

Determining the thermal flow structure inside fermenters with different shapes using Ultrasonic Doppler Velocimetry

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In this work the experimental investigations of the flow and the temperature field in fermenters are presented. The investigated tank is used for fermentation and storing of beer. The flow stability and the fermentation process are affected of the height/diameter ratio and the bottom shape of the fermenter. The modern cylindroconical tanks are generally equipped with sharp conical bottom (60° to 70° cone angle). Various studies have shown that a hemispherical bottom offers advantages in terms of the fermentation process. In the presented study, a tank with two different shapes of bottom (classic conical with 60° angle and hemispherical bottom) have been used in the laboratory, which were equipped with special design features. The velocity fields are measured by means of Ultrasound Doppler Velocimetry. Furthermore temperature measurements are conducted to analyze the interrelationship between the heat transfer and flow structure. In the course of our research the experiments have been performed with model fluid and it is intended to be measure in real turbid fermentation fluid (wort).

Keywords: Ultrasound Doppler Velocimetry, flow field measurements, fermentation, multiphase flow

1. Introduction

The process steps of fermentation, maturation and storage following the wort production have a decisive influence on the efficiency and product quality in beer production. In particular, the fermentation and maturation have complex interactions between the exothermic yeast metabolism and the resulting convection in the fermenter. The description of the thermo-fluid-dynamical 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.

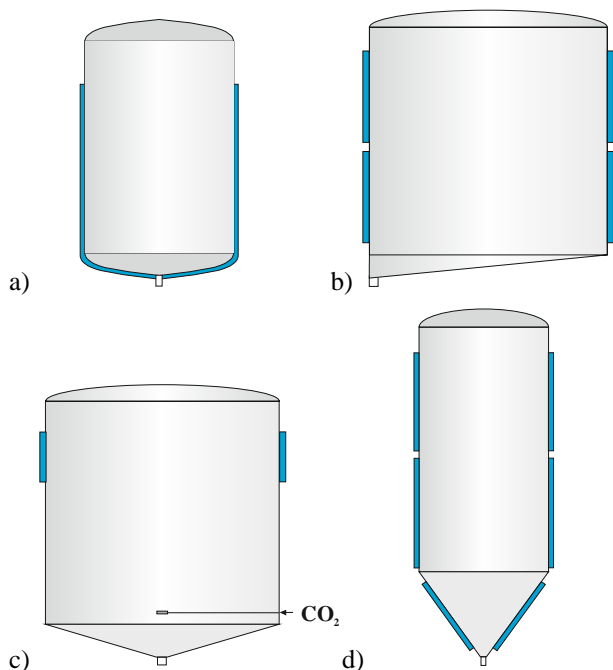


Figure 1: Fermenting tanks: a) Nathan-tank, b) Asahi-tank, c) Uni-tank, d) Cylindroconical tank [1]

In the course of the last century, various fermentation vessels have formed starting out from the open fermenting vat to closed fermenting tanks. One of the oldest method of performing the fermentation, maturation and storage in closed fermenting tanks represents the Nathan method. Nathan [2] developed in 1902 in connection with his quick method of brewing a cylindrical and multi-functional closed tank (Hansena apparatus) made of cast iron with a conical bottom part (Fig. 1a). This cylindroconical tank had a maximum volume capacity of 30,000 liters at a height to diameter ratio of 4. Lindner [3] conducted a series of studies to these tanks. Since the mid-1960s the accelerated development and the industrial mass production of closed fermenting tanks took place worldwide. The Japanese Asahi - Brewery developed the Asahi-tank under the global effort of the tank developments in the brewing industry (Fig. 1b). One special feature is the flat inclined bottom (about 10%) [4]. Due to a special suction device inside the tank, the finished green beer always has the same content of CO₂. An advancement of the Asahi-Tanks carried out in the early 1970s by Knudsen and Vacano [5] of the American "Rainier Brewing Company" with the development of the Uni-tanks (Fig. 1c). The Uni-tank could be used in one-Tank process, while fermentation, maturation and storage are carried out successively in this tank. The tank has a flat conical bottom (155° cone angle) and approximately the same height to diameter ratio. The special feature of this tank is a nozzle ring which is located in the lower cone area and CO₂ can be injected through the ring. With the rediscovery and introduction of cylindroconical tanks in the mid-1960s, production times could be reduced and the tank capacity in the brewing industry can be increased significantly [6].

