KOMUNIKÁCIE
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STECHIOMETRICKÝ ZÁŽIHOVÝ MOTOR NA CNG S TROJCESTNÝM KATALYZÁTOROM

NATURAL GAS-FUELLED, SPARK-IGNITED $\lambda = 1$ / TWC ENGINE

Popis použitia riadeného katalytického systému na motore, používajúceho ako palivo zemný plyn, určeného pre zariadenia na združenú výrobu elektrickej energie a tepla. Popis chovania systému spätno-väzobného riadenia zloženia zmesi a zariadenia pre dodatočnú úpravu spalín. Príklady postupu a výsledku optimalizácie konkrétneho motora s ohľadom na jeho emisné a energetické parametre. Porovnanie motora s riadeným katalytickým systémom a ochudobnenej koncepcie.

Description of the implementation of stoichiometric concept on natural gas-fuelled, spark-ignited engine for co-generation plant (CHP). Description of behavior of closed loop λ-control system and exhaust gas aftertreatment. Examples of optimization procedure and its results at particular engine concern its environmental properties, power and efficiency. Comparisons are made between the stoichiometric engine and lean burn one.

1. Gas-fuelled engines for vehicle and stationary use

Combined generation of heat and electrical power (CHP) is a state-of-the-art method of distributed energy supply. Overall efficiency of CHP plant reaches more than 90 % when both types of energy output are taken into account. Transport losses are eliminated since electricity and heat are produced near the site of their consumption. Intelligent management of CHP plant operation can contribute to cope with the necessity of peak shaving within whole electricity network bringing advantages to end users and the network supervisor. A natural gas-fuelled engine is often used as a prime mover of the CHP. That is why the manufacturers of stationary natural gas-fuelled engines experience expansion of production and sales. Several types of gas engines for CHP plants have been developed in ICE laboratory at Faculty of Mechanical Engineering CTU in Prague. According to author's meaning some knowledge gathered at this occasion can be useful for people engaged in R&D activities aimed at gas-fuelled vehicle engines.

There exist certain differences between stationary and vehicle gas engines.

For stationary engines emission limits of CO and especially NO_X are very strict. To fulfill the requirement of well-known TA-Luft regulation (650 mg.m^{-3} CO and 500 mg.m^{-3} NO_X, both recalculated for 5 % of exhaust gas oxygen) approximately 2.25 g.kWh^{-1} of CO and 1.5 g.kWh^{-1} of NO_X must be reached. Overall non-methane hydrocarbons (NMHC) mass flow is limited independent from engine size. Thus for small and medium-sized engine (within hundreds of kilowatts), minimization of hydrocarbon emission is not necessary. Only stationary regimes are investigated during the approval procedure.

Despite of continuous innovation of emission regulations, which is valid for vehicle engines within the whole European territory, the demands for NO_X level are still less strict (such as 7 g.kWh^{-1}).

European regulations require the same level of hydrocarbon emission independent from the kind of fuel used (and from actual composition of emitted hydrocarbons). The total hydrocarbons (THC) limits counts 1.1 g.kWh^{-1} for all heavy-duty vehicle engines even if the unhealthiness of emitted hydrocarbons from natural gas-fuelled engines was proved to be almost negligible.

During operation of CHP engines typically only constant engine speed occurs, defined by synchronous alternator speed. Especially important is the rated power regime. Moreover, the sequence of load changes can often be planned beforehand according to prediction of heat and electricity demands.

A wide range of speed and load must be taken into account in vehicle operation. Low power range is important from the point of view of average fuel economy.

In any fuel vehicle system layout, the fuel pressure at the inlet to engine fuel system is high enough. Either mixer or fuel injection can be chosen purposely.

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Only very moderate gas pressure is at disposal in a low-pressure gas pipeline (In Czech Republic rated overpressure in gas network is 2.1 kPa). Gas mixer (carburetor) is only solution for fuel metering and its delivery into engine.

