

Article

Ways to Improve the Effectiveness of Depressant Additives for the Production of Winter and Arctic Diesel Fuels

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Abstract: Diesel fuel is the main fuel for transport and power generation for remote areas, especially the Arctic. For these territories, it is important to produce low-freezing fuel grades. The most effective way to improve the low-temperature properties of diesel fuels (cloud point, pour point, and cold filter plugging point) is the use of depressant additives. Existing research shows that the depressant additives’ effectiveness is influenced by many factors. The most important factors are diesel fuel composition, additive concentration, and the temperature of additive introduction into the fuel (adding temperature). The purpose of this work is to find ways to increase the efficiency of depressant additives for the production of low-freezing diesel fuels by choosing the most effective additive concentration and adding temperature for fuels of various compositions. During the work, low-temperature properties were determined and the effectiveness of three depressant additives was assessed on four samples of diesel fuel at four concentrations (0.5, 1.0, 2.0, and 5.0 c.u., where c.u. (conditional unit) is the concentration recommended by the manufacturer of the additives). In addition, low-temperature properties for blends of six depressant additives and two samples of diesel fuel at five adding temperatures (15, 25, 35, 45, and 55 °C) were determined. In this work, in contrast to existing works, it was established for the first time that the composition of the fuel affects not only the depressant additives effectiveness, but also the dependence of the additive effectiveness on the concentration in which it is used. It is shown that the higher the content of paraffins in the composition of the diesel fuel, the less the depressant additive’s effectiveness in relation to cold filter plugging point depends on the concentration and the more the depressant additive’s effectiveness in relation to the power point depends on the concentration. An inverse relationship was revealed for the content of aromatic hydrocarbons in diesel fuel. It was also found for the first time that an increase in the adding temperature of depressant additives up to 35–55 °C enhances the effectiveness of their action in relation to the cold filter plugging point (maximum at 6–7 °C). It is shown that the greater additive effect on the cold filter plugging point of the diesel fuel, the more strongly the depressant effectiveness depends on the adding temperature. The work provides recommendations for obtaining the most low-freezing classes of fuel based on the samples considered. The regularities identified in the work will make it possible, depending on the composition of the fuel, to select the optimal concentration of the additive and the temperature of its adding, which will increase the efficiency of the additives, as well as the volume of low-freezing grades of diesel fuel production.

Keywords: diesel fuel; depressant additive; fractional composition; hydrocarbon composition; n-paraffins; cold filter plugging point; pour point; input temperature



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1. Introduction

The volume of diesel fuel production is growing every year. The production growth trend can be explained by a wide range of diesel consumption: the transport sector of the

economy (cars and trucks, river and sea vessels, railway transport), agriculture, industry, construction, etc., [1]. Despite the development of alternative fuels, diesel is still a key fuel in the world [2].

The global trend of active development of the Arctic territories with harsh climatic conditions also contributes to the growth in demand for diesel fuel [3]. However, in this case, we are talking about low-freezing grades for which the most important are low-temperature characteristics, such as the cloud point (T_c) and pour point (T_p), as well as the cold filter plugging point (CFPP) [4]. T_c characterizes the change in the phase composition of the fuel, namely the formation of not only the liquid phase of the fuel, but also the solid phase—in which the crystallization of n-paraffins that make up the fuel begins. With a further decrease in temperature, the growth and association of n-paraffin crystals and the formation of framework structures occurs. At this point, CFPP is noted as the fluidity of the fuel decreases, preventing it from passing further through the fuel filters. T_p characterizes the temperature at which the fuel finally loses its mobility, the frame structures become more branched, the length of the paraffins chains increases, and the fuel solidifies.

According to the standard EN 590 2009 “Automotive fuels—diesel—requirements and test methods” [5], low-freezing diesel fuel is divided into several classes: for Class 0, the T_c should be no more than $-10\text{ }^\circ\text{C}$, the CFPP should not be more than $-20\text{ }^\circ\text{C}$; for Class 1: $-16\text{ }^\circ\text{C}$ and $-26\text{ }^\circ\text{C}$; for Class 2: $-22\text{ }^\circ\text{C}$ and $-32\text{ }^\circ\text{C}$; for Class 3: $-28\text{ }^\circ\text{C}$ and $-38\text{ }^\circ\text{C}$; and for Class 4: $-34\text{ }^\circ\text{C}$ and $-44\text{ }^\circ\text{C}$, respectively.

The history of the oil-refining industry includes about a dozen technologies that improve the low-temperature properties of fuels, which are based on different approaches. Now low-freezing diesel fuels are obtained by lowering the end boiling point of the fraction, compounding of fuels with different low-temperature properties, and using catalytic processes (the dewaxing process, for example). However, these methods are quite labor-intensive and inevitably lead to deterioration in the quality of the resulting fuel and noticeable losses of the target product [6]. To date, one of the most effective and cost-effective ways to improve the low-temperature characteristics of diesel fuel is the addition of depressant additives; this method is especially relevant when it comes to fuel production in mini refineries and remote areas [4,7]. According to statistics [8], the additives market in regions such as North America, Asia-Pacific, Europe, South America, the Middle East, and the Africa will grow by 5.11% per year from 2022 to 2029. However, the effectiveness of depressants largely depends on the composition of the fuel [9–11], which can vary significantly depending on the place of production and feedstock [12], which leads to a different effect of the depressant on the low-temperature characteristics of fuels.

As a rule, additives are a blend of an active substance, which directly possesses depressant properties, and an organic solvent necessary for the uniform and rapid distribution of the depressant in fuel and oil products [13–15].

There is currently no unified theory that could explain the effect of a particular chemical compound used as an active substance in depressant additives on the low-temperature characteristics of diesel fuel. There are two common and at the same time competing theories about the mechanism of action of depressants on diesel fuels.

According to the first one, depressant molecules interact with the surface of formed n-paraffin crystals and prevent their growth and association. This mechanism of action involves the adsorption of the depressant molecule on the surface of the n-paraffin crystal. During adsorption, the depressant molecule is sorbed on the surface of the crystal by the polar part. The nonpolar part is directed into the medium and prevents the approach of n-paraffin crystals and their association into an ordered structure. The second theory assumes the co-crystallization of n-paraffin and the depressant molecule. The nonpolar part of the depressant molecule is incorporated into the structure of the n-paraffin crystal, while the polar part faces the solution, which prevents further convergence and coarsening of the crystals [16,17].

It can be assumed that, depending on the structure of the active substance of the depressant, the first or second mechanism of interaction of the depressant with n-paraffin crystals will prevail. Also, the possibility of a mixed mechanism cannot be ruled out [18].

Presumably, additives acting by the adsorption mechanism are more effective at relatively low concentrations, since the possibility of crystallization of the active substance itself at elevated concentrations will be excluded, which will lead to a deterioration in low-temperature characteristics. Additives that co-crystallize with n-paraffins, on the contrary, are most effective at relatively high concentrations.

In addition, there are experimental data according to which the mechanism of depressants' action is considered as the mechanism of surfactants' action in dispersed systems [19]. This mechanism leads to an increase in the stability of the fuel dispersed system, resulting in an improvement in the low-temperature characteristics of diesel fuel [20].

To date, a wide range of depressant additives is presented on the world market, which differ among themselves in the content and type of active substance, as well as in other characteristics. There is also an active development of new depressants, which would meet all modern requirements for them [21–24].

The additive effectiveness, in addition to the composition of the fuel, is also affected by the concentration at which the depressant is used and at what temperature it is added into the fuel. The content of n-paraffins also has the greatest influence on the low-temperature characteristics of diesel fuel, since they are the first to crystallize when the temperature goes down [25,26].

Thus, research into the influence of fuel composition and other characteristics on the efficiency of depressants is extremely relevant.

Literature analysis shows that despite the many researchers noting that the composition of diesel fuel significantly affects depressants' effectiveness, there are no works which consider the regularities of fuel composition influence in dynamics—under conditions of varying additive concentrations and adding temperatures. From a practical point of view, understanding the regularities of the concentration and temperature of depressant adding influence on the effectiveness of its action on diesel fuel samples with various compositions will allow the use of additives as efficiently as possible.

Thus, the aim of this work is to evaluate ways to improve the effectiveness of depressant additives for the production of winter and arctic diesel fuels, as well as to identify regularities of influence in the concentration and adding temperature of depressant additives on the effectiveness of their action.

2. Materials and Methods

The objects of study in the work were four different samples of straight-run diesel fuel (DF) No. 1–4, and their blends with six different commercial depressant additives (DA)—A, B, C, D, E, F.

To prepare the blends of DF with DA, 100 mL of a DF sample was taken using a graduated cylinder; the flask with the test sample was closed by a stopper with a thermometer so that the thermometer was immersed in DF and did not touch the bottom or walls of the flask.

Next, the flask was placed in a liquid thermostat, and held to a given temperature for 30 min, stirring occasionally. Upon reaching the specified temperature, a depressant was added into the DF sample.

The blend was stirred for 1 min and placed in a thermostat, thermostatically controlled for 20 min. The resulting blend was left for 1 day in a cold, dark place.

