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(54) **INTERNAL COMBUSTION ENGINE**

(57) A heat-insulating thin layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of a base material constituting the combustion chamber comprises a first heat-insulating material and a second heat-insulating material. The second heat-insulating material has a thermal conductivity not higher than that of the base material, and the first heat-insulating material has a thermal conductivity and a heat capacity per unit volume lower than those of the base material and also has a thermal conductivity and a heat capacity per unit volume lower than those of the second heat-insulating material. The first heat-insulating material having a low thermal conductivity and a low heat capacity per unit volume is mixed into the second heat-insulating material having high heat resistance and high strength. Thus, the first heat-insulating material can be protected against a high-temperature, high-pressure gas present in the combustion chamber.

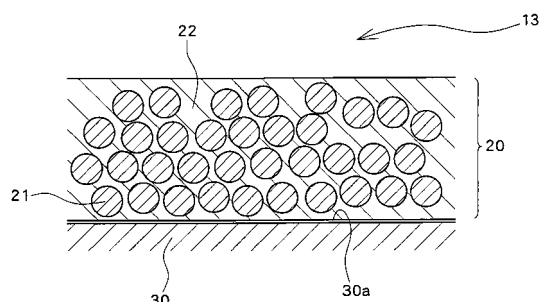


FIG. 2

Description

TECHNICAL FIELD

[0001] The present invention relates to an internal combustion engine, and more particularly to an internal combustion engine having a heat-insulating layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of at least a part of a base material which forms the combustion chamber.

BACKGROUND ART

[0002] To improve the thermal efficiency of an internal combustion engine, there is proposed a technology of forming a heat-insulating layer on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of at least a part of a base material forming the combustion chamber (e.g., Nonpatent References 1 and 2 given below). According to the Nonpatent References 1 and 2, a single-material heat-insulating layer made of ceramic (zirconia) having low thermal conductivity is formed on the top face of a piston in order to improve the thermal efficiency by reducing the heat transfer from the gas in the combustion chamber to the piston.

[0003] A heat loss Q [W] within the cylinder of the internal combustion engine can be expressed by a formula (1) given below, by using a heat transfer coefficient h [$W/(m^2 \cdot K)$] based on the pressure and gas flow in the cylinder, a surface area A [m^2] in the cylinder, an in-cylinder gas temperature T_g [K], and a temperature T_{wall} [K] of a wall surface, which faces (contacts the gas in the cylinder) the interior of the cylinder.

[0004]

$$Q = A \times h \times (T_g - T_{wall}) \quad (1)$$

[0005] In one cycle of the internal combustion engine, the in-cylinder gas temperature T_g changes momentarily, but the value $(T_g - T_{wall})$ in the formula (1) can be lowered and the heat loss Q can be reduced by varying the wall surface temperature T_{wall} momentarily to follow the in-cylinder gas temperature T_g .

[0006] In order to vary the wall surface temperature T_{wall} to follow the in-cylinder gas temperature T_g , the heat-insulating layer to be formed on the wall surface, which faces the interior of the combustion chamber, is desired to have low thermal conductivity and a low heat capacity per unit volume. However, even if the single-material heat-insulating layer made of ceramic (e.g., zirconia) is formed on the wall surface which faces the interior of the combustion chamber, the thermal conductivity and heat capacity per unit volume are not sufficiently low. As a result, the followability of the wall surface temperature T_{wall} to the in-cylinder gas temperature T_g lowers and an effect of reducing the heat loss Q becomes insufficient.

[0007] Some single materials have a thermal conductivity and a heat capacity per unit volume lower than those of ceramic (e.g., zirconia), but many of them, such as resins and foams, are low in heat resistance and strength and do not have sufficient heat resistance and strength to resist the high-temperature, high-speed gas flow and the high pressure found in the cylinder of the internal combustion engine.

[0008]

Patent Reference 1: Pamphlet of (PCT) International Publication No.89/03930

Patent Reference 2: US Patent No. 4495907

Patent Reference 3: US Patent No. 5820976

Nonpatent Reference 1 : Gerhard Woschni, et. al., "Heat Insulation of Combustion Chamber Walls - A Measure to Decrease the Fuel Combustion of I. C. Engines?", SAE Paper 870339, Society of Automotive Engineers, 1987

Nonpatent Reference 2: Victor W. Wong, et. al., "Assessment of Thin Thermal Barrier Coatings for I.C. Engines", SAE Paper 950980, Society of Automotive Engineers, 1995

DISCLOSURE OF THE INVENTION

[0009] The present invention provides an internal combustion engine according to the invention which improves thermal efficiency by improving the followability of the combustion chamber wall surface temperature to the in-cylinder gas temperature.

[0010] According to an aspect of the invention, there is provided an internal combustion engine having a heat-insulating layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of at least a part of a base material forming the combustion chamber, wherein the heat-insulating layer comprises a first

heat-insulating material which has a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than that of the base material, and a second heat-insulating material which has a thermal conductivity not higher than that of the base material and protects the first heat-insulating material against a gas in the combustion chamber, and the first heat-insulating material has a thermal conductivity lower than that of the second heat-insulating material and a heat capacity per unit volume lower than that of the second heat-insulating material.

[0011] According to the invention, the first heat-insulating material is protected by the second heat-insulating material from the gas in the combustion chamber, so that for the first heat-insulating material, a heat-insulating material having sufficiently low thermal conductivity and a sufficiently low heat capacity per unit volume can be selected without a restriction that adequate heat resistance and pressure resistance must be secured against the gas in the combustion chamber, and the thermal conductivity and heat capacity per unit volume of the entire heat-insulating layer can also be decreased sufficiently. As a result, the followability of the combustion chamber wall surface temperature to the in-cylinder gas temperature can be improved, and the thermal efficiency of the internal combustion engine can be improved. The first heat-insulating material can be constituted of one type of heat-insulating material and can also be constituted of multiple types of heat-insulating materials. Further, the second heat-insulating material can also be constituted of one type of heat-insulating material or multiple types of heat-insulating materials.

[0012] According to an aspect of the present invention, the first heat-insulating material is preferably mixed into the second heat-insulating material. According to this aspect, the second heat-insulating material, into which the first heat-insulating material is mixed, is formed into a fibrous form, and the second heat-insulating material formed into the fibrous form is preferably carpeted in plural numbers on the wall surface. According to this aspect, the mixing proportion of the first heat-insulating material is preferably variable depending on a position within the second heat-insulating material. According to this aspect, the first heat-insulating material is preferably arranged regularly within the second heat-insulating material. According to this aspect, the first heat-insulating material is preferably a heat-insulating material having a hollow structure, and the first heat-insulating material preferably has a multilayer structure.

[0013] According to an aspect of the present invention, preferably, the first heat-insulating material is formed on the wall surface, and the second heat-insulating material is formed on the first heat-insulating material to cover the same. Here, the first heat-insulating material can be directly bonded to or coated on the wall surface, and the first heat-insulating material can also be bonded to or coated on the wall surface with the intervention of an intermediate layer such as an adhesive layer. The second heat-insulating material can also be directly bonded to or coated on the first heat-insulating material, and the second heat-insulating material can also be bonded to or coated on the first heat-insulating material with the intervention of an intermediate layer such as an adhesive layer. According to this aspect, the second heat-insulating material is preferably provided with protruded portions which are protruded toward the first heat-insulating material.

[0014] According to an aspect of the present invention, the second heat-insulating material is preferably a shell-like heat-insulating material which contains therein the first heat-insulating material.

[0015] According to an aspect of the present invention, the first heat-insulating material and the second heat-insulating material are preferably arranged alternately in the thickness direction of the heat-insulating layer.

[0016] According to an aspect of the present invention, the second heat-insulating material preferably has a heat resistance temperature which is higher than that of the first heat-insulating material. According to an aspect of the present invention, the second heat-insulating material preferably has strength higher than that of the first heat-insulating material.

[0017] According to an aspect of the present invention, the second heat-insulating material preferably has a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than or substantially equal to that of the base material.

[0018] According to an aspect of the invention, there is provided an internal combustion engine having a heat-insulating layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion chamber, of at least a part of a base material which forms the combustion chamber, wherein the heat-insulating layer is constituted to include a heat-insulating material which has a large number of bubbles formed within a material having a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than or substantially equal to that of the base material.

[0019] According to the invention, the thermal conductivity and heat capacity per unit volume of the entire heat-insulating layer can be lowered sufficiently. As a result, the followability of the combustion chamber wall surface temperature to the in-cylinder gas temperature can be improved, and the thermal efficiency of the internal combustion engine can be improved.

BRIEF DESCRIPTION OF THE DRAWINGS

[0020]

FIG. 1 is a diagram showing a schematic structure of the internal combustion engine according to an embodiment

of the invention.

FIG. 2 is a diagram showing an example structure of a heat-insulating thin layer 20.

FIG. 3A is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 3B is a diagram showing an example structure of a heat-insulating material 21.

FIG. 3C is a diagram showing another example structure of the heat-insulating material 21.

FIG. 4 is a diagram showing example waveforms when a combustion chamber wall surface temperature T_{wall} is varied with respect to a crank angle.

FIG. 5 is a diagram showing the calculated results after examining a fuel consumption improvement effect when swing range ΔT of the combustion chamber wall surface temperature T_{wall} is varied.

FIG. 6A is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 6B is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 6C is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 7 is a diagram showing the calculated results after examining the change of the combustion chamber wall surface temperature T_{wall} in one cycle while varying thickness t_1 of the heat-insulating thin layer 20.

FIG. 8 is a diagram showing characteristics of swing range ΔT of the combustion chamber wall surface temperature T_{wall} with respect to the thickness t_1 of the heat-insulating thin layer 20.

FIG. 9 is a diagram showing the calculated results after examining the change of the combustion chamber wall surface temperature T_{wall} in one cycle while varying thickness t_0 of a heat-insulating thin layer (single material).

FIG. 10 is a diagram showing characteristics of swing range ΔT of the combustion chamber wall surface temperature T_{wall} with respect to the thickness t_0 of the heat-insulating thin layer (single material).

FIG. 11 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 12 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 13 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 14 is a diagram showing the calculated results after examining the change of the combustion chamber wall surface temperature T_{wall} in one cycle while varying thickness t_2 of the heat-insulating material 21.

FIG. 15 is a diagram showing characteristics of the swing range ΔT of the combustion chamber wall surface temperature T_{wall} with respect to the thickness t_2 of the heat-insulating material 21.

FIG. 16 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 17 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 18 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 19 is a diagram showing another example structure of the heat-insulating thin layer 20.

FIG. 20 is a diagram showing another example structure of the heat-insulating thin layer 20.

MODE FOR CARRYING OUT THE INVENTION

[0021] Embodiments of the invention are described in detail below with reference to the drawings.

[0022] FIG. 1 is a diagram showing a schematic structure of an internal combustion engine 1 according to an embodiment of the invention, schematically showing an internal structure of a cylinder 11 as viewed from a direction perpendicular to its axial direction. The internal combustion engine (engine) 1 includes a cylinder block 9 and a cylinder head 10, and the cylinder 11 is configured of the cylinder block 9 and the cylinder head 10. The cylinder 11 takes therein a piston 12 which moves reciprocally in its axial direction. The space surrounded by a top face 12a of the piston 12, an inner wall surface 9a of the cylinder block 9, and a bottom face 10a of the cylinder head 10 forms a combustion chamber 13. The cylinder head 10 is formed with an intake port 14 communicated with the combustion chamber 13, and an exhaust port 15 communicated with the combustion chamber 13. In addition, an intake valve 16 which opens and closes the boundary between the intake port 14 and the combustion chamber 13 and an exhaust valve 17 which opens and closes the boundary between the exhaust port 15 and the combustion chamber 13 are also disposed. The cylinder block 9 is formed with a cooling water jacket 18, and cooling water is fed to the cooling water jacket 18 to cool the internal combustion engine 1.

[0023] For convenience of explanation, components such as a fuel injector, a spark plug, and the like are omitted from FIG. 1. The internal combustion engine 1 according to this embodiment may be a compression self-ignition type internal combustion engine such as a diesel engine, or a spark-ignited internal combustion engine such as a gasoline engine. In the compression self-ignition type internal combustion engine, for example, when the piston 12 approaches compression top dead center, a fuel is injected from the fuel injector into the combustion chamber 13, and the fuel in the combustion chamber 13 self-ignites and burns. In the spark-ignited internal combustion engine, the engine ignites an air-fuel mixture in the combustion chamber 13 by a spark discharge caused by a spark plug at the ignition timing, and the air-fuel mixture in the combustion chamber 13 undergoes flame propagation combustion. The gas in the combustion chamber 13 is discharged to the exhaust port 15 during an exhaust stroke.

[0024] In this embodiment, a heat-insulating thin layer 20, which inhibits the heat transfer from the gas in the combustion

chamber 13 to a base material, is formed on a wall surface, which faces (is opposed to) the interior of the combustion chamber 13, of at least a part of the base material forming the combustion chamber 13. As the base material forming the combustion chamber 13, the cylinder block (cylinder liner) 9, the cylinder head 10, the piston 12, the intake valve 16, and the exhaust valve 17 can be listed. The wall surface which faces the interior of the combustion chamber 13 can be at least one of the cylinder block inner wall surface (cylinder liner inner wall surface) 9a, the cylinder head bottom face 10a, the piston top face 12a, an intake valve top face (bottom surface of an umbrella portion) 16a and an exhaust valve top face (bottom surface of an umbrella portion) 17a. FIG. 1 shows an example where the heat-insulating thin layer 20 is formed on the cylinder block inner wall surface 9a, the cylinder head bottom face 10a, the piston top face 12a, the intake valve top face 16a, and the exhaust valve top face 17a. It is not essential to form the heat-insulating thin layer 20 on all of the cylinder block inner wall surface 9a, the cylinder head bottom face 10a, the piston top face 12a, the intake valve top face 16a, and the exhaust valve top face 17a. In other words, the heat-insulating thin layer 20 can be formed on at least one of the cylinder block inner wall surface 9a, the cylinder head bottom face 10a, the piston top face 12a, the intake valve top face 16a, and the exhaust valve top face 17a.

[0025] In this embodiment, the heat-insulating thin layer 20 is constituted to contain multiple types of heat-insulating materials each having different thermal conductivity and heat capacity per unit volume. Each of the multiple types of heat-insulating materials has a thermal conductivity not higher than that of the base material and a heat capacity per unit volume lower than or substantially equal to that of the base material. Example structures of the heat-insulating thin layer 20 are described below.

