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STARCH GELATINISATION IN COUETTE-TAYLOR FLOW APPARATUS

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In this paper starch gelatinisation in Couette-Taylor flow (CTF) apparatus (equipped with a water heat jacket) has been investigated. CTF (characterised by the presence of Taylor vortices) provides good environment for gelatinisation, e.g. effective mixing, fast heat transfer, positive influence on starch rheological properties. During experiments starch gelatinisation degree and starch swelling has been studied. It was accompanied by temperature measurements performed along the apparatus. Additionally, starch gelatinisation was investigated by computer simulation. A complete starch gelatinisation was obtained for the shortest investigated residence time in the apparatus when the temperature in the heat jacket was above 85 °C. Nevertheless, it seems that it is still possible to reduce a residence time value, as well as, the value of T_{hj}, but it may require some acceleration of rotor rotation. The swelling degree of gelatinised starch increased with growing values of residence time, rotor rotation and process temperature. Heat transferred could be affected by the structure of the Taylor vortex flow. No significant destruction of starch granules was observed during the treatment in Couette-Taylor flow apparatus. A quite satisfactory agreement between computer simulation and experiments results was achieved.

Keywords: starch gelatinisation, Couette-Taylor flow, computer simulation

1. INTRODUCTION

Starch is a biopolymer, which consists of two kinds of polysaccharides: amylose, which is characterised by linear molecules, and amylopectin, whose molecules are bigger than those of amylose but are highly branched. Starch gelatinisation (a process frequently used in food industry e.g.: food sterilisation, starch hydrolysis) takes place when heat is added to aqueous starch suspension and temperature increases to about 60 °C. During gelatinisation starch (mostly amylose) dissolves in water, simultaneously starch granules (composed of amylopectin) swell by absorbing water. This is accompanied by a significant and rapid increase in the apparent viscosity of suspension, which obviously causes serious problems. Additionally, in order to avoid separation of starch granules from water and to ensure sufficient mass transfer coefficients, agitation of the suspension is needed (Sakonidou et al., 2003).

In industry, jet cooker is typically used for starch simultaneous gelatinisation and liquefaction, when geletinisation is the first step of enzymatic starch hydrolyses e.g. Baruque Filho et al. (2000). The utilisation of a jet cooker is, however, limited to rather small starch concentrations (see Baks et al., 2008), because of a very high apparent viscosity of the gelatinised starch. On the other hand, many authors recommend applying an extruder for processing concentrated starch slurries. A good review of the papers on gelatinisation in extruders can be found in Baks (2008).

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In the presented investigations, starch gelatinisation was conducted in a Couette–Taylor flow apparatus. It is worth noting that because of its interesting feature, Couette-Taylor flow has been studied by many researchers. Let us name only a few recently published examples: biotechnology Zhu et al. (2010); multiple emulsion preparation Dluska and Markowska-Radomska (2010), liquid–solid flow Saomoto et al. (2010); and precipitation Jung et al. (2010). Couette-Taylor flow takes place between two coaxial cylinders with the inner one rotating (rotor). Such a flow is characterised by the presence of Taylor vortices, which occur above the critical rotor rotation frequency (ω_c). The value of ω_c depends on apparatus geometry and fluid properties. The most significant advantage of using Couette-Taylor flow for starch gelatinisation seems to be a positive influence of shear stress field (generated by rotor rotation) on starch slurry rheological properties by causing a significant reduction of starch slurry apparent viscosity. Taylor vortices (similar to Dean vortices in Kelder, 2004) also ensure good heat transfer conditions, uniform heating and an effective (but gentle) mixing of the suspension. Additionally, there is a possibility of almost independent adjustment of mixing intensity and residence time of reactants in the apparatus (by controlling rotor rotation and axial flow). It is expected that CTF apparatus will enable to process much more concentrated starch slurry than a jet cooker or coil heater. Starch granules should also be less damaged during treatment in CTF apparatus than in an extruder.

The objective of this work was to find a range of values of the operating parameters which ensure complete starch conversion during gelatinisation. Therefore, during the experiments the degree of starch gelatinisation (*DSG*) was measured. Moreover, in order to test how treatment in Couette-Taylor flow influences the properties of gelatinised starch, the swelling degree of starch granules (*SGDS*) was measured and structure of gelatinised starch was observed using light microscopy. This paper reports the first approach to understanding the problem of starch gelatinisation in CTF apparatus, hence gelatinisation of low starch concentration was investigated.

2. EXPERIMENTS

Starch gelatinisation experiments were carried out in a continuous Couette-Taylor flow apparatus with a water heat jacket see Fig. 1. The length of the apparatus was 0.3 m; the radius of inner and outer cylinder was $R_1 = 0.016$ and $R_2 = 0.026$ m, respectively. The operating parameters are presented in Table 1. In order to check heat transfer performance in the apparatus, temperature of working fluid was measured at the midway between the cylinders. The measurements were made at 3 points that were located at the distance of 0.05, 0.15 and 0.25m from the inlet of the apparatus.

