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HYDRODYNAMICS OF LIQUID JET APPLICATION IN HIGH-SPEED JET COATING
Newtonian and Shear-thinning Fluids

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The hydrodynamics of jet coating at high web speed has been experimentally investigated with Newtonian and non-Newtonian fluids. Two theoretical approaches have been compared for the determination of the wetting contact line location on the web, namely a force balance involving the jet kinetics and the air pressure forces acting on the jet, and a boundary layer approximation for thin film flows.
The visualization of the impingement flow has allowed the determination of the stable coating conditions. In the stable coating window, an apparent contact line was obtained from the analysis of the jet free surface profiles. Results showed that the trend for the deflection and the development length of the liquid layer at high web speed is different from that at low speed. The apparent contact line location for web speed ranging from 4.1 to 8.3 ms^{-1} has been suitably explained with the boundary layer model while the force balance model better applies at high web speed ($U > 12.5\ ms^{-1}$). The effects of the air pressure generated by the moving web, the jet impinging pressure and the rheological properties of fluids on the location of the apparent contact line have also been assessed.

Keywords: boundary layer; coating stability; thin film flow; jet coating; jet hydrodynamics; wetting contact line.

INTRODUCTION

In the paper industry, jet applicators provide an interesting alternative to more traditional coating applicators because they allow better runnability at high speed while ensuring good coated paper quality (Kustermann and Damrau, 1994; Tyrväinen and Anttila, 1994; Elovaara, 1998; Kuni and Lares, 2002). The main advantages of jet coating have been related to cleanliness of coating transfer to the web, elimination of ring-patterning and edge losses, as well as improved quality due to absence of film splitting or vortex generation in the application zone. In addition, this coating method has been shown to reduce coating colour losses, dewatering process and paper breaks (Roper *et al.*, 1997; Trefz and Hess, 1997; Presenti, 1998; Urscheler and Salminen, 1998). Nevertheless, some limitations still exist with jet applicators, for instance instabilities of the wetting contact line due to air entrainment between the coating colour layer and the web interface, coating skip and sometimes break-up of the jet (Roberts *et al.*, 1999).

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In jet coating systems, a steady position of the colour wetting contact line on the web is of utmost importance as a stable contact line is essential for optimal running conditions. The jet applicator has a dynamic wetting contact line corresponding to the line of contact where the liquid jet displaces the air along the moving web. At this point, the location of the contact line may move with respect to the web depending on the operating conditions. As in curtain coating, the operating window of jet coating is characterized by a stable coating region bounded by two unstable regions (Presenti, 1998). At a given web speed, the minimum flow rate required to establish and maintain a stable jet defines the stable region (Figure 1). A ‘lack of flow region’ occurs at low flow rates or high web speeds when the jet fails to wet the web leading to fall off (air entrainment). A ‘back flow region’ appears at high flow rates when an excess of coating colour accumulates on the backside of the jet (heel formation). From a process point of view, an optimum balance between the air pressure generated by the moving web and the jet velocity is required to achieve a complete and uniform film transfer. Unfortunately, the operating limits of jet application cannot be completely quantified, because the range of admissible values for relevant process parameters, for instance the web speed, always depend on the values of other process parameters and the fluid properties, e.g., wet

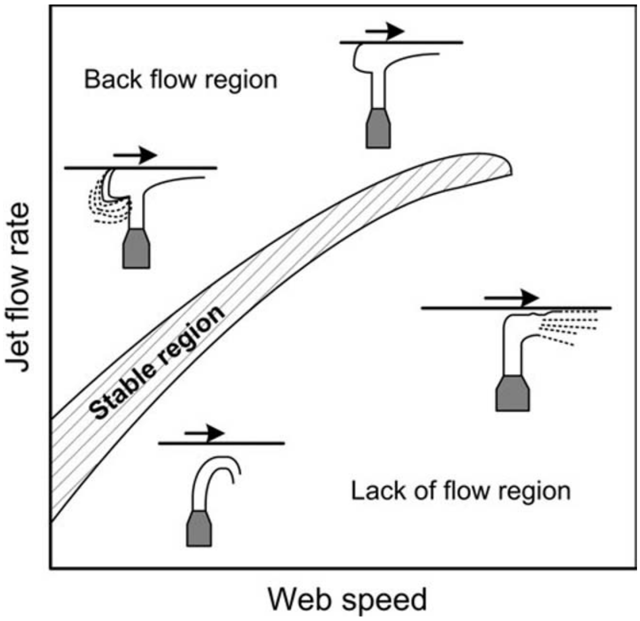

Figure 1. Schematic of coating windows in jet coating.

film thickness, rheological properties, surface tension, length jet, nozzle arrangement, etc.