"EMBODIMENT 1"

[0026] FIG. 2 is a sectional view showing an example structure of the heat-insulating thin layer 20. In the example structure (EMBODIMENT 1) shown in FIG. 2, the heat-insulating thin layer 20 formed on a wall surface 30a, which faces the interior of the combustion chamber 13, of a base material 30 which forms the combustion chamber 13 is formed to include a large number of heat-insulating materials (first heat-insulating materials) 21 assuming a granular form and a heat-insulating material (second heat-insulating material) 22 assuming a layer form. Here, the base material 30 may be the cylinder block (cylinder liner) 9, the cylinder head 10, the piston 12, the intake valve 16, or the exhaust valve 17. In other words, the wall surface 30a of the base material 30 may be the cylinder block inner wall surface (cylinder liner inner wall surface) 9a, the cylinder head bottom face 10a, the piston top face 12a, the intake valve top face 16a, or the exhaust valve top face 17a.

[0027] The heat-insulating material 22 has a thermal conductivity not higher than (or lower than) that of the base material 30 and a heat capacity per unit volume lower than or substantially equal to that of the base material 30. Meanwhile, the heat-insulating material 21 has a thermal conductivity lower than that of the base material 30 and a heat capacity per unit volume lower than that of the base material 30, and also a thermal conductivity lower than that of the heat-insulating material 22 and a heat capacity per unit volume lower than that of the heat-insulating material 22. The heat-insulating material 22 is coated on or bonded to the wall surface 30a of the base material 30 and in contact with the gas within the combustion chamber 13. The heat-insulating material 22 has heat resistance and pressure resistance against a high-temperature, high-pressure gas present in the combustion chamber 13, a heat resistance temperature higher than that of the heat-insulating material 21, and strength higher than that of the heat-insulating material 21. Meanwhile, since the large number of heat-insulating materials 21 are mixed into the heat-insulating material 22, they are not in contact with the gas in the combustion chamber 13. Here, the heat-insulating material 22 has a function to suppress the heat transfer from the gas in the combustion chamber 13 to the base material 30 and also a function as a protective material to protect the heat-insulating material 21 against the high-temperature, high-pressure gas present in the combustion chamber 13. The heat-insulating material 22 also has a function as an adhesive material to connect the large number of heat-insulating materials 21. Meanwhile, the heat-insulating material 21 has a function to lower a thermal conductivity and a heat capacity per unit volume of the entire heat-insulating thin layer 20. Although not shown in FIG. 2, a thin intermediate material may be formed between the heat-insulating thin layer 20 (heat-insulating material 22) and the base material 30 to strengthen the coating or the bonding between the heat-insulating thin layer 20 (heat-insulating material 22) and the base material 30. As a method to strengthen the coating or the bonding between the heat-insulating thin layer 20 and the base material 30, it is considered to reinforce the bonding between materials or to prevent peeling due to a thermal shock by making the heat-insulating thin layer 20 and the base material 30 have the same thermal expansion coefficient. Therefore, as the intermediate material, there is preferably used an intermediate material for strengthening the bonding between the heat-insulating thin layer 20 and the base material 30 or an intermediate material for reducing the difference in linear expansion coefficient between the heat-insulating thin layer 20 and the base material 30. Preferably, the intermediate material has a thermal conductivity and a heat capacity per unit volume nearly equal to those of the heat-insulating material 21 or the heat-insulating material 22. FIG. 2 shows an example where the heat-insulating thin layer 20 (heat-insulating material 22) has a smoothed surface and the heat-insulating materials 21 are mixed in a large number into the heat-insulating material 22, but as shown in, for example, FIG. 3A, the heat-insulating

materials 21 may be mixed into the heat-insulating material 22 to provide a state where some irregularities are formed on the surface of the heat-insulating thin layer 20 (heat-insulating material 22).

[0028] Specific examples of the heat-insulating material 22 include, for example, solid ceramic such as zirconia (ZrO_2); silicon; titanium or zirconium; an organic silicon compound containing carbon, oxygen, and silicon; and ceramic fibers having high strength and high heat resistance. In addition, a plurality of such materials can be combined and used for the heat-insulating material 22. The ceramic (zirconia) has a thermal conductivity λ of about 2.5 [W/(m·K)], a heat capacity per unit volume ρC of about 2500×10^3 [J/(m³·K)], a heat resistance temperature T_m of about 2700 [°C], and a strength (bending strength) σ of about 1470 [MPa]. For the ceramic, here instead of zirconia, cordierite (a thermal conductivity λ of about 4 [W/(m·K)], and heat capacity per unit volume ρC of about 1900×10^3 [J/(m³·K)]) can also be used, and alumina-based or silicon nitride-based ceramic can also be used in a partly mixed form. The ceramic fibers here can be constituted to contain, for example, silicon, titanium, or zirconium, and have a thermal conductivity λ of about 2.5 [W/(m·K)], a heat capacity per unit volume ρC of about 1600×10^3 [J/(m³·K)], a heat resistance temperature T_m of about 1300 [°C], and a strength (tensile strength) σ of about 3300 [MPa].

[0029] Meanwhile, specific examples of the heat-insulating materials 21 include, for example, hollow ceramic beads, hollow glass beads, a heat-insulating material having a microporous structure and mainly consisting of silica (silicon dioxide, SiO_2), or silica aerogel. In addition, such materials can be combined in plural numbers and used for the heat-insulating materials 21. The hollow ceramic beads have a thermal conductivity λ of about 0.1 [W/(m·K)], a heat capacity per unit volume ρC of about 300×10^3 [J/(m³·K)], a heat resistance temperature T_m of about 1600 [°C], and a strength (tensile strength) σ of about 70 [MPa]. Here, the heat-insulating material having a microporous structure can be used by partly mixing titanium dioxide (TiO_2) in addition to the main component silica, and has a thermal conductivity λ of about 0.04 [W/(m·K)], a heat capacity per unit volume ρC of about 400×10^3 [J/(m³·K)] and a heat resistant temperature T_m of about 1025 [°C], and very low strength. The silica aerogel has a thermal conductivity λ of about 0.02 [W/(m·K)], a heat capacity per unit volume ρC of about 190×10^3 [J/(m³·K)], and a heat resistant temperature T_m of about 1200 [°C], and its strength is very low.

[0030] An example structural of the heat-insulating materials 21 is shown in FIGs. 3B and 3C. In the example of FIG. 3B, the heat-insulating material 21 is a heat-insulating material having a hollow structure in which a hollow portion 21a is formed by the decompressed air or inert gas within a shell portion 21b made of zirconia, glass, or the like. Further, in the example shown in FIG. 3C, since a coat layer 21c is formed on the exterior of the shell portion 21b made of glass, the heat-insulating material 21 has a multilayer structure consisting of the shell portion 21b and the coat layer 21c. For the coat layer 21c, it is preferable to use a material, such as zirconia, having a low thermal conductivity nearly equal to that of the shell portion (glass) 21b, and its thickness is preferably thin, to about several micrometers. Covering the shell portion (glass) 21b with the coat layer (zirconia) 21c enables an increase in the heat resistance temperature of the heat-insulating material 21. When bolosilicate glass is used for the shell portion 21b in the example of the heat-insulating material 21 shown in FIG. 3B, thermal conductivity λ is about 0.07 [W/(m·K)], and heat capacity per unit volume ρC is about 220×10^3 [J/(m³·K)]. When the bolosilicate glass is used for the shell portion 21b and zirconia is used for the coat layer 21c in the example of the heat-insulating material 21 shown in FIG. 3C, thermal conductivity λ is about 0.35 [W/(m·K)], and heat capacity per unit volume ρC is about 512×10^3 [J/(m³·K)].

[0031] Specific examples of the material of the base material 30 include, for example, iron (steel), aluminum or aluminum alloy, or ceramic. Iron has a thermal conductivity λ of about 80.3 [W/(m·K)] and a heat capacity per unit volume ρC of about 3500×10^3 [J/(m³·K)]. Aluminum has a thermal conductivity λ of about 193 [W/(m·K)] and a heat capacity per unit volume ρC of about 2400×10^3 [J/(m³·K)] (substantially equivalent to that of zirconia). For example, when iron (steel) is used for the base material 30, the ceramic (zirconia) for the heat-insulating material 22, and the hollow ceramic beads for the heat-insulating material 21, the heat-insulating material 22 has a thermal conductivity and a heat capacity per unit volume lower than those of the base material 30, and the heat-insulating material 21 has a thermal conductivity and a heat capacity per unit volume lower than those of the heat-insulating material 22. Also, the heat-insulating material 22 has a heat resistance temperature and strength higher than those of the heat-insulating material 21.

[0032] As described above, the in-cylinder gas temperature T_g changes momentarily during a cycle of the internal combustion engine, but when the combustion chamber wall surface temperature T_{wall} is varied to follow the in-cylinder gas temperature T_g , the value $(T_g - T_{wall})$ in the formula (1) can be reduced, along with the heat loss Q in the cylinder. As a result, the thermal efficiency of the internal combustion engine can be improved, along with fuel consumption. Here, the calculated results obtained by examining an influence of fuel consumption on a fluctuation range (swing range) ΔT of the combustion chamber wall surface temperature T_{wall} are shown in FIGs. 4 and 5. FIG. 4 shows example waveforms in a case where the combustion chamber wall surface temperature T_{wall} is varied against crank angle (a compression top dead center of 0°), and waveforms when the swing range ΔT of the combustion chamber wall surface temperature T_{wall} in one cycle is 500°C, 1000°C, and 1500°C are shown in comparison with that of a case (base condition) where the combustion chamber wall surface temperature T_{wall} does not change substantially. In FIG. 4, a waveform when $\Delta T = 1500^\circ\text{C}$ is equivalent to a waveform in which the combustion chamber wall surface temperature T_{wall} is varied to substantially follow the in-cylinder gas temperature T_g . FIG. 5 shows the calculated results obtained by examining the

fuel consumption improvement effect when the swing range ΔT of the combustion chamber wall surface temperature T_{wall} in one cycle is varied to 500°C, 1000°C, and 1500°C as shown in FIG. 4. For calculation, the operation conditions of the internal combustion engine (diesel engine) are determined to be an engine rotational speed of 2100 rpm, and an indicated mean effective pressure P_i of 1.6 MPa. In FIG. 5, the circle mark (o) indicates the results when the combustion chamber wall surface temperature (base wall temperature) in the intake stroke barely is increased against the wall surface temperature under the base conditions, and the triangle mark (Δ) indicates the results when the combustion chamber wall surface temperature (base wall temperature) in the intake stroke is increased by 100°C against the wall surface temperature under the base conditions. As shown in FIG. 5, the fuel consumption improvement effect can be improved by increasing the swing range ΔT of the combustion chamber wall surface temperature T_{wall} . However, even if the swing range ΔT of the combustion chamber wall surface temperature T_{wall} increases, the fuel consumption improvement effect decreases if the base wall temperature increases. Therefore, in order to further improve the fuel consumption improvement effect, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} is preferably increased without substantially increasing the base wall temperature. The heat insulating rate [%] indicated on the horizontal axis of FIG. 5 is expressed by a formula (2) given below using the amount of heat loss Q_s under the base conditions and the amount of heat loss Q_b when the wall surface temperature T_{wall} is varied.

[0033]

$$\text{Heat insulating rate} = (Q_b - Q_s) / Q_b \times 100 \quad [\%] \quad (2)$$

[0034] To increase the swing range ΔT of the combustion chamber wall surface temperature T_{wall} without substantially increasing the base wall temperature, the heat-insulating layer formed on the wall surface which faces the interior of the combustion chamber preferably has a low thermal conductivity and a low heat capacity per unit volume. However, as described above, many of the single materials having a low thermal conductivity and a low heat capacity per unit volume are low in heat resistance and strength and do not have sufficient heat resistance and strength to resist the high-temperature, high-speed gas flow and the high pressure in the cylinder of the internal combustion engine. Meanwhile, the single material having sufficiently high heat resistance and strength to resist the high-temperature, high-speed gas flow and the high pressure does not have sufficiently low thermal conductivity and heat capacity per unit volume, and the swing range ΔT of the combustion chamber wall surface temperature T_{wall} decreases. In addition, heat is easily transferred to and accumulated in the heat-insulating layer, and the base wall temperature increases. When the base wall temperature increases, the following adverse effects (1) to (5) occur.

- (1) Intake gas receives heat and expands during the intake stroke, charging efficiency lowers, and power drops.
- (2) Operation gas receives heat during the compression stroke to increase the in-cylinder pressure, negative work increases in the compression stroke, and fuel consumption decreases.
- (3) Average gas temperature increases by receiving heat during the intake stroke and compression stroke, a specific heat ratio of the in-cylinder gas decreases, and cycle efficiency lowers.
- (4) Gas flow in the cylinder is laminarized by a temperature increase of compression end gas, a degree of mixing between fuel and air decreases during the air-fuel mixture formation process, and a soot generation amount increases.
- (5) Combustion temperature is increased as the compression end gas temperature increases, and a generation amount of nitrogen oxide (NO_x) increases.

[0035] Meanwhile, in the example structure shown in FIG. 2, the heat-insulating materials 21, which are low in thermal conductivity and heat capacity per unit volume, are mixed into the heat-insulating material 22 having high heat resistance and high strength, and the heat-insulating materials 21 can be protected against a high-temperature, high-pressure gas present in the combustion chamber 13. Therefore, for the heat-insulating materials 21, a degree of freedom of selection of the heat-insulating material, which is emphasized to have a low thermal conductivity and a low heat capacity per unit volume, is increased without a restriction that the adequate heat resistance and pressure resistance must be secured against the high-temperature, high-pressure gas present in the combustion chamber 13, and the heat-insulating material, which has sufficiently low thermal conductivity and a heat capacity per unit volume can be used. Therefore, the thermal conductivity and heat capacity per unit volume of the entire heat-insulating thin layer 20 can also be decreased sufficiently. Thus, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased while suppressing an increase in the base wall temperature, and the followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the heat loss Q of the internal combustion engine 1 is decreased, so that thermal efficiency can be improved, along with fuel consumption. In addition, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be adjusted by adjusting the thermal conductivity

and heat capacity per unit volume of the heat-insulating materials 21, 22 by selecting materials for the heat-insulating materials 21, 22. In addition, the exhaust temperature can also be increased, so that the exhaust emission can be decreased by enhancing the activity of a catalyst which is disposed downstream of the engine, and a supercharged engine based on a turbo-charger can further use exhaust energy more effectively. Specially, since a highly supercharged engine which is aimed at reducing exhaust emissions and increasing thermal efficiency has the exhaust temperature lowered notably by the decrease of the combustion temperature, the effect of increasing the exhaust temperature according to this embodiment is enhanced further.

[0036] In the example structure shown in FIG. 2, a volume percent of the heat-insulating materials 21 occupying the heat-insulating thin layer 20; namely, a mixing proportion of the heat-insulating materials 21, can also be varied (distributed) according to the positions within the heat-insulating material 22. For example, the heat-insulating materials 21 are made to have irregular grain sizes and varied depending on the positions within the heat-insulating material 22, so that the mixing proportion of the heat-insulating materials 21 can be varied depending on the positions within the heat-insulating material 22. Further, the number per unit volume of the mixed heat-insulating materials 21 is also varied depending on the positions within the heat-insulating material 22, and the mixing proportion of the heat-insulating materials 21 can be varied depending on the positions within the heat-insulating material 22. By configuring as described above, the thermal conductivity and heat capacity per unit volume of the entire heat-insulating thin layer 20 can be distributed, and the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be varied (distributed) depending on the positions on the combustion chamber wall surface.