The cylindroconical tank (CCT) is nowadays the preferred shape of the tank in a modern European brewery and has an acute conical bottom (60°-70° cone

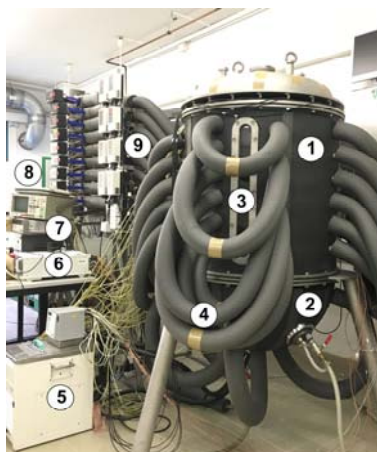
angle) as well as an upper torispherical or semi-ellipsoidal head (Fig. 1d). In outdoor tanks height to diameter ratios of up to 6 are realized, whereby in particular in indoor tanks from the mid-1980s, the trend towards a height to diameter ratios of 2 [7]. In many breweries in the indoor area of buildings because of technical reasons smaller height to diameter ratios (e.g. 1 or 0.8) are installed.

Due to strong turbidity of wort, the advantages of the Ultrasonic Doppler Velocimetry (UDV) are used for comprehensive studies of the convection flow in real wort during the last years in several projects [1, 8]. These provided measurements of the velocity fields in opaque fluids for any time during the fermentation. In these previous experimental studies of flow fields, mainly the cylindrical part was investigated. In this work the entire tank, especially the lower part (cone area) is in the focus. For the current studies, a new modular tank was developed.

2. Experimental Setup

2.1 Experimental Arrangement

For the experimental investigation of flow phenomena and temperature fields an existing experimental setup with a cylindroconical tank (270 liter) has been enhanced with a new modular tank which can be equipped with different bottoms (Fig. 2). In the present studies, the tank is equipped with a conical bottom (60°) and a hemispherical bottom with a total capacity of 350 liter respectively 375 liter.



- 1 - cylindrical part
- 2 - modular bottom
- 3 - optical access
- 4 - tube connection cooling panels
- 5 - bottom heating
- 6 - UDV – System
- 7 - data acquisition
- 8 - 10 kW cooling aggregate
- 9 - heating tubes and temperature control

Figure 2: Test rig with modular tank

Several openings in the new tank enable the integration of sensors for the temperature and flow measurement technology (Fig. 3). The modular tank was equipped with six separately controlled heating or cooling zones in the cylindrical part and one in the bottom part.

For the control of test facility, a program was created based on the software tool "LabView", to implement the automated continuous data acquisition of temperature and flow rates during operation of the test rig. Two operation modes are possible, the one is the simulated fermentation

by means of a model fluid and the other, the real fermentation operation.



Figure 3: Cylindrical Part of the new modular tank with the temperature measuring grid and the arrangement of transducers

2.2 Implementation of the temperature measurement

The temperature detection inside the tank is carried out by a conventional temperature measuring method in a grid array of 57 temperature sensors (RTD). The grid is installed in cross-section of the tank and will be adjusted accordingly for the two bottoms. Calibrations of all sensors are performed by comparison against a thermometer with a high accuracy.

2.3 Implementation of UDV

For the measurement of the flow fields, the Ultrasound Doppler Velocimetry is used, because in the planned experiments it is intended to be measure in real turbid wort (Table 1). The measurement of the flow field is carried out by means of the Ultrasonic Velocity Profile Monitor System UVP-XW-PSi from Met-Flow S.A.. The system was enhanced to a two dimensional diagnostic system for investigations of convection flow inside fermenters. The main principle is the combination of the measurements of the ultrasound echo time delay and the Doppler frequency. The basic feature of this system is the ability to establish the velocity in 128 separate points along measurement axis. For two dimensional measurements of velocities it is necessary to measure two velocity components at one spatial point in order to form a vector. Due to the fact that a two-dimensional measurement system is used, the array is aligned in the cross section of the tank. Here a certain degree of rotational symmetry of the flow is assumed. As the measurements have shown, however, the fluid movements are not symmetrical and fluctuate strongly.

The measuring array in the cylindrical part is rectangular and consists of 10 horizontal and 10 vertical transducers arranged (Fig 4 left). The vertical transducers are immersed in the fluid and the horizontal transducers measure through the wall (acrylic glass). In order to measure the velocities in the conical bottom, the 10 vertical transducers are lowered and 7 transducers are aligned orthogonal to the surface of the cone (Fig 5 right). In this study these transducers measure

through the bottom wall (stainless steel). This results in a corresponding angular orientation of the measuring array. The installation of the transducers on the hemispherical bottom is much more complicated because of the rounding there is a constant change of the angle (Fig 5 left). In a first arrangement, 7 transducers are mounted horizontally at the bottom. Due to the strong refraction angle a nearly radial distribution of the measuring lines is generated. This leads to non-uniform distribution of the intersection points in one half of the hemispherical bottom.

