Particle Tracking Velocimetry zur Bestimmung von Strömungsmustern beim Transport von Proteinschaum in Innengeometrien

Particle Tracking Velocimetry for determination of flow patterns of protein foam transport in inner geometries

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Abstract

Foam encounters a lot of attention in industrial applications due to their sensory properties from manufacturing of aerated chocolates to production of beverages. Therefore, foam transport through pipes, is of high importance in the food industry.
In this contribution, equipment has been developed to generate protein foam, transport it in a pipe flow, and analyze the flow and foam stability optically. The flow patterns of the generated foam in the pipe and its associated structures have been investigated. Experimental results have been obtained on the effects of thermophysical properties of the liquid, surfactant type, concentration, and pipe diameter on the velocity profile. The velocity measurements reveal - as result of the prevailing yield stress - plug flow profile of the foam in the center of the pipe and shear flow at the wall. The flow of the foam is dominated by the properties of a thin liquid layer in the vicinity of the wall, which produces the effect of foam "slip" at the wall (Calvert and Nezhati 1986; Calvert 1990).
The introduced experimental optical method enables flow visualization and characterizes flow velocities of foam and bubbles at the wall. The flow behavior of foam is examined as a function of gas volume fraction and protein concentration. The local velocity in the liquid film at the wall and the foam structure are measured optically based on particle tracking velocimetry (PTV). PTV technique scans different frames with an objective connected to a high speed camera and the captured pictures are evaluated by image processing.
The results show that the foam structure, average velocity, and the bubble size distribution significantly depend on the humidity of the foam (wet or dry foam). In wet foams, the gas bubbles tend to be spherical in contrast to dry foams that form polyhedral bubbles. The effect of secondary motion in the foam on the stability is analyzed in horizontal and vertical nozzle and diffuser configurations.

Introduction

Foams attract many applications in food industry, chemical engineering, civil engineering such as insulating materials, firefighting agents, and whipping cream. Although there is a widespread foam production, there is still not enough detailed knowledge about foam flow in

pipes in systems of complex constitution. This contribution presents kinematic measurement of dry protein foam, especially milk protein (Caseins) during transport in pipes.
In the present system, the foams are stabilized by the present natural surfactants, i.e. proteins. Milk protein can act as a stabilizer and the surface viscoelastic properties of proteins can drastically enhance foam stability by decreasing the liquid drainage rates in the foam lamellae. Foam stability is a function of different parameters such as the surface covering kinetics of the surfactants, secondary motion, phase separation due to gravity, pH value, ionic strength, sporadic decay, rheological changes including foam deformation, foam topology and pressure drop.
In this work, the foam flow is analyzed in inner flow geometries such as horizontal and vertical nozzles and diffuser configurations in a channel. However, the discussion is limited here to the horizontal configurations. The gas volume fraction of the foam was varied by controlling the volumetric flow rate of liquid and gas, resulting in different flow types.

Experimental Procedure

The foam was produced by mixing a watery protein solution with compressed air in a foam generator. Calcium and Natrium Caseinat are the two types of proteins that have been used here. Calcium Caseinat EM 9N made by Friesland Campina consisted of 92% Calcium Caseinat and Natrium Caseinat EM 7 produced by Friesland Campina had a purity of 90.5%. The surfactant solution was diluted with distilled water to a protein concentration of 2.6% w/w. The foam was produced by means of a porous glass frit, injecting the compressed air into the protein solution in the foam generator. The solution was pumped with the help of a VIP-Plus immersed pump made by the company Comet. The air volumetric flow rate was measured by means of a MV-104 mass flow meter made of Bronkhornst. A sketch of the experimental setup is shown in Fig. 1.
Air and solution were mixed in a frit consisting of a porous plate with porosity of 40-100 µm. The optically accessible horizontal test section is made out of transparent Plexiglas and has a length of 1 m. The test section is connected to the foam generator by means of a PVC fitting. To facilitate the optical access the channel has a square cross section (27 × 27 mm^2).

