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RESEARCH OF INFLUENCE OF OPERATIONAL FACTORS ON PARAMETERS FUEL DELIVERY ACCUMULATOR SYSTEM CR ENGINES RT-FLEX

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Abstract. *The results of a computational study of the influence of operational factors on the fuel supply process by the accumulator system CR of RT-flex engines are presented.*

In the model used in the study of fuel supply in the accumulator system processes that occur in all its essential elements are described. As an accumulator, a constant pressure source is considered. The most detailed analysis is the operation of the injection control unit that determines the processes in the high-pressure system. Carefully presented nozzles, the elements of which are fully consistent with the real design.

A change in the basic characteristics of injection with variable values of the temperature of heating the fuel, its viscosity, pressure in the accumulator and the pressure of the nozzle needle lift is considered. The most significant effect is the viscosity and pressure in the accumulator. An increase in viscosity (lowering the heating temperature) leads to a significant decrease in the cyclic supply of fuel and a decrease in the stroke of the metering piston with constant fuel supply phases.

The cycle delivery increases with temperature from 50 ^{o} C to 90-110 ^{o} C from 0,013 to 0,022 kg – 1,69 times. Obviously, the determining factor in this dependence is the movement metering piston injection control unit. This indicator changes in a close way, increasing in the same range from 7.4 to 10.5-10.8 mm.

Additional information about the movement of the QP is the speed of its movement. In the direct (working, injection) stroke, it increases with increasing temperature in the above range from 0,135 to 0,244 m / s.

As for the fuel pressure in the nozzle, then the influence of temperature is small. It decreases from 610 to 600 bar − less than 2 % (in the ratio of 1,016). This pattern indicates the decisive influence of the hydraulic resistance of the elements of the high pressure path on the pressure in the nozzle.

In a similar way, the injection parameters change with decreasing pressure in the accumulator.

One of the operational parameters of the fuel supply system is the liftingpressure of the nozzle, which depends on the force from the spring.

To assess the influence of the pressure of the nozzle lift, the injection process was simulated at various spring tightening pressures. The range of variation of was 300-450 bar with a nominal value of 375 bar. No noticeable effect was on injection characteristics. The change in the cyclic delivery does not go beyond 3,2 %; the difference in the path of the QP for the boundaries of the range is 2,2 %, and the velocity of the QP remains within 1,8 %. The pressure in the nozzle channel remains unchanged.

Keywords: *accumulator system fuel delivery CR, operational factors, characteristics of injection.*

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ДОСЛІДЖЕННЯ ВПЛИВУ ЕКСПЛУАТАЦІЙНИХ ФАКТОРІВ НА ПАРАМЕТРИ АКУМУЛЯТОРНОЇ СИСТЕМИ ПОДАЧІ ПАЛИВА CR ДВИГУНІВ RT-FLEX

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Анотація. *Наведено результати розрахункового дослідження впливу експлуатаційних факторів на процес подачі палива акумуляторною системою CR двигунів RT-flex.*

У моделі, використаній при дослідженні паливопостачання в акумуляторній системі, описані процеси, що відбуваються в усіх її основних елементах. В якості акумулятора розглядається джерело постійного тиску. Найбільш детально аналізується робота блоку управління уприскуванням, що визначає процеси в системі високого тиску. Ретельно представлені форсунки, елементи яких повністю відповідають реальній конструкції.

Розглянуто зміну основних характеристик упорскування при змінних значеннях температури нагріву палива, його в'язкості, тиску в акумуляторі та тиску підйому голки форсунки. Найсуттєвішим впливом є в'язкість і тиск в акумуляторі. Збільшення в'язкості (зниження температури нагріву) призводить до значного *зменшення циклічної подачі палива і зменшення ходу дозувального поршня (ДП) при постійних фазах подачі палива.*

Циклова подача палива збільшується при температурі від 50 ^{0} С до 90 ^{0}-110^0 С з 0,013 до 0,022 кг − у 1,69 рази. Очевидно, що визначальним фактором у цій залежності є хід поршня-дозатора блока управління уприскуванням. Цей показник змінюється близько, збільшуючись у тому ж діапазоні від 7,4 до 10,5-10,8 мм.

Додатковою інформацією про хід ДП є швидкість його руху. У прямому (робочому, нагнітаючому) такті вона зростає з підвищенням температури в зазначеному вище діапазоні від 0,135 до 0,244 м/с.

Що стосується тиску палива в форсунці, то тут вплив температури незначний. Він зменшується від 610 до 600 бар − менше ніж на 2 % (у співвідношенні 1,016). Ця закономірність свідчить про вирішальний вплив гідравлічного опору елементів тракту високого тиску на тиск розпилювачі.

Подібним чином змінюються параметри вприскування зі зниженням тиску в гідроакумуляторі.

Одним з робочих параметрів системи подачі палива є тиск відкриття форсунки, який залежить від зусилля пружини.

Щоб оцінити вплив тиску підйому голки форсунки, процес впорскування моделювався при різних тисках затягування пружини. Діапазон зміни становив 300-450 бар при номінальному значенні 375 бар. Немає помітного впливу на характеристики ін'єкції. Зміна циклової подачі не перевищує 3,2 %; різниця в ході ДП у межах діапазону становить 2,2 %, а швидкість ДП залишається в межах 1,8 %. Тиск у каналі сопла залишається незмінним.