Typically, a water-cooled intercooler is used for turbocharged CHP engines. Either separate water circuit (approx. 35 °C coolant temperature) is installed, or the mixture cooler is included as a part of utility water circuit (75 °C).

Air-to-mixture heat exchanger is only possibility to perform the mixture cooling for a turbocharged vehicle engine.

Frequently, water-cooled exhaust manifold is arranged as a part of waste-heat utilization system in CHP engines. This design feature is not used as a part of vehicle engine at all.

Design, accessory layout and adjustment of stationary engine are often tailored to suit the particular user demand.

A vehicle is designed, experimentally developed and optimized to satisfy the demands of various potential users.

On the other hand, certain equal features of stationary and vehicle gas engine exist.

High specific power and good fuel economy are desirable. The durability and reliability demands are enhanced continuously. At lean burn engines the running roughness must be minimized purposely.

The same types of basic engines (either diesel or gasoline-fuelled spark-ignited (SI) ones) are rebuilt to use gaseous fuel. The same types of ignition systems are used, especially at highly turbocharged lean-burn engines, with high spark voltage demand.

2. Lean-burn and stoichiometric spark ignited engine

In Fig. 1 a plot of engine properties is introduced as they are measured at constant engine speed at full throttle. Mixture composition expressed in term of air-excess value λ is used as an independent variable. Value pe means brake mean effective pressure (proportional to engine specific power). Value mpe is brake specific fuel consumption (reciprocally proportional to engine overall efficiency). The curves marked CO and NO_X introduce the molar fraction of pollutant in exhaust gas.

A very low level of content of both investigated pollutants is reached if an engine works with extremely lean mixture (high λ value). This environmental friendly behavior is exploited in lean-burn engine design. Lean-burn strategy is not applicable in gasoline-fuelled SI engines due to the significant fall of engine power as is also seen in Fig. 1. At natural gas-fuelled engine it is possible to enhance engine power by turbocharging. Thanks to very good anti-knock properties of natural gas, it is possible to choose an engine compression ratio high enough to obtain satisfactory engine thermal efficiency (an even higher compression ratio is usually used in turbocharged natural gas-fuelled engines than those in naturally-aspirated gasoline-fuelled ones).

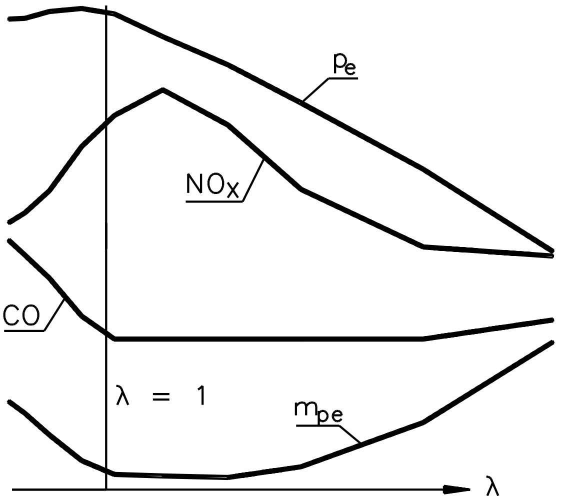

Fig. 1. Engine properties depending on mixture strength

Another possibility to reach acceptable tailpipe emission of pollutants is the application of so-called three-way catalyst (TWC) as it is used in conventional gasoline-fuelled engines usually used as a part of a passenger car power unit. To ensure a good condition for exhaust gas after-treatment, it is necessary to keep mixture strength very close to so-called stoichiometric value ($\lambda = 1$). Usually a closed-loop mixture strength control system is used to perform this task.

Additional expense for a catalytic reactor itself is a considerable disadvantage of $\lambda = 1$ / TWC engine concept. Cost of the catalyst is approximately proportional to engine rated power; thus, the rise of an investment cost in a great power unit is significant.

On the other hand, certain advantages are obvious.

