Experimental Investigations of the Influence of Different Bottom Shapes on the Temperature and Velocity Fields in a Fermentation Tank with a Biological Multiphase Flow

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In this investigation, the influence between different bottom shapes of fermentation tanks and the different resulting velocity and temperature fields at the beer production are investigated. The difficulties of an investigation with a biological fermentation fluid (wort) are the many complex interactions between the different three phases (yeast, carbon dioxide bubbles, wort). Furthermore, natural convection processes are superimposed by rising gas bubbles and the high turbidity of the fluid only allows acoustic or magnetic resonance tomography velocity measurements. This leads to high requirements for the measurement technology and the following evaluation. In this study, latest measurements with two coupled UDV-Systems for a high-resolution velocity field combined with a data acquisition unit for the temperature field in the fermentation tank with two bottom shapes (conical, hemispherical) are presented. The new experimental setup consists of a velocity field of 16 x 2 MHz and 19 x 4 MHz transducers, 56 temperature sensors and enables an improved resolution compared to the previous measurements. For a precise evaluation, the filtering of interferences is carried out by an additional, self-written program. Finally, the experimental analysis of the flow and temperature measurements and the transport mechanism (momentum and heat) with a real fermentation fluid, in different bottom shapes, are presented.

Keywords: Ultrasonic Doppler Velocimetry, flow field measurements, biological fluid, multiphase flow

1. Introduction

In the context of investigations of multiphase flows, the beer production is currently being investigated, especially fermentation, maturation and storage in cooperation with the local brewery. Beer may not be as old as man himself. But beer-like, fermented beverages have always been an important part of human civilization. The ancient Babylonians, for example, knew 20 different varieties. These include black beer, red beer, sweet beer, sour beer. Before them, the Sumerians were regarded as the high culture of brewing beer. The oldest proof of beer in Germany dates to around 800 BC. Many cultures regarded beer not only as a staple food, but also as a currency. In ancient Egypt, for example, slaves were paid exclusively in beer. Brewing beer is a craft that requires meticulous planning. [1]

The university has its own 350 litre fermentation tank with comprehensive acoustic flow and temperature measurement technology for the systematical investigation of the influence of the fermentation activity, distribution of yeast and occurring convection phenomena.

The description of the thermo-fluid dynamic processes and the economic benefit of this knowledge have despite increasing scientific and technological progress in this field still innovative potential especially in the structural design of the fermenter and in the effective control of the cooling zones.

In this study, the structural design will be analyzed against the background of the influence of different bottom shapes on the temperature and velocity fields in a fermentation tank with a biological multiphase flow.

There are two different configurations of the fermentation tank for the investigation. The first configuration is the conical and the second configuration is the hemispherical bottom. Nowadays the conical bottom shape is preferred in a modern European brewery and has a 60° to 70° cone angle.

2. Experimental Setup

2.1 Experimental Arrangement

For the experimental investigation of the flow and temperature fields, an existing experimental setup with a 350 litre fermentation tank with different bottom shapes will be used (see at figure 1). In this study, the tank is equipped with two different bottom shapes, a conical and a hemispherical bottom (375 litre). Several openings in the fermentation tank allows the integration of temperature sensors for the temperature field measurement and transducer for the flow field measurement.

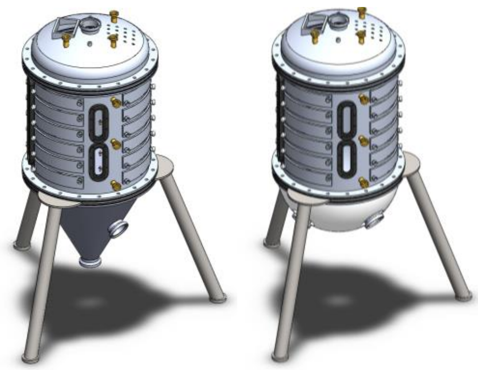

Figure 1: Fermentation tank with conical bottom shape (left) and hemispherical bottom shape (right)

For a defined managed fermentation process the tank is equipped with six separately controlled cooling or heating zones and one additional zone in each bottom (in figure 2 and figure 3 the cooling zones are additionally shown). To control the cooling zones during the fermentation and maturation process, a new completely re-engineered program was created on the software tool "LabView" for the triggering of control valves. This program is not only used for the control of the cooling zones but also allows the automated continuous data acquisition of the temperature and flow rates of the cooling liquid flow in the cooling zones. In this study, the program is used to hold defined temperatures at the selected process of the beer production.

2.2 Implementation of the temperature measurement

The temperature detection inside the tank, in contrast to earlier investigations, is now adjusted for the flow measurement system to enable a simultaneous measurement process. The temperature measurement arrangement for this study is carried out by a conventional measuring method in a grid array of 56 resistance temperature detectors (RTD). The installed temperature sensors in the grid of the fermentation tank are shown in figure 2. For a high accuracy, all detectors are calibrated with five cycles of a thermometer with the accuracy class A and the grid will be adjusted for each bottom shape.