Several pilot coater studies have been carried out in recent years in order to determine the process parameters controlling the runnability of jet coaters at high speed. Empirical in nature, they have enabled to successfully optimize jet applicators installed in traditional coating machinery (roll or SDTA) as well as develop new colour formulations (Roper *et al.*, 1997; Trefz and Hess, 1997; Hiorns *et al.*, 1999). The main parameter used to assess the runnability has been the coated paper quality (gloss, brightness, smoothness, printability, coat uniformity, etc.). It has been found, from a technological point of view, that the feed chamber and nozzle arrangement are the most important factors controlling the uniformity and stability of the metering jet (Johnson and Benjamin, 1998; Presenti, 1998).

The investigation of the wetting contact line behaviour in jet coating has received little attention. Roper and co-workers have measured the contact point of the jet on the web and calculated its deflection under different operating conditions (Roper *et al.*, 1997). They also modelled the wetting line behaviour using a computer model based on a force balance. They found that the two main factors influencing the wetting contact line location are the jet impingement angle and the jet velocity. The base paper, the surface tension and the rheology of the coating colour have been shown to have little effect on the deflection.

Dynamic wetting is a very common characteristic in many coating processes (Blake and Ruschak, 1997). Most of the experimental and theoretical contributions have focused on a molecular-kinetic viewpoint for the wetting, where the surface tension and viscosity of the fluid, and the surface energy of the solid substrate play a central role. In the simplest case, the wetting line movement is due to the individual molecular displacements. It means that, for the wetting line to advance across a solid surface, molecules already adsorbed at localised sites on the initial solid/surface interface must be displaced by molecules from the advanced fluid (Blake, 1988; Blake, 1993; Blake and Ruschak, 1997). This approach however, has not yet been experimentally verified for general use in coating applications. In the literature, experiments on wetting are concerned with steady immersion or withdrawal of a flat substrate or a scraped rotating cylinder surface from a liquid pool (Inverarity, 1969; Wilkinson, 1975; Bolton and Middleman, 1980; Veverka and Aidun, 1991; Ghannam and Esmail, 1997; Benkreira and Cohu, 1998; Blake and Shikhmurzaev, 2002) at capillary and Weber numbers of the order of the unity. We recall here that the capillary number is defined as:

$$Ca = \frac{\mu U}{\sigma} \tag{1}$$

and the Weber number as:

$$We = \frac{\rho q U}{\sigma} \tag{2}$$

were μ is the shear viscosity, ρ is the density, σ is the surface tension, q is the volumetric flow rate per unit width and U is the web speed.

However, in typical paper coating operations both *Ca* and *We* are significantly higher than one because coating colours are rather viscous and the process is run at high speed. At high capillary numbers, the contribution of surface forces can be neglected and the observed dynamic wetting is entirely dominated by macroscopic hydrodynamics (Blake, 1988). The above conditions (high *Ca* and *We* numbers) correspond to high-speed jet coating, as already suggested by Roper *et al.* (1997).

In the jet coating process, when the fluid exits from the nozzle, it forms a jet that accelerates as it impinges on the moving web. As the liquid jet reaches the web surface, the viscous drag generated by the web shifts the contact line and forces the liquid jet to bend near the impingement region developing a curved-shape interface (Figure 2). The contact line location is controlled by a balance between the macroscopic hydrodynamic mechanisms, namely the

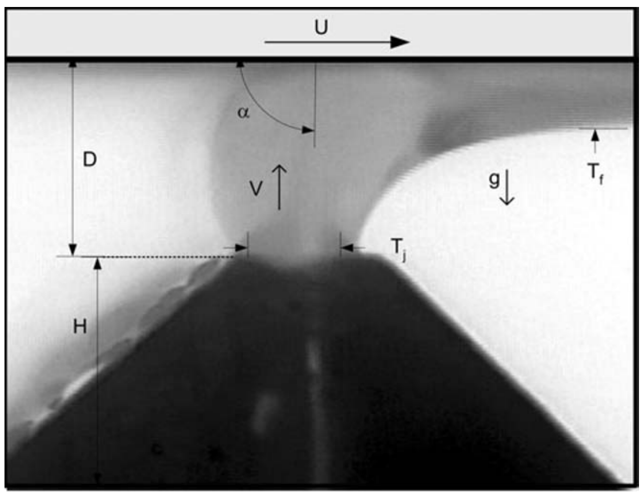

Figure 2. Flow configuration.