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DEVELOPMENT OF SUPERCHARGING SYSTEMS OF INTERNAL COMBUSTION ENGINES WITH THE CASCADE PRESSURE EXCHANGER

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Summary. New principles of working processes organization of the supercharging diesels systems with cascade pressure exchangers are disclosed, the possibility of the significant expansion of the area of efficient air supply and deep cooling of supercharging air by using units of cascade exchange by pressure are shown. The results of the studies of the different supercharging systems with cascade pressure exchangers in composition of the diesels GAZ-560 and K164 are presented.

Key words: cascade pressure exchanger, supercharging system, air supply, deep cooling, the thermal multiplier

INTRODUCTION

Nowadays the further forcing of internal combustion engines by supercharging appreciably is restrained by number of negative factors. First of all, they are revealed in deterioration of dynamic characteristics of the combined engine (such as the acceleration capability, adaptability, qualities of transient processes) and growth of calorific intensities of cylinders of piston group. From this point of view, the perspective direction of development of supercharging systems is application as the basic unit of air supply the cascade pressure exchangers (CPE) representing essentially new version of supercharger devices, based on a direct exchange of energy between compressing and compressed air-gas mediums. [Krajniuk A.I., Krajniuk A.A., 2006]

THE ANALYSIS OF PROPERTIES OF THE CASCADE PRESSURE EXCHANGER

The wave pressure exchangers are known since 50th years of last century and received limited application in supercharging systems of internal combustion engine «Comprex». Along with high speed of exchange processes and ability to provide satisfactory air supply under the high-velocity characteristic of engine work the wave pressure exchangers have a number of the negatives caused by wave character of exchange processes [Golec K. 1995; Myslowski J. 1991; Mystowski J. 2002]. The deviations of an operating mode of wave pressure exchangers from rated conditions on rotational speed of a rotor, on consumption and temperature of the active medium are accompanied by sharp deterioration of characteristics of work both owing to a mismatch of the moments of connection of a cell to the windows of a high pressure with phases of movement of primary waves, and owing to increase in incompleteness of replacement of compressed air from rotor cells. Besides, inevitable dissipative phenomena in processes of formation and interaction of strong shock waves limit coefficient of efficiency in the best specimens of WPE on rated modes by values 0,55 … 0,56 [Krajniuk A.I., Storcheous J.V., 2000].

The CPE running cycle on the base of regenerative use of potential energy of residual pressure of the compressing medium for realization of the basic air compression in the course of a cascade power exchange with mainly stationary character of direct interaction of mediums, is distinguished by high coefficient of efficiency (to 85 … 87 %), and also low sensitivity of the unit to incompleteness of replacement of air from rotor cells.

Typical construction of exchanger (fig. 1.) is the rotor with longitudinal head-exchanging cells, revolved in stator. Mass-changing channels as well as the window of admission and rejection of compressing gas are located in one of end face covers of stator, but the window of admission and rejection of compressed gas are located in other of end face covers. The rotor is driven to the rotation with rotational speed of 2000…3000 min-1 by means of an electric motor or other drive of small power. The still pictures of basic units of one of the CPE construction are shown on the fig. 2.

Fig.1. Principal view of cascade pressure exchanger

a b c d

Fig. 2. Basic elements of construction of the experimental model of the CPE:
a – stator; b – rotor; c – body; d – end face cover from the side of admission and rejection of compressing gas

Rather low rotational speed of the CPE rotor causes essentially high reliability and less rigid technology requirements to manufacturing of cascade exchangers relative to turbo-compressors and wave pressure exchangers.

CPE high efficiency and reliability is confirmed by tests of some pre-production models at the motor test stand on the basis of a diesel engine K-164 (fig. 3.) in laboratory of department "Internal Combustion Engine" (EUNU). So, under parameters of compressing gas T_{g1}=850 K, P_{g1}=250 kPa reached coefficient of efficiency of exchanger makes 0.84 [Klyus O.V., Krajniuk A.I., Alekseev S.V. 2008]. Power perfection of the CPE running cycle is realized in considerable increase of the consumption of compressed air concerning the compressing medium, that in a greater degree, than higher temperature of the medium (fig. 4).

