POLISH JOURNAL OF NATURAL SCIENCES
Abbrev.: Pol. J. Natur. Sc., Vol 29(4): 393–403, Y. 2014

EFFECT OF STORAGE OF DILUTED CARBOXYMETHYLCELLULOSE ON RHEOLOGICAL PROPERTIES

Jan Limanowski

Department of Process Engineering and Equipment
University of Warmia and Mazury in Olsztyn

K e y w o r d s: carboxymethylcellulose, CMC, rheological properties.

A b s t r a c t

The study was aimed at determining changes in properties of CMC solutions over different storage times. Rheometric analyses were made for solutions with CMC concentrations 1%, 2%, 3%, 4% and stored between 24 and 120 hours. Courses of the flow curves were described by Ostwald-de Waele (O-dW), Herschel-Bulkley (H-B), Casson and Ellis models. The study showed that the best fitting of the curve to measuring points was provided by the power model. Changes in the rheological properties of diluted CMC were, therefore, evaluated based on the analysis of differences in shearing stress in the samples described with the O-dW model. Analyses demonstrated that the value of the estimated differences was changing from 0.51 Pa in the case of the 1% solution to 5.1 Pa in the case of the 4% solution, sheared at a shear rate of 72.9 s^{-1}. It seems that such minute changes in the properties of the solutions enable their application for research analyses for a period of at least five days.

WPŁYW CZASU MAGAZYNOWANIA ROZTWORZONEJ KARBOKSYMETYLOCELULOZY NA WŁAŚCIWOŚCI REOLOGICZNE

Jan Limanowski

Katedra Inżynierii i Aparatury Procesowej
Uniwersytet Warmińsko-Mazurski w Olsztynie

S ł o w a k l u c z o w e: karboksymetyloceluloza, CMC, właściwości reologiczne.

Address: Jan Limanowski, University of Warmia and Mazury in Olsztyn, phone: +48 89 523 35 78, e-mail: jan.limanowski@uwm.edu.pl

Abstrakt

Wodny roztwór soli sodowej karboksymetylocelulozy (CMC) jest tanim i łatwo dostępnym płynem modelowym, zdolnym zastąpić podczas badań wiele rzeczywistych wyrobów spożywczych, symulować ich przepływ, badać pracę maszyn, projektować technologie. Celem pracy było określenie zmian właściwości roztworów CMC zachodzących w czasie jej przechowywania. Badaniom reometrycznym poddano roztwory wodne CMC o stężeniu 1, 2, 3 i 4%, magazynowane w czasie od 24 do 120 godzin. Przebiegi krzywych płynięcia oparte o średnie wartości naprężenia stycznego wyznaczonego przy rosnącej i malejącej szybkości ścinania opisano modelami Ostwalda-de Waele (O-dW), Herschela-Bulkleya (H-B), Cassona i Ellisa. Stwierdzono, że wyznaczone stałe równań H-B i Ellisa nie spełniają warunków stosowalności modeli, a spośród dwóch pozostałych, dokładniejsze dopasowanie krzywej do wyników pomiarów zapewnia model potęgowy. Zmiany właściwości reologicznych roztworzonego CMC oceniano więc w oparciu o analizę różnic wartości naprężenia stycznego w próbkach opisanych modelem O-dW, przechowywanych w czasie 24h i 120h, przy szybkości ścinania 72,9 s^{-1}. Stwierdzono, że wartość oszacowanych różnic zmieniała się od 0,51 Pa w przypadku roztworu o stężeniu 1% do 5,1 Pa w przypadku roztworu o stężeniu 4%. Wydaje się, że tak małe zmiany właściwości magazynowanych roztworów CMC umożliwiają ich wykorzystanie do badań przez okres co najmniej pięciu dni od chwili roztworzenia CMC.

