The efficiency of heating the gasoline engine while working in cyclic mode: acceleration - coasting

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Abstract: The article provides a rationale for a way of increasing the efficiency of the engine post-launch by transferring it to the “free acceleration-coasting” operating mode. The method allows to download the coupling and engine parts by means of inertial forces arising while working on non-braking unsteady speed modes, which significantly increases the efficiency of the post-start heating of internal combustion engines in relation to the steady-state idling. A comparative assessment of the run-out of parts of the main details of the major coupling of the ZMZ-4062.10 gasoline engine during the start-up period in the dynamic capacity mode and at idling is given. It remains completely acceptable and by no means can be considered threatening. It is worth noting that the application of the method is accompanied by an increase in efficiency due to the reduction of the warm-up time and fuel consumption, which makes it reasonable to consider it acceptable for use in automobile operation conditions.

1. Introduction
The Russian Federation territory is located in a temperate and moderate cold climatic region, where about 80% of the country's autotractor park is used. In spite of severe weather and temperature conditions during equipment operation, ensuring the storage of all vehicles in heated garages in the winter period is an impracticable task. Most of the units of equipment are stored in open areas [1].

Under these conditions the time spent on thermal preparation of the engine is 20–80 min that is explained by an increase in heat transfer from the surface of the unit to the environment and causes a sharp increase in the engine warm-up time after starting up to optimum operating temperatures and reducing the cooling down period after stopping.

Low temperatures of the environment and the engine during start-up, as well as subsequent heating, cause an increase in relative pumping and heat losses, deterioration of the mixture formation processes and, consequently, an increase in the specific fuel consumption at a lower crankshaft rotation frequency and a decrease in engine power in steady state at idle [2], which leads to prolonged downtime of the vehicle, accompanied by increased run-out of engine parts and an increase in harmful emissions into the atmosphere, as well as the negative impact on road safety.

The solution of these problems in conditions of low temperatures is possible due to the choice of the optimal mode of thermal preparation of the vehicle for operation.

Improving the efficiency of thermal preparation using modern methods and means depends on the method of equipment storage in the inter-shift period. Work in this area is carried out in several independent scientific areas, pre-launch and post-launch, presented in Figure 1.
Figure 1. Methods and means of thermal preparation for storing equipment without any garage.

The most widely used methods under thermal conditions after post-launch heating are the ones of thermal preparation for non-garaged storage:

- individual (autonomous);
- self-heating of the engine.

Individual means include insulating covers, heaters operating on liquid fuel, or electric ones. Electric heaters are used to preheat or heat up the engine cooling fluid, engine oil and gearbox oil, fuel in the fuel system, and electrolyte in the battery.

Self-heating is an even bringing the thermal state of all units and components of the car after starting to the operating temperature, allowing you to start normal (economical) work. The practice of operating the internal combustion engine and numerous studies show that at low temperatures it is impossible to warm up the engine to the optimum temperature recommended by the manufacturer by idle running, and efficiency can be achieved at the expense of using technical devices and tools requiring changes in the standard design of various engine systems and also by increasing the engine load during its operation after start.

The engine operation under load promotes the reduction of the warm-up time, therefore the use of various methods and devices controlling the engine load level by means of microprocessor technology in some cases is of great scientific and practical interest.

It is proposed to solve the problem at the operational level, i.e. choose the most effective mode of warming up the engine after a long storage of the car in the open parking lot at low temperatures.

2. Purpose of the study
Improving the efficiency of post-launch of a gasoline engine operated at low temperatures due to the dynamic capacity.

To achieve this goal it is necessary to solve the following tasks:
1. To set the intensity of change in heat flux depending on the heating mode.
2. To reveal the regularity of changes in thermal conditions on the number of cycles.
3. To estimate the degree of run-out of the main coupling with different modes of loading the engine during post-launch warming.

4. To evaluate the efficiency of the method of warming up the engine by dynamic capacity at low temperatures.

Under production conditions, taking into account a lot of operational and design factors affecting the warming up of the engine of an unprepared stationary machine, one of the possible ways of loading the engine is to work in unsteady mode.

The easiest way of implementing this mode accessible to automatic control is transferring the work to the free acceleration-coasting mode. In this case, the loading is made by its own inertial masses, with successive alternating acceleration and coasting cycles created by the fuel supply control.

