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Acoustic streaming flows in discharge lighting

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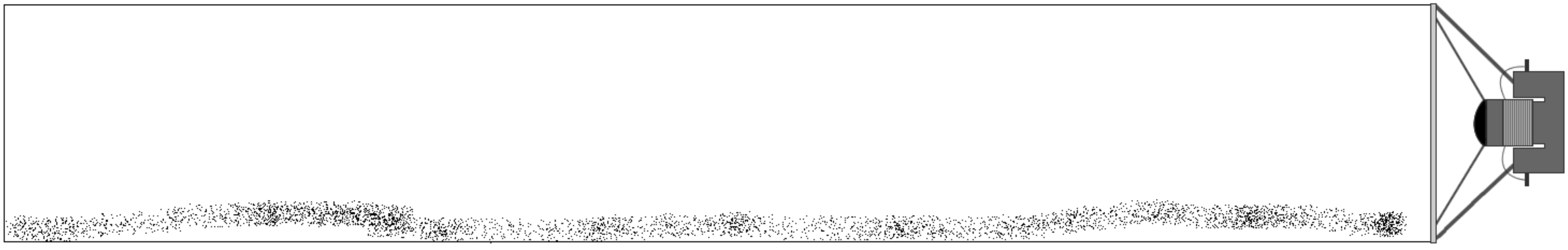
Outline

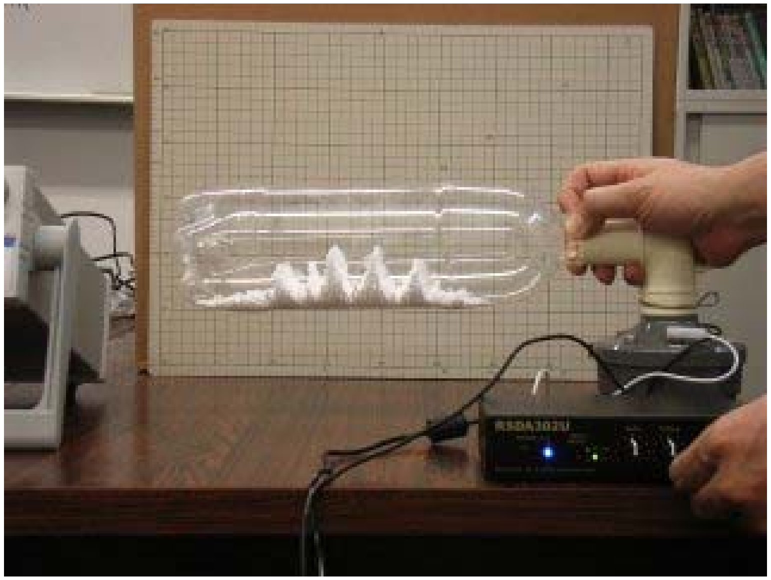
- **Early accounts of acoustic streaming**
- High-intensity discharge lamps
- Construction of the Model
- Results
- Conclusion

The dust tube of A. Kundt[1] (1866)



Tube with cork dust

- Standing sound waves cause cork-dust particles to form regularly-spaced clusters.
- The speed of sound can be derived from frequency and cluster spacing.



A modern demonstration[2]

[1] Kundt, A.. (1866). "Ueber eine neue Art Akustischer Staubfiguren und über die Anwendung derselben zur Bestimmung der Shallgeschwindigkeit in festen Körpern und Gasen„, Annalen der Physik (Leipzig: J. C. Poggendorff) 127 (4): p.497–523.

[2] Tatsuya Kitamura, 2008. Intelligent Information Processing Lab, Department of Speech and Acoustics, Konan University Faculty of Information Science

Theory of steady streaming, Lord Rayleigh[1] 1883

- Acoustic effect:
    - High-frequency pressure gradients
    - High-frequency velocity ***U***
- *Streaming* effect from convection:
    - Streaming velocity ***<U>*** is the time-average of ***U***.
    - Streaming flow causes observed particle clusters.

- Streaming time scale is slower than acoustic time scale.

[1] Lord Rayleigh, On the Circulation of Air observed in Kundt's Tubes, and on some Allied Acoustical Problems, Transactions of the Royal Society of London, 175 (1), 1883

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What is a high-intensity discharge lamp?

- Produces light from a discharge that is created by forcing electric current through a gas.
- Highly efficient, used where large amounts of light are needed.
- HID lamps consume 400-500 TWH per year of electricity worldwide.

