Modelling of the imbibition of the polypropylene fiber cloth with emulsions
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Modelling of the imbibition of polypropylene fiber cloth with emulsions

J. Sek

Faculty of Process and Environmental Engineering, Lodz Technical University
ul. Wolczanska 213, 90-924 Lodz, Poland

Abstract

The paper deals with an adsorption of emulsions by polypropylene pneumothermic fiber cloth. A theoretical model was proposed for prediction of the imbibition rate. This model was verified for the cases of adsorption of pure kerosene and machine oil and oil-in-water systems, in which a disperse phase was kerosene and machine oil. Investigations covered the observations of soaking of the fiber cloth strips immersed partially in the tested liquids.
The tests showed first of all that during soaking not only the liquid that formed a disperse phase but also the emulsion was adsorbed. Additionally, it was found that the rate of soaking depended on the disperse phase viscosity and its content in the emulsion. The accuracy of the developed model was in the range acceptable from the engineering point of view.

Keywords:
Emulsions, polypropylene fiber cloth, imbibition

1. Introduction

Every spill of oil and oil derivatives is a tremendous hazard for the natural environment. Emergencies and negligence in the elimination and reduction of systemic source impacts lead to significant economic losses. Due to multiple long-lasting effects, their size is difficult to determine explicitly. Hard to estimate are also social costs, which encompass reduced use of contaminated areas or even their long-term degradation and complete elimination from economic use. Society and economy suffer significant losses, among the others, due to reduction in water use. Undoubtedly, the impact of these pollutants on people’s health not limited directly to the contaminated area should be taken into account.

Emulsion sewage that contains emulsified substances, mainly oil derivatives, fats and lubricants, are extremely hazardous to the natural environment. They disturb the processes of both biological and mechanical sewage treatment and have a negative effect on sewerage network. The presence of oils hampers water treatment, decreases water suitability for drinking, economic use and recreation. So, oil must be removed from sewage and especially from industrial wastewater. This is connected with regeneration of spent oils to obtain products neutral for the natural environment. In a typical emulsion sewage, spent cooling and lubricating emulsions generated by machine and metallurgical industry, the content of mineral oil can reach even dozens of kilograms per cubic meter [Morrow N. R., Mason G., Mason G., Mellor D. W.].

One group of sorption materials used to adsorb oil and oil derivatives from water are the polypropylene fibers. They are used in the form of cloth, pillows or sleeves. Their sorption properties are dependent on the structure and thickness of fibers in the cloth. The rate of sorption is also dependent on the properties of the emulsions – their viscosity and concentration.

This study concerns the modelling of the adsorption process of emulsions by polypropylene fiber cloth. Theoretical model was developed and verified on the basis of imbibition of the polypropylene cloth strips immersed partially in kerosene/water and machine oil/water emulsions.

2. Modelling consideration

The theoretical model was developed for prediction of the velocity of soaking of the polypropylene strips immersed vertically with one end in the tested liquid as presented in Fig. 1.

Because of the porous structure of the material it soaks with the tested medium due to the capillary forces. Such structure can be considered as the bunch of the tortuous capillary tubes [Bird R., Stewart W., Lifghtfoot E.]. For the single capillary as one knows [Atkins P.W.] two opposite forces are acting on the rising liquid. One of them, the force F_1 is a capillary force defined as

$$F_1=2\pi r_h \sigma \cos\theta \tag{1}$$

where: σ – surface tension, [N/m]
θ – wetting angle, [rad]

The parameter r_h expressed in meters corresponds to the diameter of the capillary. Here it can be considered as the overall hydraulic radius of the channels of arbitrary cross–section formed inside the cloth.

The second one is a gravitational force F_2 given by

$$F_2=\pi r_h^2 h \rho_c g \tag{2}$$

where: g – gravitational acceleration, [m/s^2]
ρ_c – liquid density, [kg/m^3]
h – height of the liquid in capillary, [m]

