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INVESTIGATION OF THE PHYSICAL PROPERTIES OF FLUIDS FOR REMOVING INDUSTRIAL CONTAMINANTS

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ABSTRACT

The aim of this study was to investigate the influence of concentration and temperature on the physical properties of selected industrial cleaning fluids, focusing on parameters relevant to the cleaning process, such as viscosity, shear stress, density, activation energy, and wettability. Four cleaning agents from the company Noyen were examined, including both concentrated products and their 10% aqueous solutions. The rheological properties of the fluids were evaluated using a rotational viscometer; density was measured with a pycnometer; surface tension and wettability were assessed using a goniometer; and activation energy was determined based on the Arrhenius equation. The results of the viscosity and shear stress tests indicated that all tested fluids exhibited Newtonian behaviour in both concentrated and diluted forms. Surface tension and wettability analysis showed good wetting properties for all tested fluids (contact angle <55°), although significant differences in wettability were observed depending on the type of surface and the specific fluid used.

Introduction

Cleaning of machine components used in production is one of the fundamental stages in many industrial processes (Wilson et al., 2022). It plays a crucial role in the food industry, as product quality and consumer safety largely depend on effective cleaning procedures (Chai et al., 2024; Półtorak et al., 2025). Goode et al. (2013) proposed a classification of contaminants in the food industry based on the difficulty of their removal. The authors also discussed the impact of various cleaning parameters on the effectiveness of removing different types of deposits.

The cleaning process is complex and can be analysed on multiple levels, as it involves various physical and chemical processes. The composition and structure of the contamination, as well as the cleaning fluid, largely define the cleaning mechanism (Fryer and Asteriadou, 2009). The structure of the surface on which the contamination occurs is also significant (Hanisch et al., 2024).

Understanding the forces responsible for the mutual attraction of contaminant molecules (cohesion) and the forces bonding the contamination to the substrate surface (adhesion) is fundamental for selecting the appropriate cleaning agents (Landel and Wilson, 2021). Cleaning begins after a short period called the reptation time, when molecular chains separate in the fluid or when the fluid deforms and displaces the contamination layer (Joppa et al., 2020; Kricke et al., 2022).

Chemical agents are often introduced to facilitate cleaning by reducing adhesion to the substrate (detachment or exfoliation), breaking the contamination into movable elements, or changing its rheology. The simplest chemical action involves altering the environment, e.g., temperature, pH, or composition (Palabiyik et al., 2022) so that the contamination or part of it dissolves. If the heterogeneous contaminant contains a soluble phase, dissolution increases the volume fraction of the cleaning agent and reduces material cohesion, aiding erosion by mechanical forces. A cleaning agent can also absorb into the contamination, causing it to swell (or shrink), thus modifying its rheological and chemical properties, and altering its spatial structure (Kricke et al., 2024; Landel and Wilson, 2021). Fernandes et al. (2021) described a method for measuring the rheological properties of contaminants directly on the surface of industrial equipment. Avila-Sierra et al. (2021) investigated how surface temperature affects the effectiveness of chlorinated-caustic cleaning of milk residues from stainless steel. They found that higher surface temperatures result in less swelling of deposits, while simultaneously facilitating their removal.

Cleaning agents have varied chemical compositions depending on their intended application. The ingredients of cleaning agents may include alkaline, acidic, or neutral active substances, surfactants, enzymes, water-softening agents, pH regulators, chelating agents, and other additives that enhance the cleaning effect (Su et al., 2024).

Surfactants, also known as surface-active agents, are chemical compounds that possess both hydrophilic (water-attracting) and lipophilic (fat-attracting) properties (Sar et al., 2019). This allows surfactants to reduce surface tension between liquids or between liquids and solid surfaces, thereby facilitating processes such as cleaning, emulsification, and dissolving greasy substances. Essentially, any compound with both hydrophilic and lipophilic functional groups can act as a surfactant (Rosen and Kunjappu, 2012). Important physicochemical properties of surfactants include: critical micelle concentration (CMC), good solubility in water, Krafft point and temperature, surface tension, interfacial adsorption, phase behavior, emulsifying capacity, calcium tolerance, and dispersibility (Tripathy et al., 2018).