[0037] Alternatively, as shown in, for example, FIG. 6A, a large number of heat-insulating materials 21 can also be arranged regularly within the heat-insulating material 22. In the example shown in FIG. 6A, the heat-insulating materials 21 having a single particle diameter are arranged at regular intervals in the thickness direction and in-plane direction (vertical direction with respect to thickness direction) of the heat-insulating thin layer 20. By regularly arranging the heat-insulating materials 21 within the heat-insulating material 22, the heat-insulating materials 21 and the heat-insulating material 22 are uniformly distributed; i.e., the heat-insulating materials 21 can be prevented from becoming present in a locally biased form in the thickness direction and in-plane direction of the heat-insulating thin layer 20. As a result, the heat-insulating thin layer 20 having uniform thermophysical properties (a low thermal conductivity and a low heat capacity) can be realized. In addition, since portions where the heat-insulating material 22 becomes locally thin (fine) can be avoided, the probability of existence of a structural defect that affects the strength of the heat-insulating thin layer 20 can be suppressed, and the strength of the heat-insulating thin layer 20 can be enhanced. The heat-insulating materials 21 can be regularly arranged within the heat-insulating material 22 by a conventional technology such as that described in Brian T. Holland, et. al., Science, 281, 538-540 (1998). A deposit of regularly arranged spherical particles can be obtained by slowly filtering a solution such as water in which monodisperse spherical particles are dispersed. Therefore, this method can be used to realize the structure shown in FIG. 6A by depositing the heat-insulating materials 21 having a single particle diameter, flowing the heat-insulating material 22 (binder layer) in a liquid state into the deposit, and firing.

[0038] In the example structure shown in FIG. 2, the heat-insulating materials 21 are mixed into the heat-insulating material 22 to form the heat-insulating thin layer 20, but as shown in FIG. 6B, a large number of bubbles 31 can also be formed instead of the heat-insulating materials 21 within the heat-insulating material 22. In the example structure shown in FIG. 6B, the heat-insulating thin layer 20 is constituted to include a heat-insulating material (foamed heat-insulating material) 22 which has a large number of bubbles 31 formed within a material having a thermal conductivity lower than that of the base material 30 and a heat capacity per unit volume lower than or substantially equal to that of the base material 30. The bubbles 31 (air) have a thermal conductivity λ of about 0.02 [W/(m·K)], and a heat capacity per unit volume ρC of about 2.3×10^3 [J/(m³·K)]. The material forming the heat-insulating material 22 has sufficient heat resistance and pressure resistance against the high-temperature, high-pressure gas present in the combustion chamber 13. A specific example of the material (bubbles 31 formed therein) forming the heat-insulating material 22 is similar to the specific example of the heat-insulating material 22 in the example structure shown in FIG. 2. For example, when iron (steel) is used for the base material 30 and ceramic (zirconia) is used for the material which forms the heat-insulating material 22, the thermal conductivity and heat capacity per unit volume of the material forming the heat-insulating material 22 become lower than those of the base material 30 and higher than those of the bubbles 31.

[0039] In the example structure shown in FIG. 6B, since the thermal conductivity and heat capacity per unit volume of the entire heat-insulating thin layer 20 can be lowered sufficiently, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased while an increase in the base wall temperature is suppressed, and followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the thermal efficiency of the internal combustion engine 1 can be improved. In the example structure shown in FIG. 6B, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can also be varied depending on the positions of the combustion chamber wall surface by, for example, making the bubbles 31 have irregular diameters, and varying a volume percent of the bubbles 31 (formed percent of the bubbles 31) occupying the heat-insulating thin layer 20 depending on the positions within the heat-insulating material 22. Alternatively, as shown in, for example, FIG. 6C, a large number of bubbles 31 can also be arranged regularly within the heat-insulating thin

layer 20 (heat-insulating material 22). In the example shown in FIG. 6C, bubbles 31 having a single particle diameter are arranged at regular intervals in the thickness direction and in-plane direction (vertical direction with respect to thickness direction) of the heat-insulating thin layer 20. By regularly arranging the bubbles 31 within the heat-insulating material 22, the heat-insulating thin layer 20 having uniform thermophysical properties (low thermal conductivity and low heat capacity) can be realized, and the strength of the heat-insulating thin layer 20 can also be enhanced. The regular arrangement of the bubbles 31 within the heat-insulating material 22 can also be realized by using, for example, a known technology such as that described in Brian T. Holland, et. al., Science, 281, 538-540 (1998); namely, a method of obtaining a deposit of regularly arranged spherical particles by slowly filtering a solution such as water in which mono-disperse spherical particles are dispersed. At that time, as the spherical particles, a material (e.g., resin beads) which is gasified by firing is used. The resin beads having a single particle diameter are deposited, the heat-insulating material 22 (binder layer) in a liquid state is flowed into the deposit, and firing is performed. The resin beads are gasified and burnt off by heating to not less than several hundreds of degrees when firing to form the bubbles 31 at the locations where the resin beads were present. Thus, the structure shown in FIG. 6C can be realized.

[0040] Resultsofanalysis (numerical calculation) conducted by the inventors of the invention are described below. In a case where the internal combustion engine 1 is a supercharged direct-injection diesel engine, the example structure shown in FIG. 6B was examined by calculating changes of the combustion chamber wall surface temperature T_{wall} in one cycle while the thickness t_1 of the heat-insulating thin layer 20 (heat-insulating material 22) was varied. The calculated results are shown in FIGs. 7 and 8. FIG. 7 shows the waveforms of the combustion chamber wall surface temperature T_{wall} with respect to the crank angle (a compression top dead center of 0°) when the heat-insulating thin layer 20 has thickness t_1 of 10 μm , 50 μm , 100 μm , 200 μm , and 500 μm . FIG. 8 shows characteristics of the swing range ΔT of the combustion chamber wall surface temperature T_{wall} to the thickness t_1 of the heat-insulating thin layer 20.

[0041] In addition, as a comparative example, a structure in which the heat-insulating thin layer is made of a single material was examined by calculating changes of the combustion chamber wall surface temperature T_{wall} in one cycle while the thickness t_0 of the heat-insulating thin layer (single material) was varied. The calculated results are shown in FIGs. 9 and 10. FIG. 9 shows the waveforms of the combustion chamber wall surface temperature T_{wall} with respect to the crank angle (a compression top dead center of 0°) when the heat-insulating thin layer has thickness t_0 of 10 μm , 50 μm , 100 μm and 500 μm . FIG. 10 shows characteristics of the swing range ΔT of the combustion chamber wall surface temperature T_{wall} to the thickness t_0 of the heat-insulating thin layer.

[0042] To calculate the combustion chamber wall surface temperature T_{wall} , it is determined that a displacement of one cylinder is 550 cc, a compression ratio is 16, an engine rotational speed is 2000 rpm, a fuel injection amount is 50 mm^3/st , and an indicated mean effective pressure is 1.6 MPa. Also, in the structure example shown in FIG. 6B, it is determined that the thermal conductivity λ and heat capacity per unit volume pC of a material forming the heat-insulating material 22 are $\lambda=2.5 \text{ [W/(m}\cdot\text{K)]}$ and $pC=2520 \times 10^3 \text{ [J/(m}^3\cdot\text{K)]}$ (equivalent to zirconia), and the volume percent occupied by bubbles 31 (air) in the heat-insulating thin layer 20 (heat-insulating material 22) is 80%. In the comparative example, it is determined that the thermal conductivity λ and heat capacity per unit volume pC of a single material (entire heat-insulating thin layer) constituting the heat-insulating thin layer are $\lambda=2.5 \text{ [W/(m}\cdot\text{K)]}$ and $pC=2520 \times 10^3 \text{ [J/(m}^3\cdot\text{K)]}$ (equivalent to zirconia).

[0043] In the comparative example, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} is a maximum of about 125°C (when $t_0=100 \mu\text{m}$), and the fuel consumption improvement effect is a maximum of about 2% (when $t_0=100 \mu\text{m}$), as shown in FIGs. 9 and 10. If the thickness t_0 of the heat-insulating thin layer is smaller than 100 μm , the swing range ΔT of the combustion chamber wall surface temperature T_{wall} decreases, and the fuel consumption improvement effect lowers and cannot be obtained substantially. Meanwhile, if the thickness t_0 of the heat-insulating thin layer is larger than 100 μm , the base wall temperature increases, and the fuel consumption improvement effect lowers and cannot be obtained substantially.

[0044] Meanwhile, in EMBODIMENT 1 (structure example shown in FIG. 6B), the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased substantially to about 550°C to 650°C , and the fuel consumption improvement effect can be increased substantially to about 7 to 8%, as shown in FIGs. 7 and 8. In the calculated results shown in FIGs. 7 and 8, when t_1 is in a range of 50 μm to 200 μm , the swing range ΔT of about 550°C to 650°C is obtained without substantially increasing the base wall temperature, and a fuel consumption improvement effect of about 7 to 8% can be obtained. Further, in case where $t_1=100 \mu\text{m}$, the swing range ΔT becomes maximum. Thus, it is confirmed by the structure of EMBODIMENT 1 that the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased substantially, and a fuel consumption improvement effect of about 7 to 8% can be obtained.

"EMBODIMENT 2"

[0045] FIGs. 11 and 12 are diagrams showing another example structure of the heat-insulating thin layer 20; FIG. 11 shows a diagram as viewed from a direction (the normal direction) agreeing with the normal of the wall surface 30a of the base material 30, and FIG. 12 shows its sectional view. In the following descriptions given in EMBODIMENT 2, like

components or components corresponding to those of EMBODIMENT 1 are denoted by like reference numerals, and repeated descriptions are omitted.

[0046] In the example structure (EXAMPLE 2) shown in FIGs. 11 and 12, the heat-insulating material 22 in which a large number of granular heat-insulating materials 21 are mixed is formed into a fibrous form. The heat-insulating material 22 formed into the fibrous form is carpeted in plural numbers on the wall surface 30a of the base material 30. FIG. 12 shows an example where the heat-insulating materials 22 assuming a fibrous form are stacked in plural numbers to form a multi-layer form. FIG. 11 shows an example where multiple heat-insulating materials 22 assuming a fibrous form are woven (interwoven) to form the heat-insulating thin layer 20. A specific example of the heat-insulating materials 21, 22 and the base material 30 is similar to that of EMBODIMENT 1. Although omitted from FIGs. 11 and 12, a thin intermediate material to strengthen the bonding between the heat-insulating material 22 and the base material 30 may be formed between the heat-insulating material 22 and the base material 30, and a thin intermediate material to strengthen the mutual bonding of the fibrous form heat-insulating materials 22 may be formed between the respective heat-insulating materials 22. Preferably, the intermediate material has thermal conductivity and heat capacity per unit volume nearly equal to those of the heat-insulating material 21 or the heat-insulating material 22.

[0047] In EMBODIMENT 2, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can also be increased while an increase in the base wall temperature is suppressed, and the followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the thermal efficiency of the internal combustion engine 1 can be improved. In EMBODIMENT 2, in the same manner as in EMBODIMENT 1, a large number of bubbles 31 can be formed instead of the heat-insulating material 21 within the fibrous formed heat-insulating material 22. In addition, in EMBODIMENT 2, in the same manner as in EMBODIMENT 1, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be varied depending on the positions on the combustion chamber wall surface by having, for example, the heat-insulating materials 21 (or bubbles 31) with irregular diameters and varying a volume percent of the heat-insulating materials 21 (or bubbles 31) in the heat-insulating thin layer 20 depending on the positions within the heat-insulating material 22.

"EMBODIMENT 3"

[0048] FIG. 13 is a sectional view showing another example structure of the heat-insulating thin layer 20. In the following descriptions given in EMBODIMENT 3, like components or components corresponding to those of EMBODIMENT 1 and 2 are denoted by like reference numerals, and repeated descriptions are omitted.

[0049] In the example structure (EMBODIMENT 3) shown in FIG. 13, a heat-insulating material 21 assuming a layer form is coated on or bonded to the wall surface 30a of the base material 30. Further, the heat-insulating material 22 assuming the layer form is formed on the heat-insulating material 21 to cover the surface of the heat-insulating material 21 by coating or bonding and brought into contact with the gas within the combustion chamber 13. Thus, the heat-insulating thin layer 20 has a multi-layer structure containing the heat-insulating materials 21, 22 assuming a layer form, and the heat-insulating material 22 becomes a layer positioned on the top of the heat-insulating material 21. A specific example of the heat-insulating materials 21, 22 and the base material 30 is similar to that in EMBODIMENT 1. A thin intermediate material, which is omitted from FIGs. 13, for strengthening coating and bonding between the heat-insulating material 21 and the base material 30 may be formed between the heat-insulating material 21 and the base material 30, or a thin intermediate material for strengthening coating and bonding between the heat-insulating material 21 and the heat-insulating material 22 may be formed between the heat-insulating material 21 and the heat-insulating material 22. Preferably, the intermediate material here has a thermal conductivity and a heat capacity per unit volume nearly equal to those of the heat-insulating material 21 or the heat-insulating material 22.

[0050] In EMBODIMENT 3, the heat-insulating material 21, which is low in thermal conductivity and heat capacity per unit volume, is covered with the heat-insulating material 22 having high heat resistance and high strength. Thus, the heat-insulating material 21 can be protected against the high-temperature, high-pressure gas present in the combustion chamber 13. Therefore, for the heat-insulating material 21, a heat-insulating material having a thermal conductivity and a heat capacity per unit volume which are sufficiently low can be selected without a restriction that the adequate heat resistance and pressure resistance must be secured against the high-temperature, high-pressure gas present in the combustion chamber 13, and the thermal conductivity and heat capacity per unit volume of the entire heat-insulating thin layer 20 can be decreased sufficiently. Therefore, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased while an increase in the base wall temperature is suppressed, and followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the thermal efficiency of the internal combustion engine 1 can be improved.

[0051] Results of analysis (numerical calculation) conducted by the inventors of the invention are described below. In a case where the internal combustion engine 1 is a supercharged direct-injection diesel engine, the example structure shown in FIG. 13 was examined by calculating changes of the combustion chamber wall surface temperature T_{wall} in one cycle while the thickness t_2 of the heat-insulating material 21 was varied. The calculated results are shown in FIGs.

