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CONTROL OF WATER-DIESEL EMULSION STABILITY USING TURBIDITY MEASUREMENTS

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Abstract. *This paper describes a technical solution for emulsion homogeneity monitoring. It consists of turbidity sensors mounted in existing emulsion storage tanks, an electronic module, and corresponding measuring instruments. An experimental setup was developed to test the metrological characteristics of the turbidity sensors using standard kaolin suspension samples. Experiments have shown that turbidity sensors have an extensive measuring range, high sensitivity, and a close-to-linear transfer function. Using turbidity sensors allows for monitoring the stages of emulsion breakdown, such as sedimentation, coalescence, and complete separation into two liquids. Detecting the moment of emulsion breakdown in real-time makes it possible to apply three different modes to restore emulsion homogeneity by repeated mixing at different time intervals. An automated system for monitoring emulsion homogeneity, consisting of turbidity sensors, an electronic module, and a programmable logic controller, is proposed. Monitoring the emulsion destabilization process in real time makes it possible to use three different modes to restore its homogeneity by repeated mixing at different time intervals. This provides a significant reduction in the time to restore the homogeneity of the water-fuel emulsion. The proposed system can be integrated into most existing installations for the production and storage of water-fuel emulsions.*

Keywords: water-diesel emulsion, homogeneity, turbidity sensor, transfer function

KONTROLA STABILNOŚCI EMULSJI WODA-DIESEL ZA POMOCĄ POMIARÓW ZMĘTNIENIA

Streszczenie. *W artykule opisano rozwiązanie techniczne do monitorowania jednorodności emulsji. Składa się ono z czujników mętności zamontowanych w istniejących zbiornikach do przechowywania emulsji, modułu elektronicznego i odpowiednich przyrządów pomiarowych. Opracowano układ eksperymentalny do testowania charakterystyk metrologicznych czujników zmętnienia przy użyciu standardowych próbek zawiesiny kaolinu. Eksperymenty wykazały, że czujniki zmętnienia mają szeroki zakres pomiarowy, wysoką czułość i funkcję transferu bliską liniowej. Zastosowanie czujników mętności pozwala na monitorowanie etapów rozpadu emulsji, takich jak sedymentacja, koalescencja i całkowite rozdzielenie na dwie ciecze. Ustalenie momentu rozpadu emulsji w czasie rzeczywistym umożliwia zastosowanie trzech różnych trybów przywracania jednorodności emulsji poprzez wielokrotne mieszanie w różnych odstępach czasu. Zaproponowano zautomatyzowany system monitorowania jednorodności emulsji, składający się z czujników zmętnienia, modułu elektronicznego i programowalnego sterownika logicznego. Monitorowanie procesu niszczenia emulsji w czasie rzeczywistym umożliwia zastosowanie trzech różnych trybów przywracania jej jednorodności poprzez wielokrotne mieszanie w różnych odstępach czasu. Zapewnia to znaczne skrócenie czasu przywracania jednorodności emulsji wodno-paliwowej. Proponowany system można zintegrować z większością istniejących instalacji do produkcji i przechowywania emulsji wodno-paliwowych.*

Słowa kluczowe: emulsja woda-diesel, jednorodność, czujnik zmętnienia, funkcja transferu

Introduction

The most promising and versatile way to improve the environmental and economic performance of diesel engines is the use of water-fuel emulsion as fuel, the water phase of which has been pre-treated to reduce its acid and alkaline components. This technique is attractive due to the possibility of solving a number of serious problems – reduction of carbon monoxide formation, smokiness and toxicity of exhaust gases, and fuel consumption [13].

The combustion process of water-fuel emulsion differs from the combustion of unwatered fuel [14]. A water-fuel emulsion droplet, which has a nucleus consisting of one or more water droplets covered by a solvate layer and fuel, starts to heat up when injected into the combustion chamber. As the temperature rises, the fuel shell of the droplet still remains in a liquid state, as the boiling point of fuel is higher than that of water, while water begins to evaporate as the droplet warms up. The fuel viscosity and surface tension forces decrease and the water vapour pressure inside the droplet increases, leading to an increase in the droplet size followed by a sharp breakup into tiny particles [10]. This phenomenon is known as a 'micro explosion' [8].

This increases the fuel vaporisation surface and leads to intensive mixing of fuel with air oxygen, which promotes its more complete combustion and significantly reduces the content of incomplete combustion products in exhaust gases [4]. Also water vapours actively participate in chemical reactions of combustion processes, contribute to carbon gasification, loosening of soot and its burning. During combustion of a water-fuel emulsion, part of the heat released as a result of reactions is spent on water evaporation, resulting in a reduction of exhaust gas temperature and NO_x output by more than 60% [7]. The concentration of water in the emulsion has its optimum value, at which the maximum reduction of specific fuel consumption is achieved. In most cases, the maximum fuel economy can be provided at water concentration in water-fuel emulsion of 10–20% [9].

For water-fuel emulsion the main quality indicators are the percentage of water content, droplet size distribution (fractionality) and stability, the values of which depend on the emulsion preparation methodology. The values of these parameters directly determine the economic and environmental performance of the combustion process [17].

The complexity of water application in the mixture with diesel fuel is to ensure the stability of water-diesel mixture [1]. Unlike mixtures based on heavy fuels – boiler fuel and mazut, diesel fuel does not contain natural emulsifiers in the form of asphaltenes and petroleum resins. The stability of the emulsion should be maintained continuously because when the water-fuel emulsion stops retaining its homogeneity, it loses all benefits from usage and can become destructive for engines because of fuel water cuts [2, 3, 12, 18, 19]. There is a strong need for automatic control of the water-fuel emulsion stability and the detection of the beginning of the layering process, which can be implemented in the existing equipment for water-fuel emulsion production, storage, and transportation.