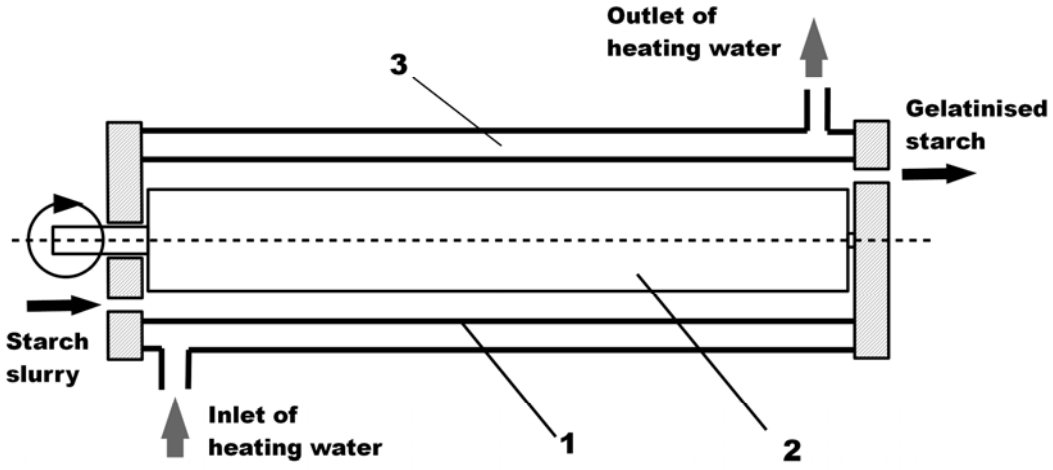

Fig. 1. Couette-Taylor flow apparatus: 1-outer cylinder, 2- rotor, 3-heat jacket

Table 1. Conditions of experiments

Inlet ungelatinised starch concentration [kg/m^3]	50
Inlet axial velocity of starch slurry u [m/s]	0.00016 - 0.00099
Inlet temperature of starch slurry [ºC]	20
Temperature of the water in heat jacket T_{hj} [ºC]	60, 65, 73, 85, 90
Rotor rotation frequency ω [1/s]	5.78, 11.57, 19.27

2.1. Degree of starch gelatinisation (DSG) measurements

A sample taken at the outflow of the apparatus was immediately cooled (in order to stop the process of gelatinisation) in an aluminium vessel (with a thin wall). The outside of the vessel was covered with 1 cm layer of ice (about -5 ^{o}C). The procedure was similar to that described in Beleia (2006), where a sample was cooled in ice-cold water. Subsequently, the sample was frozen and dried by using freeze-dryer (Christ Alfa 1-4) in the temperature -30. Having been dried the sample was ground and sieved to obtain fine powder which can be easily dissolved.

The degree of gelatinisation was estimated by using amylose–iodine complex formation method, described in Birch and Priestley (1973) and Baks et al. (2007). The freeze dried sample (0.04 g) was dissolved in 50 ml of KaOH (0.15 M) and then the solution was mixed for 15 min. Afterwards, the part of the sample, which was not dissolved, was separated using high speed centrifuge. In the next step of the procedure, 1 ml of the supernatant was added to 8.1 ml of HCl (0.018 M) in order to be neutralised and next 1 ml of iodine reagents (0.1 g iodine and 0.4 g potassium iodide in 100 ml water) was added to this solution. Finally, light absorbance (Abs1) was measured at room temperature and light wavelength 600 nm. The light absorbance measurement was performed using Helios spectrophotometer. The procedure was repeated using 0.4 M KOH and (0.05 M) HCl in order to dissolve all the amylose present in the sample. Afterwards, the value of Abs2 was measured. According to Birch and Priestley (1973) and Baks et al. (2007) the ratio of Abs1/Abs2 should give a measure of starch gelatinisation degree.

2.2. Measurements of starch granules swelling degree

A sample taken at the outflow of the apparatus was immediately cooled to the ambient temperature. Its structure was observed using light microscopy. A part of the sample (about 10 ml) was centrifuged for 15 min and the supernatant was removed. The remaining part was weighted (to measure *M1*), then freeze-dried and once again weighted (to measure *M2*). The ratio *M1/M2* will be called (for the purpose of this paper) a starch granules swelling degree (*SGSD*). The method of *SGSD* measurement is an adapted method of starch swelling power measurement described in: Mitrus et al. (2010) and in Li and Yeh (2001). The value of swelling power in Li and Yeh (2001) was estimated after heating starch aqueous suspension for 1 h in a chosen temperature. The authors probably expected to achieve a kind of equilibrium; therefore swelling power is probably a maximum value of *SGSD* for given conditions. In our case it was not checked whether or not the equilibrium of starch granules swelling was achieved, and the time of treatment was shorter than 1 h. This is why it was decided to use a term *SGSD* instead of swelling power.

SGSD is a measure of degree to which starch granules swell in experiments. This parameter says how much water was absorbed by starch granules during gelatinisation in given values of the operating parameters.

