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Optimization of Water-Fuel Emulsion Component Composition and the Dynamics of Continuous Action Preparation Systems

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Abstract: The study and the review of the component composition optimization system concerning Water-Fuel Emulsions (WFE) according to the indicators of diesel power plant functioning. The optimization criteria determination according to static characteristics. The research deals with the dispersant dynamic model and provides the guidance to the development of water concentration stabilization circuit in WFE. The solution of this problem for diesel engines was carried out on the basis of experimental data generalization, WFE application issue published by researchers. The smoothing of experimental data was performed by the method of least squares. Power polynoms were used as an approximation function. According to the study results it is clear that an open loop stabilization system by the volume flow of fuel and water costs is the easiest one in terms of implementation, availability and the cost of components (sensors). An open stabilization system was developed and tested for the main tanker boilers. Concentration setting period at the level of 2% from the desired one made 180-200 sec. Such system indicators satisfy entirely according to output speed parameter to the nominal steam output. The researchers conducted a number of works on the analysis and the description of the component composition optimization system in respect of Water-Fuel Emulsions (WFE) according to the indicators of diesel power plant functioning. The solutions are offered to overcome the disadvantages in continuous operation systems, optimizing the component structure of WFE during a power plant operation. The optimization criteria for static characteristics are provided. The dynamic model of the dispersant is described and the guidance to the stabilization circuit construction are provided concerning the water concentration in WFE.

Key words: Optimization systems, water-fuel emulsion, pyroelectric charges, power plant, engine, diesel power plant

INTRODUCTION

The composition of fuel equipment in many industrial diesel devices and transport include Water-Fuel Emulsion (WFE) preparation systems. Most of them support a fixed, a priori defined WFE composition which is considered as the best one according to the economic indicators of fuel combustion. The analysis of this best composition determination principles can be found by Treea and Svensson (2007) and Lapuerta *et al.* (2007). At that they are guided. However, such systems have a number of disadvantages. The main of them is the discrepancy between the fixed WFE content and the best one according to environmental indicators. Due to a number of WFE combustion physical-chemical characteristics the optimum water concentrations are different for economic and environmental indicators. They also differ for the various toxic components of combustion products. Piacentini (2006), Bertola (2003), Aswani *et al.* (2005) and Ganigin (2005) presents a two-parameter approach to determine the optimal composition according to NO and exhaust gas smoke indicators. Another disadvantage is the absence of impact consideration on operation mode combustion performance of a power plant and the change of its parameters during functioning and during the entire period of operation.

These drawbacks can be eliminated in continuous operation systems by the optimization of WFE component composition during a power plant operation. The structure of this control system is shown on Fig. 1.

The structure of the management system includes the determination contour of WFE optimal composition (the top level of management), WFE composition stabilization contour (lower level of management), WFE preparation device, the feeder which regulates the water supply. In this case, a diesel engine is considered as a management object.

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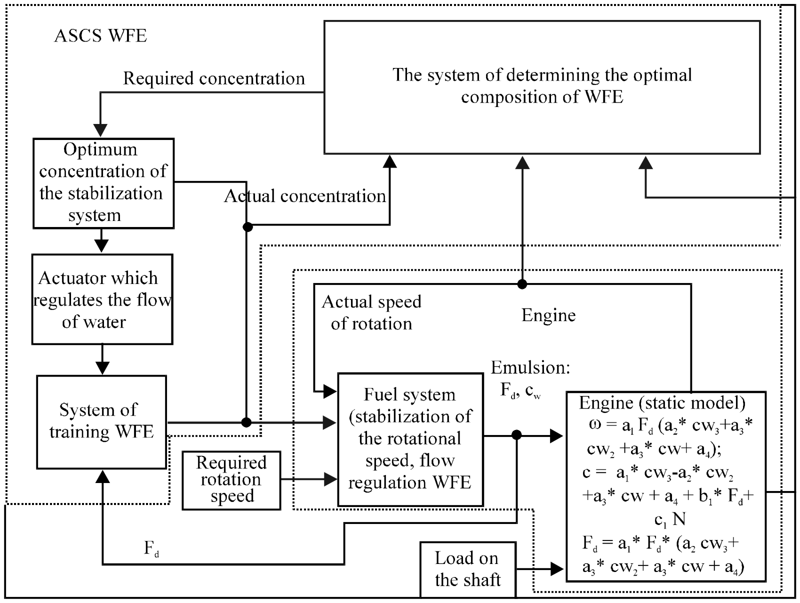

Fig. 1: ASCS WFE Model for a diesel engine

MATERIALS AND METHODS

The optimum composition of the emulsion is determined according to engine operation observation results (the observed values-rotation speed, the concentration of toxic components in the exhaust gas, the actual concentration of water in WFE). The data concerning the engine functioning are subjected to statistical analysis, on the basis of which an optimal emulsion composition is determined according to optimization criteria. The obtained value of water concentration is supplied into the stabilization contour as the desired output value. The stabilization contour develops the control actions which come on the dispenser in order to stabilize the actual concentration at the level required during the minimum time.