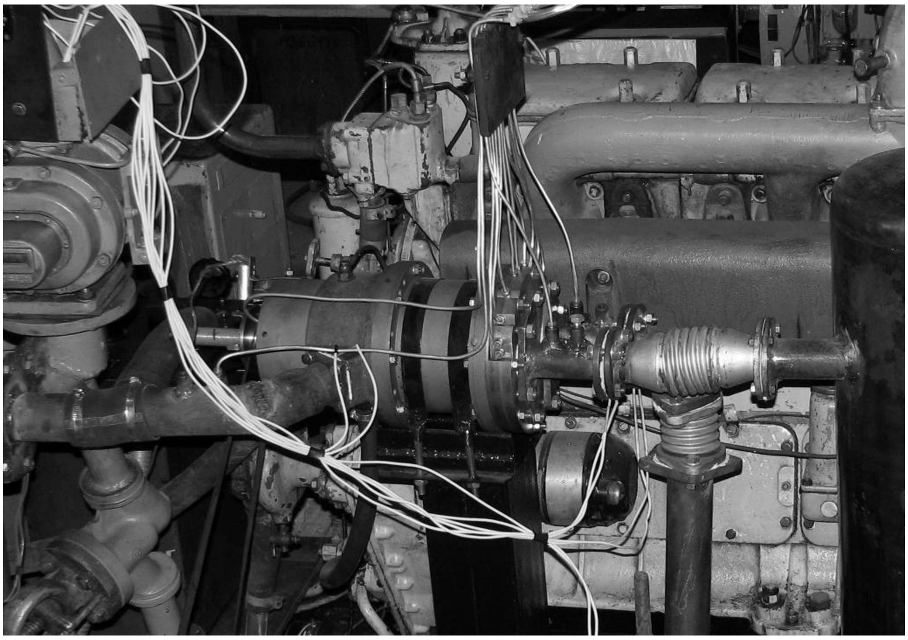

Fig.3. The stand of motor tests of the CPE.

The CPE running cycle feature is some excess of pressure P_{g1} of compressing medium concerning the pressure P_{air} of compressed air. And the increase in difference of pressure (P_{g1}- P_{air}) between the windows of high pressure of the CPE promotes reduction of the exchanger dimensions; however it is accompanied by decrease of its efficiency and deterioration of combined engine cylinders scavenging.

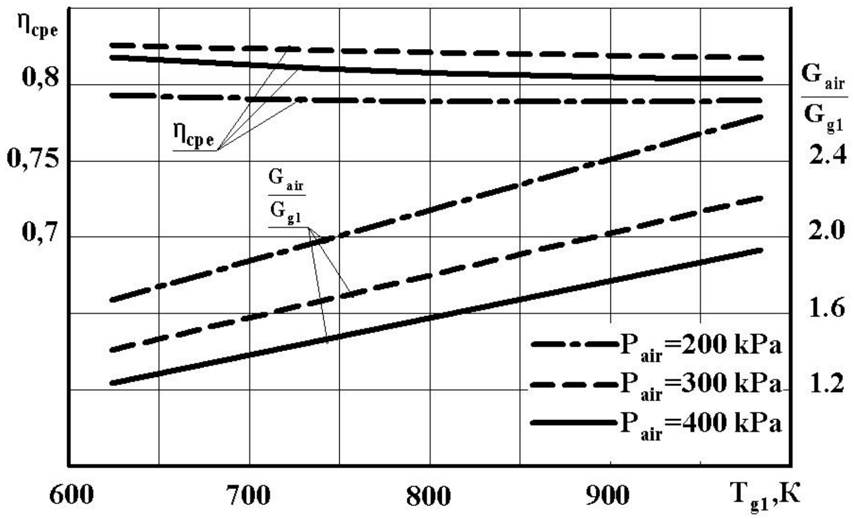

Fig.4. Influence of temperature T_{g1} of compressing medium on the relation of the consumption of compressed and compressing mediums G_{air}/G_{g1} in the CPE

In the elementary scheme of the CPE application as the independent unit of the engine air supply the deterioration of conditions of cylinders scavenging on off-design modes is compensated by the favorable characteristic of pressure P_{int} of supercharging in all range of operational modes of transport engine, including the operating modes of small rotational speed of crankshaft. Thus, surplus pressure is established already on no-load conditions. The ability of the CPE to carry out engine hyper supercharging (P_{int}> 0,35 MPa) by the one step unit is confirmed.

At the same time, presence of almost twofold excess of air forced by the CPE predetermines expediency of creation of a new generation of engine air supply systems realizing power advantage of the cascade exchanger of pressure. A research objective is the analysis of directions of development of air supply systems with the CPE.

