MATEC Web of Conferences **18**, 02003 (2014)
DOI: 10.1051/matecconf/20141802003

Thermofluidynamics of the multiphase flow inside cylindroconical fermenters with different scales

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Abstract. In this work the experimental investigations of the flow and the temperature field during the fermentation of beer in cylindroconical tanks are presented. The flow stability is affected of the height/diameter ratio. Increasing the ratio leads to an unsteady, three-dimensional flow with several smaller vortices. In the course of our research the experiments have been performed with real fermentation fluid (wort) under various height/diameter ratio. In the study, two tanks have been used in the laboratory and on an industrial scale, which were equipped with special design features. The velocity fields during a real fermentation process are measured by means of Ultrasound Doppler Velocimetry. It permits measurements in opaque fluids. Furthermore temperature measurements are conducted to analyse the interrelationship between the heat transfer and flow structure.

1 INTRODUCTION

In most European breweries fermentation, maturation and conditioning of beer is usually carried out in cylindroconical tanks. These tanks are made of stainless steel equipped with cooling segments for the thermal treatment of the wort in the various processing steps. The shape of cylindroconical tanks differ in principle in different height/diameter ratios and various cone angles.

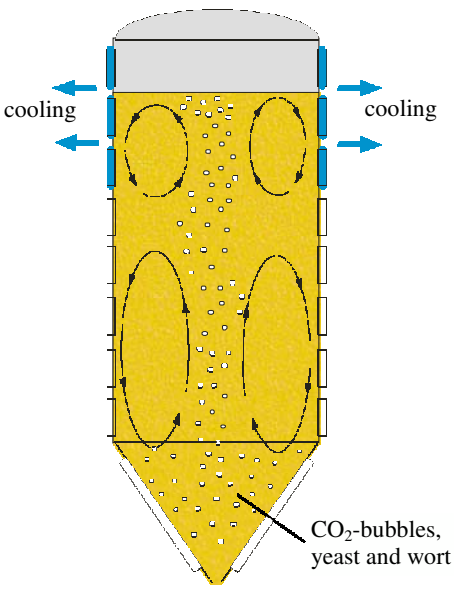

Figure 1. Abstract illustration of fluid and flow characteristics during the primary fermentation.

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The multiphase flow in the tank generated by the fermenting process is unsteady, three-dimensional and turbulent (Fig. 1). The fluid "wort" is not transparent and composed of several phases and components. 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 3 percent by weight during fermentation. The process is characterizes by different temperature levels and local temperature, velocity and concentration differences. The resulting flow in fermenters strongly influences the heat transfer and the transport of yeast cells [1].

In the past exists only few experimental works and investigations which are considered the determination of the convection flow inside a fermenter. Most of the experimental studies have been carried out in model liquids. Denk et al. [2], for example, describe observations by experiments with water as model fluid inside a cylindroconical model tank. Their experiments show that a rotationally symmetric vortex is formed with a central bubble column and a radial flow at the surface in the direction of the tank wall. Furthermore, the flow stability is affected of the height/diameter ratio. Increasing the ratio leads to an unsteady, three-dimensional flow with several smaller vortices. In the course of our research the experiments with different cylindroconical fermenters have been performed with real fermentation fluid under various height/diameter ratio. Furthermore temperature measurements are conducted to analyse the interrelationship between the heat transfer and flow structure.

Due to turbidity, the velocity measurements cannot be performed easily by using common techniques like Laser Doppler Anemometry or Particle Image Velocimetry. Therefore the Ultrasound Doppler Velocimetry got utilised. It permits measurements in opaque fluids and provides velocity fields for any time during the fermentation [3].

2 EXPERIMENT

2.1 Experimental Arrangements

For the investigation of the fluid mechanics and the heat distribution inside the fermenting tank a cylindroconical industrial tank (30.000 liters) and a laboratory tank (270 liters) with special design features was developed (Fig. 2). The tanks were equipped with separately controlled cooling zones and several accesses for the measurement equipment in the cylindrical and upper part. The volume flows in these zones were adjustable to the various test conditions and process requirements. Due to the different filling levels and tank sizes resulting three different slenderness ratios.

Table 1. height/diameter ratios of the used cylidroconical fermenters.

