A. Bilohub, F. Sirenko

THERMAL ANALYSIS OF AIRCRAFT PISTON ENGINE

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MINISTRY OF EDUCATION AND SCIENCE OF UKRAINE
National Aerospace University
«Kharkiv Aviation Institute»

A. Bilohub, F. Sirenko

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Подано методику теплового розрахунку авіаційного чотиритактного поршневого двигуна легкого пального з запалюванням від електричної іскри, а також приклад розрахунку двигуна з визначенням його основних розмірів – діаметра циліндра і ходу поршня.

Для студентів спеціальності «Авіаційні двигуни і енергетичні установки» при курсовому і дипломному проектуванні.

Reviewers: Doctor of technical sciences, Professor V. Pylov,
Candidate of technical sciences, Associate Prof. V. Korogodsky

Bilohub, O.
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The manual considers the method of the thermal analysis of the aircraft four-stroke spark ignition piston engine and its particular sample including the method to get the main geometrical parameters of the engine (diameter of the cylinder and piston stroke).

The manual will be interesting for the students studying "Aircraft engines and power plants" as a reference for the term works and a master thesis.

Figs. 2., Ref. : 6 items.

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1. INFORMATION ABOUT THE PROCESSES IN AIRCRAFT PISTON ENGINES

Modern aircraft piston engines belong to the light-fuel electric-ignition four stroke engines. The air and the fuel are intermixed in a carburetor or by the gasoline direct injection system. Regardless of mixing method, all fuel must evaporate and form the mixture prior to the ignition moment. The combustion occurs right inside the cylinder. The chemical energy of a mixture combustion is converted to the pressure acting on the piston, and finally – to a shaft rotation. The force of the gas pressure gets to the crankshaft through the connecting rod.

Hence, the piston engines are different from other heat machines because of the cylinder and the piston.

The generic scheme of the light-fuel four-stroke piston engine is shown in Figure 1.

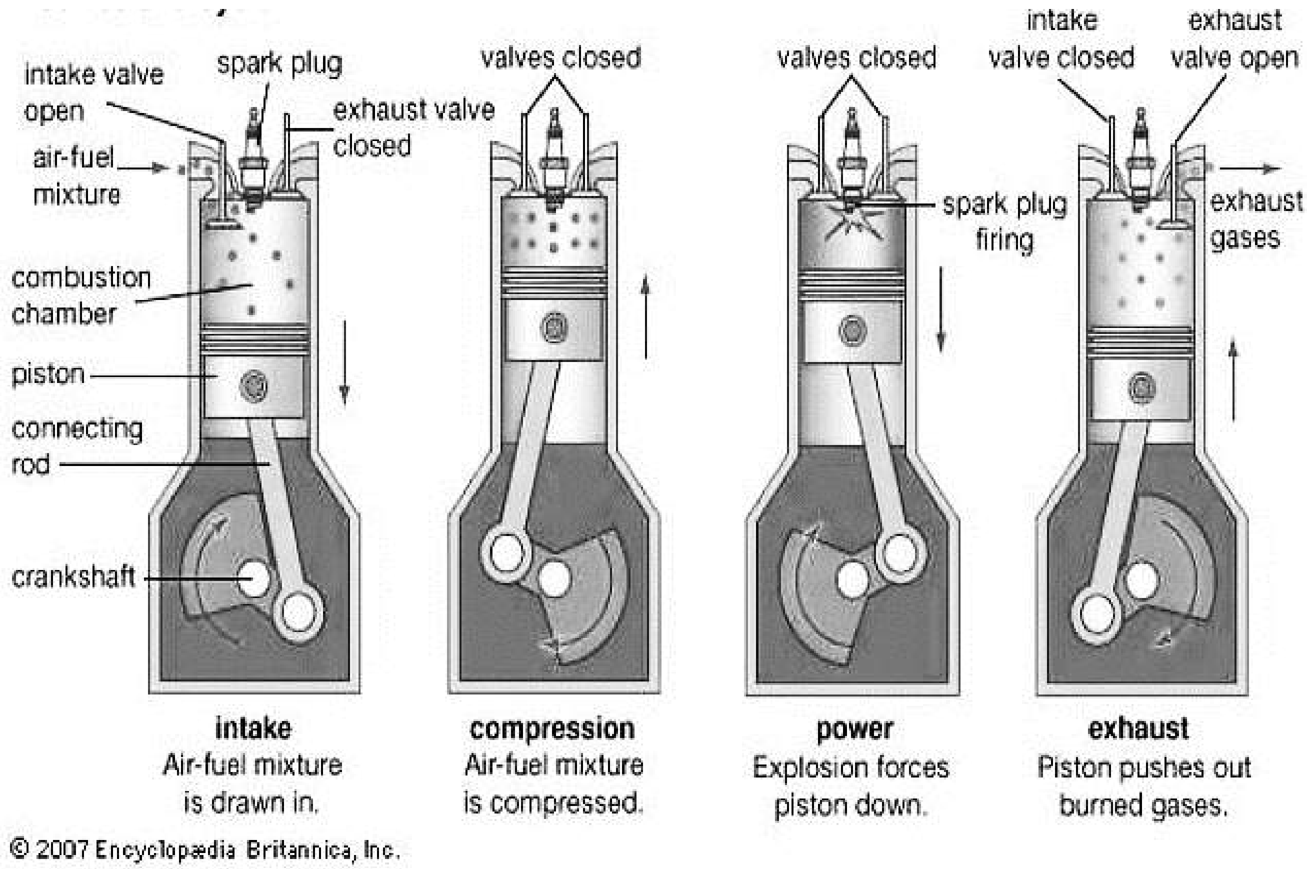


Figure 1 – The generic scheme of a four-stroke piston engine operation

The extreme positions reachable for the piston are called dead centers. There are two dead centers: top dead center (the farthest position from the crankshaft) and bottom dead center (the nearest position to the crankshaft). The distance piston travels from the TDC to the BDC is called a piston stroke. It is designated as S_P and is equal to doubled crank radius $S_P = 2R$.

The clearance volume corresponds to the volume above the piston when the latest is in the TDC. The clearance volume (V_c) is sometimes called a compression chamber or a combustion chamber. The volume of the piston travel S_P is called displacement volume (V_h). The working volume of all cylinders presented in liters is called an engine displacement volume. The following formula evaluates the displacement volume

$$\boldsymbol{V}_\mathrm{h} = \boldsymbol{F}\boldsymbol{S}_\mathrm{P} = \frac{\pi \boldsymbol{D}^2}{4}\boldsymbol{S}_\mathrm{P},$$

where F is the piston area;

D is a cylinder diameter;

S_P is a piston stroke.

The sum of V_c and V_h is called a total volume (V_a). The ratio of the total volume to the clearance volume is called a compression ratio (ε), i. e.

$$\boldsymbol{\varepsilon} = \frac{\boldsymbol{V}_\mathrm{a}}{\boldsymbol{V}_\mathrm{c}} = \frac{\boldsymbol{V}_\mathrm{h} + \boldsymbol{V}_\mathrm{c}}{\boldsymbol{V}_\mathrm{c}} = \frac{\boldsymbol{V}_\mathrm{h}}{\boldsymbol{V}_\mathrm{c}} + 1.$$

The compression ratio to a great extent belongs to the parameters that determine the power and fuel efficiency of the engine as a whole. The piston engines, which working cycle consists of four piston strokes are called four stroke engines.

The collection of the strokes has the following sequence (see Figure 1):

Intake stroke: The piston travels from the TDC to the BDC. All increasing volume above the piston is filled with the fresh charge rushing through the open intake valve. The fresh charge is mixed with the residual combustion products in the cylinder. The mixture finally forms the working substance for the new working cycle.

