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# Quench Severity and Kinetics of Wetting of Vegetable Oil Blends and Nanofluid for Heat Treatment

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Original scienfic paper

In the present work, investigation was carried out to study the suitability of vegetable oil blends with mineral oil and alumina based nanofluids as quench media for heat treatment. Palm oil, sunflower oil, gingili oil were blended with mineral oil in the ratio of 2:1, 3:1, 1:1, 1:2, and 1:3... Heat transfer coefficients were determined using a lumped heat capacitance model. A dynamic contact angle analyzer was used for determination of dynamic and static contact angle of the droplet on the substrate. The wetting behaviour of oils and their blends was modelled by a power law of the type: $\theta = kt^n$. Wettability of nanofluids was found to be poor.

**Intenzitet kaljenja i kinetika vlaženja biljnog ulja i nanofluida za toplinsku obradu**

Izvornoznanstveni članak

U ovom radu istraživalo se prikladnost mješavine biljnih i mineralnih ulja s nanofluidima na bazi aluminija kao sredstva za kaljenje. Palmino ulje, suncokretovo i sezamovo ulje izmiješani su s mineralnim uljem u omjerima 2:1, 3:1, 1:1, 1:2 i 1:3. Koeficijenti provođenja topline su određeni korištenjem modela sumarnog toplinskog kapaciteta. Analizator dinamičkog dodirnog kuta korišten je za određivanje dinamičkog i statičkog kontaktnog kuta kapljice na podlozi. Vlaženje ulja i njihovi mješavina modelirano je zakonom snage tipa $\theta = kt^n$. Otkriveno je da je vlažnost nanofluida slaba.

## 1. Introduction

The selection of a quench medium depends on the hardenability of the particular alloy, the section thickness and shape involved and the cooling rates needed to achieve the desired microstructure. The basic function of a quench medium is to control the rate of heat transfer from the surface of the part being quenched [1]. As an alternative to mineral oil generally used for quenching, vegetable oils are used as quench media. They are cheap, abundantly available, biodegradable and environment friendly [2]. However they have poor oxidation properties and their performance as a quench medium can be enhanced by using suitable antioxidants. The present investigation was carried out with the objective of assessment of wetting behaviour and severity of quenching of vegetable oils and their blends.

## 2. Experimental details

For wetting studies, the experimental set up consisted of a dynamic contact analyzer (Model: FTA 200 First Ten Ångstroms, Virginia, USA). The surface texture of copper substrate (Ra = 0,33 μm) was similar to the copper probe (Ra = 0,34 μm) used for estimation of heat transfer coefficients. Captured images were analyzed using FTA image analysis software to determine the contact angle. For determination of severity of quenching, the experimental set-up consisted of a vertical tubular electric resistance furnace open at both ends. For assessment of quench severity, a quench probe was prepared from EC grade copper. The probe was instrumented with a calibrated K-type thermocouple of 0,45 mm diameter enclosed in a ceramic sheath of 3 mm diameter. The thermocouple was inserted in a hole of diameter 3mm drilled on the top surface of the probe and care was taken to ensure tight fit and good contact condition. The thermocouple junction was exposed and is in direct contact with the probe for quick response. The other end of the thermocouple was connected to a PC based temperature data acquisition system (NI SCXI 1000). The probe was heated to 850 °C in an electric resistance furnace and was immediately transferred to a beaker containing 2000 ml of quench medium. Mineral oil (Indian Oil Corporation - Servoquench11), sunflower oil, palm oil, gingili oil and various blends of mineral oil with vegetable oil (3:1, 2:1, 1:1,1:2,1:3) and alumina based nanofluids were used as quench media.

**Symbols/Oznake**

| | | | |
|---|---|---|---|
| $k$ | - kinetic power law constant<br>- konstanta kinematske eksponencijalne funkcije | $T$ | - time<br>- vrijeme |
| $n$ | - kinetic power law exponent<br>- eksponent kinematske eksponencijalne funkcije | $\theta$ | - dynamic contact angle<br>- dinamički dodirni kut |
| $R_a$ | - surface roughness<br>- površinska hrapavost | | |

## 3. Results and discussion

### 3.1. Wetting behaviour

Wettability can be characterized by the degree and the rate of wetting. The degree of wetting indicates the extent to which the liquid wets the surface and is generally quantified in terms of contact angle ($\theta$) formed at the three phase interface. To investigate the effect of wetting of the probe by quench medium, the contact angle of quench medium on a copper plate substrate was measured. The surface roughness of the substrate (Ra=0,33 μm) is maintained similar to that of the probe material (Ra=0,34 μm) used for quenching. Figure 1 shows a typical plot of relaxation of contact angle of a quench medium on copper substrate. For all quench media, rapid spreading was observed in the early stages and the spreading rate diminished at later stages. Sunflower oil showed lower equilibrium contact angle (15,6 °) indicating good wettability with the substrate. Among the blends, a blend of gingili with mineral oil (2:1) and blend of sunflower oil with mineral oil (3:1) showed lower contact angle (11,6 ° and 9,08 ° respectively) indicating good wettability with the substrate. The spreading behaviour of various oils and their blends on a substrate consists of different stages, namely, capillary, gravity and viscous regimes.