NEW SCHEMES OF SYSTEMS OF SUPERCHARGING WITH THE CPE AND PRINCIPLES OF COMBINED INTERNAL COMBUSTION ENGINE AIR SUPPLY ORGANIZATION

System of supercharging with the divided exhaust of the used gases. On the scheme (fig 5) it is envisaged the placing of the additional exhaust valve $\mathbf{e_2}$ in each cylinder of the engine, which is connected by means of the pipeline with atmosphere. It is intended to decrease the back pressure to exhaust of gases during scavenging the cylinders by a fresh charge.

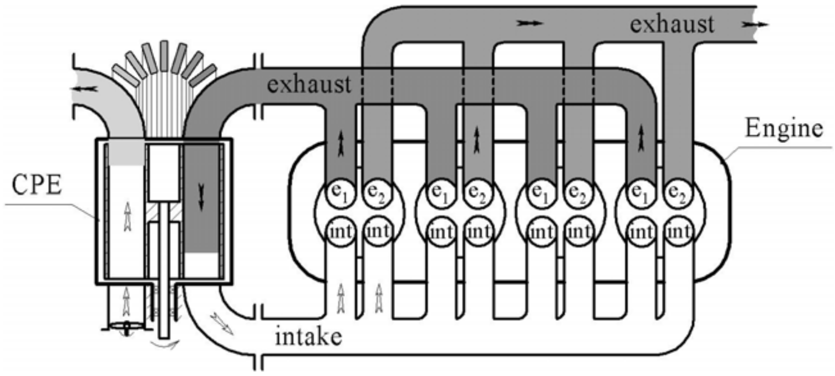

Fig.5. System of supercharging with the divided exhaust of gases from cylinders.

Initial exhaust of gases from the cylinder is carried out through the valve $\mathbf{e_1}$, connecting up-piston space with a supply pipe of the CPE compressing medium. At piston approach to top dead center the valve $\mathbf{e_2}$ opens and the valve $\mathbf{e_1}$ is closed that provides the subsequent exhaust of gases directly into atmosphere (fig. 6). Pressure decrease in up-piston cylinder space in the second part of exhaust stroke allows to improve filling of cylinders by a fresh charge and to reduce work of pump strokes.

In the light of up-to-date trend of application of multi-valve cylinders heads the realization of this technical decision is not practically connected with serious complication of engine design.

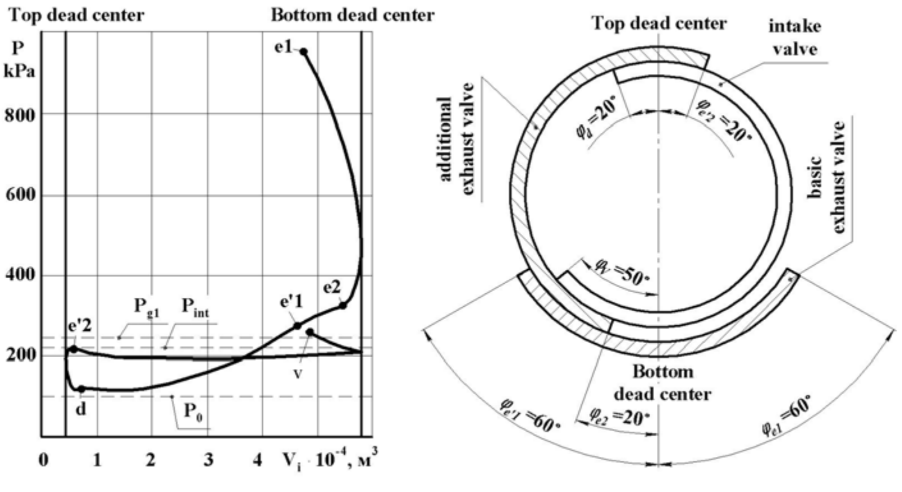

Fig.6. Indicator diagram of pump strokes of the piston and the diagram of the valve timing

External velocity characteristic of the engine with the divided exhaust resulted on fig. 7, that is received on the basis of calculated data for a diesel engine GAZ - 560, illustrates sufficient efficiency of supercharge of the CPE in a wide range of change of rotation speeds of crankshaft. Decrease of supercharging pressure P_{int} in the field of the crankshaft minimum rotation speeds **n** (curve 2, fig. 7) is caused by the superfluous consumption of fresh charge in the scavenging process, in view of excessive time of opening of the additional exhaust valve $\mathbf{e_2}$ on these modes. On the mode **n**=1200 rpm the scavenging ratio, for the valve timing, specified in fig. 6, makes 1.7.On the contrary, some decrease of P_{int}, at high rotational speeds of crankshaft is caused by deficiency of time of opening of the basic exhaust valve $\mathbf{e_1}$.