To solve this problem, a method in which the engine is operated by periodically repeated cycles consisting of fuel feed cycles (acceleration cycles) and total fuel shutdown cycles (coasting cycles) is proposed. It can be represented graphically (Fig. 2).

![Figure 2. Diagram of the cyclic mode of the engine "acceleration-coasting".](image)

The total amount of heat required to warm up the engine is determined by the expression:

$$Q_{tot} = \bar{c} \cdot \bar{m}_{ice} \cdot \Delta T$$  \hspace{1cm} (1)

where $\bar{c}$ - the average heat capacity of engine materials, J/C; $\bar{m}_{ice}$ - total engine weight, kg; $\Delta T = T_v - T_{zh}$ – cold start temperature (difference between environment temperature and coolant, accordingly).

During the cyclic mode of "free acceleration-coasting", the heat to warm up the engine comes in the form of two components:

$$Q_{tot} = Q_p + Q_v$$  \hspace{1cm} (2)

where $Q_p$ – the heat generated during the free acceleration cycle of the engine; $Q_v$ – the heat generated during the run-out cycle.

This mode allows to redistribute the indicator work into cycles: during the acceleration cycle due to the increased cyclic fuel supply (compared to idling), it increases by the amount of work spent on overcoming inertial forces ($A_v$) of moving parts of the engine. This happens by the accumulation of the kinetic energy; on the run-off cycle due to zero cycle fuel supply, the indicator operation is zero (). That is the kinetic energy accumulated in the acceleration cycle is spent on overcoming the mechanical losses. During the acceleration cycle, the engine's working is carried out with increased cyclic fuel supply with a slight presence of residual gases in the cylinders, which promotes better mixing and complete combustion of the air-fuel mixture. That is, for some period of time the engine works with a maximum load (similar to the brake tests) releasing the maximum amount of heat.

$$Q = G_t \cdot t_v \cdot q.$$

$$Q = G_t \cdot t_v \cdot q.$$  \hspace{1cm} (3)
where $Q_i$ is the amount of heat supplied to the engine, $J$; $G_i$ – hour fuel consumption in free acceleration mode, $g$/kW·h; $t_p$ – time in overclocking mode, $s$; $q$ – the heating value of the fuel, $J$/kg.

When the engine reaches the set frequency of rotation of a cranked shaft fuel supply is switched off. The engine goes into free run mode turning the accumulated kinetic energy into heat.

$$Q_{kr} = \frac{1}{2} \left( \omega_t^2 - \omega_{en}^2 \right) \cdot \lambda$$  \hspace{1cm} (4)

where $l_{en}$ – given moment of inertia of moving parts of the engine, N·m²; $\omega_t$ and $\omega_d$ – the angular rotation speed, initial and final relatively, $s^{-1}$; $\lambda$ – heat equivalent.

When the specified frequency during the run-on process is reached, the fuel supply is turned on, thereby transferring the engine into acceleration-coasting cyclical mode of operation.

Without taking into account the heat and mass transfer, the heat balance equation of the engine during heating in one cycle is the following:

$$\overline{C} \cdot \overline{m}_{ice} \cdot \Delta T = \left( q \cdot G_{tp} \cdot t_p + \frac{l_{en}}{2} \left( \omega_t^2 - \omega_{en}^2 \right) \cdot \lambda \right) \cdot n_{ts}$$  \hspace{1cm} (5)

where $n_{ts}$ is the number of cycles;

$$n_{ts} = \frac{\overline{C} m_{ice} \Delta T}{q G_{tp} t_p + \frac{l_{en}}{2} \left( \omega_t^2 - \omega_{en}^2 \right) \lambda}$$  \hspace{1cm} (6)

Taking into account that the warm-up time is $t_1 = t_{ts} \cdot n_{ts}$, we get:

$$t_{ts} = t_p + t_n = t_p + t_p \frac{\eta_m}{1 - \eta_m} = t_p \left( 1 + \frac{\eta_m}{1 - \eta_m} \right) = t_p \cdot \frac{1}{1 - \eta_m}.$$  \hspace{1cm} (7)

Heat loss during acceleration and coasting:

$$Q_{pb} = \alpha \cdot K \cdot F \cdot \Delta T \cdot (t_n + t_p).$$  \hspace{1cm} (9)