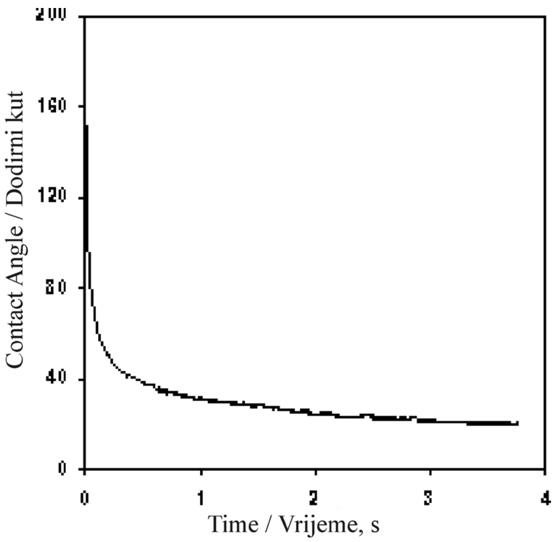



**Figure 1.** Relaxation of contact angle for the blend of mineral oil and gingili oil (1:3)

**Slika 1.** Smanjenje dodirnog kuta smjese mineralnog i sezamovog ulja (1:3)

Capillary force is the dominating factor during the initial stages of the spreading of liquid and this initial stage is called capillary regime. Capillary action is the ability of a substance to draw a liquid against the force of gravity. It occurs when the adhesive intermolecular forces between the liquid and solid are stronger than the cohesive intermolecular forces within the liquid. Gravitational force is the deciding factor in a gravity regime. Viscous force is the dominating force, to stem the flow of liquid due to intermolecular resistance in viscous regime [3]. According to Cazabat et al. different regimes could be identified from the value of the exponent in their behaviour quantified by the relation $R \propto t^n$. The values of 'n' were 1/10 and 1/8 in capillary and gravity regimes, respectively, in their experiments of spreading silicone oil on hydrophilic glass substrates [4]. However, the values of exponent obtained in the present investigation could not be used to differentiate the occurrence of capillary and gravity regimes. On the other hand, the change of slope in the ln (D) versus ln (t) plot could be conveniently used to distinguish the various regimes. Figure 2 shows the spreading regimes of oil. However, an initial capillary regime could not be identified clearly in number of cases and the viscous regime has yet to evolve in the relaxation of some oils and their blends.

