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Analytical investigation of free surface flow in multi-layer porous media

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ABSTRACT

In this paper, the free surface flow passing through a multi-layer porous medium is analyzed. An analytical model to describe the flow in multi-layer porous media driven by surface tension and vacuum pressure is proposed. The structure of the medium studied is modeled after those found in Rigid-Capillary-Press (RCP) dewatering devices. The capillary phenomenon is used in RCP to improve the water removal efficiency and the energy consumption in a paper making process. The porous medium is composed of six layers with complex woven fabric structures and pore sizes that range from 5 μm to 2 mm The dewatering performance predicted by the analytical model is compared to the pilot plant experiments with good agreements. The potential of the model to be applied as a parametric optimization tool for industrial RCP porous media design is discussed.

1. Introduction

The capillary penetration in porous media is of considerable importance for a variety of fields and applications, such as soil science [1], powder technology [2,3], suspensions and emulsions stability [4–7], and paper-making technology [8–11].

In paper industry, a paper machine consists of three main sections: forming, press, and dryer. For a typical wood pulp containing 166–200 kg water/kg fiber in the headbox, the water amount can be 4–5 kg water/kg fiber after the forming section, 1.5 kg water/kg fiber after the press section, and 0.05 kg water/kg fiber after the dryer section [12]. The amount of the removed water in the dryer section is moderate compared to those in other sections, but about two thirds of the total energy consumption for a paper machine can occur in this section. Normally, it costs more than 10 times as much to remove water by evaporation in the dryer section than the mechanical dewatering in the press section. For some grades, such as bath and facial tissue, a strong, compact, smooth sheet is not desired. Rather, a soft, open, high loft sheet is needed. For these grades, it is desirable to mechanically remove as much water as possible without significant mechanical pressing and then remove the remaining water by evaporation. This can be achieved by using a new method, called Rigid-Capillary-Press (RCP) technology [8–11]. Experiments have shown that capillary dewatering can result in 16–20% thermal energy savings in the dryer section. Experimental data indicate that the RCP process does not affect the physical properties of the final sheet [12]. Moreover, the dewatering efficiency in the paper-making process can also be improved by using the RCP technology. During such a dewatering process, the capillary flow passes through a multi-layer porous medium with large change in pore sizes ranging possibly from 5 μm to 2000 μm. Methodologies to model the capillary flow in such complex porous media is important, but not fully explored.

For flows in porous media, a capillary penetration method is widely used. The model assumes that the porous body consists of assemblies of cylindrical uniform capillary tubes, and the process of the liquid penetration into the single cylindrical capillary is described by using Lucas–Washburn equation [13]. Elley and Pepper [14] used such a cylindrical tube model to determine the adhesion tension of Nujol, benzene, and water in a vertical plug of Pyrex glass powders. Studebaker and Snow [15] developed this method to determine the contact angle of a liquid flow in porous media by comparing the data of a reference liquid with the calculated results of Lucas–Washburn equation. Similar studies estimating adhesion tension and contact angles of liquids with powders using this approach have been carried out by Crowl and Wooldridge [16], and Bruil and Van Aartsen [17]. Good [18] discussed the validity of the Lucas–Washburn equation when applied to a porous medium. An additional driving force due to the reduction in free energy of the solid covered by an adsorbed vapor film was identified, which may lead to a faster rate of penetration than that predicted by the Lucas–Washburn equation. Lavi et al. [19] assessed the validity of using the Lucas–Washburn equation for porous media characterization by the two-liquid capillary penetration method numerically and experimentally. It was found that using the Washburn equation and ignoring inertia and dynamic

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contact angle effects may lead to erroneous assessment of the capillary radius and the equilibrium contact angle, for a relatively wide range of capillary radii and equilibrium contact angles.

A significant amount of attention has also been devoted to the study of the static [20,21] and dynamic [22–25] characteristics of free surface liquid in irregular cross-sectional uniform geometries. In addition to the commonly used circular uniform tube model, similar approaches have also been extended to consider irregular cross-sectional uniform geometries in modeling the capillary flow in porous media. For example, the modeling of fluid flow in porous petroleum reservoir rocks can be improved upon by considering the pores to be triangular tubes [26,27].

The drawback of the uniform tube model is that a sole effective capillary radius cannot be ascribed to describe the nature of the real porous media with constrictions and expansions along the flow paths. Typically, kinetics of capillary rise by taking an average pore radius based on the pore size distribution was found to be faster than that observed experimentally [28,29]. More realistic models of nonuniform capillaries have been proposed to incorporate the essential convergent–divergent nature of flow path in a porous medium. Dullien et al. [30] attempted to approximate the nature of flow in a porous medium by a simple stepped tube model which ascribed the slow capillary rise in porous media to the small driving forces on the meniscus in the divergent sections. Einset [31] used the two-sized single pore model to analyze the rate of capillary rise of a liquid into a porous medium made up of consolidated particulates, and the predicted infiltration rate is consistent with the experimental results. Sinusoidal capillary models [32,33] with convergent–divergent sections have been developed as a more realistic representation of flow paths in porous bodies. Erickson et al. [34] studied the dynamic capillary driven flow in straight convergent–divergent and divergent–convergent capillary tubes by using finite element numerical simulation. Young [35] extended the sinusoidal capillary model to analysis the capillary driven flow in Erickson et al.'s specific non-uniform geometries. Patro et al. [28] adopted the same non-uniform capillary model to explain the capillary rise kinetics inside porous Al_2O_3 compacts by using a sinusoidal capillary wall with convergent–divergent sections to approximate the real flow path in the porous medium.