Cylindroconical Tanks	Height/diameter ratios
Laboratory tank (270 liters)	1.80
Industrial tank 1 (30.000 liters)	0.82
Industrial tank 2 (30.000 liters)	0.72

Figure 2. Test facility in the Stralsund brewery (30.000 liters) and in the laboratory (270 liters).

The measurements of the velocity fields inside of the both fermenter are carried out by means of Ultrasound Doppler Velocimetry. The transducers are arranged in an orthogonal array of 10 x 8 with a dimension of 630 mm x 560 mm in the industrial fermenter (Fig. 3) and 10 x 10 transducer with an dimension of 450 mm x 675 mm in the laboratory fermenter (Fig. 5 left).

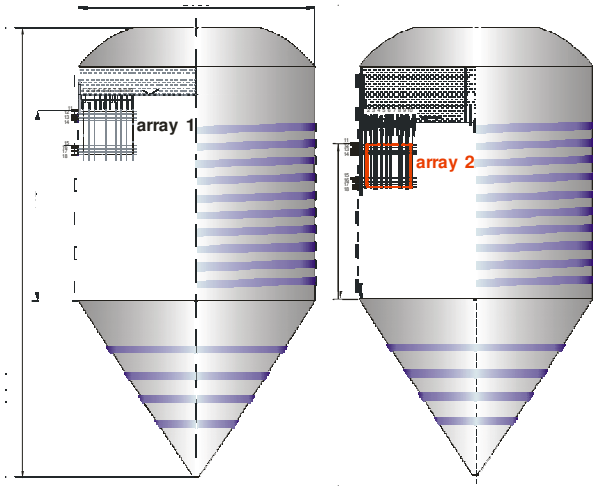

Figure 3. Arrangement of the transducers and the velocity measuring arrays in the industrial fermenter (30.000 liters).

The measurements of the temperature fields in the industrial fermenter is carried out by a conventional temperature measurement procedure using a grid arrangement of 43 resistance temperature detector elements. The measured data of the temperature field is continuously scanned in intervals of two minutes during the process.

2.2 The boundary conditions of fermentation

The process procedure inside the cylindroconical fermenter is divided into the onset of fermentation, the main fermentation and the maturation. The fermentation process characterizes by different temperature levels and pressures and is distinguished in the warm and cold fermentation method.

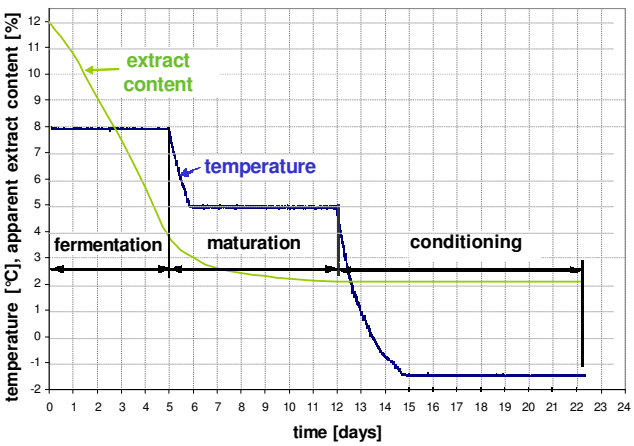

Figure 4. Course of temperature and apparent extract during the entire process inside of the fermenter.

In the present studies the cold fermentation method was used at a bulk temperature of 8 °C during the primary fermentation and 5 °C during the maturation (Fig. 4). After completion of the primary fermentation, are fermented in about 75% of the extract, this is reduced in the following maturation phase up to the final gravity.

3 RESULTS AND DISCUSSION

3.1. Comparison of flow field using the example of the upper torus vortex

corresponding with the same composition of the wort (Fig. 4). By means of a brewing chemical analysis the finished beers were compared and showed approximately the same characteristic values. This means that a comparison of fermentations exists in both tanks.

The investigations have shown that a torus vortex forms in both tanks during the fermentation process inside the top of the tank below the surface near the tank wall. This torus vortex dominates strongly the flow structure during the end of the primary fermentation process.