Introduction

The difficulties faced when investigating real-life manufacturing processes in the food industry frequently arise from limited access to the product, its complex physical or chemical properties, changes occurring during the process and its price. The properties of non-Newtonian liquid products, which are the most commonly used in food industry, depend on the duration and type of processing, type and component contents in a mixture, temperature, pressure, etc. Hence, if it is possible, a real product is replaced with a model agent with similar properties at the study stage. One of the most commonly used agents is an aqueous solution of carboxymethylcellulose sodium, known under its technical name as CMC (JAWORSKI and KILJAŃSKI 2005). CMC is an easy and commonly available product, which can be used in experiments as a replacement for such foodstuffs as yoghurt, cottage cheese (LIMANOWSKI 2001), buttermilk (BUTLER and MCNULTY 1995), orange juice (TELIS-ROMERO et al. 1999) and many others. It can be used to simulate liquid flow in aseptic processes (FAIRHURST and PAIN 1999) or to investigate the operation of such machines and devices as extruders (POULESQUEN and VERGNES 2003a, 2003b), heat exchangers (ALCAIRO and ZURITZ 1999), separators (ALKHADDAR 2001). A CMC suspension is prepared by dissolving powder in water and waiting some time for it to swell. Despite the common use of CMC in experiments, the literature does not provide many reports on a safe time of use for the solution after dissolving the powder, so that it does not falsify the measurement results as a consequence of changes caused by ageing. This is important because in prolonged experiments, and when an agent with unchanged properties has to be used, it is common practice to prepare larger amounts of a solution to be used in consecutive measurements.

The aim of the study was to determine the course and range of change of properties of carboxymethylcellulose dissolved in water, which take place during the period of its storage, and to find out whether it is possible to use stored CMC solution for experiments.

Materials and experimental methods

Solutions were prepared from powdered CMC of the AS-90/2 type, with the trade name of Jelocel-S, produced at Jeleniogórskie Zakłady Chemiczne Jelchem (PL). According to the data provided by the manufacturer, the chloride content in the product was less than 19%, and the viscosity of a 2% solution of CMC should not be lower than 70 mPa · s. Such information is not complete because it does not mention the measurement temperature or the range of the changes of shear rate at which the viscosity was determined. It was also found that the data provided in the control certificates for different CMC batches differed significantly. Therefore, in order to avoid errors, all the basic measurements of rheological properties of solutions were conducted on material from the same production batch.

CMC, which is poorly soluble in cold water, was dissolved in water heated up to about 60°C (ABDELRAHIM et al. 1994) with a rotary agitator. Subsequently, the solution was transferred to a larger vessel and made up with water. The solution was additionally stirred for about 20 minutes. The tank with the prepared solution was covered tightly from the top in order to prevent water evaporation and drying of the film formed on the walls. The solution was left for 24 hours for CMC to swell. Before the rheometric measurements were conducted, the solution was stirred briefly again and brought to a constant temperature of about 15°C. Two hundred liters of solution were prepared at a time.

In order to demonstrate the effect of time of storage of CMC solution on its properties, flow curves were plotted for solutions at 1%, 2%, 3%, and 4% stored for 24, 48, 72, 96 and 120 hours after the powder was dissolved. Shear stress was measured with a Rheotest-2 rotary rheometer with an S/S1 cylinder system, at an increasing and decreasing shear rate, ranging from 1.5 to 656 s^{-1}. The measurements were conducted at 15°C (FAIRHURST and PAIN 1999). The flow curves were analyzed by three of the most highly valued mathematical models used to estimate the properties of pseudoplastic liquids (BAILEY and WEIR 1998):

Ostwald-de Waele: $$\tau = K \cdot \dot{\upsilon}^n \tag{1}$$

Herschell-Bulkley: $$\tau = \tau_0 + K \cdot \dot{\upsilon}^n \tag{2}$$

Casson: $$\tau^{1/2} = \tau_0^{1/2} + (\eta \cdot \dot{\upsilon})^{1/2} \tag{3}$$

where:
τ – shear stress, Pa
τ_0 – yield stress, Pa
$\dot{\upsilon}$ – shear rate, s^{-1}
η – viscosity, $Pa \cdot s$
K – consistence coefficient, $Pa \cdot s^n$
n – flow behaviour index,

and the less-commonly used Ellis model, regarded as one of the most precise models which describes the flow of foodstuffs – pseudoplastic liquids (HOLDSWORTH 1971):

$$- \dot{\upsilon}^n = (\varphi_0 + \varphi_1 \cdot |\tau|^{\alpha-1}) \cdot \tau \tag{4}$$

gdzie:
φ_0 – equation constant, $m^2 \cdot s^{-1} \cdot N^{-1}$
φ_1 – equation constant, $m^{2\alpha} \cdot s^{-1} \cdot N^{-\alpha}$
α – equation constant