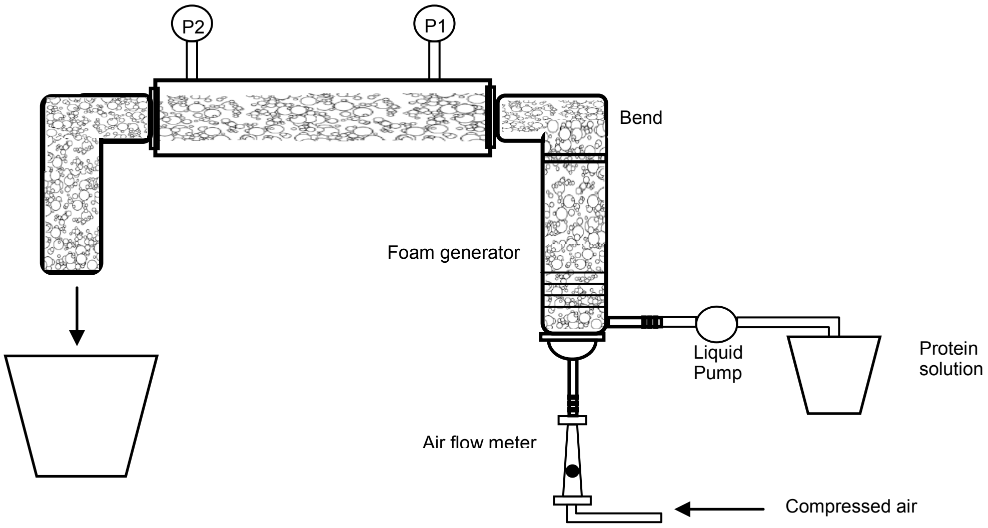

Fig. 1: Foam transport experimental setup consisting of a foam generation unit including a porous glass frit and an optically accessible horizontal test section.

The PTV setup makes use of a 400 mW laser to illuminate a plane of the foam. The thickness of the light sheet cross-section is around 1 mm. The observation area is 27 × 35 mm^2. A high speed CMOS camera pso 1200 hs (1280 x 1024 Pixel) captures successive images.

The velocity field is obtained by tracking of individual bubbles between two successive frames, which can be evaluated with the help of image processing. The bubble identification and determination of their position in space is a very important step in image processing, which has been carried out using Imagej[1], a Java based image processing program. Fig. 2 shows a schematic view of the experimental investigation.

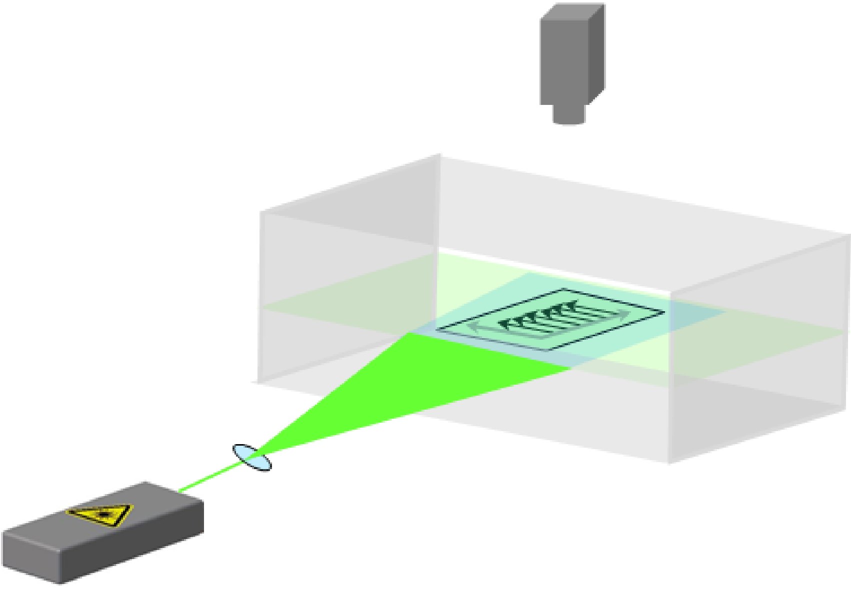

Fig. 2: Particle Tracking Velocimetry setup: Illumination by laser from frontal plane, generation of light sheet by lens system and observation of the flow in light sheet by a perpendicularly mounted camera.

Results and Discussion

Not only the foam structure but also its fluid mechanical transport as studied here exhibits significant complexity. In addition, with respect to optical flow visualization, the major issue is to get optical access into the foam. As a consequence of this, no holistic figure but partial information is currently available in the early stage of these investigations. Thus, for sake of convenience, some aspects of particular interest are discussed here.