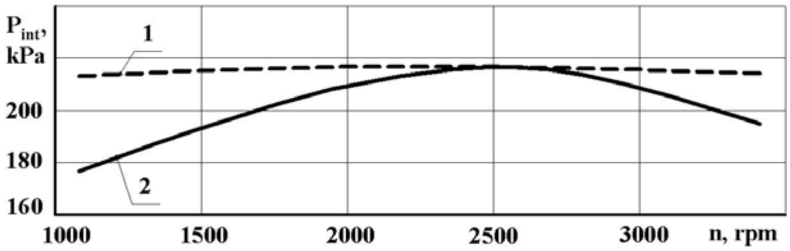

Fig.7. Velocity characteristic of supercharging pressure of the engine GAZ – 560 with the divided exhaust of the used gases

It is quite obvious that the basic reserve of the further improvement of the internal velocity characteristic (full-load curve) of supercharging is connected with use of adjustable drives of gas-distributing valves (a curve 1, fig. 7).

The system of mechanical supercharging with the thermal multiplier of the air consumption of the CPE. In modern motor car industry the increasing interest is appearing to forcing of engines by supercharging by means of actuating volumetric superchargers (screw, spiral, roots, etc.). The advantages of so-called mechanical supercharging concerning extended gas-turbine one consists in almost invariable pressure of supercharging in all range of engine operating modes, including the field of crankshaft minimum rotational speed, and also in absence of "failures" of supercharging pressure on transient modes of engine operation. The engines with actuating volumetric compressor are unreceptive to an increase of counter pressure to the exhaust that can be caused, for example, by installation of neutralizer of exhaust gas.

The basic lack of mechanical supercharging is the raised consumption rate of fuel of the engine because of losses of mechanical energy on a compressor drive. And with increase in forcing of the engine by supercharging the share of consumption of mechanical energy on a compressor drive increases and reaches 20 … 25 % of effective engine power at degree of increase of air pressure in the compressor π_c =1,8 … 2,2. For this reason the actuating volumetric compressors, despite favorable supercharging characteristics, practically have not found applications in engines of diesel locomotives, freight and road-building machines.

Possible direction of reduction in expenditures of mechanical energy on supercharging realization is application of the CPE as the multiplier of the air consumption forced by the compressor with concerning small productivity. In this case "waste" heat of the exhaust gases serves as a power source of multiplication of the supercharging air consumption of the exhaust gases. Such approach allows to reduce essentially dimensionality and the power inputs of actuating compressor, keeping the favorable characteristic of mechanical supercharging [Mystowski J., 2002.,Krajniuk A.I., Krajniuk A.A., Alekseev S.V., Bryantsev M.A. 2008].

The principal scheme of the CPE application as a part of the combined system of supercharging is shown in fig. 8.

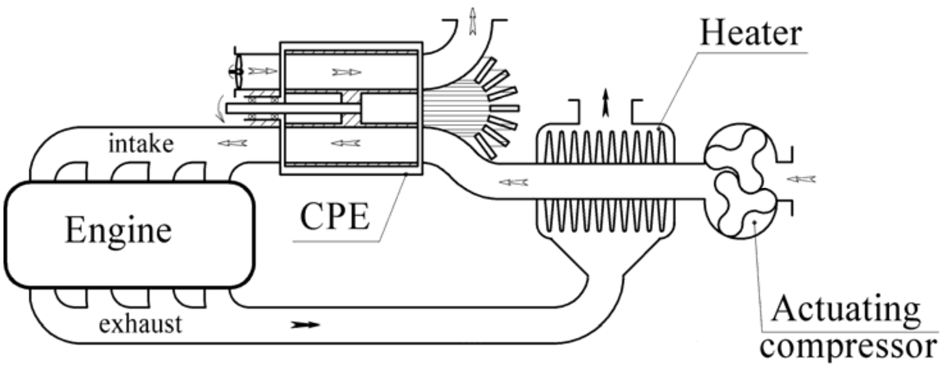

Fig.8. The scheme of the combined system of supercharging with the CPE

Experimental-calculated characteristics of operation of engine GAZ - 560 with combined system and CPE in comparison to experimental data of the engine equipped with turbo-compressor's systems and actuating supercharger are presented in fig. 9.

