P. Zeuschner, J. Fischer, M. Holewa and R. Pahl

A new method for a simplified comparison of gentle conveyance properties of centrifugal pumps for breweries

It is generally known and accepted that shear forces, which are in the brewing process especially caused by centrifugal pumps, can lead to quality as well as to processing problems. Besides the sensitivity of yeast to mechanical stress, the formation of β-glucan gels is feared by brewers, because of their filter blocking and turbidity increasing properties. For that reason, a test method to evaluate the gentle conveyance properties of centrifugal pumps objectively was developed and the gentle conveyance indices 'φ' and 'Φ', with and without respect to the pump power output were introduced. The method is based on the shear force induced gel formation behavior of barley β-glucans in an aqueous solution and the resulting change in its rheological properties. A detailed comparison between two centrifugal pumps of the same model, with low-speed and with high-speed motor, each with a nominal operation point of 10 m^3*h^{-1} on 20 m hydrostatic head was carried out, using the new method. The slower running pump showed thereby significantly better results by a factor of 1.2 at full load. Additionally, pump curves were developed to demonstrate the gentle conveyance behavior as well on different operation points, where the difference between the two possibilities of flow rate adjustment – throttling and speed control by frequency converter – could be quantified. Besides the possibility to compare pumps according to their gentle conveyance properties, the gained results showed that some theories concerning parameters that are often subjectively made responsible for gentle conveyance of centrifugal pumps could be questioned.

Descriptors: shear forces, gentle conveyance, beta-glucan, beta-glucan gel, pumps, test method

1 Introduction

Pumps belong in the brewing and beverage industry to omnipresent plant equipment, fulfilling the task of transportation, dosage and sometimes circulation of liquid and pasty media. The conveyed medium is brought from a lower to a higher energy level, differences in height are overcome, pressures or flow rates are increased. From water over mash, wort, yeast to beer, the transported media are manifold and thus the pumps in use often have to fulfill numerous requirements. One of those requirements, which was and is main target of product development for pump manufacturers, is gentle conveyance or low shear force operation [1]. Besides brewer's yeast which shows a certain sensitivity towards mechanical stress [2], barley originating high molecular β-glucans are known for their ability to form intermolecular crosslinks, agglomerates and subsequently hydrogels under the impact of shear forces [3]. The polysaccharide which mainly originates from cell walls in the endosperm of the barley kernel consists of D-glucose units, glycosidically linked in β-1,3 and β-1,4 position [4–6]. Due to the fact that during the malting process the degradation of β-glucans is not complete and also during mashing a further enzymatic digestion takes place only in part, it is inevitable that also high molecular β-glucans are dissolved in wort and subsequently in beer (as long as no technical enzymes are added) [7, 8]. If the process conditions on those dissolved long-chained molecules is unfavorable it can lead to undesired gel formation with various filtration problems as a consequence [9, 10]. For those gel formation favoring conditions mainly high molecular weight of the dissolved β-glucans, high concentration of β-glucans in the medium and high shear stress are named [3, 9, 11]. Here, the latter one should be understood as a supporting parameter. If the concentration of high molecular β-glucans in aqueous solution is above a critical value, gel formation will occur also without shear forces being applied to the medium. However, shear forces favor the encounter of β-glucans as they lead to a temporary and local decrease of the solution space. Hence, also far below critical concentrations, crosslinking and agglomeration by the formation of hydrogen bonds between the regularly occurring cellotriose and cellotetraose sections of the molecular strands can occur [9].

As this behavior of β-glucans as well as the resulting process technological challenges are well known, deeply investigated and part of numerous publications, it is quite understandable that in R&D, but also in product descriptions and advertising of pumps, gentle conveyance plays a central role [12–14]. However, especially with centrifugal pumps a certain input of shear forces into the conveyed medium is unavoidable. In order to evaluate this shear

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force input and thus the gentle conveyance properties of centrifugal pumps the authors developed a test method, using the above described shear force induced gel formation of barley β-glucans. The principle idea is that if in a closed system other gel formation influencing parameters are standardized, differently strong shear forces originating from different pumps should have a different impact on the gel formation behavior of β-glucans in a conveyed medium. Therefore, a test track was designed where a β-glucan medium is recirculated by the tested pump. The general concept was already proven in preparatory research, where the change of the β-glucan gel proportion over the number of recirculations in the test track was used to make differences in the shear force impact of the pump work visible [15–18].

In this study, the development of the final, marketable method of which a patent is pending together with first results is described. The significant difference is that the classic laboratory analysis of β-glucan gel played only a secondary role. Here, the evaluation of the gentle conveyance properties of a tested pump was based on the changing rheological properties of the β-glucan test medium, which is dependent on the gel proportion in it. *Wagner and Krüger* described dissolved β-glucan in its sol state as Newtonian fluid, whereas β-glucan gel shows a thixotropic flow behavior [19]. In wort or beer, this behavior does not play a role, but if the concentration of β-glucans in the medium is high enough, a rising gel proportion in the circulating medium leads to a decrease in viscosity, resulting in a measurable increase of the flow rate (constant temperature provided). The advantage of this approach is that the determination of a threshold value in rising gel proportion in the medium is independent of sample numbers and intervals and thus provides a higher accuracy with less labor. The method is however still dependent on the standardization of the previously mentioned parameters that influence the gel formation, besides shear forces. Most of the parameters, such as β-glucan concentration, pH and temperature can easily be standardized. However, the molecular weight distribution of β-glucan in each raw material batch needed to be seen as a naturally fluctuating parameter, which is of main importance to the gel formation ability of the containing β-glucans and which cannot be standardized when using different raw material batches [16, 20, 21]. In order to circumvent this problem, the test method was designed as a comparative method, comparing a pump to be tested with a reference pump. As this reference pump, simply the pump that in pre-trials so far showed the best results was determined and is following named as pump A. For every batch of β-glucan raw material a determination of the gentle conveyance behavior of the reference pump at full load was carried out to which other results were then set into relation. The gentle conveyance indices for which the Greek letters φ and Φ were determined were the result of this relation. Their determination and interpretation was the main topic of this study. The term "gentle conveyance index" was chosen to differentiate from shear rate and shear stress, which are not directly measured with the test method. The therefore existing electrochemical methods or the Laser Doppler Anemometry deliver excellent results on the flow conditions inside centrifugal pumps, which is shown in extensive research e.g. by *Lutz* [22]. The big disadvantage of those methods however is that the investigated pumps need to be substantially modified whereas the here shown method allows a comparative evaluation of the centrifugal pump in the same condition as it would be supplied to the end user.