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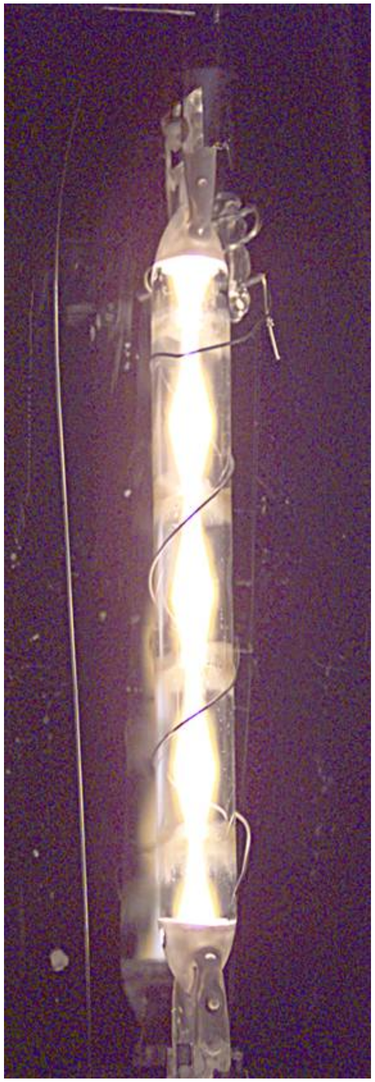
Why should streaming in a 1.5 century-old dust tube interest a lighting company today?



A prototype lamp under acoustic excitation

•Sound waves are generated by current modulation at a known acoustic frequency.
•“Dust” rings are molten salt made of rare-earth elements and iodine.

•The brightest portion is called the arc which emits much of the useful light.
•The regularly-spaced arc constriction demonstrates Rayleigh’s point: net flows in the shape of smoke rings create the observed pattern.

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Why model HID acoustic streaming?

Standing sound waves inside of an HID lamp are known experimentally to alter lamp behavior in both beneficial and detrimental ways:

•Stability
•Color consistency
•**Energy efficiency improvements up to 50% (100 -> 150 lpw)[1]**
•Arc flicker
•Wall overheating
•Extinction

Modeling exposes key fluid mechanisms to facilitate understanding, prediction, and control of acoustic streaming in HID lamps.

[1] K. Stockwald, et.al., “Significant Efficacy Enhancement of Low Wattage Metal Halide HID Lamp Systems by Acoustically Induced Convection Configuration”, ICOPS 2008, Karlsruhe, Germany, June 2008

What are the stakes?

- Worldwide, lighting consumes approximately 2800 TWH/year of electricity[1].
- At 10 cents / KWH, this electricity costs $280 billion.
- Gross annual income for light sources as an industry is ~ $25 billion.
- Each 10% improvement in efficiency covers the cost for operation of our industry.

[1] R. Van Heur, “Lighting”, Leonardo Energy website, www.leonardo-energy.org/

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Lighthill's distinction[1] in streaming analysis

Derive governing equations for **<*U*>** from Navier-Stokes equations.

•In *RNW streaming* (Rayleigh, Nyborg, & Westervelt), **<*U*>** is much smaller than ***U***. This linearizes the convective dependence on **<*U*>** .

•In *Stuart streaming* (1963), **<*U*>** is significant and its nonlinear dependence must be included. *J. T. Stuart anticipated streaming in acoustically-enhanced HID lamps*.

[1] J. Lighthill, Acoustic Streaming, *J. Sound & Vib.,* **61**(3), 381-418, 1978.

Model building blocks using COMSOL PDE modes: Streaming flow in HID lamp conditions

- 1: 2d Navier-Stokes.
- 2: Propagate sound waves:
  - Compressible and unsteady terms
  - Energy equation
  - Ideal gas law
- 3: Drive acoustics with electric current:
  - Current-continuity equation
  - Integration coupling variable to relate current to electric field

COMSOL solves the fully-coupled, unsteady system.

Governing equations

- Red terms dominate on the acoustic time scale.
- Blue terms dominate on the streaming time scale.

