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CFD study of the bottling process with carbonated soft drinks

Dissertation synthesis

In industrial applications, foaming during the bottling of a carbonated soft drink is an unwanted phenomenon, since it reduces the production rate. It is, in fact, necessary to left the foam resting in order to reduce its thickness before continuing the process, thus slowing down the production process. Furthermore, the generation of foam can lead to the outflow of the liquid from the bottle, with the consequent waste of the product.

The bottling process consists of two actual phases: filling and pressure reduction. The filling step is carried out keeping the liquid and the bottle under pressure through an injection of CO_2, to keep this gas dissolved in the liquid (i.e. the carbonated soft drink). The liquid falls from a storage tank to the bottle only by gravity. A valve give to the liquid a swirl motion in order to keep it attached to the walls as a film, reducing as much as possible the gas (i.e. CO_2) entrapment and the gas entrainment. At the end of the filling step, after a very short resting time interval, the pressure is reduced. The pressure reduction induces the nucleation of the bubbles within the liquid bulk, with the subsequent rising of the liquid level and then the generation of foam. Although only two actual phases exist (i.e. filling and pressure reduction) the process can be conceptually and schematically divided into three steps: filling, degassing and foam generation, where the last occurs simultaneously.

The depressurization leads to the volume increase of the bubbles entrapped in the surfaces, generating a foam thickness increase. We refer to this increase as “first foam thickness peak”. During the depressurization, the gas entrapped mechanically during the filling acts as heterogeneous nucleation clusters, generating a new wave of rising bubbles. This brings to an increase of the liquid height, which will be labelled as “liquid elevation”. These bubbles accumulate on the foam present on the surface, increasing the foam thickness again. This second increase generates another peak in the foam thickness, which will be labelled as “second foam thickness peak”.

The “liquid elevation” and the “second foam thickness peak” are two critical quantities in the bottling process since they are related respectively to the gas nucleated and the maximum foam thickness produced during the bottle filling process. The “second foam thickness peak” is more important than the first, since it is formed by smaller and more stable bubbles, resulting in a foam that degrades very slowly, thus slowing down the process.

In this work we aim to develop a CFD model capable of describing the filling, the degassing and the foam generation phase. From the filling simulation, we want to estimate the amount of entrained gas. Then, by modelling the degassing and foam generation steps, we want to estimate the “liquid elevation” and the “second foam thickness peak”. A secondary objective is the estimation of the “first foam thickness peak” from the quantification of the gas entrained during the filling phase.

The volume-of-fluid method is employed to model the filling step and the diffusion mixture model to model the pressure reduction phase. However, a detailed study of the interface capturing method was done during this PhD in collaboration with Optimad Engineering Srl, a software engineering company based in Turin. The study focused on Level Set Methods and Conservative Level Set Methods, even if for the final simulation set up the volume-of-fluid was chosen.

The diffusion mixture model has been modified to account for gas bubble nucleation during degassing. A further change was made in order to quantify the “liquid elevation”.

The diffusion mixture model has been further modified to account for the foam formation and to quantify the “second foam thickness peak”.

All the steps were simulated with the open source code OpenFOAM. The filling process was described with a Volume-Of-Fluid (VOF) method, using the interFoam solver. The degassing and the foam generation were described with the Diffusion Mixture Model, which is a multi-fluid model. The Diffusion Mixture Model (DMM) was developed starting from a pre-existing solver, i.e. the driftFluxModel.

An experimental campaign was conducted to tune the parameter for the Diffusion Mixture Model to obtain experimental data with which validate the models.

The VOF simulations predict the falling film behaviour correctly. Moreover, the VOF can estimate the amount of gas entrained, confirming its correlation with the filling rate. Although the entrained gas is underestimated, the VOF can also be used to estimate the “first foam thickness peak”. The entrained gas versus filling rate trend is reliable, making it possible to use the VOF as a tool to predict the entrained gas at different filling rates than the ones tested in this work.

The DMM has been modified to account for gas bubble nucleation during the degassing step and therefore to quantify the “liquid elevation”. This improved DMM considers the effects of the CO_2 concentration, the temperature and the depressurization recipes on the “liquid elevation”. Two parameters were used to take into account the effect of the filling rate since it is the only variable not considered by the model. The DMM estimates the experimental results accurately. The first parameter, labelled as K_d, value shows a strong correlation with the inlet filling rate and therefore with the amount of mechanically entrained gas bubbles. This paves the way to use the VOF method to estimate the amount of gas mechanically entrained indirectly. The K_d and the second parameter, labelled as γ_d, fitted in this work model are specific for the carbonated soft drink treated in this study. However, they can also be fitted to model other fluids.

The DMM has been modified with a spurious stress term which can be employed to simulate the foam generation step correctly, reproducing the experimental “second foam thickness peak”. The added spurious stress represents the resistance of both gas bubbles and liquid flowing through the bubbles when the foam is present. Moreover, with a reasonable decrease in accuracy, the DMM can also increase its predictivity in the estimation of the “second foam thickness peak”, since it already considers the effects of the depressurization recipes, CO_2 concentrations, temperature and filling rate in the degassing simulations.