2 Materials and Methods

2.1 Pump test track

For the purpose of the evaluation of the gentle conveyance properties of different pumps, a test track was designed into which a pump

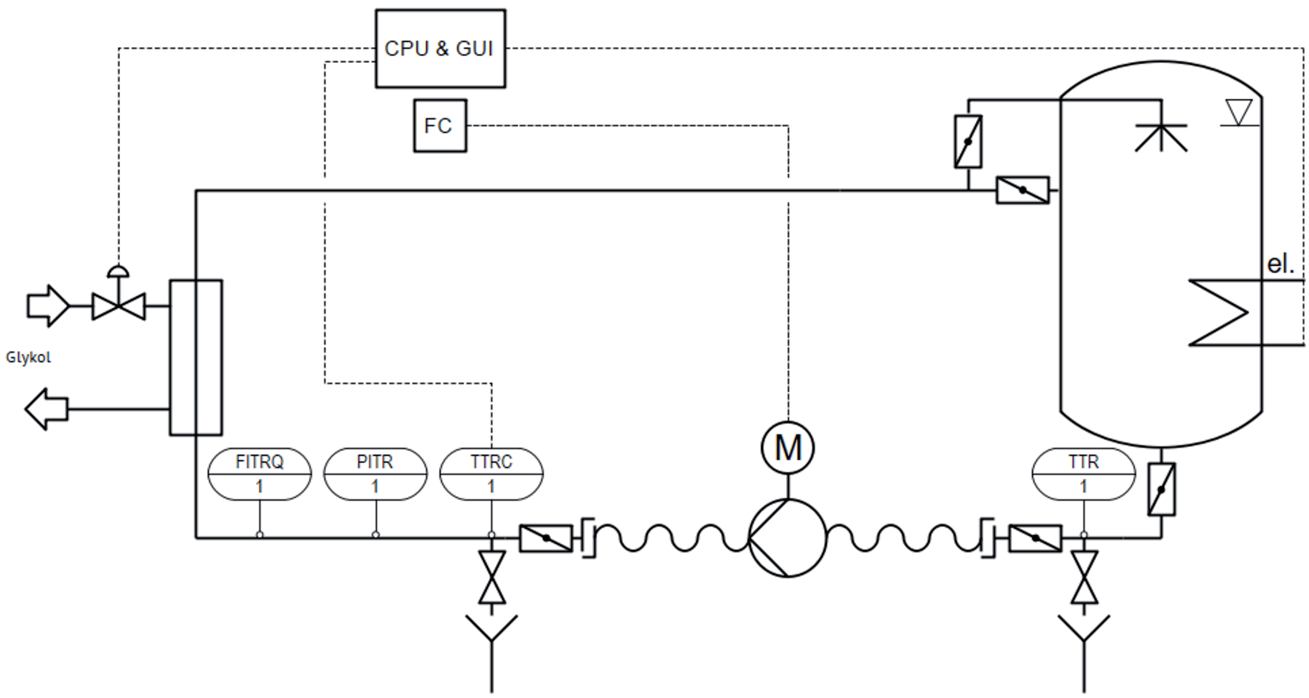

Fig. 1 Plant scheme of the pump test track. The upper re-entry into the reservoir vessel is for CIP purposes only

Table 1 Nominal attributes of the tested pumps

attribute, nominal	unit	pump A	pump B
flow rate	m³/h	10.0	10.0
pump head	m	20.0	20.0
pump efficiency	%	36	45
relative pump efficiency (calculated)	%	95	83
power requirement	kW	1.51	1.20
rotational speed	min^{-1}	1459	2900
required NPSH	m	0.93	0.80
discharge nozzle	/	DN 40	DN 40
suction nozzle	/	DN 50	DN 50
impeller diameter	mm	242	126
free passage	mm	5.0	11.0
surface quality	µm	3.2	3.2
circumferential speed (calculated)	m/s	18.49	19.13

as testing object is hydraulically integrated by hose connections. The pump drive is connected to a frequency converter, which is integrated in the test track. A plant scheme can be seen in figure 1. The operational filling volume of the test track including the pipe system and the reservoir vessel from which the respective pump is primed is 240 l. On the pressure side of the pump, the medium passes a tubular heat exchanger, arranged as a tube coil without change in pipe diameter in order to maintain equal flow velocities over the track. The majority of pipes in the system is designed in DN32 with a few wider sections in DN40 and a tapering to DN25 at the flow meter. The pipe system with the tube coil creates a system head of 10 m at a flow rate of 20 m^3*h^{-1}. Flow, pressure and temperature on the pressure side of the pump as well as temperature on the suction side are transmitted to the control panel and automatically recorded every 10 seconds. The PT100 on the pressure side also serves to regulate the temperature of the circulating medium by the glycol control valve supplying the tubular heat exchanger. Additionally, an electric heating element is implemented into the reservoir vessel to provide flexibility for possible future trials with different process conditions. The heating element was not used in the here presented study.

2.2 Pumps

As the attempt to carry out an objective comparison between different pumps can be a challenging matter, the two pumps which were used in the here presented study were chosen with the attempt to simulate a practical scenario. This means that to the supplier the desired operation point in terms of flow rate and hydrostatic head was specified, together with the specification to have one pump with 4-pole (here pump A) and the other with 2-pole motor (here pump B). The two pumps were thus of the same model from the same manufacturer for the same operation point on the pumps' Q/H-curve with pump A operating with a lower rotational speed, bigger impeller and bigger housing, compared to pump B. Both pumps were hygienic pumps for the food and beverage industry with open impeller, six impeller veins and volute casing in closed-coupled design. The nominal data of the two pumps are given in table 1 and figure 2. The specific names of the pumps needed to be anonymized, as it was a prerequisite of the involved suppliers for donating the pumps.