There are always three positive constants in this model φ_0, φ_1 and α. When α>1 and at low values of the shear stress p and at α<1 and at high values of τ, the behavior of a real liquid is approximated by the behavior of a non-Newtonian liquid. In extreme cases, the model describes a Newtonian liquid ($\varphi_1 = 0$) or a power-law liquid ($\varphi_0 = 0$). The Ellis equation was used in measurements of the properties of aqueous solutions of CMC, for example by PAVEZ 2002 and LAREO and FRYER 1998 found the model to be capable of describing the flow curve of a CMC solution more precisely than the power-law model.

Changes in the properties of CMC solutions caused by their storage were evaluated by comparing the differences between the values of a shear stress in samples stored for 24 hours and for 120 hours, sheared at a shear rate of 72.9 s^{-1}, which is the closest to feeling the consistency and texture of food by humans.

Results and Discussion

An analysis of the flow curves of the solutions under study showed that the maximum differences in shear stress between part of the hysteresis determined at an increasing shear rate and the part of the hysteresis determined at a decreasing shear rate occurred at shear rate exceeding 121.5 s^{-1}. This means that both parts of the curve were nearly coincident in the area responsible for human organoleptic sensations and, hence, there is no need to consider it as a curve specific to thixotropic liquids. The maximum difference in shear stress of 11.02 Pa, i.e. 5.33% of the stress measured at an increasing shear rate, was found for the 24-hour solution at a concentration of 4%, and only a slightly smaller difference, of 5.16%, was found for the 4% solution stored for 120 hours. Similar stress differences were found for solutions at smaller concentrations. In a 1% solution, the differences ranged from 0.73% to 3.72%, in a 2% solution they ranged from 1.57% to 2.92%, 3% – from 0.94% to 1.96% and in a 4% solution they ranged from 2.40% to 5.33%. Fig. 1 shows the flow curves for the solutions with the widest hysteresis in the group of solutions with the same concentration. The differences were not found to depend significantly on the duration of the storage period. This was the grounds for the conclusion that the measured shear stress differences are sufficient to estimate the rheological properties of CMC solutions based on mean values of stress determined at growing and decreasing shear rate.

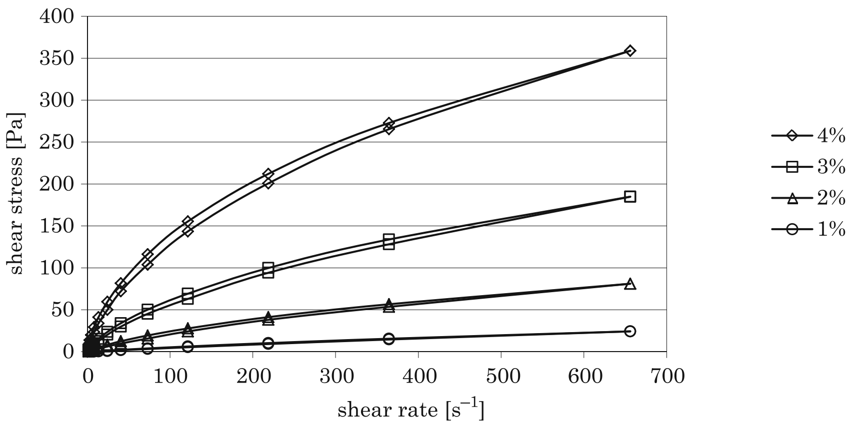

Fig. 1 Flow curves hysteresis for solutions with the greatest difference between the shear stress curves designated with increasing and decreasing shear rate

All of the analyzed flow curves have confirmed the non-Newtonian character of the solutions and the features typical of shear-thinned liquids (FERGUSON and KEMBŁOWSKI 1995, ILLICALI and ENGEZ 1996, PRUSOV et al. 2003, STEFFE 1992). Attempts at describing the curves with model solutions 1–4 have shown that the highest values of correlation coefficients and the most exact fitting of model solutions to the measurement results was achieved by using Ellis and H-B models (Table 1–4). In both cases, the majority of the values of the yield stress τ_0^{HB} and constant a were smaller than zero, which is contrary to

