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Misting of non-Newtonian liquids in forward roll coating

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ABSTRACT

Misting of liquids in forward roll coating is a problem under certain conditions. The relaxation time is known to influence misting but the fundamental mechanisms are not clear. A new mechanism for misting of dilute non-Newtonian liquids was proposed based on visualizations with a high-speed camera. With these liquids, filaments were created which sometimes transformed into beads-on-string structures and the beads were ejected as mist droplets when the structures broke. Misting was quantified by measuring sizes of the generated droplets, their count and mass concentration. The measurements were related to elasticity of the solutions through their relaxation times. Small levels of elasticity reduce the amount of misting, but higher levels lead to an increase.

1. Introduction

In forward roll coating, a liquid is carried through the upstream region of the gap between two cylinders. It splits into two films in the downstream region with each film coating a cylinder. The cylinders can be rigid or soft (rubber covered); they can move at same or different speeds; the liquids can be Newtonian or non-Newtonian. In industrial coating operations, a series of multiple cylinders splits the film multiple times, once between two successive cylinders. This enables thin films to be coated on a substrate moved by the last cylinder. Thin films can also be coated by using a soft cylinder in the series which is compressed by a rigid cylinder to create a "negative gap" (gap is zero when the cylinders touch each other) between them. Thin films are prone to break-up at higher speeds and generate air borne particles in the downstream region of the gap where the film splits. This is called misting.

Misting is hazardous and lowers efficiency in industrial production of adhesives, inks, silicone release liners, coated papers, etc. Misting has been an industrial problem for a long time and cavitation has often been claimed to be the cause. This belief implies that pressure in the liquid falls below its vapor pressure thus causing bubbles to form, grow and produce mist [1–9]. Even though it appears intuitive, the cavitation mechanism for misting is dubious. In fact, in misting experiments it has been reported that the measured pressure in the liquid did not fall below its vapor pressure [10,11].

A new mechanism for misting was proposed by Owens et al. [12] based on their high speed images of Newtonian liquids in forward roll coating. As speed was raised, they showed that flow instabilities in the film-split region evolved into continuous liquid sheets, called septa, between the cylinders with each septum having a depressed leading edge whose ends are attached to the cylinders. Fig. 1 shows septa of Newtonian liquids (pure glycerol) across two cylinders placed side-by-side. When the coating thickness was reduced (see Section 2.1 and Fig. 3) the septa broke to produce mist.

Addition of certain high molecular weight polymers has been claimed to reduce misting in inks and low viscosity silicone release liners by several patents [13–16]. The mechanism for misting of non-Newtonian liquids is different from that of Newtonian liquids. Unlike septa of the latter, those of the former break and generate cylindrical threads, called filaments, attached to the cylinders. Vadillo et al. [17] described formation of filaments with non-Newtonian liquids in their experiments of stretching a drop placed between two plates. The filaments are transformed into beads-on-string structures while they are stretched by the rotating cylinders. Fig. 2 shows septa and filaments, generated during start-up of rotation of the cylinders, with an aqueous solution of glycerol with 0.05% of high molecular weight poly(ethylene oxide) added. When the filaments break, the beads were ejected as mist.

Most of the experiments to understand and quantify misting have been performed with complex formulations: high molecular weight polymer solutions and liquid/solid suspensions containing binders, pigments and thickeners. Roper et al. [4] studied misting of water-based dispersions, largely composed of latex and clays, in metered size press coating. They presented empirical trends of misting but did not attempt to correlate their results to rheology. Roper [18] reported that addition of high-molecular weight associative thickeners to coating solutions raised its viscosity and

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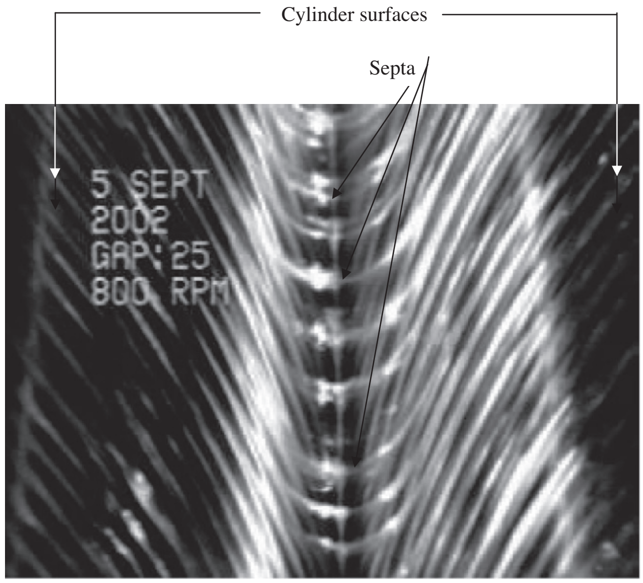

Fig. 1. Septa of pure glycerol produced with two 0.102 m diameter steel cylinders placed side-by-side in a pan containing glycerol. Both the cylinders were rotated at 500 rpm and they picked up glycerol as they rotated. Excess glycerol brought to the upstream region of the gap was rejected to the pan.