2.3 β-glucan test medium

For every test run, the β-glucan test medium was mixed out of 1,000 g barley β-d-glucan with a purity of 72 % according to AOAC method 995.16 (Beijing Packbuy M&C Co., Ltd, Beijing, China), 5.00 l ethanol, high purity, 99.8 %, denaturated (AppliChem GmbH, Darmstadt, Germany) to dissolve the β-glucan concentrate, ad 240 l de-ionized water. Calculative, the test medium thus had a β-glucan concentration of 3 g/l and an alcohol content of 2 % (v/v). The pH of the medium was adjusted to 5.0 ± 0.5 by orthophosphoric acid, technical grade (WHC GmbH, Hilgertshausen-Tandern, Germany).

2.4 Determination of β-glucan gel proportion

The proportion of gelatinized β-glucan of total β-glucan in the sampled medium was determined according to methods 2.5.4 and 2.5.5 in MEBAK Wort, Beer and Beer-based Beverages [23]. After sampling, all samples were stored at 3 °C for 7 days, as this time was needed to fully develop gels of β-glucans where gel formation was induced in the trials [18]. Before the actual measurements, the samples were brought to 20 °C.

2.5 Turbidity measurement

During the course of the method development, an increase in turbidity was visible in the samples. The turbidity thus was meas-

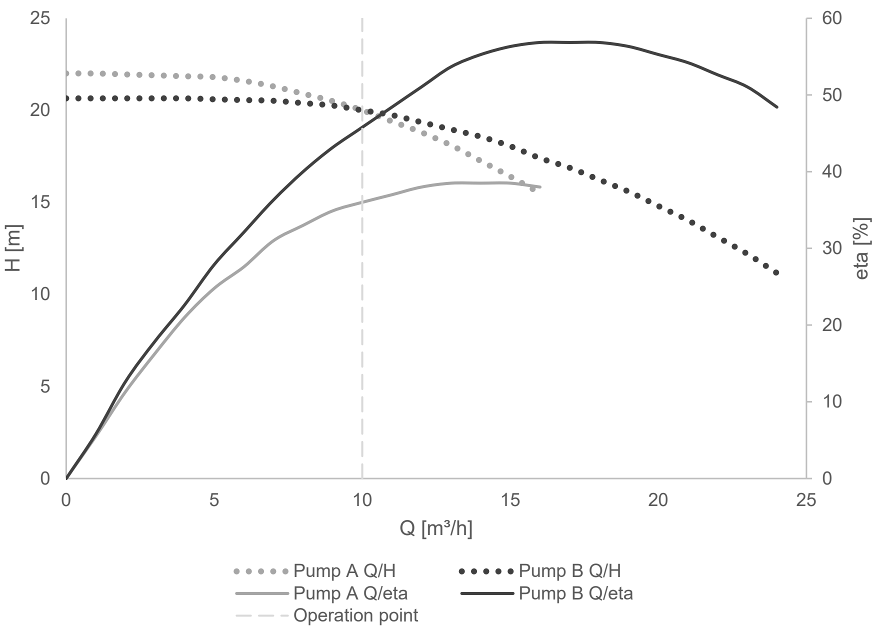

Fig. 2 Characteristic curves of the two tested pumps (hydrostatic head and hydraulic efficiency in relation to flow rate). The specified operation point of 10 m³/h on 20 m hydrostatic head is indicated with the vertical dashed line

ured by 90° light scattering in a Sigrist LabScat turbiditymeter (Sigrist-Photometer AG, Ennetbürgen, Switzerland). Also here, after sampling, all samples were stored at 3 °C for 7 days and before the actual measurements, the samples were brought to 20 °C.

2.6 Determination of viscosity decrease

The decrease of viscosity due to the transition from Newtonian to thixotropic fluid was determined indirectly by the resulting change in flow rate in the test track. The flow rate was measured by an inductive flow meter, type IZMAG (GEA Diessel GmbH, Hildesheim, Germany) with a nominal measurement inaccuracy of ± 0.2 %. The point of the transition where thixotropic properties overlap the Newtonian properties in the pumped fluid was the main criterion for the determination of the gentle conveyance indices.

2.7 General process description of the test method

After the hydraulic and electric integration of the respective pump into the test track, the components of the test medium were mixed and filled into the reservoir vessel. In order to start the cooling process in the tubular heat exchanger, the medium was directly circulated at a maximum of 1/3 of the nominal pump speed or at a maximum flow of 2.5 m^3*h^{-1} which corresponded to a maximum flow velocity of 1.4 $m*s^{-1}$ at the narrowest section in the pipe system. After the target temperature of 10 °C – which was chosen in order to meet the NPSH requirements of the tested pumps – was reached, a control sample was taken to be analyzed according to section 2.4 and in part 2.5. After that, the test run was started. Therefore, the regulation of the pump speed and the position of the throttle before the re-entry into the reservoir vessel was adjusted to the respective test settings. Initially, the change of β-glucan gel concentration was determined in periodically taken samples, according to 2.4 in order to confirm the relation between rising flow rate and rising β-glucan gel concentration. In later trials, only the flow rate increase was determined.