The fluid mechanics of the cleaning process have been thoroughly discussed by Landel and Wilson (2021). The authors noted, among other points, that cleaning efficiency is strongly related to the dynamics of detergent wetting on different substrates. Avila-Sierra et al. (2019) described a method for measuring contact angles of various liquids on stainless steel surfaces. They indicated that on hydrophilic surfaces like stainless steel, the contact angle decreases with an increase in wall temperature. The highest contact angle was observed on surfaces exhibiting the lowest surface roughness, with contact angle values decreasing progressively as the surface roughness increased. In general, minor changes in roughness have a negligible effect on the contact angle. However, for liquids with high surface tension, such as water, the equilibrium contact angle (ECA) changes significantly, influencing wettability. Thus, wettability is enhanced by increasing both temperature and surface roughness for all tested liquids. There are models that allow prediction of the ECA based on surface tension.

Cleaning quality can be assessed by various methods. Escrig et al. (2020) evaluated cleaning efficiency using a camera and ultrasonic measurements. The method is based on the analysis of ultrasonic waves reflected from the surface. The presence of contamination changes the acoustic impedance at material boundaries, affecting the reflected wave's energy. Fan et al. (2023) used the BCA (Bicinchoninic Acid Assay) test to assess the initial and residual protein on surfaces before and after cleaning. Vijayasarathi et al. (2021) analysed the cleaning process based on variations in Reynolds number, shear stress, and flow velocity. They used fluorescence spectroscopy to measure cleaning efficiency.

Cleaning efficiency can be analysed by calculating indicators describing various aspects of the cleaning process. Examples of such indicators include: a time index, defining the mass of removed contamination per unit of time; a fluid consumption index, calculated as the mass of removed residue per unit volume of used fluid; an energy index, defined as the mass of removed residue per unit of energy used during cleaning; and a cost index, relating the mass of removed residue to the total process cost (Köhler et al., 2015).

In many cases, cleaning process parameters are not optimally adjusted to the specific type of contamination, leading to excessive use of water, chemicals, energy, and time. Therefore, understanding the individual physicochemical properties of contamination is essential to ensure environmentally friendly cleaning (Fryer and Asteriadou, 2009; Herrera-Márquez et al., 2020; Agüeria et al., 2020). To optimize the cleaning process, various models are developed that describe this process while accounting for contamination characteristics and cleaning fluid parameters.

In surface cleaning simulations, knowing the specific cleaning mechanism is essential for selecting the correct cleaning model (Golla et al., 2023). Golla, Boddin, et al. (2024) presented a method using FCN neural networks for automatic analysis of cleaning mechanisms on surfaces covered with thin layers of contamination. Golla, Köhler, et al. (2024) developed a numerical model to predict the time required to remove thin contamination layers.

Deshmukh et al. (2022) conducted a CFD simulation to investigate how different cleaning mechanisms work for two types of contaminants. They studied how fluid flow and shear stress affect erosion of contaminants. Köhler et al. (2021) proposed a model for predicting the cleaning time of adhesively bonded residues in industrial processes, which also considers fluid flow and detergent viscosity. The effects of temperature, shear stress, and concentration on cleaning efficiency were also studied by Fan et al. (2023). The authors demonstrated that higher shear stress significantly improves the removal of protein deposits. They indicated that activation energy value is a measure of the cleaning reaction's sensitivity to temperature. They also determined critical values of shear stress and temperature, beyond which further increases do not significantly enhance cleaning efficiency. The results of the CFD simulation were compared with experimental results obtained in laboratory studies. A good agreement between experimental and simulated data confirmed the reliability of the numerical approach. It should be noted that, in industrial applications, fluid dynamics simulations must account for acceptable computational effort, which often comes at the cost of accuracy (Köhler et al., 2022). In practical applications, developing new cleaning procedures can yield tangible benefits. Mauermann et al. (2024) presented a case study of cleaning a dairy tank. A tailored and improved cleaning procedure, supported by cleaning simulations, reduced cleaning time by 32%, fluid flow from 130 $l \cdot min^{-1}$ to 55 $l \cdot min^{-1}$, and energy consumption by approx. 227 MJ per cycle, without compromising cleaning efficiency.