2.3. Starch origin and its properties

During the experiments unmodified wheat starch from Sigma-Aldrich (S5127) was used (11% of moisture contents and 0.2% of protein). It is commonly accepted that an average concentration of amylose and amylopectin in wheat starch is 25% and 75 %, respectively.

3. THE CFD SIMULATION

A numerical simulation of starch gelatinisation requires simultaneous calculation of flow hydrodynamics, heat transfer and starch transformation rate. Such numerical calculations require knowledge of a model describing rheological properties of wheat starch slurry during the entire process of gelatinisation. We could find a sufficiently developed model only for cross linked waxy maize (Kelder et al., 2004). This model was not valid in our case where gelatinisation of unmodified wheat starch was investigated. Additionally, even this rather sophisticated model needed an artificial assumption about the initial value of starch apparent viscosity in order to ensure laminar flow regime along the whole apparatus (Kelder et al., 2004). It stems from the fact that starch apparent viscosity grows significantly during gelatinisation, which may cause a transition of flow regimes from turbulent vortex flow to laminar flow with or without vortices along the apparatus. It can be the reason for serious numerical problems.

Taking into account the aforementioned information it is not yet possible to carry out a complete numerical simulation of wheat starch gelatinisation in Couette-Taylor apparatus. Nevertheless, it is possible to conduct some simplified calculations, which can help to understand how Couette-Taylor flow pattern affects process of gelatinisation. Therefore, in order to check how the vortex structure (which is related to the circumferential to axial velocity ratio) may affect starch gelatinisation, it was assumed that the working fluid has a constant value of apparent viscosity during the calculations. The value of that viscosity was chosen (Jung et al., 2000) so that the apparatus would operate just at the critical value of rotor rotation frequency:

- μ = 0.0123 Pas for ω = 5.78 1/s
- μ = 0.0246 Pas for ω = 11.56 1/s
- μ = 0.0411 Pas for ω = 19.27 1/s

In such a case the expected flow regime in the apparatus was laminar vortex flow characterised by axially symmetrical Taylor vortices. The presence of these vortices was confirmed by calculations. Calculations were also carried out for μ = 0.0123 Pas and ω = 0 1/s, which represents laminar flow without vortices. It is important to underline, that it was not possible to conduct experiments for ω = 0 1/s, because of intensive separation of starch and water. Although this simplified approach could not predict real hydrodynamics of the flow during starch gelatinisation, it enabled to look at the influence of Taylor vortices structure on the rate of starch gelatinisation.

Other properties of the working fluid were assumed to be constant during the calculations: density 998.2 kg/m^3, heat capacity C_p=4182 J/(kg °C), and thermal conductivity 0.6 W/(m °C). According to Brandam et al. (2003) cereal starch transformation during gelatinisation can be approximated by the first order reaction:

ungelatinised starch → gelatinised starch

$$r_g = k_g \, exp\left(\frac{E_g}{RT}\right) C \tag{1}$$

Where r_g is the rate of starch gelatinisation, C is ungelatinised starch concentration, and $k_g = 5.7 \cdot 10^{31}$ 1/s, $E_g = 220.6$ kJ/mol for $T < 60$ºC, $k_g = 3.1 \cdot 10^{14}$ 1/s, $E_g = 108.3$ kJ/mol for $T > 60$ ºC. Because starch transformation is approximated by the first order reaction, its rate is affected mostly by heat transfer from the wall into the fluid.

All the calculations presented in this work have been conducted using Ansys 12.1.2 (Fluent) computer code assuming steady state conditions and incompressible flow. Computer calculations were conducted in 2D geometry applying axisymmetric swirl model, based on the assumption that Taylor vortices are axially symmetric. Such an assumption provides a correct approximation of hydrodynamics of CTF apparatus, see e.g. Coufort et al. (2005). Axisymmetric swirl model is based on the assumption that there is no circumferential gradient in the flow, although, there may be no-zero circumferential or swirl velocity. Such an approach simplified equations describe transfer of momentum, heat and mass. The model can be expressed by the following equations (see Ansys 12.1.2 documentation):

1. Continuity and momentum equations:

$$\frac{\partial u_x}{\partial x} + \frac{\partial u_r}{\partial r} + \frac{u_r}{r} = 0 \tag{2}$$

$$\rho\left(u_r \frac{\partial u_r}{\partial r} - \frac{u_\theta^2}{r} + u_x \frac{\partial u_r}{\partial x}\right) = -\frac{\partial p}{\partial r} + \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r u_r)}{\partial r}\right) + \frac{\partial^2 u_r}{\partial x^2}\right] \tag{3}$$

$$\rho\left(u_r \frac{\partial u_\theta}{\partial r} + \frac{u_\theta u_r}{r} + u_x \frac{\partial u_\theta}{\partial x}\right) = \mu\left[\frac{\partial}{\partial r}\left(\frac{1}{r}\frac{\partial (r u_\theta)}{\partial r}\right) + \frac{\partial^2 u_\theta}{\partial x^2}\right] \tag{4}$$

$$\rho\left(u_r \frac{\partial u_x}{\partial r} + u_x \frac{\partial u_x}{\partial x}\right) = -\frac{\partial p}{\partial x} + \mu\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial (u_x)}{\partial r}\right) + \frac{\partial^2 u_x}{\partial x^2}\right] \tag{5}$$

where x is the axial coordinate, r is the radial coordinate, u_x is the axial velocity, u_r is the radial velocity, u_θ is the angular velocity, and p - pressure. It was assumed that because of rotor rotation and a high value of apparent viscosity the effect of gravitation was negligible.