2.8 Regression analysis and modelling

In order to be able to determine the β-glucan gel proportion in the test medium independent from sampling points, its course was modeled using equation 1 with 'G' as β-glucan gel proportion [%], 'G_{end}' as gel proportion on the plateau of the sigmoid function [%], 'G_{start}' as initial gel proportion and delay factor [%], 'k' as growth rate [h^{-1}] and 't' as time [h].

$$G = \frac{G_{end}}{1+\left(\frac{G_{end}}{G_{start}}-1\right)e^{-kt}} \quad \text{(Eq. 1)}$$

The equation was empirically developed. According to it, the gel proportion is dependent on the time the medium is being circulated inside the test track and the constants G_{start}, G_{end} and k. Those were

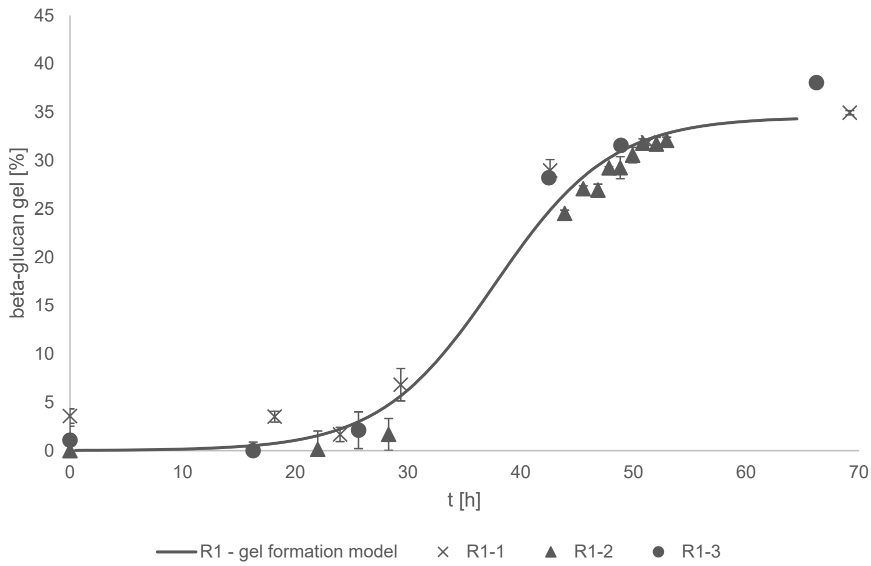

Fig. 3 **Course of beta-glucan gel proportion in the medium while being circulated in the test track. Data points are average values with the error bars indicating the standard deviation of each β-glucan gel analysis (n = 3). The data points are concentrated on the areas of strongly changing incline of the curve. R1 stands for reference runs with β-glucan batch no. 1. The second number stands for the repetition. RMSE of the gel formation model is 0.4 % beta-glucan gel**

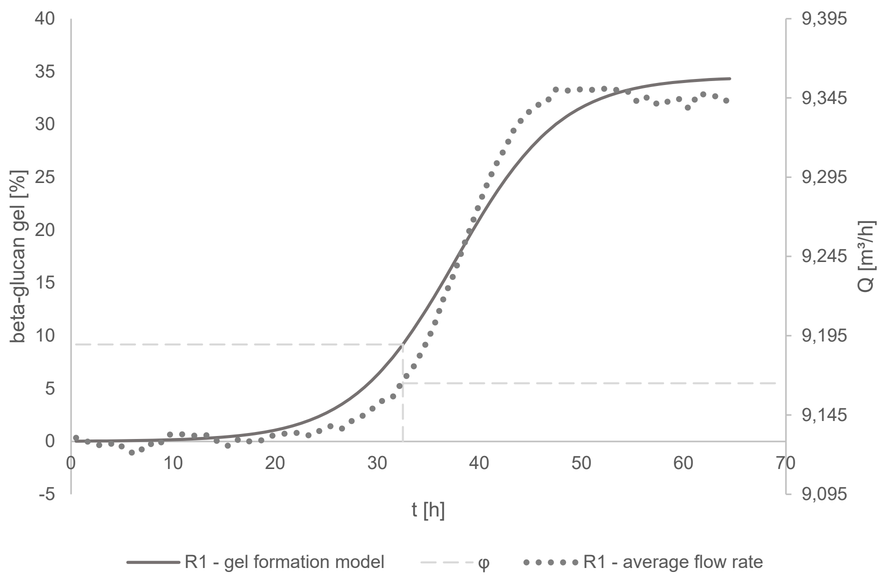

Fig. 4 **Gel formation model and average curve of the recorded flow rates of three reference runs with β-glucan batch no. 1, indicated as R1 as in fig. 2. The intersections of the vertical axes with the horizontal axis which lead to negative numbers on the primary vertical axis support to visualize the same starting point of the initial average flow rate of Q_0 = 9.128 m^3*h^{-1} with the initial gel proportion of 0 %. This illustrates the temporal shift between the start of the increase of flow rate and gel proportion. 'φ' marks the chosen reference point at a flow rate increase to 100.4 % at $Q_φ$ = 9.165 m^3*h^{-1} after $t_φ$ = 32 h when a gel proportion of 9 % was reached**

calculated using the GRG Nonlinear function of Solver (Frontline Systems, Inc., Incline Village, USA) in Excel (Microsoft Corporation, Redmond, USA) with the target that the mean squared error between the analytically determined and the modeled β-glucan gel proportion is minimal.

3 Results and Discussion

3.1 Reference values

For every batch of β-glucan concentrate, test runs with the reference pump (pump A) were carried out. In those runs, the pump worked on full load and the throttle before the re-entry into the reservoir vessel was completely opened. The evaluation of the reference runs was carried out both, on basis of measured β-glucan gel formation as well as on basis of flow rate increase.

Figure 3 shows the increase in gel proportion over the time the medium circulated inside the test track. Together with the laboratory results the model according to section 2.8 is given. The model describes the development of the gel formation with an RMSE of 0.4 %. The sample points were chosen with respect to the distinctive points of the sigmoid graph as the general shape of the course of gel development was known from various pre-trials [15, 16, 18]. The course of the flow rate, which was recorded by the flow meter integrated into the test track, showed a very similar behavior with a certain temporal shift in the start of the increase (see Fig. 4). Together with the relatively high concentration of 3 g/l β-glucan in the medium (compared to wort or beer) and in accordance to the findings of Wagner and Krüger [19], it was concluded that the temporally leading increase in gel proportion – and hence decrease of viscosity while sheared – was the reason for the rising flow rate, as temperature and pump performance remained unchanged. A check test with water resulted in no flow rate change. A change in electric conductivity of the medium, which could have an influence on the measurement of the electromagnetic flowmeter, could not be determined either. Air bubbles in the fluid, which would as well be a device influencing parameter, could not entirely be excluded. However, their occurrence – at least to a significant amount – should be seen as unlikely as the re-entry of the fluid into the pressureless reservoir vessel is 18 cm under the liquid surface.