The main objective during the design of such systems is the development of optimization criteria and their formalization for control purposes. The solution of this problem for diesel engines was carried out on the basis of experimental data generalization published by the researchers of WFE use issue and the reliability of SamSTU mechanical systems received by the SRC staff (Ganigin, 2005) (Fig. 2 and 3).

Experimental data smoothing was performed by the method of least squares. Power polynoms were used as an approximate function. Polynom coefficient vector is determined from the following matrix expression:

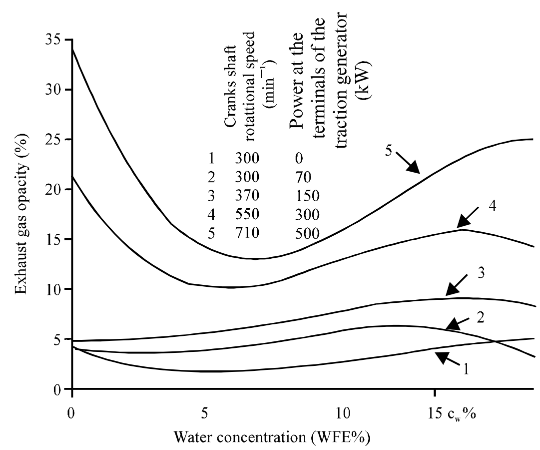

Fig. 2: The dependence of exhaust gas smoke rate on water concentration in WFE during rheostat tests of PD-1M at the locomotive TEM-2

$$\tilde{A} = (F^T F)^{-1} F^T \tilde{Y} \quad (1)$$

Where:

F = The matrix of an input coordinate degrees

Y = The average value vector of the output coordinate in the selected nodes

The best results in each of the considered cases were obtained using the third-degree polynomials. On the basis of these data analysis we can draw the following general conclusions about the nature of toxicity and efficiency indicator change, depending on the proportion of the emulsion components:

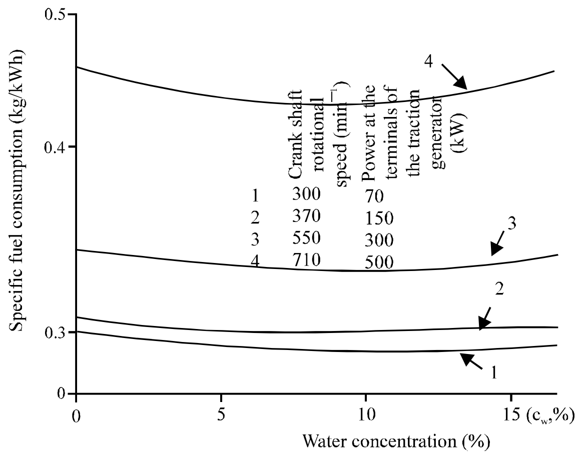

Fig. 3: The dependence of the specific fuel consumption on water concentration in WFE during rheostat tests of PD-1M at the locomotive TEM-2

- At the change of water concentration in WFE the exhaust gas toxicity values (CO, NOx, smoke, etc.) in the steady states (at a fixed load) are monotonic ones or have an extreme behavior with a single point of extremum (the bulge of static characteristic functions). The character of monotony (increase or decrease) depends on fuel equipment design, an engine type, etc.
- Profitability index specific fuel consumption at a fixed power has an extreme character depending on the concentration of water in WFE with the portion of the minimum specific consumption in a certain range of Cw change
- Due to a number of physical-chemical characteristics concerning WFE combustion in DEU the points of static characteristics extremum are not the same according to the economic and environmental indicators
- The static characteristics of a control object with the sufficient accuracy for a control problem solution can be approximated by the third degree polynomials

From a practical point of view, taking into account the abovementioned features of the control objects one may identify the main conditions of these objects and the optimization modes corresponding to these states (Fig. 4 and 5).

