

# Experimental studies of convection flow during the fermentation process of beer by means of Ultrasonic Doppler Velocimetry

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The measurement of the flow field is conducted by means of the Ultrasonic Doppler Velocimetry. The system was enhanced to a two dimensional system for investigations of convection flow inside fermenting tanks. In the presented paper the special features of the velocity field measurements during a real fermentation in an industrial cylindroconical fermenter are described. In particular, the measurement data of the multiphase flow consisting of the turbid wort and the CO<sub>2</sub>-bubbles require special handling. Furthermore, there is a change in concentration due to fermentation. This leads to the change of the sound velocity. The results of the investigations provide a wide range of information to optimize the fermentation process.

**Keywords:** Ultrasonic Doppler Velocimetry, flow field measurements, fermentation, multiphase flow

## 1 INTRODUCTION

The entire brewing process consists of a series of sub-processes. An important process section presents the fermentation, which has been conventionally carried out in brewery tanks with different shapes. Cylindroconical tanks are used particularly for bottom-fermented beers in many European breweries. These tanks are made of stainless steel with separated cooling spirals for the different processing steps.

The fermentation of wort represents a key process in the production of beer. The current applied technology and procedures established from many years of experience with fermentation tanks (since 1965). The technological interest of fermentation of beer in cylindroconical fermentation tanks was very often the subject of investigations and scientific papers. In the past exists only few experimental works and investigations which are considered the determination of the convection flow inside a fermenter [1], [2]. Most of the experimental studies have been carried out in model liquids.

Initial investigations of velocity measurements by means of an ultrasonic measuring principle during real fermentation were carried out by Kojima et al. in 1992 [3]. Kojima et al. investigated the influence of CO<sub>2</sub>-bubbles on the flow tank and the foam formation during fermentation. In a coarse grid, the flow field in a variety of models and industrial tanks, during the first and second day of fermentation is described.

During the fermentation it comes to the overlapping of physical, biochemical and microbiological processes and hence there is an interaction between these effects and the onset of convection. Due to strong turbidity of wort, the velocity measurements cannot be performed easily by using common techniques like Laser

Doppler Anemometry or Particle Image Velocimetry. The advantages of the Ultrasonic Doppler Velocimetry (UDV) are used for extensive studies of convection flow in real wort during the last years in several projects. It permits measurements in opaque fluids and provides velocity fields for any time during the fermentation [4], [5].

## 2 EXPERIMENTAL SETUP

### 2.1 Experimental Arrangement

To study the convection flow under real conditions two experimental arrangements have been developed.

The first experimental setup is a cylindroconical laboratory fermenter (270 liters), which can be used in two modes of operation, simulated and real fermentation. The second one is a cylindroconical test tank (30000 liters) installed in the brewery, which was equipped with process and flow measurement technology. The automatic control of the components and the management of all process parameters has been realized using the programming software "HP-VEE". The programmed control and data acquisition software allow online monitoring of all important process parameters in high temporal resolution.

The test tank in the brewery was equipped with six separately controlled cooling zones and several accesses for the measurement equipment in the cylindrical and upper part (figure 1). The volume flows in these zones were adjustable to the various test conditions and process requirements. The cooling medium was a glycol/water mixture, which was able to supply the six cooling panels with a temperature of minus 3 °C. In both tanks numerous fermentations has been performed to get the necessary data for the

velocity fields. In addition a number of other parameters, such as temperature and several biochemical parameters like extract content, cell viability and pH-value were determined.

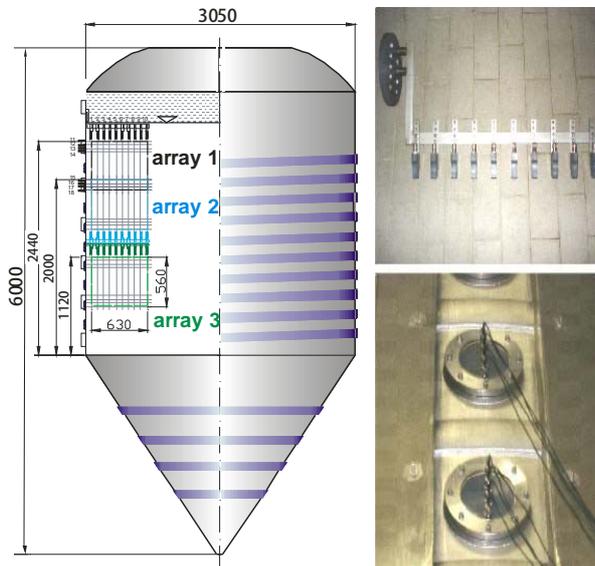


Figure 1: Arrangement of the transducers and position of the velocity measuring arrays in the industrial fermenter (30000 liters).