The above-mentioned studies identified various factors influencing the course of the cleaning and degreasing process. Among them, the role of detergent concentration, temperature, and shear stress was emphasized. It was also pointed out that cleaning efficiency depends not only on the individual values of these parameters but also on their synergy. To optimize the cleaning process, different models are developed that describe it, taking into account various detergent parameters. Based on these models, simulations are conducted to determine the optimal values of individual process parameters for achieving the highest cleaning efficiency. Selecting optimal process parameters based on simulations increases cleaning efficiency and reduces resource consumption, such as energy and chemicals. The aim of this study was to determine the effect of concentration and temperature of selected cleaning fluids on changes in their physical properties such as: viscosity, shear stress, density, activation energy, and wettability. The characteristics of the cleaning fluids presented in this article can serve as input data for cleaning process simulation models as well as validation data for those models).

Materials and Methods

Four industrial cleaning agents manufactured by Noyen were tested. The technical specifications of the tested agents are presented in Table 1. This table was compiled by the authors based on the technical data sheets provided by the manufacturer.

Rheological properties of the fluids were determined using a rotational viscometer from Brookfield Engineering Laboratories: model LVDV-II+PRO with UL adapter (ultra-low viscosity). Viscosity measurements were performed for concentrated agents and for their aqueous solutions at 10% concentration. The viscosity tests were carried out at rotational speeds ranging from 10 to 60 min^{-1}, and at six temperature levels: 10°C, 20°C, 30°C, 40°C, 50°C, and 60°C. A Brookfield TC-502 temperature control bath was used to stabilize the temperature during the measurements. Data acquisition and viscometer control were managed using the Rheocal V3.1 software. Spindle rotation speeds were automatically adjusted in 10 min^{-1} increments using a custom-written testing procedure in the software.

Table 1.
Specification of the tested cleaning agents

Product name	Working concentration (%)	Washing temperature range (°C)	Cleaning methods used	Application	Specific use
PAL+	1.5-10	15-70	- manual - immersion - ultrasonic - spray	- steel - cast iron - non-ferrous metals	
LF	3-100	15-55	- manual, - immersion - ultrasonic	- copper - copper alloys	
DB	2-20	20-60	- manual - immersion - ultrasonic - spray	- steel - cast iron	for cleaning difficult industrial contaminants
TIP2	2-20	25-80	- manual - immersion - ultrasonic - spray	- steel - cast iron - aluminium	for removing carbon deposits

The densities of the liquids were determined using a pycnometer with a capillary tube (class "A", volume: 25 mL) and a balance with an accuracy of 0.001 g, by dividing the mass of the liquid (the difference between the mass of the filled and empty pycnometer) by the known volume of the pycnometer, at a temperature of 20°C.

Surface tension and wettability were determined using the DSA30 goniometer from KRÜSS. Surface tension measurements were carried out using the pendant drop method, with at least 30 repetitions for each fluid. The drop volumes used were: 10 µL for PAL+, LF, and TIP2; 5 microliters for DB (Krawczuk et al., 2024).

Contact angle measurements were performed on flat samples of carbon steel, stainless steel, galvanized steel, and brass. To evaluate whether wettability on a specific metal surface differed significantly among the tested cleaning fluids, contact angles of 10% aqueous solutions were analysed using one-way analysis of variance (ANOVA). The significance of differences between mean values was assessed with Tukey's HSD test at a significance level of $\alpha = 0.05$. Statistical analyses were conducted using Statistica 13 software (StatSoft Inc., Tulsa, OK, USA).

Activation energy was determined using the Arrhenius equation:

$$\eta = A \cdot e^{\frac{E_a}{RT}} \quad (1)$$

where:

- η – viscosity, (Pa·s)
- A – pre-exponential factor, (Pa·s)
- E_a – activation energy, ($J \cdot mol^{-1}$)
- R – universal gas constant, (8.314 $J \cdot mol^{-1} \cdot K^{-1}$)
- T – temperature, (K)

This equation was transformed into its linear form:

$$ln(\eta) = ln(A) + \frac{E_a}{R} \cdot \frac{1}{T} \quad (2)$$

Based on the measured values of viscosity at different temperatures, a plot of ln(η) versus 1/T was created. A linear regression was fitted to the experimental data using the least squares method. The slope of the obtained line (m) corresponds to the expression E_a/R. The activation energy was calculated from the equation $E_a = m \cdot R$. The results were expressed in $kJ \cdot mol^{-1}$, with units converted from $J \cdot mol^{-1}$.

