Rheological behaviour of egg white and egg yolk from different poultry specimen

V Kumbár¹, Š Nedomová², J Votava¹ and J Buchar¹

¹Department of Technology and Automobile Transport, Mendel University in Brno, Brno, Czech Republic
²Department of Food Technology, Mendel University in Brno, Brno, Czech Republic

E-mail: vojtech.kumbar@mendelu.cz

Abstract. The main goal of this study is differences in rheological behaviour of hen (ISA BROWN), goose (Anser anser f. domestica) and Japanese quail (Coturnix japonica) egg white and egg yolk. The rheological behaviour of egg white and egg yolk was studied using a concentric cylinder viscometer. Rheological behaviour was pseudoplastic and flow curves were fitted by the Herschel-Bulkley model and Ostwald-de Waele model with high values of coefficients of determination R². The meaning of rheological parameters on friction factors during flow of egg white and egg yolk in real tube has been shown. Preliminary information on time-dependent behaviour of tested liquids has been also obtained.

Keywords: egg white, egg yolk, rheology, viscosity, shear stress, shear strain rate, fluid dynamic, thixotropy, time-dependent behaviour

1. Introduction
Rigorous knowledge of the rheological properties of food products is essential for the product development, quality control, sensory evaluation and design, and evaluation of the process equipment. The flow behaviour of a fluid can be varied from Newtonian to time dependent non-Newtonian in nature depending on its origin, composition and structure behaviour and previous history [1]. The knowledge of this behaviour is also very important for egg liquids owing to an increasing demand on the processed egg products. The term “egg products” refers to eggs that are removed from their shells for processing and convenience forms of eggs for commercial, foodservice, and home use. These products can be classified as refrigerated liquid, frozen, and dried products. Traditionally, eggs are marketed as shell eggs, but in recent years, egg consumption in the form of egg liquid products has increased [2]. Several researchers [3-10] studied the rheological characteristics of egg yolk, white and liquid whole egg and reported Newtonian as well as time-dependent non-Newtonian flow behaviour of egg. These works are summarized in [11]. Most of these studies have been usually carried out with only egg yolk. There is a lack of information about the rheological behaviour of liquid egg white at different temperature range [12]. Nearly no information are available of the rheological behaviour of liquid products of another eggs as e.g. Japanese quail eggs, which are more and more used in food industry.

Considering this lack of published information on fluid dynamics of egg yolk and egg white, the main purpose of this work was to determine rheological properties of these products for eggs of three domestic fowls: hen (ISA BROWN), goose (Anseranser f. domestica) and Japanese quail (Coturnix japonica). The meaning of these data for the calculation of friction factors for tube flow is discussed in details.
2. Materials and methods

2.1. Materials
Fresh shell eggs hen (ISA BROWN), Japanese quails (Coturnix japonica) and goose (Anseranser f. domestica), no older than 3 days, were purchased from local farms (region South Moravia). Egg shells were washed with deionized water and hand broken properly. All liquids were filtered in order to separate impurities (chalaza, membranes). Samples, with volume 200 ml, for egg yolk and egg white were prepared and stored at 4 °C before measurement. From many physical parameters which have been measured only the densities of the tested liquids are presented in the Table 1.

Table 1. Density of liquid egg products (data are displayed as mean value ± standard deviation, n=20)

| Product          | Poultry         | Density $\rho$ (kgm$^{-3}$) |
|------------------|-----------------|-----------------------------|
| Egg white        | Japanese quail  | 1020.4±1.8                  |
| Egg yolk         |                 | 1027.6±2.9                  |
| Egg white        | Hen             | 1034.1±1.9                  |
| Egg yolk         |                 | 1027.0±2.4                  |
| Egg white        | Goose           | 1035.5±2.8                  |
| Egg yolk         |                 | 1031.9±3.1                  |

2.2. Rheological measurement
Rheological measurements were carried out using an Anton Paar DV3-P rotary viscometer, equipped with a coaxial cylinder sensor system. Rotational speed ranged between 0.3 (0.279 s$^{-1}$) and 200 rpm (186 s$^{-1}$). Apparent viscosity $\eta$ which is the ratio of shear stress $\sigma$ and shear strain rate $\gamma$. By [13] it has been evaluated as:

$$\eta = \frac{\sigma}{\gamma} \text{[Pas]}$$  \hspace{1cm} (1)

All measurements were performed at the room temperature 18°C.

3. Results and discussion
In the Figures 1 and 2 the flow curves, i.e. shear stress vs. shear strain rate, are shown. These curves can be fitted using of Herschel–Bulkley model [14]:

$$\sigma = \sigma_0 + K\gamma^n$$  \hspace{1cm} (2)

Figure 1. Effect of shear strain rate on the shear stress – egg yolk
In Eq. (2), $\sigma$ is the shear stress, $\dot{\gamma}$ is the shear strain rate, $K$ is the consistency index, $n$ is the flow behaviour index and $\sigma_0$ is the yield stress.