Molar fraction of CO and NO_X in tailpipe exhaust gas (downstream of the catalyst) is very low as far as the catalyst itself and closed loop λ-control system works properly. Usually, lower emission is obtainable as in case of lean-burn engine.

Since the closed-loop control is integrated as a part of an engine accessory, long-term stability of environmental behavior is expected.

High heating value of stoichiometric mixture makes it possible to obtain high engine specific power at the same degree of turbocharging (or taking into account both naturally aspirated stoichiometric and lean-burn engines).

Tailpipe emission of $\lambda = 1$ / TWC engine depends primarily on technical efficiency of exhaust gas after-treatment and is almost not influenced by molar fraction of pollutants in raw exhaust gas (upstream of the catalyst). Thus, engine design and its optimization can be realized by only taking into accounts its power and efficiency.

Running roughness of an engine operated on stoichiometric mixture is better than in a case of lean-burn engine. This feature is especially important when an engine drives synchronous alternator. In this case the fluctuation of instantaneous crankshaft (flywheel) speed causes deformation of voltage waveform and/or current of delivered electricity. With rising amount of small CHP unit within certain territory the network supervisor authority will constitute more strict rules concerning quality of delivered electricity to enable the small power plants to link into the network.

From the mentioned reason it is assumed that the use of stoichiometric concept in the region of co-generation engines will be not limited to the lowest edge of rated power range.

3. Description of λ-control system

As it was already mentioned, the use of common mixer with a fixed air-metering orifice is the only possibility to design a fuel system layout of a CHP engine. A variable cross sectional area of fuel-metering orifice must be applied for exact mixture strength control to ensure good technical efficiency of catalyst. Conventional layout of closed-loop λ-control system is illustrated in Fig. 2.

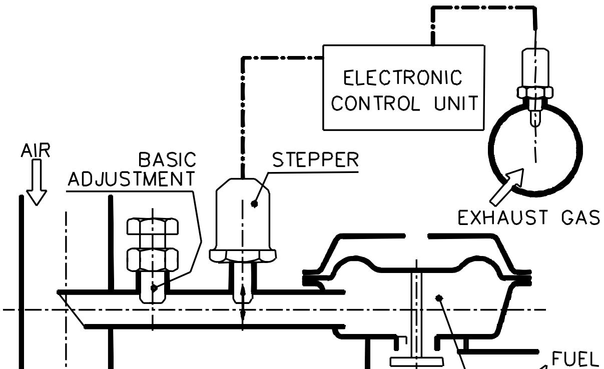

Fig. 2. Typical λ-control layout

λ-sensor is installed in engine exhaust manifold upstream of the catalyst. Sensor generates voltage, which depends on exhaust gas oxygen content. Its response is very steep when mixture strength lies within narrow range in vicinity of air-excess value of $\lambda = 1$.

Usually the movable part of fuel-metering orifice is driven by step motor. Concerning such a type of λ-control actuator it is necessary to take into account possible range of control performance and rate of its change.

The optimization of behavior of controlled catalytic system will be discussed later.

Conventional λ-control system for gas-fueled engines (e.g. passenger car ones) works according to the (so-called one-threshold) algorithm described in Fig. 3 using dashed lines. Electronic control unit (ECU – see Fig. 2) transmits (constant frequency) pulses for step motor forcing it to increase (decrease) the cross sectional area of the fuel-metering orifice as an actual λ-sensor voltage becomes lower (higher) than the preset threshold (point 0 at voltage deviation axis in Fig. 3).

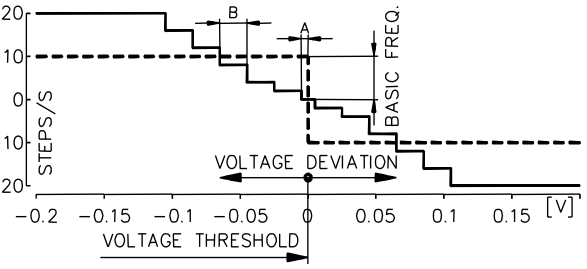

Fig. 3. Algorithm of λ-control operation

During operation a step motor stops only in dead center of its periodic motion.

