold mode” quantity is less than the “normal mode” quantity.

The “normal mode” quantity of cryogen will generally be understood to be the rate and quantity of cryogen injection such that the cryogenic liquid vaporises into its gaseous phase during the compression stroke of the compression piston, such that a rise in temperature caused by the compression stroke is limited to approximately zero by the absorption of heat by the cryogenic liquid. This may allow more efficient compression. This may also allow a maximal amount of heat to be recuperated from exhaust gases.

When the indicated temperature is greater than a target temperature for “normal mode” operation, a “hot mode” of operation may be enabled. In this mode, the amount of cryogenic liquid added may be optimised based on the temperature at the inlet, so under high load conditions when more heat is available, temperature is lower at the end of compression than before performing compression work. The “hot mode” quantity of cryogen will be understood as being a higher quantity and/or rate of cryogen injection per compression stroke than the “normal mode” quantity, such that the temperature of the fluid within the compression cylinder is allowed to be controlled within safe limits. For additional temperature control and hardware protection, water could be added to the recuperator under high load conditions.

The “cold mode” quantity of cryogen will be understood as being a lower quantity and/or rate of cryogen injection per compression stroke than the “normal mode” quantity, such that the temperature of the fluid within the compression cylinder is allowed to rise as a result of the compression. This allows the compressed fluid to exit the compression cylinder in a hotter state, to compensate for the lack of heat available in the recuperator.

In other examples, the cryogen injection control is based on the measurement of a pressure and/or an oxygen concentration, optionally in addition to a temperature measurement.

In other examples, the exhaust valve timing and cryogen injection are both controlled based on one or more measured engine parameters.

Brief description of the figures

Embodiments of the present invention will now be described, by way of example, with reference to the accompanying drawings.

Figure 1 shows a schematic diagram of a split cycle internal combustion engine.

Figure 2a shows stages in the operation of a combustion cylinder of the split cycle engine during a cold start mode.

Figure 2b shows stages in the operation of the combustion cylinder during a normal running mode.

Figure 3 shows a decision chart for controlling an exhaust valve of the combustion cylinder.

Figure 4 represents relative valve timings in the combustion cylinder.

Figure 5a shows examples of exhaust valve closure positions illustrated by positions of the combustion piston within the combustion cylinder.

Figure 5b shows a controller decision process for controlling the exhaust valve.

Figure 5c shows a look-up table for use in controlling the exhaust valve.

Figure 6 shows a decision process for controlling a cryogen inlet valve of a compression cylinder of the split cycle engine.

Figure 7 shows examples of valve arrangements within the cylinder head of the combustion cylinder.

Detailed description of the figures

Figure 1 shows a schematic diagram of a split cycle internal combustion engine 101. As illustrated, the engine comprises a compression cylinder 104 and a combustion cylinder 126, each cylinder having an associated piston configured to reciprocate within it. As the skilled person will appreciate, multiple similar compression cylinders and combustion cylinders may be present. The compression cylinder 104 comprises a cryogen inlet valve 110 that is connected to a cryogen reservoir 112. The compression cylinder 104 has a fluid inlet valve 106 connected to a turbo charger 102 to receive a compressed air supply and a fluid outlet valve 116. A fluid inlet valve 124 of the combustion cylinder 126 is coupled to the fluid outlet valve 116 to receive compressed fluid from the compression cylinder 104. The combustion cylinder also has a fuel inlet valve 130 coupled to a fuel source 132 and an exhaust valve 134.

Along the path 120 between the compression cylinder fluid outlet valve 116 and the combustion cylinder fluid inlet valve 124, compressed fluid passes through a recuperator 118. This recuperator 118 is heated by exhaust gases from the combustion cylinder exhaust valve 134 passing along an exhaust pathway 136 to an exhaust outlet 138.

The split cycle engine 101 comprises a controller 100. This controller 100 is connected to at least one sensor 122. In examples, at least one sensor 122 could be a temperature sensor, a pressure sensor, an oxygen concentration sensor or any combination thereof. In the illustrated example, a temperature sensor 122 is disposed near the combustion cylinder 126 fluid intake, at a point along the path 120 of the compressed fluid between the recuperator 118 and the combustion cylinder fluid intake valve 124. This sensor 122 is operable to sense the temperature of the compressed fluid and report sensed temperature data back to the controller 100. The controller 100 is arranged to receive this temperature data and control the timing of the exhaust valve 134 on the combustion cylinder 126 based at least in part on the received temperature data. The controller 100 may also be operable to adjust the operation of the cryogen inlet valve 110 to control the amount of cryogen that is injected into the compression cylinder 104.