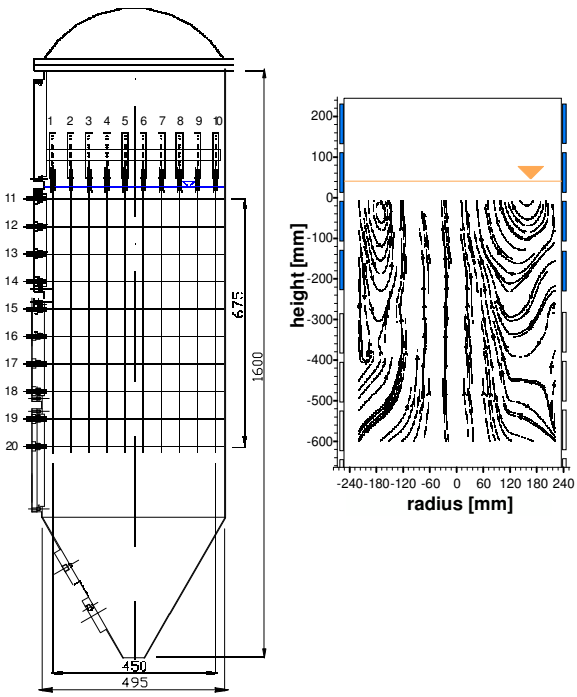

Figure 5. Test facility in the labaratory (270 liter) with used measuring array and flow field measurement (h/d ratio = 1.8).

In the laboratory fermenter with a h/d ratio of 1.8, the horizontal diameter of the torus vortex is 150-200 mm and extends up to 65% of the tank radius (Fig. 5). The vertical diameter is 350-400 mm and it has a strong stretch in this direction. In the industrial fermenter with a h/d ratio of 0.82, the horizontal diameter of the torus vortex is 600-650 mm and extends only about 40% of the tank radius. The vertical extension is up to 2000 mm, and extends approximately over the entire height of the cylindrical part with a downward flow close to the tank wall. In the h/d ratio of 0.72 the horizontal diameter of 750 mm is slightly larger and expands up to 50% of the tank radius. Vertical it was measured with 800-850 mm (Fig. 6). With decreasing h/d ratio this torus vortex is in its form much more stable and shows only a slight variation in its position.

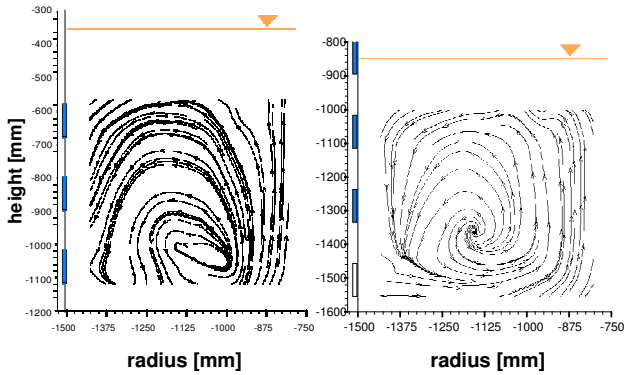

Figure 6. Torus vortices in the industrial tank on the last day of primary fermentation h/d ratio = 0.82 (left) and 0.72 (right).

The intensities of the maximum average velocities in the vicinity of the surface and the cooling zones are nearly equal at the h/d ratios 0.82 (Fig. 8) and 0.72 (Fig. 9). In the core area maximum average velocities at the h/d ratio of 0.72 at 20 mm/s were measured (Fig. 9). That is a difference of about 30 mm/s to the h/d ratio of 0.82. The flows in the laboratory tank (h/d ratio of 1.8) reach in the upper region of the core zone also 50 mm/s, as in the other investigated h/d ratios were measured (Fig. 7). In the vicinity of the surface and cooling zones but were only 20 to 25 mm/s measured. This corresponds to approximately half the average velocities in the industrial tanks. This reduction is caused by a lower temperature (3 °C) in the cooling zones of the model tank, which cause a lower heat flux and consequently lower velocities in the boundary layer.

