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Detailed investigations of two-liquid phase flows on a packing surface

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Abstract

In the three phase distillation process in packed towers, two immiscible liquid phases flow down countercurrently to a vapor phase. To understanding this process, it is necessary to investigate the three phase flow behavior inside packed towers in detail. In this contribution, a three-dimensional CFD model will be presented, which is able to describe this complex flow behavior on packing surfaces. The simulation results are compared to the measurements of the liquid velocity profile obtained from a new developed micro-PIV technique with high resolutions. For one liquid phase on a flat inclined plate, the simulation shows good agreements with the experiment. Additionally, numerical investigations of a packing segment are given and the liquid-liquid interactions will be discussed.

Keywords

CFD, vapor-liquid-liquid flow, three-phase distillation, packed towers, micro-PIV measurements

1. Introduction

Packed columns are widely used for distillation processes. The reason for that is the higher separation efficiency and capacity in comparison to tray towers. The efficiency of packing columns strongly depends on the flow behavior of the liquid inside the packing. The behavior is influenced by the geometric structure of the packing, the liquid and vapor load, the material properties, and system parameters like the contact angle [1]. Depending on the parameters, the liquid film can break up with a formation of rivulets and droplets [2]. With appearance of a second liquid phase e.g., in the three phase distillation, the problem gets even more complicated [3]. It can be observed that one liquid phase forms a film while the other phase forms rivulets and droplets, which move below and/or above the film surface [4]. Due to that, both liquids influence each other, which leads to strong changes of the separation efficiency [5,6]. For the design of such processes, reasonable models for the prediction of the liquid flow behavior are required [7].

In this connection, one of the important points is the determination of the interfacial area between all phases. With the aid of Computational fluid dynamics simulations (CFD), it is possible to "look" into the packing and to describe and analyze the flow behavior, by varying the system parameters without strong experimental efforts. However, the CFD simulation has to be validated with experimental data. Therefore, the complex geometric structure of the packing is simplified and substituted by a flat inclined plate of stainless steel. The advantage is that the measurement system offers a free optical access and the CFD model requires less computational effort due to a simplified geometry. Additionally, the vapor phase is initially motionless.

In the first research stage, the fluid thickness, the surface velocity, and the shadow area have been measured and compared to CFD results for one and two liquid phase flows [1,4,8-9]. Additionally, morphological investigations of the flow behavior have been carried out [2-3,10]. Here, it was found that the two liquid phases interact with each other, which leads e.g. to stabilization and deceleration of the flow. These first investigations are helpful and necessary, but do not explain the interactions. Therefore, a new Particle Image Velocimetry (PIV) method with high resolution is developed and presented in this contribution for the case of a single liquid water flow on a steel plate.

2. Numerical Procedures

Multiphase liquid flows are characterized by a complex three-dimensional flow structure like film break-up and an overlaying of different flow behaviors. Therefore, a three-dimensional and transient model is required [1]. The CFD calculations are carried out with the commercial software tool CFX 5. It uses an Euler-Euler algorithm with one set of equations for all phases. Like the Volume of Fluid (VOF) method [11], the phases are implemented with averaged phase fractions for each finite volume cell. The method of Brackbill et al. [12] is used to implement the surface tension, and the contact angles are given as wall boundary conditions. To account for the higher gradients near the plate, the mesh has to be very fine for accurate resolution in this region. Hoffmann et al. [10] have found that ten cells for the height of the liquid film are sufficient.

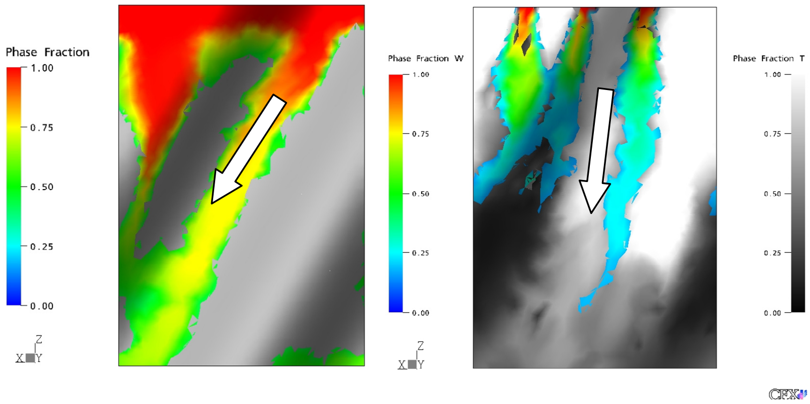

Fig. 1: Flow behavior of a single-liquid water flow (left) and a water-toluene flow (right) on a Sulzer Mellapak® sheet

