Applied Mathematical Modelling 38 (2014) 3222–3232

Contents lists available at ScienceDirect

Applied Mathematical Modelling

journal homepage: www.elsevier.com/locate/apm

An evaluation of interface capturing methods in a VOF based model for multiphase flow of a non-Newtonian ceramic in tape casting

M. Jabbari [a,*], R. Bulatova [b], J.H. Hattel [a], C.R.H. Bahl [b]

[a] Department of Mechanical Engineering, Technical University of Denmark, Nils Koppels Allé, 2800 Kgs, Lyngby, Denmark
[b] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, Building 779, Roskilde, Denmark

ARTICLE INFO

Article history:
Received 21 August 2012
Received in revised form 11 November 2013
Accepted 26 November 2013
Available online 21 December 2013

Keywords:
VOF method
Tape casting
Non-Newtonian
Power law

ABSTRACT

The aim of the present study is to evaluate the different interface capturing methods as well as to find the best approach for flow modeling of the ceramic slurry in the tape casting process. The conventional volume of fluid (VOF) method with three different interpolation methods for interface capturing, i.e. the Geometric Reconstruction Scheme (GRS), High Resolution Interface Capturing (HRIC) and Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM), are investigated for the advection of the VOF, both for Newtonian and non-Newtonian cases. The main purpose is to find the best method for the free surface capturing during the flow of a ceramic slurry described by a constitutive power law equation in the tape casting process. First the developed model is tested against well-documented and relevant solutions from literature involving free surface tracking and subsequently it is used to investigate the flow of a $La_{0.85}Sr_{0.15}MnO_3$ (LSM) ceramic slurry modeled with the Ostwald de Waele power law. Results of the modeling are compared with corresponding experimental data and good agreement is found.

1. Introduction

Tape casting is a forming method that has mainly been used in the electronics industry to produce multi-layer capacitors and electronic substrates [1,2]. This method basically starts with a specially designed slurry which can be cast by a blade to a flat sheet or layer, then dried into a flexible solid tape which can be sintered subsequently into a hard ceramic substrate layer [3]. This technique is a well-established process which is used to produce ceramic layers and multi-layered ceramics (MLC). The parallel (doctor) blade process was first used in preparing ceramic tapes in the 1940s and today it plays a key role in producing thin and flat ceramic tapes [4,5].

Generally, the fluid flow in the doctor blade region and the subsequent outflow can be analyzed using Navier–Stokes equations in two dimensions assuming that flow is generated by both viscous drag due to the peeling velocity of the substrate and the static hydraulic pressure in the slurry reservoir. There are a few research papers in which the flow field and the resulting tape thickness were modeled analytically. Chou et al. [6] modeled the flow in the parallel blade region and due to the low Reynolds number, they neglected the inertia forces by assuming Newtonian-Stokes flow.

* Corresponding author. Tel.: +45 45254734; fax: +45 45930190.
E-mail address: mjab@mek.dtu.dk (M. Jabbari).

0307-904X/$ - see front matter © 2013 Elsevier Inc. All rights reserved.
http://dx.doi.org/10.1016/j.apm.2013.11.046

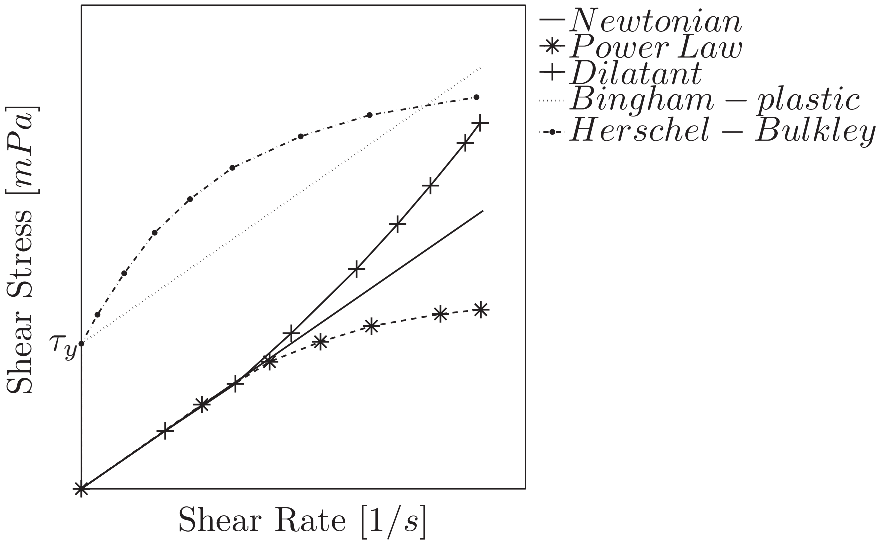

Fig. 1. Rheological classification of fluids.