At realization of supercharging by the combined system with the CPE, the operation of under-dimensional actuating compressor was simulated by way of restart-up of excess air into atmosphere directly before heat-recovery heat exchanger of the system. The reduction factor of dimensionality of actuating compressor on the consumption of forced air makes 1.65 in a considered variant of combined system design with the CPE. As it is seen from fig.9, the external velocity characteristic of supercharging P_{int} of the engine with combined system and the CPE practically repeats the characteristic of the engine with actuating compressor except of crankshaft low rotational speeds **n**. However, in all range of velocity modes the torque moment T_{tq} of the engine with combined system and the CPE exceeds on 3…6% the similar index of the engine with mechanical supercharging. The last is connected with decrease on 45 … 68 % of power of the drive of compressor $N_{c,}$ distracted from the crankshaft. In its turn, decrease in power of mechanical losses and increase in effective power of the engine with combined system with CPE at invariable position of fuel feed pump defines decrease in the specific effective fuel consumption $\mathbf{b_c}$ on the average on 6 %.

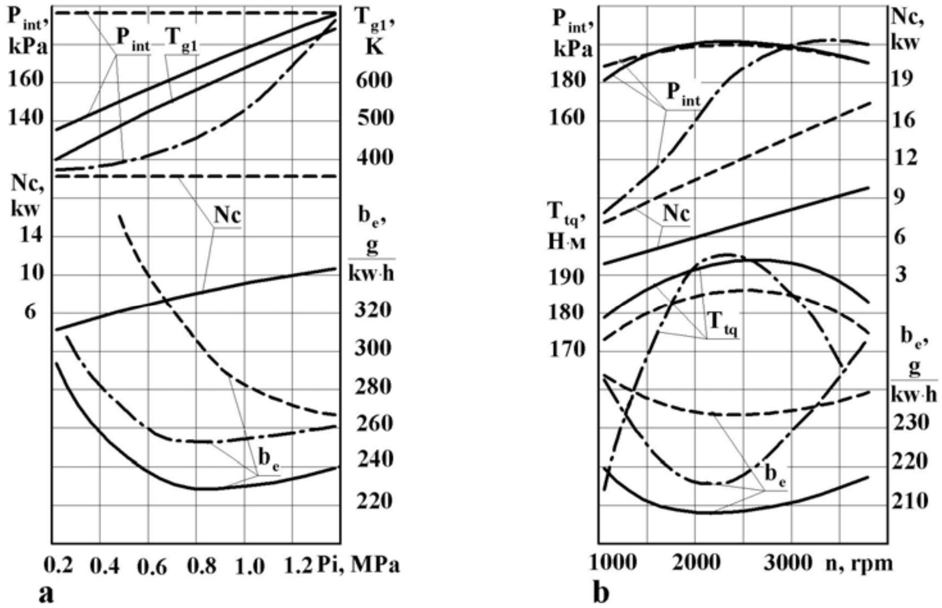

Fig.9. Loading (a) and velocity (b) characteristic of engine GAZ – 560
- - - with the mechanical compressor; – · – · – with turbo-supercharging; – – with combined system of supercharging with CPE

The curves of changes of supercharging pressure P_{int} of the examined systems differ rather considerably at engine operation on the loading characteristic. Decrease in loading mode of the ICE operation because of reduction of temperature of exhausted gases $\mathbf{T_{g1}}$ and, hence – amount of heat that is fed to compressing air in the heat exchanger, involves decline of productivity of the CPE and decrease in supercharging $\mathbf{P_{int}}$.

Let's notice that on modes of partial loads the need in high head supercharging is absent, as the factor of air excess on these modes is not critical for providing of effective combustion of fuel in engine cylinders. At the same time, supercharging pressure decrease is accompanied by reduction of mechanical energy expenditures on the drive of supercharger that causes additional decrease in specific fuel consumption $\mathbf{b_e}$.

Higher fuel efficiency of the engine with combined system of supercharging concerning base one with a turbo-supercharging is connected with utilization of heat energy component of the exhaust gases and absence of backpressure to exhaust of gases from cylinders.

It is necessary to notice that the big dimensions and design complication are the shortages of the examined combined system of supercharging with the CPE.

The most expedient field of application of such systems is high forced engines of road-building and special techniques working under heavy conditions of frequent change of loading modes in which the factor of rise in price and increase in metal consumption of system of supercharging is compensated by priority value of the best adaptability.

Supercharging system of a two-stroke engine. In the two-stroke forced by supercharging engines the free turbo-compressor does not provide qualitative gas exchange in cylinders because of decrease in temperature of exhaust gases in front of the turbine owing to their diluting with scavenging-off air. In these conditions the power developed by the turbine will be insufficient for creation of necessary difference of pressure between the intake and exhaust gas distributing valves of cylinders of the engine by the compressor. Necessary increase of pressure in classical schemes of two-stroke combined engine is reached by application of actuating compressor of the second stage, thus considerable part of engine effective power distracts on actuating compressor. Use of the CPE unit as the basic supercharging stage allows not only to improve the engine adaptability on a torque moment, but also to lower expenditures of mechanical energy for the drive of supercharger of the second stage.