Total heat loss (when $\alpha \rightarrow C, \alpha \rightarrow K, F = C$):

$$Q_{\Sigma} = Q_p + Q_n = \alpha \cdot K \cdot F \cdot \Delta T \cdot (t_n + t_p) = \alpha \cdot K \cdot F \cdot \Delta T \cdot t_p \cdot \frac{1}{1 - \eta_m}.$$  \hspace{1cm} (10)

Heat balance equation:

$$\overline{C} \cdot \overline{m}_{ice} \cdot \Delta T = \left( \frac{A_1}{q G_{tp}} \cdot t_p + \frac{l_{en}}{2} \left( \omega_t^2 - \omega_1^2 \right) \cdot \lambda - \alpha \cdot K \cdot F \cdot \Delta T \cdot t_p \frac{1}{1 - \eta_m} \right) n_{ts}$$  \hspace{1cm} (11)

taking into account heat loss in one cycle:

$$n_{ts} = \frac{\overline{C} m_{ice} \Delta T}{A_1 + A_2 - A_3}$$  \hspace{1cm} (12)

$$t_1 = t_{ts} \cdot t_{ts} = t_{ts} \cdot t_p \left( 1 - \eta_m \right)^{-1}.$$  \hspace{1cm} (13)

The complexity of thermodynamic processes and the available results of research on the efficiency of heat transfer give reason to estimate the actual energy consumption by the expression:

$$Q_{\Sigma} = Q_p \cdot \eta_m^{-1}.$$  \hspace{1cm} (14)

The expediency of the method is determined by:

$$\Phi_{ts} = \frac{Q+}{Q-} = \frac{q G_{tp} t_p \frac{l_{en}(\omega_2^2 - \omega_1^2)}{\alpha K F \Delta T t_p (1 - \eta_m)}}{Q+ > 1}$$  \hspace{1cm} (15)

Taking into account that the initial warm-up conditions are determined by the stable working of the engine $\omega_2 > \omega_1 > \omega$ start, the practicability of the method is obvious.

The speed mode during warm-up is determined by the average value of the crankshaft angular speed range considering that these values are variable and depend on the degree of warm-up of the engine. The limiting values of the speed range in the acceleration-coasting cycle are determined by stable work and engine response at a lower value, and engine run out time, determined by the moment of resistance to rotation depending on the viscosity of the engine oil at the actual temperature as the upper limit.

Thus, the thermal state, i.e. increasing the engine temperature and reducing the time required will be improved as the load increases, effective power and the acceleration-coasting speed range, and the proposed method will reduce the time spent to post-launch of the internal combustion engine and
to improve the combustion quality of the fuel mixture by cleaning the cylinder during engine working in coasting mode.

It is known that gas pressure in the engine cylinder has a significant effect on run-out. Heating in normal mode is characterized by an indicator pressure \( P_{i}^{xx} \), and for a transitional mode - by an average pressure per cycle:

\[
P_{p-b} = \frac{\overline{P}_i t_p + \overline{P}_c t_u}{t_p + t_u}
\]

(16)

where \( \overline{P}_i \) – an average indicator pressure, Pa; \( \overline{P}_c \) – average pressure of the end of compression stroke, Pa; \( t_p \) – acceleration time, s; \( t_u \) – coasting time, s.

In order to confirm the differences in these indicators and assess the run-out of parts of CPGs during heating at a steady working state and with dynamic capacity experimental studies were carried out.

3. Conditions, materials and methods

The choice of the physical object for the experiments was carried out on the basis of the prospects of the engine brand, due to the presentability, physical, geometric and thermal similarity, as well as the possibility of distribution of the research results to engines of other brands.

Based on this the ZMZ-4062.10 engine with a complex microprocessor control system for fuel injection and ignition, equipped with the Mikas 7.1 control unit being basic engine with electronic control in the ZMZ line, was chosen as a physical object of research.

The study of the self-heating effect of the engine of the Zavolzhsky Motor Plant on the run-out rate of CPG parts was carried out on the basis of the Engineering Institute of the Novosibirsk State Agrarian University in 2018-2019. The tests were held on an experimental unit (Figure 3) consisting of an engine equipped with all standard systems and attachments located in welded chassis. Additionally, we installed thermal converters of resistance DTS 044 - 50 M which are part of the measuring and computing complex "Aries" on the basis of a personal computer to control the temperature of the coolant and oil at various points of the engine.