Fluctuation of basic parameters of λ-control system is illustrated in Fig. 4 (rated power regime of a particular engine and correct setting). In this figure actuator position is expressed in terms of number of steps from actuator position corresponding to smallest possible cross-sectional area of fuel-metering orifice. This means 0 steps correspond to minimum (but still not zero) cross-sectional area, 180 steps correspond to maximum adjustable size of fuel-metering orifice.

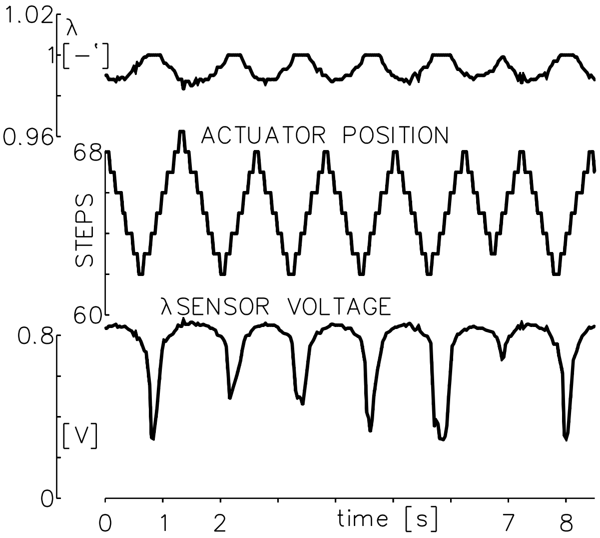

Fig. 4. Behavior of simplest λ-control system

Period and amplitude of periodic changes of actuator position become greater as the working fluid flow through the engine decreases. This phenomenon is caused by increase of delay between change of fuel flow at the inlet port of mixer and response of λ-sensor, which takes place as late as the new composition of exhaust gas reaches the site of sensor installation.

Voltage threshold and basic frequency are electrically adjustable. Moreover, the intensity of mixture strength response to actuator movement is influenced by position of manually controlled screw usually installed in a fuel pipeline upstream of fuel inlet port of mixer (BASIC ADJUSTMENT screw in Fig. 2). Thus, altogether three adjustable elements are at disposal (as far as the simplest algorithm is concerned according to it description by solid lines in Fig. 3) to optimization of system behavior.

Optimization demands are as follows:

- Level of fluctuation of molar fraction of particular component of exhaust gas must be high enough to keep heterogeneous nature of catalytic reaction. On the other hand, the oxygen capability of the catalyst must not be expired. The curves in Fig. 4 introduce a good example of proper setting. This behavior must be ensured over whole engine operating range at various atmospheric conditions and so on.
- Reasonable compromise must be found between system stability at stationary condition and its adequate response when change is demanded (in transient regimes).
- The amplitude of motion of actuator movable part must be maintained as low as possible to ensure sufficient durability, reliability and long-term stability of engine properties (still taking into account previous items of this list).
- The limits of stepper motion must not be exceeded. The limits are determined either by the mechanical design of fuel-metering orifice or by the enabled format of numbers for digital operation inside ECU processor (maximum = 255 occurs frequently as a limit to make possible one-byte expression)

To enable high effectiveness of the development procedure mathematical model of λ-control system behavior was created. The following items are used as inputs for calculation process:

- Description of the relevant part of engine geometry (engine displacement, volume of intake manifold between mixer and engine inlet, volume of exhaust manifold between engine outlet and position of λ-sensor.
- Description of running regime (engine rpm and its actual volumetric efficiency, which depends on throttle position and exhaust temperature)
- Description of λ-control system setting (actuator position limits, threshold voltage, frequency of driving pulses)
- Additional metering orifice cross sectional area (position of BASIC ADJUSTMENT screw in Fig. 2) is defined indirectly entering starting actuator position (this means in the moment of start of computation) and corresponding air-excess value.