Table 1

Results of the estimation of flow curves of a stored 1% aqueous solution of CMC

Model	Constants, correlation coefficient R	Storage time				
		24h	48h	72h	96h	120h
Ostwald-de Waele	K, $Pa \cdot s^n$ n R	0.07204 0.88320 0.99917	0.08192 0.86544 0.99925	0.08064 0.87487 0.99926	0.08617 0.86306 0.99928	0.08967 0.86424 0.99922
Herschel-Bulkley	τ_0^{HB}. Pa K, $Pa \cdot s^n$ n R	-0.38998 0.09858 0.83670 0.99974	-0.39625 0.11157 0.81968 0.99980	-0.40191 0.10917 0.82998 0.99979	-0.40674 0.11695 0.81780 0.99981	-0.43931 0.12279 0.81767 0.99979
Casson	τ_0^C, Pa η_C, $Pa \cdot s$ R	0.06189 0.03073 0.99805	0.08896 0.03054 0.99790	0.07872 0.03227 0.99805	0.09634 0.03155 0.99789	0.09803 0.03315 0.99782
Ellis	φ_0, $m^2 \cdot s^{-1} \cdot N^{-1}$ φ_1, $m^{2\alpha} \cdot s^{-1} \cdot N^{-\alpha}$ α R	23.3980 0.10985 2.32440 0.99985	21.5050 0.02829 2.07870 0.99988	21.4930 0.14080 -0.22946 0.99989	20.559 0.29065 -0.055 0.99989	19.814 0.21861 2.10584 0.99988

Table 2

Results of the estimation of flow curves of a stored 2% aqueous solution of CMC

Model	Constants, correlation coefficient R	Storage time				
		24h	48h	72h	96h	120h
Ostwald-de Waele	K, $Pa \cdot s^n$ n R	0.90727 0.69720 0.99939	0.92004 0.69331 0.99910	0.91859 0.69740 0.99923	0.88395 0.70268 0.99935	0.89530 0.69538 0.99906
Herschel-Bulkley	τ_0^{HB}, Pa K, $Pa \cdot s^n$ n R	-1.7035 1.2017 0.65592 0.99986	-2.0244 1.2801 0.64488 0.99977	-1.7553 1.2206 0.65567 0.99972	-1.7546 1.17943 0.66032 0.99985	-2.0339 1.25415 0.64596 0.99975
Casson	τ_0^C, Pa η_C, $Pa \cdot s$ R	2.11427 0.09373 0.99398	2.12321 0.09250 0.99299	2.13868 0.09505 0.99363	2.04337 0.09531 0.99400	2.05737 0.09151 0.99297
Ellis	φ_0, $m^2 \cdot s^{-1} \cdot N^{-1}$ φ^1, $m^{2\alpha} \cdot s^{-1} \cdot N^{-\alpha}$ α R	2.0006 0.25023 0.28292 0.99992	2.7391 0.08693 0.06439 0.99998	2.5186 0.12012 0.14292 0.99993	2.4555 0.01531 0.01935 0.99996	2.8244 0.08639 0.05874 0.99998

Table 3

Results of the estimation of flow curves of a stored 3% aqueous solution of CMC

Model	Constants, correlation coefficient R	Storage time				
		24h	48h	72h	96h	120h
Ostwald-de Waele	K, $Pa \cdot s^n$	3.03494	2.96513	3.19242	3.23465	3.20138
	n	0.62986	0.63313	0.62673	0.62444	0.62633
	R	0.99926	0.99938	0.99918	0.99925	0.99916
Herschel--Bulkleya	τ_0^{HB}, Pa	-4.6786	-4.368	-5.1657	-4.9151	-5.1889
	K, $Pa \cdot s^n$	4.14298	3.9816	4.43925	4.42778	4.45585
	n	0.58451	0.59014	0.57873	0.57872	0.57820
	R	0.99985	0.99990	0.99985	0.99985	0.99983
Casson	τ_0^C, Pa	7.24586	7.09933	7.59413	7.71615	7.61457
	η_C, $Pa \cdot s$	0.18564	0.185993	0.19071	0.18959	0.19064
	R	0.99055	0.99109	0.99013	0.99023	0.99005
Ellis	φ_0, $m^2 \cdot s^{-1} \cdot N^{-1}$	0.83424	0.75964	0.80721	0.79951	0.81431
	φ_1, $m^{2\alpha} \cdot s^{-1} \cdot N^{-\alpha}$	0.01755	0.02598	0.015	0.01491	0.0143
	α	0.017192	0.087903	-0.00174	-0.0041	-0.01046
	R	0.99998	0.99998	0.99999	0.99998	0.99998