For egg yolk and egg white of goose eggs this model reduces to the Ostwald–De Waele model, given by Eq.(3), also known as the power-law model [15]:

$$\sigma = K\dot{\gamma}^n$$

Eqs.(2) and (3) can be used for both Newtonian and power law fluids. For Newtonian fluids $n$ equals 1, and $K$ equals $\eta$ or $\eta+\sigma_0$, respectively.

The Eq.(2) can be used for the egg yolk and egg white of hen and quail. Parameters of Eq.(2) are given in the Tables 2–3 ($R^2$ is the coefficient of determination).

**Table 2.** Parameters of Herschel–Bulkley model for egg yolk

| EGG   | $\sigma_0$ (Pa) | K (Pas$^n$) | n (1)   | $R^2$  |
|-------|----------------|-------------|---------|--------|
| HEN   | 0.1466         | 1.499       | 0.8951  | 0.9999 |
| GOOSE | 0              | 2.678       | 0.8982  | 0.9989 |
| QUAIL | 0.4115         | 0.6533      | 0.9164  | 0.9999 |

**Table 3.** Parameters of Herschel–Bulkley model for egg white

| EGG   | $\sigma_0$ (Pa) | K (Pas$^n$) | n (1)   | $R^2$  |
|-------|----------------|-------------|---------|--------|
| HEN   | 0.2372         | 0.05134     | 0.672   | 0.9954 |
| GOOSE | 0              | 0.4831      | 0.457   | 0.9415 |
| QUAIL | 0.1904         | 0.007022    | 0.9192  | 0.9923 |

The apparent viscosity is given using the Eq. (1). The viscosity of tested egg liquids is shown in the Figures 3–4.

The egg liquids exhibit shear thinning behaviour. The main differences between liquids of different eggs can be observed for the egg yolks. The highest values of the apparent viscosity were achieved for the goose eggs, following by the hen eggs and the minimum values exhibited mail eggs. The differences between egg white of different eggs are not too significant. The differences in rheological properties of egg liquids are caused by chemical composition of eggs from hens, geese and quail (differences in water and lipid content).

In order to study of the time on the liquid egg products these liquids were sheared at constant shear rates (46.5 s$^{-1}$) for one hour (3600 seconds) and changes of apparent viscosity with time was considered as time dependence, see Figures 5–6.
Figure 3. Viscosity of the egg yolk

Figure 4. Viscosity of the egg white

Figure 5. Time dependence if apparent viscosity of the egg yolk
Figure 6. Time dependence of apparent viscosity of the egg white

The egg yolk exhibits typical thixotropic behaviour as is described in [4]. The egg white (especially hen and quail) is shown time-depend behaviour of apparent viscosity [16].

The experimental data were fitted by Gaussian function [17]:

\[
\eta = a_1 e^{-\left(\frac{\tau - b_1}{c_1}\right)^2} + a_2 e^{-\left(\frac{\tau - b_2}{c_2}\right)^2},
\]

where \(\eta\) is apparent viscosity, \(\tau\) is time and \(a_1, b_1, c_1\) are parameters. These parameters are given in the Table 3.

Table 3. Parameters of Gaussian model for egg yolk and egg white

| PARAMETERS: | GOOSE | HEN | QUAIL |
|------------|-------|-----|-------|
| EGG YOLK   | 410.3 | 51.25 | 489 |
|            | −148.5 | −40.28 | −1776 |
|            | 1098 | 573.9 | 2.621e4 |
|            | 5.029e7 | 1.378e4 | 6.706 |
|            | −2.057e6 | −2.124e5 | 2464 |
|            | 6.375e5 | 1.322e5 | 1050 |
|            | 0.9969 | 0.9949 | 0.9945 |
| EGG WHITE  | 3.52 | 2.321 | 10.18 |
|            | 241 | −526.7 | 1863 |
|            | 694.8 | 2052 | 6306 |
|            | 6.067e12 | 17.29 | 0.7469 |
|            | −5.343e6 | 3009 | 3853 |
|            | 1.047e6 | 8982 | 829.8 |
|            | 0.9966 | 0.9693 | 0.9264 |