Ключові слова: *акумуляторна система подачі палива CR, експлуатаційні фактори, характеристики вприскування.*

1. Introduction. The present stage of development ship diesel construction is characterized by universal use of computer control by the basic working processes. Hydromechanical elements of corresponding systems of diesel engines have simultaneously changed also. This change to the full concerns to fuel delivery processes and to injection systems. The RT-flex engines equipped with accumulators systems fuel delivery Common Rail (CR) are characteristic in this respect.

Till now there was no sufficient information on influence of operational factors on characteristics fuel delivery of the specified system. The materials presented by article contain results of imitating modelling processes injection at change of operational conditions. The information on their influence on characteristics fuel delivery will promote an effective operation of the fuel equipment and as a whole of the specified engines.

2. Object of research and its technological audit. Object of research are hydrodynamical processes of fuel injection by the accumulator system called in operational documentation Common Rail. Feature of system is computer control and the unique dosing out device − the Injection Control Union (ICU). Technological process fuel delivery consists in hydraulic maintenance of movement of dosing piston ICU with working fuel.

Nonconventional configuration of system defines an originality of processes which research is lead in the given work.

3. The purpose and research problems. The purpose of research is studying processes in elements of fuel delivery accumulator system in various operational conditions.

As problem is reception of dependences of characteristics of injection from conditions which change is possible while engines operates.

4. Research of existing decisions of a problem. Accumulator systems for fuel delivery recently have received sufficient distribution to diesel engines of various purposes. It is promoted appreciably by development of computer technologies in control of engines.

Features of ship diesel engines with accumulator systems fuel delivery and electronic control are investigated Lin K., P.Wu and P.Li [1]. Their positive qualities, such as reduction in the charge of fuel, reduction of harmful emissions, compactness, safety, reliability are noted.

Shen Haosheng, Zhang Jundong, Cao Hui [2] consider necessary to provide to the engineers maintaining specified engines, an opportunity of deep studying of processes in engines. With this purpose they develop model of accumulator system. Functions of some elements of system and their parameters are described. The kinematics of fuel pumps of a high pressure, the form and sizes of pressure (up to 120 МПа) is presented.

Processes in two accumulators − intermediate and working CR are described. Moving the dosing out piston of the block of Control by injection and change of pressure to a head part of the block is presented. The motion of a needle of an fuel valve, and also a curve of pressure in its working cavity is shown.

Tomi R. Krogerus and Kalevi J. Huhtala study [3] the diagnostics and identification of injection duration of common rail (CR) diesel injectors. Using the developed method, the relative duration of injection events can be identified. A diagnostics method based on analysis of CR pressure. The relative duration of injection events can be identified. According to the result, ≥ 10 μs change (2 %, 500 μs) in injection time can be identified.

The most influential component of the diesel engine is the fuel injection equipment; even minor faults can cause a major loss of efficiency of the combustion and an increase in engine emissions and noise [4].

Estimation of injected fuel amount has been studied in [5- 8]. Hoffmann et al. [5] developed a model-based injection rate estimator, which takes into account the change in the injection behavior due to wear and aging effects within the injector's nozzle. Satkoski et al. [6; 7] summarize the development of a physics-based fuel flow estimator. Available measurements of piezo stack voltage and rail-to-injector line pressure are used for dynamic state estimation. Estimator results are compared against both open-loop simulation and experimental data for a variety of profiles at different rail pressures, and show improvement, particularly, for more complex multi-pulse profiles. Bauer et al. [8] have developed a model for online estimation of fuel property parameters. It was found that it is possible to estimate the parameters and that the method is generally suitable.

Using the rail pressure signal for the diagnostics of injector events has been previously studied in [9-12]. Akiyama et al [9] investigated a method to compensate the difference between an actual amount of injected fuel and a target one. In order to compensate the difference, the influence of pressure wave on fuel amount injected is investigated and injection period will be corrected is realized in an actual engine control system.

Isermann et al. [10] developed a model-based fault detection module for diesel CR injection systems. Payri et al. [11] studied injection diagnosis through diesel CR pressure measurements, where the objective was to design an algorithm for the isolation of the injection events. Marker et al. [12] studied the diagnostics of large light fuel oil diesel engines where the main diesel injections were investigated, and the beginning and duration of injection were determined.

The specified set of observable processes does not cover the full list of parameters necessary for carrying out of researches of processes fuel delivery. Therefore studying of processes of injection by considered system is actual and carrying out of the research presented given article, expediently.

5. Methods of research. Research is lead by a method of imitating modelling. In the model, used at studying, the processes fuel delivery in accumulator system is considered. Work of the Control block as the injection determining processes in high pressure system is in most details analyzed. Fuel valves which elements completely correspond to a real design are carefully presented.

There is an opportunity freely to change constructive and operational parameters of fuel delivery system. It, first of all, are characteristics of fuel, adjusting and regime options. Pressure of fuel valve opening was concern to last.

6. Statement of the basic material. One of the most essential parameters describing operational characteristics of heavy fuel, the temperature of its heating is. For definition of influence of this factor on process of injection it is carried out settlement research with use of model of accumulator system CR. Processes in various elements of system are examined with use of heavy fuel with the characteristics corresponding grade RMG 380 under standard ISO 8217.

