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A METHOD OF OPTIMIZING THE RAPESEED OIL TRANSPORTATION COSTS IN BIOFUEL PRODUCTION INSTALLATIONS

METODA OPTYMALIZACJI KOSZTÓW TRANSPORTU OLEJU RZEPAKOWEGO W INSTALACJACH DO PRODUKCJI BIOPALIW

Summary

Background. Rapeseed oil is the main source of production biofuels in the Polish climatic conditions. This oil in the raw state has a high kinematic viscosity, much higher than the esters derived from it RME. Such a property rapeseed oil generates additional costs during its transport in industrial hydraulic systems. The goal of study was to develop a technology to reduce the viscosity of rapeseed oil by heating it before further pumping between the tanks.

Material and methods. The research was raw rapeseed oil prior to transesterification. The simulation tests in the laboratory were performed on a specially designed test bench for testing the properties of a viscous liquid having a volume of 5 liter tank. The oil is heated heater at 5°C temperature range 20÷80°C and determined the cost of its heating HC, the costs of pumping PC, making up the total cost of transport TC. Then the analytical method and graphical establish optimum temperature rapeseed oil during transport in pipelines.

Results. Heating the fresh rapeseed oil temperature from 20°C to 80°C causes a significant reduction in the kinematic viscosity from 62 to 10 $mm^2 \cdot s^{-1}$. In this temperature range, the cost of oil heating grow faster than the benefits of a lower load the electric motor driving the pump.

Conclusions. In the case of small volumes of liquid heating method proposed rapeseed oil preparation tank in order to reduce its viscosity without any recognizable economic benefits. Mathematical analysis showed that the total costs were the smallest in the lower temperature range studied (here T_o = 20°C). Yet, the method can become profitable for large flows and low temperatures of hydraulic installations operation e.g. in the winter season when a oil puts up a meaningful resistance of flow. This requires further research conducted on an industrial scale.

Key words: biofuels, rapeseed oil, kinematic viscosity, transportation costs, heating costs, pumping costs, optimization

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Introduction

One of alternative engine fuels in relation to fossil fuels is rapeseed biodiesel (Canakci and Van Gerpen, 2001; Dobrucali, 2013; Ramadhas et al., 2004; Recep et al., 2001; Reksa, 2001). Rapeseed methyl esters RME show properties close to those of diesel oil. Such parameters as: molecular mass, density, or cetane number (Table 1), show similar values. Kinematic viscosity is higher (nearly twice), while the net calorific value, as well as sulfur content are lower (Agarwal and Das, 2001; Jóźwiak and Szlęk, 2006; Książ et al., 2001).

Table 1. Comparison of the physiochemical parameters of RME fuel to ON diesel and OR rapeseed oils
Tabela 1. Porównanie parametrów fizykochemicznych paliwa RME z olejem napędowym ON i olejem rzepakowym OR

Parameter Parametr	Unit Jednostka	RME	ON	OR
Molecular mass Masa cząsteczkowa	$g \cdot mol^{-1}$	300	120÷320	900
Density at 20°C Gęstość w 20°C	$g \cdot cm^{-3}$	0.88	0.83	0.92
Cetane number Liczba cetanowa	–	45÷59	47÷58	40÷44
Kinematic viscosity v at 20°C Lepkość kinematyczna v w 20°C	$mm^2 \cdot s^{-1}$	6.9÷8.2	4.2	75.0
Calorific value Wartość opałowa	$MJ \cdot kg^{-1}$	37÷39	42÷43	37
Sulfur content Zawartość siarki	%	0.002÷0.006	0.280	0.009÷0.012

To obtain the fuel characteristics of rapeseed oil approaching the ones of motive oil some modification of the first one needs to be carried out. It can be achieved via e.g. transesterification (Mochacki, 2002). The process conducted in the industrial practice most frequently takes place at the temperature of 60÷70°C in the presence of the base catalyst. It is the so-called „cold" technology, contrasted to the „hot" one, in which reactions run at 240°C and the pressure of approx. 10 MPa.

However, the chemical and logistic processes, indispensable at the production stage, are expensive and make the technological process lowly competitive compared to the traditional refineries operation. Heating fresh rapeseed oil before its transesterification, to decrease its high viscosity ($\nu = 75\ mm^2 \cdot s^{-1}$), and at the same time, the forcing through resistance, can be a method of lowering the costs.