3. Numerical Case Study

To understand and explain the performance of three-phase distillation columns, shown in [5], investigations of the interaction between the both immiscible liquid phases inside of a structured packing are necessary. Therefore, a packing segment of a Sulzer Mellapak Y series is modeled in CFX [13]. The qualitative results of the simulation of this packing segment are shown in Fig. 1. On the left-hand side, the flow behavior of a single liquid water phase is shown. Water tends to break up and forms rivulets, which follow the macroscopic structure of the packing down to the left corner. If this is transferred to a whole structured packing, it means that the water phase is not equidistributed over the complete packing cross section. This behavior is also known as maldistribution.

The investigation of a water-toluene flow, which is illustrated on the right-hand side of Fig. 1, shows that the multiphase flow behavior is more stable and the main flow direction of the water rivulets follows more the gravitational force downwards. Toluene forms a closed film and water forms separated rivulets, which are surrounded and covered by the toluene phase. Considering the whole packing, the distribution here is much better and the maldistribution is reduced. Additionally it was found that the velocity of the single liquid water flow is much higher. The reason for that seems to be the intensive interaction between the two liquid phases. This is the same behavior as found in Ausner et al. [4,8] by the examination of a multiphase water-toluene film flow down an inclined flat plate.

To understand the interactions between the two liquid phases detailed investigations from the liquid-liquid interface are required. Therefore, the following μ-PIV method is developed and the first experimental result are compared with CFD simulations for a single-phase flow.

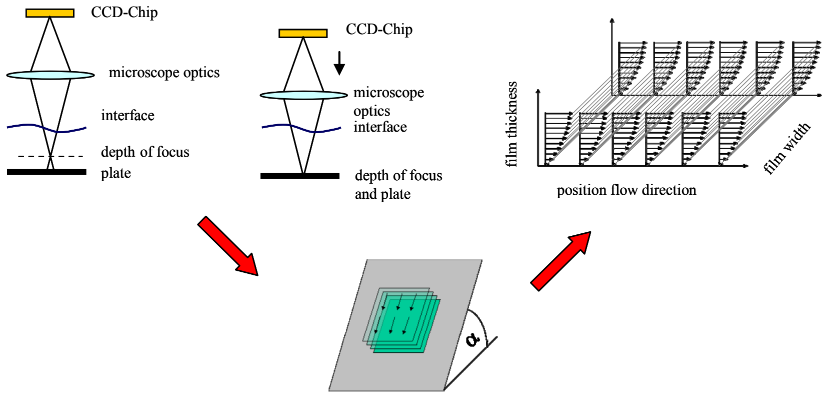

Fig. 2: Principle of Focal Plane Scanning with velocity field reconstruction

4. Experimental Method

In principal, PIV is an optical method and tracks small particles, which are moved with the flow. It acquires and analyzes the observed flow field in a plane at a certain time. On the developed measurement system [14], a water film is delivered on a smooth plate of stainless steel with an inclination angle of 60° to the horizontal. For the visualization of the flow, Rhodamine B labeled tracer particles with an averaged diameter of 10.2µm are suspended in the water phase. A charge-coupled device (CCD) camera is installed orthogonally to the overflown plate for image acquisition. In front of the CCD camera, a strong magnification lens is attached, which enables a high resolution image of the observed area. With the aid of a widened laser beam, the tracer in the desired measuring area are excited. The image processing follows the double frame / single exposure principle [15]. The velocity measurement consists of the imaging of the tracers in the flow field and the analysis of the imaged data with correlation methods [16].
Flow investigations through a wavy interface can result in strong distortions, which are caused by refraction and reflection effects on the liquid interface. To avoid that, the common procedure is to meaure the flow from behind through transparent wall materials. As far as it is known, research on industrial used wall materials like stainless steel has not been published up to now. It can be observed, when the camera view is installed perpendicularly to the flow, that the influence of the wavy surface of the film flow to refractions and reflections is minimized and can be neglected. First investigations of this imaging method suggest that distortion corrections on own obtained images are not necessary for the considered application. The developed measurement technique, called Focal Plane Scanning, utilizes the characteristic of microscopic optics: the depth of focus of a microscopic lens system is very small. Particles, which are moved in the depth of focus, are imaged very sharp and are considered in the evaluation

