

# COMPUTATIONAL FLUID DYNAMICS APPLIED TO COMPOSITES MANUFACTURING

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## Introduction

Computational fluid dynamics (CFD) has been used to simulate the flow during vacuum infusion [1-2], sheet moulding compound (SMC) [3-4], the auto-clave process [5] and twin-screw extrusion. Three-dimensional geometries were studied and porous media and multiphase flows were treated with a homogenous approach. The advantages and drawbacks of such a methodology are here discussed based on previous work [1-5] and some new results on twin-screw extrusion. To exemplify: For the vacuum infusion process the porous media can be located in a complex mould with moving boundaries and can have an anisotropic, spatial and time dependent permeability. The pressure within the mould during compression moulding of SMC can be predicted if shear-thinning effects are accounted for.

## Vacuum infusion

In vacuum infusion the impregnation is characterised by a full 3D flow in a thin porous medium having an anisotropic, spatial- and time-dependent permeability. Also the shape of the porous media alter as a function of time since it is subjected to forces from the difference between the atmospheric pressure and the pressure inside the mould and since the compliance of the fibre network may change as it is wetted, see experimental results in [6-7]. In [1] it was shown how this can be implemented in a general computational fluid dynamic software through written subroutines that couple the equations of the flow to the equations describing the stiffness of the fibre reinforcement, modify the momentum equations to account for the Darcy flow and remesh the computational domain in each time step to account for the deformation caused by pressure changes. The method was verified with a mesh refinement study and analytical solutions and validated with experiments. The strength of the approach was also demonstrated by simulations of mould filling during vacuum infusion of a circumferential stiffener [2]. In addition to the overall development of the model, a couple of issues were studied. Local lead of the flow front due to poor fitting was shown to have a major influence on the filling pattern while effect of lubrication of the fibers and the corresponding ditch trailing the flow front on the fill time were negligible for the case studied. Regardless of which phenomenon in focus it was clear that experimental observations, characterisations and measurements are of outmost importance for the simulations.

## Sheet mould moulding compound

Compression moulding of sheet moulding compound has been studied with CFD by applying three different approaches. This includes a surrogate based optimization methodology applied on simulations with a relatively simple model for the rheology [3], a study where different rheological models are compared including shear thinning effect and a study where the layers of the compound nearest to the mould surfaces are given a much lower viscosity than the viscosity in the bulk layers [4]. The pressure can be accurately predicted with both of the latter approaches while with the first method the temperature dependent Newtonian viscosity model was not good enough to describe all details of the flow of the compound. The multi-objective surrogate-based inverse modeling method in it-self worked very well. The shape of the derived flow fronts in [3] was also similar to those obtained in experiments in [8]. An additional result in [4] was that altering the heating time until the prepreg was

assumed to start to flow had a significant effect regardless of the considered process settings. Also in this case it is of outmost importance that the material and processing conditions are known.

### **Autoclave processing**

Simulations of heat transfer to a tool placed within an autoclave have been carried out with CFD with and without taking thermal radiation into account [5]. Hot air is forced to flow over the tool and the pressure is increased within the autoclave. The predicted temperature at several discrete positions on the tool is in agreement with experimental measurements presented in [9], especially for simulations when thermal radiation was included in the model. The points with good agreement are often located at positions with relatively simple flow. For some points, however, the agreement was not as good, and these points are often located at positions with more complex flow. The discrepancy may be traced to issues such as the modelling of turbulence and the quality of the mesh for a more complicated flow. Still it may be stated that CFD can be used to predict the heat transfer within an autoclave during manufacturing of composites and thermal radiation should be considered when modelling heat transfer for such a case. The study also shows that it is important to use a proper inlet velocity profile. Simulation results with a height-dependent velocity profile compared much better to the experimental results than those obtained when the average velocity inside the autoclave was set as the inlet velocity profile. Even better agreement may be achieved by disclosing the full velocity profile inside the autoclave. A final result was that small differences in tool symmetry resulted in rather large temperatures differences for the process setting applied in the simulations. This behavior was also observed in the experimental study in [9].

### **Twin-screw extrusion**

Liquid-mediated melt compounding of nanocomposites in twin-screw extruders is an emerging method that combines solution-assisted and melt mixing methods in such a way that the disadvantages of these two methods is overcome. The liquids used work both as temporary carrier of nanomaterials as plasticizer after evaporation of the liquid. Modelling the flow of thermoplastic polymers in twin-screw extruders is challenging and the mixing, the changing of volumes of an evaporating solvent and the non-spherical particles add considerably to the complexity. In the current case a two-phase flow approach is chosen and the particles are assumed to follow the carrier fluid through the mixing section of the extruder. The mixing elements are modelled with the immersed boundary method and results are presented in the form of mixing ratio and areas of maximum shear.

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