Comprehensive studies of the physical and thermophysical properties of wort

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Abstract. The study is devoted to the study of physical and thermophysical properties of hoped, filtered beer wort in order to obtain graphical and mathematical relationships to calculate the numerical values of density, thermal conductivity and thermal conductivity coefficients, as well as the study of rheological properties. This will allow specialists in various fields related to heat and mass exchange processes to apply a science-based approach in hydraulic and thermal calculations when designing modern designs of heat and mass exchange apparatuses and technological pipelines connecting them. The study of physical properties, particularly rheological properties, was carried out in the temperature range from 283 to 343 K, density and thermophysical properties – from 293 to 353 K. Dry matter content varied from 10.2 to 72.4% dry wt. Density of the solutions was determined using an electronic Excellence D4 Mettler Toledo density meter. The mathematical dependence suggested for its calculation is linear and depends on temperature and dry matter content. Rheological tests were carried out for high-solids solutions with the Rheotest RN 4.1 Rotary Viscometer and for low-viscosity solutions with the Geppler Falling-Ball Viscometer HÖPPLER® KF 3.2. In studies on the rotary viscometer the shear rate gradient varied from 1 to 500 s^{-1}. It was found that at shear rates up to 50 s^{-1} the solutions exhibit pseudoplastic properties and above Newtonian properties. Thermal conductivity and thermal diffusivity were measured using a Hot Disk TPS 2500S analyzer based on the unsteady plane heat source method. The results of the study are recommended to be used for calculation of density, heat conductivity and diffusivity that will allow further calculation of the specific heat capacity according to the known equation, solving technological problems of the brewing industry, and the data on rheology can be used in the calculation practice.

Keywords: wort, density, momentum transfer, dynamic viscosity, temperature conductivity, thermal conductivity.

1 Introduction

Industrial brewing is a quite complex and logically related set of machines and units designed to convert raw materials into finished products (beer). In less detail, brewing consists of three main production segments, namely: the section of raw material preparation for the main technological process; the section for the transformation of prepared raw material into a final end product and the section for product presentation.

The brewing machinery scheme [1] is shown in Fig. 1 (the section for product presentation is not shown in Fig. 1 due to the lack of basic technological processes).

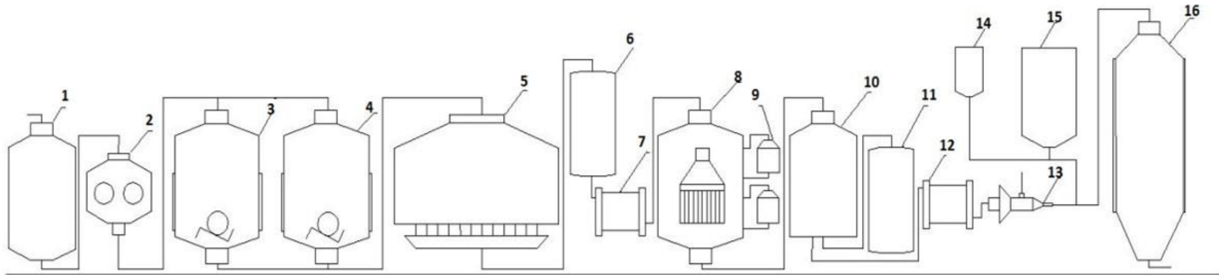

Fig. 1. Standard brewing machinery scheme: 1 – malt bin; 2 – rollcrusher; 3 – mash tub; 4 – mash tun; 5 – filter tank; 6 – unhopped wort collector; 7 – heat exchanger, 8 – wort kettle; 9 – hop vessels; 10 – hydrocyclone; 11 – suspension collector after wort filtration; 12 – heat exchanger-cooler; 13 – aerator-mixer; 14 – yeast seed container; 15 – propagator, 16 – fermenting tank