14 and 15. FIG. 14 shows the waveforms of the combustion chamber wall surface temperature T_{wall} with respect to the crank angle (a compression top dead center of 0°), and waveforms when the heat-insulating material 21 has thickness t_2 of 10 μm , 50 μm , 100 μm , and 190 μm . The heat-insulating material 22 is determined to have a fixed thickness (10 μm). FIG. 15 shows characteristics of the swing range ΔT of the combustion chamber wall surface temperature T_{wall} to the thickness t_2 of the heat-insulating material 21.

[0052] To calculate the combustion chamber wall surface temperature T_{wall} , it is determined that a displacement of one cylinder was 550 cc, a compression ratio is 16, an engine rotational speed is 2000 rpm, a fuel injection amount is 50 mm^3/st , and an indicated mean effective pressure is 1.6 MPa. Also, it is determined that the thickness of the heat-insulating material 22 has a definite value of 10 μm , the thermal conductivity λ and heat capacity per unit volume ρC of the heat-insulating material 22 are $\lambda=2.5 [\text{W}/(\text{m}\cdot\text{K})]$ and $\rho C=2520 \times 10^3 [\text{J}/(\text{m}^3\cdot\text{K})]$ (equivalent to zirconia), and the thermal conductivity λ and heat capacity per unit volume ρC of the heat-insulating material 21 are $\lambda=0.04 [\text{W}/(\text{m}\cdot\text{K})]$ and $\rho C=400 \times 10^3 [\text{J}/(\text{m}^3\cdot\text{K})]$ (equivalent to a heat-insulating material having a microporous structure).

[0053] In the example structure shown in FIG. 13, as shown in FIGs. 14 and 15, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased substantially to about 420°C , and the fuel consumption improvement effect can be increased substantially to about 5%. In the calculated results shown in FIGs. 14 and 15, when t_2 falls within a range of 10 μm to 50 μm , the swing range ΔT of about 420°C is obtained, and when $t_1=10 \mu\text{m}$, the swing range ΔT of about 420°C is obtained without increasing the base wall temperature substantially, and a fuel consumption improvement effect of about 5% is obtained. When the thickness t_2 of the heat-insulating material 21 becomes 50 μm or more, the base wall temperature increases, and the fuel consumption improvement effect decreases to less than 5%.

"EMBODIMENT 4"

[0054] FIGs. 16 and 17 are sectional views showing another example structure of the heat-insulating thin layer 20. In the following descriptions given in EMBODIMENT 4, like components or components corresponding to those of EMBODIMENTS 1 to 3 are denoted by like reference numerals, and repeated descriptions are omitted.

[0055] In the example structure (EMBODIMENT 4) shown in FIGs. 16 and 17, in comparison with the example structure (EMBODIMENT 3) shown in FIG. 13, the heat-insulating material 22 is provided with protruded portions 22a which are protruded toward the heat-insulating material 21 (base material 30 side), so that the heat-insulating thin layer 20 has a structure where the protruded portions 22a of the heat-insulating material 22 enter into the heat-insulating material 21. FIG. 17 shows an example where the protruded portions 22a are formed to have a grid shape, but forming the protruded portions 22a into the grid shape is not essential.

[0056] The swing range ΔT of the combustion chamber wall surface temperature T_{wall} can also be increased while suppressing the base wall temperature from increasing in EMBODIMENT 4, and followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the thermal efficiency of the internal combustion engine 1 can be improved. In addition, in EMBODIMENT 4, since the bonded area between the heat-insulating material 21 and the heat-insulating material 22 can be increased by the protruded portions 22a disposed in the heat-insulating material 22, the bonded strength between the heat-insulating material 21 and the heat-insulating material 22 can be increased.

"EMBODIMENT 5"

[0057] FIGs. 18 and 19 are diagrams showing another structure example of the heat-insulating thin layer 20, FIG. 18 shows a diagram as viewed from a direction (the normal direction) agreeing with the normal of the wall surface 30a of the base material 30, and FIG. 19 shows a sectional view. In the following descriptions given in EMBODIMENT 5, like components or components corresponding to those of EMBODIMENTS 1 to 4 are denoted by like reference numerals, and repeated descriptions are omitted.

[0058] In the example structure (EMBODIMENT 5) shown in FIGs. 18 and 19, shell-like heat-insulating materials 22 each contain therein a heat-insulating material 21. Further, the heat-insulating materials 22 containing the heat-insulating material 21 therein are arranged in a large number on the wall surface 30a of the base material 30. The specific example of the heat-insulating materials 21, 22 and the base material 30 is similar to that in EMBODIMENT 1. A thin intermediate material, which is omitted from FIGs. 18 and 19, for strengthening the coating and bonding between the heat-insulating materials 22 and the base material 30 may be formed between the heat-insulating materials 22 and the base material 30. Here, the intermediate material preferably has thermal conductivity and heat capacity per unit volume nearly equal to those of the heat-insulating materials 21 or the heat-insulating materials 22. Also, FIG. 18 shows an example where the outer shapes of the heat-insulating materials 22 as viewed from the normal direction have a roughly square shape, but the outer shapes of the heat-insulating materials 22 may be other than the square shape.

[0059] In EMBODIMENT 5, the heat-insulating materials 22 having high heat resistance and high strength contain

therein the heat-insulating material 21, which is low in thermal conductivity and heat capacity per unit volume. Thus, the heat-insulating material 21 can be protected against the high-temperature, high-pressure gas present in the combustion chamber 13. Therefore, for the heat-insulating material 21, a heat-insulating material having a thermal conductivity and a heat capacity per unit volume which are sufficiently low can be selected without a restriction that the adequate heat resistance and pressure resistance must be secured against the high-temperature, high-pressure gas present in the combustion chamber 13, and the thermal conductivity and heat capacity per unit volume of the entire heat-insulating thin layer 20 can be decreased sufficiently. Therefore, the swing range ΔT of the combustion chamber wall surface temperature T_{wall} can be increased while an increase in the base wall temperature is suppressed, and the followability of the combustion chamber wall surface temperature T_{wall} to the in-cylinder gas temperature T_g can be improved. As a result, the thermal efficiency of the internal combustion engine 1 can be improved.

"EMBODIMENT 6"

[0060] FIG. 20 is a sectional view showing another example structure of the heat-insulating thin layer 20. In the following descriptions given in EMBODIMENT 6, like components or components corresponding to those of EMBODIMENTS 1 to 5 are denoted by like reference numerals, and repeated descriptions are omitted.

[0061] In the structure example (EMBODIMENT 6) shown in FIG. 20, a layer of the heat-insulating materials 21 and a layer of the heat-insulating material 22 are alternately stacked a plurality of times, and the heat-insulating materials 21 and the heat-insulating material 22 are alternately arranged in the thickness direction of the heat-insulating thin layer 20. The heat-insulating thin layer 20 preferably has a thickness of, for example, about 100 μm , and the heat-insulating material 22 has a small thickness of 10 μm or less (e.g., about several μm). A specific example of the heat-insulating materials 21, 22 and the base material 30 is similar to EMBODIMENT 1, and as an example structural of the heat-insulating material 21, for example, the structure shown in FIG. 3B and the structure shown in FIG. 3C can be used.

[0062] In EMBODIMENT 6, the heat-insulating materials 21 are uniformly distributed in in-plane directions (vertical direction with respect to thickness direction) of the heat-insulating thin layer 20, and the heat-insulating materials 21 can be prevented from being biased locally in the in-plane directions of the heat-insulating thin layer 20. As a result, the heat-insulating thin layer 20 which has substantially uniform thermal conductivity in the thickness direction can be realized, and the existence of portions where heat is apt to be lost locally and portions where heat is not apt to be lost can be suppressed. Therefore, the heat-insulating thin layer 20 having uniform thermophysical properties can be realized.

[0063] The heat-insulating thin layer 20 formed on the wall surface which faces the interior of the combustion chamber 13 can have a structure that combines a plurality of example structures according to EMBODIMENTS 1 to 6, and the structure of the heat-insulating thin layer 20 can be varied depending on the portion where the heat-insulating thin layer 20 is formed. Further, the heat-insulating thin layer 20 is not necessarily required to have a fixed thickness and thickness can be varied according to the portion where the heat-insulating thin layer 20 is formed. In addition, the heat-insulating thin layer 20 of this embodiment can also be used in combination with another heat-insulating structure.

[0064] Although the modes of working the present invention have been described above, the present invention is not limited to the embodiments described above, and it is to be understood that modifications and variations of the embodiments can be made without departing from the spirit and scope of the invention.

Claims

1. An internal combustion engine having a heat-insulating layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of at least a part of a base material forming the combustion chamber, wherein the heat-insulating layer comprises:

a first heat-insulating material which has a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than that of the base material, and

a second heat-insulating material which has a thermal conductivity not higher than that of the base material and protects the first heat-insulating material against a gas in the combustion chamber, and the first heat-insulating material has a thermal conductivity lower than that of the second heat-insulating material and a heat capacity per unit volume lower than that of the second heat-insulating material.

2. The internal combustion engine according to claim 1, wherein the first heat-insulating material is mixed into the second heat-insulating material.

3. The internal combustion engine according to claim 2, wherein:

the second heat-insulating material in which the first heat-insulating material is mixed assumes a fibrous form, and the second heat-insulating material formed into the fibrous form is carpeted in a large number on the wall surface.

4. The internal combustion engine according to claim 2, wherein a mixing proportion of the first heat-insulating material is varied depending on a position within the second heat-insulating material.

5. The internal combustion engine according to claim 2, wherein the first heat-insulating materials are arranged regularly within the second heat-insulating material.

6. The internal combustion engine according to claim 2, wherein the first heat-insulating material is a heat-insulating material having a hollow structure.

7. The internal combustion engine according to claim 6, wherein the first heat-insulating material has a multilayered structure.

8. The internal combustion engine according to claim 1, wherein:

the first heat-insulating material is formed on the wall surface, and
the second heat-insulating material is formed on the first heat-insulating material to cover the first heat-insulating material.

9. The internal combustion engine according to claim 8, wherein the second heat-insulating material is formed with protruded portions which are protruded toward the first heat-insulating material.

10. The internal combustion engine according to claim 1, wherein the second heat-insulating material is a shell-like heat-insulating material which contains therein the first heat-insulating material.

11. The internal combustion engine according to claim 1, wherein the first heat-insulating material and the second heat-insulating material are alternately arranged in the thickness direction of the heat-insulating layer.

12. The internal combustion engine according to claim 1, wherein the second heat-insulating material has a heat resistance temperature higher than that of the first heat-insulating material.

13. The internal combustion engine according to claim 1, wherein the second heat-insulating material has strength higher than that of the first heat-insulating material.

14. The internal combustion engine according to claim 1, wherein the second heat-insulating material has a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than or substantially equal to that of the base material.

15. An internal combustion engine having a heat-insulating layer formed on a wall surface, which faces the interior of a combustion chamber of the internal combustion engine, of at least a part of a base material which forms the combustion chamber, wherein:

the heat-insulating layer is constituted to include a heat-insulating material which has a large number of bubbles formed within a material having a thermal conductivity lower than that of the base material and a heat capacity per unit volume lower than or substantially equal to that of the base material.