After combustion occurs in the combustion cylinder 126, the exhaust gas leaves the combustion cylinder 126 via the exhaust valve 134 and travels along exhaust pathway 136 coming into thermal communication with the recuperator 118 to heat compressed fluid travelling along the pathway 120 between the compression cylinder outlet valve 116 and the combustion cylinder inlet valve 124.

The above mentioned sensor or sensors can be located in a multitude of places. In particular, one or more sensors may be placed near the inlet valve 124 on the combustion cylinder as shown in Figure 1, in the recuperator 118 or near the compression cylinder outlet valve 116.

Figure 2a shows schematically a process of controlling the combustion cylinder during a cold start mode of operation, including stages 200a, 202a, 204a, 206a and 208a by comparison to Figure 2b which shows stages 200b, 202b, 204b, 206b and 208b of a normal running mode. At stage 200a the compressed fluid-fuel mixture is igniting as the combustion piston 128 is at TDC. Depending on the type of fuel of the engine, this ignition could be initiated by a spark plug or auto-ignition. The increased pressure due to the released energy from the fuel combustion drives the combustion piston towards bottom dead centre (BDC), further driving the crankshaft 114. Once the piston reaches BDC the combusted mixture has expanded to fill the combustion cylinder 126 and the exhaust valve 134 is opened (stage 202a). The combustion piston then proceeds towards TDC, expelling the exhaust gases out the exhaust valve 134.

In the cold start mode, the exhaust valve 134 is closed before the combustion piston reaches TDC. This is shown at stage 204a, where the exhaust valve 134 is closed when the piston is about 65% of the way from BDC to TDC. The remaining exhaust gas is then compressed as the piston reaches TDC and, as shown at stage 206a, the inlet valve is opened to allow the compressed fluid into the combustion cylinder 126. The inlet valve 124 is closed and the injected fuel is ignited (stage 208a), starting the cycle over again. The exhaust gas left in the combustion cylinder 126 when the exhaust valve 134 is closed will heat up the compressed fluid. This may lead to an increase in efficiency of the engine by offsetting the lack of heat in the engine, and in particular the recuperator 188. The compressed fluid therefore arrives at the combustion cylinder inlet at a sufficiently high temperature, having recuperated heat from the exhaust gases.

This is in contrast to the normal running mode in Figure 2b. In this cycle, stage 200b, 202b, 206b and 208b correspond to 200a, 202a, 206a and 208a respectively. The difference between the cold start mode and the normal running mode is highlighted at stage 204b. Here, the exhaust valve 134 is open until the combustion piston reaches TDC such that most of the exhaust gas is expelled from the cylinder. In this mode, the engine is running “normally” whereby all, or most, of the exhaust gases are expelled into the recuperator.

Figure 3 shows a flow diagram for a control process that occurs at the controller 100. The controller 100 receives an indication of the combustion cylinder 126 inlet temperature from a temperature sensor located near the combustion cylinder 126 inlet. This temperature, T_i, is then compared against a target temperature, T_{target}. In this example, T_{target} is a desired temperature for the compressed fluid at the combustion cylinder inlet 124, such as will allow efficient combustion when the fuel is injected.

If T_i is not greater than or equal to T_{target} (corresponding to a "normal running" mode), the controller controls the exhaust valve 134 timing so that the exhaust valve 134 is closed before the combustion piston reaches TDC, causing a portion of the exhaust gas to be trapped in the combustion cylinder 126.

If T_i is greater than or equal to T_{target} (corresponding to a "cold start" mode), controller controls the exhaust valve 134 operation timing so that the exhaust valve 134 is closed at the point at which the combustion piston is at TDC, at which point, most of the exhaust gas will have been expelled as the compressed gas is sufficiently heated by the recuperator.

Figure 4 shows a representation of the relative timings (as phase angles) of the opening and closing operations of the combustion cylinder valves in a normal running mode. The longer radial lines (400, 404 and 408) represent valve control events. A full 360^O clockwise traverse of the circle represents a full piston cycle. .

At phase angle 408, all of the valves of the combustion cylinder 126 are closed and a combustible mix is present in the combustion cylinder. The combustion piston is at TDC. The mixture is then ignited and the piston moves towards BDC.