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Table 1. Sequence of transformation of feedstock and its morphology during physicochemical processes within the main technological processes

n/n in Fig. 1	Process stage	Physical and chemical process	Working medium structure at the inlet	Working medium structure at the outlet
2	Malt crushing on roller or hammer crushers	Mechanical process – malt grinding	Solid particles larger than 2.5 mm	400–1000 μm solid particles
3	Mashing in a mash tub	Heat and mass exchange process – water-soluble matter leaching. Mashing temperature from 298 to 348 K	Two-phase medium: water and ground malt particles (suspension)	Two-phase medium: multicomponent aqueous solution and undissolved malt particles
4	Mashing in a mash tub. Water-thermal fermentation treatment (WTFT) of malt raw materials	Heat and mass exchange process – polysaccharide extraction and dissolution at elevated temperatures. Mashing temperature from 338 to 373 K	Two-phase medium: water and ground malt particles (suspension)	Two-phase medium: multicomponent aqueous solution and undissolved malt particles
5	Mash filtering in a filter tank	Hydromechanical process – liquid-solid separation process	Two-phase medium: multicomponent aqueous solution and undissolved malt particles	Liquid medium: multicomponent aqueous solution (unfiltered, unhopped wort)
6	Wort collection	Collection and accumulation of wort for uniform feeding for further boiling	Liquid medium: multicomponent aqueous solution (wort)	Liquid medium: multicomponent aqueous solution (unfiltered, unhopped wort)
7	Wort heating	Heat exchange process – wort preheating. Heating temperature 373 K	Liquid medium: multicomponent aqueous solution (wort)	Liquid medium: multicomponent aqueous solution (unfiltered, unhopped wort)
8	Wort boiling in a wort kettle	Heat and mass exchange process – extraction at elevated temperatures (up to 376–379 K)	Two-phase medium: ground hop particles and multicomponent aqueous solution (suspension)	Two-phase medium: ground hop particles and modified multicomponent aqueous solution (unfiltered, hopped wort)
10	Removal of hot wort suspensions in a whirlpool	Hydromechanical process – liquid-solid separation in a centrifugal force field	Two-phase medium: ground hop particles and modified multicomponent aqueous solution (suspension)	Liquid medium: multicomponent aqueous solution (filtered, hopped wort)
11	Suspension collection after removal from a whirlpool	Collection and accumulation of wort for uniform feeding for aeration	Liquid medium: multicomponent aqueous solution (hopped wort)	Liquid medium: multicomponent aqueous solution (filtered, hopped wort)
12	Cooling of hot wort in a plate heat exchanger	Heat exchange process – hopped wort cooling. Decrease in mash temperature from 368–371 to 279–281 K	Liquid medium: multicomponent aqueous solution (hopped wort)	Liquid medium: multicomponent aqueous solution (hopped wort)
13	Wort aeration	Mass exchange process – dissolution of atmospheric oxygen into hopped wort. Wort temperature during aeration 279–281 K	Two-phase medium: gas (air) and liquid (multicomponent aqueous solution (hopped wort))	Liquid medium: oxygenated multicomponent aqueous solution (hopped wort)
14	Cultivation of pure beer yeast culture	Biosorption mass exchange process – aerobic cultivation of brewing yeast. Wort temperature during cultivation 293–298 K	Multiphase medium: gas (air), liquid (multicomponent aqueous solution) and quasi-solid phase (yeast cells with C_s concentration)	Two-phase medium: liquid (multicomponent aqueous solution) and quasi-solid phase (yeast cells with C_f concentration)
15	Wort fermentation	Biosorption mass exchange process – anaerobic cultivation of brewing yeast. Temperature: for cold fermentation 281–282 K, for warm fermentation 283–288 K	Two-phase medium: liquid (multicomponent aqueous solution) and quasi-solid phase (yeast cells with C_f concentration)	Multiphase medium: gas (CO_2), liquid (modified multicomponent aqueous solution) and quasi-solid phase (yeast cells with C_f concentration)

It is obvious that the first two sections are the most labor- and energy-intensive in the brewing industry. They have the entire set of the technological equipment, which ensures mechanical, hydrodynamic, thermal and mass exchange processes aimed at the main intermediate product, i.e. filtered hopped wort of the required quality. High quality wort, filtered and cooled to fermentation temperature, having the required composition and viable yeast seed biomass, in the required amount, is the key to successful production of a final product (beer) [2].