Criteria optimization and a corresponding algorithm of an optimal concentration search can be formally represented as follows:

$$\Omega: C(Cw, N) < T_{lim} \quad (2)$$

$$Cw \in [0; Cw_{np}] \quad (3)$$

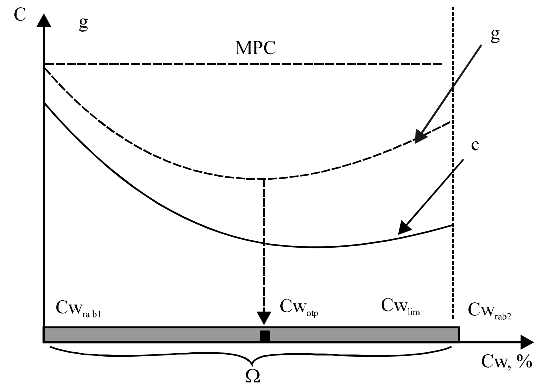

Fig. 4: Toxicity indicators do not exceed the corresponding MPC in the range of permissible Cw. The optimum concentration is the minimum point of the specific fuel consumption static characteristics

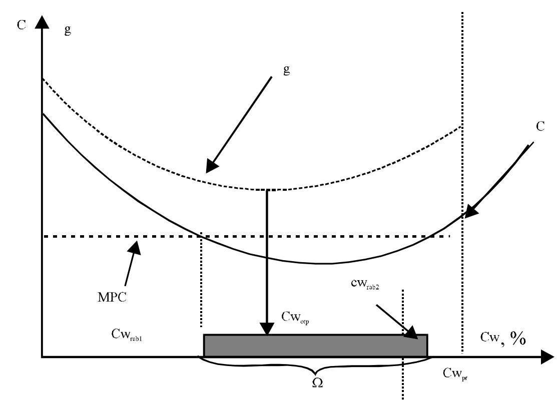

Fig. 5: Toxicity indicators do not exceed relevant MPCs in the range of Cw variation, comprising the extreme behavior of a net fuel consumption curve

$$Cw = \arg\min_{Cw \in \Omega} g(Cw, N) \quad (4)$$

Where:

- Cw = The concentration of water in an emulsion
- T_{lim} = The maximum permissible concentration (MPC, Table 1) of a toxic component in the combustion products (Treea and Svensson, 2007; Mendez and Thirouard, 2008; Lin and Wang, 2004)
- N = Diesel plant performance rate
- g = The specific consumption of clean fuel
- C_{wpr} = Permissible concentration range-the concentration range within which the toxic components do not exceed the respective MPCs

The first two inequalities set the water concentration range in WFE within which the toxicity values do not

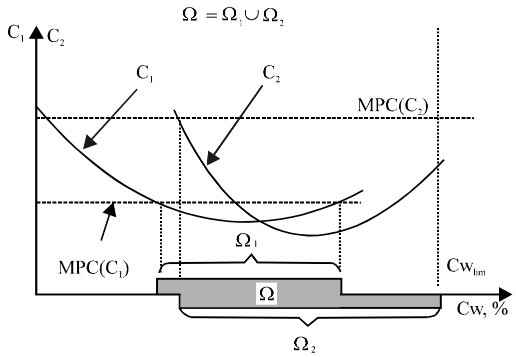

Fig. 6: Determination of water concentration allowable range according to the static characteristics of two toxicity indicators (C_1 and C_2)

Table 1: Maximum permissible concentrations of major pollutants in the air

Substance	Single maximum one (MPC, mg/m^3)	Daily average (MPC, mg/m^3)
Nitrogen dioxide	0.085	0.04
Nitrogen oxide (II)	0.400	0.06
Carbon oxide	5.000	3.00
Soot	0.150	0.05

exceed MPC (C_{lim}). The last equation determines a single concentration value as the minimum point of the economic indicators in the obtained interval. The interval of permissible concentrations is determined according to the inequality set solution:

$$\begin{aligned} &C_1(Cw) \le PPD_1 \\ &C_2(Cw) \le PPD_2 \\ &\cdots\cdots\cdots \\ &C_n(Cw) \le PPD_n \end{aligned} \quad (5)$$

where, $C_1(Cw)$, $C_2(Cw)$, $C_n(Cw)$: the static characteristics of toxicity indicators (third-degree polynomials). Figure 6 shows the solution of these inequalities graphically.

During the implementation of algorithm control and formalization system these inequalities can be solved by known numerical methods.

So within the range of acceptable values as the result of an error approximation, the static characteristics of toxicity values may not be convex functions. It is necessary to conduct an additional analysis of the obtained roots.

During the determination of the allowable concentration range an ambiguity may appear during the analysis of various toxic components. If the intervals are not intersected:

$$\Omega_1 \cup \Omega_2 \cup .. \cup \Omega_n = \phi \quad (6)$$

One may set the selection priorities, based on the reduction requirements of the most harmful components of the combustion products in the first case. The monoxides of carbon and nitrogen are the most toxic ones.

In practice, the data collection concerning a system operation is carried out at the beginning of the control system operation. At that an object input is supplied with concentration test values and after the completion of transient processes the values of output variables are measured and kept, on the basis of which the polynomial coefficients of the static characteristics are determined.

The first two above determined results and the Eq. 3 of the optimization criteria allow to use the extreme control algorithms in the cases when a found working concentration interval includes the extreme behavior range of specific fuel consumption. By the application of extreme algorithms one may increase the effectiveness of control system at the change of load and speed mode of a power plant operation as well as at the change of its parameters during operation.