In the scheme shown in fig. 10 surplus part of exhaust gases is directed to the power turbine, cinematically connected with crankshaft of the engine.

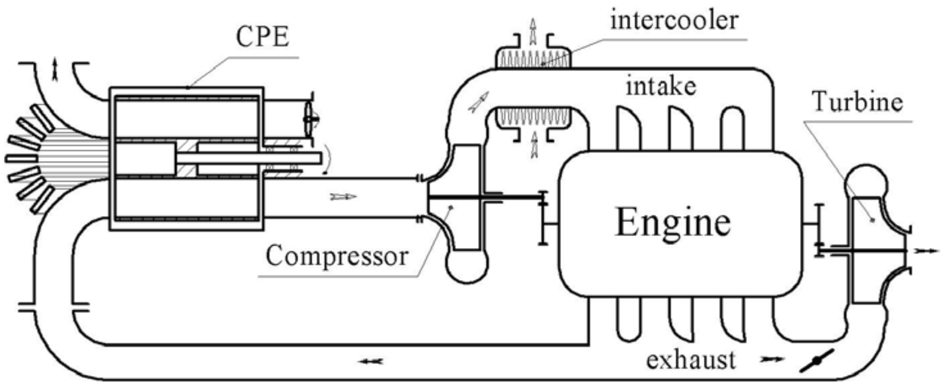

Fig.10. Supercharging system of a two-stroke engine with the CPE

Preliminary computations of working process of the tank engine “3TD-2” show that, already at temperature of the exhaust gases T_{g1}=712 K, the power realized by the turbine exceeds expenditures of mechanical energy for the drive of the scavenging-off compressor. The surplus power of the power turbine reaches 8-10 % of rated power of combined engine on a mode of full loads. If the engine works under the restrictive characteristic (T_{g1}=800), the calculated adaptability factor on a torque moment raises to 1,25 by the application of CPE system of supercharging. In the range of the crankshaft minimum rotational speeds (n=800 min^{-1}) increase of torque moment concerning the indicator of the base engine makes 76 %.

Supercharging system of the CPE with deep cooling of supercharging air. Perhaps, most full power perfection of cascade exchangers is revealed in the combined systems of supercharging and cooling of charging air.

Deep cooling of air submitted to cylinders of the engine (below an ambient temperature) is effective mean of decrease in thermal intensity of cylinder-piston group and increase of density of a fresh charge.

Not less important positive aspect of deep cooling of supercharged air is increase of fuel efficiency due to increase of thermal coefficient of efficiency of diesel cycle in view of expansion of its temperature limits and possibility of increase of the real degree of compression.

Despite perspectives of this direction there are only not numerous attempts of the organization of working process of combined engine with deep cooling of a charge [Radchenco R., 2008], may be, because of the absence of highly effective air refrigerators. Equipment of traditional supercharging systems by complex devices of low temperature cooling not always justified operational of such combined engine with cooling of the charge on an intake as the advantages are appreciably lowered by power inputs on realization of a refrigerating cycle.

Surplus air concerning consumed by a piston part of the engine and forced by an exchanger can serve as a power source and a coolant agent in supercharging systems with the CPE. In this case the air supply unit simultaneously is a refrigerating machinery component. In instillation of supercharging system of deep cooling with CPE that is developed in Department of Internal Combustion Engines of EUNU, according to the scheme shown in fig. 11, as the gas-expansion-compressor we used the cascade exchanger of pressure CPE 2.The contour of low pressure of CPE 2 is connected to a refrigerator of deep cooling.