Results and Discussion

The experimental results obtained from the measurements carried out are presented below. Figure 1 shows the viscosity curves of the concentrated PAL+ cleaning agent.

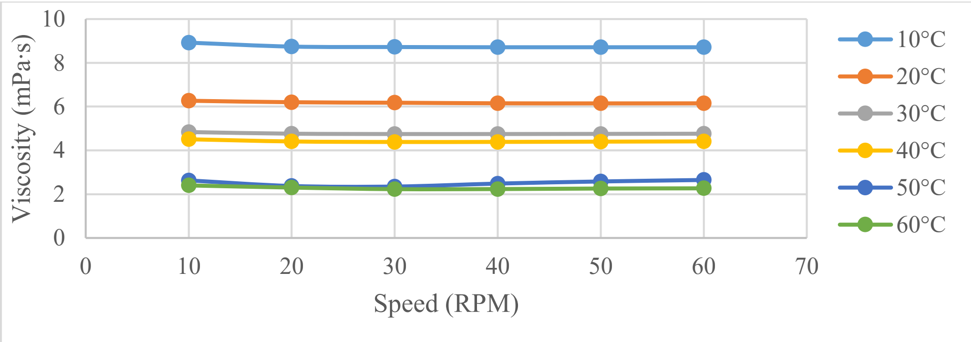

Figure 1. Viscosity curves of the concentrated PAL+ agent

The figure above shows that the viscosity of the agent, measured at various temperatures, remains constant regardless of the shear rate. This is a characteristic of Newtonian fluids.

Figure 2 presents the flow curves of the concentrated PAL+ agent.

The graph below shows that the shear stress increases linearly with increasing shear rate, and the flow lines pass through the origin of the coordinate system, which is also characteristic of Newtonian fluids.

Next, viscosity and flow curves were determined for a 10% aqueous solution of this agent. For the diluted fluid, the viscosity and flow curves maintained the shape characteristic of the concentrated agent, indicating that after dilution, the fluid still behaves as a Newtonian fluid.

Similarly, viscosity and flow curves were determined for the other three cleaning agents. Based on these results, it was concluded that all tested fluids (PAL+, LF, DB, TIP2) exhibit Newtonian behaviour.

The viscosity of the tested cleaning agents decreases with increasing temperature, which is typical for most Newtonian fluids. The graph shows that for DB and LF, there is a significantly greater variation in viscosity with temperature compared to the other two agents.

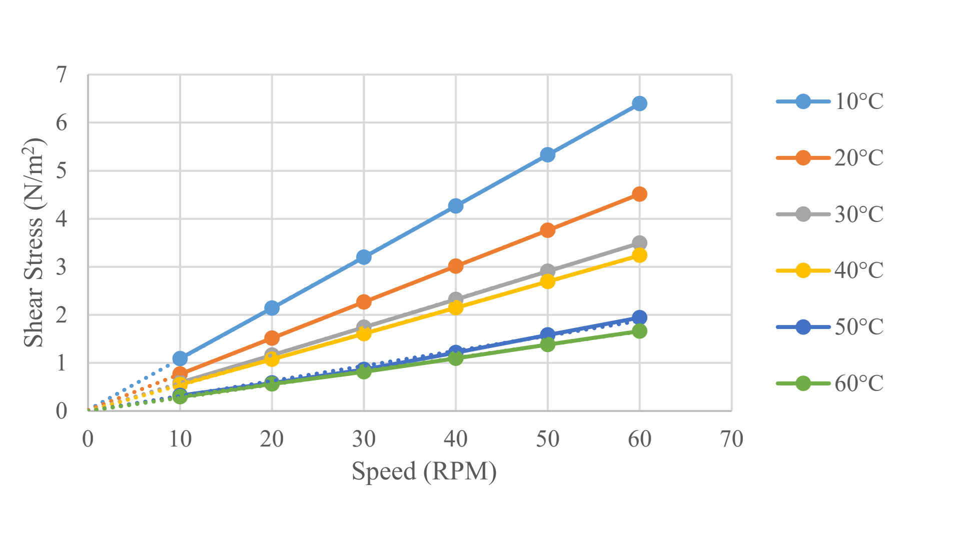

Figure 2. Flow curves of the concentrated PAL+ agent

Figure 3 shows the effect of temperature on the viscosity of the concentrated agents.