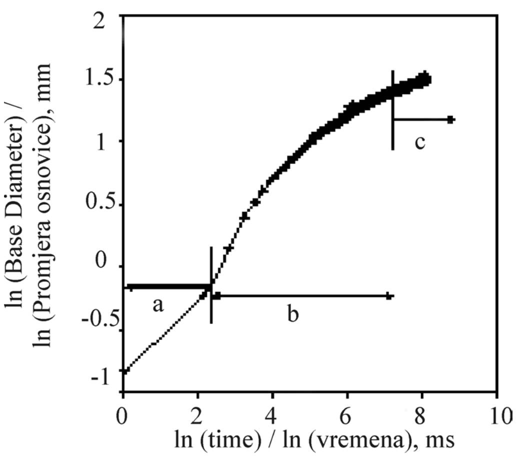



**Figure 2.** Spreading of vegetable oil showing (a) capillary (b) gravity (c) viscous regimes

**Slika 2.** Širenje biljnog ulja u (a) kapilarnom režimu, (b) gravitacijskom i (c) viskoznom režimu

It is seen that mineral oil when compared to other oils has almost reached the viscous regime. This can be attributed to the high viscosity of mineral oil (8,9 x $10^{-3}$ $m^2/s$). Viscous forces dominated in the spreading of mineral oil compared to that of sunflower oil whose contact angle relaxation was not yet complete. Sunflower oil has low viscosity (4,5 x $10^{-3}$ $m^2/s$) and therefore longer periods of time are generally required to achieve equilibrium during spreading. Figure 3 shows photographs of drops of blends of mineral oil and vegetable oils spreading on a copper substrate. Vegetable oils and blends are non-polar in nature and, therefore, show high wetting tension and low contact angle resulting in higher spreading, good affinity towards the surface, requiring higher energy to detach the liquid from the surface It was found that as the percentage of sunflower oil increases in the blend, the contact angle decreases, indicating improvement of wettability of the blend with an increasing quantity of sunflower oil. This behavior is not observed in the blending of other vegetable oils like palm oil and gingili oil with mineral oil. For these oils, the static contact angle decreases upto 45 %-55 % of vegetable oil addition respectively. The value of 'k' remains unaffected by the type of oil used. On the other hand, the value of 'n' rose with the increase in percentage of sunflower oil and gingili oil in mineral oil. This can be attributed to the higher viscosity of the sunflower oil. Palm oil has comparable viscosity as that of mineral oil. Hence, blending with palm oil showed a marginal increase in the value of 'n'. Wettability of nanofluids was found to be poor compared to oils. The static contact angle varied between 40 °-56 °. The lowest contact angle was obtained with 8 % alumina based nanofluid.

## 4. Quench Severity

The cooling curve data during immersion quenching of a copper probe in different quenchants was used to calculate heat transfer coefficients using a lumped heat capacitance method. Figures 4 (a) & (b) show the typical variation of heat transfer coefficient with time. Among pure oils, sunflower oil showed maximum peak heat transfer coefficient (914 $W/m^2K$) and mineral oil showed minimum peak heat transfer coefficient (505 $W/m^2K$).

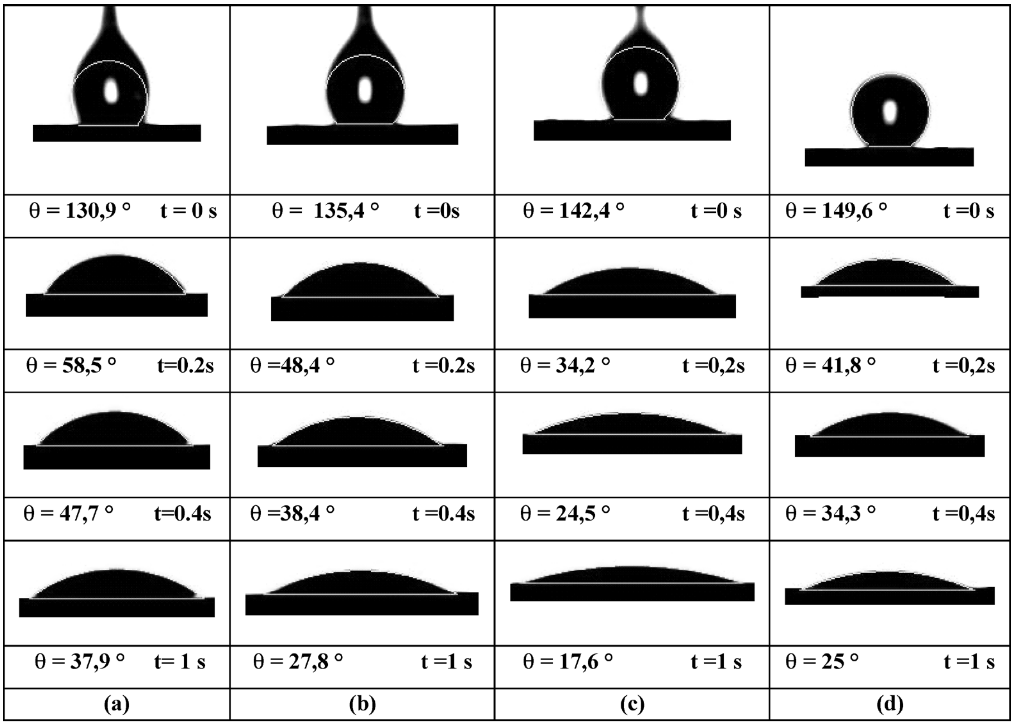
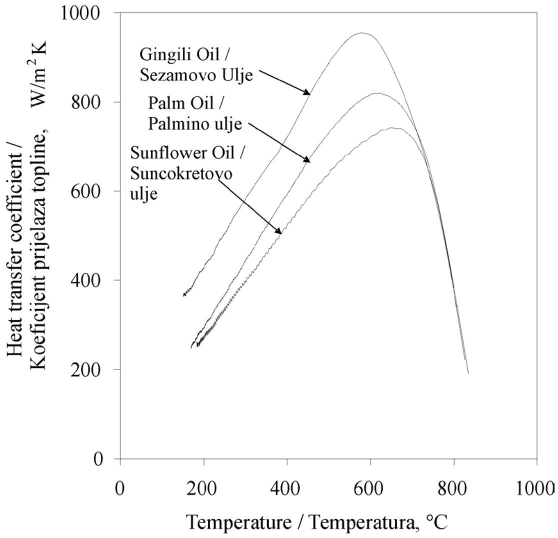