One of these aspects is closely related to the macroscopic rheological behavior of foams. In the literature and also through own measurements (not presented here) foams have been proven as a complex viscoelastic matter with dominant elastic effects. With respect to the apparent viscosity, shear thinning can be observed. But even, a more characteristic feature of foam is the availability of a yield stress. In the case of an inner flow field, this yield stress must lead to flow regions that flows without deformation, i.e. as a rigid body. This scenario is in general referred to as a plug flow. In fact, some indications on the existence of prevailing plug flow have been observed by PTV. Here, this method is used for tracking the trajectories of individual bubbles. As Fig.3 shows, for the bulk flow, the bubble arrays that are aligned along the laser beam do not exhibit a change in the relative positions. Thus, this is in fact a strong indication of the

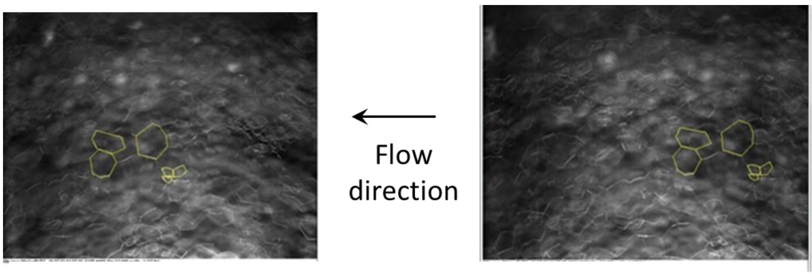

Fig. 3: Indication of plug flow regime of Casein foam with a foam quality of 66% (see also bellow for the definition of this foam parameter).

[1] http://imagej.nih.gov/ij/

presence of plug flow behavior. As this flow regime leads to a “soft treatment” of the foam, it also guarantees a preservation of a generated foam structure. Of course, this possesses high relevance for the production of protein foam food as the structure of the food is interlinked with essential properties such as product quality and mouth feeling, incl. aroma release that, in turn, determines the acceptance of customers.

A further aspect of particular interest here consists in the dependency of the velocity field. By increasing the gas flow rate the foam velocity rises as well. Three different gas flow rates 0.1, 0.5 and 1 l/min have been examined, which correspond to an average foam velocity of 2.15, 7.87 and 15.4 mm/s, respectively. The foam characterization significantly depends on foaming condition. The quality of foam, given by

$$\beta = \frac{Q_g}{Q_g + Q_l},$$

was varied by controlling the volumetric flow rate of liquid Q_l and gas Q_g, and different flow types were observed. The foam quality β, is determined by the ratio of imposed gas to liquid flow rates. By low flow rates, uniform foams move as a rigid body again. However, when increasing the flow rate, the bubbles tend to relocate according to their size. The smaller bubbles gather at the top of duct, while larger bubbles place on the bottom. At very high flow rate, large bubbles appear in the foam. They mark the onset of transition to a new flow regime, more concrete to slug flow where the foam collapses. From the point of view of production of food foams this represents a drastic situation. The risk of instabilities of food production rise enormously. Products with large voids as resulting from foam collapse are in general considered by the customers as low quality product.
Another effect of particular interested is the restructuring of the foam as a consequence of the fluid mechanical transport. In this context, foam with a quality of 83% has been analyzed for obtaining the velocity distributions in the neighborhood of the wall (see Fig.4). In this region most pronounced effects are expected due to the fact of the presence of shear deformation as well as three dimensional flow structures. According to the results obtained by PTV, the bubbles near to the top of duct have a plug flow profile. In contrast to this, by approaching to the bottom, velocity becomes greater than the velocity of the upper bubble layers and the foam start to shear at the liquid–foam interface. Fig.4 depicts graphically the velocity profile at the wall.