Compression stroke: The piston goes back to the TDC compressing the charge thereby. The valves are at their seats. At the end of the compression stroke, the working substance is ignited by the spark plug (usually 20 – 40° prior to the TDC).

Power stroke: The piston again travels to the BDC. This travel is initiated by the air/gasoline mixture combustion and the combustion products expansion. The valves are at their seats during the entire stroke.

Exhaust stroke: The piston moves to the initial position in the TDC, forcing the combustion products to the exhaust manifold through the exhaust valve.

As you may notice, the only one stroke (the power stroke) outputs the positive work making the shaft rotate. The rest strokes serve to prepare and combust the air/gasoline mixture. Obviously, they consume the work.

All piston engines for aircraft can be divided into two classes – altitude and sea-level engines.

The sea-level engines have no supercharger to increase the pressure of fresh air, i.e. air gets inside the cylinder at almost atmospheric pressure. At higher altitudes, the amount of the fresh charge quickly decreases, which in its turn results in severe decrease of power (approximately 2 times each 5 km). These engines found their use only for trainers and sporting airplanes.

The specific feature of the altitude engines is the usage of the supercharger. The supercharger sustains the constant pressure of the air that gets to the cylinder till some altitude, called a design altitude. When the design altitude is broken, the pressure progressively drops with the rate mostly equal to the sea-level engines.

The thermal analysis of the engine outputs the engine parameters at the design operational conditions. The cylinder is being supercharged with air (air/gasoline mixture) during the intake stroke. It is very important to fill the cylinder with the maximum possible amount of charge because it is directly interrelated with the work of cycle and, respectively, the power, which is outputted by a single cylinder at the definite cylinder volume and rotational speed. The degree of filling the cylinder with the fresh charge is estimated with volumetric efficiency. The volumetric efficiency η_v is defined as the ratio of the mass density of the (air) air/fuel mixture drawn into the cylinder at atmospheric pressure (during the intake stroke) to the mass density of the same volume of air in the intake manifold

$$\eta_{\mathrm{v}} = \frac{\boldsymbol{m}_{\text{fresh charge}}}{\boldsymbol{m}_{\text{theoretical}}} = \frac{\boldsymbol{M}_{\text{resh charge}}}{\boldsymbol{M}_{\text{theoretical}}} = \frac{\boldsymbol{G}_{\text{fresh charge}}}{\boldsymbol{G}_{\text{theoretical}}},$$

where $\boldsymbol{m}_{\text{fresh charge}}$ and $\boldsymbol{m}_{\text{theoretical}}$ are masses of fresh and theoretically possible charges respectively, kg;

$\boldsymbol{M}_{\text{fresh charge}}$ and $\boldsymbol{M}_{\text{theoretical}}$ are amounts of fresh and theoretically possible charges respectively, kilomoles;

$\boldsymbol{G}_{\text{fresh charge}}$ and $\boldsymbol{G}_{\text{theoretical}}$ are mass flow rates of fresh and theoretically possible charges respectively, kg/hour;

The volumetric efficiency is also affected to a certain extent by the combustion products, which remain in the cylinder from the previous working cycle (after the exhaust stroke). The effect can be estimated with the residual gas ratio

$$\gamma = \frac{\boldsymbol{M}_{\text{residual}}}{\boldsymbol{M}_{\text{fresh charge}}},$$

where $\boldsymbol{M}_{\text{residual}}$ is the amount of residual gas, kilomoles.

The compression is a “must have” stroke to provide the cylinder with the conditions that are the most suitable for the combustion. At these conditions, the combustion will output more heat and hence higher work made by the gas during the power stroke. The higher compression ratio corresponds to the higher expansion ratio. The higher expansion ratio is, the more work can be obtained from the working cycle. Finally, we can conclude that when the compression ratio increases, the work done by the gas in a single cycle increases too. The engine power respectively grows. The engine becomes more fuel efficient. But at the same time, knocking becomes more probable.

The combustion process is a collection of the chemical processes between the fuel components and the oxygen that is available in the air. The reactions are accompanied by the heat generation. The combustion starts at the moment when the spark plug initiates the spark to ignite the air/gasoline mixture. The combustion is considered to terminate when pressure in the cylinder gains the maximum magnitude.

The expansion transforms the emitted heat into the mechanical energy. The conversion takes place during the entire power stroke.

The mission of the exhaust stroke lies in cylinder scavenging and making it ready for a fresh charge injection. The higher scavenging perfectness is, the less amount of the residual gas stays in the cylinder. Obviously, it is a very important problem because the scavenging determines the amount of the fresh charge that will get to the cylinder in the next working cycle. The residual gas coefficient γ determines the amount of the gas that remains in the cylinder after scavenging ends.

1.1. Stoichiometric air charge

The aircraft gasolines are formed with the carbon (C), hydrogen (H) and oxygen (O_F). The mass portions of the chemical elements constituting the gasoline are known as an atomic fuel composition

$$\boldsymbol{C}(\mathrm{kg}) + \boldsymbol{H}(\mathrm{kg}) + \boldsymbol{O}_\mathrm{F}(\mathrm{kg}) = 1.0.$$

The fuel in the cylinder is able to be combusted thanks to the oxygen available in the air. In the engineering analysis, you can assume that dry air has 23.2% of oxygen and 76.8% of nitrogen (mass portions), or 20.9% of oxygen and 79,1% of nitrogen (volume portions). The stoichiometric amount of air to oxidize the carbon and the hydrogen can be easily determined from the following stoichiometric equations:

$$1\ \text{kmole}\ (\boldsymbol{C}) + 1\ \text{kmole}\ (\boldsymbol{O}_2) = 1\ \text{kmole}\ (\boldsymbol{CO}_2)$$

or

$$12\ \text{kg}\ (\boldsymbol{C}) + 32\ \text{kg}\ (\boldsymbol{O}_2) = 44\ \text{kg}\ (\boldsymbol{CO}_2).$$

Considering that 1 kg (***C***) = 1/12 kmole (***C***), then the molar balance formula can be transformed into

[1 kg (***C***) => 1/12 kmole (***C***)]+ 1/12 kmole (O_2) = 1/12 kmole (CO_2),

or

$$1 \text{ kg } (C) + 8/3 \text{ kg } (O_2) = 11/3 \text{ kg } (CO_2);$$

$$1 \text{ kmole } (H_2) + 1/2 \text{ kmole } (O_2) = 1 \text{ kmole } (H_2O)$$

or

$$2 \text{ kg } (H_2) + 16 \text{ kg } (O_2) = 18 \text{ kg } (H_2O),$$

i. e.

[1 kg (H_2) =>1/2 kmole (H_2)] + 1/4 kmole (O_2) = 1/2 kmole (H_2O),

or

$$1 \text{ kg } (H_2) + 8 \text{ kg } (O_2) = 9 \text{ kg } (H_2O).$$

As you can see, to burn one kilogram of carbon you need $\frac{8}{3}$ kilogram of oxygen. To burn one kilogram of hydrogen, you need 8 kilograms of oxygen. If a specific fuel contains C kg of carbon and H kg of hydrogen, then the amount of oxygen required O_0 can be evaluated as

$$\boldsymbol{O}_0 = \frac{8}{3}\boldsymbol{C} + 8\boldsymbol{H} \;\; \boldsymbol{kg/kg\ fuel}.$$

As one kilogram of air contains 0.232 kg of oxygen, so the stoichiometric mass of air to burn the specific fuel is equal to

$$\boldsymbol{L}_0 = \frac{\boldsymbol{O}_0}{0.232} = \frac{\frac{8}{3}\boldsymbol{C} + 8\boldsymbol{H}}{0.232} \;\; \boldsymbol{kg/kg\ fuel}.$$

The needed air to burn the specific fuel can also be expressed in moles. To do this, you should get the ratio between the stoichiometric mass of air L_0 into its apparent molecular mass $(\boldsymbol{m}_{\text{air}} = 28{,}95)$. Let us use the stoichiometric equations, which conclude that to burn 1 kg of carbon you must supply $\frac{1}{12}$ moles of oxygen or to burn 1 kg of hydrogen you must supply $\frac{1}{4}$ moles of oxygen.