**Figure 3.** Images showing contact angle relaxation of (a) pure mineral oil (b) mineral and sunflower oil blend (1:1) (c) mineral and palm oil blend (1:2) (d) mineral and gingili oil blend (1:2) on copper substrate

**Slika 3.** Slike prikazaju smanjenje dodirnog kuta (a) čistog mineralnog ulja, (b) smjese mineralnog i suncokretovog ulja (1:1), (c) mineralnog i palminog ulja (1:2) i (d) mineralnog i sezamovog ulja (1:2) na bakrenoj podlozi

But beyond this, an increase in the contact angle is observed. The kinetics of wetting during spreading of an oil based quench media on copper substrate can be expressed by the power law: $\theta = kt^n$, where $\theta$ is the dynamic contact angle, t is the spreading time, k is pre-exponent constant and n is the exponent. All the liquids investigated exhibited similar behaviour although the extent of spreading, indicated by their equilibrium contact angles, was different for different liquids. The values of k and n were in the range of 3,19-5,30 and -0,40 to - 0,23 Among the blends, gingili oil blended with mineral oil (2:1) showed maximum peak heat transfer coefficient (963 $W/m^2K$) and palm oil blended with mineral oil (3:1) showed minimum peak heat transfer coefficient (565 $W/m^2K$). The blending of sunflower oil, gingili oil and palm oil to mineral oil improved its heat transfer characteristics. However, the use of sunflower and gingili oils for blending with mineral oil was found to be more effective than palm oil. For example, with the addition of 33% vegetable oil to mineral oil, sunflower and gingili oils resulted in a 43 % and 40 % increase of peak heat flux respectively whereas the corresponding increase in the peak heat flux with palm oil addition was only 24 %. Activation energy for spreading plays an important role in the spreading phenomenon of oil media. The spread activation energy of oils has been found to be influenced by the fatty acid composition of oils [5]. Oils having a higher percentage of mono unsaturated fatty acids generally show higher spread activation energy and lower degree of spreading. Palm oil contains about 40% monounsaturated fatty acids compared to sunflower oil, which contains only 19 % monounsaturated fatty acids. This could be a decisive factor for better heat transfer behaviour of blends containing sunflower oils. Higher peak transfer coefficient (1325 W/m$^2$K) was observed for nanofluid with 0,01 % of alumina.



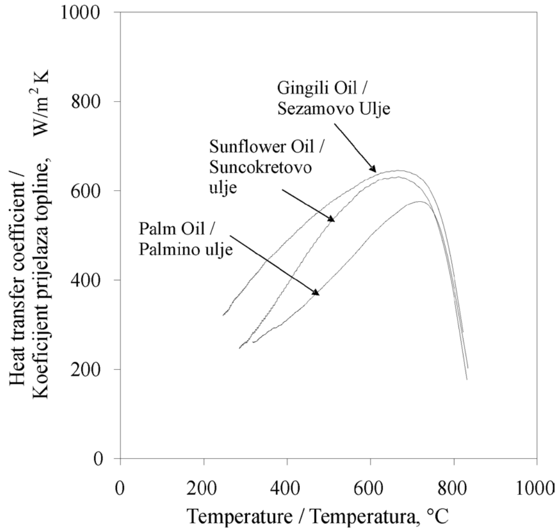




**Figure 4.** Variation of heat transfer coefficient with probe temperature for blends of mineral and vegetable oils (a) (1:2) (b) 3:1

**Slika 4.** Promjena koeficijenta toplinske vodljivosti u odnosu na temperaturu uzorka za mješavine mineralnog i biljnih ulja u omjeru (a) (1:2) (b) 3:1

## 5. Conclusions

The wetting kinetics of vegetable oils exhibited a power law of the type: $\theta = kt^n$. Contact angle decreased linearly with an increase in the percentage of sunflower oil in the oil blend, whereas for palm oil and gingili oil there was a decrease up to 45 %-55 % with their addition to mineral oil followed by an increase. Among the blends, the highest peak transfer coefficient (963 W/m$^2$K) was observed for a blend of gingili oil with mineral oil (2:1) and lowest peak heat transfer coefficient (565 W/m$^2$K) was observed for a blend of palm oil with mineral oil (3:1). For oils and their blends, the peak heat transfer coefficient decreased monotonically with an increase in contact angle. The use of nanofluids for heat treatment looks promising. However, much work needs to be done towards the development of cheaper nanofluids and their characterization.

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