Jet and film

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8. Jet and film

A thin liquid jet impacts on a soap film. Depending on relevant parameters, the jet can either penetrate through the film or merge with it, producing interesting shapes.

Explain and investigate this interaction and the resulting shapes.
Existing work

Jet impact on a soap film

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We experimentally investigate the impact of a liquid jet on a soap film. We observe that the film and that two qualitatively different steady regimes may occur. The column-like behavior obtained at small incidence angles when the jet crosses the film in the film-jet interaction. For larger incidence angles, the jet is absorbed by the film, leading to a new class of flow in which the jet undulates along the film with a characteristic period. Besides its fundamental interest, this study presents a new way to guide a microjet in the inertial regime and to probe foam stability submitted to violent perturbations at the film scale.
Existing work

Jet impact on a soap film

3 modes of interaction:

1. The jet **is reflected** by the film
2. The jet **penetrates** the film
3. The jet **undulates** on the film
Our apparatus

- Soap : water 1:10 (both jet and film)

- Density $\rho = 1000 \text{kg} / \text{m}^3$

- Surface tension $\gamma = 0.025 \text{kg} / \text{s}^2$

- Inertia dominated

- $30 < \text{We} < 400$ (Weber number)

- Film thickness $\approx \lambda_{\text{VISIBLE LIGHT}}$
Apparatus

Soap water supply

Film

Changing height
different speed
Jet **angle** and **radius** changed
Basic forces in a jet

- Surface tension
  \[ F_{\text{SURFACE TENSION}} = 2\pi R \gamma \]

- Capillary pressure
  \[ P = \frac{\gamma}{R} \]
  \[ F_{\text{PRESSURE}} = P \pi R^2 \]
Basic forces in a jet

- **Surface tension**

- **Capillary pressure**

\[ P = \frac{\gamma}{R} \]
• Thin jets
• Low impact speeds
• Lower incident angles

Reflection  Penetration  Undulation

\( \alpha \)
Reflection

• Thin jets $\rightarrow$ drops
  (Plateau-Rayleigh instability)

• Drops do not merge with the film, they bounce and roll

• No full theory exists yet
Reflection – drops
Reflection on a bubble

Spherical shape of the film
– the jet keeps some of its momentum, “escapes”
Intermediate state

Unstable waves, oscillate, small drops are splashed away
- Thick Jets
- High impact speed
- Low incident angles

Reflection  Penetration  Undulation
Penetrating the film

(View from below the film)
Penetrating the film

- Theory from the cited paper

\[ F_{FILM} = 2 \rho_{PROJECTED} \gamma \]

\[ \frac{d\mathbf{p}}{dt} = Q \rho (\mathbf{v}_{AFTER} - \mathbf{v}_{BEFORE}) \quad Q_{AFTER} = Q_{BEFORE} \]
“Refraction” of the jet

- Numerical solution

- Analogy to Snell’s law of refraction

\[
\frac{\sin \beta}{\sin \alpha} \approx 1 + 30W_e^{-1.5}
\]

\[
W_e = \frac{\rho v^2 R}{\sigma}
\]
“Refraction” of the jet

\[ \sin \beta = 1.34 \sin \alpha \]

\[ (\text{We} = \text{const}) \]

Measurements

Best linear fit
• Thinner jets
• Lower impact speed
• High incident angle
Undulation
Undulation

(Jet coloured by blue ink)
Force analysis
Forces on jet element
Forces on jet element

\[ F_{\text{FILM}} \]

\[ \pi R \gamma \]
Force of the film – jet cross section

\[ F_{FILM} = 4dl \gamma \cos \theta \]
Net force on jet element

Centripetal force:

$$4d\gamma \cos \theta + \frac{dl \pi R \gamma}{r_{CURVATURE}}$$
Kirstetter: Approximation – circle arcs

- Constant centripetal force
Kirstetter: Theoretical prediction

- Radius of curvature (based on centripetal force):

\[ r_{CURVATURE} = \frac{\pi R(W_e - 1)}{4 \cos \theta} \quad W_e = \frac{\rho v^2 R}{\gamma} \]

- Assuming: \(|\cos \theta|\) is constant (i.e. circle arcs):

\[ \lambda = \frac{\pi}{|\cos \theta|} R(W_e - 1) \sin \alpha_{INCIDENT} \]

- Correlation with experiments with fitted \(|\cos \theta|\)
Comparison to our measurements

\[ \lambda \text{ [m]} \]

Experiment vs. Theory

\[ \lambda \text{ [m]} \]