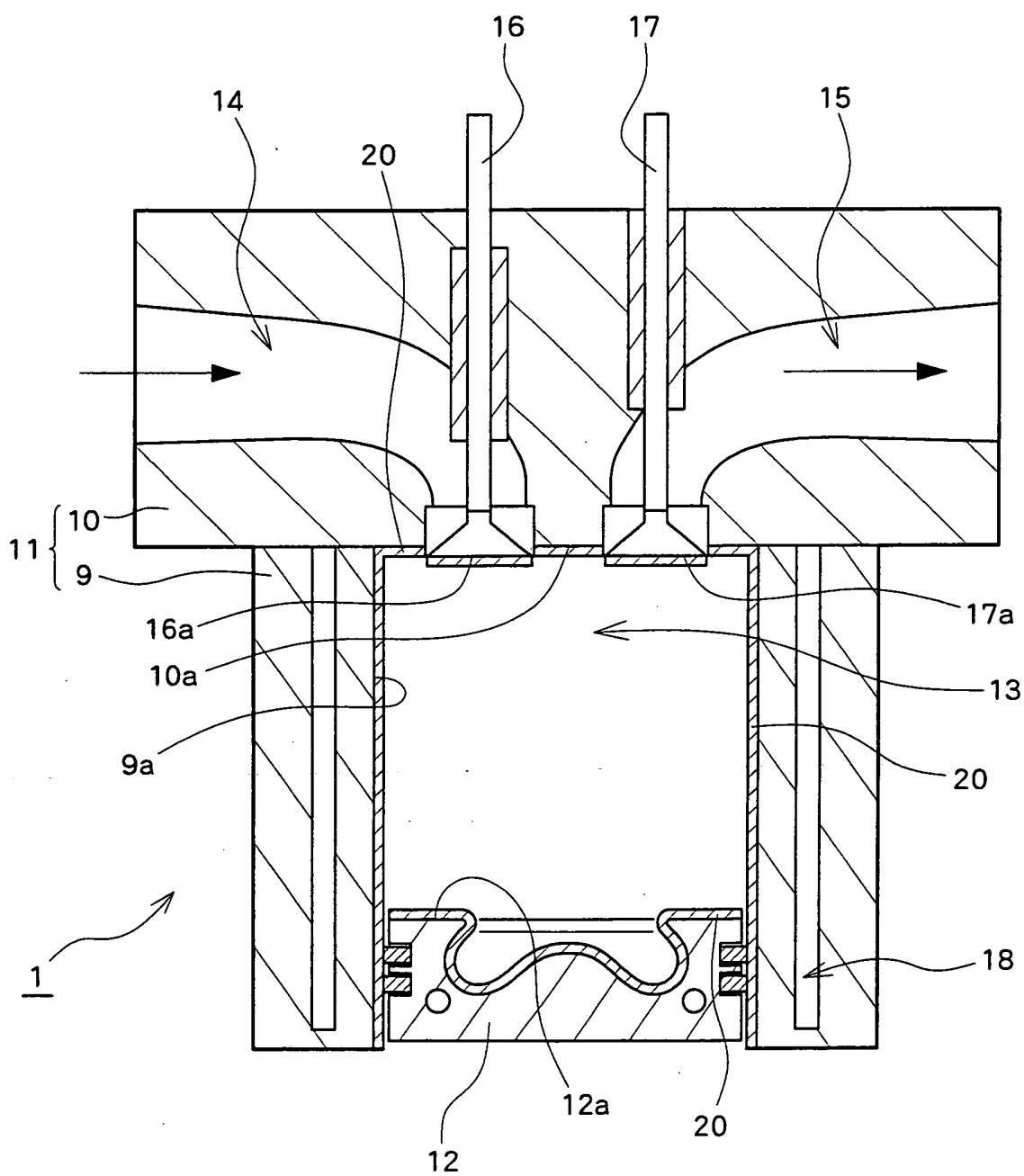


FIG. 1

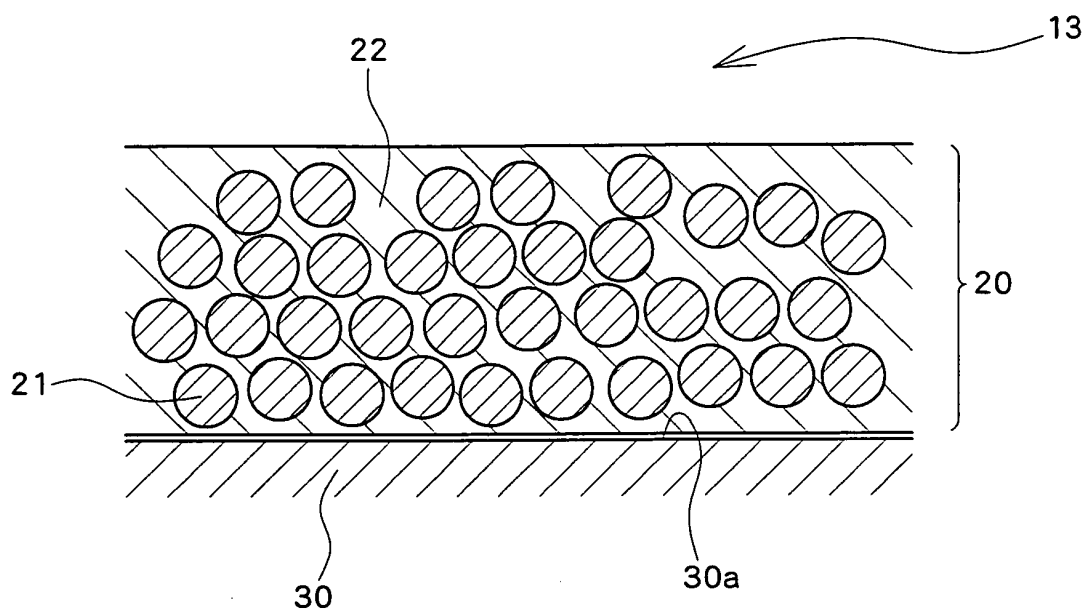


FIG. 2

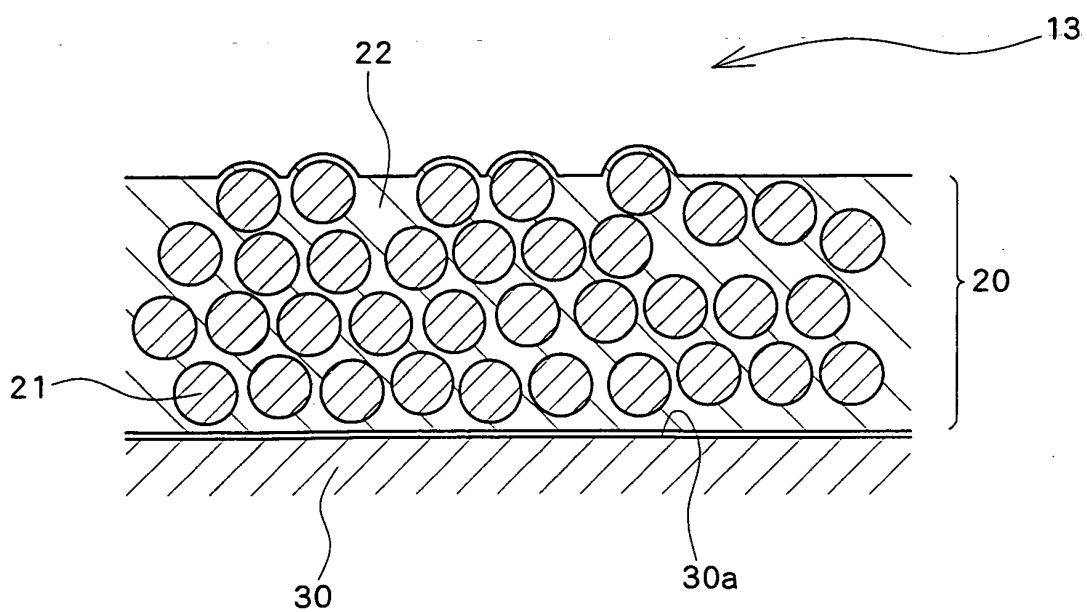


FIG. 3A

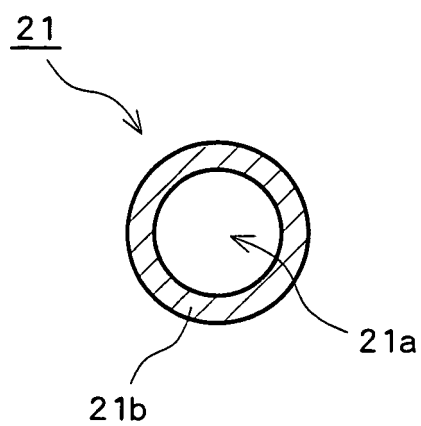


FIG. 3B

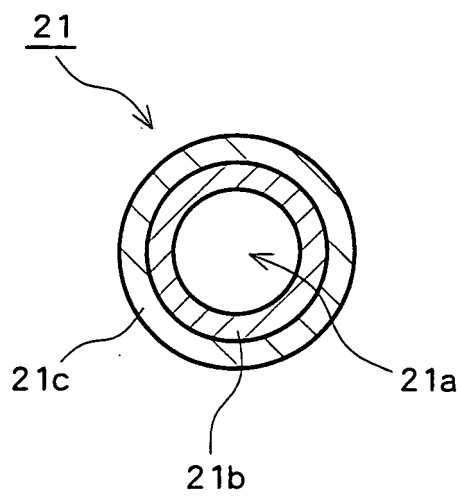


FIG. 3C

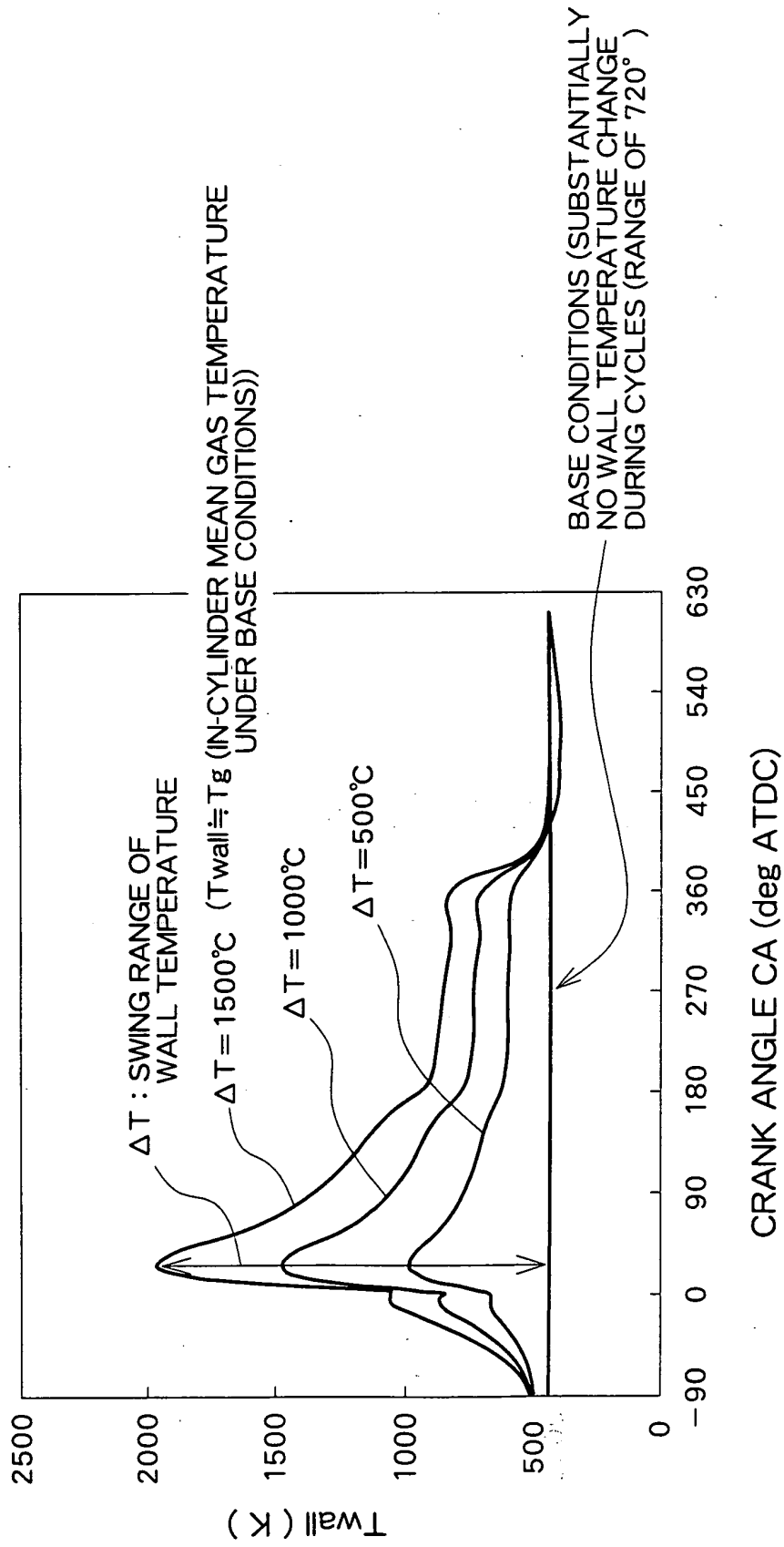


FIG. 4

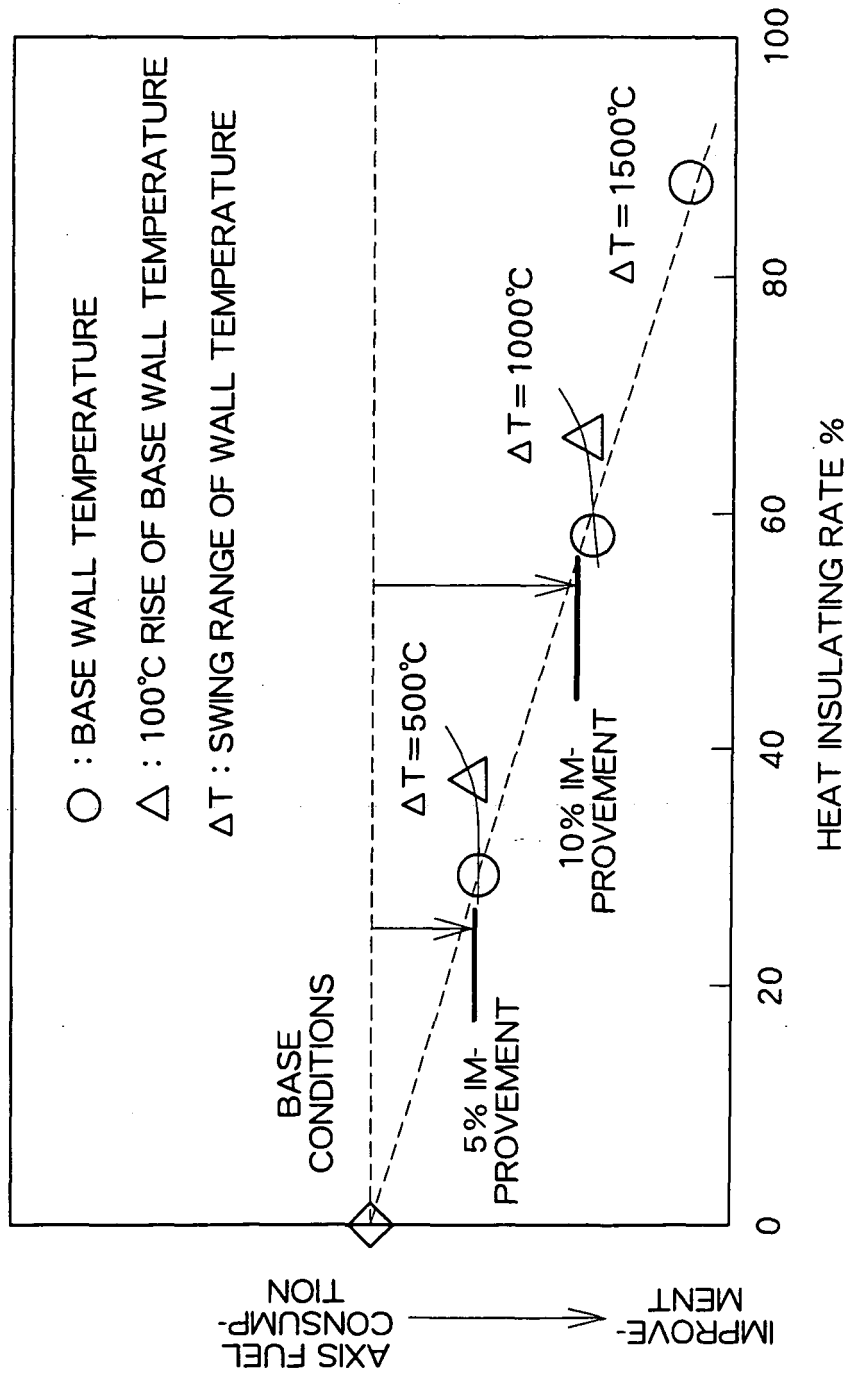


FIG. 5

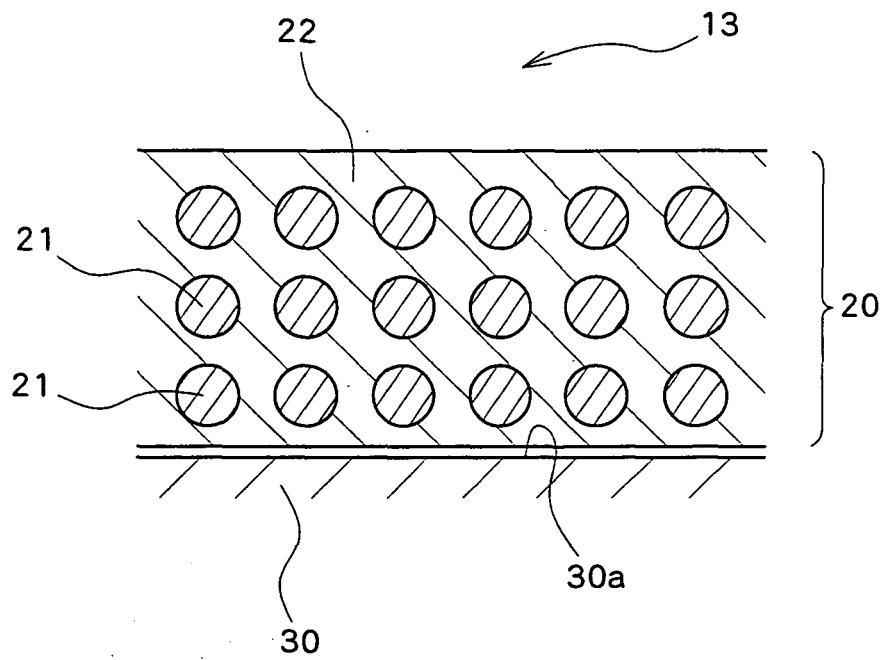


FIG. 6A

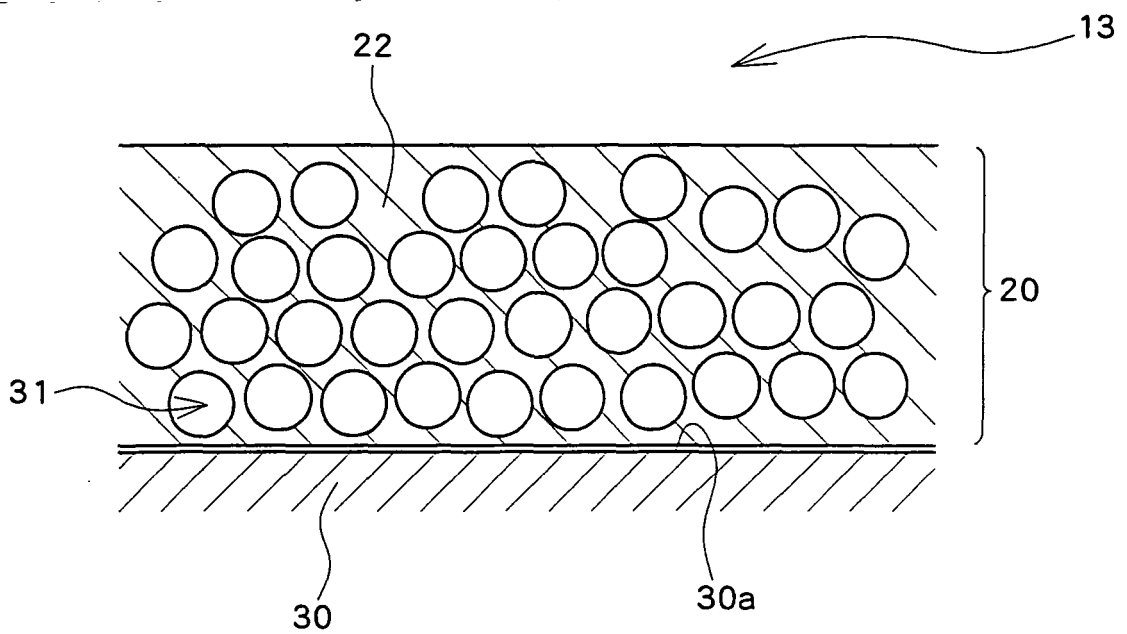


FIG. 6B

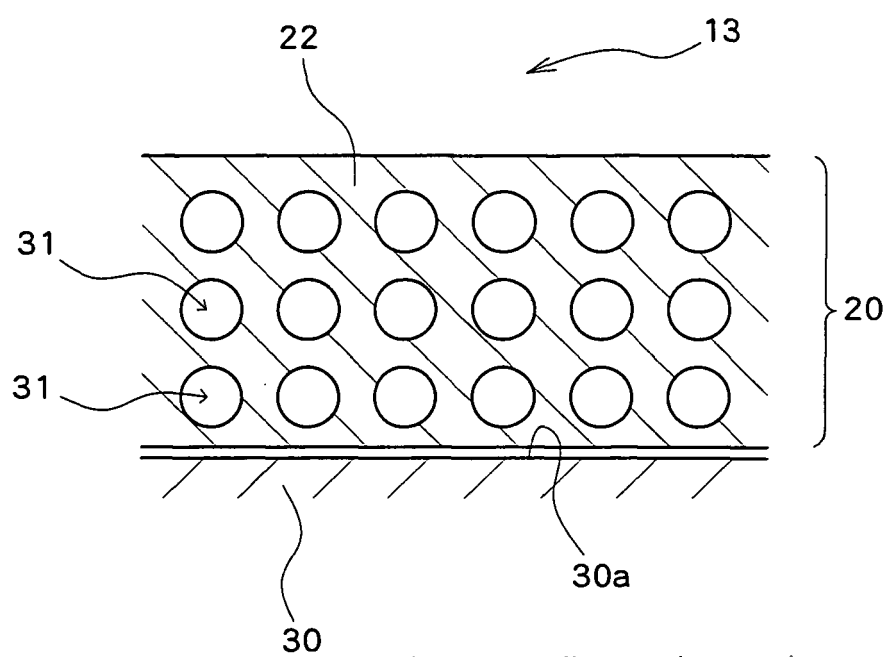


FIG. 6C

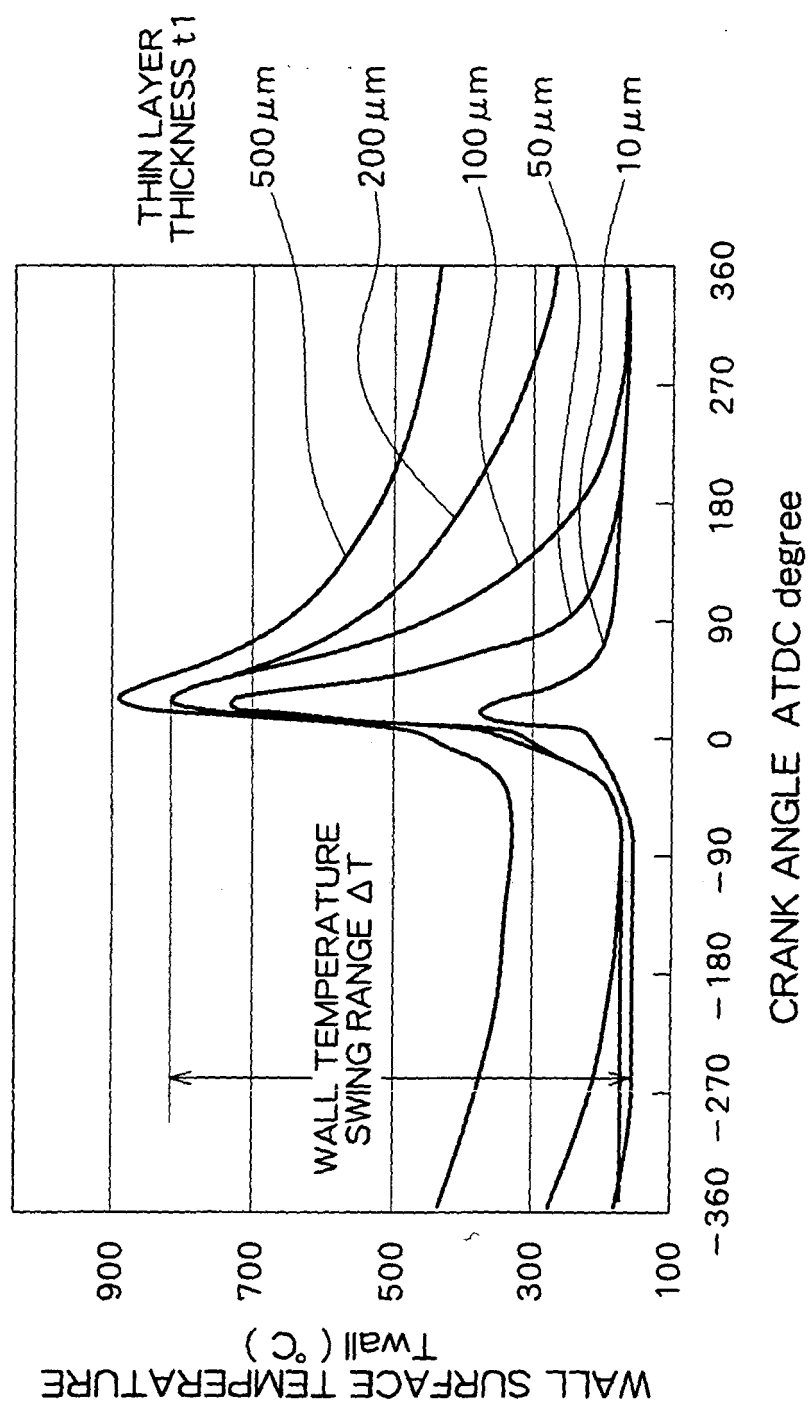


FIG. 7

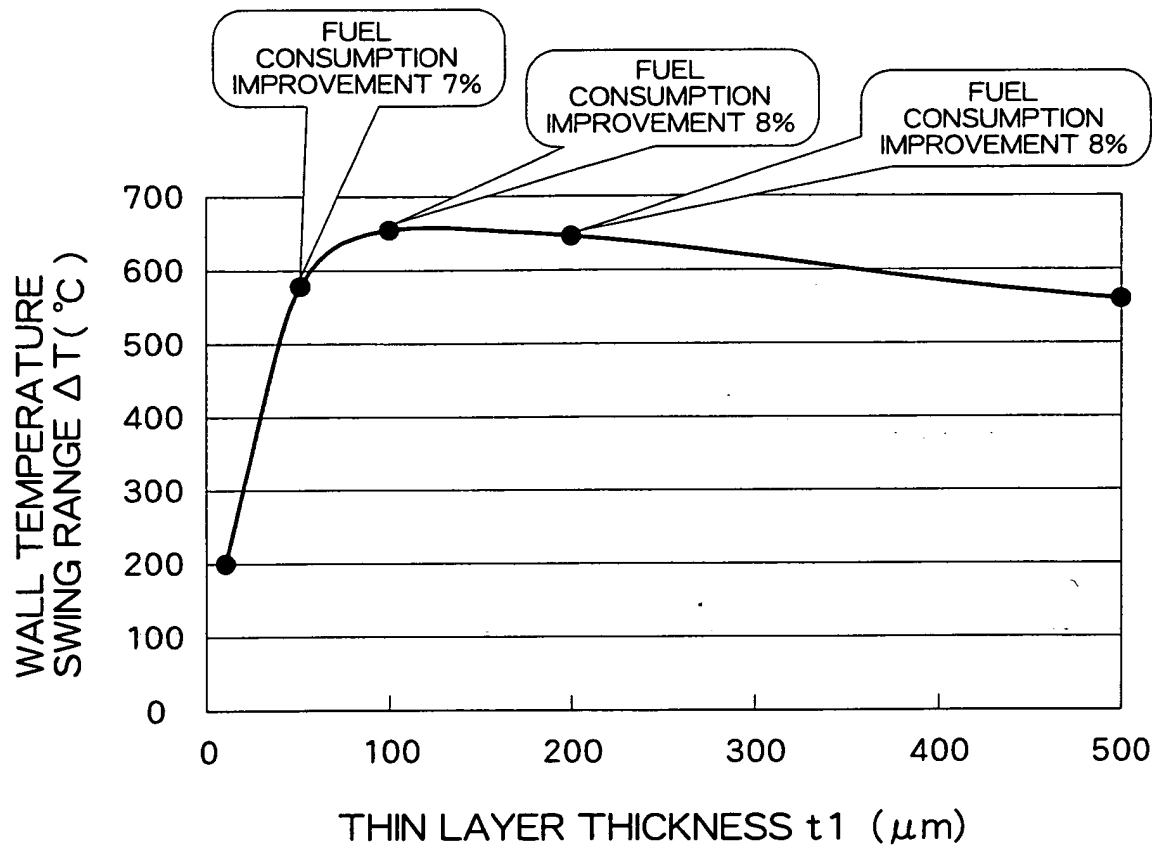


FIG. 8

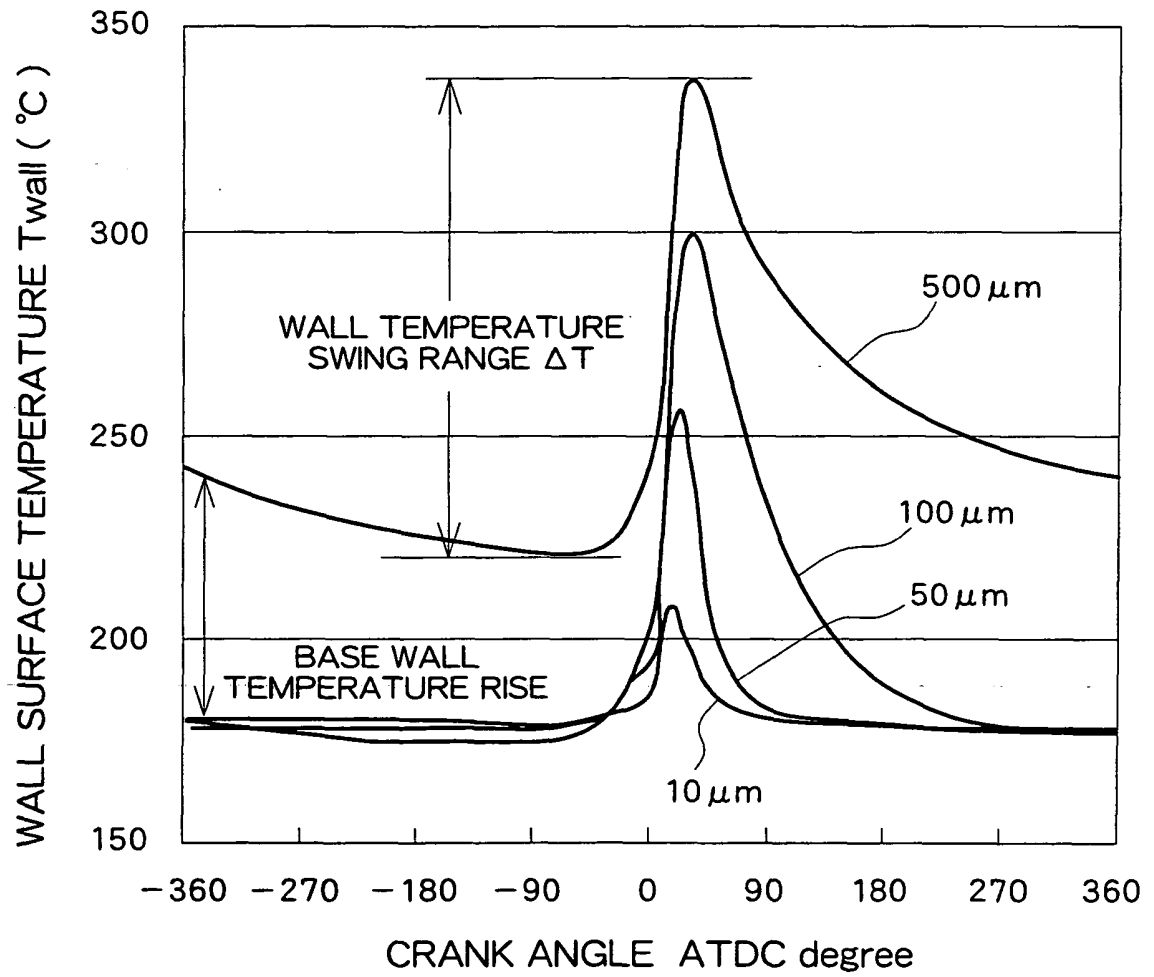


FIG. 9

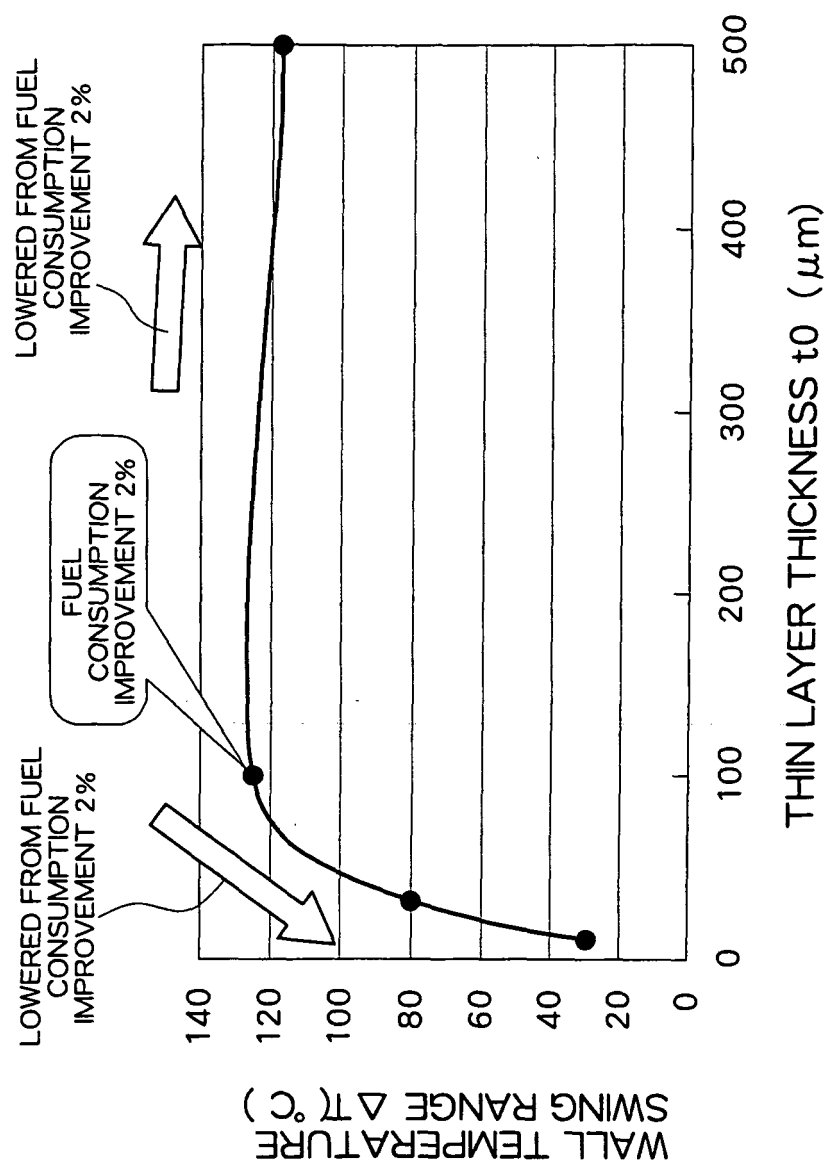


FIG. 10

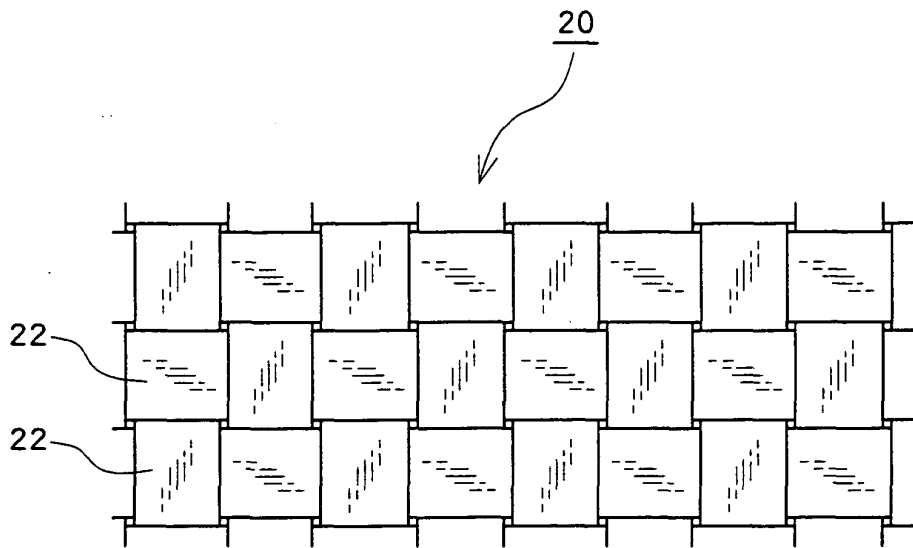


FIG. 11

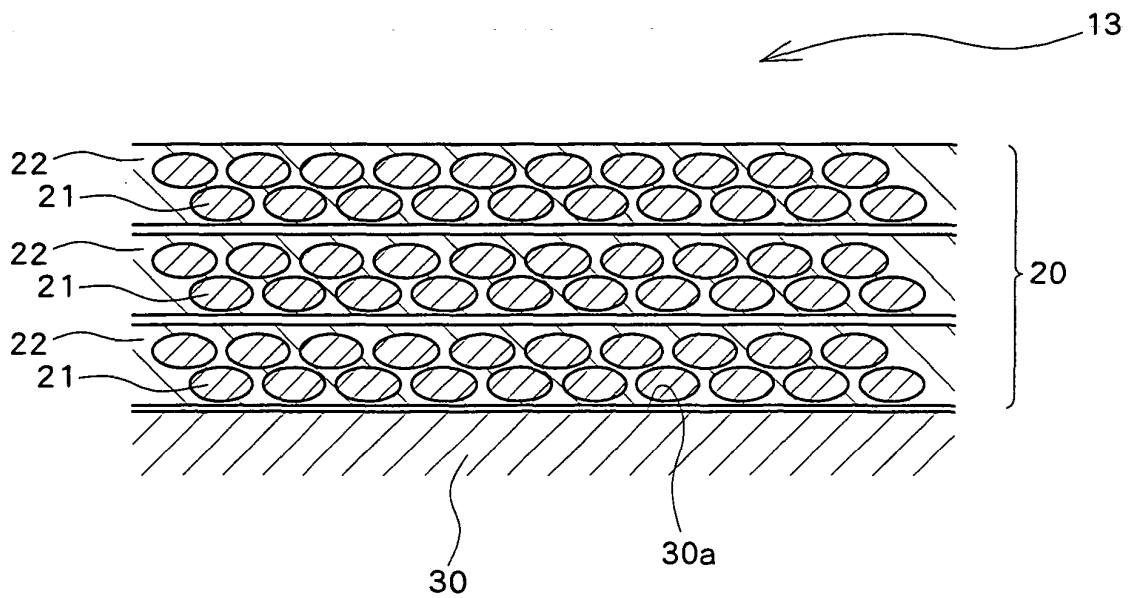


FIG. 12

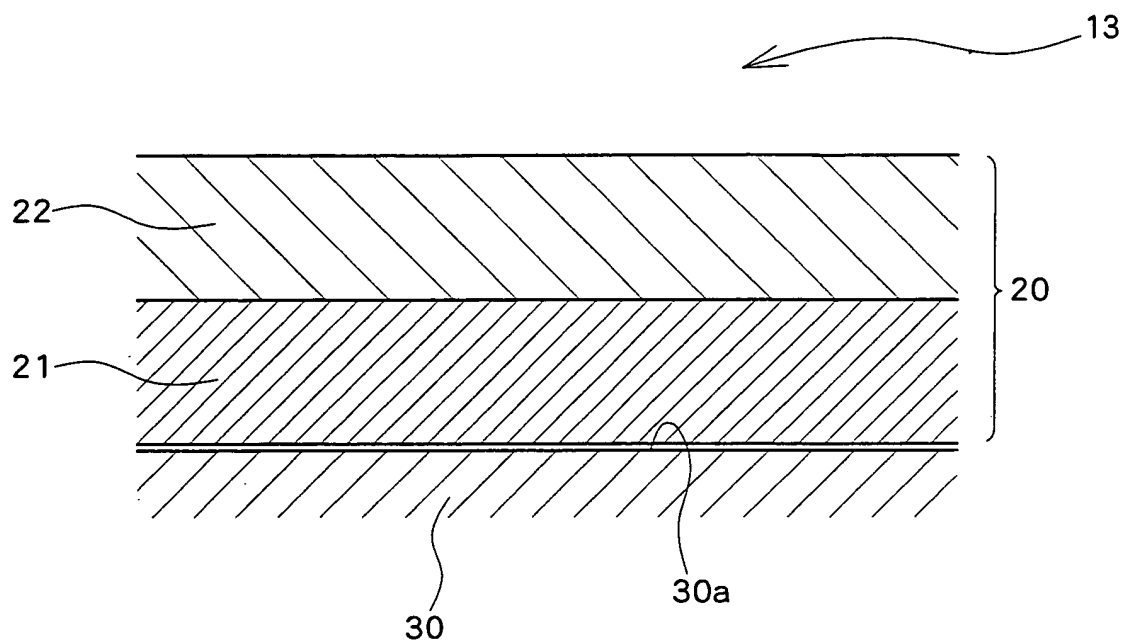


FIG. 13

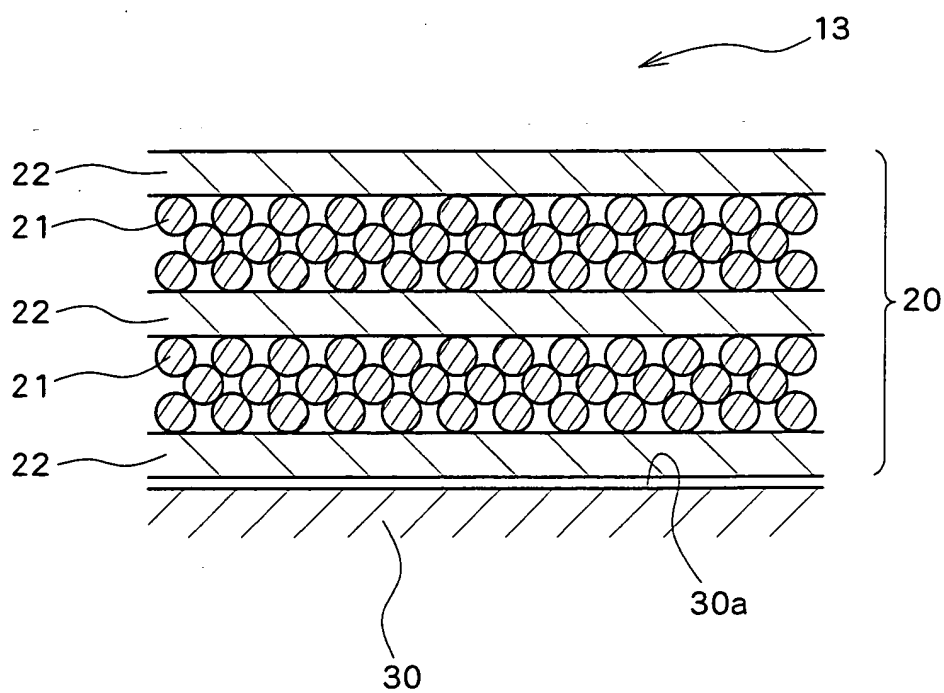


FIG. 20

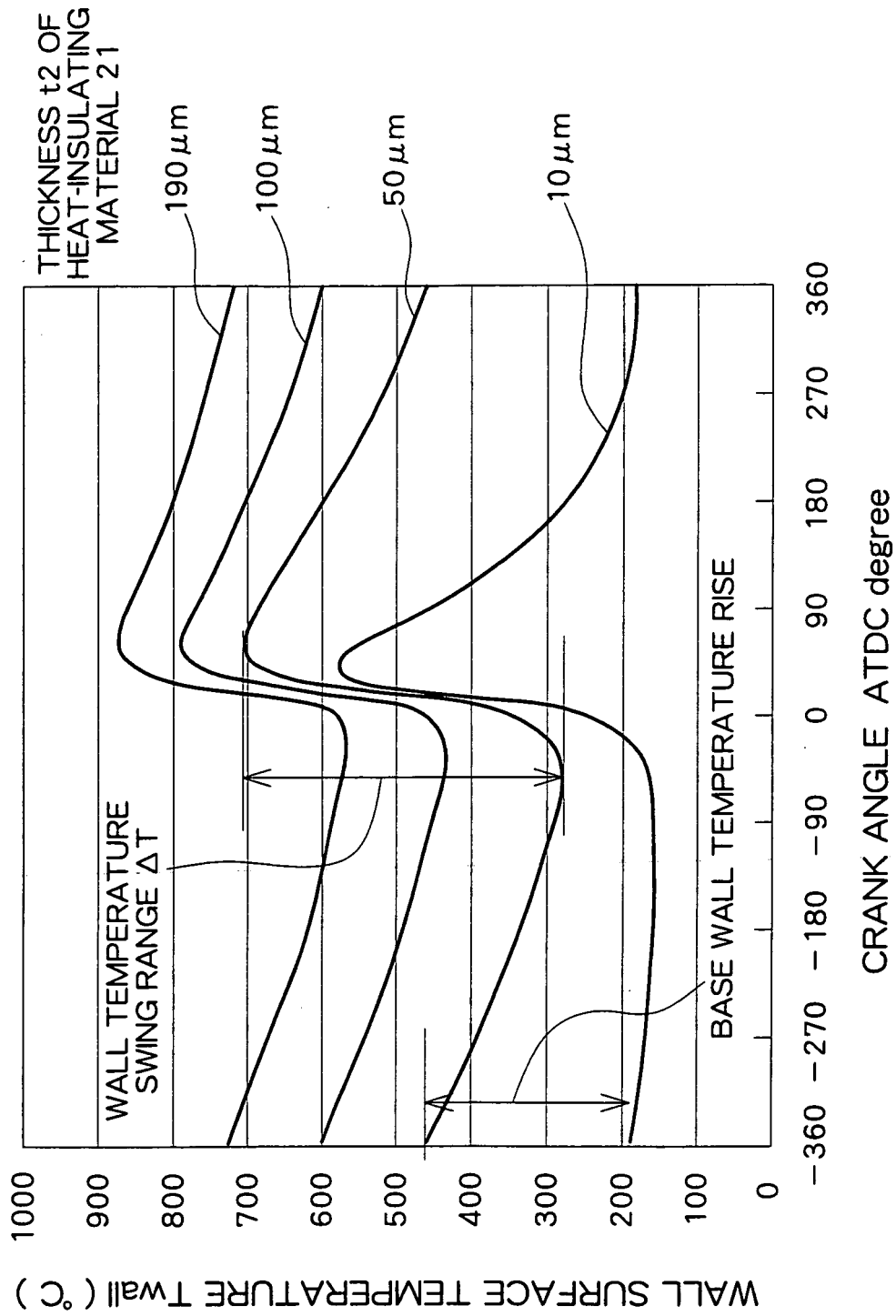


FIG. 14