On the other hand, certain features are not included in the mathematical model properly, including:

- λ-sensor characteristic is transferred into model from manufacturer's documentation. Impact of appearance of particular components on actual relationship between air excess and sensor voltage is not taken into account. Especially in case of natural gas fuelled engine the influence of relatively high methane concentration is not negligible.
- The flow coefficients of metering orifices were not investigated. Only pure geometry sizes and their changes appear in the model.

Even if above mentioned simplifications were applied the model results show good agreement with experimental reality as is documented in Fig. 5. Real shapes of actuator position were acquired using RS232 of λ-control ECU. Shapes of sensor voltage were recorded using conventional A/D converter. In presented case the change of working fluid flow was caused by change of engine speed maintaining fully open throttle. Both period and amplitude of fluctuation of stepper position as well as sensor voltage increase, as working fluid flow becomes lower. The reason was described above.

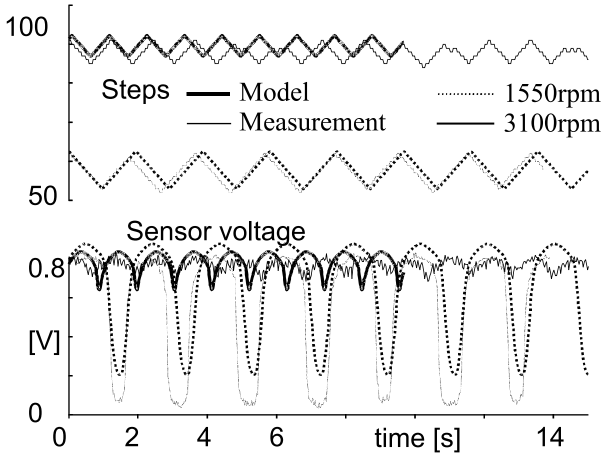

Fig. 5. Model / experiment comparison

The model is usable for various optimization purposes. Either experimental result can be extrapolated or the behavior of real engine (in this case of its electronic control system) can be predicted. It is even possible to simulate transient behavior entering starting value of air excess outside the range of its natural fluctuation during steady state operation.

An example of integral result of model computation is introduced in Fig. 6.

Threshold voltage adjustment is used as independent variable in this figure. All other items in the set of input values for computation were kept constant.

The fluctuation of sensor voltage, actuator position and air excess value is represented by plot of maximum and minimum value of their periodic changes (in case of sensor voltage the average value is also plotted). It is to be seen that over wide range of independent value in the midst of horizontal axis all investigated values are not influenced by change of adjustment of threshold voltage.

In this time only very simple mathematical model exists to describe the chemical reaction which takes place inside of the

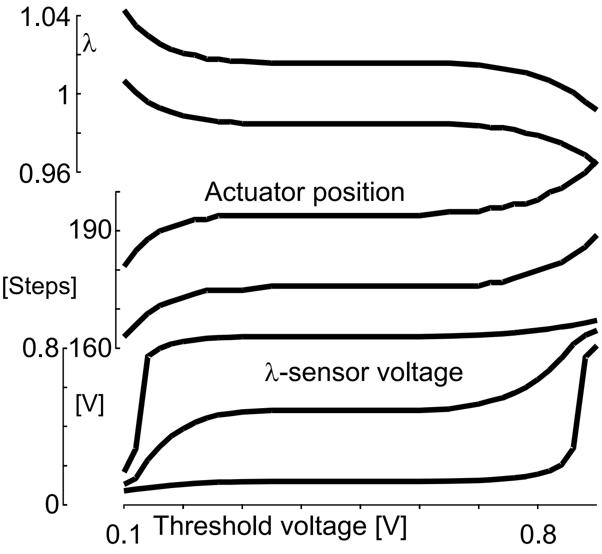

Fig. 6. Predicted influence of treshold voltage

catalytic reactor. This model does not take into account any of mentioned features of closed loop control system behavior. Only equilibrium composition is calculated and reaction rate is estimated to obtain good agreement with experimental results. Such a model is not suitable as a tool for research and development work. Thus only empirical knowledge is at disposal concerning technical efficiency of exhaust gas after-treatment.