1. Materials and methods

Paper [15] described a method based on the passage of light through an oil-in-water emulsion to assess its delamination. The emulsion stability analyser consisted of five light emitters and five optical receivers. The analyser was used to record the time of emulsion separation. The method also made it possible to control the delamination zones using five points for receiving and emitting light. The method has great promise, but is designed to test the stability of pre-selected emulsion samples in the laboratory.

To control the stability of the water-fuel emulsion, TS-300B electronic modules were used together with TSW-30 sensors for measuring turbidity (Fig. 1). The operation principle of the sensors is based on measuring the intensity of the light flux scattered by suspended particles of the examined substance with reference to the standard turbidity units NTU (Nephelometric Turbidity Units) [11, 20]. The sensors design allows installation in existing tanks or containers with the emulsion, which simplifies the emulsion stability control during storage, transportation and immediately before use.

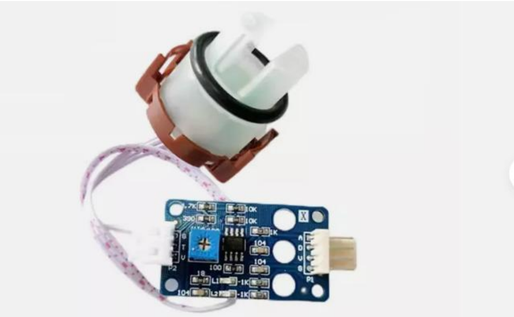

Fig. 1. Electronic module TS 300B and TSW-30 turbidity sensor

Both diesel fuel and water are transparent liquids and create no obstacles for light transmittance. Water-fuel emulsion is a homogenous substance in which suspended water particles (dispersed phase) are evenly distributed in fuel (continuous phase) and lose their transparency during production. When the value of the output DC voltage, obtained from TS 300B, is close to zero, the emulsion can be called homogenous, and when the output signal is more than 3.0 volts, we can speak about a complete layering into water and fuel.

To calibrate the turbidity sensors, we chose one of the standard methods using sample mixtures of kaolin and water [6]. In the preparation of the sample suspensions, we used measuring containers, a mechanical mixer with a capacity of 10,000 rpm, and an electronic balance with a resolution of 0.01 g. Distilled water and kaolin of the highest degree of purification were also used (Fig. 2).

Fig. 2. Laboratory setup for turbidity sensors calibration

Standard suspensions with kaolin content in the following proportions were prepared during the study: 50, 100, 200, 500, 700, 1562, 3125, 6250, 7812, 9375 mg/l. They cover the full measuring range of the TSW-30 sensor, which is ≥ 3000 NTU.

Laboratory setup for water-fuel emulsions turbidity measurement consisted of graduated containers, three TSW-30 sensors, three secondary transducers TS-300B, DC power supply and three digital multimeters, operating in a DC voltage measuring mode (see Fig. 3).

To prepare water-diesel emulsions, we used 0.45 liters of winter, summer, and arctic diesel fuels and 0.05 liters of transmission oil added to each diesel fuel sample as an emulsifier. Water-diesel emulsions with 5%, 10%, 15%, and 20% of water volume concentrations were prepared for each type of diesel fuel with the help of a mechanical mixer at 10000 RPM with 10 minutes of initial ingredients mixing.

DC voltage into turbidity transfer function, used for TSW-30 sensors, is given below:

$$NTU = -865.68 \cdot U + \mathrm{K} \quad (1)$$

where U is the output DC voltage, obtained from TS 300B sensors' output, K denotes an index, which can differ for different sensors, temperature and light intensity of medium [16].

Fig. 3. Laboratory setup for water-fuel emulsions turbidity measurement

2. Theory/calculation

Due to the individual metrological differences between individual turbidity sensors, the influence of ambient light and temperature, a preliminary calibration is necessary to obtain measurement results with sufficient accuracy. Prior to the widespread use of formazin, kaolin was one of the standard reference materials for calibrating turbidity sensors, where the unit of turbidity is mg/dm³ on a kaolin basis.

First, it is necessary to prepare a basic standard suspension of kaolin according to the method given in [6]. To prepare working standard suspensions of turbidity, the basic standard suspension is shaken and an intermediate suspension containing 100 mg/dm³ of kaolin is prepared from it. In our case, working suspensions with a concentration of 50, 100, 200, 500, 700, 1562, 3125, 6250, 7812, 9375 mg/dm³ were prepared from this suspension, respectively.

Next, we need to calculate the value of the K coefficient for each of the three sensors using the formula:

$$\mathrm{K} = 865.68 \cdot U_{\max} \quad (2)$$

At the last stage, it is necessary to substitute the calculated K values into formula (1) to calculate turbidity in standard units (NTU).

Results of output DC voltage ten separate measurements, received from the three secondary transducers TS-300B, taken for each standard kaolin-water suspension, can be found in Table 1.

Table 1. Output DC voltage values, taken for the three TS-300B sensors, merged into each standard kaolin-water suspension

Kaolin concentration	Arithmetic mean values of DC voltage, *U* [V]			
C, mg/l	$\overline{U}_1$	$\overline{U}_2$	$\overline{U}_3$	$\overline{U}$
0	3.680	3.740	3.740	3.720
50	3.651	3.706	3.724	3.694
100	3.627	3.672	3.698	3.666
200	3.592	3.642	3.657	3.630
500	3.515	3.561	3.562	3.546
700	3.375	3.413	3.483	3.424
1562	3.032	3.027	3.158	3.072
3125	2.457	2.398	2.612	2.489
4687	1.885	1.799	1.898	1.861
6250	1.232	1.165	1.400	1.266
7812	0.748	0.705	0.888	0.780
9375	0.080	0.070	0.122	0.091

Next, it is necessary to calculate the values of the K coefficients for each of the three sensors using formula (2):

$$\mathrm{K}_1 = 865.68 \cdot \overline{U}_{1\max} = 3185.70$$

$$\mathrm{K}_2 = 865.68 \cdot U_{2\max} = 3237.64$$

$$\mathrm{K}_3 = 865.68 \cdot U_{3\max} = 3237.64$$

Now it is possible to obtain the turbidity value of the created suspensions using formula (1). The results are shown in Table 2.