2. Energy conservation equation:

$$\rho C_p\left(u_r \frac{\partial T}{\partial r} + u_x \frac{\partial T}{\partial x}\right) = \lambda\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial T}{\partial r}\right) + \frac{\partial^2 T}{\partial x^2}\right] \tag{6}$$

The source of energy due to starch transformation during gelatinisation was neglected here, because it was small in comparison to the heat needed for temperature increase (compare the data about enthalpy of gelatinisation in e.g. Baks et al., 2007).

3. Species transport equation:

$$\rho\left(u_r \frac{\partial X_j}{\partial r} + u_x \frac{\partial X_j}{\partial x}\right) = D_j \rho\left[\frac{1}{r}\frac{\partial}{\partial r}\left(r\frac{\partial X_j}{\partial r}\right) + \frac{\partial^2 X_j}{\partial x^2}\right] + R_j \tag{7}$$

where X_j – the mass fraction of species j, D_j – is the dispersion (diffusion) coefficient of species j (its value was arbitrary chosen to be 10^{-13} m^2/s because of a relatively big size of starch granules), and R_j is the net rate of production of species j by chemical reaction (in this case it is just starch transformation rate). In our model it was assumed that there are 3 species: water, ungelatinised starch and gelatinised starch. Equation (7) was solved for water ($R_j = 0$) and ungelatinised starch ($R_j = -r_g$). Gelatinised starch mass fraction was calculated as one minus the sum of the mass fractions of other species.

As was noted earlier the calculations were conducted in 2D geometry. The size of the investigating apparatus was: rotor radius $R_1 = 0.016$ m, outer cylinder radius $R_2 = 0.026$ m, and length of the apparatus was $L = 0.4$m. The boundary conditions were defined in the following way:

- *Inlet boundary conditions*: constant axial inlet velocity $u_x = 0.00099$ m/s (u_r and $u_\theta = 0$), temperature of fluid $T = 20$ C, mass fraction of water and ungelatinised starch was 0.95 and 0.05 respectively.
- *Outer cylinder boundary condition*: $u_\theta = u_r = u_x = 0$, temperature of the wall T_{hj} was constant for given calculations and its value was between 60 and 85°C, no mass transfer through this wall.
- *Rotor*: $u_r = u_x = 0$, $u_\theta = \omega R_1$ (ω =5.78 or 11.56 or 19.27 1/s), no heat and mass transfer through this wall.
- *Outlet boundary conditions*: because of the possibility of "back flows" at the outlet form the apparatus, Fluent Pressure Outlet Boundaries were chosen. It was assumed that the gauge pressure was 0 for $R_1 = 0.016$ m, for other radial positions the pressure was calculated using the expression $\frac{\partial p}{\partial r} = \frac{\rho u_\theta^2}{r}$. This boundary condition also allows to assume back flow temperature and back components concentration. The calculation was repeated until the results were not influenced by this assumption. Additionally, the calculations were conducted assuming that the axial gradients of variables at the outlet plane are zero. These calculations were carried out for the length of the apparatus which equalled 0.4 m and 0.6m (in the latter case at the location between 0.4 and 0.6 m from the inlet to the apparatus no rotor rotation was imposed). No significant influence of the outlet boundary conditions on the results was observed at the distance of 0.3 m from the inlet of the apparatus (it corresponds to the length of the experimental apparatus).

A staggered grid with a cell number of 16 000 was used in the calculations. The calculations were later repeated using 64 000 cells grid with no significant impact on the results. The second order upwind scheme was used to discretise the equations. The pressure-velocity coupling for incompressible flow was performed using flows SIMPLE schemes.

4. RESULTS OF EXPERIMENTS

The heat transfer performance of the apparatus is illustrated in Fig. 2. It can be seen that rotor rotation intensified heat transfer from the wall into the fluid. The temperature for $\omega = 5.78$ 1/s was relatively lower than for $\omega = 11.56$ and $\omega = 19.27$ 1/s. An explanation can be provided by consideration how flow hydrodynamics influences heat transfer. It is easy to deduct that Couette-Taylor flow hydrodynamics during starch gelatinisation is characterised by the presence of Taylor vortices in the inlet zone of apparatus, where apparent viscosity of starch slurry is still low. The character of these vortices can be even turbulent. However, it changes gradually along the apparatus as a result of increasing viscosity. Eventually in the far end of the apparatus, flow becomes laminar without vortices. The heat transfer intensified by the presence of Taylor vortices in the inlet zone of the apparatus slows down when these vortices disappear. For $\omega = 5.78$ 1/s the length of the zone, where Taylor vortices exit, is of course shorter and the vortex mixes less effectively than for $\omega = 11.56$ and $\omega = 19.27$ 1/s.