Due to the fact, that the characteristic of the gel formation model is dependent on number of samples, sampling time as well as accuracy in laboratory work, it was decided to use a certain increase in flow rate and not directly in β-glucan gel proportion as a reference point to evaluate the gentle conveying performance of the tested pumps. This reference point was determined as the flow rate Q_φ which is 0.4 % higher than the initial flow rate Q_0. As the used flow meter has a nominal measurement inaccuracy of 0.2 % at standard conditions, 0.4 % was empirically chosen as safe value to speak of a significant flow rate increase. Hence, in each test run, the time that is needed for an increase to 100.4 % of the initial flow rate (100 %) is determined as t_φ. As shown in figure 4, for the reference runs t_φ was in average 32 hours at a gel proportion of 9 %. The lower initial flow rate compared to the specified one (see Table 1) can be explained by a higher viscosity of the β-glucan medium at 10 °C compared to water at 20 or 25 °C which usually serves as medium for generating nominal pump parameters.

If one pump creates a different flow rate than another, time cannot serve as comparative parameter anymore, as the medium would pass the respective pump differently often within the same time. Thus, in order to be able to compare different operation points as well as pumps that create different flow rates, the number of recirculations of the medium in the test track was used as a point of comparison, instead of the time. This number of recirculations 'n' was defined as the pumped volume at a given time divided by the filling volume of the test track (240 l). To create a comparative value, n_φ was thus defined as the average number of recirculations at t_φ. For the above-mentioned reference runs, n_φ resulted in 1236. Thus, the β-glucan medium was recirculated in average 1236 times by the reference pump in the test track to form sufficient gel so that the thixotropic properties overlap the Newtonian properties of the fluid. This on the other hand caused a viscosity decrease in the medium while being sheared and the flow rate rose at this moment by 0.4 %.

The necessity of working with the number of recirculations instead of the time because of possibly different flow rates and thus different numbers of recirculations on a fixed time is explained above. However, as at different operation points not only the flow rate, but also the pump power output in general differs, this parameter needed to be included into the calculation of the gentle conveyance indices as well. The comparative pump power output $P_{Q,\varphi}$ [W] is thus calculated as in equation 2, with 'n_φ' describing how often the total volume of the β-glucan medium in the test track passed the pump until a flow rate rise of 0.4 % occurred and '$P_{Q,0}$' [W] as the initial pump power output, itself defined as product of flow rate and pressure generated by the pump.

$$P_{Q,\varphi} = n_\varphi \cdot P_{Q,0} \quad \text{(Eq. 2)}$$

In other words, the comparative pump power output $P_{Q,\varphi}$ describes the useful power transmitted to the fluid handled by the centrifugal pump over all recirculations necessary to reach the above-described point of comparison n_φ.

The whole procedure (determination of n_φ and $P_{Q,\varphi}$ for the reference pump) was carried out for three different batches of β-glucan concentrate. Between the dates of manufacture of the concentrates lie between 7 and 11 months. This allows the assumption that at least two of them originate from barley of different harvests, even though there is no data about the exact origin of the used barley available. The determined reference values are shown in table 2. Especially on the results for the third β-glucan batch, it can be seen that the method can only be a comparative one, as the gel formation behavior alters with the molecular weight distribution of the β-glucan.

Table 2 Reference values n_φ, $P_{Q,\varphi}$ and the respective critical gel proportions for three different β-glucan batches

β-glucan batch	$n_{\varphi,R}$	$P_{Q,\varphi,R}$	critical gel proportion
1	1237	553.25 kW	9 %
2	1163	552.57 kW	10 %
3	1447	657.02 kW	12 %