As noted above, to compensate for the influence of metrological differences in individual sensors and to conduct experiments with water-oil emulsions, it was necessary to synthesize a new transfer function for sensors with a revised value of the coefficient K in formula (1) and the multiplier before the output voltage *U*, which in the original formula is equal to -865.68.

Table 2. Correlation of working suspension concentrations and results of indirect turbidity measurements using TS-300B sensors

Kaolin concentration	Turbidity measurements, NTU			
C, mg/l	NTU_1	NTU_2	NTU_3	$\overline{NTU}$
0	0	0	0	0
50	25.1	29.07	13.49	22.55
100	45.87	58.51	36.00	46.79
200	76.17	84.48	71.49	77.38
500	142.83	154.6	153.73	150.38
700	264.03	282.72	222.12	256.29
1562	560.95	616.87	503.47	560.43
3125	1058.72	1161.38	976.13	1065.41
4687	1553.89	1679.93	1594.22	1609.34
6250	2119.18	2228.77	2025.33	2124.42
7812	2538.17	2626.98	2468.56	2544.57
9375	3116.44	3176.69	3131.67	3141.60

One of the easiest ways to implement this idea is to approximate the data from Table 2 using the least squares method with a first-order polynomial:

$$\mathrm{K} + \mathrm{C}\cdot\overline{U}_i = \overline{NTU}_i \tag{3}$$

To calculate the theoretical values of the coefficients K and C of the first-order approximating polynomial, a system, consisting of twelve conditional equations was formed, with a purpose to receive the experimental values of K and C coefficients and build the nominal transfer function of DC voltage, taken from the TSW-30 output into the NTU values of oil-water emulsion turbidity:

$$\begin{cases} \mathrm{K}+\mathrm{C}\cdot 3.720=0 \\ \mathrm{K}+\mathrm{C}\cdot 3.694=22.55 \\ \mathrm{K}+\mathrm{C}\cdot 3.666=46.79 \\ \mathrm{K}+\mathrm{C}\cdot 3.630=77.38 \\ \mathrm{K}+\mathrm{C}\cdot 3.546=150.38 \\ \mathrm{K}+\mathrm{C}\cdot 3.424=256.29 \\ \mathrm{K}+\mathrm{C}\cdot 3.072=560.43 \\ \mathrm{K}+\mathrm{C}\cdot 2.489=1065.41 \\ \mathrm{K}+\mathrm{C}\cdot 1.861=1609.34 \\ \mathrm{K}+\mathrm{C}\cdot 1.266=2124.42 \\ \mathrm{K}+\mathrm{C}\cdot 0.780=2544.57 \\ \mathrm{K}+\mathrm{C}\cdot 0.091=3141.60 \end{cases} \tag{4}$$

Then we have to transform the system of conditional equations into a system of normal equations:

$$\begin{cases} 12\mathrm{K}+31.239\mathrm{C}=11599.16 \\ 31.239\mathrm{K}+99.713\mathrm{C}=14213.659 \end{cases} \tag{5}$$

Calculating the values of the coefficients K and C:

$$\mathrm{K}=3228.941,\ \mathrm{C}=-869.0474 \tag{6}$$

Thus, the nominal transfer function of the DC voltage values, received from the TSW-30 sensor output, into the NTU values of the water-diesel emulsion turbidity, can be obtained by substituting the values of the coefficients C and K into formula (3):

$$3228.941-869.0474\cdot U = NTU \tag{7}$$

The variance of conditional equations is calculated using the formula:

$$\mathrm{S}^2 = \sum v_i^2 \Big/ (n-m) \tag{8}$$

where v_i is the deviation between the experimental and theoretical values of the NTU for each conditional equation, respectively (see Table 3), *n* is a number of conditional equations, *m* is a number of unknown coefficients.

Table 3. The deviation between the experimental and theoretical values of the NTU

NTU	NTU_{theor}	v_i	v_i^2
0	-3.915	3.915	15.327
22.55	18.582	3.968	15.745
46.79	43.013	3.783	14.311
77.38	74.299	3.081	9.492
150.38	147.299	3.081	9.492
256.29	253.323	2.967	8.803
560.43	559.227	1.203	1.447
1065.41	1065.88	-0.47	0.221
1609.34	1612.644	-3.304	10.916
2124.42	2128.727	-4.307	18.550
2544.57	2552.084	-7.514	56.460
3141.60	3150.858	-9.258	85.710

$$\mathrm{S}^2 = \sum v_i^2 \Big/ (n-m) = 246.354 \Big/ (12-2) = 24.635$$

Weighting coefficients are used to calculate the estimates of the dispersions of coefficients K and C (see formula (5)):

$$\mathrm{P}_K = \frac{12\cdot 99.713-31.239^2}{99.713} = 2.213$$

$$\mathrm{P}_C = \frac{12\cdot 99.713-31.239^2}{12} = 18.39$$

Estimates of the dispersions of coefficients K and C can be calculated using the following formulas:

$$\mathrm{S}_K^2 = \frac{\mathrm{S}^2}{\mathrm{P}_K} = \frac{24.635}{2.213} = 11.132,\ \mathrm{S}_C^2 = \frac{\mathrm{S}^2}{\mathrm{P}_C} = \frac{24.635}{18.39} = 1.34,$$

$$\mathrm{S}_K = \sqrt{\mathrm{S}_K^2} = 3.336,\ \mathrm{S}_C = \sqrt{\mathrm{S}_C^2} = 1.158$$

The extended uncertainty for coefficients K and C is calculated as follows:

$$\mathrm{u}_K = \pm \mathrm{t}_s\cdot \mathrm{S}_K = \pm 2.23\cdot 3.336 = \pm 7.439$$

$$\mathrm{u}_C = \pm \mathrm{t}_s\cdot \mathrm{S}_C = \pm 2.23\cdot 1.158 = \pm 2.582$$

where the coverage coefficient t_s is selected from the Student's statistics table for a confidence level of P = 0.95 and a number of degrees of freedom k = n – m.