The results presented in Fig. 2 were obtained for the shortest investigated residence time in the apparatus. It is obvious that when the residence time increases the temperature in the apparatus also goes up and its value becomes less influenced by rotor rotation.

When the temperature in the heat jacket was 85 or 90°C the measurements of starch gelatinisation degree were independent from the operating parameters, because the rate of the process was sufficiently quick to ensure complete starch gelatinisation. It is interesting to note that a complete conversion was achieved even for the highest investigating axial velocity $u = 0.00099$ m/s, which

denotes the shortest residence time in the apparatus (5 min). Consequently, the next tests were conducted just for that value of axial velocity (Fig.3). Still, father reduction of residence time seems to be possible. Conversion of starch was also very high at T_{hj} = 73°C. When the value of T_{hj} was below 73ºC the degree of starch gelatinisation (*DSG*) increased with a growing value of heat jacket temperature. Moreover, an increase in the value of rotor rotation frequency caused a growth in *DSG*, see Fig.3.

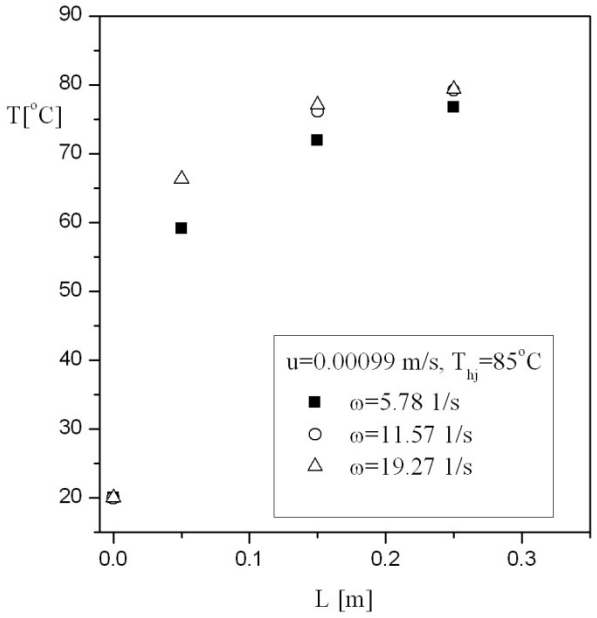

Fig. 2. Temperature distribution along the length of apparatus

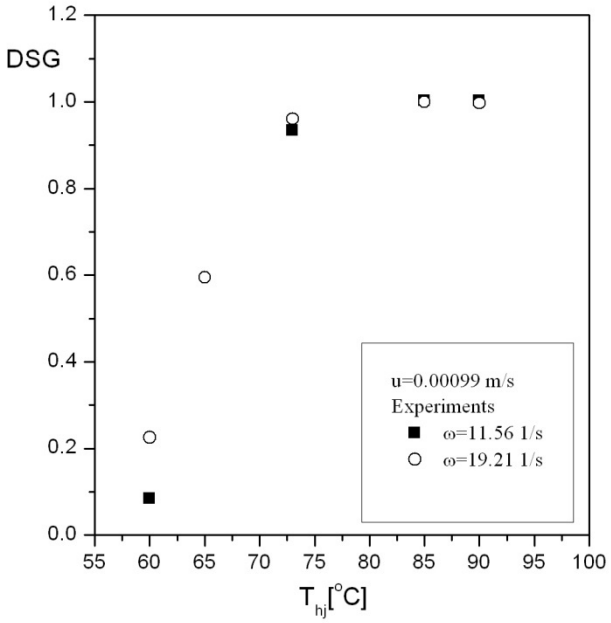

Fig. 3. Starch gelatinisation degree

The results of the experiments reported in Hubacz et al. (2010) and Matsuka et al. (2010) showed that the properties of gelatinised starch depend on the values of such parameters as residence time in CTF apparatus, ω and T_{hj}. Any growth in the values of these parameters stimulated a growth in the values of gelatinised starch apparent viscosity and in concentration of dissolved starch (amylose). This phenomenon can be explained (at least partly) by swelling of starch granules during their

thermomechanical treatment. This phenomenon is connected to starch pasting and starts after starch gelatinisation, (Nelles et al., 2000). When starch granules swell their size increases (compare Fig. 4), which causes augmentation of gelatinised starch apparent viscosity. Additionally, water absorption by swelling of starch granules is the reason for change in the concentration of dissolved amylose.