At certain value of h the equilibrium state between forces is reached and the liquid stops to rise along the strip. At this moment

$$F_1=F_2 \tag{3}$$

and using equations (1) and (2) one can write

$$2\pi r_h \sigma \cos\theta = \pi r_h^2 h_k \rho_c g \qquad (4)$$

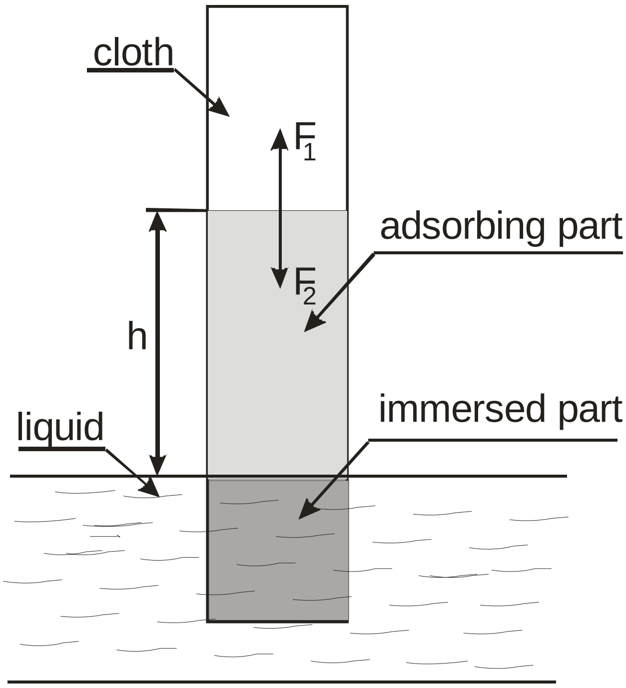

Fig. 1 Forces acting on the rising liquid during imbibition

Parameter h_k is the final height expressed in meters of the liquid in capillary when condition given by equation (3) occurs. For the considered process of soaking it is the final imbibition height of stripes of the cloth.

After rearrangements equation (4) can be written as

$$r_h = \frac{2\sigma\cos\theta}{h_k \rho_c g} \qquad (5)$$

So one can get a formula – equation (5), for calculations of the hydraulic radius of the channels in the cloth absorbing the liquid.

During the sorption process the driving force F, the moving the liquid in the material can be calculated using the following equation

$$F = F_1 - F_2 \qquad (6)$$

This formula, after substitution of equations (1), (2) can be presented in the form

$$F = 2\pi r_h \sigma \cos\theta - \pi r_h^2 h \rho_c g \qquad (7)$$

Parameter h in equation (7) is the given imbibition height in meters after given time from the beginning of the process.

The force F is responsible for the velocity of a rising of the liquids in the vertical stripes of the immersed cloth. It is counterbalanced by the shearing force F_s resulting from the viscous flow in the structure of the sorption material. These force can be calculated using the formula

$$F_s = \tau_s S_h \tag{8}$$

where: τ_s – shearing stresses, [Pa]
S_h – overall side surface of capillary channels, [m^2]

Shearing stresses on the wall of capillary tubes of an arbitrary cross–section can be calculated using equation [3]

$$\tau_s = K_0 \frac{v_c \eta_c}{r_h} \tag{9}$$

where: v_c – velocity of rising of the liquid along the strip, [m/s]
η_c – viscosity of the liquid, [Pas]
K_0 – constant dependent on the shape of the capillary cross – section, [-]

Value of the S_h can be obtained from the formula

$$S_h = 2\pi r_h h \tag{10}$$

Substituting equations (9) and (10) into (8) one gets

$$F_s = 2K_0 \pi h v_c \eta_c \tag{11}$$

Assuming, that in steady state conditions the force F is equal to F_s it is possible to write using equations (7) and (11)

$$2\pi r_h \sigma \cos\theta - \pi r_h^2 h \rho_c g = 2K_0 \pi h v_c \eta_c \tag{12}$$

After simplifications and rearrangements equation (12) can be presented as follows to predict the velocity of the liquid soaking the fiber cloth

$$v_c = \frac{1}{K_0}\left(\frac{\sigma r_h \cos\theta}{h\eta_c} - \frac{r_h^2 \rho_c g}{2\eta_c}\right) \tag{13}$$

The values of the hydraulic radius in equation (13) can be calculated using equation (5).

Equation (13) can be also written in the following general form

$$v_c = \frac{A}{h} - B \tag{14}$$

where:

$$A = \frac{\sigma r_h \cos\theta}{K_0 \eta_c} \tag{15}$$

$$B = \frac{r_h^2 \rho_c g}{2 K_0 \eta_c} \tag{16}$$

3. Experimental

The proposed model allows to predicted velocity of imbibition of polypropylene cloth on the basis of the liquid properties – density, viscosity, surface tension and the wetting angle. It was verified using the results of preliminary experimental tests.