The function chart of fuel delivery system is represented on fig. 1, the diagram of its model − on fig. 2.

Basic elements of accumulator system of injection (fig. 1) are, alongside with fuel valve, the block of injection Control 1 (Injection Control Unit – ICU), the fuel accumulator (fuel Rail) and valves of the system.

Working cavity of ICU 2 is connected during injection with fuel valves, and in a phase of preparation next delivery − with the fuel accumulator. The buffer cavity 3 has no communications with fuel valves and is connected constantly to the accumulator. Functions of ICU carry out by valves (two for each fuel valve). One of them (Rail valve) with a solenoidal bilateral drive is intermediate part in a control system, working with service (control) oil. For dellivery of fuel it passes oil to Injection control valve, and then provides removal of oil through a drain canal.

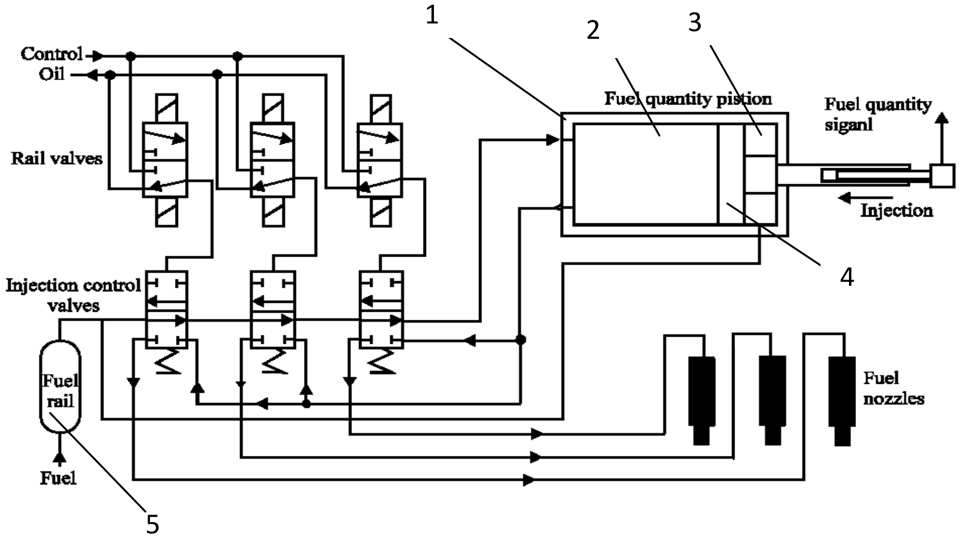

Fig. 1. Accumulator system of fuel injection (CR-Common Rail):
1 – block of injection control - Injection Control Unit - ICU;
2 – Working cavity (WC) ICU; 3 – buffer cavity (BC) ICU;
4 – dosing piston ICU (QP – Quantity Piston); 5 – fuel accumulator (Fuel Rail)

The second valve connects working cavity ICU serially with fuel valves (during injection of fuel) and with the accumulator. The working motion of the dosing piston 4 is provided with pressure difference at connection WC with fuel valves. Its return moving is defined by a difference of areas QP – from WC it is more. On fig. 1 the system is represented in a final phase of filling WC ICU by fuel from the accumulator. Control of injection processes is carried out by computer system WECS-9520 (Wartsila Engine Control System). On the scheme of CR model (fig. 2), made in the environment of package GT-Power, two systems of digital indication are used. Names of mainframes 1-5 are specified a field of the scheme. Other part of the specification (circles) concerns to points of the given processes in separate elements of system:

1 − pressure of fuel at input in the valve 3 – port And;
2 − pressure in the accumulator 1;
3 − pressure in working cavity ICU 2;
4, 5 − pressure in the channel of fuel valve (4.1, 4.2);
6, 7 − pressure at input of fuel valve;
8, 9 − rise of a needle of fuel valve;
11 − moving of ICU piston;
12 − pressure upon at outputof the valve – port T;
13 − speed moving dosing piston of ICU.