## 2.2 Measurement of flow fields

The measurement of the flow field is conducted by means of the Ultrasonic Doppler Velocimetry (Ultrasonic Velocity Profile Monitor UVP-XW-PSi, Met-Flow S.A.). The system was enhanced to a two dimensional diagnostic system for investigations of convection flow inside fermenting tanks. The main principle is the combination of the measurements of the ultrasonic 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 this fact the transducers are arranged in an orthogonal grid with a dimension of 630 mm x 560 mm and 10 x 8 measuring lines. In the figure 1 (right) the arrangement of the 18 transducers are displayed. 10 transducers are attached to a horizontal arm inside the tank and 8 transducers are mounted outside in the wall of the tank. The horizontal arrangement is interrupted into two groups of 4 transducers by the cooling spiral. Due to the fact that the measuring field is very small compared to the dimensions of the tank the velocity fields are measured in three different arrays. For the validation of the raw velocity data a special analysis program was created with a view to managing the velocity information of the multiphase flow.

## 2.3 Characteristics of the multiphase flow during fermentation

The flow during the fermentation process are influenced by the fermentative formation of  $\text{CO}_2$ , the rise and the sedimentation of yeast particles or agglomerates. This leads to a multiphase flow and a special assessment of the measurement data is necessary.

In general, the yeast particles have a diameter of 5-10 microns and have a round or ellipsoidal shape. It is assumed that the most yeast particles follow the flow. During the first day of fermentation ( $8.0^\circ\text{C}$ ) an average sound velocity of Ultrasonic (4 MHz) of 1487 m/s in the fermenting fluid is measured. This corresponds to the wavelength of about 0.37 mm.

This means that the tracer particle must have a diameter of greater than 92.5 microns. However, because a good signal quality achieved during the measurement, it must be assumed that the yeast particles agglomerate in part and reach a diameter of greater than 90 microns. Some yeast particles combine to form larger agglomerates and can reach diameter of 1-2 mm. The forming  $\text{CO}_2$ -bubbles have diameters of 50 microns initially up to 1 mm [1], wherein during fermentation few bubbles with diameters of 3-4 mm were observed. The velocities of the liquid phase with the yeast particles as a tracer and the rising  $\text{CO}_2$ -bubbles determine the total flow pattern in each of the measuring array. The velocities of the rising  $\text{CO}_2$ -bubbles depend on their diameter and are in the range of approximately 50 mm/s to 300 mm/s. The velocities in the liquid phase have a maximum of 70 mm/s.

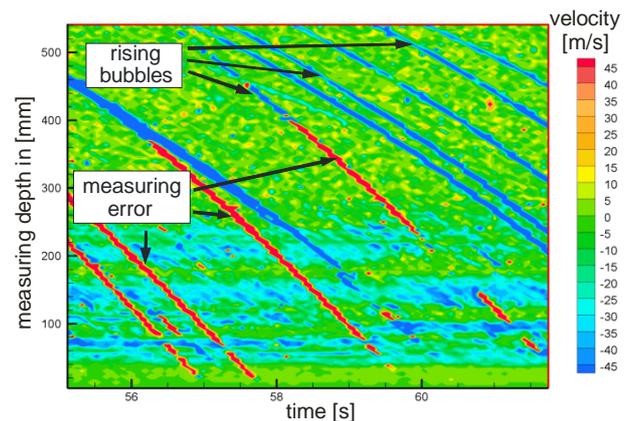


Figure 2: Example of a time sequence of velocities of 100 measurements on a vertically oriented transducer (No. 9, array 1) during fermentation.

In the present measurement arrays with dimensions of 630 x 560 mm maximum velocities of 90 mm/s can be measured without reducing the measurement range. This leads to an exceedance of the measuring range and hence to an incorrect

evaluation of the measured signals in the commercial analysis software. Smaller bubbles move toward the sensor and are usually represented as negative velocities (blue streaks in Fig. 2). The velocities of the larger bubbles rising up to 300 mm/s and are tilted as faulty velocities into positive range (red streaks in Fig. 2). This measurement error due to the multiphase flow has been fixed by a separate software procedure and created a revalued data set from the raw data of the commercial measurement system.