For each DA, the manufacturer has set the concentration in which it is recommended to be used [27–32]. The concentration recommended by the manufacturer, converted to 100 mL of DF, for each DA is taken as 1 c.u. (conditional unit) and is presented in Table 1.

Table 1. The volume of a single concentration (1 c.u.) of DA per 100 mL of DF.

DF	DA Volume, mL	DF	DA Volume, mL
A	0.10	D	0.31
B	0.10	E	0.20
C	0.65	F	0.26

For the study of the DA concentration's influence on the efficiency of action, blends of all DF samples with three DAs (D, E, F) in various concentrations were prepared. These DAs (D, E, F) are used as the most effective. The concentrations of the added DA were 0.5; 1.0; 2.0; 5.0 c.u. from the one recommended by the manufacturer. In this part of the work, the depressant additives were added at a temperature of 25 °C.

Table 2 shows the labeling of the prepared blends depending on the used DA and its concentration.

Table 2. Labeling of blends of DF samples with DA depending on the used DA and its concentration.

DA	Concentration, c.u.	Labeling DA	DA Volume, mL
D	0.5	D _{0.5}	0.155
	1.0	D ₁	0.310
	2.0	D ₂	0.620
	5.0	D ₅	1.550
E	0.5	E _{0.5}	0.100
	1.0	E ₁	0.200
	2.0	E ₂	0.400
	5.0	E ₅	1.000
F	0.5	F _{0.5}	0.130
	1.0	F ₁	0.260
	2.0	F ₂	0.520
	5.0	F ₅	1.300

For the study of the DA adding temperature influence on the efficiency of action, blends of two DF samples (No. 1 and No. 2) with all DAs were prepared, taking into account the DA adding temperature. No. 1 and No. 2 DF samples were used as characterized by the most unsatisfactory low-temperature properties. The DA concentration was 1 c.u., and the adding temperature was varied in 10 °C increments (15, 25, 35, 45, and 55 °C).

Table 3 shows the labeling of the prepared blends depending on the adding temperature of the DA and its concentration.

Table 3. Labeling of blends of DF samples with DA depending on the used DA and its adding temperature.

Adding Temperature, °C	Labeling DA
15	DA ₁₅
25	DA ₂₅
35	DA ₃₅
45	DA ₄₅
55	DA ₅₅

To determine the composition and characteristics of DF samples, as well as the resulting blends, the following methods were used in the work:

- The fractional composition according to [33]. A 100 mL test portion using the distillation flask, condenser tube, and cooling bath is distilled under the specified conditions appropriate to the group into which the sample falls, and systematic observations of thermometer readings and volumes of condensate recovered are made. The volume of the residue in the flask is measured, and the loss on distillation recorded. The thermometer readings are corrected for barometric pressure and the data are then used for calculations appropriate to the nature of the sample and the specification requirements;

- The density at the temperature of 15 °C is determined using the Stanbinger SVM3000 Anton Paar viscometer according to [34]. The test sample is introduced into a temperature-controlled sample cell. The density of the test sample is noted. Repeatability for transparent middle distillates: $r = 0.2 \text{ kg/m}^3$, reproducibility for transparent middle distillates: $R = 0.5 \text{ kg/m}^3$;
- The kinematic and dynamic viscosity at 20 °C is determined using the Stanbinger SVM3000 Viscometer Anton Paar, according to [35]. The charged, by the sample, viscometer is placed in the bath in the manner dictated by the design of the instrument. After that, the viscometer is allowed to remain in the bath long enough to reach the test temperature. Next, using the suction, the head level of the test sample is adjusted to a position in the capillary of the instrument above the first timing mark. With the sample flowing freely, in seconds to within 0.1 s, the time required for the meniscus to pass from the first to the second timing mark is measured. The described procedure is repeated to make a second measurement of the flow time and to record the results. The calculated average of the two measurements is used as the kinematic viscosity. Repeatability of the method: $r = 0.11\%$, reproducibility of the method: $R = 0.65\%$;
- The sulfur content is determined using the X-ray fluorescence energy dispersive analyzer "SPECTROSCAN S", according to [36]. The sample is placed in the beam emitted from an X-ray tube. The resultant excited characteristic X radiation is measured, and the accumulated count is compared with counts from previously prepared calibration samples to obtain the sulfur concentration in mass percent or mg/kg, or both;
- The cetane index is calculated according to [37,38]. The density at 15 °C and the temperatures at which 10 vol.%, 50 vol.%, and 90 vol.% are recovered (distillation temperatures) are determined by standard test methods [33,34] and the cetane index is calculated from these test data using known correlations. The precision of the cetane index equation is dependent on the precision of the original density and distillation temperature determinations which enter into the calculation. The precision of these determinations is stated in [33,34];
- The group composition of the feedstock DF sample and the products of the upgrading process is determined by the aniline method [39] and calculated from these test data using known correlations;
- The structural-group composition is calculated using the n-D-M method according to [40]. This test method covers the calculation of the carbon distribution and ring content of olefin-free petroleum oils from measurements of the refractive index, density, and molecular weight (n-d-M). The refractive index and density of the oil are determined at 20 °C. The molecular weight is determined experimentally. These data are then used to calculate the carbon distribution (aromatic structures, naphthenic structures, annular structures, alkyl substituents) or the ring analysis (average number of rings, average number of aromatic rings, average number of naphthenic rings) using the appropriate set of equations. The precision of the carbon distribution equation is dependent on the precision of the original refractive index, density, and molecular weight determinations which enter into the calculation. The precision of these determinations is stated in [33,41,42];
- The cloud point (T_c) is determined according to [43]. The method for determining T_c is as follows: a double-walled test tube filled with the test sample is immersed in a liquid low-temperature thermostat and gradually cooled. Every 1–2 °C, the test tube is removed from the thermostat and compared with a previously prepared test fuel sample at room temperature. If there is visible turbidity of the fuel relative to the standard, T_c is recorded. Repeatability of the method: $r = 1 \text{ °C}$, reproducibility of the method: $R = 3 \text{ °C}$;
- The cold filter plugging point (CFPP) is determined according to [44]. The method for determining CFPP is as follows: in a low-temperature liquid thermostat, using a CFPP determination unit on a cold filter, the sample under study is gradually cooled. At intervals of 1 °C, the test sample is automatically pumped through a standardized wire mesh filter into a glass pipette under a controlled vacuum. If the test sample does

not have time to fill the pipette within 60 s, then the experiment is stopped and CFPP is recorded, because the fuel has lost the ability to pass through the filter. Repeatability of the method: $r = 2\text{ }^{\circ}\text{C}$, reproducibility of the method: $R = 0.102(25 - x)\text{ }^{\circ}\text{C}$, where x —average of two measurements;

- The pour point (T_p) is determined according to [45]. The method for determining T_p is as follows: a double-walled test tube filled with the test sample is immersed in a liquid low-temperature thermostat and gradually cooled. Every 1–2 $^{\circ}\text{C}$, the test tube is removed from the thermostat. T_p is fixed when the test tube is tilted at 45 $^{\circ}$ and held in this position for 1 min and the meniscus of the sample does not shift. Repeatability of the method: $r = 3\text{ }^{\circ}\text{C}$, reproducibility of the method: $R = 6\text{ }^{\circ}\text{C}$.

3. Results and Discussion

3.1. Composition and Characteristics of DF Samples

Tables 4–6 show the results of determining the composition, basic physicochemical, and low-temperature characteristics of DF samples.

Table 4. Composition and characteristics of DF samples.

Characteristic	Measure Unit	DF No. 1	DF No. 2	DF No. 3	DF No. 4
Density at 15 $^{\circ}\text{C}$	kg/m ³	822.0	837.3	827.2	839.5
Dynamic viscosity at 20 $^{\circ}\text{C}$	mPa/s	2.5774	3.3033	2.352	3.7745
Kinematic viscosity at 20 $^{\circ}\text{C}$	mm ² /s	3.1492	3.9629	2.8559	4.5159
Sulphur content	mg/kg	2865	5781	1704	516
Cetane index by [35]	Point	50.7	50.1	47.0	51.4
Cetane index by [36]		49.4	48.9	46.1	49.6
Fractional composition					
IBP		149	145	125	118
10 vol.%	$^{\circ}\text{C}$	170	190	164	199
50 vol.%		242	261	236	270
90 vol.%		348	329	300	310
95 vol.%		–	–	–	326

Table 5. Hydrocarbon composition of DF samples.

Characteristic	Measure Unit	DF No. 1	DF No. 2	DF No. 3	DF No. 4
Content:					
paraffins	% wt.	60.29	49.62	52.24	53.26
naphthenes		17.55	23.74	23.32	24.64
aromatic hydrocarbons		22.16	26.64	24.43	22.09
Carbon content in:					
aromatic structures	% wt.	13.997	16.875	14.911	15.984
naphthenic structures		30.282	27.511	37.100	50.200
annular structures		44.279	44.386	52.011	66.184
alkyl substituents		55.721	55.614	47.989	33.816
Average number of rings		1.182	1.181	1.174	1.315
Average number of aromatic rings	–	0.372	0.453	0.329	0.306
Average number of naphthenic rings		0.81	0.73	0.85	1.01

Table 6. Low-temperature characteristics of the DF samples.