![Figure 3. Experimental installation.](image_url)

The tests were held in the open parking lot at negative environment temperatures (below \(-20\) °C), the engine was not insulated during the tests. According to the operation manual, the entire period of testing fuel AI-95 (control batch was purchased), oil with a viscosity of 5w-30, and antifreeze А-40 as a coolant were used.

The engine was started according to the requirements for the thermal preparation of a cold engine according to GOST R 54120-2010 [3]. The initial launch temperature was 20 ° C below zero which is...
the minimum of the launch temperature for an unprepared engine without the use of additional means to facilitate it.

According to the manual of the operation, maintenance and repair of the engine ZMZ-4062.10 [4] the minimum temperature of the engine prepared for taking full load is 40 °C, which was taken as the upper limit of thermal preparation.

Comparative tests to estimate changes in the values of heat flow and the pattern of the run-out of parts of the PQG were performed in two phases:

The first phase included start-heating of the engine by dynamic capacity; the engine worked in a cyclic acceleration-coasting mode. It is assumed that in this mode of operation at the acceleration cycle an increased fuel cycle is accompanied by rising the duration of combustion and a lift in the average temperature of the cycle, which promotes more complete combustion of the fuel and reduces the probability of corrosive run-out, and the upsurg speed mode helps to ensure the hydrodynamic grease of crankshaft bearings. During the coasting cycle when the fuel supply is completely turned off the probability of corrosive run-out further decreases, and due to lack of combustion, the specific pressure of the rings on the cylinder walls is reduced, burnout of the oil film from the linking surfaces is eliminated, which contributes to the reduction of mechanical run-out.

The second phase is engine start-warming by idling (normal mode).

The operation of the engine was carried out by the standard electrical elements of the system using the device for controlling the operation of gasoline nozzles to switch the engine to the dynamic capacity mode developed at the university (Figure 4). The device was plugged into the electrical circuit controlling the engine working by connecting to a power supply, a crankshaft position sensor and connecting it through the rupture of the common control wire work to the petrol injectors.

![Figure 4. Device for controlling the operation of gasoline injectors.](image)

Measurements of fuel consumption were made by the gravimetric method according to GOST R 54810-2011 [5].

The change in the thermal state at the control points was carried out permanently in an automatic mode using a thermometry installation (Figure 5).

The measuring unit of the experimental setup includes a set of sensors, connecting cables, measuring and conversion devices. It serves to measure the current values of the coolant temperature, the oil temperature in the engine crankcase, analog-digital processing of the received signals, conversion and output of their value to a computer unit for recording all measured parameters, processing and analyzing them, and storing the received information.

The measuring complex consisted of four temperature sensors (resistance thermometers TTS 044 - 50 M), an eight-channel temperature recording unit (UKT 38 U 4-TP), an automatic interface converter (USB / RS 485 AC-4 together with interface converter ‘a current loop””), a personal computer with the software "Owen process manager".
Figure 5. Structural diagram of the experimental installation of thermometry.

To study the equability of distribution of heat generated in the engine, 3 sensors were installed (resistance thermometers TTS 044 - 50 M). Sensor №1 was installed in the area of the oil sump drain, sensor No. 2 – in the middle part of the cylinder block, sensor №3 - in the middle part of the cylinder block into the hole for draining coolant.

The run-out of the main coupling (piston rings, bushings) was determined by the gravimetric method, and cylinder sleeves - by the method of artificial bases (cut holes) using the APOI-6 device developed at the Institute of Mechanical Engineering of the USSR Academy of Sciences by Khrushchev M M and Berkovich E S

This method allows to establish the amount of run-out of parts of the CPG when the engine is running for at least 2 hours with reasonable accuracy.

Since the launch and warming-up time under equal conditions in the compared modes differs significantly, from the point of view of acceptable accuracy at each stage 20 warming-up starts were held. A greater number of warming-up launch can only reduce the measurement accuracy, and considering the fact that while analyzing the results the relative amount of run-out per one start-warming-up was used, the results of these stages are quite comparable.