As one kilogram of the gasoline contains C kg of carbon and H kg of hydrogen, and one mole of air contains 0.209 moles of oxygen, the stoichiometric amount of air L_0' for burning 1 kg of the gasoline can be calculated as

$$M_0 = \frac{O'_0}{0.209} = \frac{\frac{C}{12} + \frac{H}{4}}{0.209} \textbf{\textit{ mole/kg mole.}}$$

Formulas for L_0 and M_0 determine the minimum and theoretically necessary amount of air to burn one kilogram of the gasoline.

The ratio between the really supplied amount of air to the theoretically necessary one is called the excess air to fuel ratio:

$$\alpha = \frac{L_{\text{real}}}{L_0},$$

where L_{real}, L_0 are the real and theoretically necessary amounts of air to burn 1 kg of the gasoline.

The modern mixing systems of aircraft engines are good enough to form the homogenous mixture of the air and the gasoline. So, the complete combustion is achieved at the relatively low excess air to fuel ratios $(\alpha = 1.03 - 1.05)$.

An insufficient air share in the mixture carries the incomplete combustion, thereby trending to the lower efficiency of the engine as a whole. At the same time, the rich mixtures contribute to getting higher power (the engine outputs the maximum power at $\alpha \approx 0.85 - 0.90$). The temperature of the cylinders and the exhaust valves becomes lower.

The maximum fuel efficiency is achieved at complete fuel combustion, i.e. $\alpha > 1$. It was experimentally proved that the minimum specific fuel flow corresponds to $\alpha \approx 1.05 - 1.10$.

As far as you know from the lecture, the mixture is called rich, when $\alpha < 1.0$, i.e. the actual amount of air in the mixture is less than theoretically needed $L_{\text{actual}} < L_0$.

If the excess air to fuel ratio is equal to a unity, then the mixture is called stoichiometric. The actual amount of air in the mixture is equal to the theoretically needed $L_{\text{actual}} = L_0$

The mixture is lean, in the case when $\alpha > 1.0$, i. e. the actual amount of air in the mixture is more than theoretically needed $L_{\text{actual}} < L_0$.

Depending on the operational mode of the aircraft engine and its maintenance conditions, the excess air-to-fuel ratio alternates within the range $0.65 - 1.05$.

The fresh charge consists of the gasoline and the air. One kilogram of the fresh charge requires αL_0 kilograms of air. Let us designate the mass of the fresh charge related to a specific fuel as $\bar{m}_{\text{fresh charge}}$

$$\bar{m}_{\text{fresh charge}} = 1 + \alpha L_0 \textbf{\textit{ kg/kg fuel}},$$

If you need to express the amount of the fresh charge in moles, then the amount of the fresh charge is equal to

$$\bar{\boldsymbol{M}}_{\text{fresh charge}} = \frac{\boldsymbol{1}}{\boldsymbol{\mu}_{\text{fuel}}} + \alpha \boldsymbol{L}_0' \;\; \boldsymbol{kmole/kg\,fuel}\,,$$

where $\dfrac{1}{\mu_{\text{fuel}}}$ is the amount of fuel (denominator – the molecular mass of the specific fuel). For the gasoline $\mu_{\text{fuel}} \approx 100$.

1.2. Combustion products

The combustion outputs are carbon dioxide, carbon monoxide, water, hydrogen, and nitrogen. The proportions between the combustion products depend on fuel, excess air to fuel ratio, temperature and pressure of combustion.

When the stoichiometric air/gasoline mixture $(\alpha = 1{,}0)$ is combusted, then the outputs are carbon dioxide, water, and nitrogen. In the case of a lean mixture $(\alpha > 1{,}0)$, the combustion outputs are carbon dioxide, water, and nitrogen. In the case of a reach mixture $(\alpha < 1{,}0)$ – carbon dioxide, carbon monoxide, water and nitrogen. In the most general case, a number of combustion products is different from the amount of fresh charge.

The alternation of the volume occupied by the fresh charge, which happens during the combustion process, is described with β_0 (the theoretical coefficient of molecular change of the fresh charge).

$$\beta_{\boldsymbol{0}} = \frac{\boldsymbol{M}_{\text{comb products}}}{\boldsymbol{M}_{\text{fresh charge}}}\,,$$

where $\boldsymbol{M}_{\text{comb products}}$ is the amount of the combustion product (after the combustion), $\boldsymbol{M}_{\text{fresh charge}}$ is the amount of the fresh charge (before the combustion).

1.3. Indicator diagram

Indicator diagram is a diagram of the variation of pressure and volume within a cylinder of a piston engine during a single cycle.

The indicator diagram is taken periodically from the indicator valve equipped on the cylinder head and combustion condition is to be confirmed. Moreover, the indicator diagram can be obtained from the thermal analysis of the engine.

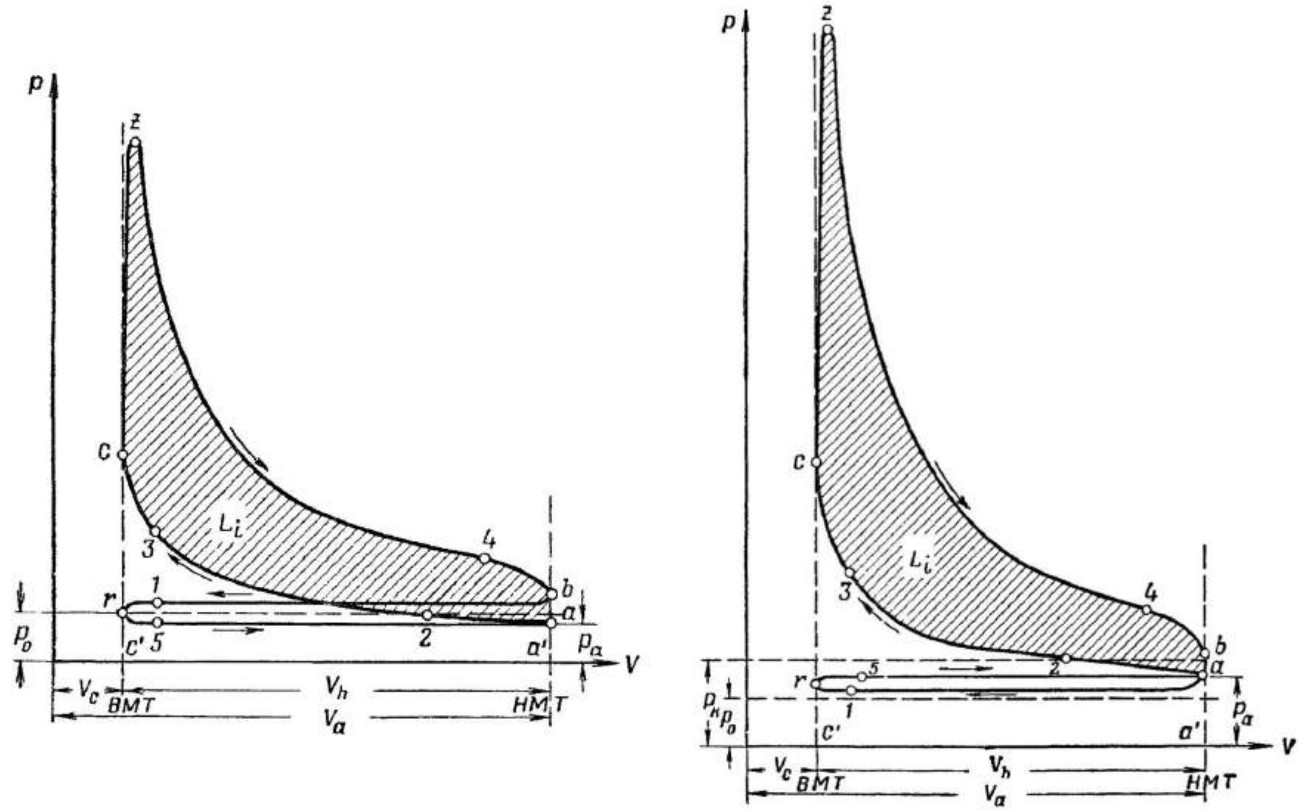
The indicator diagram is very handy to:

- determine the engine power produced by the gas in the cylinder;
- check the timings, especially the ignition timing;

– get the information about combustion, compression, and expansion;

– find out how does the gas exchange mechanism affect the engine operation.