- Streaming velocity:

$$\langle u_i \rangle (t) = \int_{t-2\pi/\omega}^{t} u_i \, d\tau$$

This method captures Stuart streaming

$$\frac{\partial u_i}{\partial t} + u_j \frac{\partial u_i}{\partial x_j} = -\frac{\partial p}{\partial x_i} - \rho g_i + \frac{\partial \tau_{ij}}{\partial x_j}$$

$$\frac{\partial \rho}{\partial t} + u_i \frac{\partial \rho}{\partial x_i} = -\rho \frac{\partial u_i}{\partial x_i}$$

$$\rho c_v \left(\frac{\partial T}{\partial t} + u_i \frac{\partial T}{\partial x_i} \right) = -p \frac{\partial u_i}{\partial x_i} + \varepsilon$$

$$+ \frac{\partial}{\partial x_i} \left(\kappa \frac{\partial T}{\partial x_i} \right) + \sigma E^2 - q$$

$$p = \rho R_{gas} T$$

$$I = \int_A \sigma E \, dA$$

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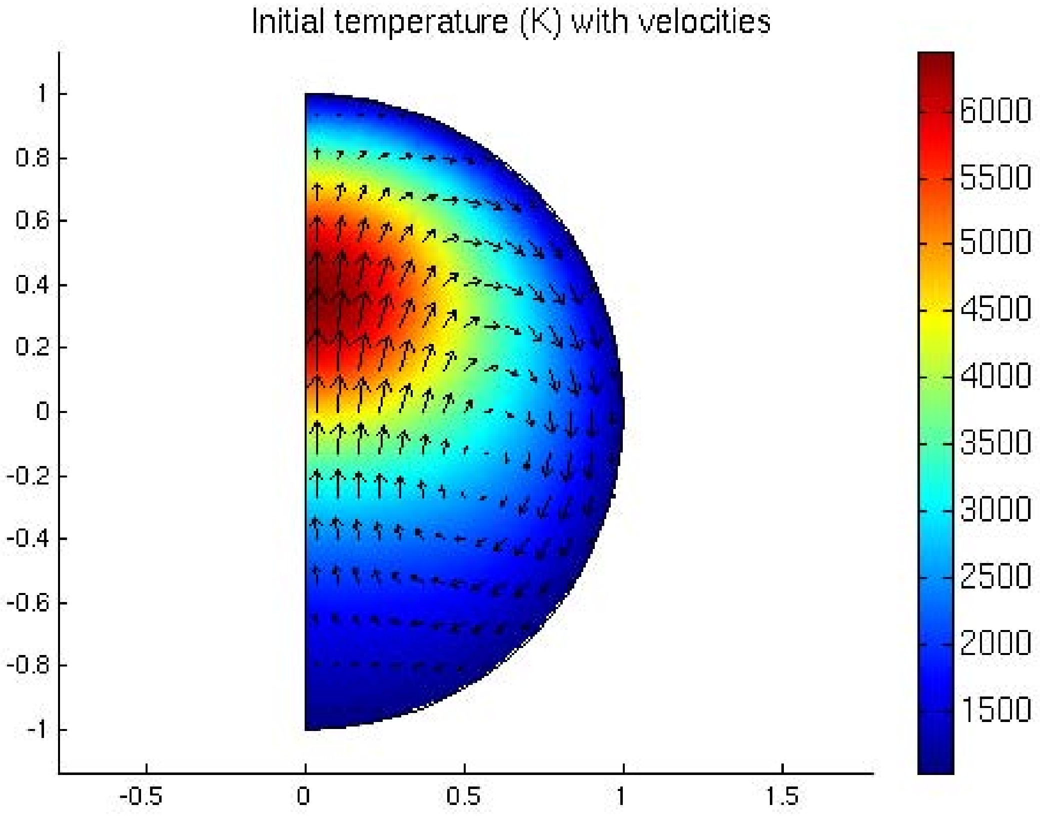
The acoustics-free case: (half of) a horizontally-running lamp shown in cross section.

Most light comes from the arc at 5000-6000 K. Gravity and density gradients cause natural convection which raises the arc above center.



Acoustic streaming in a horizontally-running lamp

Imposed current is a modulated sin wave centered with driving frequency of 30-32 kHz.