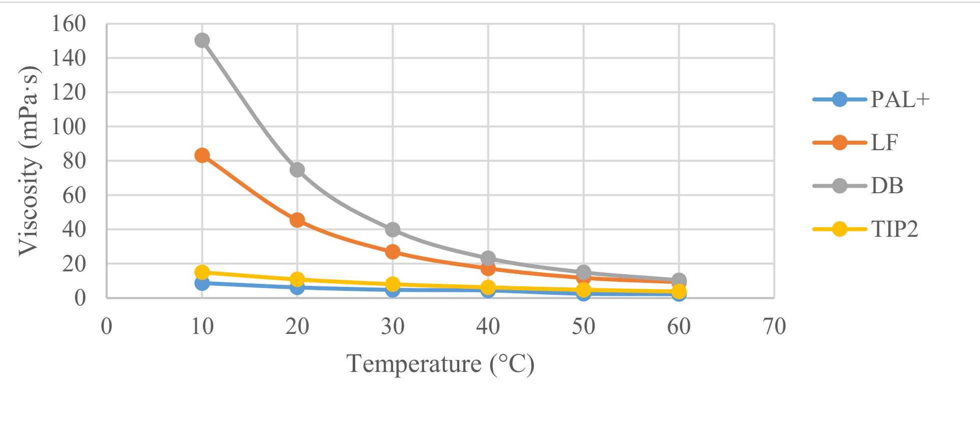

Figure 3. Effect of temperature on the viscosity of concentrated agents

Figure 4 presents the effect of temperature on the viscosity of the tested cleaning fluids at a 10% concentration. Dilution of the fluids resulted in a decrease in viscosity and altered the nature of the relationship between temperature and viscosity. After dilution, fluid TIP2 was the most sensitive to temperature changes. The curvature changes in such graphs may indicate phase transitions or structural changes within the fluid. The region where fluid viscosity stabilizes may suggest the optimal temperature range for effective cleaning action.

The slope of the viscosity curve in the Arrhenius system (logarithm of viscosity versus inverse temperature) allowed for the determination of the activation energy of fluid flow, which is a measure of the sensitivity of viscosity to temperature changes. Table 2 presents the calculated activation energy values for the concentrated agents.

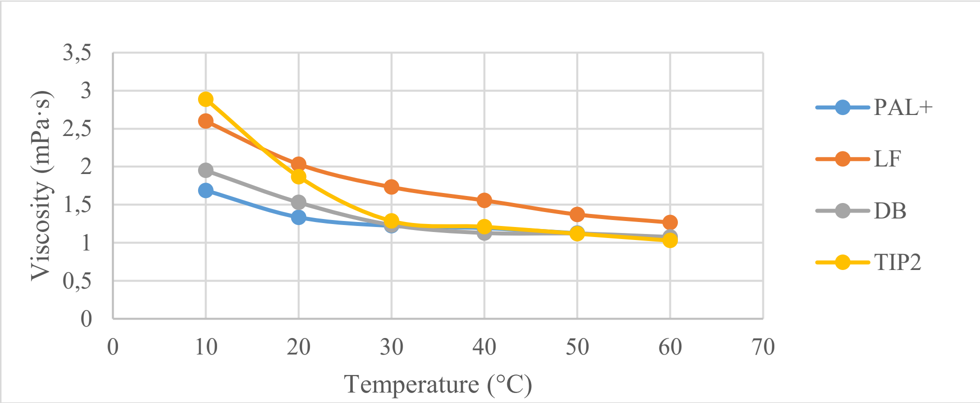

Figure 4. Effect of temperature on the viscosity of 10% solutions

Table 2.
Calculated activation energy values for concentrated agents

Agent	ln A	A	E_a/R	E ($kJ \cdot mol^{-1}$)
PAL+	-13.774	$1.04 \cdot 10^{-3}$	2559.2	21.28
LF	-17.378	$2.84 \cdot 10^{-5}$	4193.0	34.86
DB	-19.878	$2.33 \cdot 10^{-6}$	5070.3	42.15
TIP2	-13.315	$1.65 \cdot 10^{-3}$	2578.1	21.43

Table 3 presents the calculated activation energy values for the diluted agents at 10% concentration.