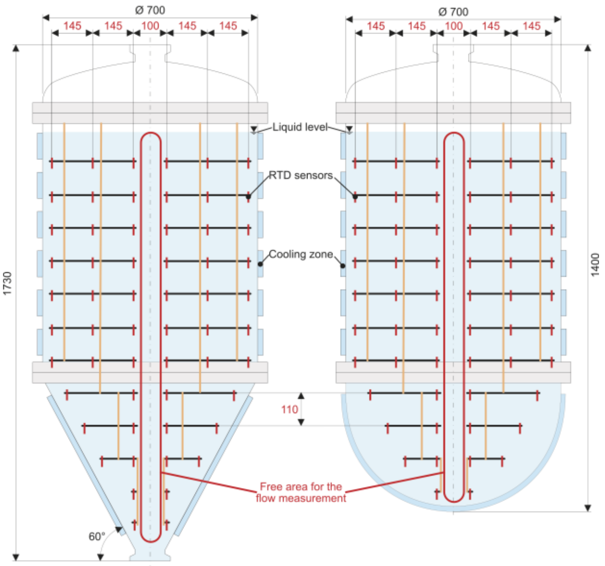

Figure 2: Temperature implementation and measuring fields in the cylindrical part and the conical (left) and hemispherical (right) bottom shape

2.3 Implementation of the flow measurement

The difficulties of a flow investigation with a biological fermentation fluid (wort) are the many complex interactions between the different three phases (yeast as solid, carbon dioxide bubbles as gas, wort as fluid). Furthermore, natural convection processes are superimposed by rising gas bubbles and the high turbidity of the fluid only allows acoustic or magnetic resonance tomography velocity measurements. This leads to high requirements for the measurement technology and the following evaluation. In case of that, the Ultrasonic Doppler Velocimetry are used. The measurement of the flow field is carried out by means of the Ultrasonic Velocity Profile Monitor System UVP-DUO from Met-Flow S.A. In this study, two coupled UDV-Systems for a high-resolution velocity field are combined with two different frequencies (2 MHz, 4 MHz). To reduce interference and for a higher accuracy, the transducers are now implemented with small sleeves, in the bottom shapes. The transducers are furthermore protected in front of the matching layer against destruction (acid and base cleaning, disinfection, fermentation residues) by a 0.5 mm plastic plate. The new implementation allows a cartesian grid not only in the cylindrical part but also in the bottom shapes.

The experimental setup consists of a velocity field of 19 x 4 MHz, 16 x 2 MHz transducers and enables an improved resolution compared to the previous measurements with model liquids. The velocity measuring arrays are shown in figure 3.

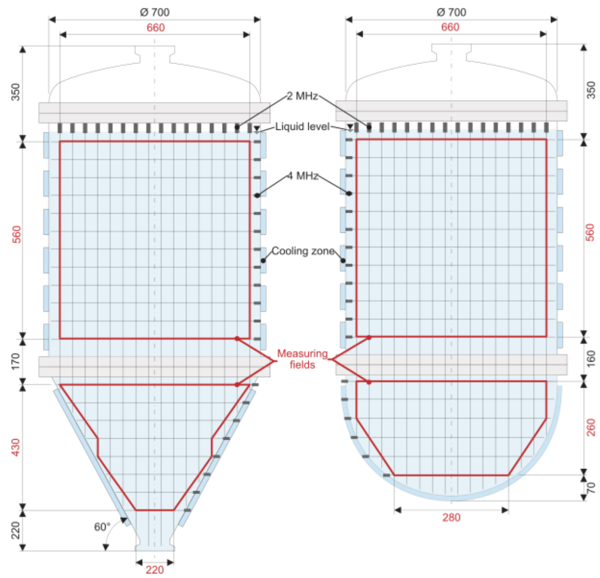

Figure 3: Measuring arrays for the velocity measurement in the cylindrical with conical (left) and hemispherical (right) bottom shape

The properties of the measuring field are shown in table 1. In the new arrangement, are 192 intersection points in the cylindrical part and additional 80 intersection points in the conical bottom and 84 intersection points in the hemispherical bottom.

Table 1: Properties of the measuring fields

measuring fields	cylindrical part	conical bottom	hemispherical bottom
Transducer (2 MHz)	16 (for the cylindrical part and the bottom shapes)		
Transducer (4 MHz)	12	8	6
intersection points	192	80	84

Each intersection point represented in table 1 consists of three-dimensional measuring volumes in the form of two combined truncated cones or in simplified form of two disks. In each disk, all Doppler shifted frequencies are calculated, averaged and checked for possible errors with a self-written program in order to reduce or remove the influence of bubbles, echoes and interferences. Finally, only one resulting vector is calculated for each intersection point. For a better understanding of the intersection points, the two special intersection points of the 2 MHz and 4 MHz transducer are shown in figure 4 and figure 5.