The uncertainty of the measurement result (NTU values) is estimated as the result of indirect measurements using the formula (9), taking (5) as a basic measurement equation:

$$\Delta_{NTU} = \sqrt{\left(\frac{\partial NTU}{\partial \mathrm{K}}\cdot \mathrm{u}_K\right)^2 + \left(\frac{\partial NTU}{\partial \mathrm{C}}\cdot \mathrm{u}_C\right)^2} \tag{9}$$

where $\frac{\partial NTU}{\partial \mathrm{K}} = 1$, $\frac{\partial NTU}{\partial \mathrm{C}} = \bar{u}_i$:

$$\Delta_{NTU} = \sqrt{(\mathrm{u}_K)^2 + (\bar{u}_{\max}\cdot \mathrm{u}_C)^2} =$$

$$= \sqrt{7.439^2 + (3.72\cdot 2.582)^2} = \pm 12.15$$

3. Results and discussion

The next step was to investigate the workability of TSW-30 sensors in water-diesel emulsions and the possibility of monitoring the water-diesel emulsions' stability trough performing turbidity measurements. The monitoring was performed for three types of diesel fuel simultaneously: firstly, it was three water-diesel emulsions with 5% water content, then it was three water-diesel emulsions with 10% water content, etc. The monitoring process stopped when the NTU values from TS 300B secondary transducer outputs stopped decreasing.

To provide long-term stability of the TS 300b sensors, plastic case of each sensor was preliminary covered with epoxy glue to protect it from direct interaction with diesel fuel (potentially aggressive medium).

The wavelength range of light received by the sensor's photodiode is 500–1050 nm. The wavelength of sunlight or daylight affects the sensor's phototransistor reception and measurement results. Direct sunlight or intense lighting increases the measurement error of the sensor. When using the sensor, direct sunlight or intense lighting should be avoided. The measurements were made using opaque protective covers installed above the measured samples. The effect of external lighting on sensor readings was not considered, since in real fuel operating conditions, opaque containers are used due to fire safety requirements and the need to protect additives from degradation. In this regard, the influence of external lighting, which can distort the measurement signal, is excluded.

The sensor's operating temperature range is from −20 to +90°C. The temperature of the measured medium was 25±2°C (for temperatures other than 25°C, a temperature correction must be applied using formula

$$\Delta_U = -0.0192\left(T^o - 25\right)$$

The parameters of uncertainty for the TS-300B module are given in corresponding datasheet and literature sources [6, 11]. If we take a range from 0 to 5 V, a ± 0.3 V error/margin is possible, what, if we take a range 0 to 3000 NTU can lead to ± 150 NTU error.

Just manufactured water-diesel emulsion is homogenous, and NTU values taken from the laboratory setup would be close to maximal possible values of NTU. Particles of water have even distribution in diesel fuel, making it not transparent and preventing penetration of light.

The water-diesel emulsions' layering process will start with sedimentation. Two emulsions would appear, and one would have a higher water concentration than the other. NTU values would start decreasing because it would become possible for the light to pass through the medium. The next layering stage is coalescence (the start of emulsion breakdown). NTU values taken from the laboratory setup would continue decreasing. Minimal NTU values will detect the complete emulsion breakdown (complete layering into two liquids) [5].

Table 4. NTU values monitoring for the emulsions with 5% of moisture content

Winter 5%				Summer 5%				Arctic 5%			
No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*
1	31350	…	…	1	3148.1	…	…	1	3168.9	…	…
2	3118.5	3404	238.5	2	3139.4	3404	3089.0	2	3168.9	3404	3168.9
3	3105.5	3405	234.2	3	3143.7	3405	3055.1	3	3173.3	3405	3173.3
4	3080.3	3406	234.2	4	3143.7	3406	3021.2	4	3173.3	3406	3173.3
5	3062.9	3407	228.9	5	3143.7	3407	2995.1	5	3173.3	3407	3173.3
6	3058.6	3408	229.8	6	3139.4	3408	2986.4	6	3173.3	3408	3173.3
7	3050.7	3409	225.5	7	3143.7	3409	2969.9	7	3173.3	3409	3173.3
8	3042.0	3410	225.5	8	3143.7	3410	2944.7	8	3173.3	3410	3173.3
9	3033.4	3411	221.1	9	3139.4	3411	2936.0	9	3173.3	3411	3173.3
10	3024.7	3412	217.6	10	3139.4	3412	2914.3	10	3173.3	3412	3173.3
11	3021.2	3413	212.4	11	3143.7	3413	2902.1	11	3173.3	3413	3173.3
12	3016.8	3414	217.6	12	3139.4	3414	2889.1	12	3173.3	3414	3173.3
13	3008.2	3415	212.4	13	3139.4	3415	64.7	13	3173.3	3415	1343.9
14	3003.8	3416	212.4	14	3139.4	3416	64.7	14	3173.3	3416	1330.9
15	2999.5	3417	209.0	15	3139.4	3417	76.9	15	3173.3	3417	1326.5
16	2995.1	3418	208.1	16	3139.4	3418	56.0	16	3173.3	3418	1318.7
17	2990.8	3419	190.7	17	3139.4	3419	17.8	17	3173.3	3419	1326.5
18	2986.4	3420	195.0	18	3135.0	3420	30.8	18	3173.3	3420	1318.7
19	2983.0	3421	212.4	19	3135.0	3421	76.9	19	3173.3	3421	1310.0
20	2978.6	3422	182.0	20	3135.0	3422	69.0	20	3173.3	3422	1369.1
21	2983.0	3423	182.0	21	3135.0	3423	56.0	21	3173.3	3423	1339.6
22	2978.6	3424	182.0	22	3131.6	3424	9.1	22	3173.3	3424	1326.5
23	2983.0	3425	190.7	23	3131.6	3425	38.6	23	3173.3	3425	1357.0
24	2978.6	3426	190.7	24	3131.6	3426	69.0	24	3173.3	3426	1318.7
25	2983.0	3427	203.7	25	3127.2	3427	64.7	25	3173.3	3427	1330.9
26	2983.0	3428	186.4	26	3127.2	3428	43.0	26	3173.3	3428	1335.2
27	2978.6	3429	186.4	27	3127.2	3429	0.4	27	3173.3	3429	1335.2
28	2978.6	3430	186.4	28	3127.2	3430	26.5	28	3173.3	3430	1326.5
29	2983.0	3431	185.5	29	3122.9	3431	45.6	29	3173.3	3431	1297.0
30	2978.6	3432	186.4	30	3122.9	3432	26.5	30	3173.3	3432	1314.4