In order to control the change in the internal diameter of the cylinders due to run-out after each stage of testing the engines were disassembled and the micrometry of parts of the PAC was carried out. In this case, the inner diameter was measured in three zones (sections). In each of them, eight holes were cut according to GOST 27860-88. [6] The location of the belts was determined by the stop zones of the piston rings (middle of the ring). The length of the cut holes was within 2 mm, and their depth - up to 50 microns. Measuring the length of the holes before and after testing allows to determine the run-out of a cylindrical surface by the formula:

\[ \Delta h = 0.125 \left( l_2^2 - l_1^2 \right) / r \]

where \( l_1 \) and \( l_2 \) are the hole length before and after run-out, \( \mu m \); \( r \) is the radius of rotation of the tip of the incisor, \( \mu m \).
The microscope of the device UPOI-6 allows measuring the length of the hole with an accuracy of ± 0.02 mm; in terms of the depth of the hole, the accuracy of run-out determination will be ± 0.5 μm.

In addition, after each test cycle a visual assessment of the condition of all the friction surfaces of the connecting rod crank mechanism was held, the mobility of the piston rings, the level of carbon and lacquering were checked.

During disassembly the position of the rings on the pistons was recorded so as to preserve it during subsequent assembly of the engine.

4. Results and discussion

Experimental studies have shown that when the ZMZ-4062.10 gasoline engine is working at idle (Figure 6a) at an environmental temperature of 30 °C below zero, the coolant temperature rises only to 61 °C, while temperature stabilization takes place after 23 minutes of operating. While increasing environmental temperature to 20 °C below zero, the temperature reaches 82 °C after 18 work.

The warming-up mode by dynamic capacity (Figure 6b) was carried out by the electric elements of the standard system using the gasoline nozzle operation control device by completely turning off the fuel supply to the cylinders with the throttle control of the fuel supply fully open. The results have shown that when the environmental temperature is 30 °C below zero, the coolant temperature rises up to 82 °C, after 10 min of working and as the environmental temperature reaches 20 °C below zero, the warm-up time decreases to 8 min of operation.

It is worth noting that when the engine warms up in the dynamic capacity mode and when the fuel supply throttle is fully opened, the intensity of rising the coolant and oil temperatures at various points of control is almost identical which indicates increasing mechanical friction losses. Therefore, the heat generated by friction parts of the crank mechanism mainly enters the engine oil, heating it. On the one hand, this leads to steadier heating of all elements of the power unit washed by the oil, on the other hand, an increase in the crankshaft rotation frequency causes an increase in the amount of oil and air pumped in the grease system passing through the engine cylinders during the coasting causes warmth losses due to their heating and as a consequence an increase in fuel consumption per hour, which is a reserve for increasing efficiency. Optimization in this case is possible due to the narrowing of the speed range acceleration – coasting and determining the rational angle of rotation of the throttle valve opening fuel supply. The application of the method will allow to reduce the time of the launch and warming-up by 30-50% depending on the initial conditions of the launch in comparison with the warming-up when the engine is idling, which confirms the results of theoretical studies.

Figure 6. Change in engine coolant temperature depending on the environmental temperature, working time and mode: a – idling mode, b – acceleration-coasting mode.
The results of experimental studies of run-out have confirmed the irregularity of their absolute values, which is also noted by other researchers, for example [7, 8].

Measurements of run-out after carrying out each of the stages of testing showed that engine launching and warming starts at environmental temperature of 20-30 °C below zero are accompanied by cylinder run-out (Figure 7), the absolute value of the maximum diametrical run-out of which reaches 4.64 microns and parts of the CNG, weight loss of which reaches 0.21 g. At some points there was no run-out or its value was within the accuracy of the measuring tool.

Figure 7. Average run-out of cylinder sleeves of the engine ZMZ-4062.10 for 20 cycles during launch heating from 20 to 40 °C below zero.

Despite the low environment temperature the absolute run-out of cylinder sleeves was rather small, its average value over belts in different cylinders varied from 0.94 to 1.4 μm, with a higher value related to the second belt and run-out in the first and third belt almost equally varied from 0.94 to 1.28.

The average weight loss of the main and connecting rod bushings and piston rings at all stages varied in a rather wide range from 0 to 0.046 g (Table 1).