Table 3.
Calculated activation energy values for 10% solutions

Fluid	ln A	A	E_a/R	E ($kJ \cdot mol^{-1}$)
PAL+	-9.2922	$9.21 \cdot 10^{-5}$	801.6	6.66
LF	-10.686	$2.29 \cdot 10^{-5}$	1324.8	11.01
DB	-9.9222	$4.91 \cdot 10^{-5}$	1009.0	8.39
TIP2	-12.57	$3.47 \cdot 10^{-6}$	1855.7	15.43

After diluting the agents to a 10% concentration, the highest activation energy was observed for TIP2, which is used for removing carbon deposits. A higher activation energy may suggest that the required cleaning bath temperature for TIP2 should be higher.

Table 4 presents the results of density and surface tension measurements for the concentrated agents at 20°C.

The surface tension of water under standard conditions (20°C, 1013 hPa) is approximately 72.8 $mN \cdot m^{-1}$. The addition of cleaning agents significantly reduced this surface tension. Lower surface tension generally improves substrate wettability, which translates into better contaminant removal.

Table 4.
Density and surface tension measurements for concentrated agents

Agent 20°C	Density ($kg \cdot m^{-3}$)	Surface tension ($mN \cdot m^{-1}$)
PAL+	1033.5	28.91±1.09
LF	1036.1	24.66±1.03
DB	1397.5	23.17±1.45
TIP2	1076.6	22.73±1.09

Table 5 presents the results of density and surface tension measurements for the 10% solutions of the tested agents.

Table 5.
Density and surface tension measurements for 10% solutions

Fluid 20°C	Density ($kg \cdot m^{-3}$)	Surface tension ($mN \cdot m^{-1}$)
PAL+	999.0	39.45±1.05
LF	998.5	37.33±1.03
DB	1048.8	36.58±1.09
TIP2	1004.2	36.36±1.02

Analysis of variance of the measured contact angle values showed statistically significant differences in the wettability of the tested fluids on various metals. The results of the Tukey post hoc test are presented in Figures 5A–D.

In all cases presented, the contact angle was below 55°, indicating good wettability properties of all tested cleaning fluids. Tukey's test results showed that for carbon steel, there were no statistically significant differences in wettability between the PAL+ and LF fluids, or between the DB and TIP2 fluids. However, the DB and TIP2 fluids exhibited better wettability. For stainless steel, no statistically significant differences in wettability were found among the tested fluids. For galvanized steel, PAL+ showed poorer wettability compared to the other fluids, while no significant differences in wettability were observed among the LF, DB, and TIP2 fluids. In the case of brass, a statistically significant difference in wettability was found only between PAL+ and the DB and TIP2 fluids