Large-scale amount of experiments must be performed to obtain complete set of information describing the behavior of catalytic reaction depending on whole set of adjustable element of closed-loop control system. One example of measured curves is introduced in Fig. 7.

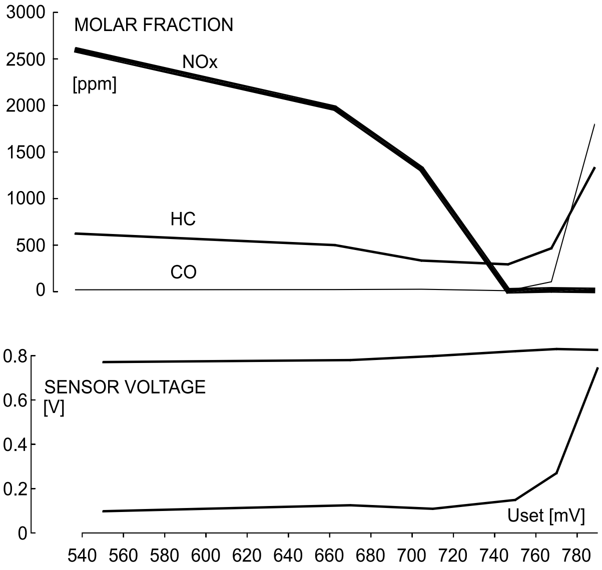

Fig. 7. $\lambda = 1$ */ TWC system behavior depending on treshold voltage setting*

Similarly to Fig. 6 threshold voltage level is used as independent variable in Fig. 7. All other circumstances were maintained unchanged during measurement including operation regime (rated power was maintained during measurements whose results are in Fig. 7).

The measured sensor voltage range (in bottom part of Fig. 7) shows good agreement with theoretically predicted shapes in Fig. 6. For particular running regime and the given position of all other adjustable entries the optimum setting of threshold voltage can be read from shape of molar fraction of pollutants (expressed in Fig. 7 in terms of ppm). Approximately 750 mV seems to be best choice in the presented case. It is seen in Fig. 7 that optimum setting from the point of view of hydrocarbon emission corresponds with the threshold voltage value leading to low tailpipe emission of both *CO* and NO_x, simultaneously. This statement is valid even if the technical efficiency of the catalyst is relatively low as far as hydrocarbon afterburning is concerned. This feature is out of scope for CHP engine manufacturers, but it is of interest for designers of vehicle engines.

Nevertheless, the problem of retrieval of optimum setting for whole range of running regimes remains still unsolved.

Full satisfaction of all demands by only three adjustable elements seems to be questionable.

A more sophisticated algorithm of step-motor control is described in Fig. 3 by a solid line. In this case driving-pulse frequency for the stepper depends on the difference between λ-sensor voltage and voltage-threshold value. The step motor does not move at all as far as the voltage difference lies within the range ± A (Fig. 3). Driving frequency increases stepwise as the voltage difference exceeds each of the B intervals. In this algorithm's particular application, values A and B are adjustable from computer console using ECU RS 232 interface. Threshold voltage is adjustable in the same way. The basic frequency, the slopes of its change and the maximum frequency are programmed in ECU processor and are not user accessible.

4. Optimization procedure and its results

The last described system (multi-threshold one) was implemented on a 6-cylinder naturally aspirated engine coupled with a synchronous generator 75 kW/1500 rpm. CHP unit was connected during the realization of R&D tasks to public 400 V electricity network. Natural gas was delivered from a low-pressure gas pipeline (2.1 kPa overpressure) through the conventional zero-pressure control valve as is indicated in Fig. 2.

