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CHANGES OF ENGINE OIL FLOW PROPERTIES DURING ITS LIFE CYCLE

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Abstract

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The work is focused on quantification of influence of operation on flow properties of motorcycle engine oil. Three different kinds of synthetic engine oil (MOTUL) were tested, namely unused oil, run-in oil (650 km after engine reboring) and regular engine oil (6200 km of motorcycle operation). The samples were frozen to below zero temperatures and kinematic viscosity was continuously monitored in the range of −5 °C and +115 °C. Consequently, the kinematic viscosity at reference temperatures of 0, 40 and 100 °C was compared. Viscosity was measured by digital viscometer with concentric cylinders measuring geometry. The biggest difference occurred in case of lower temperatures where e.g. at 0 °C decrease to 29 % and 43 % of its original value was detected for used oil and run-in oil respectively. Flow behavior was modeled using several mathematical models –Arrhenius equation, exponential, and Gaussian equation. The best match between experimental and computed data was received in case of Gaussian fit with $R^2 = 0.997$ and 0.992 for run-in and used oil, respectively. The models are generally usable for description of rheological behavior of given engine oil.

viscosity, engine oil, mathematical modeling

Oil is a complex substance with each hydrocarbon molecule consisting of many atoms of carbon, hydrogen, oxygen and others. The atoms in each hydrocarbon molecule are strongly chemically bonded together, and the energy required to break a hydrocarbon molecule apart is much higher than the energy needed to change it from a liquid state to a gaseous state.

The oil film offers resistance to flow due to its adhesion to the surfaces of the bearing. Oil which is dripping or running down a surface by gravity or is being pumped through a pipe shows resistance to flow due to its adhesion to the surface as well as its viscosity. The oil layer adhered to the stationary surface is itself stationary, whereas the oil layers farther away from the surface move progressively faster. The lower the viscosity, the less energy it takes to shear the oil and to cool the oil, but conversely, the lower the viscosity, the thinner the oil film.

It is important to have a good understanding of engine oil viscosity, because viscosity is the single most important characteristic of oil as a good lubricant. Motor oil, or engine oil, is an oil used for lubrication of various internal combustion engines. The main function of engine oil is to lubricate moving parts, but also to clean, inhibit corrosion, improve sealing and cool engine down by carrying heat away from the moving parts. Motor oils are derived from petroleum and non-petroleum synthesized chemical compounds used to make syntehetic oil. Motor oil mostly consists of hydrocarbons, organic compounds consisting entirely of carbon and hydrogen (Wikipedia, 2009).

Lubricating oil in internal combustion engines is exposed to various strains depending on the operating conditions, the fuel quality, the ambient conditions and operating parameters. The rate of deterioration strongly depends on these influences. In order to avoid an engine failure, the oil must be changed before it looses its protective properties. At the same time, an unnecessary oil change should be avoided for environmental and economical reasons. In order to determine the optimum oil change interval reliably, it is necessary to monitor the actual physical and chemical condition of the oil (Agoston et al., 2005).

There are several ASTM Standard Methods for measuring the viscosity of oils. Of these, only methods D 445 – Standard Test Method for Kinematic Viscosity of Transparent and Opaque Liquids (the Calculation of Dynamic Viscosity) and D 4486 – Standard Test Method for Kinematic Viscosity of Volatile and Reactive Liquids, will yield absolute viscosity measurements (ASTM, 1996). Both of these methods make use of glass capillary kinematic viscometers and will produce absolute measurements in units of centistokes (cSt) only for oils that exhibit Newtonian flow behaviour (viscosity independent of the rate of shear). Traditional methods for measuring oil viscosities (such us capillary, falling ball, rotary etc) are in detail described in Dawson (2000), Spearot (1989), or Troyer (2002). There are also new approaches described e.g. in Albertson et al. (2008), Anonymous (2006), or ASTM Standard (2005).

This study monitored the effect of operation time on lubricant viscosity under different temperatures. This knowledge is very important for description of processes running in the combustion engines. The work follows the results published in Severa et al. (2009).