The results of the layering process monitoring are given in tabular and graphical forms (see Tables 4–7).

As it can be seen from Table 3, for the three water-diesel emulsions with 5% of volumetric moisture content we had 3432 checkpoints to control turbidity values. Because of relatively big number of checkpoints, we have only first thirty and last thirty values of NTU, presented in Table 3. Time intervals between the two neighbour checkpoints have been provided automatically and were equal to one minute.

Table 5. NTU values monitoring for the emulsions with 10% of moisture content

Winter 10%				Summer 10%				Arctic 10%			
No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*
1	3169.8	…	…	1	3105.5	…	…	1	3186.3	…	…
2	3096.8	2586	765.1	2	3089.0	2586	561.8	2	3186.3	2586	1644.6
3	3033.4	2587	756.5	3	3055.1	2587	557.4	3	3182.0	2587	1640.3
4	2974.3	2588	748.6	4	3021.2	2588	569.6	4	3182.0	2588	1622.9
5	2936.0	2589	748.6	5	2995.1	2589	574.0	5	3182.0	2589	1653.3
6	2906.5	2590	726.9	6	2986.4	2590	574.0	6	3182.0	2590	1669.8
7	2880.4	2591	714.7	7	2969.9	2591	561.8	7	3182.0	2591	1669.8
8	2863.9	2592	714.7	8	2944.7	2592	574.0	8	3182.0	2592	1653.3
9	2850.9	2593	722.6	9	2936.0	2593	561.8	9	3182.0	2593	1631.6
10	2830.0	2594	710.4	10	2914.3	2594	553.1	10	3182.0	2594	1631.6
11	2821.3	2595	735.6	11	2902.1	2595	565.3	11	3182.0	2595	1631.6
12	2803.9	2596	735.6	12	2889.1	2596	565.3	12	3182.0	2596	1649.0
13	2803.9	2597	739.9	13	2876.1	2597	548.7	13	3182.0	2597	1674.2
14	2799.6	2598	748.6	14	2863.9	2598	548.7	14	3182.0	2598	1682.9
15	2791.8	2599	760.8	15	2842.2	2599	557.4	15	3182.0	2599	1682.9
16	2795.2	2600	753.0	16	2871.7	2600	548.7	16	3177.6	2600	1678.5
17	2774.4	2601	769.5	17	2859.5	2601	548.7	17	3182.0	2601	1665.5
18	2774.4	2602	769.5	18	2855.2	2602	553.1	18	3177.6	2602	1665.5
19	2770.0	2603	756.5	19	2850.9	2603	561.8	19	3177.6	2603	1665.5
20	2765.7	2604	760.8	20	2846.5	2604	544.4	20	3177.6	2604	1661.1
21	2761.3	2605	756.5	21	2842.2	2605	574.0	21	3177.6	2605	1649.0
22	2753.5	2606	744.3	22	2842.2	2606	548.7	22	3177.6	2606	1657.7
23	2749.2	2607	760.8	23	2837.8	2607	557.4	23	3177.6	2607	1665.5
24	2749.2	2608	753.0	24	2833.5	2608	553.1	24	3177.6	2608	1674.2
25	2749.2	2609	667.8	25	2833.5	2609	344.5	25	3177.6	2609	1504.7
26	2740.5	2610	650.4	26	2830.0	2610	395.8	26	3177.6	2610	1521.2
27	2736.1	2611	650.4	27	2830.0	2611	348.9	27	3177.6	2611	1538.6
28	2740.5	2612	663.5	28	2825.7	2612	340.2	28	3177.6	2612	1504.7
29	2727.5	2613	684.3	29	2825.7	2613	421.0	29	3177.6	2613	1512.5
30	2718.8	2614	684.3	30	2825.7	2614	382.8	30	3177.6	2614	1496.0