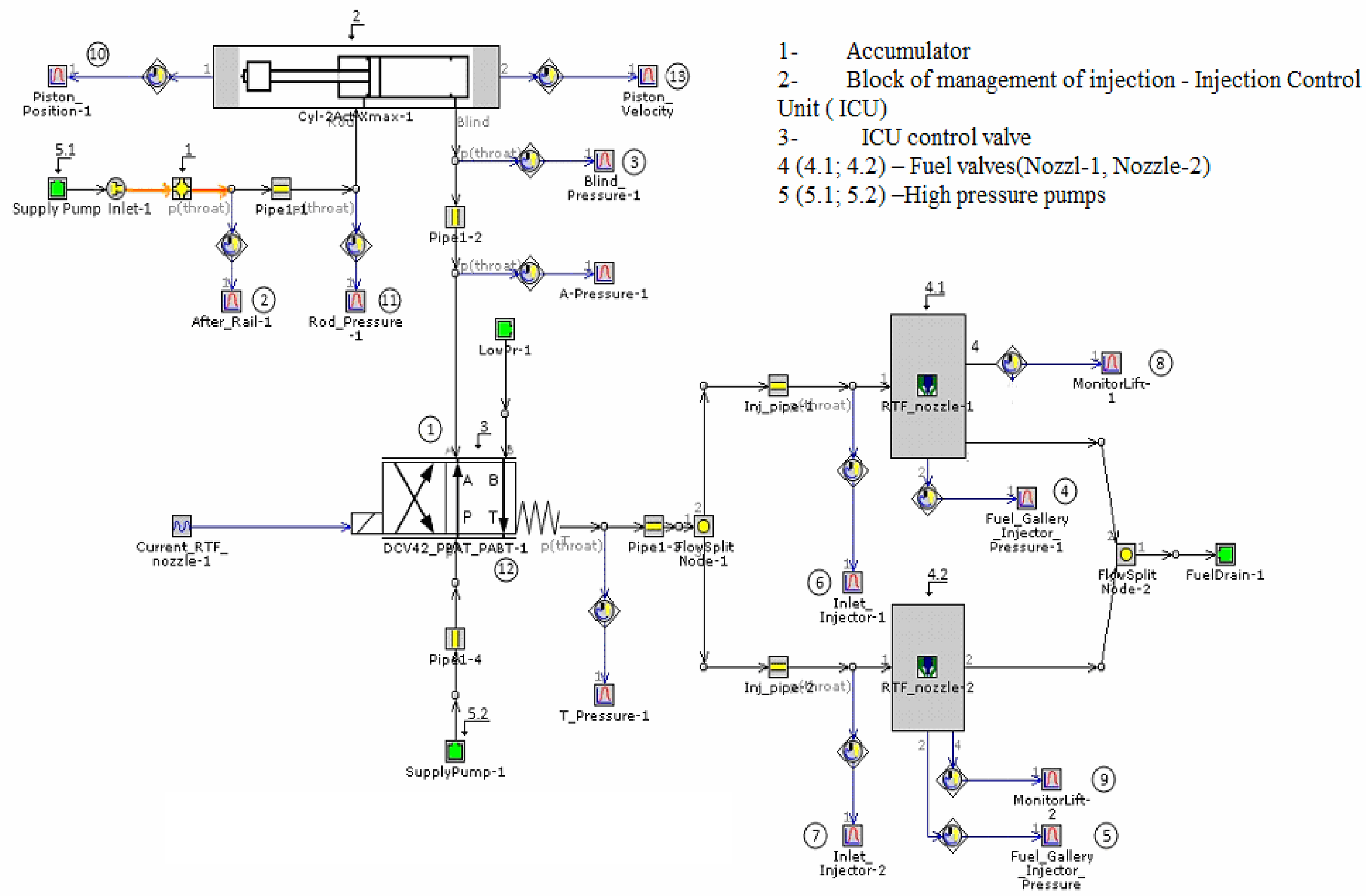

Fig. 2. Model of fuel injection accumulator system Common rail (CR)

The example of oscillograms of system's separate elements work is presented on fig. 3. Numbers of curve s correspondto the list specified above.

The basic properties of fuel at various temperatures and parameters of injection in elements of system are presented in tab. 1, and corresponding dependences are given on fig. 4.

The range of temperatures has made 50 ^{0}-150 ^{o}C, that covers values of dynamic

Table 1

Characteristics of fuel and parameters of injection depending on temperature of fuel heating

t_f, ^{o} C	q_c, kg	z_p, mm	h_p, mm	v_a, m/s	v_r, m/s	v_{max}, m/s	p'_v, bar	μ, Pa·s	ν, mm^2/s
50	0,0128	293	7,39	-0,135	0,222	-0,486	610	0,372	380
70	0,0192	290,8	9,54	-0,211	0,272	-0,59	604,8	0,117	120
90	0,0217	289,9	10,49	-0,236	0,289	-0,64	604,2	0,045	46
110	0,0219	289,6	10,79	-0,244	0,292	-0,65	603,8	0,024	25
130	0,022	289,4	10,99	-0,249	0,298	-0,647	602,4	0,013	14
150	0,022	289,3	11,09	-0,254	0,3	-0,65	600	0,0088	9

The symbols accepted in the table 1 and the text:

t_f, ^{o} C – temperature of fuel;

q_c, kg – cyclic delivery;

z_p, mm – position of dosing piston;

h_p, mm – a motion of piston;

v_a, m/s – speed of piston at a direct motion;

v_r, m/s – speed of piston at reverse motion;

v_{max}, m/s – the maximal speed of piston moving;

p'_v, bar – pressure in underneedle cavities;

μ, Pa·s – dynamic viscosity of fuel;

ν, mm^2 /s – kinematic viscosity of fuel.

The range of temperatures has made 50 ^{0}-150 ^{o}C, that covers values of dynamic viscosity of μ = 0,372-0,0088 Pa·s or kinematic ν =380-9 mm^2/s. Character of change of viscosity is presented by a curve $\mu = f\ (t)$ and illustrates known strong dependence of viscosity on temperature.

Other processes determining finall result of system work – parameters of fuel on an exit from a spray of an fuel valve, depend on interaction of separate elements fuel injecction system.

Cyclic delivery q_c grows with rise in temperatur from 50 ^{o}C to values t_f = 90-110 ^{o}C from 0,013 up to 0,022 кг – in 1,69 times. The further increase in temperature q_c does not change value.