MATERIAL AND METHODS

Engine oils

Two commercially available motorcycle engine oils were used. The first sample was used for run-in the engine after reboring (650 km). The oil was drained off from road sport motorcycle Yamaha SR 125, which is a small motorcycle with single-cylinder air and oil cooled engine with 125 ccm and 8.8 kW. The second sample was used in the engine of the same motorcycle and drained off after 6200 km of operation. The description of the oils is given in Table I.

Viscosity measurement

Kinematic viscosity of the oil is affected by the oil density. The test often use the acceleration, gravity or vibration as forces to shear the oil. The unit of measurement is millimeters^2/second (mm^2/s), also called centistokes (cSt).

There is a difference in measuring of kinematic viscosity of new and used oils (Maggi, 2006). The procedure used in Severa et al. (2009) was used. The volume (200 ml) of oil was put into the specially designed cuvette without previous mixing.

The data were received from measurements performed on digital viscometer Anton Paar DV–3 P (Austria), which is designed to measure dynamic or kinematic viscosity (η, ν), shear stress (τ), and shear rate ($\dot{\gamma}$). The DV–3 P is a rotational viscometer, based on measuring the torque of a spindle rotating in the sample at a given speed. Shear stress is expressed in [g/(cm.s^2)], shear rate in [s^{-1}], kinematic viscosity in [mm^2/s], and speed of spindle in revolutions per minute [rpm]. The experiments were performed with use of R3 spindle. The viscosity data were obtained for temperature range –5 and +115 °C.

Mathematical models

Mathematical models were created with use of software MATLAB® v. 7.1.0.246(R14) Service Pack 3, Curve fitting application (The MathWorks, Inc., USA). The suitability of the fitted models was evaluated by the determination coefficient (R^2) and the significance level ($p < 0.05$).

RESULTS AND DISCUSSION

Influence of operation (run-in period of 650 km and regular operation of 6200 km) on kinematic viscosity of synthetic engine oil was quantified. The comparison of data received for unused oil (Severa et al., 2009), run-in oil and oil used for regular operation is shown in Figure 1. The oil viscosity is strongly dependent on temperature in case of all types of oil – unused, run-in and used one. In order to get a comparative data for either dynamic or kinematic viscosity, the reference temperature must be presented. According to ISO 8217 the reference temperature for a residual fluid is 100 °C, for a distillate fluid it is 40 °C.

Decrease of viscosity with temperature was *a priori* presumed and its internal structural mechanics were described e.g. in Guo et al. (2007), Mann (2007)

I: *Characteristics of tested oils*

Oil	Oil type	Mark	Manuf.	Viscosity Grade	Country of Origin	Operation (km)
Unused	Synthetic	5100 Ester 4T	Motul	10W40	France	0
Run-in	Synthetic	5100 Ester 4T	Motul	10W40	France	650
Regularly used	Synthetic	5100 Ester 4T	Motul	10W40	France	6200

Primarily, the oils were frozen to below zero temperatures (approx –7 °C). No pre-treatment was performed since the oils were supposed to be Newtonian liquids (Noria, 2008). Although oils were assumed to be Newtonian, it is known that in the case of additives supplement, a side effect of such additives is to cause shear thinning – the oil viscosity becomes dependent on its shear rate, where high shear rates cause the oil viscosity to be reduced (Takata and Wong, 2006).

II: *Kinematic viscosity at reference temperatures*

	0 °C ν (mm²/s)	40 °C ν (mm²/s)	100 °C ν (mm²/s)
Unused oil	1804	120	52
Run-in oil	778	93	46
Used oil	528	89	41

or Severa et al. (2009). Non-linear courses of the dependencies can be explained as a consequence of chemical processes proceeding in the oil. In all cases the oil viscosity decreased with degree of its use. It is obvious (see Fig. 1) that most relevant differences are present in oils cooled to 0 °C, where original viscosity of unused oil 1804 mm²/s decreased to 528 mm²/s, which represents decrease to 29 % of initial value. Run-in oil exhibited decrease to 778 mm²/s that is 43 % of the initial value. The decrease is less dramatic in case of temperature of 40 °C, where following values were found: 74 and 77.5 % for used and run-in oil, respectively. Increasing temperature was depressing the effect of viscosity changes and this fact can be documented on case of measuring performed at 100 °C. In this temperature level, the viscosity decreased to 78 and 88 % for used and run-in oil, respectively.