Vectors show streaming velocity ***<U>***

Display three videos:
1 – model_flicker.avi
2 – experimental_flicker.wmv
3 – flicker_mode.avi

Flickering (streaming) time scale: 50 ms

Acoustic time scale: 0.2 ms

Acoustic streaming used to straighten a bowed arc

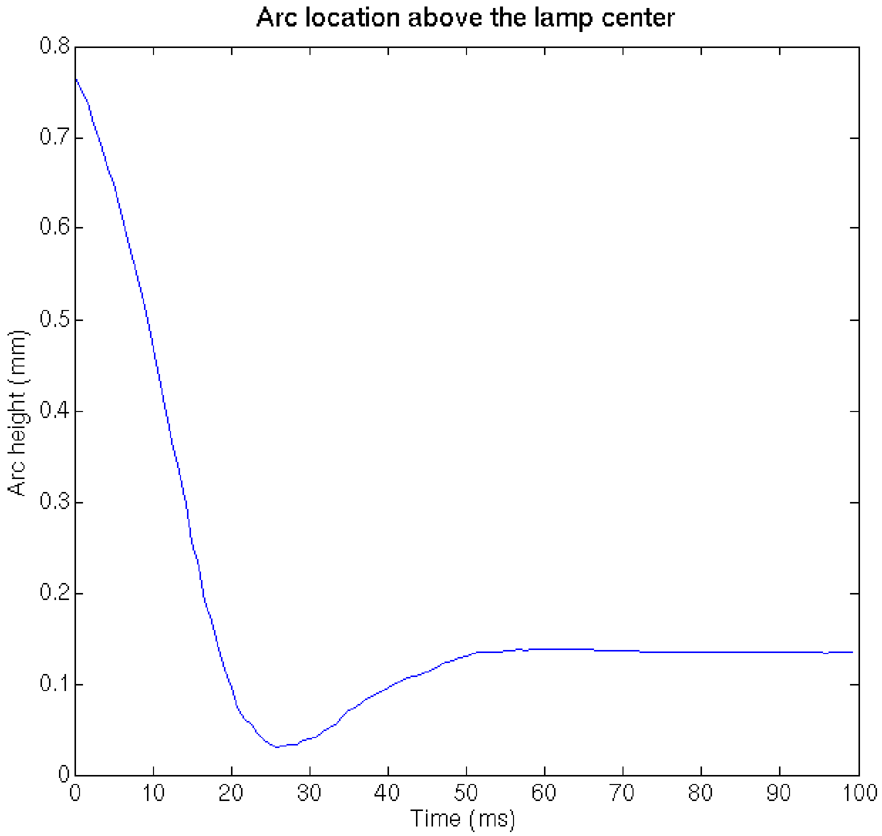
Imposed current is a *swept* sin wave of:
110-130 kHz (model)
90-110 kHz (experiment)

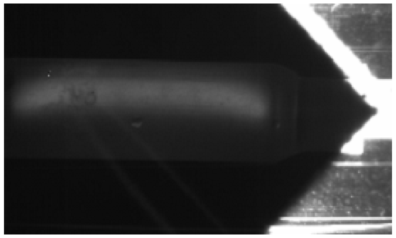
Vectors show streaming velocity
<U>

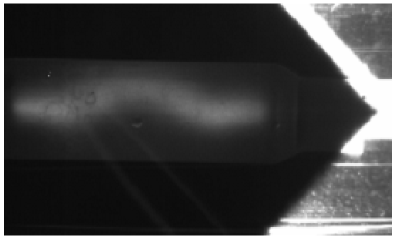
Display three videos:
1 – experimental_straightening.wmv
2 – model_straightening.avi
3 – straightening_mode.avi

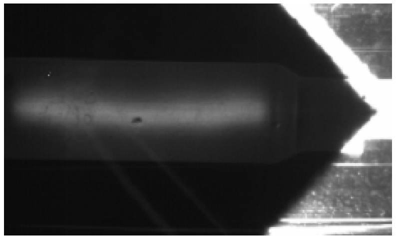
Acoustic time scale: 0.06 ms

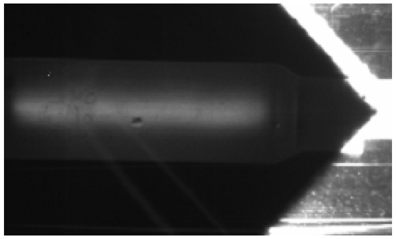
Streaming time scale: How long did it take to straighten the arc?




Time 0


18 milliseconds


30 milliseconds


38.5 milliseconds

Model: 50 ms
Experiment: 40 ms

Conclusion:

- COMSOL Multiphysics is used to successfully model Stuart streaming as it occurs in acoustically-enhanced high-intensity discharge lamps.
- We hope to use these techniques to reduce energy consumption on a global scale.

Acknowledgement: Our colleagues who have advanced the use of HID acoustics:

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- Warren Moskowitz
- Klaus Stockwald

THANK YOU

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