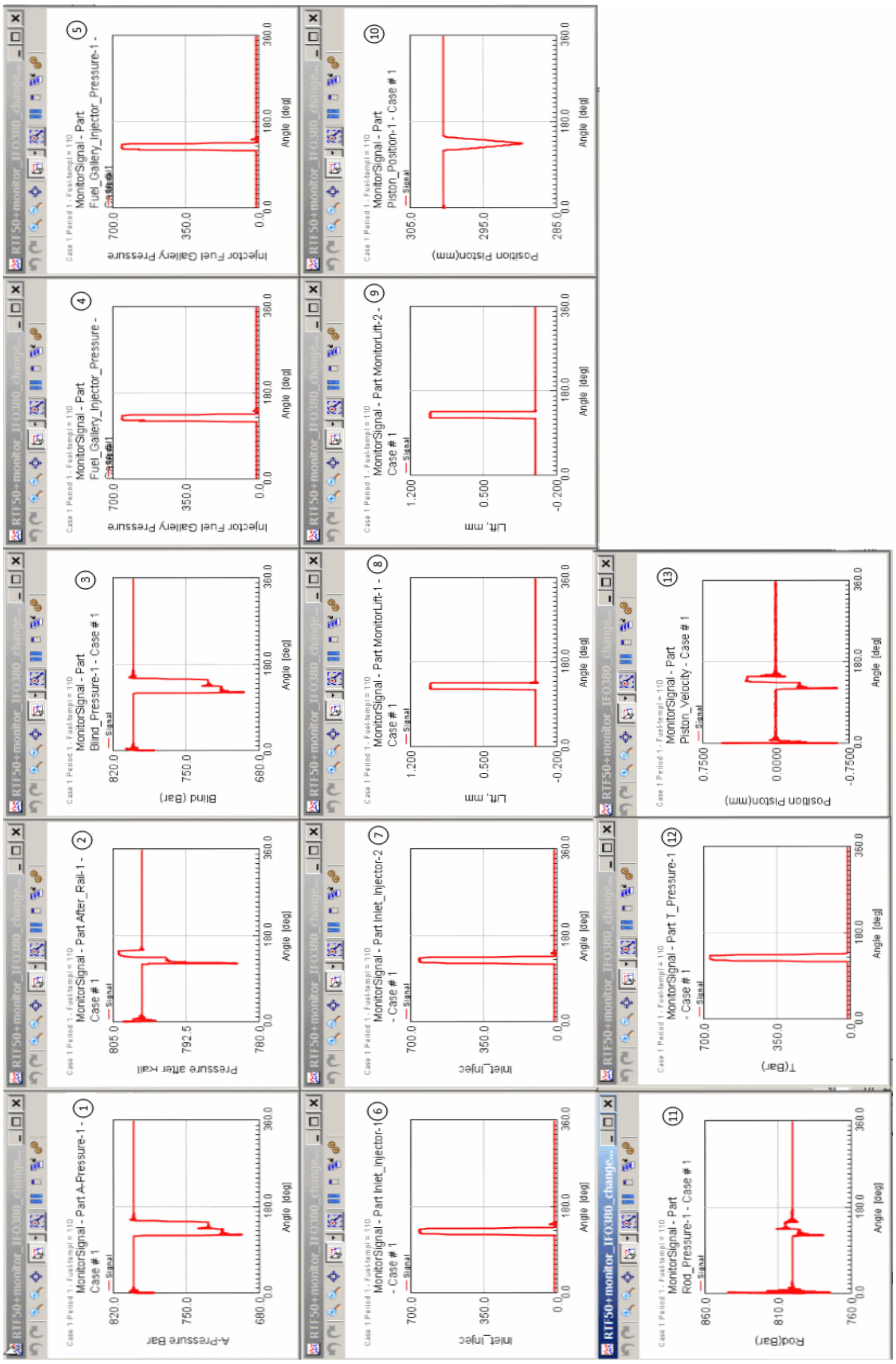

Fig.3. Oscillograms of process of injection in elements of system топливоподачи CR

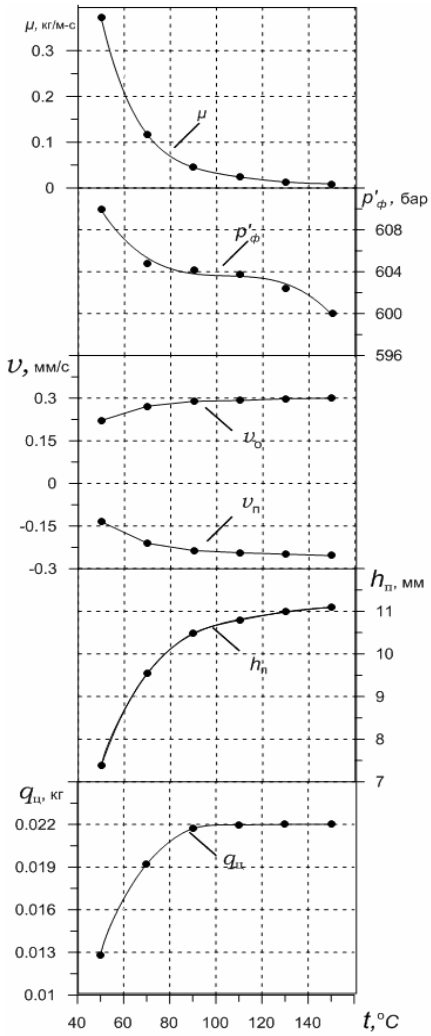

Fig. 4. Dependence of injection parameters from temperature of fuel

It is obvious, that the determining factor in this dependence is movement of dosing piston QP of the block of Control by injection ICU. This parameter (on the curve h_p – motion QP) changes in the close image, increasing in the same range with 7,4 up to 10,5-10,8 mm. The received ratio is 1,44 and in the further changes slightly.