DF Sample	T_c , $^{\circ}\text{C}$	CFPP, $^{\circ}\text{C}$	T_p , $^{\circ}\text{C}$
1	0	0	–17
2	–4	–5	–14
3	–25	–27	–33
4	–12	–19	–22

Based on the values presented in Table 4, the No. 4 DF sample is characterized by the highest density, and the No. 1 DF sample by the lowest. The No. 3 DF sample is characterized by the lowest values of kinematic and dynamic viscosity, the No. 4 DF sample is characterized by the highest values, while the sulfur content in this sample on

the contrary, is the lowest, and in the No. 2 DF sample it is the highest. The highest value of the cetane index, calculated according to two standards, is observed for the No. 4 DF sample, and the lowest for the No. 3 DF sample.

Based on the results of determining the fractional composition, the No. 1 DF sample contains the highest-boiling components, and the No. 4 DF sample contains the lowest-boiling components.

The No. 2 DF sample is characterized by the lowest content of paraffins, and the No. 1 DF sample is characterized by the highest. The content of naphthenes, on the contrary, is the lowest in the No. 1 DF sample, and the highest in the No. 4 DF sample. Analyzing the content of aromatic hydrocarbons, it can be seen that the No. 2 DF sample has the highest content of aromatic hydrocarbons, and the No. 4 DF sample has the lowest content.

The carbon content in aromatic structures is the highest in the No. 2 DF sample, and the lowest in the No. 1 DF sample. The carbon content in naphthenic structures is the highest in the No. 4 DF sample, and the lowest in the No. 2 DF sample. The highest carbon content in the annular structures is typical for the No. 4 DF sample, and the lowest for the No. 1 DF sample, and vice versa in alkyl substituents, respectively.

The largest average number of rings in molecules is typical for the No. 4 DF sample and the smallest for the No. 3 DF sample. At the same time, the largest number of aromatic rings is typical for the No. 2 DF sample, and the smallest for the No. 4 DF sample; the number of naphthenic rings, respectively, is opposite.

To evaluate the effectiveness of the DA action, it is necessary to investigate the low-temperature characteristics of the initial DF samples. The results of determining the low-temperature characteristics of the DF samples are presented in Table 6.

According to the obtained results, the No. 2 DF sample corresponds to Class 1 in terms of low-temperature characteristics. The No. 1, No. 3, and No. 4 DF samples do not meet the requirements for any of the classes [5].

3.2. Low-Temperature Characteristics of DF Samples and DA Blends under Conditions of Varying the Concentration of Additive

Table 7 shows the results of determining the low-temperature characteristics of the No. 1 and No. 2 DF samples with the D, E, and F additives blends under conditions of varying the concentration of additive.

Table 7. Low-temperature characteristics of DF samples and DA blends at various additive concentrations.

DA	DF No. 1			DF No. 2			DF No. 3			DF No. 4		
	Tc	CFPP	Tp									
Measure Unit	°C											
D _{0.5}	−2	−2	−39	−6	−23	−40	−25	−39	−58	−10	−28	−39
D ₁	−2	−4	−43	−6	−26	−42	−25	−49	−63	−10	−25	−45
D ₂	−2	−5	−50	−6	−20	−40	−25	−45	−70	−10	−25	−53
D ₅	−2	−10	−6	−7	−20	−10	−26	−38	−60	−10	−15	−45
E _{0.5}	0	−1	−17	−6	−14	−36	−26	−31	−57	−9	−20	−22
E ₁	−1	−3	−20	−6	−17	−36	−25	−31	−57	−9	−22	−24
E ₂	−1	−5	−53	−7	−17	−56	−25	−39	−62	−9	−27	−56
E ₅	−1	−9	−48	−7	−24	−59	−25	−38	−60	−9	−31	−60
F _{0.5}	−1	−6	−25	−6	−21	−27	−26	−29	−44	−11	−23	−26
F ₁	−1	−6	−30	−6	−21	−32	−26	−41	−51	−11	−33	−26
F ₂	−1	−8	−33	−6	−25	−37	−26	−46	−64	−11	−27	−32
F ₅	0	−13	−4	−6	−16	−34	−26	−50	−69	−10	−27	−43

Analyzing the obtained data, it can be seen that when F₅ was added to the No. 3 DF sample, the smallest observed CFPP value (−50 °C) was achieved, and when D₂ was added, the smallest observed Tp value (−70 °C) was achieved.

For the No. 1 DF sample, the lowest CFPP was achieved with the addition of F₂, and the lowest Tp was achieved with the addition of E₅. For the No. 2 DF sample, the lowest CFPP was achieved with the addition of D₁, and the lowest Tp was achieved with the

addition of E₅. For the No. 4 DF sample, the lowest CFPP was achieved with the addition of F₁, and the lowest Tp was achieved with the addition of E₅.

Evaluating the obtained low-temperature characteristics of DF samples and DA blends, for compliance with the classes of DF in terms of low-temperature characteristics, according to the requirements of [5], it can be concluded that all blends of the No. 1 DF sample with DAs did not meet the requirements for any of the classes.

When adding D₁ to the No. 2 DF sample, D₁ managed to obtain a DF corresponding to Class 1, and when adding D_{0.5}, D₂, and D₅, only Class 0. When adding E₅, F_{0.5}, F₁, and F₂, it was possible to obtain a DF corresponding to Class 0. In the rest of the cases, blends of the No. 2 DF sample with DAs did not correspond to any of the classes.

Class 4 was obtained by adding the additives F₂, F₅, D₁, and D₂ to the No. 3 DF sample. Blends of the No. 3 DF sample with the addition of F₁, E₂, E₅, D_{0.5}, and D₅ correspond to Class 3. The remaining blends correspond to Class 1.

Also, Class 2 corresponds to a blend of the No. 4 DF sample with the addition of F₁, and Class 1 with the addition of D_{0.5}, E₂, E₅, F₂, and F₅. A blend of the No. 4 DF sample with the addition of D₅ did not correspond to any of the classes. In other cases, blends of the No. 4 DF sample with DAs corresponded to Class 0.

Based on Table 7, the variation in DAs and their concentrations practically did not affect the change in T_c. The obtained values are within the error range of the laboratory determination of T_c (± 3 °C). Therefore, in the future, the influence of DAs and their concentrations will be analyzed only on the CFPP and Tp of DF samples of various compositions.

The obtained results do not conflict with the data presented in [9–11,25,26].

Table 8 shows the average effectiveness of DAs at various concentrations in relation to the CFPP and Tp of DF samples of various compositions. The average effectiveness of DAs was calculated as the difference between the low temperature properties before and after adding the additive. Next, for each of the low-temperature properties (CFPP, Tp), the average was calculated for all DF samples, as well as the average for all DF samples for both low-temperature properties (Total).

Table 8. Average effectiveness of DAs.

DA	Average Effectiveness, °C		
	in Relation to CFPP	in Relation to Tp	Total
D	−10.6	−22.4	−16.5
E	−7.8	−23.7	−15.8
F	−11.8	−14.6	−13.2

As can be seen from the data presented in Table 8, on average, Additive A is the most effective for CFPP, Additive C for Tp, and Additive B for both low-temperature characteristics.

Table 9 shows the average effectiveness of all DAs in various concentrations in the context of DF samples. The average efficiency of all DAs by DF samples was calculated as the difference between the low-temperature properties before and after adding the additive. Next, for each of the low-temperature properties (CFPP, Tp), the average was calculated for all additives for each DF sample, as well as the average for all additives for each DF sample for both low-temperature properties (Total).

Table 9. The average efficiency of all DAs by DF samples.

Average Efficiency, °C	DF No. 1	DF No. 2	DF No. 3	DF No. 4
in relation to CFPP	−6.0	−15.3	−12.7	−6.0
in relation to Tp	−13.7	−23.4	−26.6	−13.7
Total	−9.8	−19.4	−19.6	−9.8

As can be seen from the data presented in Table 9, on average, all DAs most effectively improve the CFPP of the No. 2 DF sample, Tp of the No. 3 DF sample, and both low-temperature characteristics also of the No. 3 DF sample.

3.3. Analysis of the DAs Concentration Effect on the CFPP and Pour Point of DF Samples of Various Compositions

Figure 1 shows the dependences of the change in CFPP of the No. 1–4 DF samples (different composition) on the concentration of the D–F additives.