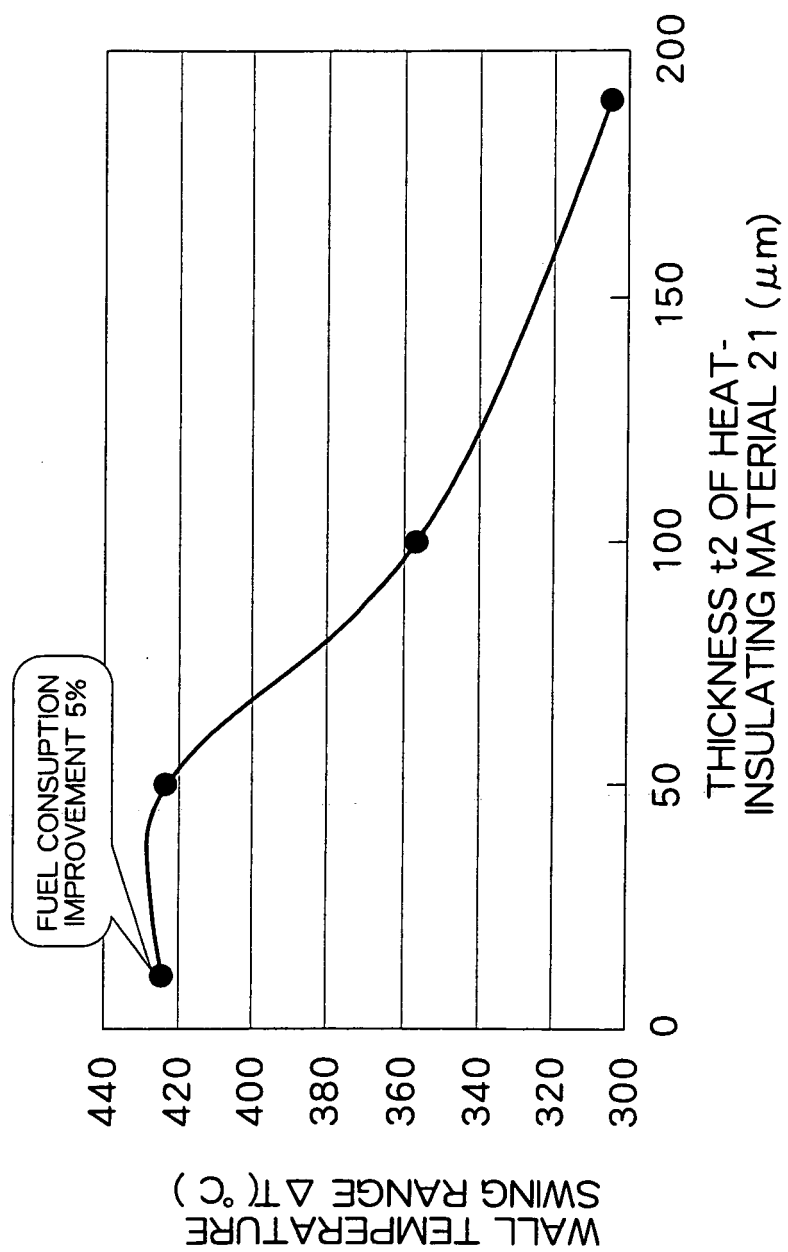


FIG. 15

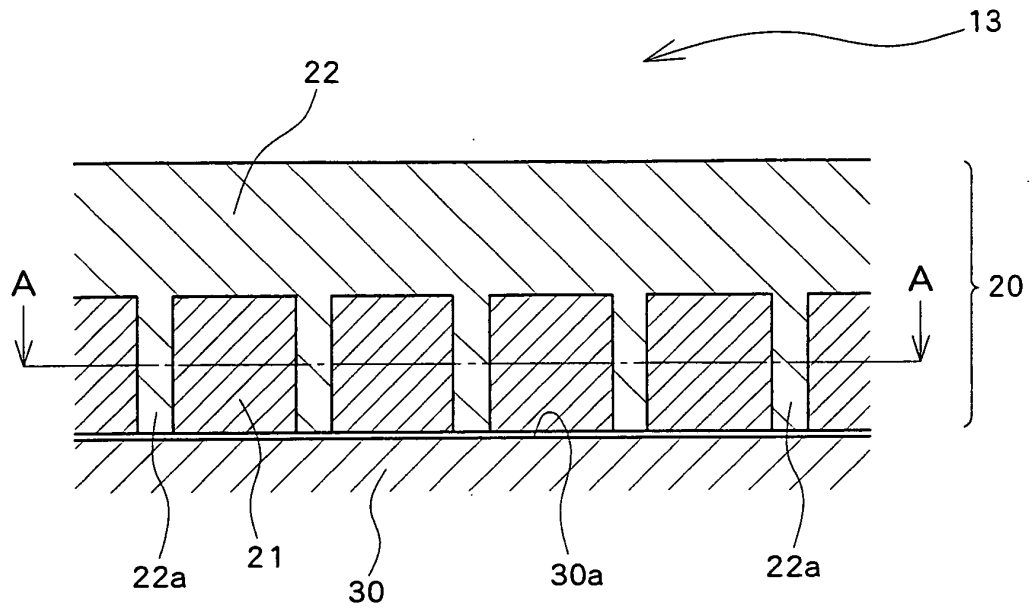
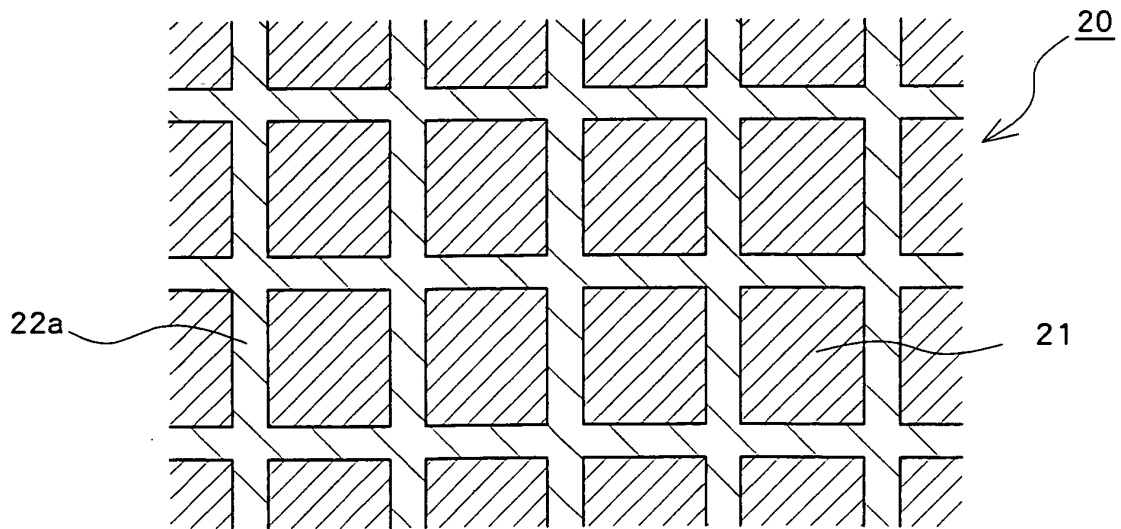


FIG. 16



A-A CROSS SECTION

FIG. 17

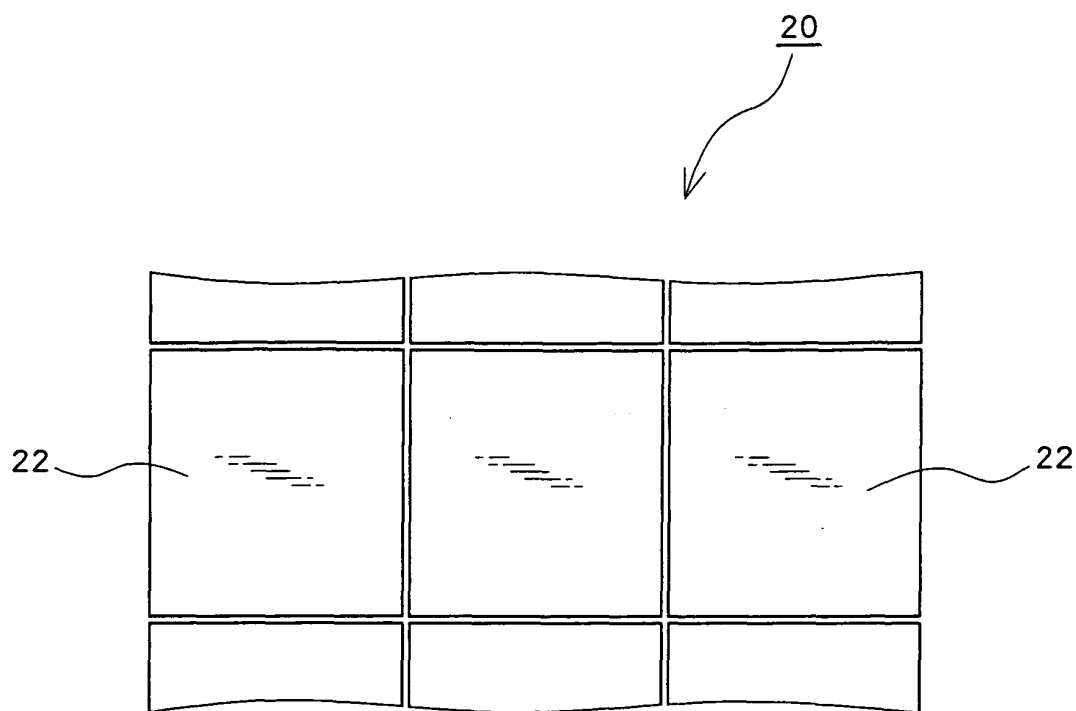


FIG. 18

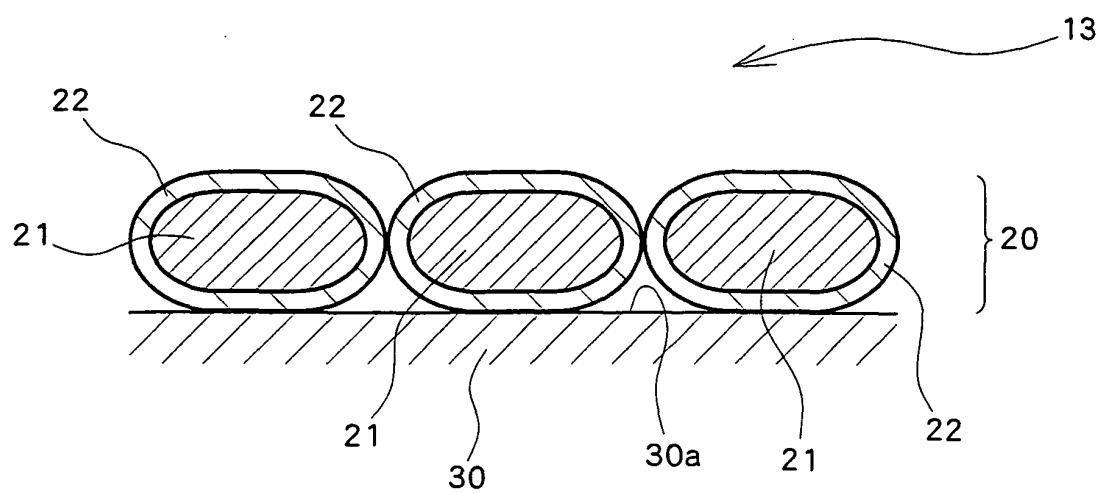


FIG. 19

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2008/064304

A. CLASSIFICATION OF SUBJECT MATTER

F02B23/00(2006.01) i, F02F1/00(2006.01) i, F02F1/24(2006.01) i, F02F3/12
(2006.01) i, F02F3/14(2006.01) i

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

F02B23/00, F02F1/00, F02F1/24, F02F3/12, F02F3/14

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Jitsuyo Shinan Koho 1922-1996 Jitsuyo Shinan Toroku Koho 1996-2008
Kokai Jitsuyo Shinan Koho 1971-2008 Toroku Jitsuyo Shinan Koho 1994-2008

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	WO 00/14396 A1 (Tadashi YOSHIDA), 16 March, 2000 (16.03.00), Page 4, line 19 to page 5, line 24; Fig. 1 & AU 4933899 A & CA 2352047 A	1, 11-14 2-10