It was investigated the imbibition of polypropylene stripes with four different media. Two of them were pure liquids – kerosene and machine oil. Two others were the emulsions containing 33 and 50 percent of kerosene as the inner phase dispersed in water with an addition of emulsifying agents. The height h – see Fig. 1, of soaked liquid as the function of time was studied. The obtained results are presented in Fig 2.

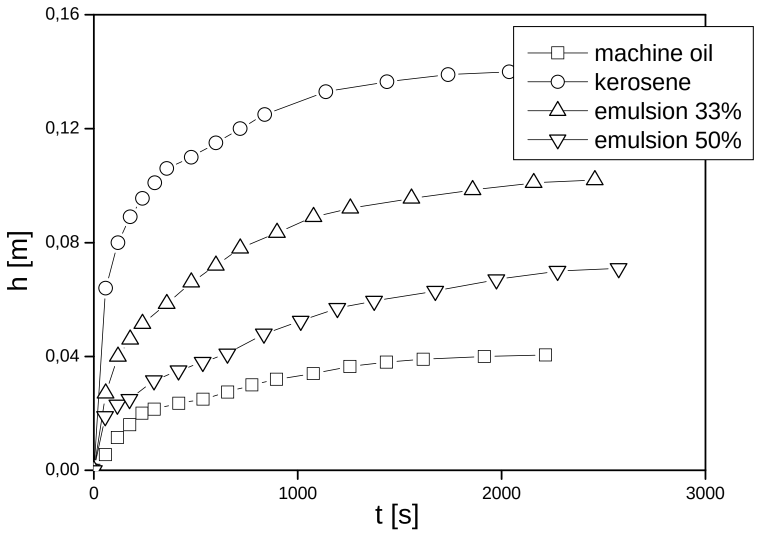

Fig. 2 Changes of the imbibition height as the function of time

It results from the graph that the process is strongly dependent on the properties of liquids. The last points on the curves represent moments when the liquid stop to rise along the stripes. It means that the height was equal h_k. One can notice that the highest value of h_k was in the case of the kerosene, the lowest one in the case of the machine oil. Also lower value was achieved for the more concentrated emulsion.

On the present stage of research it is possible to say that the final height is depended on the viscosity of the liquid. It is lower when the viscosity is higher. This dependence has been shown in Fig. 3

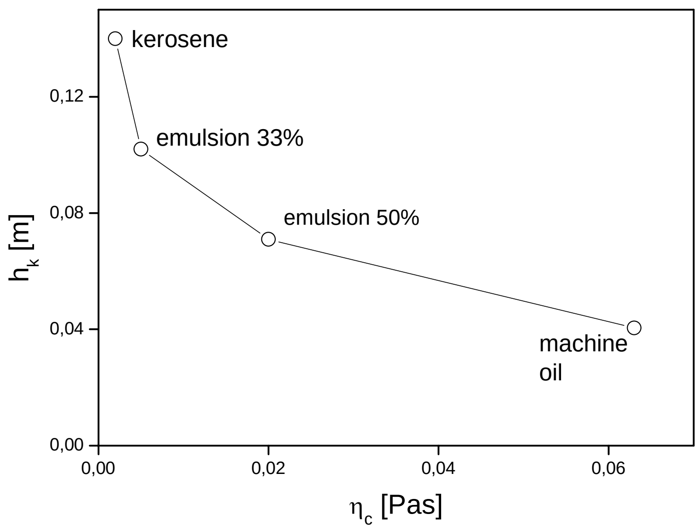

Fig. 3 The dependence of h_k on the η_c

Using the data presented in Fig. 2 it was possible to calculate the velocities of the rising liquid along the stripes. The results of this calculations are shown as the graphs in Figs. from 4 till 7.