The target of the paper was developing a method of diminishing the transportation costs of viscid liquids in hydraulic installations. The tested liquid is fresh rapeseed oil before the process of transesterification.

Material and methods

The presented methodology results from the hypothesis assuming that decreasing the rapeseed oil viscosity by heating it up to a given temperature may lower the total costs of the process of forcing through between the primary and final tanks where the esterification process takes place. Assuming that both heating and forcing-through hydraulic pump drive are electricity-driven, profits resulting from a lower engine pump duty, in the process of liquid heating, can be defined. The costs of liquid heating also have to be taken into account in the general energetic balance.

The methodology of economic decision-making according to Solek (2008) was applied to the task defined in the described manner. The method of defining the optimum level of activity (temperature T in this case) guaranteeing reaching the set aim, i.e. minimizing the total costs TC, consists in:

1. Determining the function of heating costs of oil: HC = $f(T)$.
2. Determining the function of forcing pumping/transportation costs of oil: PC = $g(T)$.
3. Determining the function of total costs TC = $h(T)$ as a sum of HC and PC costs for a given T (TC = HC + PC).
4. Determining the minimum of TC function i.e. optimum temperature T_o:
   – necessary condition for the existence of the minimum function:
   $$TC' = 0$$
   – sufficient condition for the existence of the minimum function:
   $$TC'' > 0.$$

Empirical studies are indispensable to determine functions HC and PC (points 1 and 2 of the methodology). A measurement stand for the purpose was designed and constructed within the framework of a B.Sc. thesis (Szatkowska, 2015). The stand was tailored to the needs of testing of the hydraulic liquids physical properties such as: kinematic viscosity and density in relation to temperature and pressure changes (Fig. 1).

It consists of two tanks *1* and *2* of 5 l capacity each, a hydraulic pump *3*, manometer *4,* as well as throttle-non-return *5* and cut-off *6* valves. The primary tank *1* is equipped with an extra electric heater *7* having an option to precisely set a demanded oil temperature using the thermostat (Fig. 2). Additionally, the temperature of heated oil was checked with an optical pyrometer (Fig. 3). The measurement of the kinematic viscosity was conducted applying the Pinkiewicz's viscosimeter (Fig. 4) having the constant of capillary $K = 0.1441\ mm^2 \cdot s^{-2}$. The hydraulic pump drive is carried out by a belt transmission applying an electric motor (engine) having the following parameters: $U = 400$ V, $\eta = 0.85$ and $\cos\varphi = 0.74$.

The empirical costs of oil heating hc, of V volume from the initial temperature T_1 to temperature T_i was determined from the dependence:

$$hc_{V,T_i} = P \cdot t_{T_1\text{-}T_i} \cdot ep \text{ (PLN)} \qquad (1)$$

where:

P – electric heater power (W)
$t_{T_1\text{-}T_i}$ – heating time of oil from T_1 to T_i (s)
ep – price of electricity ($PLN \cdot kWh^{-1}$).

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Fig. 1. Stand for measuring the characteristics of viscid liquids
Rys. 1. Stanowisko pomiarowe do badania właściwości cieczy lepkich

Fig. 2. Electronic oil temperature controlling system
Rys. 2. Elektroniczny układ sterowania temperaturą oleju

Whereas for the purpose of determining the empirical transportation costs of oil *pc* of *V* volume and temperature *T*, the below formula was used:

$$pc_{V,T} = 1.73U \cdot I_T \cdot \eta \cdot \cos\varphi \cdot t \cdot ep \text{ (PLN)} \tag{2}$$

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Fig. 3. Temperature and electric motor power measurement devices: *1* – IR Thermometer INI-T UT350A of measuring range –50÷1050°C, *2* – digital multimeter V&A VA18B
Rys. 3. Przyrządy pomiarowe wykorzystane do pomiaru temperatury oraz mocy silnika elektrycznego: *1* – IR Thermometer INI-T UT350A o zakresie pomiarowym –50÷1050°C, *2* – multimetr cyfrowy V&A VA18B