To simplify the analysis of the equipment scheme presented in Fig. 1, the authors in stages considered the physical and chemical processes in the technological sequence during brewing. The results of this analysis are shown in Table 1.Table 1 shows that after the ground malt is mixed with water, the resulting suspension, the so-called mash, will have well defined thermophysical properties depending on the quantitative and qualitative composition of the primary components, namely malt and water.

The analysis of the scientific and technical literature [3–5] shows that most breweries perform a mashing stage using a mixing mash ratio in the range from 1:4 to 1:2.5, thereby obtaining hopped wort of various density, some of which enters the fermenters, and the other part is supplied to the propagators as a nutrient medium for the reproduction of seed yeast.

The initial mash ratio at the beginning of the water-heat treatment of grain raw materials allows analyzing the working medium, which will have a certain composition of components, and, hence, certain structural-mechanical and thermophysical properties, because the initial and final composition of the working medium is specified by the process regulations. Besides, the process regulations inevitably determine the change of the working medium in the required direction [6–8].

The physical properties of mash with the above-mentioned mash ratio were studied earlier by the authors and are presented in works [9, 10].

Each stage of the process represents a fairly extensive system of connections between the main process equipment and auxiliary (pumps, intermediate tanks), as well as extensive transport and technological systems (pipelines, shut-off valves and control and measurement systems). In this regard, the accuracy of hydraulic, thermal, and mass ex-change calculations will largely depend on the objective representation of physical and thermophysical properties that the working medium possesses at each of the above stages stage and will make it possible to determine the energy costs and, the cost of the finished product in general [9].

A literature review shows that at this stage there has been no systematic approach to the analysis of the processes of transforming the feedstock into a finished product (beer). There are works [11, 12], which deal with the systemic consideration of transforming the feedstock (ground barley) into a finished product (ethanol). Given that the initial stages of the technological processes for producing alcohol and beer are almost identical, the approaches to the systematic study of these processes can also be considered identical with the exception of technological aspects.

The work [13] presents the results of studies where analytical expressions are established for calculating the flow rate of air entering the universal shell-and-tube jet injection device, depending on the nozzle diameter, which determines the flow rate, and the concentration (viscosity) of the water-malt suspension.

There are some works on the physical properties of the final product (beer) of various grades [14–16] and its thermophysical properties [17, 18] however, the data presented are either not systematic and are limited to the range of data presented, or are interconnected with the specific influence on a certain technological operation [19-21] which indicates the need for further study in a wide range of temperatures and concentrations of dry matter (DM).

2 Materials and methods

The concentrated malt extract Muntons “Bitter” with a dry matter content of 81 % dry wt. was chosen as the test object. This choice makes it possible to obtain various samples of wort with different densities by diluting it with distilled water, and to study their physical and thermophysical properties in a wide range of concentrations.

Seven solutions were prepared with a dry matter content of 10.2, 20.6, 30.1, 40.3, 50.1, 59.6, and 72.4 % for further study. The choice of such a range of concentrations of solutions is based on the need to understand the change in the properties of solutions over a wide range of measurements and with the greatest variability in order to be able to calculate the studied parameters of intermediate concentrations. The dry matter content in solutions was assessed in a PTR46 refractometer at 20℃.

The study of physical properties, particularly rheological properties, was conducted in the temperature range from 283 to 343 K, density and thermophysical properties – from 293 to 353 K with a discreteness of 10 K. Only density and viscosity were evaluated among the physical properties of the test objects, and thermal conductivity, temperature conductivity – among the thermophysical properties.