X Y	JP 60-182340 A (Isuzu Motors Ltd.), 17 September, 1985 (17.09.85), Column 3, line 19 to column 4, line 10; Fig. 1 (Family: none)	15 2-10
Y	JP 7-259642 A (Caterpillar Inc.), 09 October, 1995 (09.10.95), Column 4, line 38 to column 5, line 1; Figs. 1 to 3 & US 5593745 A & US 5552196 A & DE 19506529 A & DE 19506529 A1	3

☒ Further documents are listed in the continuation of Box C.

☐ See patent family annex.

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"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

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Date of the actual completion of the international search
06 November, 2008 (06.11.08)

Date of mailing of the international search report
18 November, 2008 (18.11.08)

Name and mailing address of the ISA/
Japanese Patent Office

Authorized officer

Facsimile No.

Telephone No.

INTERNATIONAL SEARCH REPORT

International application No.

PCT/JP2008/064304

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT		
Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
Y	Microfilm of the specification and drawings annexed to the request of Japanese Utility Model Application No. 151744/1983 (Laid-open No. 58824/1985) (Isuzu Motors Ltd.), 24 April, 1985 (24.04.85), Fig. 4 (Family: none)	9

Form PCT/ISA/210 (continuation of second sheet) (April 2007)

REFERENCES CITED IN THE DESCRIPTION

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Patent documents cited in the description

- US 8903930 PCT [0008]
- US 4495907 A [0008]
- US 5820976 A [0008]

Non-patent literature cited in the description

- **Gerhard Woschni.** Heat Insulation of Combustion Chamber Walls - A Measure to Decrease the Fuel Combustion of I. C. Engines?. *SAE Paper 870339*, Society of Automotive Engineers, 1987 [0008]
- **Victor W. Wong.** Assessment of Thin Thermal Barrier Coatings for I.C. Engines. *SAE Paper 950980*, Society of Automotive Engineers, 1995 [0008]
- **Brian T. Holland.** *Science*, 1998, vol. 281, 538-540 [0037] [0039]