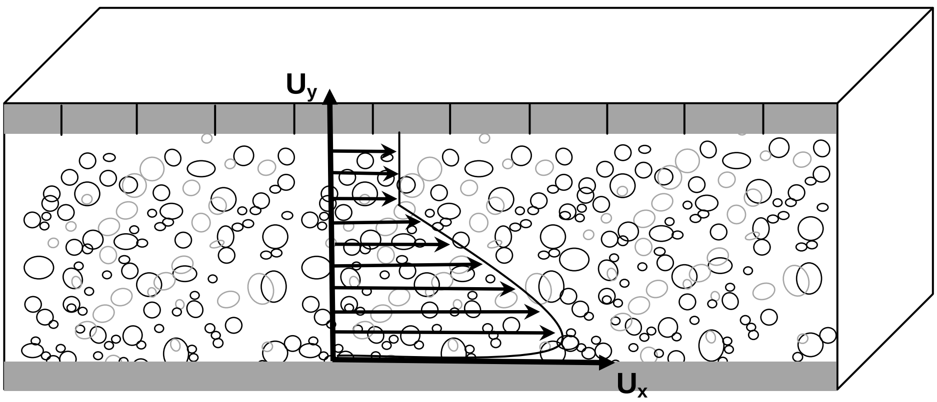

Fig. 4: Schematic velocity profiles in a vertical plane both in the foam duct flow based on the PTV experiments.

Other than the velocity distribution, the count, the position and size of bubble is of essential importance. Fig. 5 shows corresponding data extracted by image processing. It demonstrates the analyzed particle count and measured objects in binary or threshold images. The analysis is performed on the entire image. As the images demonstrate, the bubbles exhibit a polyhedral shape as characteristic of dry foams. This is in agreement with literature, but the data are at the lower gas volume concentrations for dry foams. Nevertheless, for the sake of convenience, the analysis is based on equivalent diameter, which in this case is the major diameter of fitted polygon inside of individual bubbles.

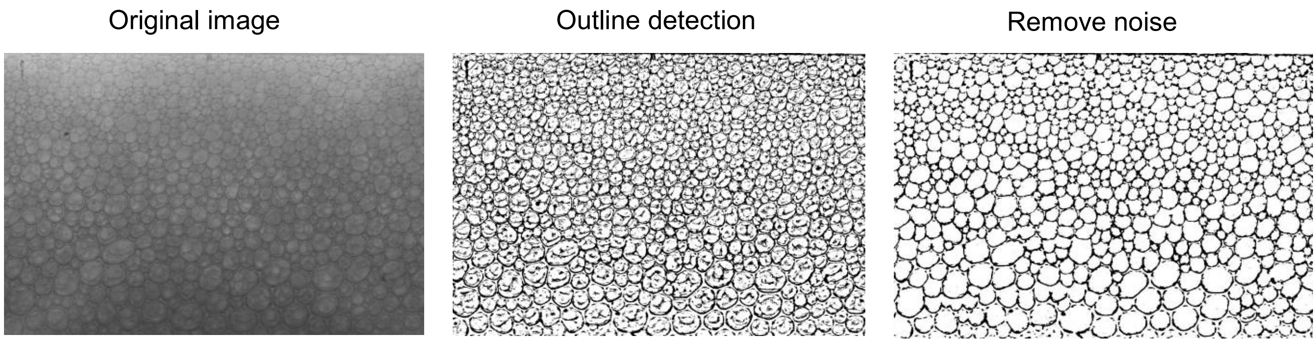

Fig. 5: Image processing development.

Fig.6 depicts graphically the bubble size distribution for two different foam flow conditions. In the first case the foam has a quality of 88% and the second it takes the value of 95% as a consequence of an increasing gas flow rate but lower than the critical rate for the onset of the slug flow (see above). The liquid flow rate was constant during the experiments. For the production of protein foam food it is essential that the bubbles become smaller with increasing gas flow rate. This knowledge enables deducing technological measures controlling the bubble diameter that, in turn, will exert a high impact on the food structure and, thus, on the mouth perception. As a rule, products with a homogeneous foam structure are often assumed by the customers to have a superior quality.