The obtained rheological parameters have great meaning in many problems of industry. For example the design of piping and pumping systems requires knowledge of the pressure drop due to flow in straight pipe segments and through valves and fittings. Friction losses caused by the presence of valves and fittings usually result from disturbances of the flow, which is forced to change direction abruptly to overcome path obstructions and to adapt itself to sudden or gradual changes in the cross section or shape of the duct. This problem is described e.g. in [18]. The pressure drop is calculated using the friction factor, \(f\). The friction factor is defined as [19]:

\[
f = \frac{2 \sigma_w}{\rho v^2},
\]

where \(\rho\) is fluid density, \(v\) is the average flow velocity, and \(\sigma_w\) is the stress in the wall, given by

\[
\sigma_w = \frac{D \Delta P}{4L}.
\]

In Eq. (6), \(D\) is the tube diameter and \(\Delta P\) is the pressure drop observed in a length \(L\) of the tube. For laminar flow, the friction factor can be obtained from a simple function of the generalized Reynolds number, which is identical to the dimensionless form of the Hagen–Poiseuille equation [20]:
in which

\[ R_{eg} = \frac{D^n v^{2-n} \rho}{8^{n+1} \eta} \left( \frac{4n}{1+3n} \right)^n. \]  

Eqs. (7) and (8) can be used for both Newtonian and power law fluids. For Newtonian fluids \( n = 1 \) and \( K = \eta \). So that the generalized Reynolds number (Eq. (8)) is reduced to well-known number \( Re = D v \rho / \eta \).

The values of generalized Reynolds number for egg liquids tested in this article are given in the Table 4. Under turbulent flow conditions, the existing correlations to estimate the friction factor are semi-empirical. For power law fluids, probably the best-known correlation is that presented by \[21\]:

\[ \frac{1}{\sqrt{f}} = \frac{4}{n^{0.75}} \ln \left( R_{eg} f^{1-n} \right) - \frac{0.4}{n^{1.2}}. \]

Let us consider a cylindrical tube of diameter \( D = 0.01 \) m and an average flow velocity \( v = 1 \) m/s. This type of tube is usually used in pasteurize process of egg products. The values of generalized Reynolds numbers are given in the Table 4.

### Table 4. Reynolds numbers given by the Eq. (8)

| Poultry            | \( R_{eg} \) (Egg yolk) | \( R_{eg} \) (Egg white) |
|--------------------|--------------------------|---------------------------|
| Japanese quail     | 27                       | 2444                      |
| Hen                | 13                       | 1670                      |
| Goose              | 7                        | 718                       |

The Reynolds number describes namely the transitive from laminar to turbulent flow. One can see that the highest \( R_{eg} \) of yolk and white exhibits the quail eggs and the smallest one the goose eggs.

Laminar flow of a power law fluid exists in the tube when:

\[ R_{eg} \leq (R_{eg})_{\text{critical}}. \]

The critical value of the power law Reynolds number depends on the value of the flow index behaviour \( n \) according to \[22\]:

\[ (R_{eg})_{\text{critical}} = 2100 + 875(1 - n). \]

Values of critical Reynolds number vary from 2888 at \( n = 0.1 \) to the familiar value 2100 for Newton liquids \((n = 1)\). In all cases the flows of liquid egg products are laminar.

The next application of the rheological properties is connected with continuous thermal processing system. Such system generally involves a heat exchanger in form of a tube. A length of this tube is known as a „hold tube”, must be sufficient in order to achieve sufficient fluid residence time. Because the hold tube is a critical part of the system, understanding velocity profiles found in tube flow is important for the numerical simulation of thermal process.

For power law fluid in laminar flow the velocity \( v(x) \) is function of the distance \( x \) from the centre of the pipe:

\[ v(x) = \left( \frac{\Delta P}{2 \pi L} \right)^{\frac{1}{n}} \left( \frac{n}{n+1} \right) \left( R \frac{n+1}{n} - x \frac{n+1}{n} \right), \]

where \( \Delta P \) denotes the driving over pressure, \( L \) is the tube length and \( R \) is its radius. For the illustration the values of \( R = 0.05 \) m, \( L = 1 \) m and \( \Delta P = 300 \) Pa were chosen. This values are usually used in pasteurize process of egg products. Results are shown in the Figures 7–8.
The higher values of flow velocities are observed for the flow of egg white. The lowest one was achieved for the flow of egg yolk. Velocities are different for different eggs. Liquids of the goose eggs exhibited the lowest values. The highest values of egg white were observed for the hen eggs. The maximum of the flow velocity of the egg yolk was observed for the quail eggs.

The velocity equation given above is valid for fully developer undisturbed flow in straight, horizontal tubes. Real processing systems contain many elements like valves, tees, elbows, etc. that cause fluid mixing during flow [23-26]. In addition pipe vibration caused by energy inputs from pumps may contribute to mixing. It means that the equation given above represents only general guidelines in examining velocity profiles during tube flow.