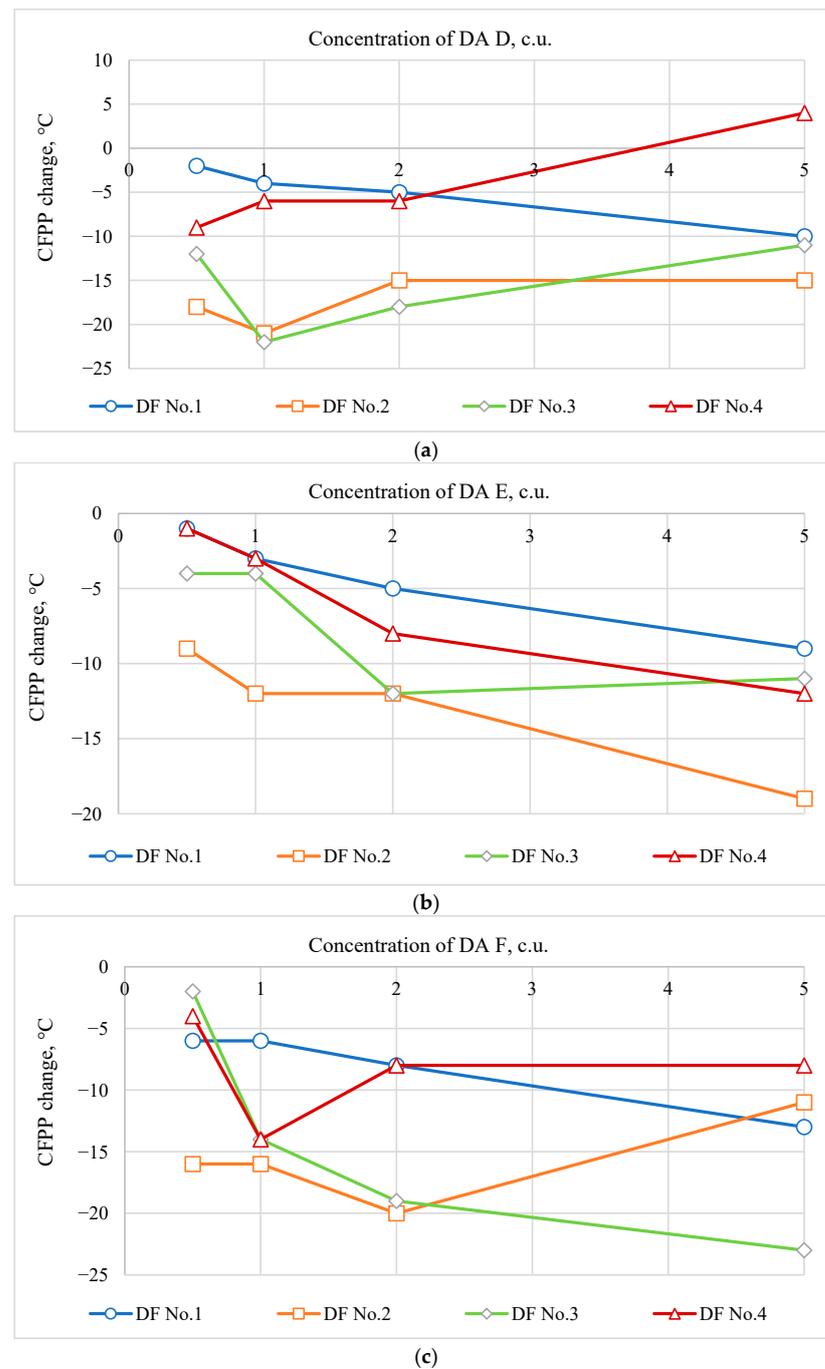


Figure 1. Effect of the DAs concentration on the CFPP of DF samples of various compositions: (a) DA D; (b) DA E; (c) DA F.

Based on Figure 1, it can be seen that the concentration of DAs that allows the most effective change in the CFPP of the DF samples is as follows:

1. Additive D: for the No. 1 DF sample—5.0 c.u.; for the No. 2, 3 DF samples—1.0 c.u.; for the No. 4 DF sample—0.5 c.u.
2. Additive E: for the No. 1–2, 4 DF samples—5.0 c.u.; for the No. 3 DF sample—2.0 c.u.
3. Additive F: for the No. 1, 3 DF samples—5.0 c.u.; for the No. 2 DF sample—2.0 c.u.; for the No. 4 DF sample—1.0 c.u.

Figure 2 shows the dependences of the change in T_p of the No. 1–4 DF samples (different composition) on the concentration of the D–F additives.

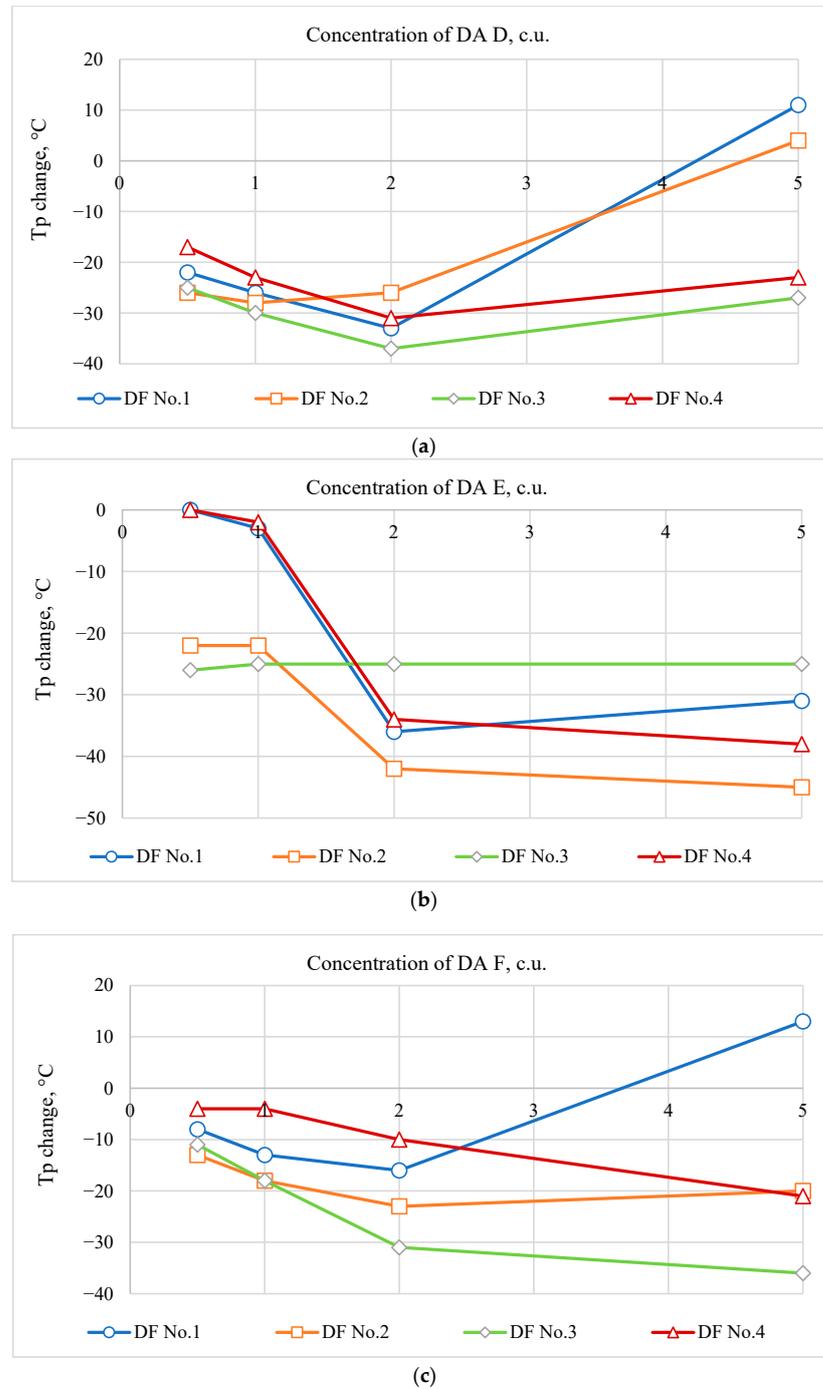


Figure 2. Effect of the DAs concentration on the T_p of DF samples of various compositions: (a) DA D; (b) DA E; (c) DA F.

Based on Figure 2, it can be seen that the concentration of DAs that allows the most effective change in the T_p of DF samples is as follows:

1. Additive D: for the No. 1, 3, 4 DF samples—2.0 c.u.; for the No. 2 DF sample—1.0 c.u.
2. Additive E: for the No. 1, 3 DF samples—2.0 c.u.; for the No. 2, 4 DF samples—5.0 c.u.
3. Additive F: for the No. 1, 2 DF samples—2.0 c.u.; for the No. 3, 4 DF samples—5.0 c.u.

A number of regularities can be identified by analyzing the data presented in Figures 1 and 2. Regularity No. 1: The No. 1 DF sample requires the highest concentration of additives (5.0 c.u.) to be most effective with respect to CFPP.

The observed regularity is explained by the influence of the composition of DF. The No. 1 DF sample is characterized by the highest content of paraffins. With a decrease in temperature, the number of formed paraffin crystals will be significant, and a large amount of DA will be required to effectively prevent their growth.

Regularity No. 2: On average, the highest efficiency of additives in relation to CFPP, when used in a minimum concentration, is achieved for the No. 4 DF sample.