The indicator diagrams of the atmospheric engine (a) and the supercharged engine (b) are shown in Figure 2. As you may notice, the indicator diagram of an atmospheric engine is different from the supercharged engine. The pressure in the cylinder of the supercharged engine at the intake open exceeds the atmospheric pressure and the pressure in the cylinder during the exhaust. That is why the line r-5-a on the diagram (see Figure 2, b) looks down on the exhaust line b-1-r.



a b

Figure 2 – Indicator diagram:
a – atmospheric engine; b – supercharged engine:
numbers: 1 – intake opens; 2 – intake closes; 3 – spark generation;
4 – exhaust opens; 5 – exhaust closes;
lines: line 1-r-5-a-2 – intake; line 2-3 – compression; line 3-c-z – combustion;
line z-4 – expansion; line 4-b-l-r-5 – exhaust

As the theory of heat engines says, the work made by the gas during intake, exhaust, compression and expansion strokes must be considered separately. The work of gas during the intake and exhaust strokes is called pumping work. The amount of work depends on the drag during the intake and the exhaust, and its sign depends on the ratio between the pressure at the intake to the one at the exhaust.

The effective work can be evaluated as a difference between the compression and expansion works, made in the compression and power strokes. The effective work gets on the piston, and next – to the crankshaft over the crank-rod mechanism.

The work taken from the gas in compression and expansion strokes is called an indicator work of the cycle (L_i). The work is equal to the hatched region c - z - b - a - c of the diagram (Fig. 2). As you may see, the indicator work of the supercharged engine is more than that of the atmospheric engine, because the charge that gets in the cylinder is of higher density.

The in-cylinder pressure rises at the compression stroke, reaches a peak after the top dead center, then decreases as the piston moves down on the power stroke. Since the cylinder pressure varies during the operation, we can calculate the average pressure line (a–b). This average pressure, if applied during the time of power stroke, would do the same indicated work as the varying one during the same period. This average pressure is known as indicated mean effective pressure.

The mean indicated pressure p_i can be geometrically evaluated as the rectangle area, which is equal to an area under the pressure curve in the indicator diagram. Hence, $L_i = p_i \cdot V_h$.

The power from gas, transferred by the piston during compression and expansion is called an indicated power N_i. As the power is a work per a specific unit of time (e. g. second), so the power is the product of the indicated work of the single cycle L_i and the number of cycles per one unit of time (e. g. per one second). One operational cycle of the four stroke piston engine takes two crankshaft revolutions. Hence, if the rotational speed is ***n*** rpm, then number of cycles per second will be equal to $\frac{n}{2 \cdot 60}$. As a result, the power outputted by a single cylinder is equal to $\frac{L_i n}{2 \cdot 60}$.

So, the indicated power of the whole engine is equal to the product of the single-cylinder power and the number of the cylinder (*i*).

$$\boldsymbol{N_i = \frac{L_i in}{2 \cdot 60} = \frac{p_i \cdot V_h \cdot i \cdot n}{120}} \; \textbf{\textit{kW,}}$$

where $\boldsymbol{p_i}$ is the mean indicated pressure, MPa;

$\boldsymbol{V_h}$ is the displacement volume, liters (dm^3).

The fuel efficiency of the engine is determined by the mass of the fuel spent by the engine per ***kW·h*** (specific fuel flow, ***kg / kW·h***).

If an engine has its fuel flow $\boldsymbol{G_f}$ and the indicated power $\boldsymbol{N_i}$, kW, then its specific fuel flow is equal to

$$g_{\mathrm{i}} = \frac{G_{\mathrm{f}}}{N_{\mathrm{i}}},\ \frac{kg}{kW \cdot h}.$$

2. THERMAL ANALYSIS ITSELF

The thermal analysis of the piston engine implies the calculation of parameters, which characterize its working processes, and the values that determine its energetic and economical indexes.

According to the analysis results, set power and rotational speed, we can determine the main sizes of the engine (cylinder diameter and piston stroke). Besides, according to the analysis results, we can plot the indicator diagram, which is necessary to determine gas forces acting on the piston, cylinder wall and head, components of the crank-rod mechanism. These forces are next used for the strength analysis of the engine parts.

The analysis of the particular engine adds up to the selection of the experimental coefficients in the separate formulas.

T A S K

Make the thermal analysis of an aircraft air-cooled star piston engine with the parameters:

1) effective power at the design altitude $N_e = 585\,\text{kW}$;
2) rotational speed of a crankshaft $n = 2150$ rpm
3) number of cylinders $\mathrm{i} = 9$;
4) compression ratio $\varepsilon = 6{,}5$;
5) charging pressure $p_{\text{charge}} = 0.133\ \text{MPa}\ (1000\,\text{mm}\,\text{Hg})$;
6) design altitude $H_{\text{d}} = 1500\ \text{m}$;
7) engine prototype ASh-62 IR (see appendix 1).

Volume of work

You must analyze the working cycle, i.e. determine the parameters, which characterize its components (intake, compression, combustion, expansion, exhaust) and the cycle as a whole. According to the obtained results you must determine the main sizes of the engine and the probable fuel efficiency.

Choosing additional initial data

1) **Excess air to fuel ratio** (α). Let us set $\alpha = 0{,}85$. The recommended range for the aircraft engines is $\alpha = 0.75 - 0.90$. When you choose the excess air to fuel ratio, you must always mind the mixing method, operational conditions, forcing rate of the engine etc.

2) **Fuel.** According to the government standards, the gasoline for the aircraft engines must be high-octane, e. g. B-70, B-91/115, B-95/130,

B-100/130. The sort of the used gasoline depends on the compression ratio and the charging pressure. The higher compression ratios and charging pressure, the more high-octane gasoline are required (in this analysis you must use the prototype). The atomic composition of the aircraft gasolines varies within the short range: carbon $C = 0.84 - 0.85$; hydrogen $H = 0.15 - 0.16$; oxygen in the gasoline $O_f = 0$. The sum is $C + H + O_f = 1.0$.

The molecular mass of the aircraft gasolines varies within the small range as well:

$$\mu_f = 100...110, \ \frac{\boldsymbol{kg}}{\boldsymbol{kmole}}.$$

Let`s take: fuel – gasoline B-91/115; elementary composition - $C = 0,842$; $H = 0,158$; $O_f = 0$; average molecular mass – $m_{\mathrm{fuel}} = 100$.

The net calorific value can be determined from the Mendeleev`s equation

$$\boldsymbol{H}_\mathrm{u} = 34013\ \boldsymbol{C} + 102990\ \boldsymbol{H} - 10900\left(\boldsymbol{O}_\mathrm{f} - \boldsymbol{S}_\mathrm{f}\right)\ \boldsymbol{kJ/kg},$$

where $\mathrm{S_f}$ is the mass portion of the sulfur in the fuel.