The additional information on movement QP is speed of its moving. At a direct (delivery) motion it increases in process of increase in temperature in the range specified above with v_a = 0,135 up to 0,244 m/s.

The further growth of temperature influences speed of moving QP a little. The sign «minus» in this case is the conditional characteristic of a direction of movement.

Returning QP in a starting position occurs to greater speed: these are 0,222-0,292 m/s for the same values of temperatures. The maximal speed of movement QP covers a range v_{max} 0,486-0,65 m/s and concerns to a direct motion.

As to pressure of fuel in an fuel valve p'_v here influence of temperature is insignificant. It decreases with 610 to 600 bar – less than 2 % (in the ratio 1,016). Such law testifies a influence of hydraulic resistance of elements of a path of a high pressure on pressure in an fuel valve.

Cited data are well coordinated with recommendations of maintenance instructions of the given class of diesel engines regarding maintenance of working value of viscosity in a range 15-20 сСт. To this value in examined data there corresponds temperature of heating 110-130 °C above which parameters of fuel delivery vary slightly.

An illustration of the above is more detailed information about the operation of the main unit of the fuel delivery system – Injection Control Unit – ICU – and its etering element-Quontity Piston-QP.

On fig. 5 dependence of a motion of the piston for two extreme values of temperature 50 and 150 °C, and on fig. 6 – the curves of corresponding speeds is shown.

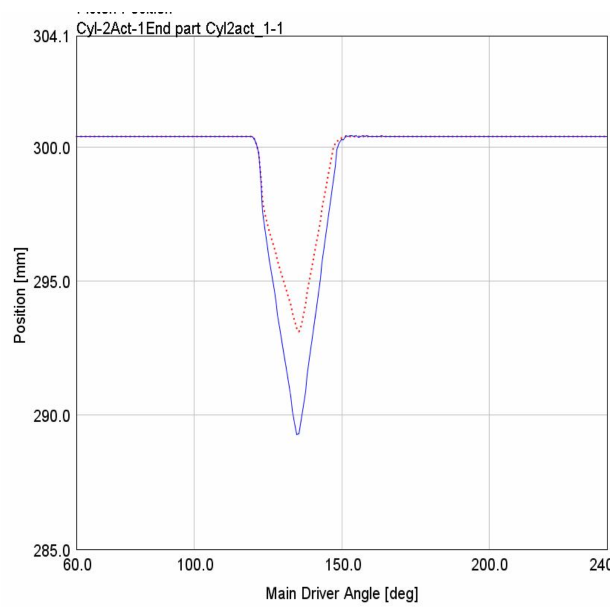

Fig. 5. QP movement at different fuel temperatures: ---- - 50 ^{0}; ____ - 150 ^{o} C

The range of motion from starting off to returning to the initial state is the same in both cases: 119,5 ^{0}-151,4 ^{o} CA. Only when approaching the initial position with a higher temperature, some lag is observed.

As for the full stroke of the piston, here the difference is significant. With an increase in temperature, h_p increases by 1,5 times.

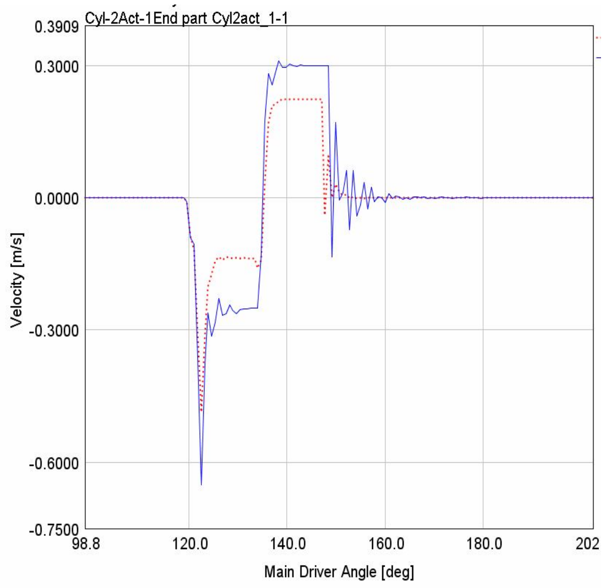

Fig. 6. The speed of QP movement at different fuel temperatures:
---- - 50^0; ____ - 150^o C

The general estimation can be given on the average sizes. To a smaller motion there corresponds also smaller speeds of moving.

For direct movement and t = 50 ° C, this is v_a = - 0,135 m/s, and at the maximum temperature v_a = - 0,254 m/s, or almost twice (more precisely, 1,83 times) more. A similar relationship was obtained for the reverse stroke: v_r = 0,222 m/s and 0,3 m/s, respectively.

The additional information is contained by data about peak values of speeds. As follows from fig. 6 graphs, these sizes fall to a direct motion, and make in a former ratio: v_{max} = - 0,486 and - 0,65 m/s. Besides oscillatory character of movement of the piston, especially appreciable is essential also at a stop of the piston during the moment of returning in a starting position. The maximal scope in fading oscillatory process makes 0,296 m/s.