The density of the solutions was determined using an electronic density meter Excellence D4 Mettler Toledo with an accuracy of ±0.0001 g/cm³.

The viscosity of the test objects was determined by two methods based on the wort concentration: for solutions with high dry matter content by rotary viscosimetry on the Rheotest RN 4.1 and for low viscosity solutions by the Geppler method on a HÖPPLER® KF 3.2 drop ball viscometer. The permissible error of the ball viscometer is 0.5 to 2% of the measured value (depending on the ball diameter). Measurements of flow curves of research objects with increased viscosity were performed on a Rheotest RN 4.1 rotary viscometer with a coaxial cylindrical measuring system in the temperature range from 283 to 343 K and in the range of shear rate gradients from 1 to 500 s^{-1}. The uncertainty limit of the instrument is ±3%. The temperature was controlled and maintained using a

JULABO circulation thermostat. Proportional-integral-differential temperature control provides heating in accordance with the set temperature conditions of the bath with accuracy of 0.1 K. The volume of each sample placed in the measurement cell was 30 ml. Before the measurements, each sample was exposed to thermostatic treatment for 20 minutes to reach the desired temperature. Each individual test lasted 60 seconds. The first 30 seconds of the test were devoted to stabilizing the flow regime in a cell.

The Hot Disk TPS 2500S analyzer was used to measure thermophysical characteristics. The measurement accuracy of the device was at least 5%. The principle of measuring thermal conductivity and temperature conductivity using this device is described in work [20].

3 Results

3.1 Density measurement results

The only initial parameter that distinguishes one test object from another was the concentration of dissolved dry matter determined using a refractometer. Given the fact that this parameter more reflects technological rather than physical properties, it has become necessary to accurately determine the density over a wide range of DM concentrations and temperatures, which will inevitably be required for hydraulic and thermal calculations of brewing (pos. 8, fig. 1) and filtering (pos.10, fig.1) equipment, as well as heat exchange equipment (pos. 12, fig. 1), propagators (pos. 14, fig. 1) and process piping connecting them.

The density measurements of test objects are presented in Table 2 and Fig. 2 as graphical dependencies of solution density on temperature and the dry matter percentage.

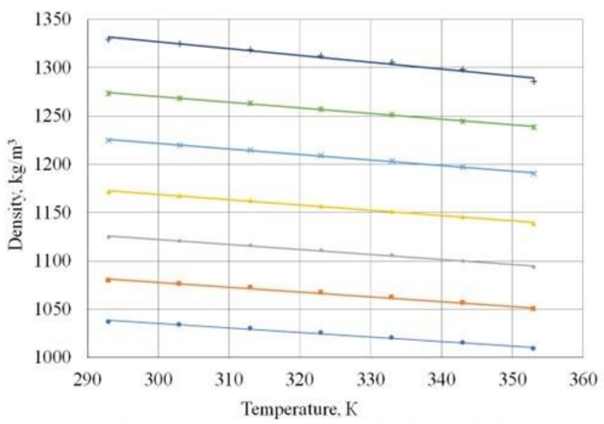

Fig. 2. Dependence of hopped filtered wort density on temperature at different DM concentrations from 10.2% to 72.4%(10,2%( ); 20,6%( ); 30,1%( ); 40,3%( ); 50,1%( ); 59,6%( ); 72,4%( ))

Table 2. Density measurements of wort test objects

Solution density, kg/m³							
Concentration, % dry wt.	Temperature, K						
	293	303	313	323	333	343	353
10.2	1037	1034	1030	1026	1021	1015	1009
20.6	1080	1076	1072	1067	1062	1056	1050
30.1	1125	1121	1116	1111	1106	1100	1094
40.3	1172	1167	1162	1157	1151	1145	1139
50.1	1225	1220	1215	1209	1203	1197	1190
59.6	1273	1269	1263	1257	1251	1245	1238
72.4	1329	1325	1319	1312	1306	1298	1286

The mathematical processing of graphical dependencies presented in Fig. 2 allowed obtaining an empirical equation 1, which makes it possible to estimate the density (ρ, kg/m³) of wort in a specified range of variable parameters with an accuracy of 1%.

$$\rho = 1152 - 0.557 \cdot T + 4.7 \cdot n\,, \qquad (1)$$

where T – temperature, K; n – dry matter content, % dry wt.