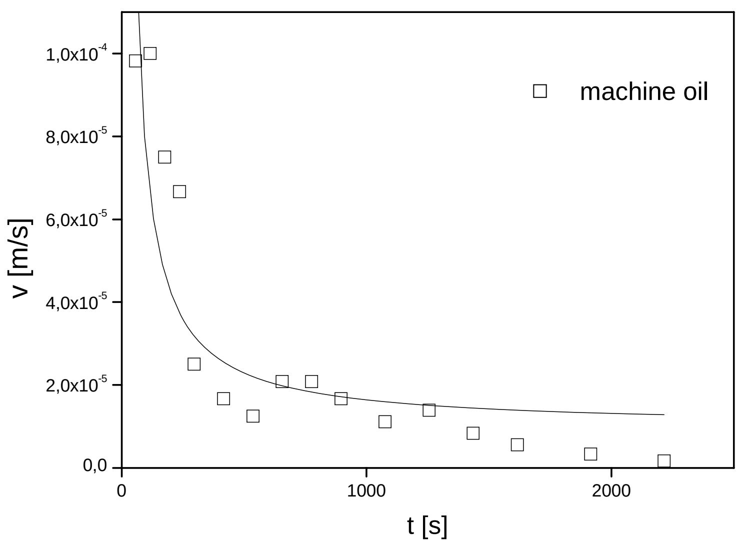

Fig. 4 Velocity changes as a function of time. Medium: machine oil

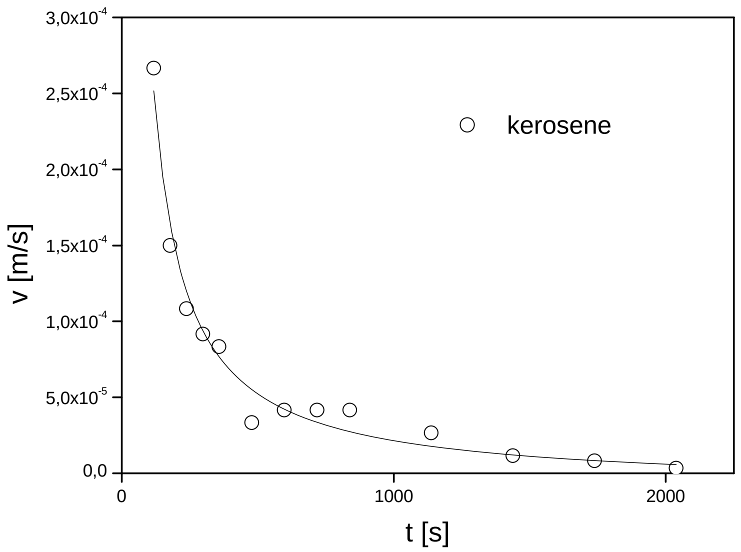

Fig. 5 Velocity changes as a function of time. Medium: kerosene

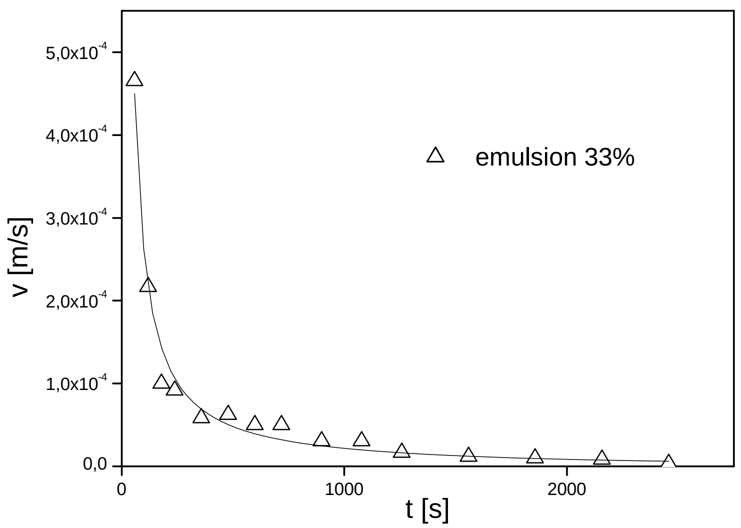

Fig. 6 Velocity changes as a function of time. Medium: Emulsion 33%

The experimental points in Figs. 4÷7 has been approximated using the proposed model given by equation (14). The results of the applications of the model are presented as the continuous lines. Due to the difficulties to measure some of the physicochemical data, mainly values of the surface tension and wetting angle for emulsions, values of A and B were determined due to the regression method. The dependence of these parameters on the liquids viscosity is presented in Fig. 8 and Fig. 9 respectively.