The curves fig. 7 contains the information similar considered earlier in the form of dependence of parameters from temperature of heating of fuel (fig. 4). However these dependences allow to submit data in a communication with the determining parameter which viscosity is.

An increase in viscosity leads to a decrease in the stroke of the h_p QP by increasing the hydraulic resistance in the elements of the system. This effect is accompanied by a change in another kinematic parameter: the speed of movement of the QP both in the forward (working) and in the reverse stroke: v_a, $v_к$.

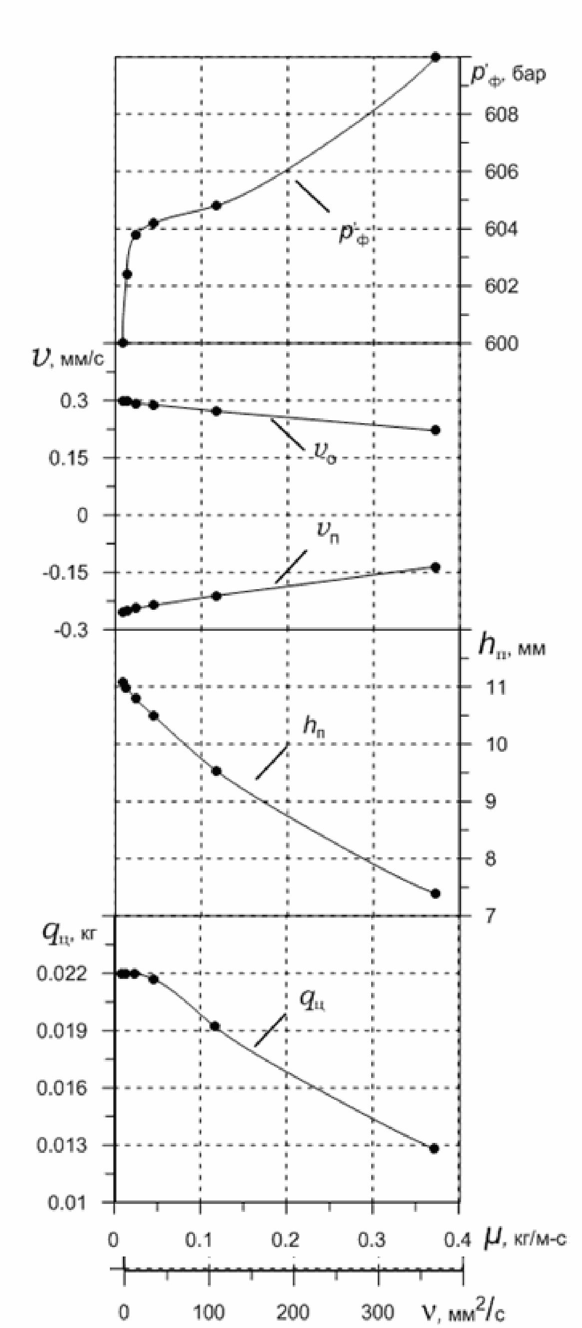

Fig. 7. Dependence of injection parameters of accumulator system CR from viscosity of fuel

According to the course of the QP, another parameter, closely related to it, also reacts − the cyclic feed q_c. Only in the area of small values of μ does the change in q_c lag behind the decrease in viscosity.

The dependences obtained make it possible to estimate the effect of a change in the effective cross section of the atomizer, which decreases with an increase in viscosity. This dependence is expressed in a certain pressure increase in the injector p'_v with increase in fuel viscosity. This change, however, is small and amounts to 10 bar, or 1,7 %, despite the fact that the viscosity increases by more than 40 times.

At an estimation of the received dependence it is necessary to consider influence and other factors on size p'_v. Speed of moving QP and hydraulic resistance of elements of system concern to them fuel delivery. The reduction noted above v_a in 1,88 times, and also growth of hydraulic resistance of valves ICU and pipelines compensate influence of decrease in effective section of fuel valve atomiser.

One of key parameters of process fuel delivery which change is accessible in a regular mode of operation, is pressure of fuel in the accumulator p_a. Its influence on parameters of injection is presented by data tab. 2 and the curve fig. 8.

The range of the investigatedvalues p_a makes 500-1000 bar. It is natural to assume interrelation p_a with pressure of fuel in an fuel valve. Really, p'_v increases with 385 up to 752 bar. As we see, the hydraulic resistance of system mentioned above is great enough and makes 115-248 bar.

Growth of resistance corresponds to increase in speed of movement of the fuel caused, in turn, by change of parameters of movement QP: increase v_a with 0,189 up to 0,28 m/s. Increases thus and speed of reverse motion QP v_r – from 0,237 to 0,331 m/s.

We shall note also, that pressure difference on QP creates the effort defining a motion of the piston.

At increase in pressure p_a on greater distance moves QP, submitting there is more than fuel. Following numerical values are received: h_p = 8,02 and 12,52 mm, and q_c = 0,0156-0,0256 kg. It is possible to note close ratio specified values:1,56 and 1,64.

One of operational parameters of system fuel delivery is pressure of fuel valve needle rise p_o, depending from a spring effort. For estimation of this factor influence modelling process of injection is lead at various spring pressure.

Results are presented in table 3.