Moving clockwise, phase angle 400 represents the opening of the exhaust valve (EVO), which occurs a short amount of time before the combustion piston reaches BDC. This position can be described by the amount of degrees clockwise from the vertical line, corresponding, to the phase angle offset of the combustion piston from TDC. For example EVO may occur at 170° as in the example shown in Figure 4.

The exhaust valve 134 is open until phase angle 404, approximately 340° in the example shown, at which point the exhaust valve closing (EVC) event, occurs. This is just before the fluid intake valve opening event (IVO) which will occur immediately after EVC. In Figure 4, the line for this event is not separately shown as the time between this event and the exhaust valve closing (EVC) event is too short to show clearly. The inlet valve is then open until the full cycle is completed at 360° at which point the inlet valve is closed (IVC), the combustion piston is at TDC and the combustible mixture is ignited at 0°/360° and the cycle is then repeated.

In a cold start mode, the phase angle of the EVC/IVO changes as the time the exhaust valve 134 is open for is reduced. This means EVC/IVO occurs at a smaller phase angle offset. This phase angle offset can be described as a number of degrees before TDC (0°). An example is shown as a dashed line 403 in Figure 4, where the EVO/IVO occurs approximately 60° before TDC.

Figure 5a shows a combustion piston 128 within the combustion cylinder 126. Various possible combustion piston 128 positions, indicated by dashed lines, corresponding to early closure positions of the exhaust valve 134 are shown.

TDC is indicated by the uppermost dashed line 500. This is the piston position that corresponds to the "normal closure" position of the exhaust valve, wherein the indicated temperature is found to be sufficiently high and all of the exhaust gases are expelled from the combustion cylinder during the course of a full return stroke of the combustion piston (128). The piston positions for various early exhaust valve closure positions, corresponding to various cold start modes of operation, are indicated by further dashed lines (501, 502 and 503).

A first early exhaust valve closure position is represented by line 501, which corresponds to the combustion piston being at a phase angle of x° before TDC. (In this example, the position marked x° represents a position (360-x)° clockwise around the circle described in reference to Figure 4.)

A second early exhaust valve closure position is represented by line (502), which corresponds to the combustion piston being at a phase angle of y° before TDC, in which y° is a greater angular from TDC offset than x°. This position corresponds to an earlier valve closure position than the first closure position.

A third early exhaust valve closure position is represented by line 503, which corresponds to the combustion piston being at a phase angle of z° before TDC. TDC, in which z° is a greater angular from TDC offset than y°. This position corresponds to an earlier exhaust valve closure position than the first and second exhaust valve closure positions. In this example, the third early exhaust valve closure position represents the maximum early exhaust valve closure position. This is the earliest that the exhaust valve 134 can close and leaves the most exhaust gas in the combustion cylinder 126 which will allow the compressed fluid, which is taken into the cylinder when the inlet valve is opened, to be heated as much as possible. Retention of any greater quantity of exhaust gas, may however have a deleterious effect.

The choice of which position the exhaust valve 134 closes at varies based on the data that the controller 100 receives from any attached sensors. As discussed above, the point at which the exhaust valve 134 closes can vary depending on temperature data from a temperature sensor. When the temperature sensor indicates a temperature that is above or equal to the target temperature, a normal running mode is used and the exhaust valve 134 closes at TDC. This target temperature could be a target temperature for combustion such that the fluid fuel mixture is at this temperature before ignition.

If the temperature is below T_{target}, the exhaust valve 134 can be closed at a position (phase angle) z°, y° or x°, for example, before TDC. The selection of the appropriate early exhaust valve closure point (cold start mode) may be determined by reference to a look-up table, such as that shown in Figure 5c, in which different early closure positions are mapped onto different indicated temperature ranges. In general, upon start-up, when T_i is generally at its lowest, the controller 100 may select the maximum early exhaust valve closure position z° 503, to retain the maximum acceptable quantity of exhaust gas inside the combustion cylinder for maximum heating effect. On a subsequent engine cycle when T_i has increased, but is still below Tt, the controller may select an intermediate early exhaust valve closure position such as y° 502. Again on a subsequent cycle when T_i has increased further but it still below T_{target}, the controller 100 may select another early exhaust valve closure position, x° 501, which is closer to TDC. On a later engine cycle when T_i matches or exceeds T_{target}, the controller may select the normal closure position, with the piston at TDC, in which all of the exhaust gases are expelled on completion of the return stroke, as no additional heating is required.