The observed regularity is also explained by the influence of the composition of DF. The No. 4 DF sample is characterized by the lowest content of aromatic hydrocarbons. It is known that polar aromatic hydrocarbons in the composition of fuel can attract DA molecules to themselves, thereby preventing their interaction with paraffin crystals that grow larger with decreasing temperature. To suppress the negative effect of aromatic hydrocarbons, the concentration of the DA needs to be increased. In the case of a fuel with a minimum aromatics content, the concentration of the DA required to effectively improve the CFPP will be less.

Regularity No. 3: The effectiveness of the additives' action in relation to the CFPP varies depending on the concentration to the greatest extent when used on the No. 3 DF sample, to the least extent when used on the No. 1 DF sample.

The observed regularity is also explained by the influence of the composition of DF. The No. 3 DF sample is characterized by the most optimal composition of all samples—the average content of both paraffins and aromatic hydrocarbons. The action of DA is not hindered by aromatic hydrocarbons; the amount of DA is sufficient to interact with all formed paraffin crystals. An increase in the concentration of DA makes it possible to stop the growth of crystals more quickly, and the effectiveness of the DA increases. This explains the greatest effect of all DAs in relation to the low-temperature characteristics of the No. 3 DF sample.

In the case of the No. 1 DF sample, which is characterized by the highest content of paraffins, the number of formed paraffin crystals is so high that they will plug the standard filter element in any case. According to the mechanism of DA action, these additives are able to stop the growth of paraffin crystals, but not prevent their formation. Moreover, without the formation of initial crystallization centers, DA cannot begin to act. The effectiveness of the additive on CFPP in this case is limited, and increasing its concentration will not give such a significant effect. In this connection, the effect of all DAs on the CFPP of the No. 1 DF sample is minimal.

Regularity No. 4: For CFPP, on average, DA C is most effective at high concentrations (5.0 c.u.), DA B at low concentrations (0.5–1.0 c.u.), and DA A at medium concentrations (1.0–2.0 c.u.).

From Table 2, it can be seen that the concentration of DA recommended by the manufacturer (single concentration, 1.0 c.u.) for DA B is at a maximum, for DA C it is at a minimum, for DA A it has an intermediate value.

Comparison of depressants in different concentrations is advisable, because any DA is an active ingredient that is dissolved in a solvent. The composition of the DA is a trade secret; the manufacturer gives recommendations on the involvement of the additive, based on the ratio of the solvent/active component in the composition of the DA.

For DA B, it can be seen that the concentration recommended by the manufacturer (the maximum among all additives) is optimal; if used on fuel with a favorable composition (No. 4 DF sample), the concentration of the additive can even be halved.

For DA C, the concentration recommended by the manufacturer is the lowest among all additives and, according to studies, is not optimal; it must be significantly increased (up to 5.0 c.u.) to effectively improve the CFPP of fuels.

Regularity No. 5: In most cases, an increase in the concentration of DA to 5.0 c.u. is inappropriate, because it results in a higher T_p than the additive effect when used at 2.0 c.u.

The active components of DAs are high-molecular compounds, which at low temperatures, like paraffins, are prone to the formation of spatial structures. In the case of the involvement of DAs at a concentration of 5.0 c.u. the content of high-molecular compounds becomes so high that they degrade the T_p of fuels.

Regularity No. 6: In relation to T_p , on average, DA A and C are most effective at high concentrations (2.0–5.0 c.u.) and DA B at medium concentrations (1.0–2.0 c.u.).

The explanation is similar to Regularity No. 4.

Regularity No. 7: The greatest efficiency of additives in relation to T_p when used in a minimum concentration is achieved for No. 1 DF sample.

As noted earlier, the No. 1 DF sample is characterized by the highest content of paraffins from the all samples. The effectiveness of the DA on the CFPP of this sample is limited. However, for T_p , the effect is reversed. DA can begin to act only in the event of the appearance of the first crystals of paraffins and stop their growth. The faster the crystals appear, the more efficiently the DA will act, and the longer the fuel will retain mobility (not freeze). In the case of the No. 1 DF sample with a high content of paraffins in the composition, the number of initial crystallization centers is high, and the DA will be effective in relation to T_p even at low concentrations. With an increase in the concentration of the DA, its effectiveness will only increase, because crystal growth will stop faster and the fuel will retain its mobility at lower temperatures.

Regularity No. 8: The effectiveness of the additives' action in relation to T_p varies depending on the concentration to the greatest extent when used on the No. 1 DF sample, to the least extent when used on the No. 3 DF sample.

The explanation of the effect for the No. 1 DF sample is similar to that presented for Regularity No. 7.

For the No. 3 DF sample, it should be noted that this sample of fuel is characterized by an extremely low T_p , both in a blend with additives (up to $-60\text{ }^\circ\text{C}$) and without them. The maximum effectiveness of the additives in relation to T_p has been achieved, and increasing the concentration does not provide a significant improvement.

Summarizing the conclusions presented above, it is possible to identify the following regularities of the DAs concentration influence on the effectiveness of their action when used on samples of DF of various compositions:

- The lower the content of aromatic hydrocarbons in the composition of the DF, the lower the concentration of DA that will improve (decrease) the CFPP;
- The higher the content of paraffin hydrocarbons in the composition of the DF, the lower the concentration of DA that will improve (decrease) the T_p ;
- The lower the content of aromatic hydrocarbons in the composition of the DF, the more strongly the DA effectiveness in relation to the CFPP depends on the concentration and the less the DA effectiveness in relation to the T_p depends on the concentration;
- The higher the content of paraffinic hydrocarbons in the composition of the DF, the less the DA effectiveness in relation to CFPP depends on the concentration and the more the DA effectiveness in relation to T_p depends on the concentration;
- The revealed regularities do not conflict with the data presented in [9–11,25,26].

3.4. Results of Determining the Low-Temperature Characteristics of DF Samples and DA Blends, under Conditions of Varying the DA Adding Temperature

The results of determining the low-temperature characteristics of the No. 1, 2 DF samples with adding the DAs A–F are presented in Tables 10 and 11.

Table 10. Low-temperature characteristics of the DF sample No. 1 and DAs blends, at different temperatures of adding.

Blend	T _c , °C	CFPP, °C	T _p , °C	Blend	T _c , °C	CFPP, °C	T _p , °C
A ₁₅	−2	−3	−35	D ₁₅	−2	−4	−31
A ₂₅	−2	−3	−35	D ₂₅	−2	−5	−31
A ₃₅	−2	−3	−35	D ₃₅	−2	−8	−31
A ₄₅	−2	−4	−36	D ₄₅	−2	−11	−31
A ₅₅	−2	−4	−36	D ₅₅	−2	−11	−31
B ₁₅	−1	−3	−30	E ₁₅	0	−3	−20
B ₂₅	−1	−3	−30	E ₂₅	0	−3	−20
B ₃₅	−1	−3	−31	E ₃₅	0	−4	−20
B ₄₅	−1	−4	−31	E ₄₅	0	−4	−20
B ₅₅	−1	−4	−31	E ₅₅	0	−4	−20
C ₁₅	−1	−2	−36	F ₁₅	−1	−4	−32
C ₂₅	−1	−2	−36	F ₂₅	−1	−4	−32
C ₃₅	−1	−2	−36	F ₃₅	−1	−5	−32
C ₄₅	−1	−3	−36	F ₄₅	−1	−5	−32
C ₅₅	−1	−3	−36	F ₅₅	−1	−5	−32

Table 11. Low-temperature characteristics of the DF sample No. 2 and DAs blends, at different temperatures of adding.

Blend	T _c , °C	CFPP, °C	T _p , °C	Blend	T _c , °C	CFPP, °C	T _p , °C
A ₁₅	−6	−7	−36	D ₁₅	−6	−10	−46
A ₂₅	−6	−7	−36	D ₂₅	−6	−11	−46
A ₃₅	−6	−7	−37	D ₃₅	−6	−14	−46
A ₄₅	−6	−7	−37	D ₄₅	−6	−15	−46
A ₅₅	−6	−7	−37	D ₅₅	−6	−15	−46
B ₁₅	−6	−7	−23	E ₁₅	−7	−9	−40
B ₂₅	−6	−7	−23	E ₂₅	−7	−10	−40
B ₃₅	−6	−9	−24	E ₃₅	−7	−10	−40
B ₄₅	−6	−9	−24	E ₄₅	−7	−12	−41
B ₅₅	−6	−9	−24	E ₅₅	−7	−12	−41
C ₁₅	−7	−8	−41	F ₁₅	−7	−20	−37
C ₂₅	−7	−8	−41	F ₂₅	−7	−23	−37
C ₃₅	−7	−9	−42	F ₃₅	−7	−25	−37
C ₄₅	−7	−9	−42	F ₄₅	−7	−26	−38
C ₅₅	−7	−10	−42	F ₅₅	−7	−26	−38

From the results presented in Table 10 it follows that addition of the DAs A–F slightly improves (reduces) the T_c of the No. 1 DF sample ($\Delta T_c = 1\text{--}2\text{ }^\circ\text{C}$). Changing the temperature of the adding of additives does not enhance the depressant effect in relation to the T_c.