Table 1. Final results on the run-out of CPG parts at 20 launch and warm-ups of the engine ZMZ-4062.10

| The parts of CPG | An average value of run-out at 20 launch and warm-ups, degrees |
|-----------------|---------------------------------------------------------------|
|                 | Dynamic capacity | Idling (standard mode) |
| Rings           | 1 compression    | –0.0075               | –0.0075 |
|                 | 2 compression    | –0.025                | –0.0050 |
|                 | Oil scraper      | –0.0075               | –0.0050 |
| Connecting rod  | lower            | –0.0325               | –0.0425 |
| bushing         | higher           | –0.0125               | –0.0600 |
| root            | lower            | –0.0060               | –0.0460 |
| bushing         | higher           | –                 | –                 |
These deviations can be explained by the presence of an oil film on the friction surfaces or its absence, high-speed working mode determining the hydrodynamic conditions of grease of crankshaft bearings and the engine warming-up time and hence the corrosive run-out time of the surfaces of CPG parts, as well as incomplete adhesion of the ring surface to the cylinder mirror, their conicity and the location of the holes.

Since the purpose of experimental studies was a comparative assessment of the method of heating by dynamic capacity and heating in the normal mode, the relative values per one start-heating are the most indicative. In addition, the results of run-out tests of the CPG that are generalized over all cylinders can be used in evaluating the effectiveness of the proposed method.

The highest average run-out of cylinders per one start occurs during launch heating in the normal mode and is within 0.060 microns. The smallest value of this indicator is noted when the engine starts with dynamic capacity – 0.052 microns. A comparative analysis showed that during launch heating in the normal mode, the run-out on the sleeves is 1.16 times greater, on the rings – about 2.2 times smaller, on bushings 2.91 times greater.

At the same time the resource of the piston group to a greater extent limits the run-out in the upper belts of the sleeve. As our studies have shown it remains quite acceptable [9].

Evaluation of the change in fuel consumption was made on the basis of a comparison of hourly fuel consumption (Gt) obtained for the entire warm-up period while working in idle mode and acceleration-coasting was: at idle speed - 1.68 kg / h, on the experimental one – 1.25 kg / h;

The decrease in fuel consumption per unit of time is due to the fact that in the experimental mode at the acceleration cycle the most economical flow of the working process is ensured, since cyclic fuel supply is 2.0-3.0 times more than at idle mode and the coasting tact as longer than the acceleration cycle is carried out with a complete shutdown of the fuel supply, which is accompanied by an increase in the efficiency of the working process by improving the quality of mixing and more complete combustion of the working mixture.

Switching the engine to an unsteady mode of operation entails a change in the parameters of the working process, which will also have an impact on environmental indicators.

Temperature rising in the engine cylinder will cause the increased formation of nitrogen oxides NOx, and therefore we can recommend the use of a neutralizer for harmful emissions. When the temperature of the cycle rises, the completeness of fuel combustion improves and therefore the content of carbon monoxide emissions of carbon dioxide and carbon black CH will be definitely reduced.

As a result we can conclude that the effect of the proposed method of intensification of heating on environmental safety is ambiguous and requires additional thorough research in this area.

5. Conclusion

1. Conducted theoretical studies have shown that the use of the heat of the engine's working process is one of the promising areas of thermal preparation of the engine for operation at low temperatures.

2. Comparative tests of the engine in the "idle" and "acceleration-coasting" show that the intensity of the warm-up and the time of stabilization of the coolant temperature of a gasoline engine to a greater extent depend on the environmental temperature and the frequency of rotation of the crankshaft.

3. The proposed method of dynamic capacity reduces the warm-up time of the ZMZ-4062.10 gasoline engine by 9 minutes at an environmental temperature of 20 °C below zero and a crankshaft speed range from 1000 to 4500 rpm, at 10 °C below zero - by 5 minutes compared to warming up of the engine during the work idling.

4. Tests have shown that the greatest average run-out of CPG parts per one start-heating takes place during launch heating at idle mode. When using this method, the average diametrically run-out of sleeves is greater than when heated by dynamic capacity, by 14%, the average weight loss of the crankshaft inserts - by 32%, but the run-out of the rings decreased by 53%.

5. The proposed post-launch warming-up mode provides an increase in efficiency by reducing the warming-up time and fuel consumption, which gives grounds to consider it acceptable to be used in cars.
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