The current nonuniform models only considered the nonuniform geometry effect on the viscous terms in the cross sectional plane. The likely variation of the axial velocity component in the main stream direction has not been accounted for in the viscous terms. Based on the Navier–Stokes equations and considering the overall nonuniform geometry effect, the authors [36,37] proposed a general model that is capable of describing the capillary flow in arbitrary irregular geometries with a straight axis of symmetry.

In this paper, an application of the proposed model to describe the dewatering process of a commercial RCP dewatering device for paper making is presented. The characteristic description of the RCP device is first introduced. The theoretical analysis on the capillary flow in general multi-layer porous media was given. Through the proposed model, the production parameters in the paper making process such as the basis weight and pore size distribution in the pulps, the geometry of the multi-layer RCP porous medium, the machine speed, and the vacuum pressure are related to the dewatering. The proposed analytical model is validated by qualitatively comparing model results with experimental data.

2. Description

2.1. Rigid-capillary-press dewatering process

A close-up view of the RCP press section is shown in Fig. 1, and a schematic side sectional view of the RCP papermaking machine is presented in Fig. 2. The RCP roll has a perforated shell which is covered with a specific designed multilayer porous medium, called the RCP medium. The woven structure of the RCP medium is discussed in detail later. The internal space of the roll may be divided into two zones: the vacuum zone and the pressure zone [12]. The vacuum zone is connected to the vacuum source through the vacuum pipe, while the pressure zone is connected the air source through the pressure pipe.

The continuous wet paper web is carried by the press fabric to wrap part of the vacuum zone. The roll is covered by the RCP

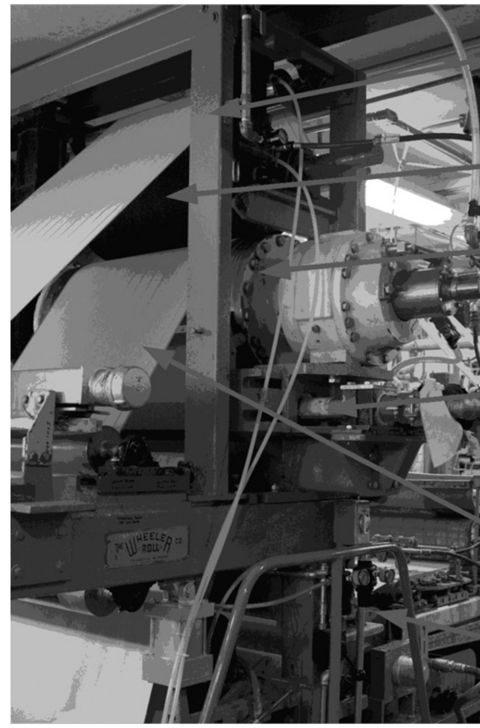

Fig. 1. Close-up view of RCP press section.

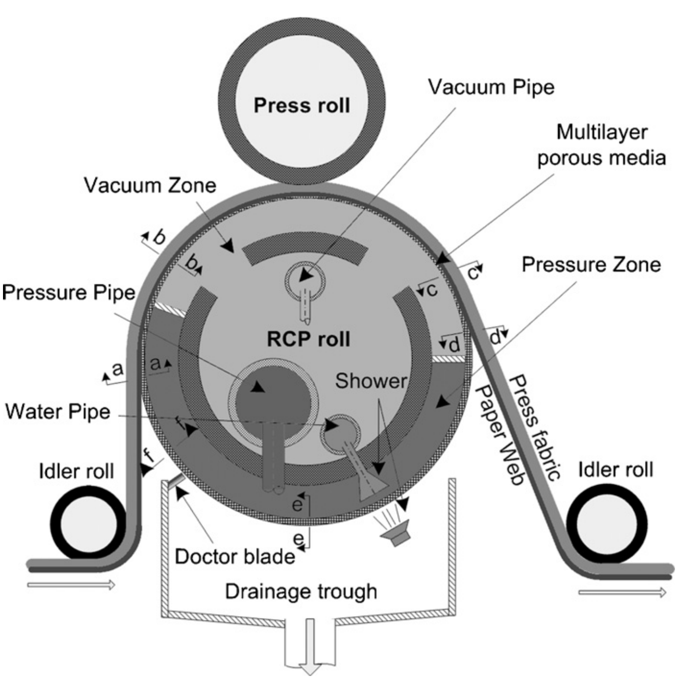

Fig. 2. Schematic fragmentary sectional view of RCP papermaking machine.