The addition of the DAs A–D and F significantly improves (reduces) the T_p of the No. 1 DF sample. The greatest depression of T_p is observed when Additives A and C are added ($\Delta T_p = 18\text{--}19\text{ }^\circ\text{C}$). The addition of the DA E had the least depressant effect ($\Delta T_p = 3\text{ }^\circ\text{C}$). Changing the temperature of adding additives slightly enhances the depressant effect in relation to the T_p (maximum enhancement is 1 °C).

The addition of the DAs A–F improves (reduces) the CFPP of the No. 1 DF sample. Additive C had the least depressant effect ($\Delta \text{CFPP} = 3\text{ }^\circ\text{C}$), and Additive D had the greatest depressant effect ($\Delta \text{CFPP} = 11\text{ }^\circ\text{C}$). At an adding temperature of 35–55 °C, an increase in the depressant effect of additives in relation to CFPP is observed. Thus, when adding Additives A–C at an adding temperature of 45–55 °C, the increase in temperature depression is 1 °C; when Additives E and F are added at an adding temperature of 35–55 °C, the increase in temperature depression is 1 °C. When Additive D is added, an increase in the effectiveness of action against the CFPP is observed over the entire range of varying the

adding temperature (15–55 °C), and the maximum increase in temperature depression is 7 °C at an adding temperature of 55 °C. The obtained results do not conflict with the data presented in [9–11,25,26].

From the results presented in Table 11, it follows that addition of the DAs A–F slightly improves (reduces) the T_c of the No. 2 DF sample ($\Delta T_c = 2\text{--}3$ °C). Changing the adding temperature of additives does not enhance the depressant effect in relation to the T_c .

The addition of the DAs A–F significantly improves (reduces) the T_p of the No. 2 DF sample. The greatest depression of T_p is observed when the C–E additives are added ($\Delta T_p = 24\text{--}29$ °C). Additive B had the least depressant effect ($\Delta T_p = 6$ °C). Changing the temperature of adding additives slightly enhances the depressant effect in relation to the T_p (maximum enhancement is 1 °C).

The addition of the DAs A–F reduces the CFPP of the No. 2 DF sample. Additive A had the least depressant effect ($\Delta CFPP = 2$ °C), and Additive F had the greatest depressant effect ($\Delta CFPP = 15\text{--}21$ °C). At an adding temperature of 35–55 °C, an increase in the depressant effect of the B–F additives in relation to the CFPP is observed. Thus, when Additive B is added at an adding temperature of 45–55 °C, the increase in temperature depression is 1 °C; when Additive C is added at an adding temperature of 45–55 °C, the increase in temperature depression is 2 °C. When adding Additives D–F, an increase in the effectiveness of action against the CFPP is observed over the entire range of adding temperature variation (15–55 °C). The maximum increase in temperature depression at an adding temperature of 55 °C is: for Additive D—5 °C, for Additive E—3 °C, for Additive F—6 °C. The effect of Additive A on CFPP is independent of the adding temperature.

In addition, it can be seen that the adding of Additive F at temperatures of 15–35 °C made it possible to obtain from the No. 2 DF sample, which does not correspond to any of the classes, a fuel corresponding to Class 0 for winter and arctic fuels, according to the requirements [5]. And the adding of additive F at temperatures of 45–55 °C produced a fuel corresponding to Class 1 for winter and arctic fuels, according to the requirements [5]. The obtained results do not conflict with the data presented in [9–11,25,26].

3.5. Influence of the Adding Temperature on the DA Efficiency

The effects of the DAs A–F at different adding temperatures on the T_c , T_p , and CFPP of the No. 1, 2 DF samples are presented in Figures 3–5, respectively. Δ values are presented in comparison with DF samples without the addition of DAs.

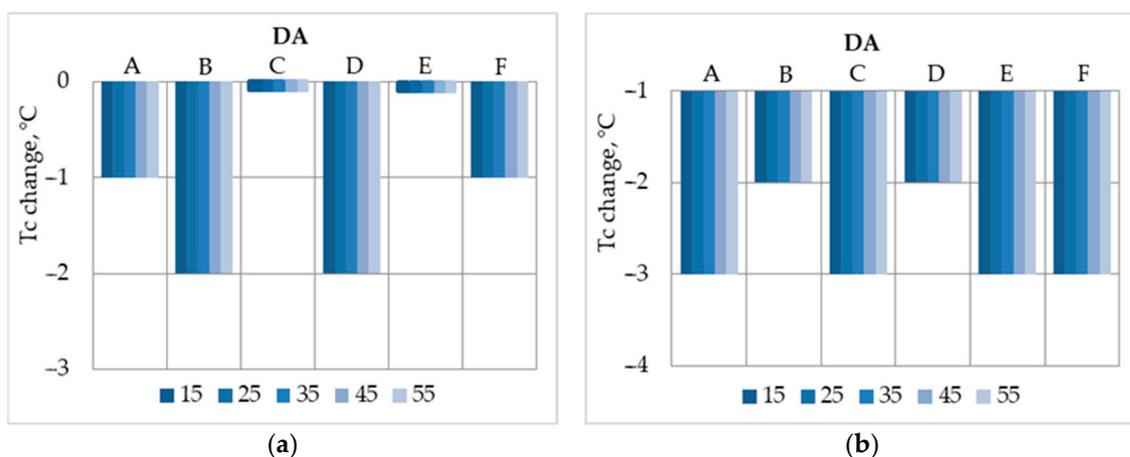


Figure 3. Influence of the DAs A–F adding temperature on the T_c of the DF samples: (a) No. 1; (b) No. 2.

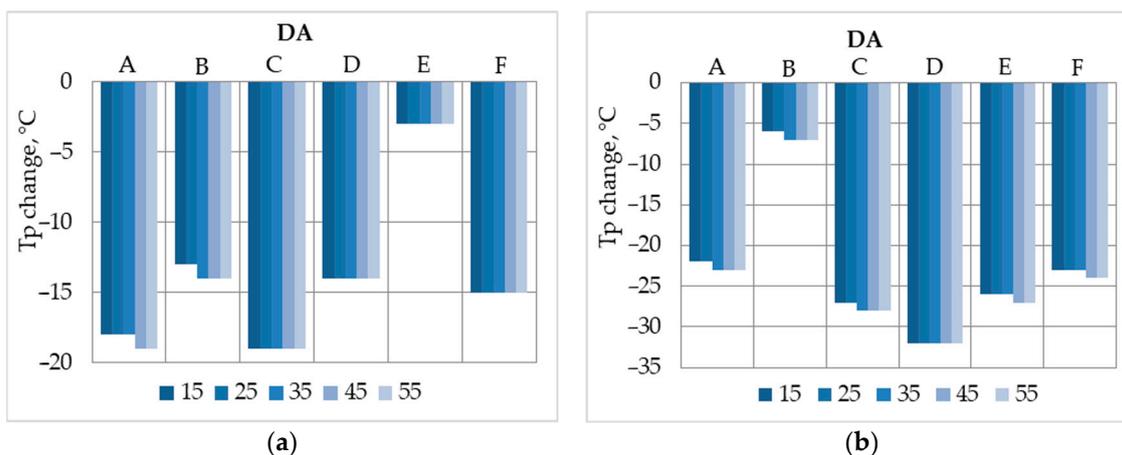


Figure 4. Influence of the DAs A–F adding temperature on the T_p of the DF samples: (a) No. 1; (b) No. 2.

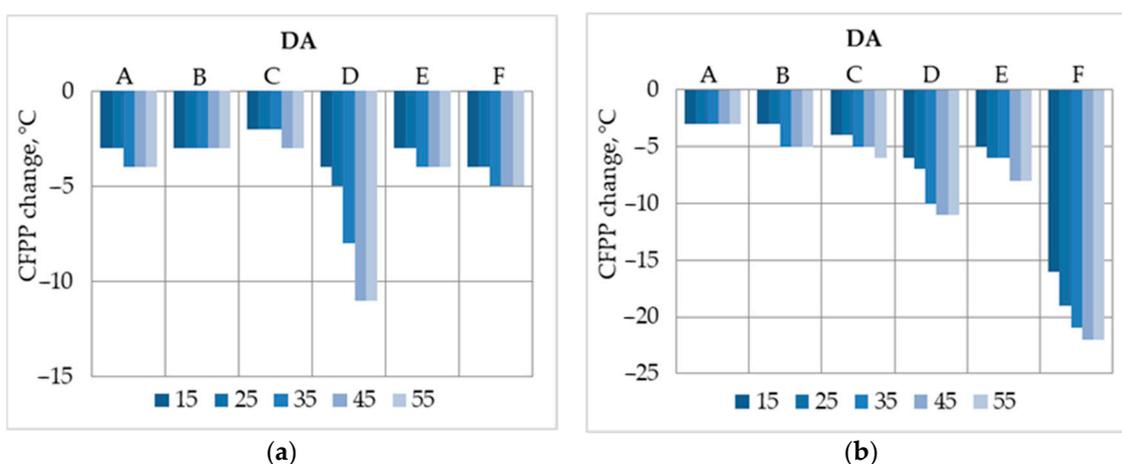


Figure 5. Influence of the DAs A–F adding temperature on the CFPP of the DF samples: (a) No. 1; (b) No. 2.