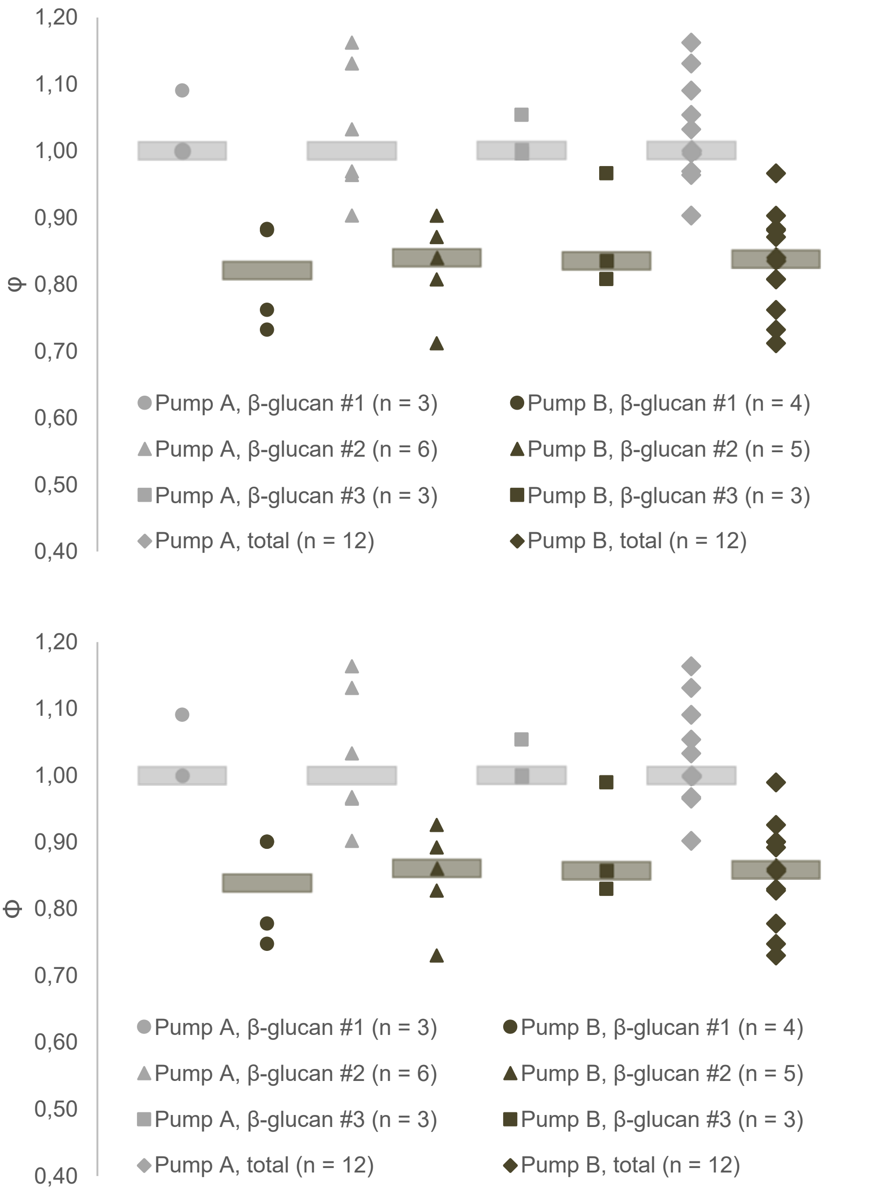

Fig. 5 **Gentle conveyance index φ (specific to pump power output) and Φ (not specific to pump power output) for pump A and pump B, determined with three different batches of β-glucan concentrate for the test medium. Data points show the results for each test run, the big rectangles indicate the respective median values**

The high number of necessary circulations of the medium in order to start the gelation of the containing β-glucans is far away of any practical relevance for brewery applications. This does however not diminish the suitability of this parameter as a basis for the desired comparison between brewery relevant centrifugal pumps. It is probably explained by matrix effects that may play a role in β-glucan gel formation in the complex media wort or beer [24, 25].

3.2 Determination of the gentle conveyance indices φ and Φ

Once determined for each β-glucan batch, the above-shown reference values were used to evaluate other pumps according to their gentle conveyance behavior or other operation points according to their impact on gentle fluid transportation. Therefore, the pump to be evaluated was integrated into the test track and ran on the desired operation point until the flow rate increased to 100.4 % of the initial value. Subsequently, the values for $n_φ$ and $P_{Q,φ}$ were determined as described above. The gentle conveyance index φ, specific to the pump power output as well as the gentle conveyance index Φ, not specific to the pump power output were calculated as shown in equation 3 and 4 with the indices 'i' standing for an arbitrary pump and 'R' for reference.

$$\varphi_i = \frac{P_{Q,\varphi,i}}{P_{Q,\varphi,R}} \quad \text{(Eq. 3)}$$

$$\Phi_i = \frac{n_{\varphi,i}}{n_{\varphi,R}} \quad \text{(Eq. 4)}$$

For both indices, φ and Φ counts that the higher the value is, the less shear forces are applied by the pump. The index Φ is suited for a direct comparison, to show if within the test settings one pump works gentler than another, regardless the performance on the respective operation point. The inclusion of the pump power output in the index φ allows a comparative evaluation with respect to the pump performance. In other words, the index φ allows an objective comparison if a pump e.g. works gentler than another, but generates less pressure or flow rate. This is most important when looking at partial load conditions as in section 3.3. The test results for pump A and pump B at full load are given in figure 5.

The results for φ and Φ show that for all three tested β-glucan batches pump A worked by a factor of 1.2 gentler, applied less shear stress, than pump B when comparing the median values. The latter was regarded necessary as the method tended to generate outliers. The observation counts for each single β-glucan batch as well as for the overall values. The initial gel proportion in the medium prior to shearing was in average 2.1 % ± 0.82 % (confidence interval with α = 0.05 and N = 24). The critical gel proportions for both pumps, i.e. the proportion when with each β-glucan batch 100.4 % of the initial flow rate was reached, corresponded to each other as well (see Table 3). It thus can be concluded that the here developed method is independent of the applied β-glucan batch and in that

Table 3 **Critical gel proportions for three different β-glucan batches with pump A and pump B. Average values and standard deviations, n = 3**

β-glucan batch	pump A		pump B	
	X̄ [%]	s [%]	X̄ [%]	s [%]
1	9	0.4	10	0.5
2	10	0.9	9	0.3
3	12	0.4	11	0.6

way standardizes the parameter of varying molecular weight distributions in different β-glucan preparations.

A limitation factor of the method is however that for each batch, a calibration with a reference pump is required and thus a single measurement from a different laboratory made with any batch of β-glucan cannot be compared.

In common-practice, it is a questionable but widespread opinion that a lower rotational impeller speed as in pump A is responsible for a gentler conveyance of the respective medium, see e.g. [14]. The generated results show however that this cannot be a seen as a generally applying correlation. If the rotational speed would be a main parameter for gentle conveyance, the difference between the two tested pumps should be bigger, as pump A runs only half as fast as pump B. Additionally, it should be considered that the circumferential speed of the impellers of both pumps is almost equal. The absolute pump efficiency neither seems to be a significant impact factor, as the efficiency of the gentler working pump A is with 36 % even lower than the efficiency of pump B with 45 %. At first glance, this result seems illogical, as the efficiency describes the amount of energy that is not utilized for pressure and velocity increase and which would thus lead to the shown differences in mechanical stress. It could however be explained by differences in the source of power dissipation for each pump (bearings, shaft seals, disc friction). The most important parameter regarding low shear force fluid transportation would according to the presented findings be the proximity of the operation point to the vertex of the pump's efficiency curve. This conclusion corresponds to findings made with micro fluid mechanic methods such as Laser Doppler Anemometry [22, 26]. The proximity to the vertex of the efficiency curve of the pump is expressed as "relative pump efficiency" in table 1 and is for pump A by the factor 1.14 higher than for pump B, even though the absolute efficiency is lower. For a practice case – at least for the two here tested pumps – the results illustrate that it is of much higher importance to operate the respective pump as close as possible to the point of its own highest efficiency than simply comparing absolute pump efficiency numbers on a particular operation point.