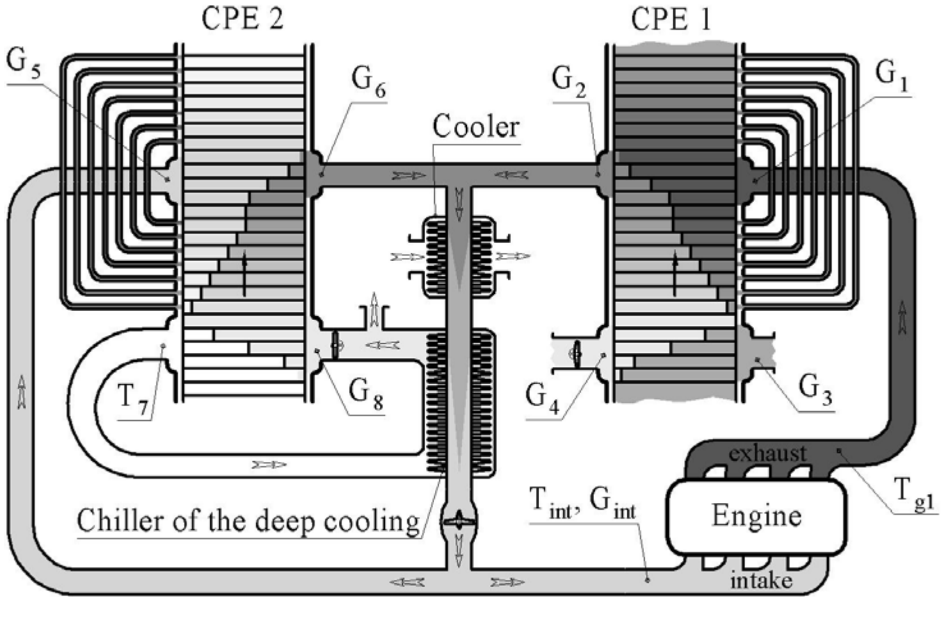

Fig.11. Schematic diagram of supercharging system of deep cooling with CPE

Generally depth of cooling of supercharged air ambiguously depends on quantity of the restarted up air in a contour of expander-compressor of the CPE 2 from a line of forcing of the CPE 1. Calculated data of the various dimensional variants of execution of the CPE 2 (the frontal area of a flowing part of rotor S_{f2}) presented in Table 1 show that increase S_{f2} till some moment (S_{f2} = 0,12 m^2) promotes temperature decrease of supercharged air T_{int} at the consumption of increase in the general compulsion of a coolant in refrigerator. However, the further increase in area S_{f2} is accompanied by decrease in cooling ability of refrigerator of deep cooling due to effect of pressure decrease in lines of a high pressure of both CPE, reduction of degree of air expansion in the expander-compressor and rise of coolant temperature (see Table. 1).

Table 1. **Supercharging parameters at the various frontal sizes of expansion-compressor of cascade pressure exchange**

S_{f2}, м^2	0,072	0,096	0,120	0,144	0,168	0,192	0,216
T_{int}, К	260	255	254	255	257	260	263
P_{int}, kPa	360	289	242	210	189	174	163
G_5/G_{int}	1,43	2,03	2,69	3,41	4,15	4,92	5,71
T_7, К	184	192	201	209	217	255	231

In our opinion, the balance relationship of expenditures of working mediums in supercharging system of deep cooling systems is being represented paradoxical one. It becomes apparent in that the air consumption G_5 in the contour of high pressure of the CPE2 considerably exceeds the air consumption G_2 forced by the CPE1 in spite of the fact that on the realization of the refrigerating cycle is spent only a part of air, forced by the CPE1 (fig. 12) . The "self-multiplication" of consumption in the CPE2 is explained by simultaneous operation of the CPE2 in compressor mode returning considerable consumption G_6 of compressed air into expander contour.

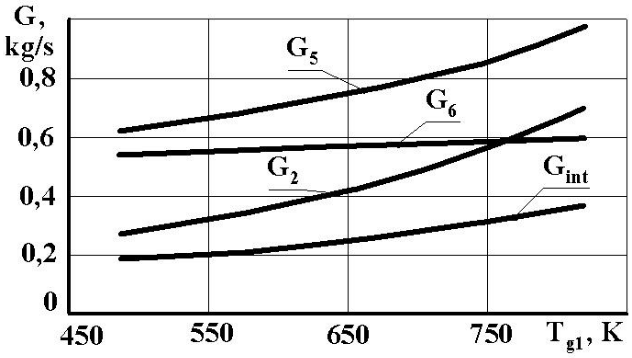

Fig.12. Dependence of consumption G_{int}, G_2, G_5, G_6 in supercharging system of deep cooling with CPE on the temperature of the used gases of the engine T_{g1}

The characteristics of work of experimental installation of supercharging system of deep cooling as a component of the engine K-164, calculated on the maximum supercharging pressure P_{int}=250 kPa are resulted in fig. 13 at T_{g1}=812 K.