As can be seen from the data presented in Figure 3, a change in the temperature of adding additives to the No. 1, 2 DF samples does not influence the additives' effectiveness in relation to the T_c ($\Delta T_c = 0$ °C). DAs do not affect the T_c of DF samples, since depressants prevent the growth of paraffin crystals that have already formed but are not able to stop their formation. Thus, the action of the additive begins when the temperature of the formation of crystals of the heaviest paraffins, which is T_c , is reached.

According to the data presented in Figure 4, a change in the additive adding temperature in individual DF samples slightly influences the additives' effectiveness in relation to the T_p ($\Delta T_p = 0$ – 1 °C), which is comparable to the error of the measurement method. The slight effect of the additive adding temperature on the T_p is also explained by the mechanism of DA action. Improving the interaction of the additive with paraffin is relevant only at the initial stage of crystal association; when the T_p is reached, all paraffin crystals line up in a single crystal lattice, the difference in the arrangement of the additive molecules, in which it does not give a significant effect.

However, one can notice the difference in the depressant effect of the additives when added to the No. 1 and No. 2 DF samples. Thus, when Additives A and C–F are added, the effect is greater on the T_p of the No. 2 DF sample both at an additive adding temperature of 15 °C and 55 °C. This result can be explained by the fact that the solubility of these additives is better in the No. 2 DF sample, while Additive B has a better solubility in the No. 1 DF sample.

From the results presented in Figure 5, it follows that the greater the effect of the DA on the DF sample CFPP, the stronger its effectiveness depends on the adding temperature.

It can also be seen that the greatest DA efficiency is achieved at an adding temperature of 45–55 °C. However, increasing the adding temperature from 45 °C to 55 °C does not change the additive effectiveness in relation to the CFPP.

The obtained result can be explained by the fact that the DA has a final solubility temperature in DF and at a temperature of additive addition above the solubility temperature, no improvement in the depressant effect is observed, which is confirmed by theoretical ideas about the mechanism of DA action described earlier.

With an increase in the additive adding temperature, the paraffin melting point is reached, as a result of which the properties of the molecules change and during crystallization a hexagonal crystal lattice with a lower packing density will form, which contributes to a more efficient interaction of the additive and paraffins. In addition, with an increase in the adding temperature, complete dissolution of the additive components occurs, which leads to their uniform distribution in the volume of the DF sample. At 45 °C, the melting temperature of the most paraffins in the composition of DF is reached, and most of the additive components are dissolved; a further increase in the temperature of adding the additive is impractical. The obtained results do not conflict with the data presented in [9–11,25,26].

4. Conclusions

In this work, in contrast to existing works, it was established for the first time that the composition of the fuel affects not only the DA effectiveness but also the dependence of DA effectiveness on the concentration in which it is used. The regularities of the DA concentration influence on the effectiveness of their action when used on samples of DF of various compositions are revealed. It was found that the higher the content of paraffinic hydrocarbons in the composition of the DF, the less the DA effectiveness in relation to the CFPP depends on the concentration and the more the DA effectiveness in relation to the Tp depends on the concentration. It was also shown that the lower the content of aromatic hydrocarbons in the composition of the DF, the more strongly the DA effectiveness in relation to the CFPP depends on the concentration and the less the DA effectiveness in relation to the Tp depends on the concentration.

The regularities of the DA adding temperature's influence on the effectiveness of their action for the first time are revealed. It is shown that a change in the additives' adding temperature does not enhance the additives' effectiveness in relation to the Tc and also slightly enhances the additives effectiveness in relation to the Tp (maximum enhancement is 1 °C). It has been established that an increase in the DAs adding temperature to 35–55 °C enhances their effectiveness in relation to the CFPP (for the No. 1 DF sample by a maximum of 7 °C when Additive D is added at a temperature of 45–55 °C; for the No. 2 DF sample by a maximum of 6 °C when Additive F is added at a temperature of 45–55 °C). In addition, it was shown that the greater the DA effect on the CFPP, the stronger its effectiveness depends on the adding temperature. It has also been established that the optimal temperature for adding a DA to increase its effectiveness is 45 °C, a further increase in the adding temperature to 55 °C is inappropriate, since it does not give an additional positive effect.

The following recommendations for the production of commercial winter and arctic fuels by varying concentrations of additives have been developed: (1) for the No. 2 DF sample (original fuel is substandard, does not meet the requirements [5] for any of the classes), it is recommended to obtain Class 0, use D_{0.5}, D₂, D₅, E₅, F_{0.5}, F₁, and F₂; to obtain Class 1, use D_{0.5}, D₂ and D₅. (2) for the No. 3 DF sample (original fuel—Class 1 according to [5]), it is recommended to obtain Class 3, use F₁, E₂, E₅, D_{0.5}, and D₅; to obtain Class 4, use F₂, F₅, D₁, and D₂. (3) for the No. 4 DF sample (original fuel is substandard, does not meet the requirements [5] for any of the classes), it is recommended to obtain Class 1, use D_{0.5}, E₂, E₅, F₂, and F₅; to obtain Class 2, use F₁.

The following recommendations for the production of commercial winter and arctic fuels by varying the additives adding temperature have been developed: for the No. 2 DF sample (original fuel is substandard, does not meet the requirements [5] for any of the classes), it is recommended to obtain Class 0, add additive F at a temperature of 15 °C; to obtain Class 1, add additive F at a temperature of 45 °C.

Methods for increasing the efficiency of DA for the production of low-freezing DF by selecting the most effective additive concentration and its adding temperature for fuels of various compositions have been developed. It has been shown that the composition of DF affects the DA efficiency in dynamics—under conditions of varying the concentration and adding temperature. The regularities identified in the work will make it possible, depending on the composition of the fuel, to select the optimal concentration of the additive and the temperature of its adding. It can allow an increase in the efficiency of the additives used, as well as the volume of production of low-freezing grades of DF. At further stages of work, it is planned, based on the obtained regularities, to develop a mathematical model for predicting the effectiveness of the DA, taking into account the fuel composition, additive concentration, and temperature of its adding.

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Data Availability Statement: Data are contained within the article. The data presented in this study are available on request from the corresponding author due to privacy.

Conflicts of Interest: The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Abbreviations

DF	diesel fuel
DA	depressant additive
T _c	cloud point
T _p	pour point
CFPP	cold filter plugging point
A	depressant additive A
B	depressant additive B
C	depressant additive C
D	depressant additive D
E	depressant additive E
F	depressant additive F

References

1. Sajjad, H.; Masjuki, H.H.; Varman, M.; Kalam, M.A.; Arbab, M.I.; Imtenan, S.; Rahman, S.M.A. Engine combustion, performance and emission characteristics of gas to liquid (GTL) fuels and its blends with diesel and bio-diesel. *Renew. Sustain. Energy Rev.* **2014**, *30*, 961–986. [[CrossRef](#)]
2. Ghadikolaie, M.A.; Wong, P.K.; Cheung, C.S.; Zhao, J.; Ning, Z.; Yung, K.F.; Wong, H.C.; Gali, N.K. Why is the world not yet ready to use alternative fuel vehicles? *Heliyon* **2021**, *7*, e07527. [[CrossRef](#)]
3. Filimonova, I.V.; Nikitenko, S.M.; Provornaya, I.V.; Dzyuba, Y. Forecast of regional structure of oil production in Russia. *Eurasian Min.* **2020**, *1*, 25–30. [[CrossRef](#)]
4. Iovleva, E.L.; Borisov, A.A.; Stepanov, P.A. Development of Arctic Diesel Fuel with Optimal Composition. *IOP Conf. Ser. Earth Environ. Sci.* **2020**, *459*, 052009. [[CrossRef](#)]
5. *EN 590; Automotive Fuels—Diesel—Requirements and Test Methods*. European Committee: Brussels, Belgium, 2009.
6. Bogomolova, T.S.; Smirnova, M.Y.; Klimov, O.V. Catalysts and know-how of environmentally friendly low pour point diesel fuels. *Ecol. Ind. Russ.* **2022**, *12*, 15–21. [[CrossRef](#)]
7. Boryaev, A.; Yuqing, Z.; Ruchkina, I.; Rajczyk, P. Control of low-temperature characteristics of motor fuels in the Arctic. *Transp. Res. Procedia* **2021**, *57*, 95–105. [[CrossRef](#)]