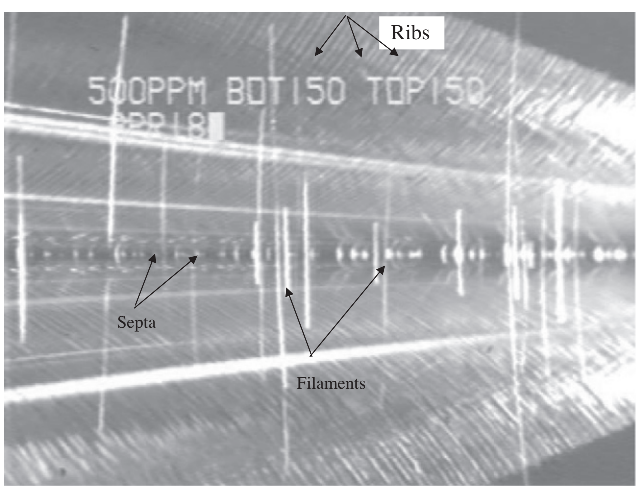

Fig. 2. Ribs, septa and filaments produced during start-up of the cylinders, which were placed one over the other and rotated at 150 rpm. The solution was 25% (v/v) glycerol in water containing 0.05% PEO having a molecular weight of 5×10^6 g/mol.

lowered mist. Others claimed that addition of linear polymers raised elastic modulus and increased mist [6,8,9,18,19]. Blayo et al. [6] reported that tack could not be correlated to mass concentration of mist. They shared Roper's opinion that the addition of high molecular weight thickeners reduced mist, but did not substantiate their claim.

MacPhee [5] mentioned that misting of inks is not understood well. Reimers et al. [7] reported that an undisclosed balance of viscous and elastic modulus was required to lower misting and that by increasing the viscous modulus of their coating liquids mist could almost be eliminated. It appears that the mechanism for misting of non-Newtonian solutions is not well-understood and the conclusions drawn on the effect of addition of high molecular weight linear and branched polymers on misting are contradictory. The rheology of the solutions used in misting studies was either poorly characterized or not measured. This paper attempts to connect rheology and misting of dilute solutions of high molecular weight polymers. We use the capillary thinning method to estimate relaxation time. We relate mass concentration of the mist, drop size and drop count to relaxation time of the solutions. Also, still images from a high-speed camera are presented to show the mechanism by which the filaments are created and the mist is generated. The details of experimental methods and materials are described below.

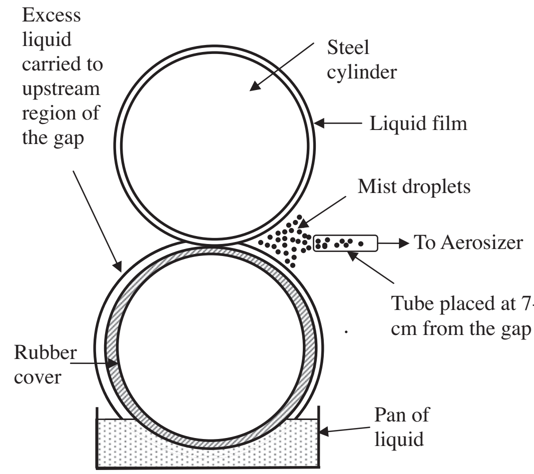

Fig. 3. Side view of the experimental apparatus used to measure misting. Bottom cylinder always carried more liquid to the gap from the pan and the excess was rejected. Due to its weight, the upper cylinder compressed the bottom one covered with rubber and created a negative gap. Both the cylinders moved in the same direction near the gap. Air borne droplets generated in the downstream region of the gap were drawn through a tube, placed 7 cm from the gap, into an Aerosizer for analysis of drop sizes and count.

2. Experiments

2.1. Apparatus

Misting experiments were conducted with an apparatus consisting of two cylinders placed one over the other as shown in Fig. 3. The top cylinder was chrome-plated and rested on the bottom one which was covered with 0.33 m thick rubber of hardness of 60 durometer (Shore A). Due to its weight, the top cylinder compressed the bottom one and created a negative gap. Thin films are produced in the downstream region of the gap because less liquid is carried through the negative gap. These films are likely to break and produce mist. The steel and rubber cylinders were 0.102 m in diameter and 0.191 m in width. Each of two computer controlled motors drove the cylinders. However, all experiments were done

Table 1
Molecular weights of PEO, concentrations of PEO and PEG, zero-shear viscosities and relaxation times.

Molecular weight of PEO, g/mol	Wt% of PEO	Wt% of PEG	Zero-shear viscosity, Pa-s	Relaxation time, ms
1×10^6	0.232	40	0.30	111
	0.100		0.181	76
	0.050		0.160	49
	0.025		0.149	29
	0.005		0.147	17
	0.0005		0.146	8
5×10^6	0.30	40	0.270	303
	0.15		0.207	202
	0.05		0.192	133
	0.025		0.153	104
	0.005		0.145	39
	0.0005		0.145	16