Typical behavior of the multi-threshold λ-control system is illustrated at Fig. 8. This time the voltage threshold level was adjusted to a 680 mV value. At engine operation at the rated load (and high working fluid flow) the delay of λ-control response is short. Fuel-metering orifice cross-sectional area changes during steady state operation only to correct the occasional fluctuation

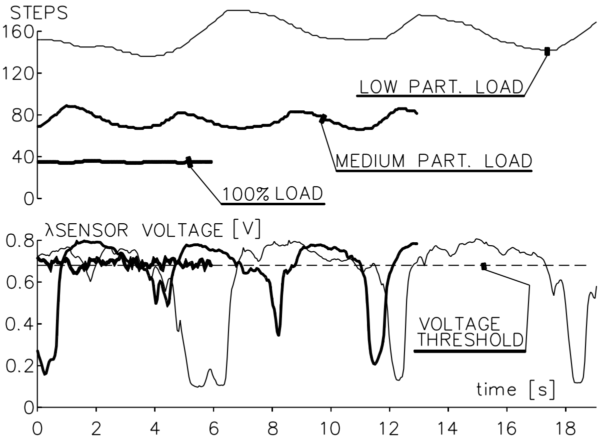

Fig. 8. Behavior of multi-treshold λ-control system

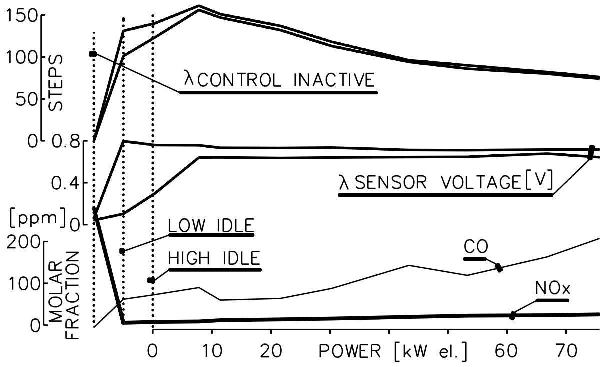

Fig. 9. Final results of optimization

of mixture strength. As the working fluid flow becomes lower the closed-loop response delays more and the system behaves periodically (similarly to a simple one-threshold system). Amplitude and period of periodical fluctuation increase with throttling of the mixture flow. Unlike one-threshold system behavior (Fig. 4) step-motor position shapes (upper part of Fig. 8) do not resemble a symmetrical triangle since driving-pulse frequency changes within one period of periodical motion. This feature is caused by nonlinear shape of λ-sensor voltage due to its nonlinear characteristic as it was briefly described in the comment to Fig. 2.

After carefully performed optimization of electrical and mechanical adjustment, parameters were obtained as they are described in Fig. 9.

In this figure fluctuation of actuator position (upper part of Fig. 9) and sensor voltage (middle part) are visualized by plot of maximum and minimum value recorded during 10-second intervals by a data acquisition system.

In the range from rated regime to zero load (generator disconnected from network, unit still runs at rated speed ≡ 1500 rpm – so-called high idle) conventional part-load characteristic is plotted. The points with horizontal coordinates of −5 kW were measured by unloaded (disconnected from network) generator and engine speed approx. 1300 rpm (so-called low idle). The points with horizontal coordinates of −10 kW describe situation with λ-control switched off. Negative powers were used as a coordinate only to ensure good readability of graph.

It is seen in Fig. 7 that over whole load range (from rated power to low idle):

- *CO* emission lies below 1/2 of legislative limit
- NO_x emission lies approx. at the level of 1/10 of legislative limit
- amplitude of fluctuation of sensor voltage and actuator position is low (except for slightly higher amplitudes of sensor voltage variation at engine idle)
- actuator position moves inside the limits (between 0 and 180 steps in this case).

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