Experimental data can be used separately as a final result and basic data source for further evaluation or used for mathematical modeling of given phenomenon. Modeling provides a means of representing a certain quantity of rheological data in terms of a simple mathematical expression. Many forms of the equations are possible and one master model, suitable for all situations, does not exist (Steffe, 1996; Hlaváč, 2008a; Severa et al., 2010).

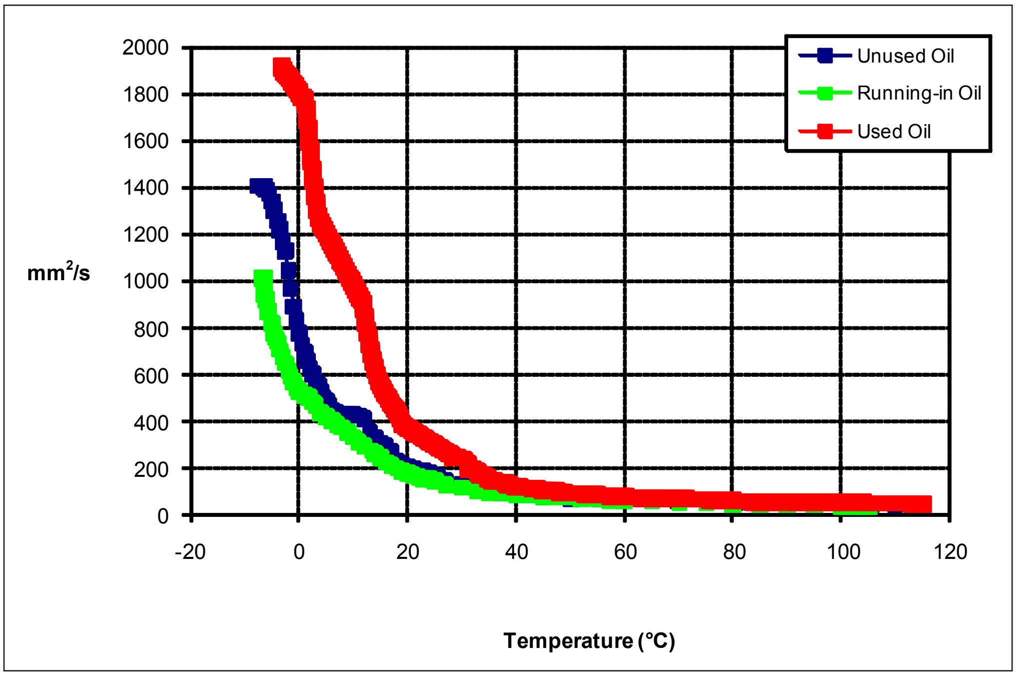
Satisfying correlation between experimental and modeled values can be obtained using e.g. Gaussian or exponential model. In case of unused oil, very good correlation of $R^2 = 0.992$ was achieved with Gaussian fit (a1*exp(–((x–b1)/c1)^2) + ... + a4*exp(–((x–b4)/c4)^2). Use of exponential fit (a*exp(b*x) + c*exp(d*x)) led to correlation of $R^2 = 0.991$. In case of run-in oil, use of Gaussian fit (a1*exp(–((x–b1)/c1)^2) + ... + a5*exp(–((x–b5)/c5)^2) led to correlation of $R^2 = 0.997$, while exponential fit (a*exp(b*x) + c*exp(d*x)) resulted in correlation of $R^2 = 0.983$. Fitting of the experimental data is shown in Fig. 2.

One of the most commonly used tools for modeling the influence of temperature on the viscosity of Newtonian fluids is Arrhenius type equation. Considering an unknown viscosity (ν) at any temperature (T) and a reference viscosity (ν_r) at a reference temperature (T_r), the equation may be written in logarithmic form:

