# Oscillation and synchronization of diffusion flames in a hydrodynamic approach

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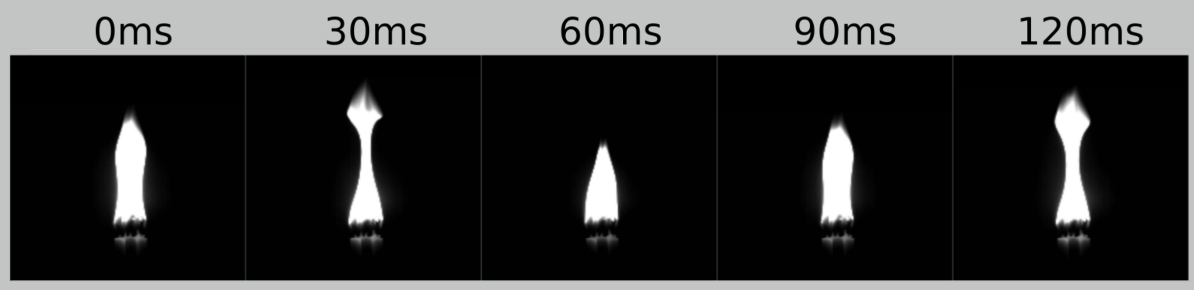
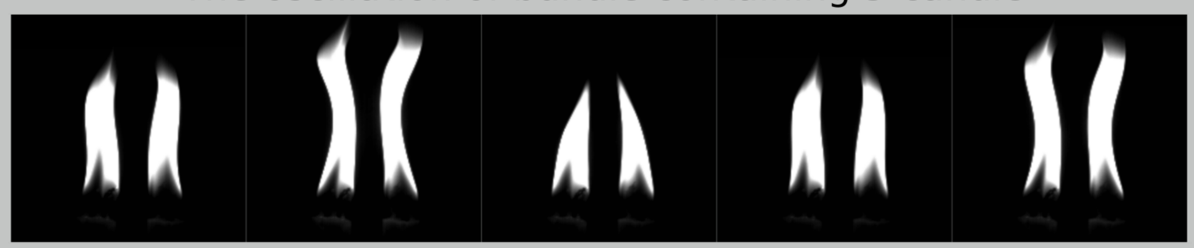
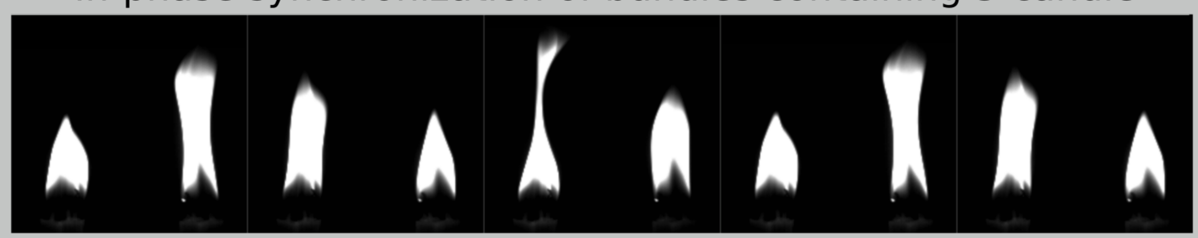
## Oscillation and synchronization for candle flames