Theory
Comparison to our measurements

\[ \lambda \text{ [m]} \]

**Experiment**

- Incident angle changed
- Thicker jets

\[ \Rightarrow \text{Circle arcs approximation} \]

- Inaccurate

Why it doesn’t work?
Arcs: cannot fit little curvatures
Our approximation: *sine function*

A rcs: cannot fit little curvatures
Sine shape approximation

\[ 4dl \gamma \cos \theta + \frac{dl \pi R \gamma}{r_{\text{CURVATURE}}} \]
Sine shape approximation

\[ 4d\gamma \cos \theta + \frac{dl \pi R \gamma}{r_{\text{CURVATURE}}} \]

Less than 3% of the total force
Sine shape approximation

\[ 4d\gamma \cos \theta + \frac{dl \pi R \gamma}{r_{CURVATURE}} \]

Less than 3% of the total force

Wavelength \( \gg \) amplitude
Sine shape approximation

\[ 4d\gamma \cos \theta + \frac{dl \pi R \gamma}{r_{\text{CURVATURE}}} \]

\[ \cos \theta = -k\gamma \]

Less than 3\% of the total force

Wavelength $>>$ amplitude

Zero force at $y=0$, increases with $|y|$
Shape – theoretical prediction

Constant speed in x direction, harmonic oscillations in y direction

\[ y(x) = A \sin \left( \frac{2\pi}{\lambda} x \right) \]

Wavelength

\[ \lambda = \pi R \nu \sin \alpha \sqrt{\frac{\pi \rho}{\gamma k}} \]

Amplitude

\[ A = \frac{1}{2} R \nu \cos \alpha \sqrt{\frac{\pi \rho}{\gamma k}} \]

free parameter \( \kappa \)
$\lambda \text{ [m]} \text{Experiment}$

$k = 114 m^{-1}$

$\lambda_{\text{EXPERIMENT}} = 1.04 \lambda_{\text{THEORY}} - 0.03$

---Linear fit
\[ k = 114 \text{m}^{-1} \]

\[ A_{\text{EXPERIMENT}} = 0.99 A_{\text{THEORY}} - 0.001 \]
Summary

• 3 modes of interaction studied
• Existing theory verified, discrepancies explained, novel approach in case of undulation
• Greater jet radii, incident angle changed and amplitude investigated

Thank you for your attention
APPENDICES

8. Jet and film
View from below the film
View from below the film
Parameters

Fixed:
- Liquid \( \rho = 1000 \text{ kg} / \text{m}^3 \quad \gamma = 0.025 \text{ kg} / \text{s}^2 \)

Varied:
- Jet radius \( r = 0.36 \text{ mm}; \quad r = 0.52 \text{ mm} \)
- Incident angle \( 30^\circ < \alpha < 80^\circ \quad \text{waves} \)
- Incident angle \( 12^\circ < \alpha < 45^\circ \quad \text{refraction} \)
- Incident speed \( 1.5 \text{ m} / \text{s} < v < 5 \text{ m} / \text{s} \quad \text{waves} \)
  \( v = 1.7 \text{ m} / \text{s} \quad \text{refraction} \)
Surface tension measurement

• Counting drops from a pipet

• Comparing to number of drops of deionized water (known surface tension)

• Calculating the mass of a single drop:

\[
\frac{m_1}{\gamma_1} = \frac{m_2}{\gamma_2}
\]

• Soap water \( m_2 \approx 0.02 \text{g} \)
• Deionized water \( m_2 \approx 0.06 \text{g} \)
Thickness of the film
Interference on a thin film

- Path difference $\propto t$
- 180° phase shift (beam 2)

Small $t$
Destructive interference of all visible light
– little light reflected

Air

Film

Air
“Hysteresis”

Identical conditions – the mode of interaction depends on previous state
Apparatus
Diagram (regions)

\[ W_e = \rho R V^2 / \gamma \]

- Refracted Jet
- Absorbed jet
Undulation
Refraction
Forces on jet element

\[ F_{\text{FILM}} = 4 \, d\gamma \cos \theta \]
Velocity change upon impact

1st contact with the film – the jet is decelerated

→ Smaller waves than we would expect
Undulation – sine shape

- Expected shape

- Real shape
  - Deceleration upon impact
Whole video
"Refractive index" of the jet

\[
\sin \beta = 1.336 \sin \alpha
\]

Theoretical prediction: 1.124
Experimental result: 1.336

\(\sin \beta\) vs. \(\sin \alpha\) graph with measurements and best linear fit line.