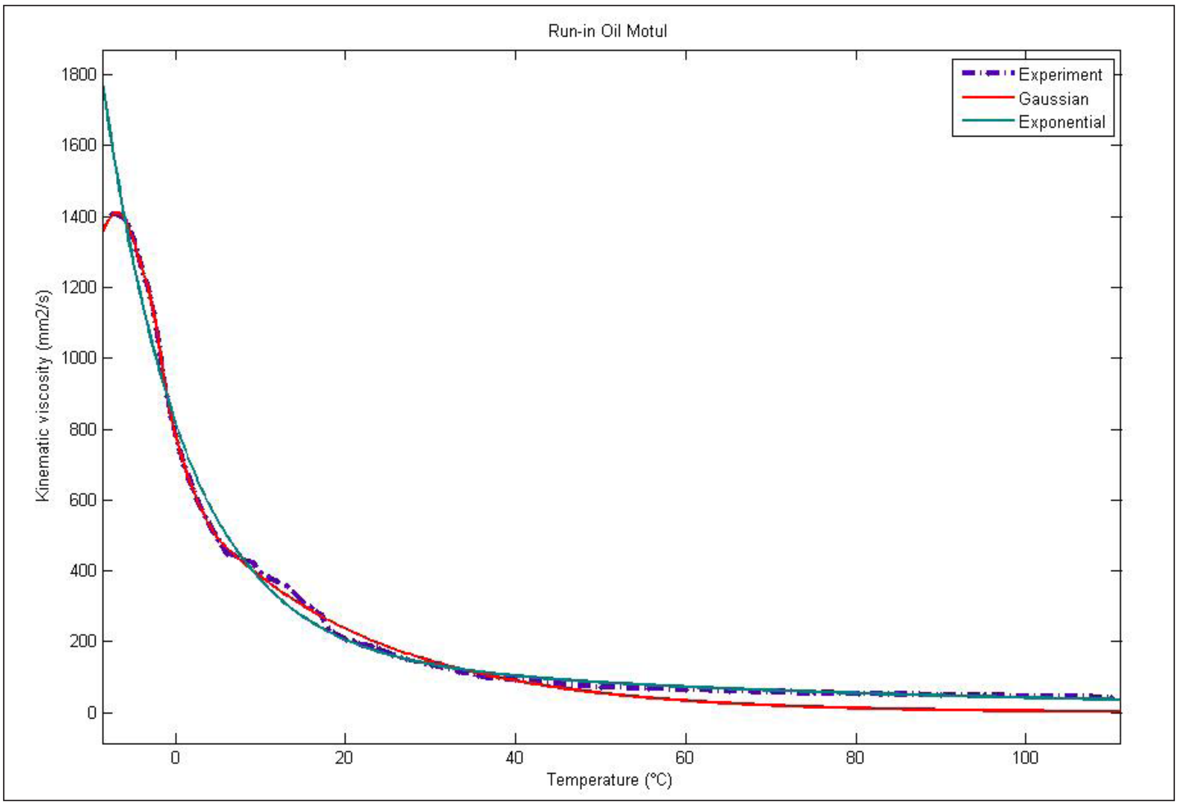
$$\ln\left(\frac{\nu}{\nu_r}\right) = \left(\frac{E_a}{R}\right) - \left(\frac{1}{T} - \frac{1}{T_r}\right).$$

Similar approach was used for modeling of temperature dependent viscosity of Newtonian fluids by many authors (Friso and Bolcato, 2004; Hlaváč, 2007; Hlaváč, 2008b; Severa and Los, 2008). Arrhenius modeling led to satisfying results with $R^2 = 0.97$, 0.96, and 0.95 of match between experimental and modeled data for unused, run-in and used oil, respectively.

Importance of viscosity behavior of an engine oil as a function of its temperature was already proven – see e.g. Severa et al. (2009), especially when considering running efficiency and performance of combustion engines. Influence of motorcycle en-



1: *Temperature dependent viscosity of 3 tested oils* gine operation on oil flow properties was confirmed and kinematic viskosity changes were quantified. The most dramatic changes evoked by oil use (6200 km of operation) were recorded in lower temperatures (decrease to 29 %) while viscosity in higher temperatures was not so sensitive to oil condition. Oil viscosity is becoming a critical factor, due to engine controls that use engine oil for precise timing (Albertson et al., 2008). Full knowledge of oil behavior in different stages of its life cycle and under different conditions is thus needed. The analysis performed by other authors also suggests that even though the kinematic viscosity decreases over time, the in-service viscosity seen by the pump only changes slightly with time. Consequently, if an oil provides adequate volumetric efficiency during the first hours of operation, it will continue doing the same even after extended operation (Herzog et al., 2009).