3.3 Changing operation points

In order to evaluate the gentle conveyance behavior at different process conditions the above-described method was applied for pump A and pump B on three different operation points. Therefore, the flow rate was adjusted once by a throttle in the test track just before the re-entry into the reservoir vessel and once by adjusting the pump speed via frequency converter. The results for φ are shown in figure 6. In general, the pump power output specific gentle conveyance index decreased with a lower flow rate, regardless of the method of flow rate adjustment. This is due to the impact on the generated pump power output, when throttling the flow or decreasing the pump speed. However, the less the flow rate, hence the more moving to the left side of the curves, the bigger became the difference between the values for

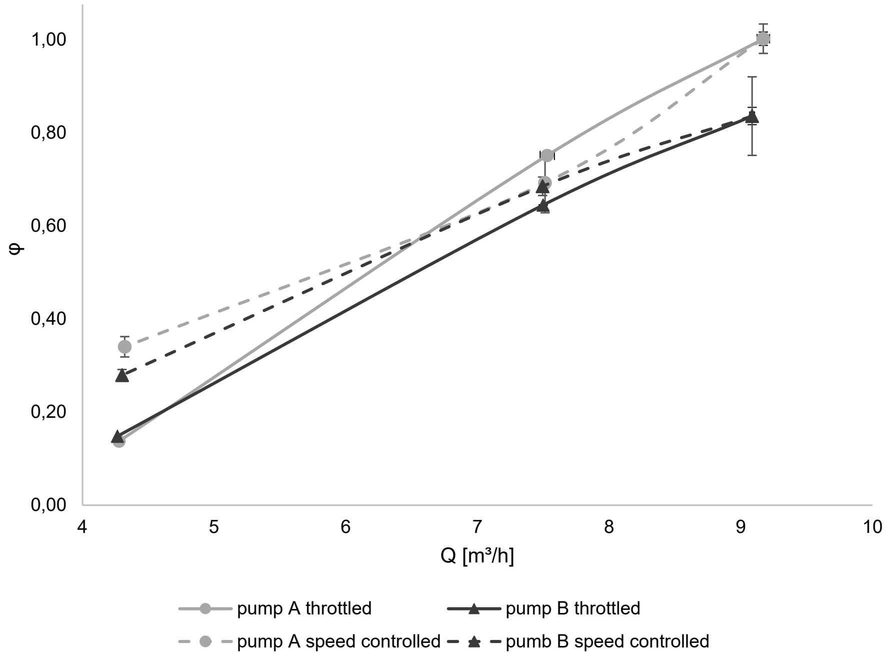

Fig. 6 Gentle conveyance index φ (specific to pump output power) for pump A and pump B on different operation points, set by throttle and by frequency converter. Data points are median values and standard deviations, n = 4 for each operation point

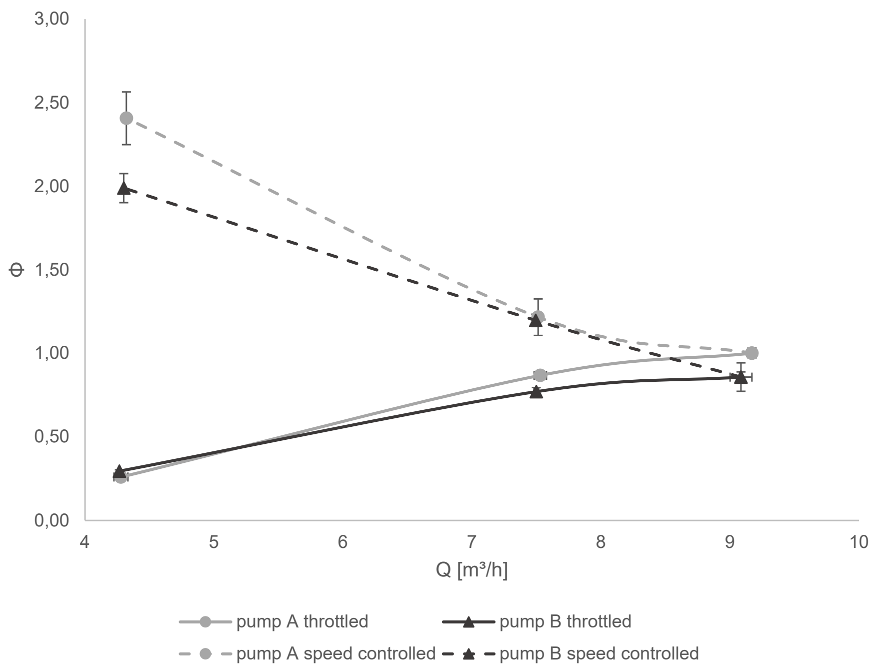

Fig. 7 Non-specific gentle conveyance coefficient Φ for pump A and pump B on different operation points, set by throttle and by frequency converter. Data points are median values and standard deviations, n = 4 for each operation point

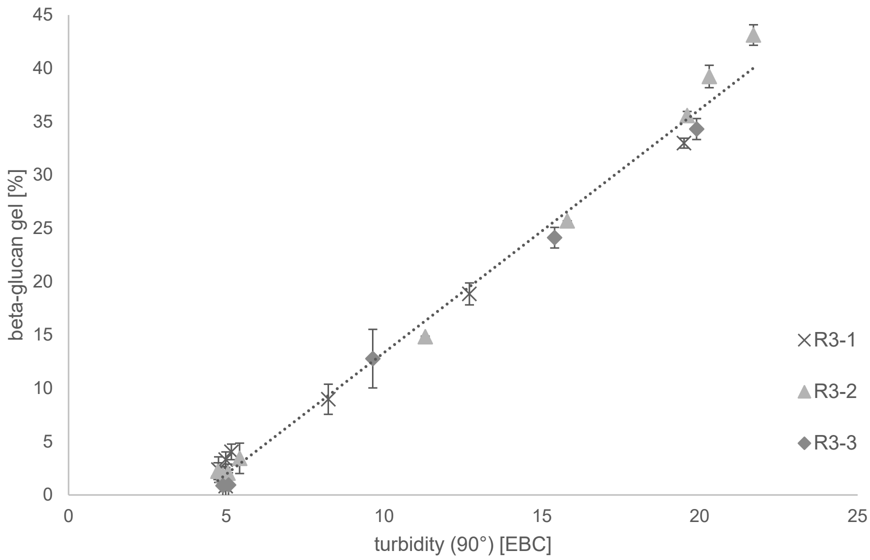

Fig. 8 Values for β-glucan gel proportion from three reference runs (average values and standard deviation, n = 3) in linear correlation to the measured turbidity at 90° light scattering (R^2 = 0.9913). R3 stands for reference runs with β-glucan batch no. 3. The second number stands for the repetition