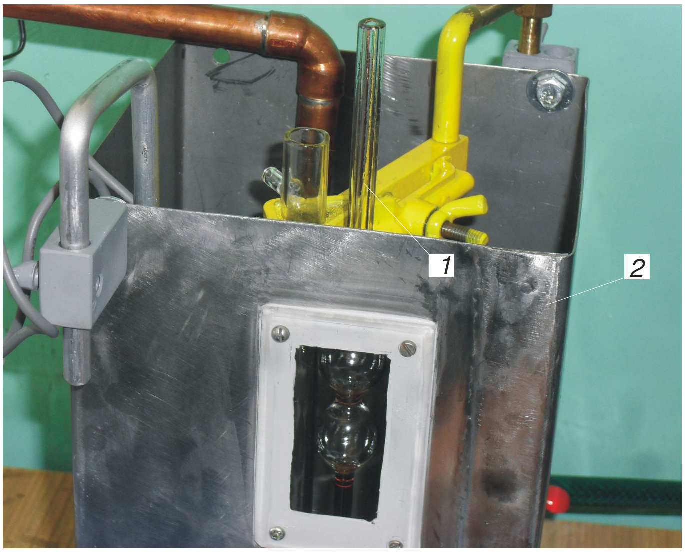

Fig. 4. Pinkiewicz 480 viscosimeter (*1*) produced by LABIT company mounted in the preliminary oil tank of 5 l volume (*2*)
Rys. 4. Lepkościomierz Pinkiewicza 480 firmy LABIT (*1*) zamocowany w zbiorniku wstępnym oleju o objętości 5 l (*2*)

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where:

U – voltage (V)
I_T – current intensity (engine load) during transportation of oil at temperature T (A)
η – efficiency of the electric engine (-)
cosφ – utilization factor of engine horse-power (-)
t – time of oil-flow of volume V (s)
ep – price of electricity (PLN·kWh^{-1}).

Rapeseed oil was heated in the primary tank from the initial temperature T_1 = 20°C (air temperature inside) to temperature T_{13} = 80°C measuring the oil heating time by every 5°C. Formula 1 takes the below presented final form for the assumed range of temperatures and the parameters of the elements of the hydraulic installation, as well as ep = 0.56 PLN·kWh^{-1}:

$$hc_{5,T_i} = 0.00028 \cdot t_{20\text{-}T_i} \text{ (PLN)} \tag{3}$$

while formula 2:

$$pc_{5,T_i} = 0.0174 \cdot I_{T_1} \text{ (PLN)}. \tag{4}$$

Results

Figures 5, 6 and 7 contain the results of both measurements and calculations obtained from the empirical data. Heating fresh rapeseed oil from room temperature of 20°C up to 80°C results in a decrease of its kinematic viscosity from 62 mm^2·s^{-1} to 10 mm^2·s^{-1}, which confirms the first part of the formulated hypothesis. Making use of the analysis of regression, the final forms of the HC and PC functions were obtained (the forms of both functions are given in Fig. 6 and 7), however, the highest value of coefficient of determination R^2 was decisive in the selection of trendline type. The best representation of the empirical data is given in both cases by quadratic polynomials.

It results from Fig. 7 that oil heating above 60°C does not cause a significant decrease of the electric pump motor load any more, and so the PC costs stay stable.

The function of total costs TC, as the sum of the HC and PC costs, receives then the following form:

$$\text{TC} = 0.0083T^2 - 0.1975T + 3.0659. \tag{5}$$

Making use of condition I of the existence of the function extremum (TC' = 0) the optimum temperature T_o was determined:

$$\text{TC}' = 0.0166T - 0.1975$$

that is T_o = 12°C and it is simultaneously the global minimum of function TC.

Condition II (TC" > 0) of the existence of the extremum of the function is met: 0.0166 > 0.

Graphical method delivered similar results (Fig. 8). Intersection of PC' and HC' graphs determines the level of activity for which TC reaches the lowest value. T_o equals also to 12°C in the example.

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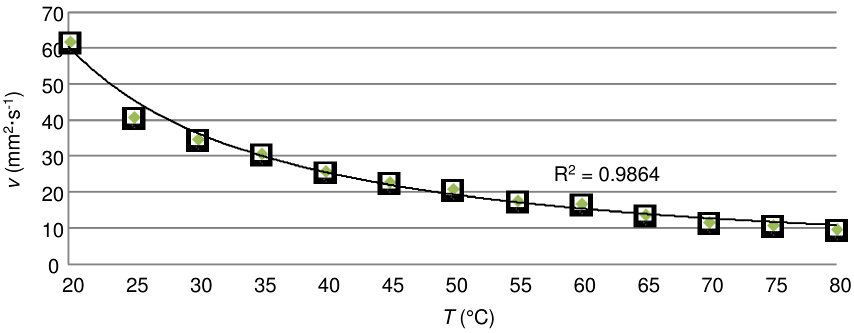