2: *Experimental data and mathematical models for run-in oil*

SUMMARY

Lubricating oil in internal combustion engines is exposed to various strains depending on the operating conditions, the fuel quality, the ambient conditions and operating parameters. The rate of deterioration strongly depends on these influences. In order to avoid an engine failure, the oil must be changed before it looses its protective properties. At the same time, an unnecessary oil change should be avoided for environmental and economical reasons. In order to determine the optimum oil change interval reliably, it is necessary to monitor the actual physical and chemical condition of the oil. The work is focused on quantification of influence of operation on flow properties of motorcycle engine oil. Three different kinds of synthetic engine oil (MOTUL) were tested, namely unused oil, run-in oil (650 km after engine reboring) and regular engine oil (6200 km of motorcycle operation). Since the oils were considered to be the Newtonian fluids, flow curves were not designed and the effort was focused on determination of kinematic viscosity at reference temperatures of 0, 40 and 100 °C. The samples were frozen to below zero temperatures and kinematic viscosity (mm^2/s) was continuously monitored in the range of –5 °C and +115 °C. Viscosity was measured by digital viscometer with concentric cylinders measuring geometry. Kinematic viscosity of all oils was non-linearly decreasing with increasing temperature as it was expected. The most significant difference occurred in case of lower temperatures where e.g. at 0 °C decrease to 29 % and 43 % of its original value was detected for used oil and run-in oil respectively. The decrease at high temperature, e.g. at 100 °C was much lower, to 78 and 88% for used oil and run-in oil respectively. Viscosity dependencies were modeled using several mathematical models –Arrhenius equation, exponential, and Gaussian equation. The best match between experimental and computed data was received in case of Gaussian fit with $R^2 = 0.997$ and 0.992 for run-in and used oil, respectively. Use of generally accepted and common Arrhenius model led to $R^2 = 0.96$ and 0.95 for run-in and used oil, respectively. Knowledge of detailed flow behavior of engine oil during its life cycle is critical for engineering evaluation of combustion engines operation. The models can be applied for description of rheological behavior of given engine oil.

SOUHRN

Změny viskozity motorového oleje během provozu spalovacího motoru

Určení správného intervalu výměny motorového oleje závisí na znalosti jeho fyzikálních a chemických vlastností. Tato práce je zaměřena na hodnocení a kvantifikaci vlivu provozu motoru na tokové vlastnosti motocyklového motorového oleje. Srovnávány byly tři druhy syntetického motorového oleje (MOTUL), a to olej nepoužitý, zajížděcí (po 650 km provozu po výbrusu válce) a olej vyjetý (po 6200 km provozu). Vzhledem k tomu, že je olej *a priori* považován za Newtonovskou kapalinu, nebyly sestavovány tokové křivky a sledována byla pouze teplotní závislost kinematické viskozity. Srovnávány byly hodnoty při třech referenčních teplotách – 0, 40 a 100 °C. Vzorky oleje byly zmraženy na teplotu a kontinuálně byla zaznamenávána hodnota kinematické viskozity v rozmezí –5 °C až +115 °C. Viskozita byla měřena rotačním digitálním viskozimetrem Anton Paar s měřicí geometrií souosých válců. Dle předpokladů kinematická viskozita všech vzorků nelineárně klesala s narůstající teplotou. Nejvýraznější rozdíly byly zjištěny u nižších teplot, kdy při 0 °C poklesla viskozita ze své původní hodnoty 1804 mm^2/s (nepoužitý olej) na 29% této hodnoty v případě vyjetého oleje a 44% v případě zajížděcího oleje. Pokles při vyšších teplotách, např. 100 °C, byl mnohem méně výrazný, konkrétně došlo k poklesu na 78 a 88% původní hodnoty u vyjetého a najížděcího oleje. Tokové vlastnosti olejů byly modelovány pomocí několika matematických modelů, konkrétně Arrhéniova modelu, exponenciálního a Gaussova vztahu. Nejvyšší shody mezi experimentálními a vypočtenými hodnotami bylo dosaženo v případě Gaussova vztahu, a to to konkrétně $R^2 = 0{,}997$ a 0,992 pro zajížděcí a použitý olej. Detailní znalost tokového chování motorových olejů je kriticky významná pro hodnocení a inženýrské výpočty v oboru spalovacích motorů. Navržené modely mohou být použity pro predikci reologických charakteristik daného typu oleje.

viskozita, motorový olej, matematické modelování

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REFERENCES

AGOSTON, A., OTSCH, C., JAKOBY, B., 2005: Viscosity sensors for engine oil condition monitoring—Application and interpretation of results, Sensors and Actuators A 121, 327–332.