#### 2.4 Influence of the fermentation at the sound velocity

The variation of sound velocity during the fermentation process is measured by a special ultrasonic transducer, wherein the time delay is evaluated between the transmission of the pulse and the reception of the back-wall echo. The velocity of a sound wave in a liquid is an important parameter in the UDV measurements and depends on several factors. In particular, material parameters such as composition, concentration, density, temperature and pressure affect the sound velocity. The initial composition of the wort is primarily determined by the content of extractives. The initial extract content (12.0 wt% in the used wort) is reduced to about 2.5 percent by weight during fermentation. The actual reduction in extract content would cause a reduction in the sound velocity. As a result of metabolic processes during fermentation alcohol and CO<sub>2</sub> are formed. The gradual increase in the alcohol concentration is reduced, the density of the wort and causes a significant increase in the sound velocity. The fermentative formation of CO<sub>2</sub> leads to a gradual saturation of the wort with the dissolved CO<sub>2</sub>. This saturation limit depends on the pressure and performs in the case of pressure-free fermentation (up to extract content of about 4.0 wt%) only a small influence on the sound velocity. After the closure of the system and setting up a pressure (0.5 bar), the percentage of dissolved CO<sub>2</sub> in the wort increases gradually. This change in concentration has a non-negligible influence on the sound velocity and leads to an increase of up to 5 m/s, as the measurements have shown (Fig. 3). The total increase in the sound velocity during the fermentation phase can cause a change of up to 25 m/s, which is confirmed by the measurements of Becker [6]. According to his studies the gaseous CO<sub>2</sub> does not significantly affect the sound velocity. However, the change in the yeast cell concentration and the resulting gas bubbles affect the signal intensity of the Ultrasonic. The attenuation of the intensity of the ultrasonic pulse at more distant measuring points is compensated by the measuring system, by

scanning with linear higher signal strength.

On the first day of fermentation the average sound velocity is 1482 m/s (8.5 °C). In the following days, the sound velocity increases due to the increase of the alcohol concentration gradually. On the last day of fermentation the sound velocity has increased by 10 m/s and is on average 1492 m/s. After lowering of the process temperature to 6.4 °C the sound velocity drops due to the temperature dependence of 6 m/s to 1486 m/s. In the course of maturation, the sound velocity increases again at 6 m/s to 1492 m/s. In the maturation phase to test various pressure tests were conducted. The tests showed that the sound velocity is strongly dependent on the pressure due to the change of the dependent concentration of dissolved CO<sub>2</sub>. After the end of the maturation phase, the wort is cooled to storage temperature (-0.5 °C). With the lowering of the temperature also reduces the sound velocity of up to 1460 m/s.

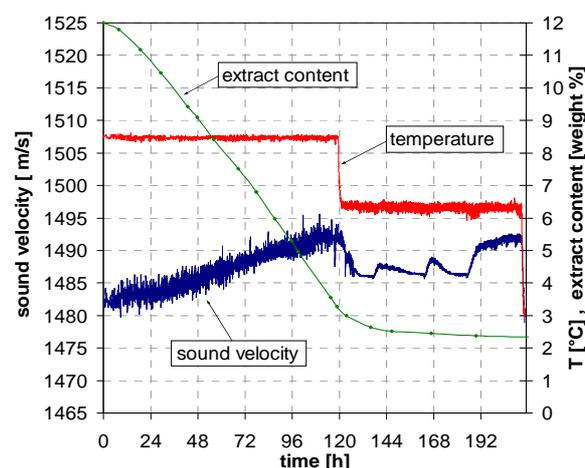


Figure 3: The variation of the sound velocity during the fermentation process.

### 3 RESULTS AND DISCUSSION

In the following, a velocity field during the fermentation is shown in an industrial fermenter as an example. The flow field was measured continuously several times during the days of fermentation. In compliance with the fermenting procedure the temperature of the interior of the fermenting tank set to 8.5 °C. Because of the dependence of the sound velocity of the temperature, the pressure and the concentration changes in the wort, the measurements during the fermentation process are evaluated with the respective predominant average sound velocities (Tab. 1). The heat transfer of the fermenting heat took place in the upper two cooling zones. On the first day of fermentation, no distinct convection areas had developed inside the tank. Velocities of 2-5 mm/s were measured.