In the considered example,

$$\boldsymbol{H}_\mathrm{u} = 34013\ \boldsymbol{C} \cdot 0.842 + 102990 \cdot 0.158 = 44890\ \ \boldsymbol{kJ/kg}$$

3) **Parameters of air at the design altitude**. The pressure and temperature of the air at the design altitude may vary on a season, day hour and other conditions. So, to evaluate the mentioned parameters at any altitude you must reference the ISA table, which interrelates different atmospheric parameters and the altitude. The parameters, evaluated according to this table are known as a standard day parameters (ISA). The ISA is presented in the Appendix 2 (see also [1]).

Following the approach described above, the pressure and temperature at the design altitude $H_{\mathrm{design}} = 1500$ m are $p_{\mathrm{atm}} = 0.085$ MPa, $T_{\mathrm{atm}} = 278\ \mathrm{K}\ \left(5^{\mathrm{o}}\mathrm{C}\right)$.

2.1. Intake stroke

The intake stroke is a process of filling the cylinder with a fresh charge (air or air/fuel mixture). The greater charge manages to get in the cylinder, the higher power it will output. The cylinder charging with the fresh air (air/gasoline mixture) can be achieved with the supercharger. As usual, the modern aircraft engines have a mechanically driven centrifugal supercharger (MDSC). The pressure at the supercharger discharge is called a charging pressure p_{ch}. The mission of the intake stroke analysis is getting the pressure and the temperature of the fresh charge at the intake`s end (p_α, T_α).

1. According to the task, the charging pressure is $p_{\text{ch}} = 0.133$ MPa. The temperature of the charge at the end of the intake stroke is

$$\boldsymbol{T}_{\text{ch}} = \boldsymbol{T}_{\text{atm}} + \Delta\boldsymbol{T}_{\text{ch}},$$

where $\Delta T_{\text{c}} = \dfrac{L_{ad}}{C_p \cdot \eta_{ad}}$ is the temperature growth in the supercharger.

The specific adiabatic work is calculated as

$$\boldsymbol{L}_{\text{ad}} = \boldsymbol{C}_{\text{p}}\boldsymbol{T}_{\text{atm}}\left[\left(\frac{\boldsymbol{p}_{\text{ch}}}{\boldsymbol{p}_{\text{atm}}}\right)^{\frac{\text{k-1}}{\text{k}}} - 1\right] = 1.004 \cdot 278\left[\left(\frac{0.133}{0.085}\right)^{0,288} - 1\right] = 38,5\ \frac{\boldsymbol{kJ}}{\boldsymbol{kg}},$$

where $C_p = 1.004\ \dfrac{\text{kJ}}{\text{kg} \cdot \text{K}}$ is a heat capacity of the air;

$k = 1.4$ is an adiabatic index of the air.

Let us set the adiabatic efficiency equal to $\eta_{\text{ad}} = 0.67$ (the recommended range is $\eta_{\text{ad}} = 0.65 - 0.70$).

Then

$$\Delta\boldsymbol{T}_{\text{ch}} = \frac{\boldsymbol{L}_{\text{ad}}}{\boldsymbol{C}_{\text{p}}\eta_{\text{ad}}} = \frac{38.5}{1.004 \cdot 0.67} = 57.3\ \boldsymbol{K},$$

and

$$\boldsymbol{T}_{\text{ch}} = \boldsymbol{T}_{\text{atm}} + \Delta\boldsymbol{T}_{\text{ch}} = 278 + 57.3 = 335.3\ \boldsymbol{K}.$$

2. Determine the volumetric efficiency of the supercharged engine at the given altitude:

$$\eta_{\text{v H}} = \eta_{\text{v cor}}\sqrt{\frac{\boldsymbol{T}_{\text{ch}}}{288}} \cdot \frac{1.15\varepsilon - \dfrac{\boldsymbol{p}_{\text{atm}}}{\boldsymbol{p}_{\text{ch}}}}{1.15\varepsilon - 1},$$

where $\eta_{\text{v cor}}$ is a standard day corrected volumetric efficiency, i.e. volumetric efficiency of the atmospheric engine in the standard day conditions ($p_0 = 0.101$ MPa, $T_0 = 288$ K).

The volumetric efficiency of the modern piston engines can be found within the tight range:

$$\eta_{\text{v cor}} = 0.80 - 0.82.$$

Let us choose $\eta_{\text{v cor}} = 0.81$, then

$$\eta_{\text{v ch}} = 0.81\sqrt{\frac{335.3}{288}}\;\frac{1.15\cdot 6.5-\dfrac{0.085}{0.133}}{1.15\cdot 6.5-1} = 0.93\,.$$

3. Determine the pressure at the end of the intake stroke:

$$\boldsymbol{p}_{\text{a}} = \frac{\boldsymbol{p}_{\text{ch}}}{\boldsymbol{\varepsilon}}\left[\eta_{\text{v H}}\left(\boldsymbol{\varepsilon}-1\right)\boldsymbol{\delta}+\frac{\boldsymbol{p}_{\text{r}}}{\boldsymbol{p}_{\text{ch}}}\right],$$

where p_{r} is the pressure of the residual gas at the end of the stroke.

As the gas from the cylinder is discharged to the atmosphere, so p_{r} of the supercharged engines can be taken $(1.05-1.15)\,p_{\text{atm}}$.

Let us choose $p_{\text{r}} = 1.12\,p_{\text{atm}}$ for our case. Note, that the mistaken p_{r} makes an minor effect on the pressure at the end of the intake.

The following is a formula to calculate a heating degree of the mixture during the intake

$$\boldsymbol{\delta} = \frac{\boldsymbol{T}_{\text{ch}}+\Delta\boldsymbol{T}_{\text{heat exchange}}}{\boldsymbol{T}_{\text{ch}}}\,.$$

The heating degree conditionally characterizes the summed up heat exchange between the air/gasoline mixture and the cylinder wall, the cylinder head, the piston head, and their cooling down thanks to the mixture evaporation. The heat exchange is positive $\left(\Delta T_{\text{heat exchange}} > 0\right)$ in the supercharged engines with low temperature at the charger discharge. When temperature grows at the supercharger discharge, the heat exchange may flip. That means that the heat will be transferred from the gas to the structural elements of the piston engine.

The following are the recommendations you may follow, when choosing the $\Delta T_{\text{heat exchange}}$ for the particular analysis:

If $T_{\text{ch}} = (310-340)\,\text{K}$ then $\Delta T_{\text{heat exchange}} = +(2-10)\,\text{K}$,

If $T_{\text{ch}} = (360-380)\,\text{K}$ then $\Delta T_{\text{heat exchange}} = -(5-15)\,\text{K}$.

In the considering case, the temperature correction for the heat exchange can be taken $\Delta T_{\text{heat exchange}} = 3\ \text{K}$.

Then

$$\delta = \frac{335.5+3}{335.3} = 1.01.$$

Now we have all necessary data to evaluate the pressure at the end of the intake stroke:

$$\boldsymbol{p}_{\alpha} = \frac{0.133}{6.5}\left[0.93(6.5-1)1.01 + \frac{1.12 \cdot 0.085}{0.133}\right] = 0.121\, \boldsymbol{MPa}.$$

Usually, the pressure of the charge in the cylinder in the end of the intake stroke is $p_{\alpha} = (0.88 - 0.96)p_{\text{ch}}$.

4. Determine the residual gas ratio as

$$\gamma = \frac{\boldsymbol{p}_{\text{r}} \boldsymbol{T}_{\text{ch}}}{\boldsymbol{p}_{\text{ch}} \boldsymbol{T}_{\text{r}} \eta_{\text{V H}} (\boldsymbol{\varepsilon} - 1)},$$

where $p_{\text{r}} = 1.12 \cdot p_{\text{H}} = 1.12 \cdot 0.085 = 0.0952$ MPa is pressure of the residual gas;

T_{r} is a temperature of the residual gas (it depends on the compression ratio, excess air/fuel ratio, charging pressure and other factors).