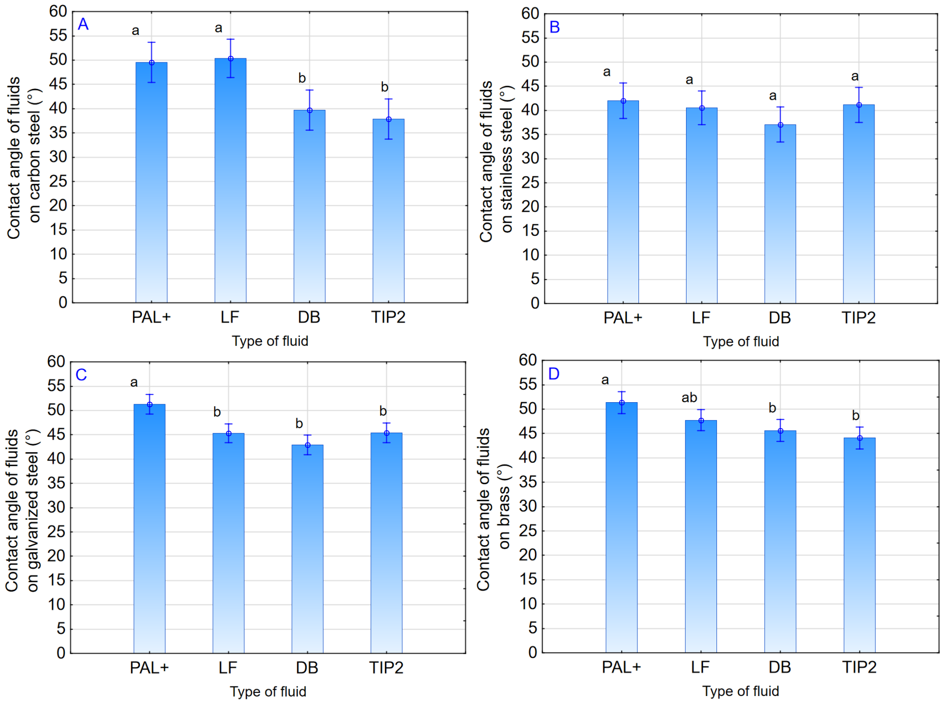

Figure 5. Wettability of 10% cleaning solutions on selected metal surfaces. The vertical bars represent mean contact angles and the whiskers denote 95% confidence intervals from Tukey's HSD test

Conclusions

The tested cleaning fluids exhibited Newtonian behaviour. Changes in fluid concentration did not affect their rheological character, which simplifies the modelling of their behaviour in technological processes.

The viscosity of all fluids decreases with increasing temperature, with the concentrated DB and LF agents showing greater sensitivity to temperature changes than PAL+ and TIP2. A change in fluid concentration caused a decrease in viscosity and affected the nature of the relationship between temperature and viscosity. After dilution, the TIP2 fluid showed the greatest sensitivity to temperature changes.

Among the 10% aqueous solutions of the examined cleaning agents, the lowest activation energy was observed for PAL+ (6.66 $kJ \cdot mol^{-1}$), whereas the highest was recorded for TIP2 (15.43 $kJ \cdot mol^{-1}$). The higher activation energy of TIP2 may suggest that a higher bath temperature may be required during the cleaning process compared to the other fluids.

The surface tension values of the concentrated agents ranged from 22.73 $mN \cdot m^{-1}$ for TIP2 to 28.91 $mN \cdot m^{-1}$ for PAL+. All tested fluids exhibited good wettability (contact angle < 55°), although wettability strongly depends on the type of surface and the specific agent. DB and

TIP2 fluids demonstrated excellent wettability across the tested materials, which is consistent with the manufacturer's information indicating that these products are intended for cleaning heavy contaminants and removing carbon deposits.

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BADANIE WŁAŚCIWOŚCI FIZYCZNYCH CIECZY DO USUWANIA ZANIECZYSZCZEŃ PRZEMYSŁOWYCH

Streszczenie. Celem badania było określenie wpływu stężenia i temperatury na właściwości fizyczne wybranych przemysłowych cieczy czyszczących, a zwłaszcza parametrów istotnych dla procesu czyszczenia: lepkości, naprężenia ścinającego, gęstości, energii aktywacji oraz zwilżalności. Zbadano cztery środki czyszczące firmy Noyen – zarówno produkty skoncentrowane, jak i ich 10% roztwory wodne. Właściwości reologiczne cieczy oceniono za pomocą wiskozymetru rotacyjnego; gęstość mierzono piknometrem; napięcie powierzchniowe i zwilżalność określono przy użyciu goniometru; energię aktywacji wyznaczono na podstawie równania Arrheniusa. Wyniki badań lepkości i naprężenia ścinającego wykazały, że wszystkie testowane ciecze przejawiają zachowanie cieczy newtonowskiej zarówno w formie skoncentrowanej, jak i rozcieńczonej. Analiza napięcia powierzchniowego i zwilżalności potwierdziła dobre właściwości zwilżające wszystkich badanych cieczy (kąt zwilżania < 55°), choć zaobserwowano istotne różnice w zwilżalności w zależności od rodzaju powierzchni i zastosowanej cieczy.

Słowa kluczowe: środki czyszczące, właściwości reologiczne, lepkość, zwilżalność, napięcie powierzchniowe