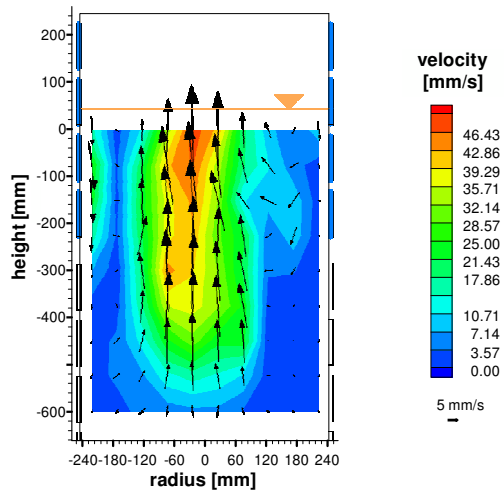

Figure 7. Average velocity field in the laboratory tank on the last day of primary fermentation (h/d ratio = 1.8).

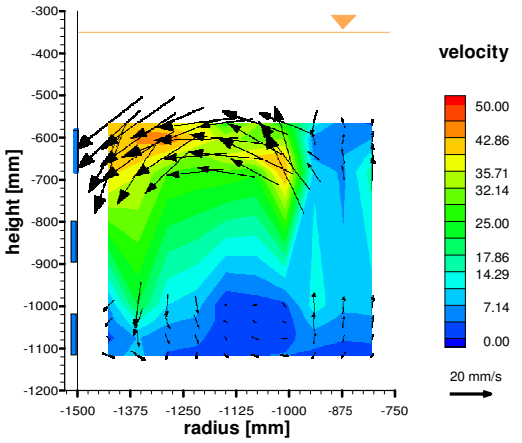

Figure 8. Average velocity field in the industrial tank on the last day of primary fermentation (h/d ratio = 0.82).

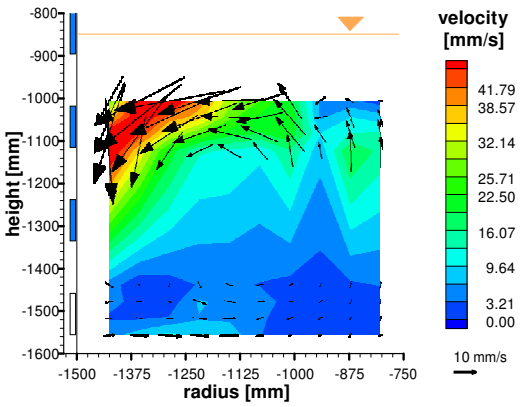

Figure 9. Average velocity field in the industrial tank on the last day of primary fermentation (h/d ratio = 0.72).

3.2. General flow regions during fermentation

The topology of the three-dimensional, unsteady multiphase flow is mainly determined by convective flows.

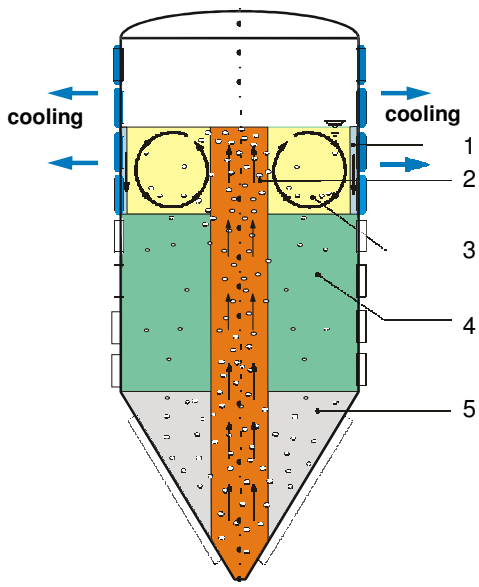

Figure 10. Topological classification of flow regimes during fermentation.

The types of convection and the areas in the tank in process, the fermentation activity and the cooling conditions. As a result, it comes to shifting and resizing process progress. At lower h/d ratios, e.g. the analyzed industrial tank (30.000 liters, the h/d ratio = 0.87 and wider, and the upper tank region (Fig. 10, region 3) with the dominant torus vortex is more on the tank wall.

Basically the flow is three-dimensional and not rotationally symmetrical in the tank. Mainly occur in the central region of the tank (Fig. 10, region 4) in the direction and intensity very strongly fluctuating flow and thus cause strong interferences in the other regions.