Table 6. NTU values monitoring for the emulsions with 15% of moisture content

Winter 15%				Summer 15%				Arctic 15%			
No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*
1	2913.4	…	…	1	2978.6	…	…	1	3135.0	…	…
2	2877.8	4260	23.0	2	2948.2	4260	17.8	2	3135.0	4260	310.6
3	2882.1	4261	23.0	3	2927.3	4261	17.8	3	3122.9	4261	323.7
4	2914.3	4262	23.0	4	2906.5	4262	17.8	4	3105.5	4262	315.0
5	2914.3	4263	23.0	5	2884.7	4263	17.8	5	3101.1	4263	323.7
6	2913.4	4264	23.0	6	2871.7	4264	17.8	6	3105.5	4264	328.0
7	2900.4	4265	23.0	7	2855.2	4265	17.8	7	3118.5	4265	328.0
8	2879.5	4266	23.0	8	2833.5	4266	17.8	8	3109.8	4266	319.3
9	2876.1	4267	23.0	9	2825.7	4267	17.8	9	3101.1	4267	328.0
10	2876.1	4268	20.4	10	2808.3	4268	17.8	10	3096.8	4268	315.0
11	2876.1	4269	23.0	11	2803.9	4269	17.8	11	3093.3	4269	323.7
12	2880.4	4270	20.4	12	2803.9	4270	22.1	12	3096.8	4270	319.3
13	2880.4	4271	20.1	13	2803.9	4271	17.8	13	3096.8	4271	310.6
14	2876.1	4272	23.0	14	2808.3	4272	22.1	14	3101.1	4272	315.0
15	2868.2	4273	19.5	15	2803.9	4273	17.8	15	3093.3	4273	323.7
16	2876.1	4274	19.5	16	2812.6	4274	17.8	16	3096.8	4274	315.0
17	2868.2	4275	19.5	17	2808.3	4275	22.1	17	3101.1	4275	315.0
18	2866.5	4276	17.8	18	2799.6	4276	22.1	18	3114.2	4276	323.7
19	2868.2	4277	17.8	19	2795.2	4277	17.8	19	3118.5	4277	323.7
20	2867.4	4278	17.8	20	2799.6	4278	22.1	20	3118.5	4278	319.3
21	2868.2	4279	17.8	21	2795.2	4279	17.8	21	3118.5	4279	310.6
22	2864.8	4280	17.8	22	2791.8	4280	17.8	22	3114.2	4280	323.7
23	2869.1	4281	17.8	23	2791.8	4281	17.8	23	3109.8	4281	315.0
24	2864.8	4282	17.8	24	2791.8	4282	22.1	24	3101.1	4282	310.6
25	2865.6	4283	17.8	25	2783.1	4283	17.8	25	3096.8	4283	323.7
26	2865.6	4284	17.8	26	2783.1	4284	17.8	26	3096.8	4284	328.0
27	2865.6	4285	17.8	27	2778.7	4285	17.8	27	3093.3	4285	328.0
28	2865.6	4286	17.8	28	2778.7	4286	22.1	28	3089.0	4286	315.0
29	2857.8	4287	17.8	29	2774.4	4287	17.8	29	3093.3	4287	319.3
30	2857.8	4288	23.0	30	2770.0	4288	17.8	30	3105.5	4288	323.7

Table 7. NTU values monitoring for the emulsions with 20% of moisture content

Winter 15%				Summer 15%				Arctic 15%			
No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*	No.	*NTU*
1	3084.6	…	…	1	3029.0	…	…	1	3161.1	…	…
2	2774.4	1587	875.5	2	2936.0	1587	697.4	2	3156.8	1587	901.6
3	2744.8	1588	863.3	3	2914.3	1588	672.2	3	3156.8	1588	852.9
4	2672.7	1589	854.7	4	2889.1	1589	654.8	4	3152.4	1589	866.0
5	2646.6	1590	884.2	5	2859.5	1590	587.0	5	3152.4	1590	868.6
6	2643.2	1591	892.9	6	2830.0	1591	600.0	6	3148.1	1591	840.7
7	2617.1	1592	884.2	7	2837.8	1592	607.8	7	3148.1	1592	859.9
8	2587.5	1593	884.2	8	2830.0	1593	641.7	8	3148.1	1593	855.5
9	2596.2	1594	875.5	9	2821.3	1594	587.0	9	3143.7	1594	838.1
10	2574.5	1595	884.2	10	2830.0	1595	595.7	10	3143.7	1595	893.8
11	2553.6	1596	884.2	11	2821.3	1596	578.3	11	3139.4	1596	895.5
12	2562.3	1597	863.3	12	2825.7	1597	569.6	12	3139.4	1597	838.1
13	2558.0	1598	863.3	13	2821.3	1598	523.5	13	3139.4	1598	834.7
14	2545.0	1599	854.7	14	2821.3	1599	535.7	14	3135.0	1599	886.8
15	2502.4	1600	854.7	15	2821.3	1600	540.1	15	3135.0	1600	868.6
16	2502.4	1601	854.7	16	2825.7	1601	553.1	16	3135.0	1601	864.2
17	2515.4	1602	846.0	17	2837.8	1602	557.4	17	3131.6	1602	904.2
18	2506.7	1603	863.3	18	2830.0	1603	535.7	18	3131.6	1603	855.5
19	2528.4	1604	854.7	19	2830.0	1604	493.1	19	3131.6	1604	914.6
20	2468.5	1605	854.7	20	2821.3	1605	400.1	20	3127.2	1605	866.0
21	2490.2	1606	854.7	21	2821.3	1606	514.9	21	3127.2	1606	842.5
22	2515.4	1607	859.0	22	2817.0	1607	523.5	22	3127.2	1607	870.3
23	2506.7	1608	871.2	23	2821.3	1608	497.5	23	3127.2	1608	840.7
24	2493.7	1609	871.2	24	2817.0	1609	472.3	24	3122.9	1609	819.0
25	2502.4	1610	850.3	25	2817.0	1610	501.8	25	3122.9	1610	836.4
26	2498.0	1611	859.0	26	2812.6	1611	454.9	26	3122.9	1611	834.7
27	2485.9	1612	863.3	27	2812.6	1612	425.3	27	3118.5	1612	799.9
28	2490.2	1613	871.2	28	2808.3	1613	408.8	28	3118.5	1613	834.7
29	2472.8	1614	841.6	29	2808.3	1614	481.0	29	3118.5	1614	833.8
30	2485.9	1615	871.2	30	2812.6	1615	501.8	30	3118.5	1615	823.4

Corresponding graphs can be found below (see Fig. 4 – 7).

If performing continuous monitoring of the NTU values of the water-diesel emulsion, taken from TS 300B transducers, it is possible to define the stage of a layering process and the time necessary for a complementary mechanical mixer to restore initial emulsion homogeneity. If the water-diesel emulsion is homogenous, there is no need for mixing. If we have the sedimentation stage, complementary mixing, which takes from 15% to 35% of the original mixing time, should be implemented. The coalescence stage will require complementary mixing, which takes 50% to 80% of the original mixing time.