Table 4

Results of the estimation of flow curves of a stored 4% aqueous solution of CMC

Model	Constants, correlation coefficient R	Storage time				
		24h	48h	72h	96h	120h
Ostwald-de Waele	K, $Pa \cdot s^n$	9.20391	9.8909	9.93985	9.51051	10.0187
	n	0.56257	0.553285	0.55528	0.56010	0.55465
	R	0.99866	0.99863	0.99853	0.99856	0.99879
Herschel--Bulkley	τ_0^{HB}, Pa	-14.205	-14.962	-15.535	-15.203	-14.196
	K, $Pa \cdot s^n$	13.7803	14.9024	15.1116	14.4783	14.7187
	n	0.50456	0.49450	0.49520	0.49976	0.49943
	R	0.99968	0.99968	0.99964	0.99967	0.99972
Casson	τ_0^C, Pa	21.1573	22.5749	22.7003	21.782	22.9543
	η_C, $Pa \cdot s$	0.32977	0.32861	0.33575	0.33421	0.33627
	R	0.98469	0.98393	0.98380	0.98420	0.98455
Ellis	φ_0, $m^2 \cdot s^{-1} \cdot N^{-1}$	0.34327	0.32913	0.36354	0.34996	0.30194
	φ_1, $m^{2\alpha} \cdot s^{-1} \cdot N^{-\alpha}$	0.86e-3	0.66e-3	0.41e-3	0.64e-3	0.87e-3
	α	-0.2828	-0.3234	-0.39585	-0.32444	-0.26918
	R	0.99996	0.99997	0.99993	0.99997	0.99997

the conditions of the model usability. The results of attempts at describing the curves with the other two equations indicated that a more exact fitting can be achieved with the power-law model. Correlation coefficients lower than 0.999 were achieved only for the 4% solution. The others were even higher. A less exact fitting was achieved with Casson's model. The description indicated the yield stress (21÷23 Pa) at the correlation coefficient ≅ of 0.984. In consequence, the curves were described by the O-dW model. A comparison of the constants which described the solutions under study revealed that a higher content of CMC in a solution corresponds to a higher consistency coefficient and a lower value of the flow behavior index. This means that as the concentration of a solution grows, its consistency is stiffer and the solution is less susceptible to flowing.

Table 5
Standard deviations values for the constants in the CMC solution flow curve equations according to the Ostwald-de Waele involution model

CMC	K $Pa \cdot s^n$	σ_K $Pa \cdot s^n$	n	σ_n
1% 24h	0.072	0.009	0.883	0.019
1% 48h	0.082	0.009	0.865	0.018
1% 72h	0.081	0.009	0.875	0.018
1% 96h	0.086	0.009	0.863	0.017
1% 120h	0.090	0.010	0.864	0.018
2% 24h	0.907	0.065	0.697	0.012
2% 48h	0.920	0.081	0.693	0.015
2% 72h	0.919	0.075	0.697	0.013
2% 96h	0.884	0.067	0.703	0.012
2% 120h	0.895	0.081	0.695	0.015
3% 24h	3.035	0.209	0.630	0.012
3% 48h	2.965	0.189	0.633	0.011
3% 72h	3.192	0.230	0.627	0.012
3% 96h	3.235	0.222	0.624	0.011
3% 120h	3.201	0.234	0.626	0.012
4% 24h	9.204	0.729	0.563	0.013
4% 48h	9.891	0.772	0.553	0.013
4% 72h	9.940	0.807	0.555	0.014
4% 96h	9.511	0.775	0.560	0.014
4% 120h	10.027	0.737	0.555	0.012

The results of error analysis for the consistency coefficient and the flow behavior index for all the CMC solutions under analysis described by the model equation O-dW are shown in table 5.