Table 1: Properties of the Measuring fields

Measuring fields	cylindrical part	conical bottom	hemispherical bottom
Transducer (4 MHz)	20	17	17
Intersection points	100	38	35

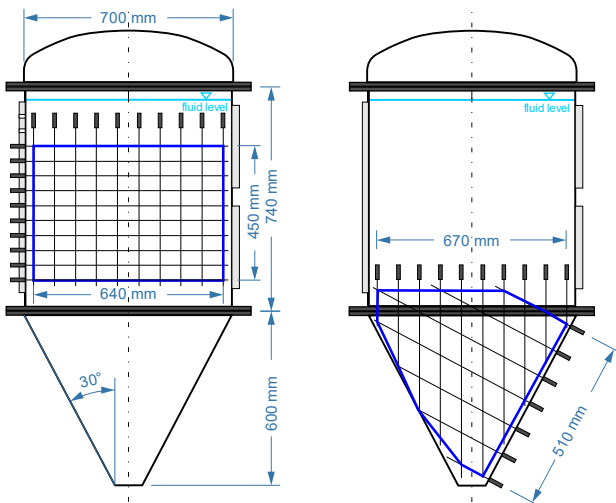


Figure 4: Measuring arrays (blue line) for the velocity measurement in the cylindrical part (left) and in the cone (right)

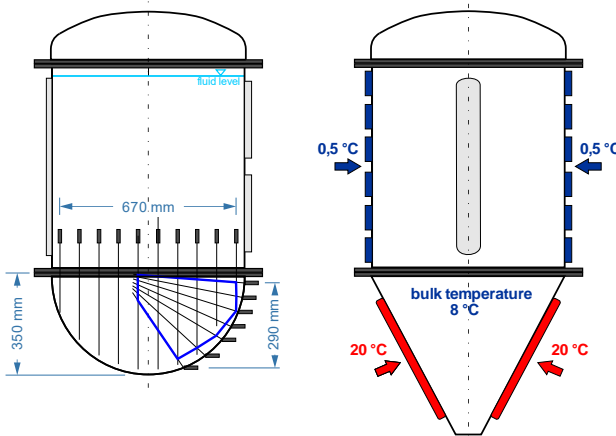


Figure 5: Measuring array for the velocity measurement in the hemispherical bottom (blue line) Figure 6: Thermal boundary condition for example in the cylindroconical fermenter

For the present experiments water is used as a model fluid, because water is very close with its properties on

the fermenting liquid. In the studies the cold fermentation was simulated used at a bulk temperature of 8°C. For simulation of the fermentation heat the bottom is heated at a temperature of 20°C. This temperature corresponds approximately to the resulting from the yeast metabolism fermentation heat. The steady state was achieved by removing the heat with the cooling zones (0.5°C) in the cylindrical part (Fig 6).

3. Results and Discussion

3.1 Measurement of temperature fields

The temperature field was measured continuously every ten minutes during the steady state of the simulated fermentation. The temperature field inside the cylindrical tank with conical bottom (Fig. 7 left) is about 0.5 K warmer than the tank with hemispherical bottom (Fig. 7 right) in the same boundary condition. The reason may be due to better mixing behavior in the cylindroconical tank. The temperature field in the upper part of this tank is determined by means of a large warm region in the middle. The lower tank area is determined by means of the cooled fluid, which sinks down to the cone due to the supporting effect of downward going flow in the boundary layer at the wall. Remarkable is the fact that there is a small temperature difference during the process of maximum of about 1°C, if the temperature gradient in the small wall region and the lowest cone is neglected. This small temperature difference is caused by the wide mixing zone with turbulent flow in the largest part of the tank. The cool area in the lower part of the tank with hemispherical bottom has a greater extension.

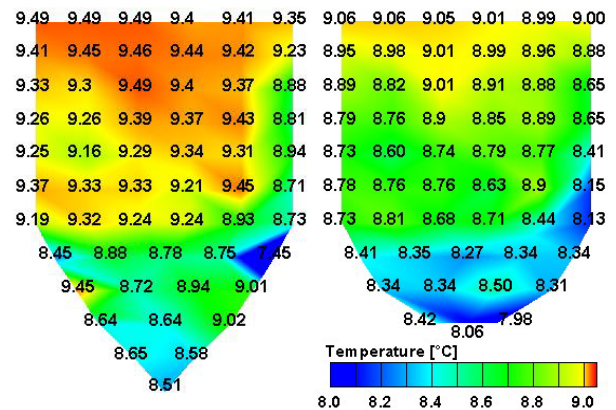


Figure 7: Temperature fields of the steady state inside the cylindrical tank with conical bottom (left) and hemispherical bottom (right)

3.1 Measurement of flow fields

The flow field in the upper area of the cylindroconical tank (Fig. 8) is determined by means of a large vortex in the middle. In the upper part of the tank with hemispherical bottom a large vortex could be detected close to the cooling zone (Fig. 9). Both vortices are driven by the rising warm fluid from the heating bottom. The fluid flows in the direction of the cooling zones and

sinks down at the border area of the tank towards the cone. The radial flow of this vortex was measured with velocities up to 20 mm/s. In general, the measured velocities are low but mostly between 2 mm/s and 10 mm/s. In the cone area no significant flow pattern can be detected with the present measurement configuration.