The results of measurements of starch granules swelling degree (*SGSD*) are shown in Table 2. Although starch gelatinisation conducted in such conditions (compare Fig.3 and Table 2) was complete, it was still possible to increase the value of *SGSD* by changing values of operating parameters. As expected, the value of *SGSD* increased when rotor rotation frequency and heat-jacket temperature increased. The value of *SGSD* seems to be connected with the amount of heat absorbed by starch slurry. On the contrary, *SGSD* decreased when axial velocity increased, because of the reduction of starch residence time in the apparatus. It is also worth noting that *SGSD* was not significantly influenced by the operating parameters for $u = 0.099$ cm/s (the highest value of the investigated axial velocity). It probably stems from the fact that the residence time of starch in the apparatus was short in comparison with the rate of water absorption by starch granules. According to the literature, Li and Yeh (2001), starch selling power could reach a value up to 20-40 kg/kg after heating in 80-90^{o}C for 1h. In the presented experiments the maximum obtained value of *SGSD* was 9.44g/g and the treatment time was much shorter than 1 h. It means that the equilibrium of starch swelling was probably not achieved and starch granules were still capable of absorbing quite a significant amount of water. Therefore, it was possible to notice that *SGSD* affected the operating conditions.

Table 2. The swelling degree of starch granules

u [m/s]	ω [1/s]	T_{hj} [ºC]	*SGSD* [kg/kg]
0.00033	5.78	85	7.50
0.00033	11.56	85	7.88
0.00033	19.27	90	9.44
0.00066	11.56	85	6.81
0.00066	19.27	85	7.96
0.00066	19.27	90	8.40
0.00099	5.78	85	6.07
0.00099	11.56	85	6.89
0.00099	11.56	90	6.79
0.00099	19.27	90	6.75

It is known that starch granules can be destroyed during thermomechanical treatment (e.g. van den Eiden et al., 2003) even in case of small starch concentrations (Lipatova et al. 2006). In order to check whether or not it happened in CTF apparatus light microscopy was used to observe the structure of gelatinised starch, see Fig. 4. No mechanical destruction of starch granules was noticed for the experimental conditions. Similarly, thermal starch degradation of starch granules was not visible. The temperature of the process was probably too low to cause thermal destruction of granules (Barron et al., 2001). Nevertheless, when comparing photos in Fig.4 it is possible to notice how starch granules swell when temperature and time of treatment increase. This observation agreed with the *SGSD* measurements.