Changes in the properties of the stored CMC solutions were evaluated by analyzing the shear stress differences in samples stored for the shortest and the longest periods (Fig. 2A). It was found that the difference in the stress for a 1% solution stored for 24 hours and 120 hours was only 0.51 Pa, but it accounted for up to 16.7% of the reference stress, i.e. the stress in a solution stored for 24 hours. Such a large difference was a consequence of the low absolute value of the reference level (3.06 Pa). As the solution concentration grew, the shear stress and the differences between the shear of the 24h and 120h solutions increased. The reference stress for 2% solutions was 18.09 Pa and the difference was 0.57 Pa, i.e. 3.1% of the reference value. The shear stress for 3% solutions after 24 h storage was 45.87 Pa and the difference was 1.76 Pa, i.e. 3.8% of the reference value. The reference stress for a 4% solution was 104.90 Pa, and the stress in the solution after 120 h storage was 110 Pa. The difference accounted for 5.1% of the stress in the 24-hour solution. It is noteworthy that the shear stress in all the solutions stored for a long time was larger than the reference stress (Fig. 2B).

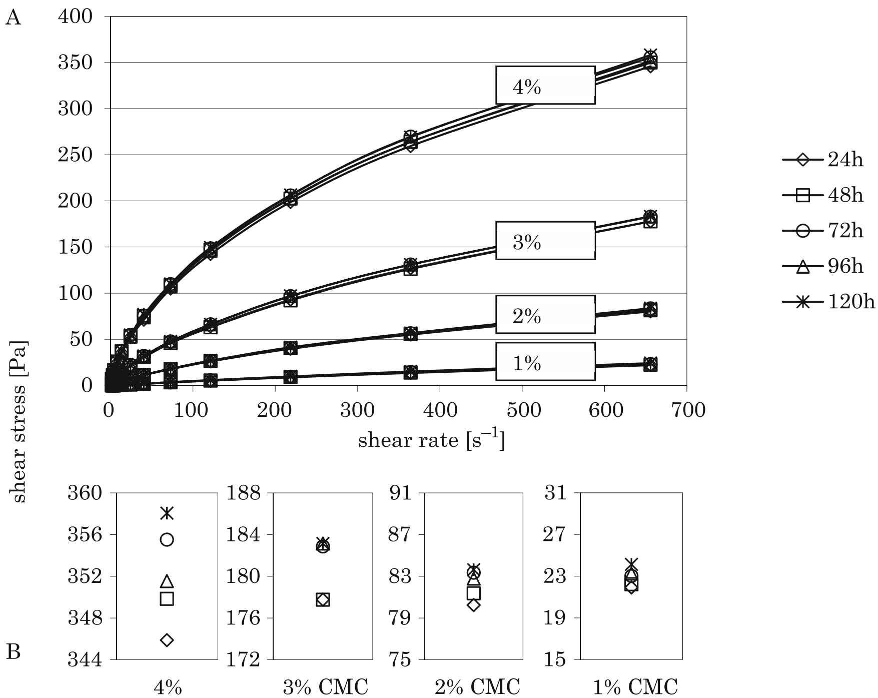

Fig. 2 *A* – Flow curves for stored CMC solutions, *B* – Distribution of measuring points at a shear rate 656 s^{-1}

This means that the storage time was a factor which strengthened the suspension structure and increased the shear stress. Only in the case of the 3% solution was the distribution of the measurement points not as distinctly proportional as for the other solutions, although this also shows the general tendency for changes in stress as a function of shear time. Therefore, it seems that aqueous solutions of CMC at concentrations below 4%, stored for

120 hours after dissolving powdered CMC can be used for experiments without fear of errors from changes in CMC properties caused by a considerable time of storage, provided that a measurement error of about 5% is accepted. This should be regarded as very convenient in planning and performing model studies of manufacturing processes in the food industry.

Conclusions

The hysteresis of the flow curve for aqueous solutions of carboxymethylcellulose at concentrations ranging from 1% to 4% can be replaced with a single curve based on mean values of shear stress determined at increasing and decreasing shear rate.