The range of change p_o has made 300-450 bar at nominal size 375 bar.

Analyzing the obtained data, it should be noted that there is no noticeable effect of p_o on the injection characteristics. Indeed, the change in the cyclic delivery q_c does not go beyond 3,2 %; the difference in the stroke of QP h_p is 2,2 % for the limits of the range, and the speed of the DP movement v_a remains within 1,8 %. The pressure in the p'_v nozzle channel remains unchanged.

In all cases, an increase of p_0 leads to a decrease in the obtained characteristics. This trend is associated with a slight reduction in the injection angle with an increase in the pressure of the nozzle needle lift due to a delay in the lift and its earlier landing.

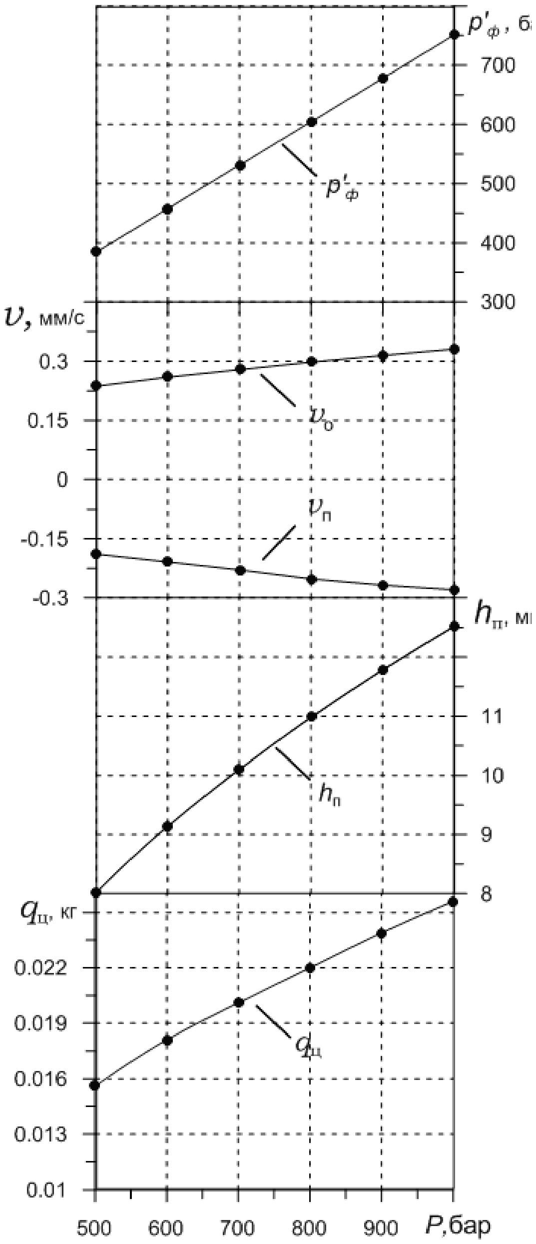

Fig. 8. Dependence of injection parameters from pressure of fuel

Table 2

Parameters of injection depending on pressure of fuel

p_a, bar	q_c, kg	$z_п$, мм	h_p, mm	v_a, m/s	v_r, m/s	v_{max}, m/s	p'_v, bar
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
500	0,0156	292,22	8,02	-0,189	0,237	-0,446	385
600	0,0181	291,15	9,14	-0,209	0,26	-0,526	458
700	0,0201	290,24	10,1	-0,229	0,279	-0,582	531
800	0,022	289,41	10,98	-0,252	0,298	-0,648	605
900	0,0239	288,66	11,78	-0,268	0,315	-0,67	678
1000	0,0256	287,97	12,52	-0,28	0,331	-0,72	752

Table 3

Various sizes of fuel valve's spring compression

p_o, bar	q_c, kg	$z_п$, mm	h_p, mm	v_a, m/s	v_r, m/s	v_{max}, m/s	p'_v, bar
1	*2*	*3*	*4*	*5*	*6*	*7*	*8*
300	0,0224	289,3	11,09	-0,2495	0,298	-0,65	605
337,5	0,0222	289,36	11,03	-0,2493	0,298	-0,65	605
375	0,022	268,41	31,98	-0,249	0.298	-0,65	605
412,5	0,0219	289,47	10,92	-0,247	0,298	-0,65	605
450	0,0217	289,54	10,85	-0,245	0,298	-0,65	605

Conclusions

1. The results of a computational study of the influence of operational factors on the fuel supply process by the accumulator system CR of RT-flex engines are presented.

2. A change in the basic characteristics of injection with variable values of the temperature of heating the fuel, its viscosity, pressure in the accumulator and the pressure of the nozzle needle lift is considered.

3. The most significant effect is the viscosity and pressure in the accumulator. An increase in viscosity (lowering the heating temperature) leads to a significant decrease in the cyclic supply of fuel and a decrease in the stroke of the metering piston with constant fuel supply phases.

4. The cycle delivery increases with temperature from 50 C to t_f = 90-110 °C from 0,013 to 0,022 kg-1,69 times. Obviously, the determining factor in this dependence is the movement metering piston QP of injection control unit ICU.

5. Additional information about the movement of the QP is the speed of its movement. In the direct (working, injection) stroke, it increases with increasing temperature in the above range from v_f = 0,135 to 0,244 m/s.

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