8. Exactitude Consultancy. Market Research and Consulting Services. Available online: <https://exactitudeconsultancy.com/ru/o%D1%82%D1%87%D0%B5%D1%82%D1%8B/26499/%D1%80%D1%8B%D0%BD%D0%BA-%D1%82o%D0%BF%D0%BB%D0%B8%D0%B2%D0%BD%D1%8B%D1%85-%D0%BF%D1%80%D0%B8%D1%81%D0%B0%D0%B4o%D0%BA/> (accessed on 15 September 2023).
9. Burov, E.A.; Ivanova, L.V.; Koshelev, V.N.; Sorokina, A.S. Influence of Group Hydrocarbon Composition of Diesel Fuels on Depressant Additive Efficiency. *Chem. Technol. Fuels Oils* **2020**, *56*, 149–156. [CrossRef]
10. Sharafutdinov, I.; Stratiev, D.; Shishkova, I.; Dinkov, R.; Batchvarov, A.; Petkov, P.; Rudnev, N. Cold flow properties and oxidation stability of blends of near zero sulfur diesel from Ural crude oil and FAME from different origin. *Fuel* **2012**, *96*, 556–567. [CrossRef]
11. Douvartzides, S.L.; Charisiou, N.D.; Papageridis, K.N.; Goula, M.A. Green Diesel: Biomass Feedstocks, Production Technologies, Catalytic Research, Fuel Properties and Performance in Compression Ignition Internal Combustion Engines. *Energies* **2019**, *12*, 809. [CrossRef]
12. Agarwal, S.; Chhibber, V.K.; Bhatnagar, A.K. Tribological behavior of diesel fuels and the effect of anti-wear additives. *Fuel* **2013**, *106*, 21–29. [CrossRef]
13. Kemalov, A.F.; Valiev, D.Z.; Kemalov, R.A. Polymer additives influence on low-temperature properties of petroleum fuels. *Astra Salvensis* **2017**, *2017*, 191–201.
14. Saeedi Dehaghani, A.H.; Rahimi, R. An experimental study of diesel fuel cloud and pour point reduction using different additives. *Petroleum* **2019**, *5*, 413–416. [CrossRef]
15. Chen, F.; Liu, J.; Yang, T.; Yin, S.; Su, B.; Xie, M.; Dai, B.; Han, S.; Xue, Y. Influence of maleic anhydride-co-methyl benzyl acrylate copolymers modified with long-chain fatty amine and long-chain fatty alcohol on the cold flow properties of diesel fuel. *Fuel* **2020**, *268*, 117392. [CrossRef]
16. Danilov, A.M. *Application of Fuel Additives*; Khimizdat: St. Petersburg, Russia, 2010. (In Russian)
17. Dickerson, R.E.; Gray, H.B.; Haight, G.P., Jr. *Chemical Principles*; The Benjamin/Cummings Publishing Company, Inc.: Menlo Park, CA, USA, 1989; Volume 3.
18. Pucko, I.; Racar, M.; Faraguna, F. Synthesis, characterization, and performance of alkyl methacrylates and tert-butylaminoethyl methacrylate tetra polymers as pour point depressants for diesel Influence of polymer composition and molecular weight. *Fuel* **2022**, *324*, 124821. [CrossRef]
19. Chen, J.; Cui, L.; Xu, B.; Lin, H.; Han, S. Influence of polymers with surfactant properties as pour point depressants on the cold flow properties of diesel fuel. *Colloids Surf. A Physicochem. Eng. Asp.* **2023**, *677*, 132390. [CrossRef]
20. Srivastava, S.P.; Tandon, R.S.; Verma, P.S.; Pandey, D.C.; Goyal, S.K. Phase transitions in middle-distillate waxes: Effect of a pour-point depressant additive. *Fuel* **1995**, *74*, 928–931. [CrossRef]
21. El Mehad, N. Efficiency of N-Decyl-N-benzyl-N-methylglycine and N-Dodecyl-N-benzyl-N-methylglycine surfactants for flow improvers and pour point depressants. *J. Mol. Liq.* **2017**, *229*, 609–613. [CrossRef]
22. Li, X.; Yuan, M.; Xue, Y.; Lin, H.; Han, S. Tetradecyl methacrylate-N-methylolacrylamide Copolymer: A low concentration and high-efficiency pour point depressant for diesel. *Colloids Surf. A Physicochem. Eng. Asp.* **2022**, *642*, 128672. [CrossRef]
23. Zhang, X.; Li, N.; Wei, Z.; Han, S.; Dai, B.; Lin, H. Synthesis of nano-hybrid polymethacrylate-carbon dots as pour point depressant and combined with ethylene-vinyl acetate resin to improve the cold flow properties of diesel fuels. *Energy* **2022**, *253*, 124186. [CrossRef]
24. Lin, H.; Yin, S.; Su, B.; Xue, Y.; Han, S. Research on combined-pour point depressant of methacrylate-acrylamide copolymers and ethylene-vinyl acetate copolymers for diesel fuel. *Fuel* **2021**, *290*, 120002. [CrossRef]
25. Bogdanov, I.; Kirgina, M.; Morozova, Y.; Altynov, A. Evaluation of the Feasibility of a Simultaneous Change in the Fractional Composition and the Involvement of Depressant Additives to Obtain Low-Freezing Diesel Fuels. *ACS Omega* **2022**, *7*, 6086–6092. [CrossRef] [PubMed]
26. Kirgina, M.; Bogdanov, I.; Altynov, A.; Belinskaya, N.; Orlova, A.; Nikonova, N. Studying the impact of different additives on the properties of straight-run diesel fuels with various hydrocarbon compositions. *Oil Gas Sci. Technol.—Rev. D'Ifp Energ. Nouv.* **2021**, *76*, 40. [CrossRef]
27. Mannol. Website of the Official Distributor Mannol SCT Germany in the Central Federal District. Available online: <https://www.mannolrus.ru/> (accessed on 15 September 2023).
28. Ravenol. Catalog Ravenol. Available online: <https://catalog.ravenol.kz/ru/ravenol-flieverbesserer/> (accessed on 15 September 2023).
29. Sintec Lubricant. Sintec Lubricant—Official Website of the Manufacturer of Motor Oils and Antifreeze. Available online: <https://sinteclubricants.ru/> (accessed on 15 September 2023).
30. AMSOIL. AMSOIL Russia. Available online: <https://www.amsoil-club.ru/produkt-amsoil/diesel-cold-flow/ACF> (accessed on 15 September 2023).
31. Hi-Gear. Hi-Gear—Auto Chemicals, Motor Oils, Auto Cosmetics. Available online: <https://hi-gear-products.ru/catalog/autochemistry/engine-power-system/diesel-engines/anti-gels/HG3421/> (accessed on 15 September 2023).
32. FILLinn. FILLinn—Auto Chemicals, Auto Cosmetics, Car Shampoo, Car Polish, Fuel Additives. Available online: <https://www.fillinn.com/product/4228/fl090-antigel-i-ochistitel-dizelnogo-topлива-kontsentrat-520-ml/> (accessed on 15 September 2023).
33. ISO 3405:2011; Petroleum Products—Determination of Distillation Characteristics at Atmospheric Pressure. International Organization for Standardization: London, UK, 2011.

34. *ISO 12185:1996*; Crude Petroleum and Petroleum Products—Determination of Density—Oscillating U-Tube Method. International Organization for Standardization: London, UK, 1996.
35. *ISO 3104:1994*; Petroleum Products. Transparent and Opaque Liquids. Determination of Kinematic Viscosity and Calculation of Dynamic Viscosity. International Organization for Standardization: London, UK, 1994.
36. *ASTM D4294-16e1*; Standard Test Method for Sulfur in Petroleum and Petroleum Products by Energy Dispersive X-ray Fluorescence Spectrometry. ASTM International: West Conshohocken, PA, USA, 2016.
37. *USS 27768-88*; Diesel Fuel. Determination of Cetane Index by Calculation Method. USSR State Committee on Standards: Moscow, Russia, 1988.
38. *ISO 4264:2018*; Petroleum Products—Calculation of Cetane Index of Middledistillate Fuels by the Four-Variable Equation. International Organization for Standardization: London, UK, 2018.
39. *ASTM-D611-01a*; Standard Test Methods for Aniline Point and Mixed Aniline Point of Petroleum Products and Hydrocarbon Solvents. ASTM International: West Conshohocken, PA, USA, 1964. Available online: <https://cdn.standards.iteh.ai/samples/16930/be10cbc5788c4f6d90690708c77d6581/ASTM-D611-01a.pdf> (accessed on 15 September 2023).
40. *ASTM D3238-17a*; Standard Test Method for Calculation of Carbon Distribution and Structural Group Analysis of Petroleum Oils by the n-D-M Method. ASTM International: West Conshohocken, PA, USA, 2017.
41. *ASTM Standards:3 D1218*; Test Method for Refractive Index and Refractive Dispersion of Hydrocarbon Liquids. ASTM International: West Conshohocken, PA, USA, 2016.
42. *ASTM D2503*; Test Method for Relative Molecular Mass (Molecular Weight) of Hydrocarbons by Thermoelectric Measurement of Vapor Pressure. ASTM International: West Conshohocken, PA, USA, 1992.
43. *ASTM D2500-05*; Standard Test Method for Cloud Point of Petroleum Products. ASTM International: West Conshohocken, PA, USA, 2005.
44. *ASTM D6371-17a*; Standard Test Method for Cold Filter Plugging Point of Diesel and Heating Fuels. ASTM International: West Conshohocken, PA, USA, 2017.
45. *ASTM D97-17b*; Standard Test Method for Pour Point of Petroleum Products. ASTM International: West Conshohocken, PA, USA, 2017.

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