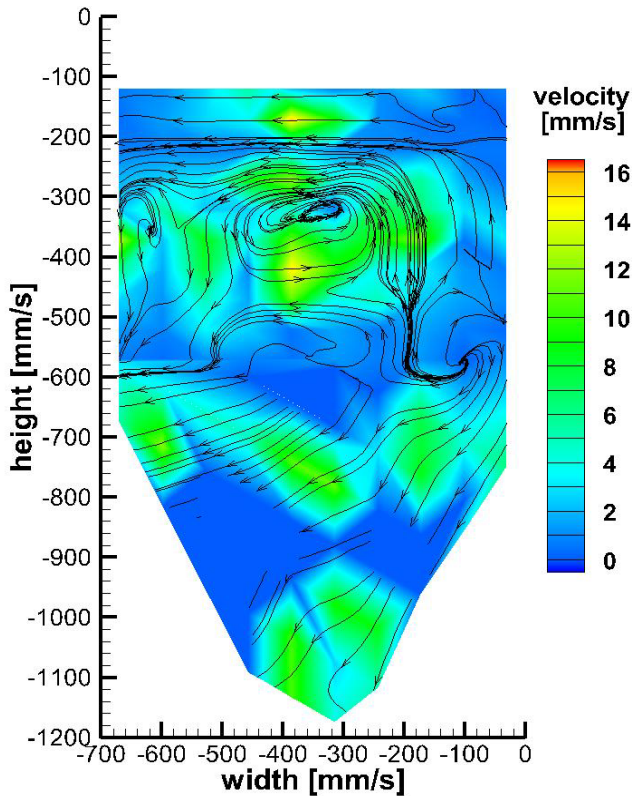


Figure 8: Velocity field and streamlines in the cylindrical tank with conical bottom

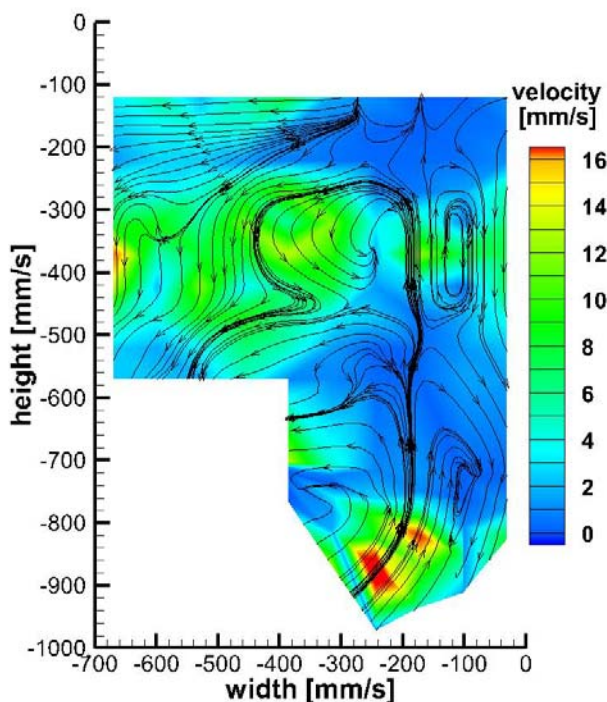


Figure 9: Velocity field and streamlines in the cylindrical tank with hemispherical bottom

4. Conclusion

In this study the temperature and velocity fields are described in a fermenter with two different bottoms. The selected thermal boundary conditions are used to simulate in the model fluid the fermenting wort during the real fermentation. The investigations have shown that, in particular the coupling of the transducers in the conical and hemispherical bottom turns out to be complicated. This relates to the measurement through the tank wall which is affected by the refraction, and the large difference in acoustic impedance. Another problem is the combination of the measurement fields, since the measuring depth of the transducers is limited.

Basically, the flow field is driven into the tank at the present boundary conditions by natural convection phenomena and thus is subject to very high fluctuation movements at very low velocities. These strong fluctuating movements to a low average velocity are also a challenge for the data acquisition.

In further tests, sensors with lower frequencies (2 MHz) will be used to detect a higher measuring depth or higher velocity range. In this context, the coupling of sensors will be optimized in both bottoms. Corresponding to this study, it is planned to investigate the flow and temperature fields during a real fermentation in this modular tank, especially focused on the lower tank area in different bottoms.

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