The controller's decision process is shown by the flowchart in Figure 5b. The controller 100 receives temperature data from the temperature sensor. The indicated temperature, T_i, is compared to the target temperature, T_{target}. If the indicated temperature, T_i, is greater than or equal to T_{target}, the controller 100 will control the exhaust valve 134 to close when the combustion piston reaches TDC. If T_i is less than T_{target} then the controller 100 will compare T_i to a second temperature, T_x, which is less than the target temperature. If T_i is larger than T_x then the controller 100 controls the exhaust valve 134 to close at a phase angle of x° before the combustion piston reaches TDC, as can be seen in Figure 5a. After this comparison the controller 100 checks to see if T_x is the cut off temperature, $T_{cut\ off}$. If these temperatures match, the controller 100 controls the exhaust valve to close at the corresponding position as this is the cut off position, or "maximum early exhaust valve closure position", for the engine. This decision tree continues in Figure 5b with T_i being compared successively to T_y and T_z. Each of these has an associated position, corresponding respectively to the combustion piston being a phase angle of y° and z° before TDC. In examples, there could be additional temperature thresholds ranging from T_{target} to $T_{cut\ off}$. Finally, T_z is equal to the cut off temperature corresponding to the maximum early closure position and therefore the controller 100 controls the exhaust valve 134 to close at a maximum early exhaust valve closure position in which the combustion cylinder is at a phase angle z° before TDC.

The maximum early exhaust valve closure position may be defined as the point at which no greater value would be derived from retaining more exhaust gases within the combustion cylinder, or at which point the negative effects of retaining exhaust gases would outweigh the temperature benefit. This decision process can occur after every cycle of the combustion piston such that the controller 100 can provide an updated early closure position for every piston cycle.

Figure 5c shows a look-up table of these values, with the set temperature points and their corresponding exhaust valve 134 closure positions. This can be stored by the controller 100 in a memory, allowing the target temperature and other threshold temperatures to be recalled from a look up table and compared to the indicated temperature. For example, there could be a situation where z° = 120°, y° = 80° and x° = 40°. In other examples there could be more or fewer intermediate positions between the maximum early closure position and TDC.

In other embodiments, the earlier closure position is calculated based on an algorithm that takes the indicated temperature and/or a target temperature into account. This may be a simple proportional dependence relation or of a more complex form.

Figure 6 shows an embodiment in which the amount of cryogen injected into the compression cylinder is controlled in dependence on a temperature indication. Upon receipt of a temperature indication, the controller 100 compares T_i to a target temperature, T_{target}. If the indicated temperature is larger, the controller 100 controls the cryogen inlet to the compression cylinder 104 to allow a "normal operation" quantity of cryogen into the compression cylinder 104. The amount may be controlled by the controller that determines the amount of cryogen.

In embodiments, this may use the same temperature data as used by the controller for operating the exhaust valve timing and can be done in addition to valve timing and recuperator water injection. In other examples, the controller may use separate temperature data, collected by a different sensor. Of course, this applies to both pressure and oxygen concentration sensor data and the corresponding sensors in embodiments where this data is collected.

If the indicated temperature is smaller than the target temperature, the controller 100 can control the cryogen inlet to allow a "cold start" quantity of cryogen into the compression cylinder 104. This quantity may be determined by further decision making, such as comparing the indicated temperature to a range of set temperature values, or calculation. In some embodiments no cryogen is injected into the compression cylinder 104 during cold start mode.

The process described above where the sensed parameter is the indicated temperature which is compared with target temperatures may be applied in the circumstance where the sensed parameter is pressure or oxygen concentration. In these cases, the pressures or oxygen concentrations sensor indication would of course be compared to target pressures or oxygen concentrations, as the case may be, enabling the controller 100 to determine an early exhaust closure position for the exhaust valve 134 based on these parameters or indications.

When the indicated temperature is greater than a target temperature for “normal mode” operation, a “hot mode” of operation may be enabled. In this mode, the amount of cryogenic liquid added may be optimised based on the temperature at the inlet, so under high load conditions when more heat is available, temperature is lower at the end of compression than before performing compression work. The “hot mode” quantity of cryogen will be understood as being a higher quantity and/or rate of cryogen injection per compression stroke than the “normal mode” quantity, such that the temperature of the fluid within the compression cylinder is allowed to be controlled within safe limits. For additional temperature control and hardware protection, water could be added to the recuperator under high load conditions.