In a general sense, fluids that exhibit characteristics not covered by the Newtonian constitutive equation are non-Newtonian. The exceptions to the Newtonian fluids are not of rare occurrence, and in fact many common fluids are non-Newtonian. Fig. 1 shows the rheological classification of the non-Newtonian fluids.

In the tape casting process, the ceramic slurry is mostly categorized as a non-Newtonian flow with relatively high viscosity. The viscoplastic description was used by Huang et al. [7] to model the flow field in the tape casting process. In their 2D analytical model the effects of pressure gradient, substrate velocity and resultant tape thickness were evaluated. The effect of different rheological behaviors of the tape slurry (Newtonian, power law and Bingham plasticity) for a generalized pressure flow in tape casting was investigated by Joshi and et al. [8]. They estimated the tape thickness analytically and controlled the size of the parallel channel in tape casting accordingly.

The flow of Bingham fluids are evaluated and investigated in different areas of the engineering sciences [9,10]. The ideal Bingham material model is characterized by a shear stress (τ) which is a linear function of shear rate ($\dot{\gamma}$). The yield stress (τ_y in Fig. 1) is the finite stress which is required for flow initiation (Fig. 1). The main mathematical difficulty when solving ideal Bingham flows is the non-differentiability of the constitutive law at the yield point. The most straightforward and convenient way to circumvent this difficulty is to approximate the material behavior by a bi-viscosity model, in which the material has no true yielding point but flows with a very high viscosity below the yield stress and with the plastic viscosity above it [11]. In most engineering applications, flow of non-Newtonian fluids are characterized by the Bingham, Herschel-Bulkley or Ostwald de Waele power law constitutive models which are shown in Fig. 1 [8,12–16]. A summary of work published regarding the rheological classification of non-Newtonian fluids and the existence of analytical/numerical models with focus on tape casting have been given previously by the authors [17].

Flow processes often involve the presence of free surfaces, the tracking of which has significant impact on the manufacturing and the final quality of the product. Examples abound, e.g., casting processes, mold filling, thin film processes, extrusion, coatings, spray deposition, fluid jetting devices in which material interfaces are inherently present. This phenomenon is also considered in multi-material flows with sharp immiscible interfaces [18]. Several CFD methods have been developed in the last decades with the aim of simulating such complex flows with free surfaces. Two very well-known example of this is the volume of fluid (VOF) and level set methods. In general, there are a lot of different research papers which are dedicated to free surface modeling, different interpolation schemes, liquid/gas phase flow, multi fluid flow, multiphase flow and different numerical methods to simulate the flow field with the presence of an interface [18–26].

A proper discretization of the convective term in the equation for transport of the VOF is crucial for simulation of a multiphase flow. It is well-known that numerical schemes, commonly used for discretization of the convection term, introduce numerical diffusion or numerical dispersion phenomena [27]. For this reason, some additional techniques are needed, i.e. high-resolution schemes. Examples of these can be found in [28–31] with special focus on capturing sharp interfaces.

The aim of this paper is to evaluate the different interface capturing methods and to find the best approach for flow modeling of the ceramic slurry in the tape casting process using the commercial software ANSYS FLUENT. The conventional VOF method will be used with three discretization schemes for the convection of the VOF: Geometric Reconstruction Scheme (GRS), High Resolution Interface Capturing (HRIC) and Compressive Interface Capturing Scheme for Arbitrary Meshes (CICSAM), which all will be discussed in detail. The main purpose is to find the best method for capturing the free surface in the flow of a non-Newtonian ceramic slurry described by the constitutive power law equation in the tape casting process. To do so, two different test cases will be investigated and compared with data in literature. One of the cases is the