RESULTS AND DISCUSSION

All of the stated above can be represented by the control algorithm shown on Fig. 7. During the development of extreme control algorithms one shall take into account the object response delay time after an input action (water concentration change in WFE).

More stringent requirements, taking into account an object dynamics are demanded to loop stabilization algorithms. This problem is most acute one for continuous WFE preparation systems, because they make the part of the fuel delivery equipment in power plants (boilers, diesel engines, etc.) in which the time of output variable setting (pressure, flow, temperature) are limited strictly.

In order to develop an optimal speed stabilization system it is necessary to have a mathematical model of a control object. A dispersant mixer is a control object for a stabilization circuit.

From the management point of view, this is a single-capacity regulation object. The input values for these objects are the flow rates of water $q_{W\,in}$ and fuel $q_{F\,in}$. The output value is the water concentration c_w in WFE and it is WFE consumption q_{out} at a dispersant output for continuous operation system. Let's consider the dynamic model of an object and state the requirements for the stabilization circuit development. The mass balance equations of the flowing volumetric consumption of components:

$$\begin{aligned} \frac{dV_F}{dt} &= q_{F\,in} - q_{F\,out} = q_{F\,in} - (1-c_w)q_{out} \\ \frac{dV_W}{dt} &= q_{W\,in} - q_{W\,out} = q_{W\,in} - (1-c_w)q_{out} \end{aligned} \quad (7)$$

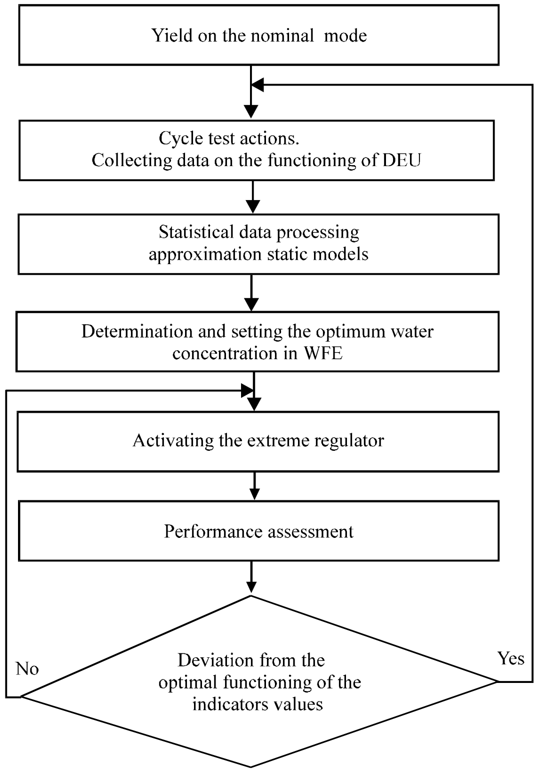

Fig. 7: The algorithm of water concentration management in WFE

Assuming that the concentration at a mixer output is determined by the ratio of component volumes within a vessel, we obtain the following one:

$$\frac{dc_w}{dt} = \frac{dV_W}{dt} \Big/ \left(\frac{dV_W}{dt} + \frac{dV_F}{dt} \right) = \frac{q_{W\,in} - c_w q_{out}}{q_{W\,in} + q_{F\,in} - q_{out}} \quad (8)$$

Finally, we obtain the equation of water concentration in WFE at a mixer output:

$$(q_{W\,in} + q_{F\,in} - q_{out}) \frac{dc_w}{dt} + q_{out} c_w - q_{W\,in} = 0 \quad (9)$$

An object acceleration period is determined by a dispersant work area volume, the component density and viscosity. This note can be used in the design of WFE preparation system (i.e., it is apparent that decrease a dispersant size decrease and the pre-treatment (heating) of the components takes place).

The most important comments on the control system structure can be obtained on the basis of expression 9 analysis.

CONCLUSION

Obviously, the best performance indicators concerning the control accuracy and reliability will be a closed system with the water concentration sensor in WFE and WFE flow sensor installed on a dispersant output. The disadvantages of such a structure are the following ones:

- The current absence of water concentration standard sensors in WFE
- The effect of water concentration (WFE density and viscosity) on WFE flow sensor readings (the most common ones are of an ultrasonic or a vortex type)

The most simple one in terms of components (sensors) implementation, availability and cost but a less accurate one is an open stabilization system by the flowing in volumetric fuel and water costs. An open stabilization system was developed and tested for the main boilers of tankers. The time of concentration establishment at the rate of 2% from the desired one made 180-200 sec. Such system indicators entirely satisfy according to the output speed parameter concerning the nominal steam production. However, this time shall be reduced during the operation process for the optimization.

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