Figure 7 shows cross-sectional view illustrating an example of combustion cylinder 126 head that may be used in the split cycle engine and including the inlet 124 and outlet 134 valves. In this diagram the inlet valve 124 opens in a direction away from the combustion cylinder 126. The inlet valve 124 is operable to move between a first closed position 710 and a second open position 712. The exhaust valve 134 is an inwardly opening valve which is operable to allow the exhaust gas out of the combustion cylinder 126, into the exhaust pathway 136 which is coupled to the recuperator 118. The valves are operated by the valve control apparatus which is connected to the controller 100 referenced in Figure 1.

It is envisaged that control of any of the cryogen input, exhaust valve timings and recuperator water injection could be implemented individually or in combination, to improve the efficiently of split cycle engines.

In examples, the split cycle engine need not employ cryogen injection in the compression cylinder.

In examples, the split cycle engine could use petrol, diesel or another fuel.

CLAIMS

1. A split cycle internal combustion engine, comprising:

a combustion cylinder accommodating a combustion piston;

a compression cylinder accommodating a compression piston and being arranged to provide compressed fluid to the combustion cylinder;

and

a controller arranged to receive an indication of a parameter associated with the combustion cylinder and/or a fluid associated therewith and to control an exhaust valve of the combustion cylinder in dependence on the indicated parameter to cause the exhaust valve to:

close during the return stroke of the combustion piston, before the combustion piston has reached its top dead centre position (TDC), when the indicated parameter is less than a target value for the parameter; and

close on completion of the return stroke of the combustion piston, as the combustion piston reaches its top dead centre position (TDC), when the indicated parameter is equal to or greater than the target value for the parameter, wherein the indication of a parameter is an indication of a temperature associated with the combustion cylinder and/or a fluid associated therewith, and the target value for the parameter is a target temperature, wherein the target temperature is a target temperature for combustion.

2. The split cycle engine of claim 1, wherein the controller has memory which defines a normal running mode for indicated temperatures equal to or greater than the target temperature and at least one cold start mode for indicated temperatures lower than the target temperature.

3. The split cycle engine of claim 2, wherein in a cold start mode, the controller is configured to close the exhaust valve at an early closure position in which the combustion piston is ahead of TDC, in which a maximum early closure position is given by the combustion piston being at a phase angle z° ahead of TDC.

4. The split cycle engine of claim 3, wherein the controller is configured to continuously vary the closure position of the exhaust valve between the maximum early closure position and a normal mode closing position in which the combustion piston is at TDC, according to the difference between the indicated temperature and the target temperature.

5. The split cycle engine of any of claims 1 to 3, wherein the controller is configured to select one of a plurality of discrete early closure positions for the exhaust valve for positions of the combustion piston between a phase angle z° ahead of TDC and TDC, according to the difference between the indicated temperature and the target temperature.

6. The split cycle engine of claim 5, wherein the controller is configured to select the discrete closure position using a look-up table.

7. The split cycle engine of claim 6, wherein, according to a lookup table, a first early closure position corresponds to the combustion piston being at a phase angle x° ahead of TDC, a second early closure position corresponds to the combustion piston being at a phase angle y° ahead of TDC and a third early closure position corresponds to the combustion piston being at a phase angle z° ahead of TDC, wherein:

the first early closure position maps onto indicated temperatures of up to x°C lower than the target temperature;

the second early closure position maps onto indicated temperatures of between y°C and x°C lower than the target temperature; and

the third early closure position maps onto indicated temperatures of between z°C and a y°C lower than the target temperature.

8. The split cycle engine of any of the previous claims, wherein the controller is arranged to receive an indication of a pressure associated with the engine or a fluid therein and to control the exhaust valve based on the indicated pressure.

9. The split cycle engine of any of the previous claims, wherein the controller is arranged to receive an indication of an oxygen concentration associated with the engine or

a fluid therein and to control the exhaust valve based on the indicated oxygen concentration.

10. The split cycle engine of any of the previous claims, wherein the compression cylinder is arranged to receive a liquid which has been condensed into its liquid phase via a refrigeration process, such that the liquid vaporises into its gaseous phase during the compression stroke of the compression piston, such that a rise in temperature caused by the compression stroke is limited by the absorption of heat by the liquid.

11. The split cycle engine of claim 10, wherein the liquid comprises at least one of liquid nitrogen, argon and neon.

12. The split cycle engine of claim 10 or 11, wherein the controller is arranged to control the amount of the liquid provided to the compression cylinder in dependence upon the indicated temperature.