Table 1: Average sound velocities used in the measurements

process		average sound velocity [m/s]
fermentation (8.5 °C)	1-2. day	1482
	3-4. day	1486
	5. day	1492
maturation (6.4 °C)	6-7. day	1487
	8. day	1489
	9. day	1492
storage (-0.5 °C)	10-24. day	1465

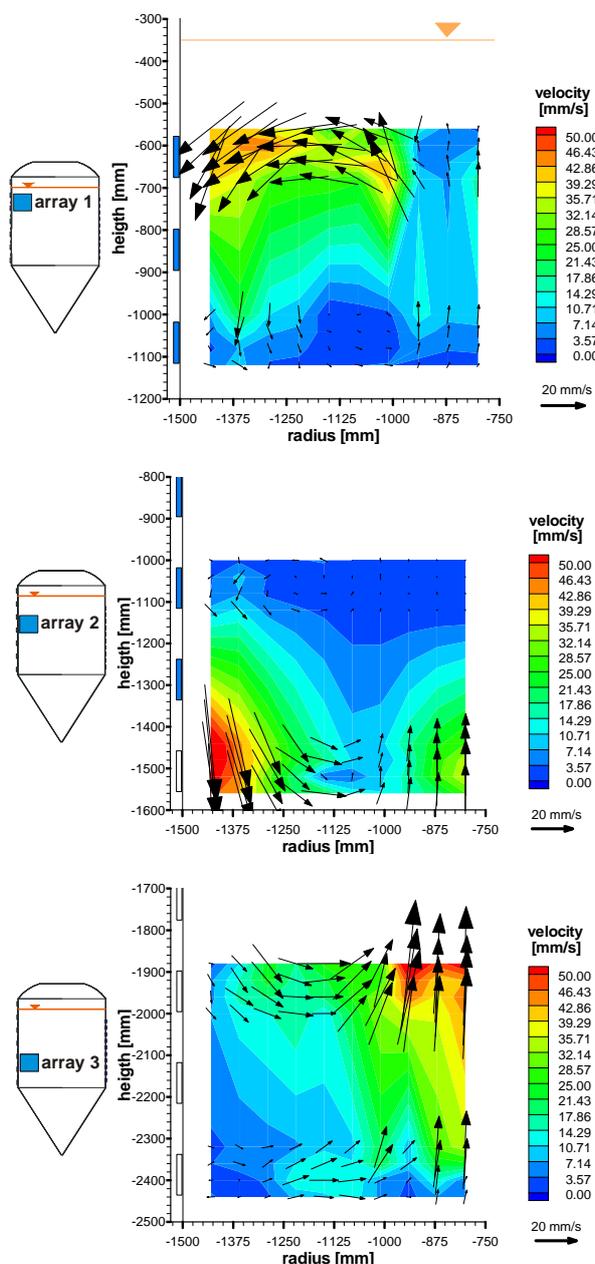


Figure 4: Average velocity fields in the three arrays on the last day of fermentation (130 h after the filling).

On the last day of fermentation the flow activity strongly increased due to the increase of the fermentation process. In the upper part of the tank, a radial flow directed at the cooling zones was detected. In figure 4 an example of the velocity field taken on the 6th day of fermentation is shown. A large torus shaped vortex with horizontal diameter of 500-600 mm and a vertical diameter up to 2000 mm is determined the flow in the three measurement arrays. The radial flow of this vortex was measured with velocities up to 40 mm/s. The warmer liquid in the cone area rises to the upper part, turns to the cooling zones and sinks at the border area of the tank downwards due to the fact of cooling zones. As a result of continuity the flow directs at the centre and completes the convection roll. The re-flow is generally not very intensive but it can be increasing up to 50 mm/s locally.

#### 4 CONCLUSION

In the presented paper the special features of the velocity field measurements during a real fermentation in an industrial cylindroconical fermenting tank are described. In particular, the multi-phase flow consisting of the turbid wort and the CO<sub>2</sub>-bubbles complicate the measurements. Furthermore, there is a change in concentration due to fermentation. This leads to the change of the sound velocity. The results of the investigations provide a wide range of information to optimize the fermentation process.

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