During the fermentation and maturation the thermal convection and the induced convection due to the CO_2-bubbles play a crucial role in the formation and direction of the flows. Due to the strong coupling of the difficult to specify a general direction of the flows in the regions (region 4 and 5). To better understand the regions inside the tank the following classifications are presented rotationally symmetric (Fig. 10).

- Region 1: **wall area**

  with directed flow
  - Downward flow in the area of active cooling zones
- Region 2: **core area**
  - Dominant, induced convection as a result of rising CO_2-Bubbles
  - Thermal convection due to temperature differences
- Region 3: **upper tank area**
  - Dominant frictional forces
  - Radial surface flow to the tank wall and formation of a large-scale vortex in close to the tank wall due to the influence of the region 1 and 2
- Region 4: **middle tank area**
  - Dominant frictional forces
  - Low thermal convection, strong influence of the upper tank region and core area with compensating flows (varying directions)
  - At the beginning of the fermentation tank wall rather upward flows and at the end of the fermentation rather downward flows
- Region 5: **cone area**
  - Thermal convection and convection induced as a result of rising CO_2-Bubbles and flows through friction effects

3.3. Temperature field during fermentation

At the beginning the activity of fermentation and the associated heat input of the yeast particles are very less. In the first hours of fermentation a horizontal density layering is developed with a maximum temperature of 8.7 °C. After about 30 hours of filling the temperature

field has been stabilised. After about 140 hours of filling two warm regions are determined the temperature field in the upper tank, supported by an existing torus shaped vortex (Fig. 11). The temperature field in the lower tank is determined by means of the cooled wort, which sinks down to the cone due to the supporting effect of downward going flow in the boundary layer at the wall. In the formation and intensity the temperature field during the whole fermentation process is very stable. One of the most important facts is the small temperature difference during the process of maximum of 0.3 °C, if the temperature gradient in the small wall region and the lowest cone is neglected. The very small temperature difference is caused by the mixing behaviour of the turbulent flow in the largest part of the tank. At the end of the fermentation the precipitate yeast particles increase the temperature in the cone area, especially at the cone wall, up to 10-15 °C. The bottom fermenting yeast is sedimented at the end of the primary fermentation in the cone region. The settled yeast caused in the cone an increase of the temperature and is removed from the tank at the end of primary fermentation.

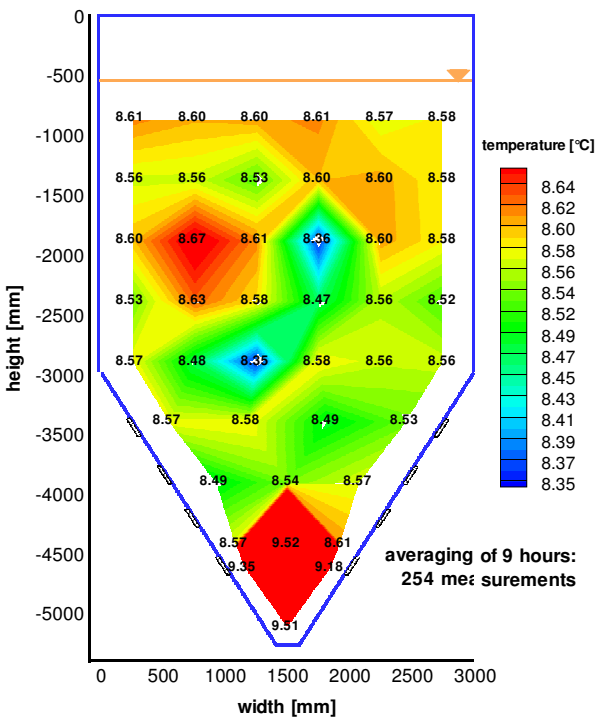

Figure 11. Average of temperature field 146-155 h after the filling (primary fermentation process)

4 CONCLUSIONS

The measurements show how Denk et al. [2] have determined in model experiments that the flow field in real fermentation in the top of the tank at a small h/d ratio is dominated of the surface vortex.

A reduction of the h/d ratio respectively the filling level results in a stabilizing effect on the flow field. Furthermore, the proportion of mixed movements increased relative to larger h/d ratios.

The results are used for the better understanding of the convection flow and provide a wide range of information to optimize the fermentation process in such fermenters.

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