This equation was obtained using the method of least squares.

3.2 Viscosity measurement results

The rheological studies made it possible to obtain the graphical dependencies for each concentration: shear stress on shear rate, dynamic viscosity on shear rate, as well as temperature-viscosity curves.

Fig. 3 shows the dependence of the dynamic viscosity of a sample with dry matter concentration of 59.6 % on the shear stress in the specified temperature range obtained using rotational viscometry, as an example of behavior reflecting the general character for all investigated concentrations, with only numerical values changing. Further, the data for this concentration were used to show the general trend in the behavior of the studied solutions.

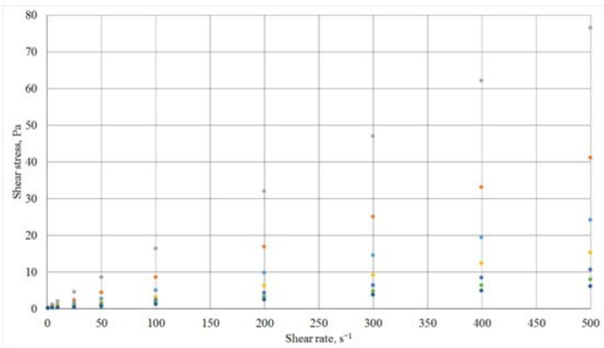

Fig. 3. Flow curves for hopped filtered wort with DM concentration of 59.6 % dry wt. in the temperature range of 283–343 K (283 K( ); 293 K( ); 303K( ); 313K( ); 323K( ); 333K( ); 343K( ))

It should be noted that the linear nature of the flow curves with a zero origin was observed for all studied samples of hopped filtered wort and over the entire temperature range. Thus, it can be stated that the flow of the hopped filtered wort is Newtonian in nature within the tested ranges of DM concentrations and temperatures.

Fig. 4 shows the dependence of the dynamic viscosity of a sample with a dry matter concentration of 59.6 % on the shear rate in the specified temperature range, which was also obtained using a rotational viscometer.

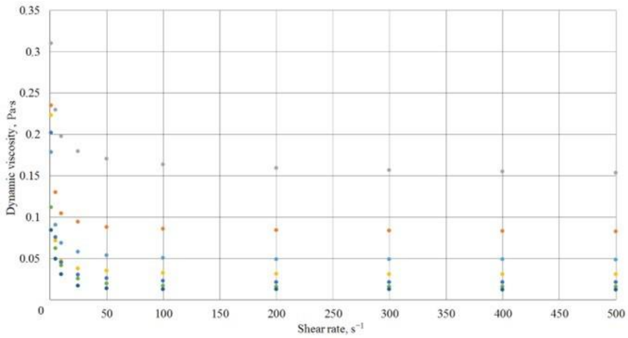

Fig. 4. Dependence of dynamic viscosity on shear rate for hopped filtered wort with DM concentration of 59.6% dry wt. in the temperature range of 283–343 K (283 K(•); 293 K(•); 303K(•); 313K(•); 323K(•); 333K(•); 343K(•))

The graph of Fig. 4 shows that the change in the shear rate has little effect on the change in viscosity at high speeds, and the greatest change is observed at the transition from shear rate 1 to 50 s^{-1}. Thus, the obtained dependencies can characterize the tested samples as pseudoplastic fluids (i.e. fluids which viscosity depends on the shear rate) only in the range of shear rate gradients up to 50 s^{-1}, while at higher values of this parameter the solutions behave like Newtonian fluids.