Fig. 5. Dependence of the kinematic viscosity v on the temperature T for the tested rapeseed oil

Rys. 5. Zależność lepkości kinematycznej v od temperatury T dla badanego oleju rzepakowego

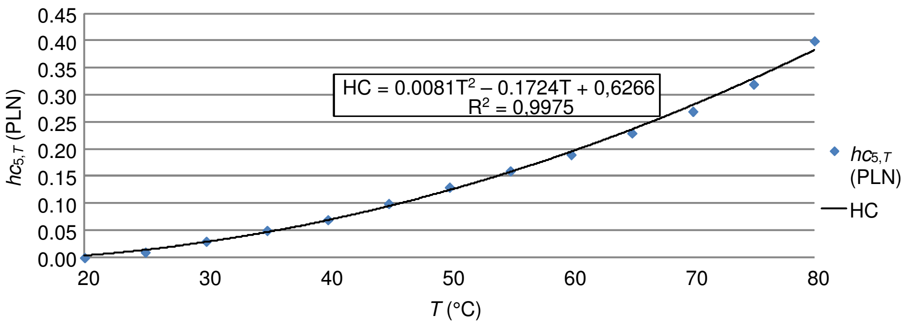

Fig. 6. Dependence of the heating costs hc on the oil temperature T

Rys. 6. Zależność kosztów podgrzewania hc od temperatury oleju T

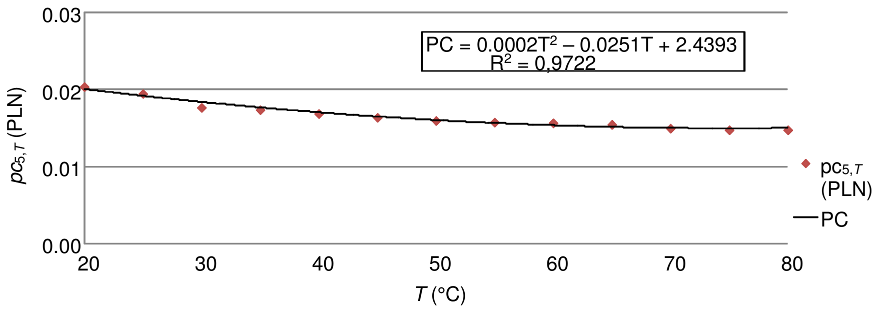

Fig. 7. Dependence of the reimbursement of transportation costs pc on the oil temperature T

Rys. 7. Zależność kosztów transportu pc od temperatury oleju T

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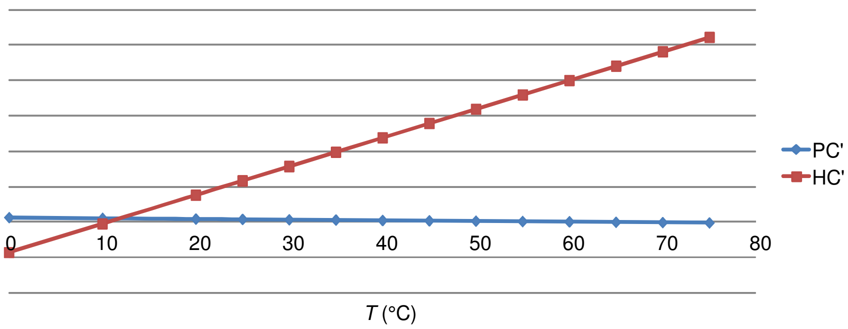

Fig. 8. Graphic technique of the optimum temperature T_o determining; intersection point of curves HC’ i PC’ denotes the optimum temperature (T_o = 12°C) at minimum costs
Rys. 8. Metoda graficzna wyznaczania temperatury optymalnej T_o; punkt przecięcia krzywych HC’ i PC’ wyznacza temperaturę optymalną (T_o = 12°C) przy minimalnych kosztach

Since the graphically and analytically determined optimum temperature is beyond the range of the investigated temperatures (20÷80°C), then finally T_o = 20°C, was accepted which is the so-called local minimum of TC function. The T_o value means that the hypothesis accepted at the beginning should be rejected. Thus, rapeseed oil heating aiming at lowering its viscosity, and at the same time lowering the load of electric pump motor (engine) finds no economical justification in the case which is confirmed by the conducted calculations of two variants of the oil pumping operation between the tanks.