ALBERTSON, W. C., STALEY, D. R., MC DONALD, M. M., PRYOR, B. K., 2008: Engine oil viscosity diagnostic systems and methods, United States Patent 20080223114.

ANONYMOUS, 2006: On-line Fluid Condition Monitoring Technology. Practicing Oil Analysis Magazine 2, 15–21.

ASTM STANDARD, 1996: Annual Book of ASTM Standards – Section 5 Petroleum Products, Lubricants, and Fossil Fuels, American Society for Testing and Materials, West Conshohocken, Pennsylvania.

DOWSON, D., 2000: Thinning films and tribological interfaces. Published by Elsevier, ISBN-13: 978-0-444-50531-6.

FRISO, D. and BOLCATO, F., 2004: Rheological properties of some newtonian food liquids. Rivista di Ingegneria Agraria 2, 75–80.

GUO, B., LYONS, W. and GHALAMBOR, A., 2007: Petroleim production engineering. Elsevier Science and Technology Books, ISBN 0750682701.

HERZOG, S. N., HYNDMAN, C. W. and SIMKO, R. P., 2009: Effect of Operation Time on Oil Viscosity and Pump Efficiency, RohMax Hydraulic Fluid Efficiency References No. 10.

HLAVÁČ, P., 2007: The rheologic properties of dark beer, Proceedings of Research and Teaching of Physics in the Context of University Education, Nitra, 5–6. 6. 2007, pp 169–175.

HLAVÁČ, P., 2008a: Dependencies of fermented brew rheological properties on temperature, Pro-

ceedings of Physics in Life Sciences, Prague, 22. 8. 2008, pp 22–27.
HLAVÁČ, P., 2008b: Temperature and time of storing dependencies of dark beer rheological properties. Journal on Processing and Energy in Agriculture 3, 114–117.
ISO 8217: 2005, Petroleum products – Fuels (class F)
MAGGI, C. P., 2006: Advantages of Kinematic Viscosity Measurement in Used Oil Analysis. Practicing Oil Analysis Magazine 5, 38–52.
MANN, D., 2007: Motor Oils and Engine Lubrication. Motor Oil Engineers, L.L.C., Detroit.
NORIA COMPANY, 2008: Lubrication and Oil Analysis Dictionary, http://www.noria.com/dictionary/.
SEVERA, L., HAVLÍČEK, M., KUMBÁR, V., 2009: Temperature dependent kinematic viscosity of different types of engine oil. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 4, 95–102.
SEVERA, L. and LOS, J., 2008: On the influence of temperature on dynamic viscosity of dark beer. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis 2, 303–307.
SEVERA, L., NEDOMOVÁ, Š., BUCHAR, J., 2010: Influence of storing time and temperature on the viscosity of an egg yolk. Journal of Food Engineering 2, 266–269.
SPEAROT, J. A, 1989: High-Temperature, High-Sheer (HTHS) Oil Viscosity Measurement and Relationship to Engine Operation, ASTM Publication, Philadelphia, ISBN: 0-8031-1280-7.
STEFFE, J. F., 1996: Rheological methods in food process engineering. East Lansing, MI: Freeman Press, East Lansing, USA.
TAKATA, R. and WONG, V.W., 2006: Effects of lubricant viscosity on ring/liner friction in advanced reciprocating engine systems. Proceedings of ICEF06 ASME Internal Combustion Engine Division 2006 Fall Technical Conference November 5–8, 2006, Sacramento, California, USA, 1526–1535.
TROYER, D., 2002: Understanding Absolute and Kinematic Viscosity. Practicing Oil Analysis Magazine 1, 15–19.
WIKIPEDIA CONTRIBUTORS, 2009: “Motor Oil” Wikipedia, The Free Encylcopedia – English Version (accessed March, 2010).

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