Fig. 5 and 6 show the temperature-viscosity curves based on the study of samples with different concentrations on a Geppler viscometer. The graphs demonstrate that the viscosity decreases as the temperature rises, and after reaching the temperature in the range of 303–313 K, the changes become less noticeable than in the temperature range of 283–303 K.

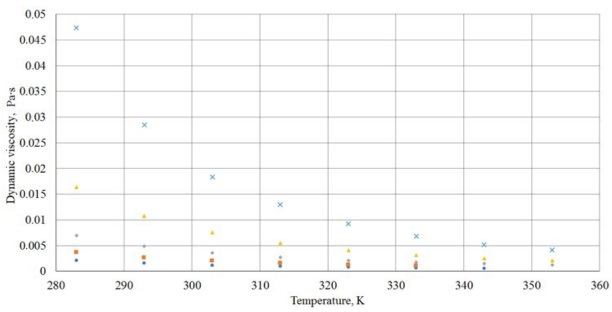

Fig. 5. Dependence of dynamic viscosity on temperature of hopped, filtered wort at dissolved DM concentrations from 10.2 to 50.1% dry wt. (10,2%(•); 20,6%(■); 30,1%(•); 40,3%(▲); 50,1%(×))

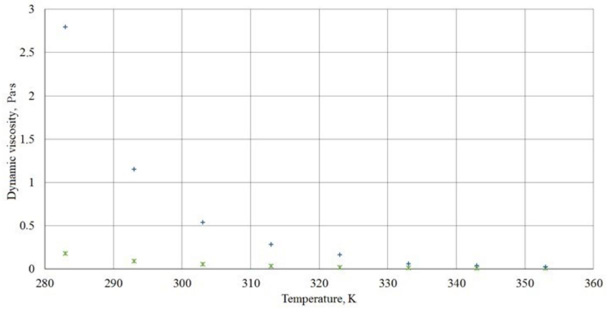

Fig. 6. Dependence of dynamic viscosity on temperature of hopped, filtered wort at dissolved DM concentrations from 59.6%(x) to 72.4%(+) dry wt.

The measurements of the dynamic viscosity of hopped filtered wort revealed that the change in temperature-viscosity characteristics of the studied samples was quite ambiguous.

3.3 Measurement of thermophysical properties

The thermophysical measurements made it possible to obtain data to further build the graphical dependencies of thermal conductivity and temperature conductivity of the studied samples on temperature at different DM content.

Fig. 7 shows the dependence of thermal conductivity on temperature at different DM content. The graph shows that as the temperature increases, the thermal conductivity increases, while the influence of the DM content has the opposite effect and leads to a decrease in this coefficient. This behavior is due to a decrease in the density of the filtered wort and the force interaction of fluid molecules, which leads to a decrease in thermal conductivity, and a simultaneous increase in the intrinsic energy of molecules of the studied wort due to an increase in the amplitude of oscillations.

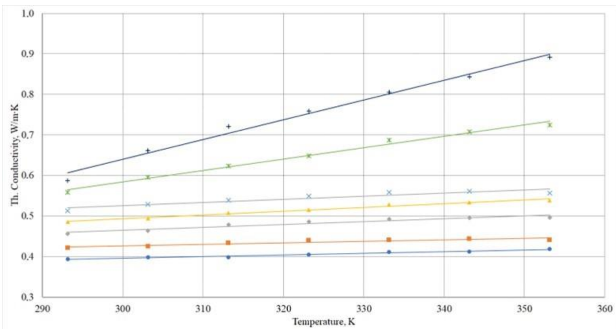

Fig. 7. Dependence of hopped, filtered wort thermal conductivity on temperature at different DM content from 16.2% to 77.7% (16,2%(—); 32,5%(—); 40,2%(—); 51,9%(—); 60,2%(—); 69,9%(—); 77,7%(—))

The equation for calculating the thermal conductivity (λ, W/(m·K)) is represented by the following mathematical dependence

$$\lambda \cdot 10^4 = 2550 + 15.53 \cdot T - 53.58 \cdot n \qquad (2)$$

The graph shows a linear change. This formula is valid with T values from 293 to 353 K and n from 10.2 to 72.4% dry wt. The maximum relative deviation of the formula from the experimental data is about 15%.