Heating the oil in the primary tank up to 60°C and its transportation generate the total cost, acc. to the dependence (5), TC = 0.21 PLN. Then the transportation of 5 l of oil at 20°C (PC = 0.03 PLN) and heating it up to 60°C in the final tank (HC = 0.19 PLN) cost TC = 0.22 PLN. Thus, both technological variants generate similar costs, and heating the liquid in the primary tank makes the technology more difficult/challenging to carry out.

Conclusions

The discussed original author's method enables to define the optimum temperature of a high viscosity liquid e.g. rapeseed oil, during its transportation in hydraulic installations due to high costs of the technological operations. Rapeseed oil heating by 50°C lowers the kinematic viscosity 5-fold, limiting the transportation costs, yet when small liquid capacities are concerned brings no evident economical profits. The costs of heating the liquid in the primary tank are too high compared to the defined profits, and so the total costs are the lowest in the lower range of the tested temperatures (here 20°C).

The optimization method can be applied if a function is defined (preferably empirically for a given installation) that would take into consideration the total costs, resulting from the initial liquid heating and transportation costs. The necessary condition of determining the minimum of the function of one variable is their continuity and differentiability.

The cost study concerning the expenses on pumping a liquid of high viscosity to a defined locality has to consider e.g. manner of operation/labour (continuous or discontinuous), pump and motive/motor engine parameters, the size of the tank and energy costs. The method can be profitable for low temperatures of installations operations e.g. at winter time when the viscous liquid performs a high resistance of flow.

Additionally, the indispensable condition of the discussed method is the necessity of mounting an oil heater and equipping the system with instruments measuring the power consumption of the electric motor driving the hydraulic pump, which has to be taken into account in the global cost study.

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METODA OPTYMALIZACJI KOSZTÓW TRANSPORTU OLEJU RZEPAKOWEGO W INSTALACJACH DO PRODUKCJI BIOPALIW

Streszczenie

Wstęp. W polskich warunkach klimatycznych głównym surowcem do produkcji biopaliw jest olej rzepakowy. W stanie surowym charakteryzuje się on dużą lepkością kinematyczną, znacznie większą niż uzyskane z niego estry RME. Taka właściwość oleju rzepakowego generuje dodatkowe koszty podczas transportowania go w przemysłowych instalacjach hydraulicznych. Celem

artykułu było opracowanie technologii pozwalającej na zmniejszenie lepkości oleju rzepakowego przez ogrzewanie go przed dalszym przetłaczaniem między zbiornikami.
Materiał i metody. Przedmiotem badań był surowy olej rzepakowy przed transestryfikacją. Badania symulacyjne w warunkach laboratoryjnych przeprowadzono na specjalnie zaprojektowanym stanowisku pomiarowym do badania właściwości cieczy lepkich o objętości zbiornika 5 l. Olej podgrzewano grzałką co 5°C w zakresie temperatur 20÷80°C i określano koszty jego podgrzewania HC oraz koszty przepompowywania PC, składające się na całkowity koszt transportu TC. Następnie metodą analityczną i graficzną wyznaczono optymalną temperaturę oleju rzepakowego podczas transportowania w rurociągach.
Wyniki. Podgrzewanie świeżego oleju rzepakowego od temperatury pokojowej 20°C do 80°C powoduje znaczne zmniejszenie jego lepkości kinematycznej z 62 $mm^2 \cdot s^{-1}$ do 10 $mm^2 \cdot s^{-1}$. W tym zakresie temperatur koszty podgrzewania oleju rosną szybciej niż korzyści wynikające z mniejszego obciążenia silnika elektrycznego napędzającego pompę.
Wnioski. W przypadku małych objętości cieczy zaproponowana metoda podgrzewania oleju rzepakowego w zbiorniku wstępnym w celu zmniejszenia jego lepkości nie przynosi wyraźnych korzyści ekonomicznych. Analiza matematyczna wykazała, że koszty całkowite są najmniejsze w dolnym zakresie badanych temperatur (tutaj T_o = 20°C). Metoda może być jednak opłacalna dla dużych przepływów i niskich temperatur pracy instalacji, np. w okresie zimowym, gdy olej stawia duże opory przepływu. Wymaga to dalszych badań na skalę przemysłową.

Słowa kluczowe: biopaliwa, olej rzepakowy, lepkość kinematyczna, koszty transportu, koszty podgrzewania, koszty przepompowywania, optymalizacja

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