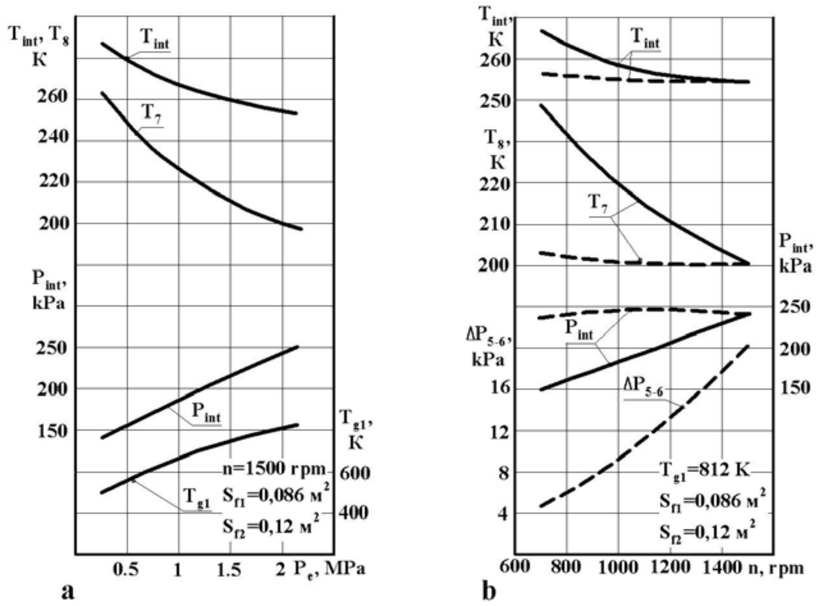

Fig. 13. Loading (a) and velocity (b) characteristics of supercharging system of deep cooling with CPE

- With regulation of pressure difference in windows of high pressure of the CPE2 $\Delta P_{5\text{-}6}$;

- without regulating.

At decrease in crankshaft rotational speed of the engine equipped by supercharging system of deep cooling with no controllable adjustment, certain falling of supercharging P_{int} and raise of T_{int} takes place. The mechanism of such parameters change is caused by excessive restart-up of air forced by the CPE1 into contour of the CPE2 in view of over dimensionality of the last on the modes of crankshaft low rotational speeds. Thus decrease in the general pressure in supercharging system of deep cooling, in its turn, causes falling of degree of air expansion in expander and rise of coolant temperature. As it has been shown above, the correction of consumption characteristic of the CPE 2 is easily reached by pressure difference regulation between windows of a high pressure by way of corresponding change of fan rotational speed. The potential of such regulation is shown in fig.13.b.

Adaptability of supercharging system of deep cooling of supercharging air at operation of combined engine on the loading characteristic becomes apparent in strengthening head and cooling ability of system on modes of the maximum loads (fig. 13 a), where increase of density of the air charge and decrease in its temperature is most expedient. At an ambient temperature of 20 ºC and cooling of supercharged air in a refrigerator of the first stage to 50 ºC on the mode P_e = 1.8MPa temperature decrease of supercharged air in refrigerator makes – 68 ºC, but on the mode P_e = 2.2MPa temperature of supercharged air is lowered on 71ºC.

So, the impressive characteristics of refrigerating cycle of supercharging system of deep cooling of supercharging air enable the parallel usages of supercharging engine system as a refrigerating machinery both of the automobile and railway refrigerator for transportation of perishable freights.

CONCLUSION

High power efficiency of cascade pressure exchangers displayed in considerable excess of the consumption of forced air concerning the consumption of compressing gases opens the prospect of creation of supercharging systems with qualitatively new air supply characteristics of combined engine in a wide range of operational modes. The ability of the cascade pressure exchanger to ensure high effective supercharging of charging air below an ambient environment temperature without additional mechanical energy on realization of refrigerating cycle stipulates the possibility of substantial increase of traction and economical characteristics of engines, especially at their operation in conditions of hot climate.

More detailed information can be received at immediate contact to author. Ph. +79184092859, +380662128077, e-mail: ljangar@rambler.ru

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РАЗВИТИЕ СИСТЕМ НАДДУВА ДВИГАТЕЛЕЙ ВНУТРЕННЕГО СГОРАНИЯ С КАСКАДНЫМ ОБМЕННИКОМ ДАВЛЕНИЯ

Крайнюк А.И.

Аннотация. Раскрыты новые принципы организации рабочих процессов систем наддува дизелей с каскадными обменниками давления, показана возможность значительного расширения области эффективного воздухоснабжения и глубокого охлаждения надувочного воздуха применением агрегатов каскадного обмена давлением. Приведены результаты исследований различных систем наддува с каскадными обменниками давления в составе дизелей ГАЗ - 560 и К-164.

Ключевые слова: каскадный обменник давления, система наддува, воздухоснабжение, глубокое охлаждение, тепловой умножитель.