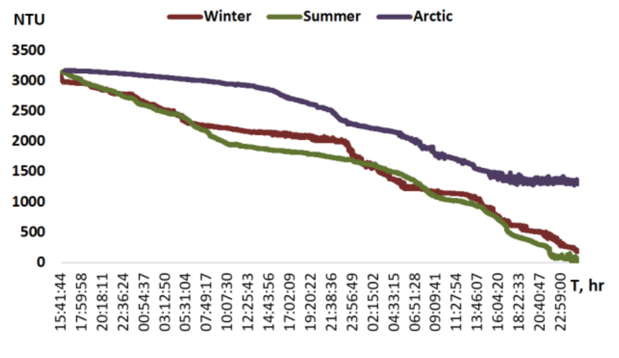

Fig. 4. Layering process monitoring for water-diesel emulsions with 5% of water content

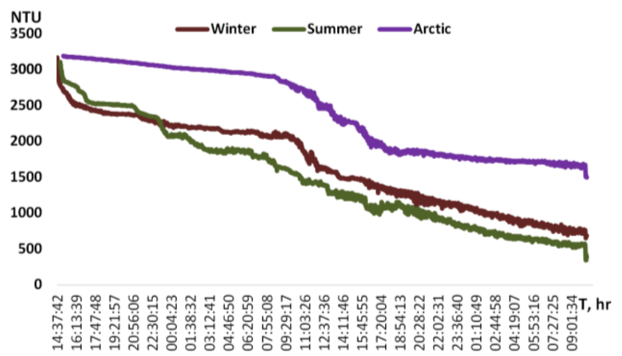

Fig. 5. Layering process monitoring for water-diesel emulsions with 10% of water content

To define the stages of layering, we should use the data related to the arctic diesel fuel emulsion with 5% water content for the situation when the type of diesel fuel and its moisture content are unknown. If the NTU value is greater than 3100, we can assume that the water-diesel emulsion retains stability. The range of NTU values between 3100 and 2450 would mean the sedimentation stage. The coalescence stage can be related to all NTU values smaller than 2200.

For the case, if we know the fuel type and moisture content, we can use data from Tables 3–6.

The sensor with an electronic module can be used to investigate and record the moment of water-diesel emulsion delamination. By monitoring the voltage at the output of the TS-300 B electronic module, it is possible to make decisions about starting the repeated stirring of the emulsion and its return to a homogeneous state in automatic mode.

To create a water-diesel emulsion homogeneity control system, it is necessary to use complementary electronic unit that will acquire and process sensor outputs, process the received signals and generate control commands to the executing devices. Such a unit can be a programmable logic controller (PLC).

The system is based on the division of the tank with emulsion into three conventional sections, in which turbidity sensors will be installed. The emulsion stability is monitored in real time in each section. Analogue outputs of TS-300 B electronic modules are connected to analogue inputs of the PLC, where the output voltage is converted using formula (2) to display the values in NTU units. The turbidity sensors are pre-calibrated at zero point under conditions close to the operating conditions with the determination of the K factor for each sensor (1). After the data is processed on the PLC, a discrete output signals are generated, which transmit commands to the control devices to start the appropriate mode of emulsion homogeneity renovation. If necessary, the emulsion status can be displayed on the operator panel (Fig. 8).

The container with the emulsion is conventionally divided into three sections, where the first sensor is mounted on top, the second in the middle, and the third at the bottom of the container, which will allow to record the moment of loss of emulsion homogeneity [5].

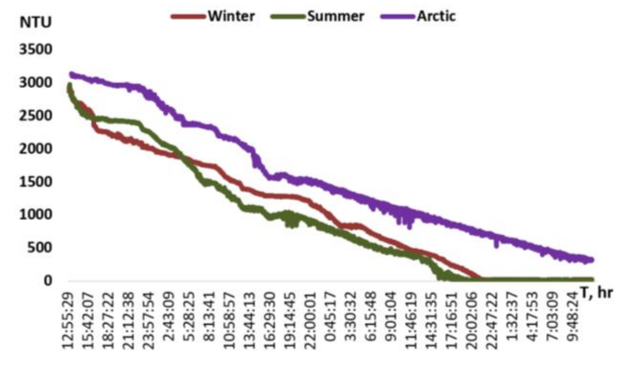

Fig. 6. Layering process monitoring for water-diesel emulsions with 15% of water content

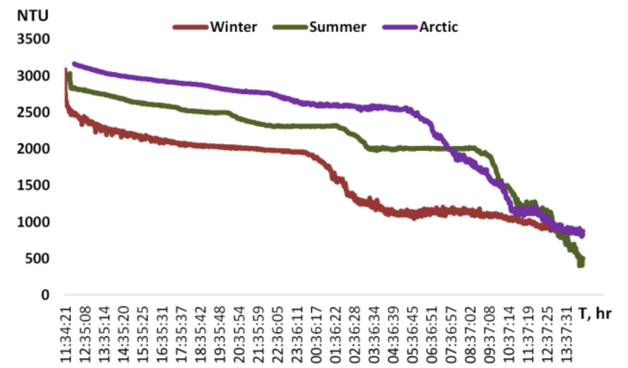

Fig. 7. Layering process monitoring for water-diesel emulsions with 20% of water content