The calculated constants for Herschel-Bulkley and Ellis equations, used to describe the flow curves for the investigated solutions of CMC do not meet the conditions of the model usability. The best fitting of the curve to the measurement results can be achieved with the Ostwald-de Waele power-law model.

The difference between the shear stress in samples of CMC solutions stored for 24 hours and 120 hours, sheared at a shear rate of 72.9 s^{-1}, changed from 0.51 Pa in a 1% solution to 5.1 Pa in a 4% solution which is about a 5% change compared to the initial stress value. Such small changes in the properties of CMC solutions make it possible to use them for model studies of food products for a period of at least five days after powdered CMC is dissolved.

Translated by Joanna Jensen

Accepted for print 20.01.2015

References

Abdelrahim K.A. et al. 1994. *Effects of concentration and temperature on carboxymethylcellulose rheology*. Int. J. Food Sci. Technol., 29: 243–253.

Alcairo E.R., Zuritz C.A. 1990. *Residence Time Distribution of Spherical Particles Suspended in Non-Newtonian Flow in a Scraped-Surface Heat Exchanger*. ASAE paper, 33: 1621–1628.

Alkhaddar R.M. et al. 2001. *Residence time distribution of a model hydrodynamic vortex separator*. Urban Water, 3: 17–24.

Bailey W.J., Weir I.S. 1998. *Investigation of methods for direct rheological model parameter estimation*. J. Pet. Sci. Eng., 21: 1–13.

Butler F., McNulty P. 1995. *Time Dependent Rheological Characterisation of Buttermilk at 50C*. J. Food Eng., 25: 569–580.

Fairhurst P.G., Pain J.P. 1999. *Passage time distributions for high solid fraction solid-liquid food mixtures in horizontal flow: unimodal size particle distributions*. J. Food Engng., 39: 345–357.

Ferguson J., Kembłowski Z. 1995. *Reologia stosowana płynów*. Wydaw. Marcus, Łódź.

Holdsworth S.D. 1971. *Applicability of Rheological Interpretation of Flow and Processing Behaviour of Fluid Food Products*. J. Texture Stud., 2: 393–418.

Illicali C., Engez S.T. 1996. *Laminar flow of power law fluid foods in concentric annuli*. J. Food Engng., 30: 255–262.

JAWORSKI Z., KILJAŃSKI T. 2005. *O charakterystykach reologicznych cieczy modelowych rozrzedzanych ścinaniem*. Inż. Chem. Proc., 26: 513–522.

LAREAO C.A., FRYER P.J. 1998. *Vertical Flows of Solid-Liquid Food Mixtures*. J. Food Engng., 36: 417–443.

LIMANOWSKI J. 2001. *Zastosowanie roztworów karboksymetylocelulozy do modelowania procesów przepływu cieczy*. Inż. Rol., 2001, 10: 217–226.

PALAZOGLU T.K., SANDEEP K.P. 2002. *Effect of holding tube configuration on the residence time distribution of multiple particles in helical tube flow*. J. Food Process Eng., 25: 337–350.

PAVEZ C.M. 2002. *Properties of fluids. Fenomenos de transporte y mecanica de fluidos – aspectos teoricosi*. Universidas Mayor, Mayor.

POULESQUEN A., VERGNES B. 2003a. *A Study of Residence Time Distribution in Co-Rotating Twin-Screw Extruders. Part I: Theoretical Modeling*. Polymer Engng. Sci., 12: 1841–1848.

POULESQUEN A., VERGNES B. 2003b. *A Study of Residence Time Distribution in Co-Rotating Twin-Screw Extruders. Part II: Experimental Validation*. Polymer Engng. Sci., 12: 1849–1862.

PRUSOV A.N. et al. 2003. *Rheological Properties and Structure of Aqueous Solutions of Polysaccharides*. Solutions of Mixtures of Sodium Carboxymethylcellulose Fractions, Fibre Chem., 35: 122–127.

STEFFE J.F. 1992. *Rheological Methods in Food Process Engineering.* Freeman Press, East Lansing, Michigan.

TELIS-ROMERO J. et al. 1999. *Friction factors and rheological properties of orange Juice*. J. Food Eng., 40: 101–106.