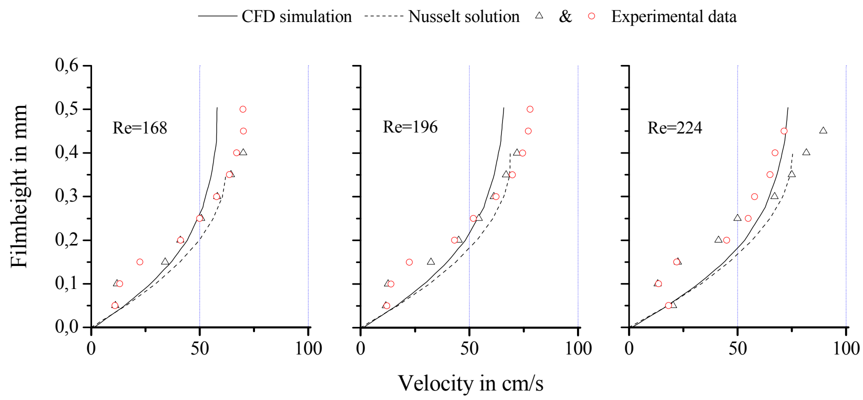

Fig. 3: Comparison of experimental data with numerical results for different Re-Numbers. Circles and triangles represent the results at different measuring positions

of the image. Particles, which lie in front of or behind the depth of focus, are blurred. Since the projected area of a blurred particle is higher, this can be used as a filter parameter for the image processing. The image processing is applied with the aid of the Image Processing Toolbox in Matlab®, Mathworks Inc. By displacement of the depth of focus in direction of the film thickness, the flow is scanned. Then the velocity field is calculated with cross correlation algorithms for each level. From these two dimensional vector maps, the three dimensional velocity field can be reconstructed and visualized, as shown in Fig. 2.
With the aid of this presented experimental method it is possible to measure the velocity field from the top side of the flow through the wavy surface.

5. Results of PIV-measurements

With that new developed PIV-method, measurements for a single liquid water flow on the inclined steel plate are carried out for different Reynolds numbers (liquid load related to the cinematic viscosity), which are shown in Fig. 3. The triangles and the circles represent the experimental results at different locations on the plate. Additionally, the results from our CFD simulations and the Nusselt solution [17] are represented for comparison.
In general, it can be seen that in the simulation as well as in the measurements with increasing Re number the maximum velocities increase, too. The comparison between the CFD simulations and the experimental data close to the water surface shows a good agreement. In the region close to the steel plate surface, the highest deviations can be found, which is caused by the fact that the particles are reflected in the steel plate, and the filter function works still with high uncertainties and will be improved. Nevertheless, the velocity profiles in Fig. 3 show that the developed PIV-method is able to measure the velocity field from the top side of the liquid surface without the use of a transparent wall material, so the method can be applied for industrial used wall materials.

6. Conclusions and Outlook

With the given PIV setup and the presented Focal Plane Scanning method, it is possible to measure and visualize the three dimensional velocity field. For the first time, the measurements are taken from the top side of the liquid film flow through the wavy interface. That enables the required investigations of flow behaviors on industrial used wall materials under process conditions. The first taken velocity profiles for a water flow with different flow rates show a good agreement with the pre-validated CFD simulations and the Nusselt solution.
Numerical investigations of an overflown packing segment (single-liquid flow and liquid-liquid flow) show that the two liquid phases are in strong interaction with each other. The liquid-liquid flow is more stabilized compared to the single-liquid flow, which results in a reduced maldistribution for the packing.
The filter function for the image processing has to be further developed so that improved results can be obtained. The method will enable a detailed observation of the interactions between the two liquid phases. In future steps, the influence of a counter current vapor flow will be investigated.

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