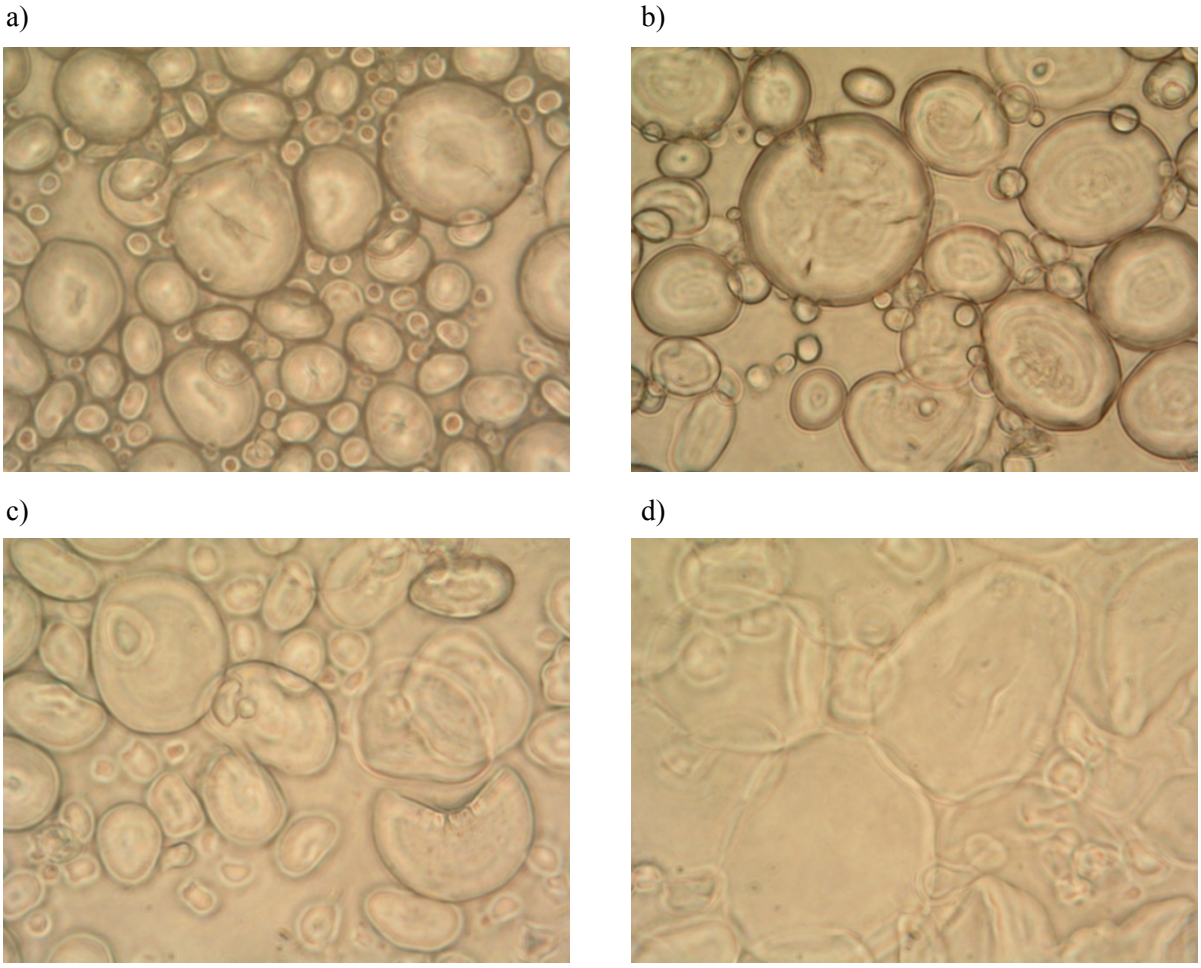

Fig. 4. a) native starch; Starch slurry after treatment in the following conditions: b) u = 0.00099m/s, ω = 11.56 1/s, T_{hj} = 60 °C; c) u = 0.00099 m/s, ω = 19.56 1/s, T_{hj} = 65°C, d) u = 0.00099 m/s, ω = 19.56 1/s, T_{hj}=85°C

4.1. Impact of Taylor vortex flow on starch gelatinisation

The results of the calculations are presented in Fig. 5. Starch conversion in case of laminar flow without vortices (ω = 0 1/s) was significantly lower than in other cases. The value of *DSG* was below 0.6 even when the temperature of the outer cylinder was 90 °C. The reason for this was a very weak heat transfer from the wall to the fluid in the absence of vortices.

The presence of Taylor vortices provided much better heat transfer conditions. However, the influence of rotor rotation was visible. The values of *DSG* were lower for ω = 5.78 1/s than for ω = 11.57 and 19.27 1/s especially when calculations were carried out for low values of outer cylinder temperature. In contrast, the results obtained for ω = 11.57 1/s and 19.27 1/s were close to each other. It can be explained by the so called "windy flow", which was already reported by Wereley and Lueptow (1999). Windy flow is defined as a stream of fluid winding around vortices centre, see Fig. 6. A significantly strong windy flow was observed for ω = 5.78 1/s, which is related to a relatively low value of ω to u ratio. Windy flow influences heat transfer in a negative way, because heated fluid from outer parts of vortices moves in the axial direction leaving behind unheated fluid in the vortex centre. This phenomenon might be another reason why the experimentally measured temperature for u = 0.00099 m/s was the lowest for ω = 5.78 1/s (see the results in Fig. 2). However, an increase of rotor rotation frequency mitigates the impact of windy flow, see Fig. 6. A similar effect can be obtained by reduction of axial flow.

Fig. 5 also shows a comparison between the values of *DSG* estimated in a numeric and experimental way, for the same axial flow and rotor rotation frequency. Quite a good agreement of the experiments with numerical simulation was achieved. In both cases a significant intensification of starch gelatinisation was visible when compared to calculations conducted for a laminar flow without vortices. It indicates in an indirect way the presence of Taylor vortices in flow during the experiments.

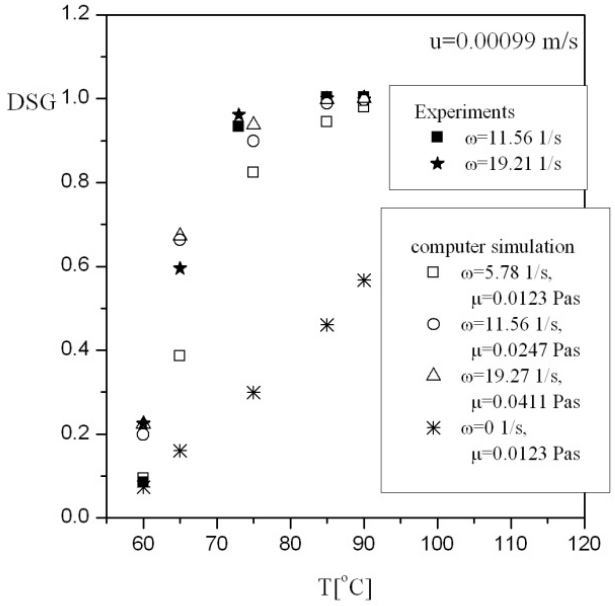

Fig. 5. Comparison of experimentally estimated values of starch gelatinisation degree with computer simulation. Symbol *T* denotes temperature of the outer cylinder (in the calculations) and heat jacket temperature (in the experiments)