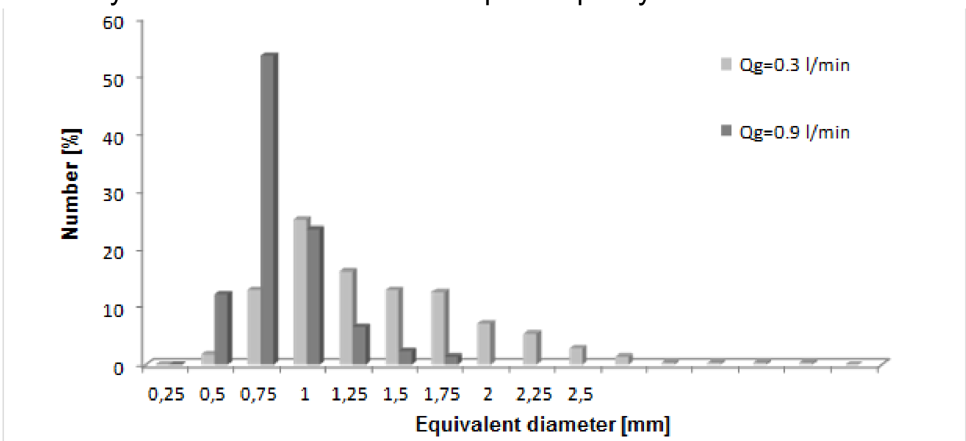

Fig. 6: Bubble size distribution for two different foam qualities.

Last but not least, restructuring of the foam by particular flow elements is of particular interest. Here, the effect of a bend has been studied. As mentioned before, it has been observed that increasing continuously the gas flow rate could alter the uniform structure of the foam. More concretely, the flowing foam starts to exhibit different pattern. The smaller bubbles are located at the top of duct and larger bubble move towards the bottom. This is obviously a consequence of the centripetal forces induced by the bend. For food production the corresponding restructuring of the foam may provide advantages or disadvantages. The latter case is given if absolute homogeneous foams are demanded. Advantages could be expected if, for example, certain nutritional effects are intentionally linked with the structure of the

foam. Providing high satisfaction at the beginning of consumption but progressive repletion due to a continuously increasing dense of the foam represents a prominent example for specific advantages.
In order to fit the intention of a particular foam production, it is basic to find an appropriate operation window, in which the foam has a homogeneous characterization. With respect to the effects of a bend the use of a dimensionless characteristic Froude number

$$Fr_C = \frac{u_m}{\sqrt{a D_h}} = \frac{u_m}{\sqrt{\frac{u_m^2}{r} D_h}} = \sqrt{\frac{r}{D_h}};$$

u_m : average velocity; a : centripetral accelaration; D_h : hydraulic diameter; r : radius of bend

is suggested. This relation expresses the fact that separation of bubbles with respect to their diameter occurs if the characteristic Froude number exceeds a certain value. Obviously, Fr becomes here a geometrical similarity simplex instead of a dynamic dimensionless group. Therefore, for the first time foam food producers can estimate the effect of the geometry of a certain bend on the foam structure a priori. Consequently, prevention of trouble can occur actively and even in the design phase of production plants. When the bend radius and hydraulic diameter takes on an identical value, the convective transport of momentum is in equilibrium with the momentum generation by the centrifugal forces. This corresponds to $Fr_C = 1$ and $r = D_h$. For $Fr_C < 1$, the bubbles in the foam flow are not able to track ideal path lines in the bend but are separated due to their local mass density distribution and, thus, to the bubble diameter in agreement with experimental observations. For production purposes it is of particular interest to know the onset point for observable separation, i.e. the corresponding value of Fr_C. Its determination is subject of current investigations. In this context, substantial efforts are being done for understanding, modelling and simulating the behavior of protein food foams. Amongst others extensive simulations on of High Performance Computing Plattform are being performed, see e.g. Anderl et al. (2014a, 2014b).

Conclusions

The results show that the foam flow, foam velocity, pressure drop and the bubble size distribution significantly depend on foaming conditions. In low gas flow rate, the foam exhibit structural homogeneity. But for increasing volumetric flow rates, large bubbles appear in the foam. This corresponds to the onset point of slug flow, where the foam starts to collapse. The velocity profile of the foam contains information on the characterization of the foam stability. The dynamic performance of the foam transport using particle tracking velocimetry method has proven plug flow existence in agreement with the expected rheological behavior. By increasing of gas flow rate, the bubbles become smaller. This can be intentionally used for generating foam food with high homogeneity. But this homogeneity can be distorted even by a single flow element such as bend. Thus, it is of essential interest to establish process windows that guarantee adequate treatment of the foam food.

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