Engines of interest have the temperature of the residual gas within the range 1100…1200 K.

Let us take $T_{\text{r}} = 1100$ K for our case.

Then

$$\gamma = \frac{0.0952 \cdot 335.3}{0.133 \cdot 1100 \cdot 0.93(6.5-1)} = 0.043.$$

Typically, the residual gas ratio of the supercharged engines is 0.02 – 0.05.

5. Determine the temperature at the end of the intake stroke:

$$\boldsymbol{T}_{\alpha} = \frac{\boldsymbol{T}_{\text{ch}} + \Delta \boldsymbol{T}_{\text{heat exchange}} + \gamma \boldsymbol{T}_{\text{r}}}{1+\gamma} = \frac{335.3 + 3 + 0.043 \cdot 1100}{1 + 0.043} = 372\, \boldsymbol{K}.$$

2.2. Compression stroke

As the result of the compression stroke analysis, we expect to obtain the pressure and temperature in the end of the compression stroke (p_{c} and T_{c}).

1. Determine the pressure at the end of the compression stroke:

$$\boldsymbol{p}_{\text{c}} = \boldsymbol{p}_{\text{a}} \boldsymbol{\varepsilon}^{\boldsymbol{n}_{\text{c}}} = 0.121 \cdot 6.5^{1.35} = 1.512\, \boldsymbol{MPa},$$

where n_{c} is a polytropic index.

Let us choose $n_{\text{c}} = 1.35$. The recommended range for the aircraft engines is $n_{\text{c}} = (1.33 - 1.35)$.

2. Let us determine the temperature at the end of the compression stroke as

$$T_c = T_\alpha \varepsilon^{n_c - 1} = 372 \cdot 6.5^{1.35-1} = 716\ K.$$

Note that the pressure and temperature at the end of the compression stroke are usually equal to (for the supercharged engines)

$$p_c = (1.3 - 2.5)\ MPa,$$

$$T_c = (600 - 800)\ K.$$

2.3. Combustion analysis

As the result of the analysis, we determine the maximal temperature and pressure after the gasoline combustion (T_z and p_z).

1. Determine the temperature at the end of the combustion (T_z). Let us use the combustion equation, which is based on the first law of thermodynamics:

$$\frac{\xi H'_u}{\left(\alpha M_o + \frac{1}{m_{fuel}}\right)\cdot(1+\gamma)} = \beta m c_{vmz} t_z - m c_{vmc} t_c,$$

If $\alpha < 1.0$, then the combustion is incomplete. In this case, the net caloric value of the fuel in the combustion conditions can be evaluated as

$$H'_u = (1.39\alpha - 0.39) H_u = (1.39 \cdot 0.85 - 0.39) 44893 = 35550\ kJ/kg;$$

ξ is the effective calorification factor; the effective calorification factor varies within the limits $\xi = (0.90 - 0.92)$.

M_o is the theoretically required amount of air to combust the specific mass of gasoline:

$$M_o = \frac{1}{0.209}\left(\frac{C}{12} + \frac{H}{4} - \frac{O_{fuel}}{32}\right) = \frac{1}{0.209}\left(\frac{0.842}{12} + \frac{0.158}{4}\right) = 0.522\ kmole/kg.$$

Note that we set in the initial data the true amount of air that enters the combustion chemical reaction with a specific mass of the gasoline $\alpha = 0.85$.

Thus

$$\alpha M_o = 0.85 \cdot 0.522 = 0.4437\ kmole/kg;$$

$\beta = \frac{\beta_o + \gamma}{1+\gamma}$ is the real coefficient of molecular change of the fresh charge,

β_o is the theoretical coefficient of molecular change of the fresh charge.

The next is the equation to calculate β_o for the considered case ($\alpha < 1.0$):

$$\beta_o = 1 + \frac{\frac{\boldsymbol{H}}{4} + \frac{\boldsymbol{O}_{\text{fuel}}}{32} - \frac{1}{\boldsymbol{m}_{\text{т}}} + 0.209 \cdot \boldsymbol{M}_o (1-\alpha)}{\alpha \boldsymbol{M}_o + \frac{1}{\boldsymbol{m}_{\text{fuel}}}} =$$

$$= 1 + \frac{\frac{0.158}{4} - \frac{1}{100} + 0.209 \cdot 0.522(1-0.85)}{0.85 \cdot 0.522 + \frac{1}{100}} = 1.1.$$

Then

$$\beta = \frac{1.1 + 0.043}{1 + 0.043} = 1.096.$$

$\boldsymbol{mc}_{\text{vmc}}$ is an averaged molar heat capacity of gases in the temperature range $[0 - \boldsymbol{t}_o,\ C^\circ]$. It is calculated as [2]:

$$\boldsymbol{mc}_{\text{vmc}} = 20.9 + 209 \cdot 10^{-5} \cdot \boldsymbol{t}_c = 20.9 + 209 \cdot 10^{-5} \cdot 443 = 21.8\ \boldsymbol{kJ/kmole}\ {}^{o}\boldsymbol{C},$$

where $t_c = T_c - 273 = 716 - 273 = 443\ {}^{o}\text{C}$;

$\boldsymbol{mc}_{\boldsymbol{vmz}}$ is an averaged molar heat capacity of gases in the temperature range $[0 - \boldsymbol{t}_o,\ C^\circ]$. It depends on the excess air-to-fuel ratio and is evaluated as it is described in [2]. For the range $0.7 \le \alpha \le 1.0$ we get

$$\boldsymbol{mc}_{\text{vmz}} = 4.18(4.53 + \alpha) + \frac{360 + 250 \cdot \alpha}{2} 10^{-5} \cdot \boldsymbol{t}_z =$$

$$= 4.18(4.53 + 0{,}85) + \frac{360 + 250 \cdot 0.85}{2} 10^{-5} \cdot \boldsymbol{t}_z =$$

$$= \left(22.55 + 286 \cdot 10^{-5} \cdot \boldsymbol{t}_z\right)\ \boldsymbol{kJ/kmole} \cdot {}^{o}\boldsymbol{C}.$$

The other variables in the equation are

$$\alpha = 0.85;\ \boldsymbol{m}_{\text{fuel}} = 100;\ \gamma = 0.043.$$

Let us substitute all known values in the equation:

$$\frac{0.92 \cdot 35550}{(0.85 \cdot 0.522 + 0.01)(1 + 0.043)} =$$

$$= 1.096\left(22.55 + 286 \cdot 10^{-5} \cdot \boldsymbol{t}_z\right)\boldsymbol{t}_z - 21.8 \cdot 443,$$

and get the quadratic equation

$$314 \cdot 10^{-5} \cdot \boldsymbol{t}_z^2 + 24{,}65 \cdot \boldsymbol{t}_z - 79000 = 0.$$

Having solved it about t_z, we get

$$\boldsymbol{t}_{\text{z}} = 2440\ {}^{\text{o}}\boldsymbol{C};\ \boldsymbol{T}_{\text{z}} = \boldsymbol{t}_{\text{z}} + 273 = 2713\ \boldsymbol{K.}$$

The expected range of aircraft engines is $T_{\text{z}} = (2600 - 2900)\,\text{K}$.

Note that this is not the only one method to get the temperature T_{z}. You may also use the method based on the internal energy calculation and T_{z} calculation (see example in [3]).

2. Determine the maximum pressure at the end of the combustion

$$\boldsymbol{p_z} = \beta \boldsymbol{p}_{\text{c}} \frac{\boldsymbol{T}_{\text{z}}}{\boldsymbol{T}_{\text{c}}} = 1.096 \cdot 1.512 \frac{2713}{716} = 6.28\ \boldsymbol{MPa}.$$

2.4. Power stroke

This part of the analysis aims getting the pressure and the temperature at the end of the power stroke (p_{pow} and T_{pow}).

