Effect of Air Impinging on a Liquid Coating Early in Drying

M. Komatsubara(*), **J. M. de Santos**(**) and **L. E. Scriven**(**)

(*) Production Engineering Development Center
Nitto Denko Corporation
Onomichi, Hiroshima 722-0212, Japan

(**) Department of Chemical Engineering & Material Science
University of Minnesota
Minneapolis, Minnesota 55455-0132

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INTRODUCTION

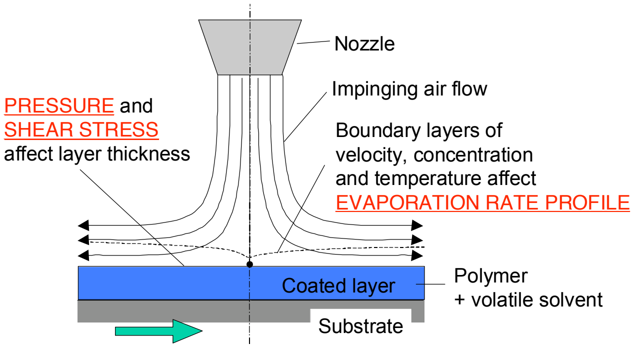

Figure 1. Effect of air impinging on a liquid coating

Forced-convection drying of liquid coatings by impinging air is generally characterized by empirical heat and mass transfer coefficients. These reveal nothing about the flow and distortion of a freshly deposited layer of liquid by the pressure and shear stresses exerted by the turbulent or possibly laminar impinging air flow. Outside the impingement zone the non-uniformities produced by those stresses tend to diminish

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as the solvents evaporate and the layer loses mobility when it thins and grows more viscous; see Figure 1.

THEORETICAL MODEL

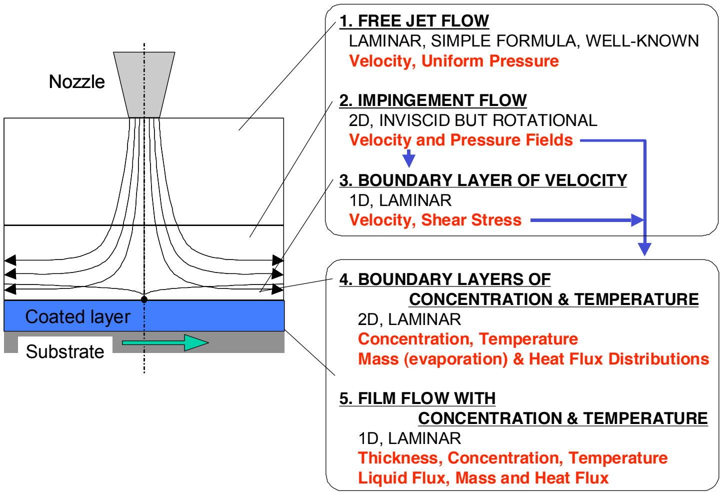

Figure 2. Combination of models

We used a combination of models that represent well the physics of impingement, as shown in Figure 2. Mass transfer, heat transfer, and layer distortion produced by pressure and shear of impinging two-dimensional air jets were investigated by coupling the stream function and vorticity equations of inviscid impinging flow with the boundary layer equation system that includes the flux of evaporating solvents to the gas above the liquid layer; the inflow is given by simple formulas for free jet flow. The equations in the impingement zone are:

Stream function and vorticity,

$$\nabla^2 \psi = \alpha \mathbf{w}, \quad \mathbf{v} \cdot \nabla \mathbf{w} = 0; \qquad \text{(1) and (2)}$$

boundary layer of velocity

$$\frac{\mathrm{d}}{\mathrm{dx}}\left(\delta_2 \mathrm{U}^2\right) + \delta_1 \mathrm{U} \frac{\mathrm{dU}}{\mathrm{dx}} = \frac{\tau_{\mathrm{w}}}{\rho}$$

boundary layer of concentration

$$\mathrm{u}\frac{\partial \mathrm{c_g}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{c_g}}{\partial \mathrm{y}} = \mathrm{D}\frac{\partial^2 \mathrm{c_g}}{\partial \mathrm{y}^2};$$

and boundary layer of temperature

$$\mathrm{u}\frac{\partial \mathrm{T_g}}{\partial \mathrm{x}} + \mathrm{v}\frac{\partial \mathrm{T_g}}{\partial \mathrm{y}} = \alpha\frac{\partial^2 \mathrm{T_g}}{\partial \mathrm{y}^2}.$$