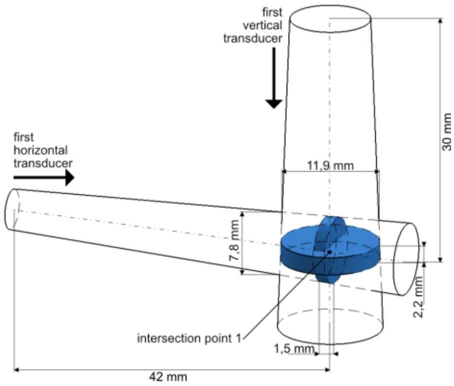

Figure 4: Smallest intersection point for both bottom shapes

Figure 4 shows the smallest intersection point in the investigation with a volume of 0.31 cm^3, over which the average is calculated. Figure 5 shows the largest intersection point in the conical bottom shape with a volume of 14.33 cm^3.

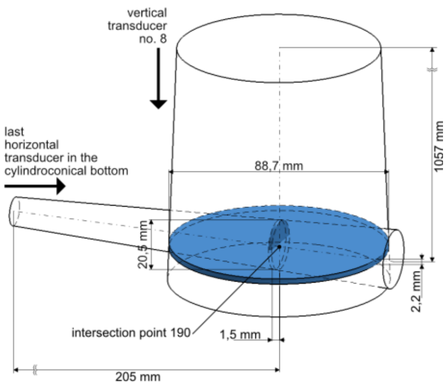

Figure 5: Largest intersection point in the conical bottom shape (lower middle)

2.4 Physical properties of the investigated fluid (fermenting wort)

In cooperation with the local brewery, two comparable beer wort`s with an original wort content of 12 %, two similar bottom-fermented yeasts and identically processes were used to compare the complex processes during real fermentation in the two bottoms.

Table 2 shows the experimental results for the physical properties of the fermenting wort. These properties change with the fermentation process and are therefore specified as a range.

Table 2: Physical properties of the fluid and gas

measuring fields	physical properties	
	fluid	gas
Density [kg/m^3]	1051 - 1105	1.913
dynamic viscosity [kg/(m·s)]	2258E-6 - 2624E-6	14.151E-6
sound velocity[m/s]	1482 - 1492	261.958
specific heat capacity [J/(kg·K)]	4065	8354
thermal conductivity [W/(m·K)]	0.555	0.015
thermal diffusivity [m^2/s]	1.325E-7	97.145E-7

3. Results and Discussion

3.1 Measurement of temperature fields

The temperature field was measured continuously every five minutes. The thermal boundary conditions of the investigation were adapted to the real brewing process. Only the two upper cooling zones (flow temperature approx. 4.5 °C) are cooled and the heat is generated by the yeast (in this study 3.5 litre). Figure 6 shows the temperature field of the fermentation tank with both bottom shapes on the eighth day of fermentation. The temperature field inside the first configuration (hemispherical bottom shape - on the left) is 0.4 K on average cooler than the second configuration (conical bottom shape - on the right). The reason for this can be a better natural convection flow. Furthermore, figure 6 shows the cooling of the upper two cooling zones and the heat influence of the yeast in the entire tank.

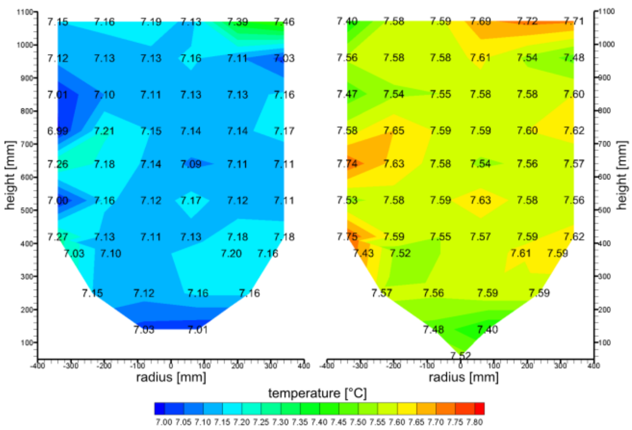

Figure 6: Temperature fields inside the cylindrical tank with hemispherical bottom (left) and conical bottom (right) on the 8th day of fermentation

3.2 Measurement of flow fields

The temperature field was measured continuously every 30 minutes. The sound velocity required for the UDV measurement system was also determined periodically by using a transit time method in the fermentation tank and averaged approx. 1485 m/s. The following two figures show the results of the velocity field measurement and the final calculation of the self-written program [3].