1. Determine the pressure at the end of the power stroke as

$$\boldsymbol{p}_{\text{pow}} = \frac{\boldsymbol{p}_{\text{z}}}{\boldsymbol{\varepsilon}^{\boldsymbol{n}_{\text{exp}}}} = \frac{6.28}{6.5^{1.24}} = 0.616\ \boldsymbol{MPa},$$

where n_{p} is the polytropic index. Let us set it being equal to $n_{\text{p}} = 1.24$. The recommended range for aircraft engines is $n_{\text{p}} = 1.24 - 1.26$.

2. Determine the temperature at the end of the power stroke as

$$\boldsymbol{T}_{\text{pow}} = \frac{\boldsymbol{T}_{\text{z}}}{\boldsymbol{\varepsilon}^{\boldsymbol{n}_{\text{exp}}-1}} = \frac{2713}{6.5^{1.24-1}} = 1713\ \boldsymbol{K}.$$

2.5. Indicated parameters of the engine

1. Determine the mean indicated pressure as

$$\boldsymbol{p}_{\text{i}} = \frac{\varphi \boldsymbol{p}_{\text{ch}}}{\boldsymbol{\varepsilon} - 1}\left[\frac{\lambda}{\boldsymbol{n}_{\text{exp}} - 1}\left(1 - \frac{1}{\boldsymbol{\varepsilon}^{\boldsymbol{n}_{\text{exp}}-1}}\right) - \frac{1}{\boldsymbol{n}_{\text{c}} - 1}\left(1 - \frac{1}{\boldsymbol{\varepsilon}^{\boldsymbol{n}_{\text{c}}-1}}\right)\right],$$

where φ is the rounding coefficient of the indicator diagram.

Let us set $\varphi = 0.96$. Usually, the rounding coefficient of the indicator diagram is in the range $\varphi = 0.94 - 0.97$;

$\lambda = \dfrac{p_z}{p_{\text{c}}}$ is a pressure ratio.

In our particular case $\lambda = \frac{6.28}{1.512} = 4.15$,

$$\boldsymbol{p}_{\mathrm{i}} = \frac{0.96 \cdot 1.512}{6.5-1}\left[\frac{4.15}{1.24-1}\left(1-\frac{1}{6.5^{1.24-1}}\right)-\frac{1}{1.35-1}\left(1-\frac{1}{6.5^{1.34-1}}\right)\right] = 1.29\ \boldsymbol{MPa.}$$

2. Determine the indicated efficiency

$$\boldsymbol{\eta}_{\mathrm{i}} = \frac{\boldsymbol{mRT}_{\mathrm{ch}}\boldsymbol{p}_{\mathrm{i}}}{\boldsymbol{H}_{\mathrm{u}}\boldsymbol{p}_{\mathrm{ch}}\boldsymbol{\eta}_{\mathrm{v\ ch}}}\left(\alpha \boldsymbol{M}_{\mathrm{o}} + \frac{1}{\boldsymbol{m}_{\mathrm{fuel}}}\right),$$

where $mR = 8{,}314\ \ \mathrm{kJ/kmole \cdot K}$ is a universal gas constant.

$$\boldsymbol{\eta}_{\mathrm{i}} = \frac{8.314 \cdot 335.3 \cdot 1.29}{44893 \cdot 0.133 \cdot 0.93}(0.85 \cdot 0.522 + 0.01) = 0.29.$$

3. Specific indicated fuel flow rate:

$$\boldsymbol{g}_{\mathrm{i}} = \frac{3600}{\boldsymbol{H}_{\mathrm{u}}\boldsymbol{\eta}_{\mathrm{i}}} = \frac{3600}{44893 \cdot 0.29} = 0.276\ \boldsymbol{kg/kW \cdot h}$$

2.6. Effective parameters of the engine

1. Determine the mean effective pressure :

$$\boldsymbol{p}_{\mathrm{e}} = \boldsymbol{p}_{\mathrm{i}} - \boldsymbol{\kappa}_{\mathrm{i}}\boldsymbol{p}_{\mathrm{i}} - \boldsymbol{p}_{\mathrm{mech}} = (\boldsymbol{1} - \boldsymbol{\kappa}_{\mathrm{i}}) \cdot \boldsymbol{p}_{\mathrm{i}} - \boldsymbol{p}_{\mathrm{mech}},$$

where $\boldsymbol{\kappa}_{\mathrm{i}} = \dfrac{\boldsymbol{L}_{\mathrm{ad}}}{\dfrac{\boldsymbol{H}_{\mathrm{u}}}{\boldsymbol{L}_{\mathrm{o}}} \cdot \dfrac{\boldsymbol{\eta}_{\mathrm{i}}}{\alpha} \cdot \boldsymbol{\eta}_{\mathrm{ch}}}$ is the factor, which indicates the portion of indicated power spent for supercharger actuation.

As you remember, the specific adiabatic work of the compression made by the charger in this analysis is equal $L_{\mathrm{ad}} = 38.5\ \ \mathrm{kJ/kg}$;

η_{ch} is the effective efficiency of the charger:

$$\boldsymbol{\eta}_{\mathrm{ch}} = \boldsymbol{\eta}_{\mathrm{ad}}\boldsymbol{\eta}_{\mathrm{mech\ ch}} = 0.67 \cdot 0.96 = 0.642;$$

L_o is a stochiometric amount of air to burn the specific amount of fuel:

$$\boldsymbol{L}_{\mathrm{o}} = \frac{1}{0.232}\left(\frac{8}{3}\boldsymbol{C} + 8\boldsymbol{H} - \boldsymbol{O}_{\mathrm{т}}\right) = \frac{1}{0.232}\left(\frac{8}{3} \cdot 0.842 + 8 \cdot 0.158\right) = 15.1\,\frac{\boldsymbol{kg\ air}}{\boldsymbol{kg\ fuel}}.$$

Let us substitute the obtained parameters and get $\boldsymbol{\kappa}_{\mathrm{i}}$:

$$\kappa_{\text{i}} = \frac{38.5}{\frac{44893}{15.1}\frac{0.29}{0.85}0.642} = 0.057 \,.$$

The mean friction pressure $\boldsymbol{p}_{\text{mech}}$ characterizes the power, spent for the friction overcoming, auxiliaries driving and so-called “pumping” losses.

The following empirical equations [4] are used to determine the mean friction pressure according to the available experimental data:

$$\boldsymbol{p}_{\text{mech}} = \boldsymbol{p}_{\text{mech cor}}\left[0.65 + 0.35\frac{\boldsymbol{p}_{\text{atm}}}{\boldsymbol{p}_{\text{o}}}\sqrt{\frac{288}{\boldsymbol{T}_{\text{ch}}}}\right],$$

where $\boldsymbol{p}_{\text{mech cor}}$ is corrected mean friction pressure.

The next empirical equation [4] can be used for the star piston engines:

$$\boldsymbol{p}_{\text{mech cor}} = 0.008(\boldsymbol{\varepsilon} + 8.5)\boldsymbol{C}_{\text{m}} \cdot 0.098 \; \boldsymbol{MPa} \,,$$

where $\boldsymbol{C}_{\text{m}} = \frac{\boldsymbol{S}\,\boldsymbol{n}}{30}$, $\boldsymbol{m}/\boldsymbol{s}$ is averaged piston speed.

For the learning purposes, you can use the prototype`s averaged piston speed.

Engines AI-26V, ASh-62IR, ASh-82T:	$\boldsymbol{C}_{\text{m}} = (\,11.3 - 12.6\,)\;\boldsymbol{m}/\boldsymbol{s}$
Engine AI-14R:	$\boldsymbol{C}_{\text{m}} = (\,9 - 9{,}5\,)\;\boldsymbol{m}/\boldsymbol{s}$

In our particular case we will set $\boldsymbol{C}_{\text{m}} = 12.5\;\; \boldsymbol{m}/\boldsymbol{s}$.