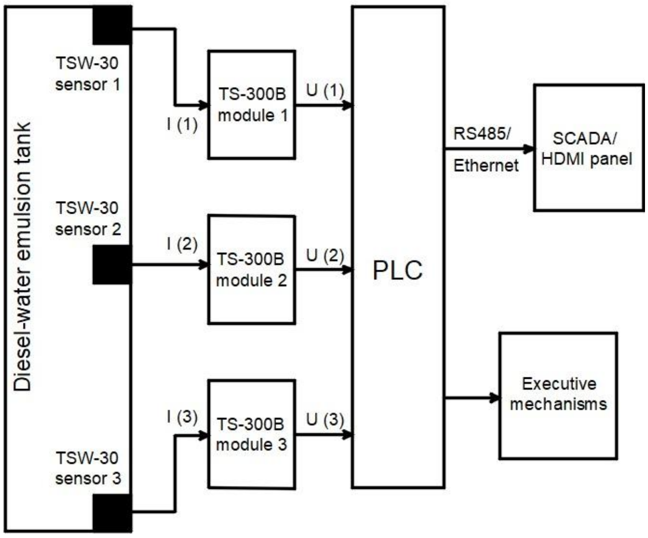

Fig. 8. Layering process monitoring for water-diesel emulsions with 20% of water content

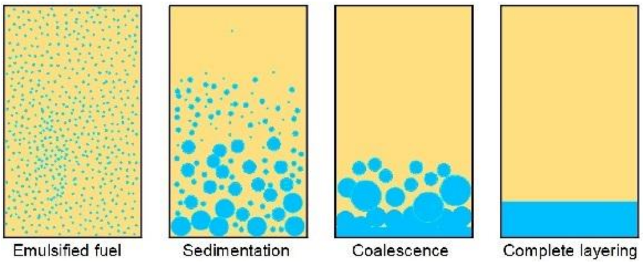

Fig. 9. Schematic representation of the water-diesel emulsion delamination process

The uniform displacement of the three sensors will allow recording the complete process of the water-diesel emulsion delamination process (schematically, the delamination process is shown in Fig. 9).

In the newly formed homogeneous emulsion, the signals from the TS-300B module output will approach 0 V. Suspended water particles will be evenly distributed in the fuel, which will impede the passage of light flux. At the beginning of the emulsion stratification the sedimentation process begins. Complete destruction of the emulsion does not occur and two emulsions are formed, one of which has a higher concentration of the dispersed phase than the other. It is during this process that the signals from all three sensors begin to change significantly due to the propagation of the emitted light flux in the liquid. The next stage is coalescence, i.e. the beginning of the complete destruction of the emulsion (separation of both liquid phases in pure form by combining the droplets of the dispersed phase). During coalescence, the sensor signals change, and the signal from the sensor output placed at the bottom of the fuel tank will be the maximum. The signals at the outputs of the middle and upper sensors will gradually increase depending on the saturation of the dispersed phase in the sensing area. After the emulsion is completely stratified, the output voltage at the outputs of the middle and upper sensors will also be equal to the maximum voltage value. This will indicate a complete loss of homogeneity of the water-diesel emulsion.

Because all automated systems consume a large amount of energy to prepare the emulsion, it will be optimal to use different modes of repeated stirring, and the algorithm for switching them on is performed in the PLC. Knowing at which stage of delamination the WPE is, three modes can be applied to reduce the time for the emulsion re-stabilisation by repeated mechanical stirring.

When the system starts up, all output voltages at the sensor outputs and the actual state of the emulsion should be analysed. It can be divided into four main types to implement the appropriate mixing mode for each type, depending on the application needs:

- stable emulsion – no repeated stirring is required;
- sedimentation – it becomes necessary to implement repeated mechanical mixing, spending from 15 to 35% of the main mixing time to re-grind and evenly distribute the dispersed phase;
- coalescence – the process of water-diesel emulsion destruction has begun, two liquid phases are separated, a mixing process lasting from 50 to 80% of the main time is required to ensure uniform distribution of liquids with further distribution and formation of suspended particles of the dispersed phase of the required size;
- complete stratification – makes necessary to repeat the standard process of water-diesel emulsion manufacturing.

4. Conclusions

In this study, the performance and sensitivity of the TSW-30 sensor in conjunction with the TS-300B electronic module were investigated to create a homogeneity control system with further integration into an automated system for the manufacture and storage of water-diesel emulsions. Sensitivity and performance were tested on standard kaolin solutions and showed that TSW-30 sensor has a large turbidity measurement range (up to 3000 NTU) and high sensitivity.

However, due to the increased measuring range, it became necessary to obtain a more accurate nominal transfer function.

TSW-30 sensor together with the electronic module TS-300B can be used to monitor the homogeneity loss and to record the processes of sedimentation, coalescence, and complete separation of the water-diesel emulsion. The emulsion separation processes monitoring allows to implement three different modes of homogeneity restoration, which will reduce the time and energy consumption for existing emulsions stabilizing.

The paper proposes a block diagram of the water-diesel emulsion homogeneity control system. The block diagram contains key components of the system, such as TSW-30 sensors placed at three points of the emulsion tank, TS-300B modules, a PLC that implements an algorithm for data storage and processing, and an HDMI panel for additional physical visualisation, as well as control devices that initiate the re-mixing of the existing emulsion.

Continuous monitoring of the NTU values of the water-diesel emulsion, taken from TS 300B transducers, provides a possibility to define the stage of a layering process and the time necessary for a complementary mechanical mixer to restore initial emulsion homogeneity. If the water-diesel emulsion is homogenous, mixing is not necessary. If we have the sedimentation stage then complementary mixing, which may take from 15% to 35% of the original mixing time, should be implemented. The coalescence stage requires complementary mixing with 50...80% of the original mixing time.

When the type of diesel fuel and its moisture content are unknown, we should use the data from Table 3 (arctic diesel fuel with 5% water content) to define the stages of delamination. If the NTU value is greater than 3100, the water-diesel emulsion is homogenous. For the NTU values range between 3100 and 2450 we would have sedimentation. The coalescence stage can be related to all NTU values smaller than 2200.

The use of the proposed system allows to increase productivity by significantly saving time and energy for maintaining the homogeneity of the emulsion immediately before transportation or use.

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