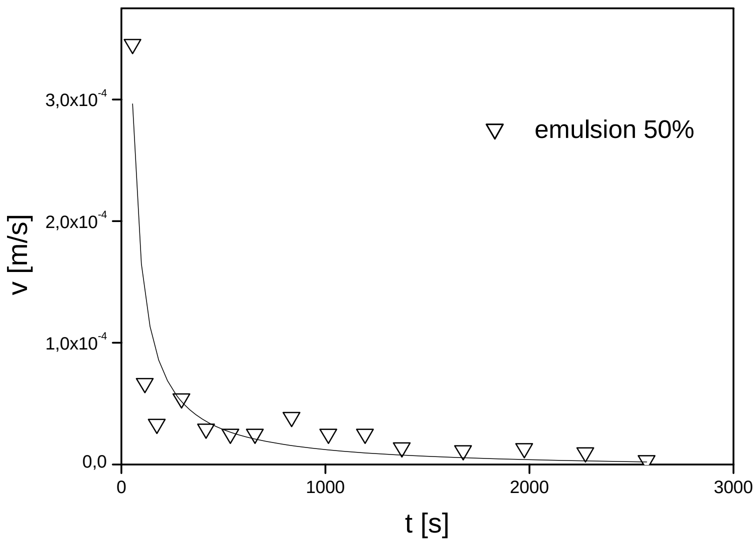

Fig. 7 Velocity changes as a function of time. Medium: emulsion 50%

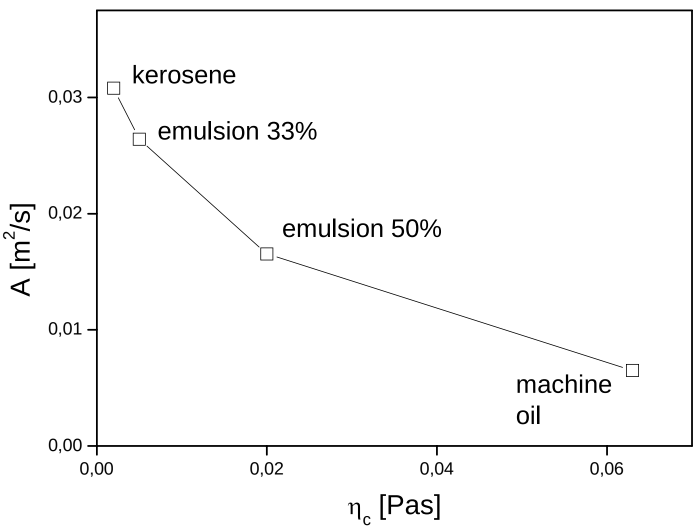

Fig. 8 The dependence of A on η_c

One can find from these graphs that the values of A and B are generally decreasing with rise of the viscosity of the experimental medium.

For the investigated cases the discrepancies between the calculated and experimental data were generally in the range ± 20%. Only in the case of the machine oil the observed differences were bigger.

Considering the presented work one can assume that the developed model allows to predict the imbibition rate with an accuracy acceptable from the engineering point of view.

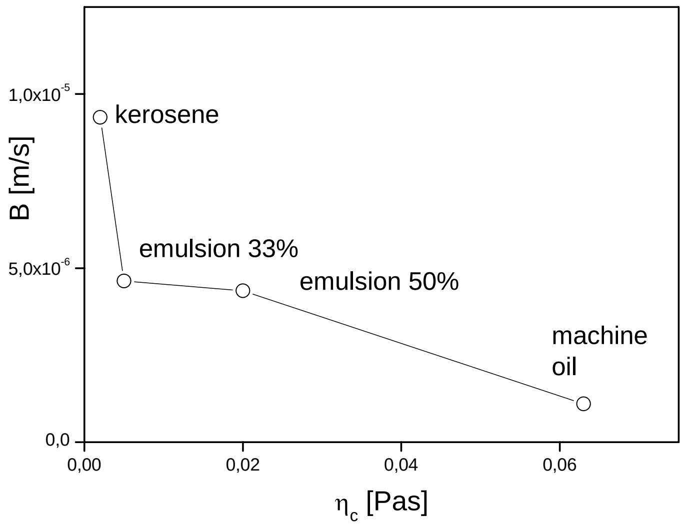

Fig. 9 The dependence of B on η_c

4. References

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