Then

$$\boldsymbol{p}_{\text{mech cor}} = 0.008(6.5 + 8.5)12.5 \cdot 0.098 = 0.147 \; \boldsymbol{MPa} \,.$$

$$\boldsymbol{p}_{\text{mech}} = 0.147\left[0.65 + 0.35\frac{0.085}{0.1013}\sqrt{\frac{288}{335.3}}\right] = 0.133 \; \boldsymbol{MPa}.$$

Having substituted $\boldsymbol{\kappa}_{\text{i}}$ and $\boldsymbol{p}_{\boldsymbol{mech}}$ in the formula for the mean effective pressure, we get

$$\boldsymbol{p}_{\text{e}} = (1 - \boldsymbol{\kappa}_{\text{i}})\boldsymbol{p}_{\text{i}} - \boldsymbol{p}_{\text{mech}} = (1 - 0.057)1.29 - 0.133 = 1.084 \; \boldsymbol{MPa} \,.$$

2. Determine the mechanical efficiency as

$$\eta_{\text{eff}} = \frac{\boldsymbol{p}_{\text{e}}}{\boldsymbol{p}_{\text{i}}} = \frac{1.084}{1.29} = 0.84 \,.$$

The supercharged aircraft engines have their mechanical efficiency within the range $\eta_{\text{mech}} = 0.80 - 0.88$.

3. Determine the effective efficiency as

$$\eta_e = \eta_i \eta_{mech} = 0.29 \cdot 0.84 = 0.244 .$$

4. Determine the effective fuel flow rate

$$\boldsymbol{q}_e = \frac{3600}{\boldsymbol{H}_u \cdot \eta_e} = \frac{3600}{44893 \cdot 0.244} = 0.325\ \boldsymbol{kg/kW \cdot h} .$$

2.7. Main sizes of the engine

1. As it follows from the formula for the effective power of the four stroke piston engine [5]

$$\boldsymbol{N}_e = \frac{\boldsymbol{p}_e \boldsymbol{i}\, \boldsymbol{V}_h \boldsymbol{n}}{120} ,$$

the displacement volume of all cylinders is equal to

$$\boldsymbol{V}_h = \frac{120 \cdot \boldsymbol{N}_e}{\boldsymbol{p}_e\, \boldsymbol{i}\, \boldsymbol{n}} \boldsymbol{, m}^3 ,$$

where i is the number of cylinders;
n is the crankshaft rotational speed;
p_e is the mean effective pressure.

In our case,

$$\boldsymbol{i} = 9;\ \boldsymbol{n} = 2150\ \boldsymbol{min}^{-1};\ \boldsymbol{p}_e = 1.084\ \boldsymbol{MPa},$$

the effective power at the design altitude is

$$\boldsymbol{N}_e = \boldsymbol{N}_{e\,p} = 585\ \boldsymbol{kW} .$$

Hence,

$$\boldsymbol{V}_h = \frac{120 \cdot 585 \cdot 10^3}{1.084 \cdot 10^6 \cdot 9 \cdot 2150} = 3.36 \cdot 10^{-3}\ \boldsymbol{m}^3$$

2. Determine the cylinder diameter ***D*** and the piston stroke ***S***. Let us designate their ratio as ***m***. Then

$$\boldsymbol{V}_h = \frac{\pi \boldsymbol{D}^2}{4} \boldsymbol{S} = \frac{\pi \boldsymbol{D}^3}{4} \boldsymbol{m} ,$$

whence

$$\boldsymbol{D} = \sqrt[3]{\frac{4 \cdot \boldsymbol{V}_h}{\pi \boldsymbol{m}}} .$$

Let us take m from the prototype (see Appendix 2). For our particular case, $\boldsymbol{m} = 1.12$. Then

$$D = \sqrt[3]{\frac{4 \cdot 3.36 \cdot 10^{-3}}{\pi \cdot 1.12}} = 0.156 \ \boldsymbol{m} = 156 \ \boldsymbol{mm}.$$

Determine the piston stroke:

$$\boldsymbol{S} = \boldsymbol{mD} = 1.12 \cdot 0.156 = 0.175 \ \boldsymbol{m} = 175 \ \boldsymbol{mm}.$$

3. The total volume of the engine (engine capacity) is

$$\boldsymbol{i}\boldsymbol{V}_{\mathrm{h}} = 9 \cdot 3.36 \cdot 10^{-3} = 30.24 \cdot 10^{-3} \ \boldsymbol{m}^3 = 30.24 \ \boldsymbol{litres}.$$

4. Check the correctness of the calculations:

$$\boldsymbol{N}_{\mathrm{e\,p}} = \frac{\boldsymbol{p}_{\mathrm{e}}\,\boldsymbol{i}\boldsymbol{V}_{\mathrm{h}}\boldsymbol{n}}{120} = \frac{1.084 \cdot 10^{6} \cdot 9 \cdot 3.36 \cdot 10^{-3} \cdot 2150}{120} = 587 \ \boldsymbol{kW}$$

According to the task, the engine we have just analyzed must output $N_{\mathrm{e\,p}} = 585$ ***kW***.

APPENDIX 1

Main data of some aircraft piston engines that are in maintenance

Engine / Parameter	M-14P	ASh-62 IR	AI-26V	ASh-82T
Number of cylinders	9	9	7	7 x 2=14
Diameter of the cylinder, mm	105	155,5	155,5	155,5
Piston stroke, mm	130	174,5	155	155
S/D	1,236	1,12	0,996	0,996
Compression ratio	6,3 ± 0,1	6,4 ± 0,1	6,5 ± 0,1	6,9 ± 0,1
Supercharger type	Driven centrifugal supercharger	Driven centrifugal supercharger	Driven centrifugal supercharger	Driven centrifugal supercharger
Charging pressure, MPa	0.106	0.120	0.101	0.136
Design altitude, m	Land use	1500	2000	1600
Power at the design altitude, kW (hp)*	213 (290)	617 (840)	338 (460)	1198 (1630)
Rotational speed, rpm	2400/2050	2100	2050	2400
Gasoline	B91/115	B91/115	B91/115	B95/130
Ignition advance (in degrees of the crank angle to TDC)	25±1	20±1	25±1	21±1
Valve opening and closing in degrees of the crank angle:				
a) intake valve:				
opening (till TDC):	20±4	15±10	20±4	23±10
closing (after BDC):	54±4	66	63	66
b) exhaust valve:				
opening (till TDC):	66±4	74	50	74
closing (after BDC):	25±4	25+10	33±4	25+10

* – takeoff mode

APPENDIX 2

Standard atmosphere

H, m	T_{atm}, K	P_{atm}, Pa
0	288.2	101330
500	284.9	95464
1000	281.7	89877
1500	278.4	84559
2000	275.2	79499
2500	271.9	74690
3000	268.7	70123
4000	262.2	61661
5000	255.7	54052
6000	249.2	47217
7000	242.7	41106
8000	236.2	35653
9000	229.7	30801
10 000	223.3	26500
11 000	216.8	22700
12 000	216.7	19399

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Білогуб Олександр Віталійович
Сіренко Фелікс Феліксович

ТЕПЛОВИЙ РОЗРАХУНОК АВІАЦІЙНОГО ПОРШНЕВОГО ДВИГУНА

(Англійською мовою)

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Національний аерокосмічний університет ім. М. Є. Жуковського
«Харківський авіаційний інститут»
61070, Харків-70, вул. Чкалова, 17
http://www.khai.edu
Видавничий центр «ХАІ»
izdat@khai.edu
61070, Харків-70, вул. Чкалова, 17

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