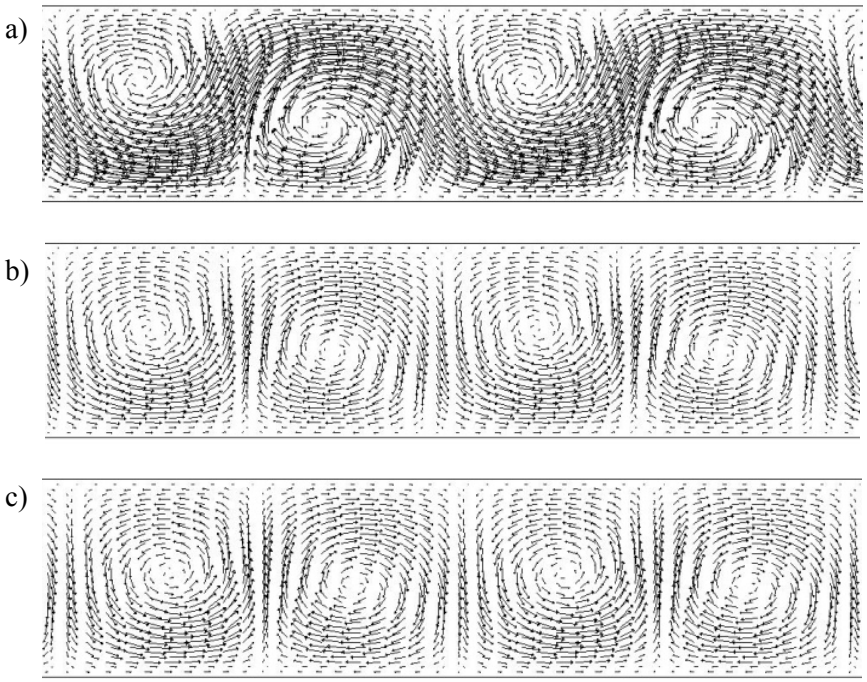

Fig. 6. Axial-radial velocity vectors for u = 0.00099 m/s: a) ω = 5.78 1/s and μ = 0.0123 Pas, b) ω = 11.56 1/s and μ = 0.0246 Pas, c) ω = 19.27 1/s and μ = 0.0411 Pas. Strong windy flow is visible for ω = 5.78 1/s, but it disappears when rotation increases

An apparent discrepancy between the experimental results and numerical simulations for T_{hj} = 60 °C and ω = 11.56 1/s can be explained by the fact that the numerical simulations predicted the existence of Taylor vortices along the whole length of the apparatus, while in the reality they existed only in the entrance part of the apparatus. This problem could be overcome by rotor rotation acceleration e.g. there are no differences between the numerical and experimental values of *SDG* estimated for T_{hj} = 60 °C and ω = 19.56 1/s, see Fig. 5. The increase of rotor rotation frequency caused lengthening of the zone, where Taylor vortices exist, and intensification of mixing in this zone.

5. CONCLUSIONS

For heat jacket temperature of 85 °C and 90 °C a complete gelatinisation can be achieved in CTF apparatus even for an axial flow faster than investigated one (shorter residence time). During the experiments for such values of $T_{hj,}$ starch gelatinisation degree was always 1 regardless of the values of operating parameters. Although a complete starch gelatinisation below T_{hj} = 85 ºC is also possible, it may need an acceleration of rotor rotation or a decrease of axial flow. The influence of operating parameters became more visible for temperatures below 73 °C.

A comparison of the experimental results with the computer simulation confirmed indirectly the presence of Taylor vortices in the flow. Moreover, these results suggested that heat transfer could be affected by the structure of the vortex i.e. the length of the Taylor vortex zone and the intensity of "windy flow". Negative effects of both phenomena could be diminished by an increase of rotor rotation frequency.

The swelling degree of gelatinised starch increased with the growing values of residence time, rotor rotation and process temperature. The swelling of starch granules continued even after the ending of starch gelatinisation. Such a continuation of starch swelling enables control (if it is important) of some properties of gelatinised starch (e.g. apparent viscosity) by changing values of process temperature, rotor rotation or axial flow.

Effective and gentle mixing conditions in CTF apparatus were confirmed because no significant destruction of starch granules was observed during the treatment in Couette-Taylor flow apparatus.

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SYMBOLS

C	concentration of ungelatinised starch, kg/m^3
C_p	specific heat capacity, J/(kg K)
D_j	diffusion (dispersion) coefficient of species j, m^2/s
DSG	degree of starch gelatinisation, -
E_g	activation energy for starch granules gelatinisation, J/mol
k_g	pre-exponential factor for starch granules gelatinisation, 1/s
L	apparatus length, m
M1, *M2*	weight of sample of gelatinised starch after centrifugation and freeze-dry, respectively, kg
p	pressure, *Pa*
r	the radial coordinate
R	the gas constant (8.31 J/mol/K)
R_j	the net rate of production of species j by chemical reaction, kg/(m^{3}s)

R_1, R_2	radios of rotor and outer cylinder, respectively, m
r_g	gelatinisation rate, kg/(m^{3}s)
SGSD	starch grain swelling degree, -
T	temperature, K
u	superficial velocity measured for the inlet conditions, m/s
u_r	the radial component of velocity vector, m/s
u_x	the axial component of velocity vector, m/s
u_θ	the angular component of velocity vector, m/s
x	axial coordinate
X	mass fraction, -

Greek symbols

λ	thermal conductivity, W/(m K)
μ	starch slurry or working fluid apparent viscosity, Pas
ρ	density, kg/m^3
τ	shear stress, N/m^2
ω	rotor rotation frequency, 1/s

Subscripts

hj	heat jacket
j	species

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