4. Conclusion
Rheological properties of liquid egg yolk and egg white were studied for the eggs of three poultry species – hen (Isa Brown), Japanese quail (Coturnix japonica) and goose (Anseranser f. domestica). Experimental data were successfully fitted to Ostwald-De Waele and Herschel-Bulkley model. The egg liquids exhibit shear thinning behaviour. The main differences between liquids of different eggs can be observed for the egg yolk. The highest values of the apparent viscosity were achieved for the goose eggs, following by the hen eggs and the minimum values exhibited mail eggs. The differences in rheological properties of egg yolk are caused by chemical composition of yolks from hens, geese and quail (differences in water and lipid content). In the publication [27] is described that the goose eggs (especially yolk) contained the highest contents of saturated and monounsaturated fatty acids but the lowest content of polyunsaturated fatty acids (PUFA). The ω-3 PUFA content and the ω-6/ω-3
ratio were higher in the yolks of goose. It can cause the higher values of apparent viscosity of goose yolk. The differences between egg white of different eggs are not too significant.

The practical importance of knowledge of rheological parameters was outlined. These parameters can be used in much software dealing with a numerical simulation of flow problems.

Acknowledgement
This work was supported by the project TP 6/2015 „Impact loading of agricultural products and foodstuffs“, financed by IGAFA MENDELU.

References
[1] Migliori M, Gabriele D, Baldino N, Lupi FR, de Cindio B: *Journal of Food Process Engineering* **34** (2011) 1266-1281.
[2] de Jesus MN, Zanqui AB, Valderrama P, Tanamati A, de Souza NE, Matsushita M *Food Science and Technology* **33** (2013) 549-554.
[3] Jones DR: *International Journal of Poultry Science* **6** (2007) 157-162.
[4] Atilgan MR, Unluturk S: *International Journal of Food Properties* **11** (2008) 296–309.
[5] Takeuchi J, Nagashima T: *Food Science and Technology Research* **16** (2010) 149-156.
[6] Toyosaki T: *Poultry Science* **89** (2010) 1009-1014.
[7] Alamprese C, Casiraghi E, Rossi M: *International Journal of Food Science and Technology* **47** (2012) 2503-2509.
[8] de Souza PM, Fernández A *Food Hydrocolloids* **31** (2013) 127-134.
[9] Toyosaki T, Sakane Y: *Advances in Food Science and Technology* **5** (2013) 1351-1354.
[10] Navidghasemizad S, Temelli F, Wu J: *LWT - Food Science and Technology* **55** (2014) 170-175.
[11] Singh J, Sharma HK, Premi M, Kumari K: *Journal of Food Science and Technology* **51** (2014) 543-550.
[12] Telis-Romero J, Thomaz CEP, Bernardi M, Telis VRN, Gabas AL: *Journal of Food Engineering* **74** (2006) 191-197.
[13] Steffe JF: Introduction to rheology. In Rheological methods in food process engineering, Freeman Press, East Lansing (1996).
[14] Travnicek P, Kralova E, Vitez T: *Polish Journal of Environmental Studies*, **22** (2013) 1499-1504.
[15] Antunes SA, Lanza M, Hense H.: *Industrial Crops and Products* **46** (2013) 111-116.
[16] Riscardo MA, Moros JE, Franco JM, Gallegos C: *European Food Research and Technology*, **220** (2005) 380-388.
[17] Kumbár V, Nedomová Š, Strmková J, Bucha J: *Journal of Food Engineering*, **156** (2015) 45-54.
[18] Cabral RAF, Telis VRN, Parkb KJ, Telis-Romero J: *Food and bioproducts processing* **89** (2011) 375-382.
[19] Garcia EJ, Steffe JF: *Journal of Food Process and Engineering* **9** (1987) 93-120.
[20] Tao J, Chen S, Su W: *Mechanics and Astronomy* **56** (2013) 263-269.
[21] Bahrani SA, Nouar C: *Journal of Applied Fluid Mechanics* **7** (2014) 1-6.
[22] Steffe JF, Daubert CR: Bioprocessing Pipelines: Rheology and Analysis. Freeman Press, Michigan (2006).
[23] Telis-Romero J, Polizelli MA, Gabas AL, Telis VRN: *Canadian Journal of Chemical Engineering* **83** (2005) 181–187.
[24] Girón-Palomares B, Hernández-Guerrero A, Romero-Méndez R, Oviedo-Tolentino F: *International Journal of Heat and Fluid Flow*, **30** (2009) 158-171.
[25] Wu B: *Water Research*, **44** (2010) 1507-1519.
[26] Courtois P, Ettefat R, Chen J: *Appl. Rheol.* **16** (2006) 275-286.
[27] Wang Q, Jin G, Jin Y, Ma M, Wang N, Liu C, He L: *European Journal of Lipid Science and Technology*, **116** (2014) 1044-1053.