The liquid layer in the wet-stage of drying was modeled with a viscocapillary film-flow equation

$$\frac{\partial}{\partial x}\left\{-\frac{h^3}{3\mu}\frac{d}{dx}\left(p_{\text{ambient}}-\sigma H\right)+\frac{h^2}{2\mu}\left(\tau_{\text{ambient}}+\frac{d\sigma}{dx}\right)+Vh\right\}+\frac{j}{\rho_{\text{solvent}}}=0\,,$$

together with conservation of mass

$$\frac{q}{h}\frac{\partial c_f}{\partial x}-\frac{j}{\rho_{\text{solvent}}h}c=0$$

and conservation of heat energy

$$\frac{q}{h}\frac{\partial T_f}{\partial x}+\frac{j}{h\rho_{\text{solvent}}}\frac{\Delta H}{Cp}+\frac{q_{\text{heat}}}{h\rho_{\text{solvent}}Cp}=0\,.$$

These equations were solved by Galerkin/finite element methods and 0th order continuation.

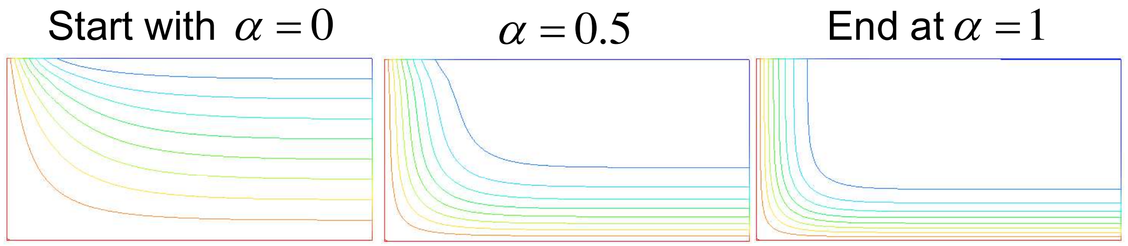
Start with $\alpha=0$ $\alpha=0.5$ End at $\alpha=1$

Figure 3. Streamlines of impinging air

RESULTS

Figure 3 shows streamlines of impinging air calculated from Equations (1) and (2). The chosen streamlines are crowded together by the effect of vorticity as the continuation factor, α, is changed from zero — a simple artificial decoupled case — to one — the problem of interest.

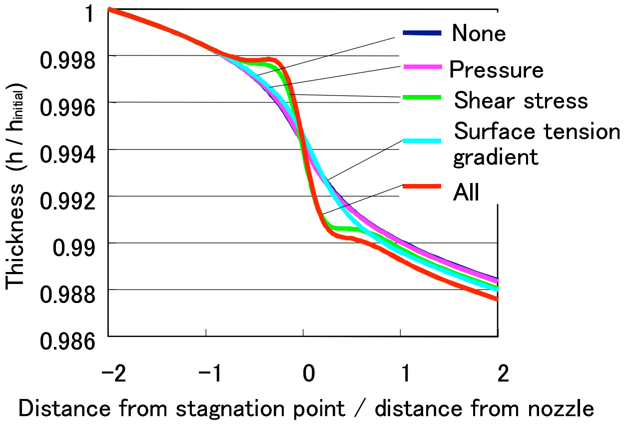

Figure 4. Effect of each force on film profile

Figure 4 shows how the film profile is affected by the pressure and shear stress distribution of impinging air, and by a surface tension gradient. The operating conditions are shown in Table 1. The film thickness decreases due to evaporation, steeply below the stagnation point of the impinging air. The film profile is mostly set by the effect of the shear stress of the impinging air.

Table 1. Conditions used to assess the effect of forces on film profile

Air	Temperature	50	C
	Concenttation	0	–
	Slit hegiht of nozzle	1	mm
	Distance between nozzle and coating	20	mm
film	Initial tickness	50	um
	Web speed	0.5	m/s

CONCLUSION

We modeled theoretically the mass transfer, the heat transfer, and the distortion of the liquid layer produced by pressure and shear of impinging two-dimensional air jets. We employed the stream function and vorticity equations of inviscid impinging flow, a system of boundary layer equations modified to include the flux of evaporating solvents in the gas nearest the liquid layer, and the viscocapillary film-flow equation of the liquid layer in the wet-stage of drying. Coating uniformity was assessed from solutions obtained by the Galerkin/finite element method.

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