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Three flow regimes of a jet falling onto a moving surface

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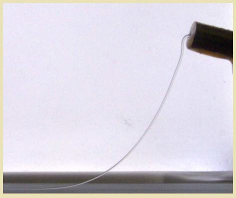
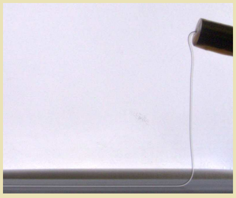
Introduction

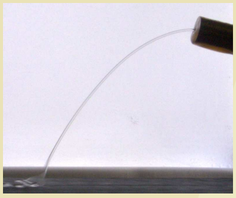
Consider a jet of Newtonian fluid falling under gravity from a nozzle onto a moving belt. Depending on the process parameters and fluid properties three flow regimes are observed.



Viscous regime



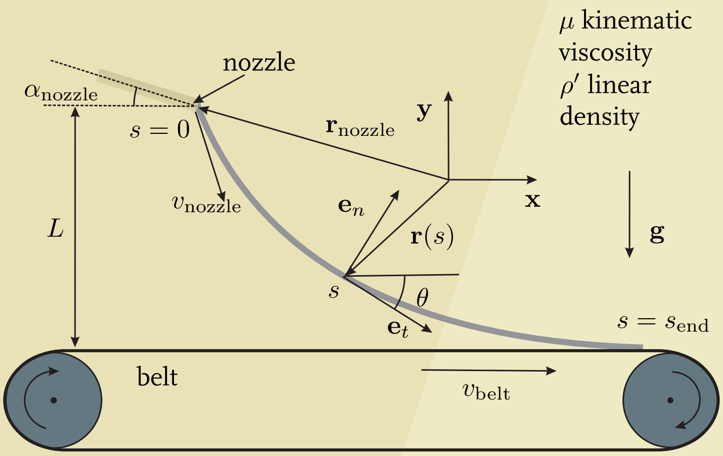
Viscous-Inertia regime



Inertia regime

- ✶ Viscous regime: viscosity dominates inertia everywhere in the jet, the jet has convex shape, the jet hits the belt with zero angle.
- ✶ Viscous-inertia regime: viscosity dominates near the nozzle and inertia dominates near the belt, the jet's shape is straight vertical.
- ✶ Inertia regime: inertia dominates everywhere in the jet, the jet's shape is concave, near the nozzle the jet is aligned with the nozzle orientation.

Model

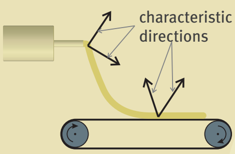


Boundary conditions

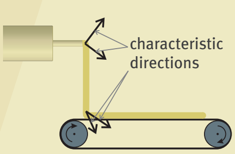
To get correct boundary conditions for each flow regime we consider conservation of momentum for dynamic jet

$$\boxed{\mathbf{r}_{tt} + 2v\mathbf{r}_{st} + \xi\mathbf{r}_{ss}} + (v_t + v_s v - P_s/\rho')\mathbf{r}_s = 0.$$

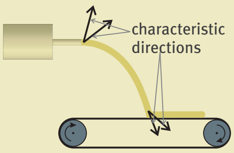
Here $\xi = v^2 - P/\rho'$ ($P = 3\mu v_s \rho'$) represents the balance between inertia and viscosity, which for stationary jet is a strictly increasing function. Therefore there are three possible situations for the direction of characteristics at the edges of the jet.



Viscous regime



Viscous-Inertia regime



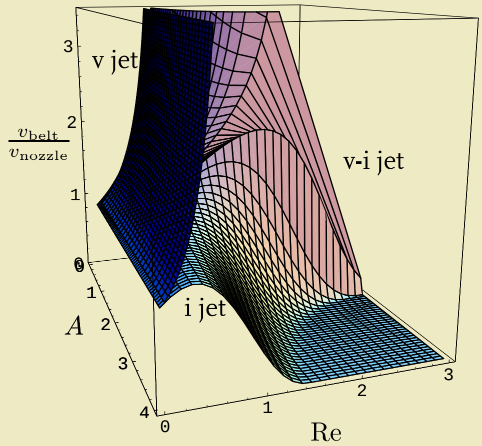
Inertia regime

From the fact that the number of boundary conditions is equal to the number of characteristics pointing inside the domain the following holds:

- ✶ Viscosity dominates everywhere in the jet ($\xi < 0$) $\Rightarrow$ two BC: $\theta(s_{\text{end}}) = 0$ and $\mathbf{r}(0) = \mathbf{r}_{\text{nozzle}}$.
- ✶ Viscosity dominates near the nozzle and inertia near the belt ($\xi = 0$ at some point in the jet) $\Rightarrow$ one BC: $\mathbf{r}(0) = \mathbf{r}_{\text{nozzle}}$.
- ✶ Inertia dominates everywhere in the jet ($\xi > 0$) $\Rightarrow$ two BC: $\theta(0) = \alpha_{\text{nozzle}}$ and $\mathbf{r}(0) = \mathbf{r}_{\text{nozzle}}$.

Parameter regions and stationary flow

- ✶ Requiring $\xi(0) = 0$ and $\xi(s_{\text{end}}) = 0$ we find regions of parameters for the three flow regimes.

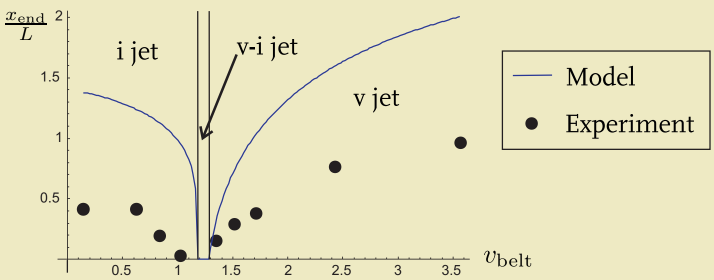


Here $A = 3g\mu/v_{\text{nozzle}}^3$ and $\text{Re} = v_{\text{nozzle}}L/(3\mu)$.

- ✶ For the stationary problem we prove existence and investigate uniqueness of a solution.
- ✶ For $\alpha_{\text{nozzle}} < \pi/2$ (nozzle does not point down vertically) multiple solutions might be possible. This leads to instabilities which is confirmed by experiments.

Comparison with experiment

The position of contact with the belt x_{end} was measured for different v_{belt} and was compared with model predictions.



The comparison gives good qualitative agreement for the regions of three flow regimes.

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