13. The split cycle engine of claim 10 or 11, wherein the controller has memory which defines a hot mode of operation for indicated temperatures in excess of a threshold temperature which is greater than the target temperature, wherein the controller is arranged in the hot mode to:

control at least one of the rate and quantity of the liquid provided to the compression cylinder in dependence upon the indicated temperature; and optionally to

control the injection of water into a recuperator of the split cycle engine in dependence upon the indicated temperature.

14. The split cycle engine of any of claims 10 to 13, wherein the controller is arranged to receive an indication of a pressure associated with the engine or a fluid therein and to control the amount of the liquid provided to the compression cylinder in dependence upon the indicated pressure.

15. The split cycle engine of any of claims 10 to 14, wherein the controller is arranged to receive an indication of an oxygen concentration associated with the engine or a fluid

therein control the amount of the liquid provided to the compression cylinder in dependence upon the indicated oxygen concentration.

16. The split cycle engine of any of the previous claims, comprising a recuperator arranged to thermally couple the compressed fluid to an exhaust product of the combustion cylinder to heat the compressed fluid provided to the combustion cylinder.

17. The split cycle engine of claim 16, wherein a catalytic coating is provided on a surface of the recuperator which is, in use, in contact with the exhaust product.

18. The split cycle engine of claims 16 or 17, wherein the catalytic coating is provided so as to be, in use, in thermal communication with the compressed fluid and the exhaust product in order to be heated by both to accelerate light-off of the catalyst.

19. The split cycle engine of any of claims 16 to 18, wherein, for indicated temperatures in excess of a threshold temperature which is greater than the target temperature, the controller is arranged to control the injection of water into the recuperator.

20. The split cycle engine of claim 16 to 19, wherein the indication of the temperature associated with the combustion cylinder is provided by a sensor which is arranged to sense at least one of: a temperature at the compression cylinder outlet, a temperature at combustion cylinder inlet, a temperature at combustion cylinder outlet, and a temperature at the recuperator.

21. The split cycle engine of claim 17, wherein the indication of the temperature of the combustion cylinder is provided by a sensor which is arranged to sense a temperature at the location of the catalyst.

22. The split cycle engine of any preceding claim, wherein an inlet valve of the combustion cylinder is arranged to open into the combustion cylinder to allow the compressed fluid into the combustion cylinder.

23. The split cycle engine of any of claims 1 to 21, wherein an inlet valve of the combustion cylinder is arranged to open outward from the combustion cylinder to allow the compressed fluid into the combustion cylinder.

24. The split cycle engine of any preceding claim, wherein the compression cylinder is thermally insulated with one or more layers, each layer comprising steel or ceramic.

25. The split cycle engine of any preceding claim, wherein the combustion cylinder is thermally insulated with one or more layers, each layer comprising steel or ceramic.

26. A split cycle internal combustion engine, comprising:

a combustion cylinder accommodating a combustion piston;

a compression cylinder accommodating a compression piston and being arranged to provide compressed fluid to the combustion cylinder;

and

a controller arranged to receive an indication of a temperature associated with the combustion cylinder and/or a fluid associated therewith and to control an exhaust valve of the combustion cylinder in dependence on the indicated parameter to cause the exhaust valve to:

close during the return stroke of the combustion piston, before the combustion piston has reached its top dead centre position (TDC), when the indicated temperature is less than a target temperature for combustion; and

close on completion of the return stroke of the combustion piston, as the combustion piston reaches its top dead centre position (TDC), when the indicated temperature is equal to or greater than the target temperature for combustion.

27. A method of operating a split cycle internal combustion engine, the engine comprising:

a combustion cylinder accommodating a combustion piston; and

a compression cylinder accommodating a compression piston and being arranged to provide compressed fluid to the combustion cylinder;

the method comprising:

receiving an indication of a parameter associated with the combustion cylinder and/or a fluid associated therewith and;

controlling an exhaust valve of the combustion cylinder in dependence in the indicated parameter to cause the exhaust valve to:

close during the return stroke of the combustion piston, before the combustion piston has reached its top dead centre position, when the indicated parameter is less than a target value for the parameter; and

close on completion of the return stroke of the combustion piston, as the combustion piston reaches its top dead centre position, when the indicated parameter is equal to or greater than the target value for the parameter,

wherein the indication of a parameter is an indication of a temperature associated with the combustion cylinder and/or a fluid associated therewith, and the target value for the parameter is a target temperature for combustion.