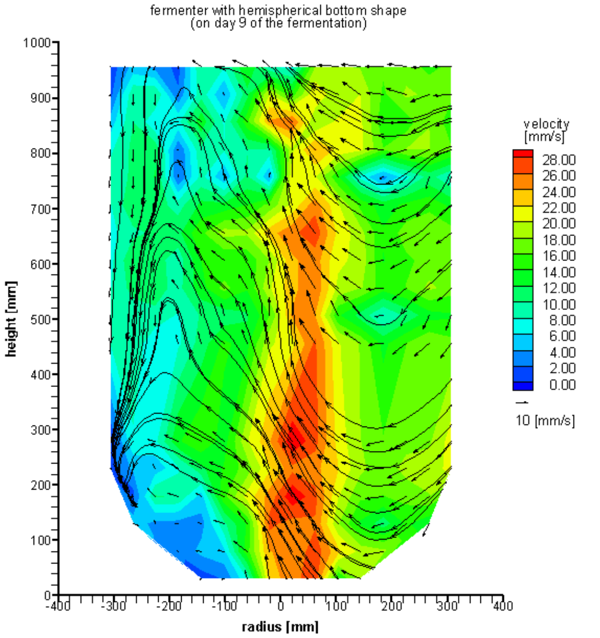

Figure 7: Velocity field and streamlines in the cylindrical tank with hemispherical bottom on the 9th day of fermentation

Figures 7 and figure 8 show the velocity fields of the fermentation tank during the ninth day of fermentation with the different bottom shapes. In figure 7, the velocity at the middle and the ground of the bottom shape is higher than in figure 8. This phenomenon is due to the hemispherical bottom shape and would allow a better, more controlled influence on natural convection.

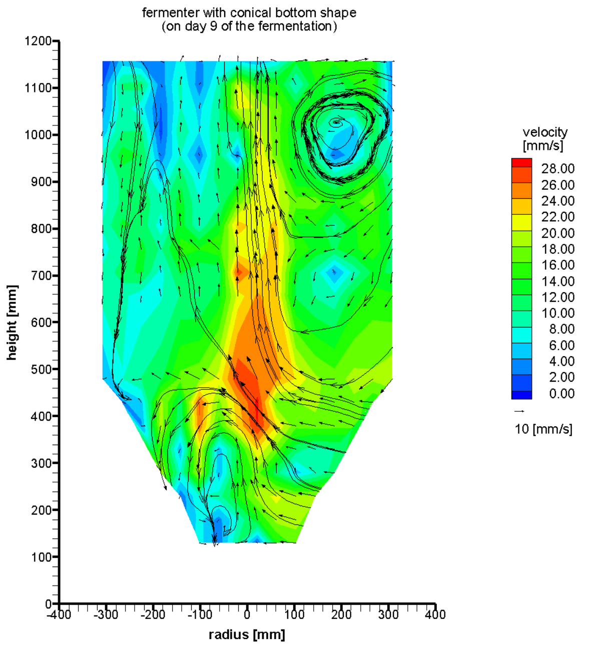

Figure 8: Velocity field and streamlines in the cylindrical tank with conical bottom on the 9th day of fermentation

3.3 Dimensionless numbers of the flow

To compare similar flow processes, dimensionless numbers are quite useful. The most important dimensionless numbers for current biological multiphase flow are listed below in table 3.

Table 3: Dimensionless numbers during fermentation

	relevant parameters	value
Prandtl		7.62
Grashof	vertical temperature difference: 9 K characteristic length: 1.150 m	4.66E10
Rayleigh		2.08E11
Nußelt	heat transfer coefficient: 1200 W/(m²·K)	346
Reynolds	bubble diameter: 2.5E-3 m	221.08
Morton	surface tension: 7.28E-2 N/m	1.09E-9
Eötvös		0.93
Weber	relative lift velocity: 0.210 m/s	1.67
Froude		1.34

4. Conclusion

In this investigation, the temperature and velocity fields in a fermenter with two different bottom shapes in a real fermentation process were measured and described. In summary, the investigation has shown that the connection and evaluation of two coupled ultrasound Doppler measuring devices can be very complicated and self-written program algorithms are absolutely necessary. Furthermore, the measurement volumes of the vertical 2 MHz transducers in the area of the bottom shapes are extraordinarily large due to the divergence and average over a wide range. Basically, the flow field is driven in the tank by the natural convection phenomena and is thus subject to very high fluctuation movements at very low speeds and is additionally superimposed by rising gas bubbles. Another result of the investigation is the distribution of the bottom-fermented yeast, because in contrast to the cylindroconical tank, the yeast is evenly distributed over the entire area in the hemispherical bottom. The next step will be the complete automation of data acquisition and above all processing and output. In addition, investigations will be carried out to reduce the influence of bubble columns on UDV measurement technology and a device for avoiding gas bubbles on the transducers.

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