Fig. 8 shows the dependence of wort temperature diffusivity (a, mm^2/s) on DM concentration and temperature.

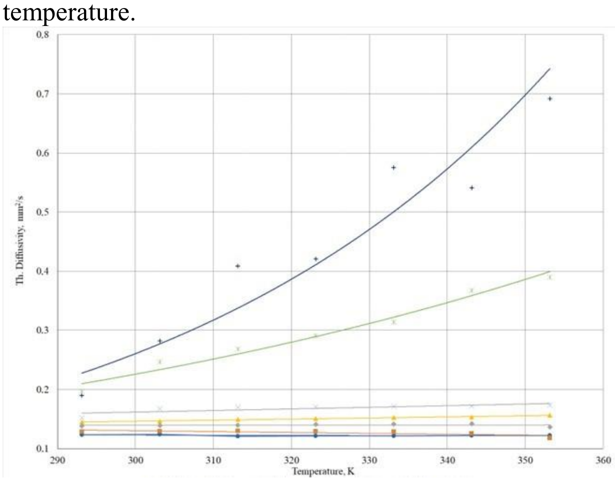

Fig. 8. Dependence of hopped, filtered wort temperature conductivity on temperature at different DM content from 16.2% to 77.7% (16,2%(—); 32,5%(—); 40,2%(—); 51,9%(—); 60,2%(—); 69,9%(—); 77,7%(—))

Further mathematical processing made it possible to obtain a formula for calculating the temperature conductivity

$$a = 0.09 \cdot 1.005^T \cdot 0.981^n \quad (3)$$

This formula is valid with T values from 293 to 353 K and n from 10.2 to 72.4% dry wt. Equations (2) and (3) for calculating the thermal properties were obtained by applying the least squares method.

The obtained equations for density ρ (1), thermal conductivity λ (2) and temperature conductivity a (3) allow calculating the specific heat capacity C_p of hopped, filtered wort in the studied ranges by the well-known equation presented below at different temperatures and DM content

$$C_p = \frac{\lambda}{\rho \cdot a} \quad (4)$$

4 Discussion

It should be noted in conclusion that the experimental studies of hopped, filtered wort made it possible to obtaine density, thermal conductivity, temperature conductivity in a wide range of temperatures and DM content, as well as mathematical dependencies for their calculation.

The nature of flow curves of hopped, filtered wort with different DM content is analyzed. Numerical values of dynamic viscosity are obtained depending on temperature variation and DM concentration.

It was found that hoped, filtered beer wort, at low shear rate gradients ($\dot{\gamma}$=1÷50 s−1), behaves as a pseudoplastic liquid, whereas at $\dot{\gamma}$>50 s−1 the character of the flow corresponds to the Newtonian liquid, which indicates its ambiguous behavior. The viscosity anomaly is related to the molecular structure of the liquid, or more precisely, to the molecular interaction forces, which appear to be commensurate, in magnitude, with the external forces that create the specified shear rate gradients.

It was shown that the dependencies ρ= $f(T, n)$, λ = $f(T, n)$ are linear in nature, and the dependence a= $f(T, n)$ – indicative, which is more clearly expressed with a decrease in the DM concentration and an increase in temperature.

5 Conclusion

The obtained equations can be recommended to determine the numerical values of density, thermal conductivity and temperature conductivity for calculation of specific heat capacity, in heat exchange calculations, to solve technological problems using hopped, filtered wort for subsequent production of finished product (beer), results of viscosimetry can also be used in design practice.

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