the throttled and the speed controlled operation points. It could be seen that when adjusting the flow by pump speed, the curves for both pumps were – considering the standard deviations – roughly linear and parallel. When adjusting the flow rate by a throttle, the curves showed a slightly different image. Here, the differences between the two pumps was the highest at a fully opened throttle and decreased with its closing angle together with the resulting pressure increase and flow rate decrease. At least concerning the three tested operation points, also here the curves were nearly linear. The more it is moved to the left side of the pump curve the less advantages the low-speed pump brought concerning the gentle conveyance properties. It should however be stated as a limitation of the validity of the pump curves when working with the throttle that the impact of the decreased passage by the throttle itself probably played an increasing role on the shear force intake, the more the armature was closed.

At nominal operation point, the results for φ and Φ were almost identical (see section 3.2). When looking at changing operation points, the generated pump power output, which has an impact on φ but not on Φ gains more importance, which can be seen when comparing figure 6 and figure 7. In figure 7, the differences between performance regulation by frequency converter and by throttling occur much more significant. Here, the general conclusion can be drawn that the lower the volume flow is set, the bigger becomes the difference in gentle conveyance between throttling and speed control by frequency converter. This widely accepted correlation was in the past already scientifically proven, e.g. by Lutz [22]. With the here developed method, this behavior can now be evaluated without prior modification of the tested pumps. The slower the pumps run, the gentler the respective medium is transported. It should however be considered that with a lower pump speed not only less shear forces are applied to the transported medium, but also the pressure and thus the generated pump power output is lower. Therefore, it is for a sound evaluation of the gentle conveyance behavior of pumps inevitable to regard both indices φ and Φ. Otherwise a difference in generated pump head on varying operation points could lead to misinterpretations within the gentle conveyance properties of the tested object. The overall evaluation of both tested pumps concerning their gentle conveyance properties is that not only at nominal speed, but also on different process conditions pump A gives better results than pump B.

An additional conclusion which can be drawn when looking to the curves in figure 7, is that the pure flow rate and thus the flow velocity within a pipe system has only a minor impact on the shear stress to the transported medium. This observation fits to known cases from brewery practice where often flow velocities of wort or beer are present which are far beyond the usually recommended ones. According to the presented results, especially for Φ (Fig. 6), the correct fit between pump and pipe system plays a much bigger role. The throttle in the test track increases the system head, which results in a longer residence time of the transported medium inside the pump with an equally fast rotating impeller as main reason for increased shear forces. This result corresponds with findings by Lutz [22] who identified higher shear stress due to re-circulation inside the pump at partial load conditions, using Laser Doppler Anemometry. Looking at the here presented results alone, it must however be restrictively said that another conclusion could be that any as a throttle acting valve has a higher impact to the mechanical stress to the fluid than a centrifugal pump.

3.4 Additional observation: β-glucan gel and turbidity

Over the course of the research project it was visible to the naked eye that the more gel was formed in the respective trials, the more turbid the samples became. A linear correlation, which was found between those two parameters within the reference runs with β-glucan batch no. 3, is shown in figure 8. The rising number of crosslinks and thus agglomeration of β-glucan molecules possibly decreases the chance of the light beams to pass the medium while instead they are scattered on the agglomerates. The effect thus gets stronger with a higher degree of agglomeration. The resulting correlation could subsequently be used as calibration curve for the determination of the β-glucan gel proportion in a sample by the usage of simple turbidity measurement. This resulted in a significant time saving in laboratory work and sample handling in other trials. Up to now, this correlation could only be proved for one β-glucan batch. In future trials it is planned to develop a calibration curve for each new batch in order to confirm the linear correlation.

4 Conclusion/Summary

In this study, a method to evaluate the gentle conveyance properties of centrifugal pumps for brewery applications in a comparative way was developed. Therefore, two indices were introduced to assess the gentle conveyance behavior with and without respect to the individually generated pump power output. The method was used to compare two pumps of the same model for the same application, but with different rotational speeds. This comparison took place on the pumps' specified operation points at full load as well as on varying process conditions in order to demonstrate possibilities as well as limitations of the new test method. For practice considerations, the presented differences in the gentle conveyance behavior between the two tested pumps opens the path for purchase decisions based on facts rather than on philosophy, especially taking into account the usually higher investment costs and power consumption for larger low-speed motor driven pumps. Due to a certain error in the gained results, it can be assumed that the method is not suitable for an internal quality control tool for pump manufacturers, i.e. for the evaluation of pumps of the same model coming off the assembly line. To compare pumps from different manufacturers with the same characteristics is rather conceivable, but tests into that direction could not yet be carried out. Not least because pumps from different manufacturers – even though for the same application – mostly show quite different characteristics. Also, additional trials with more pump models would be necessary in order to create benchmark values, as until now only comparative but no absolute statements of the gentle conveyance properties of centrifugal pumps can be made. In future trials it would be worth to investigate as well to compare pumps designed for higher flow rates and pressures in order to evaluate as well the area of the pump curves on the right and not as until now only on the left side of the optimum on the respective pump characteristic curves. A comparison of different pumps, each working on their point of highest efficiency as well as combined studies with LDA technology are other future projects that would be of interest.

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