The oscillation of bundle containing 5-candle



In-phase synchronization of bundles containing 3-candle

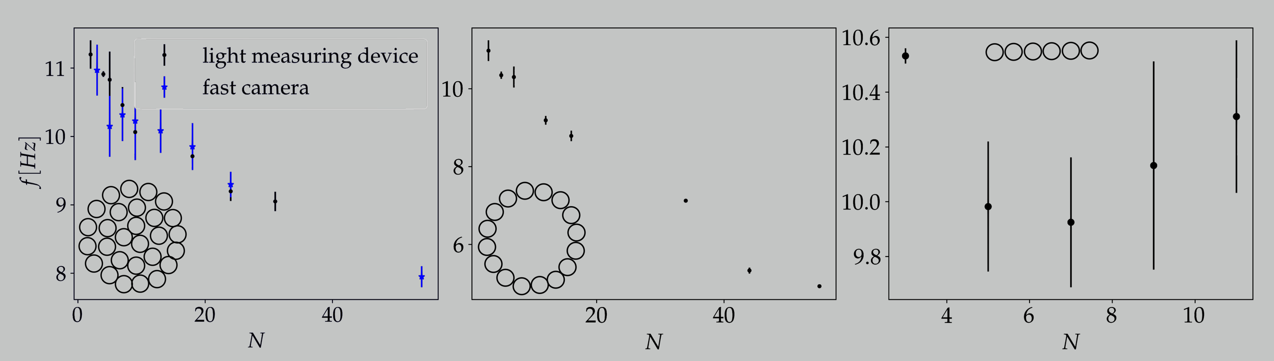


Counter-phase synchronization of bundles containing 3-candle

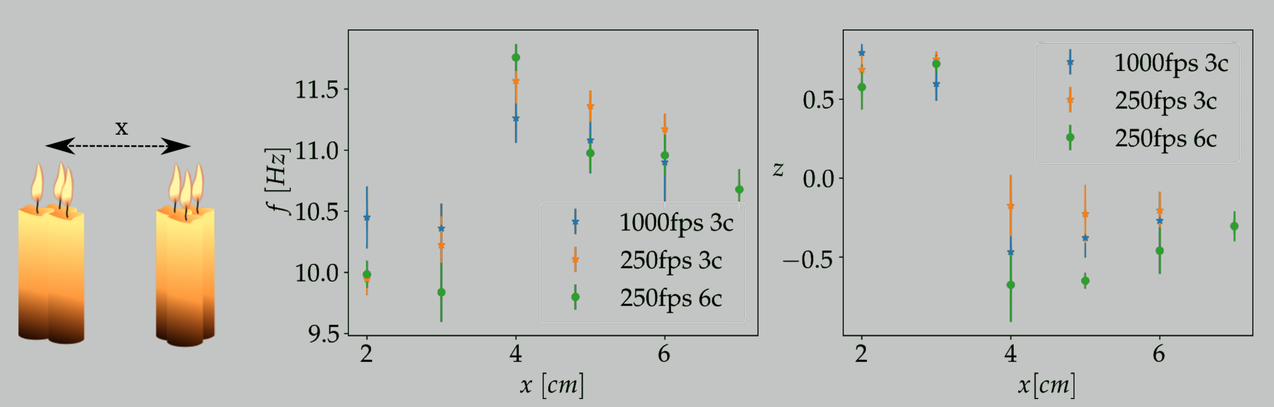
- Single candle flame $\longrightarrow$ stable burning (stationary flame)
- Candle bundle $\longrightarrow$ oscillatory behaviour
- Nearby candle bundle flames $\longrightarrow$ in-phase and counter-phase synchronization

## Results

- Effect of bundle size on the oscillation frequency




- Collective oscillation frequency $f$ and synchronization order parameter $z$ as a function of the distance between bundles
  - For $z$ values near to -1 $\longrightarrow$ counter-phase synchronization
  - For $z$ values near to 1 $\longrightarrow$ in-phase synchronization
  - For $z$ values near to 0 $\longrightarrow$ no synchronization




- Dynamical model

heat loss by convection

heat production by burning

$$C' N b(n_0) \frac{dT_i}{dt} = \omega_1 [h' N b(n_0)(T_0 - T_i) + \beta N a(n_0) n_i e^{(-\frac{E}{RT_i})}]$$

specific heat

characteristic frequencies (constants)

external temperature

external oxygen concentration

supply rate of the fuel

chemical reaction activation barrier

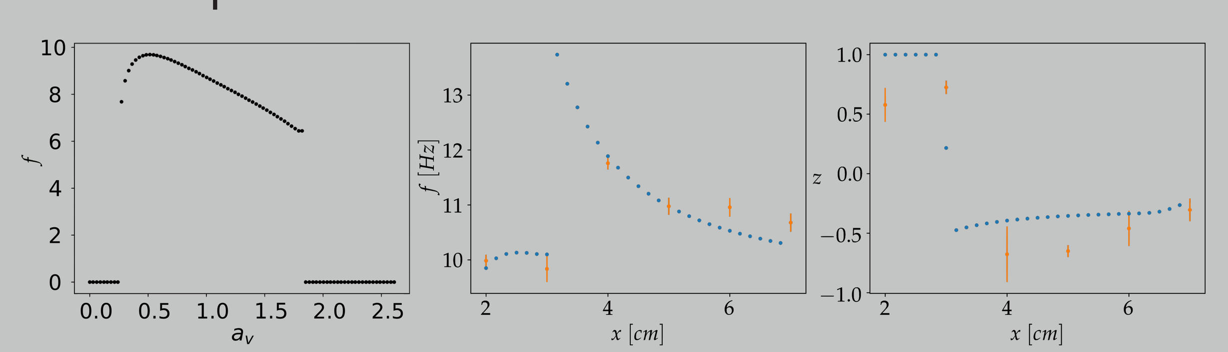
$$\frac{dn_i}{dt} = \omega_2 [k(n_0 - n_i) - N a(n_0) n_i e^{-\frac{E}{RT_i}}] + \left|\frac{dT_j}{dt}\right| \frac{\gamma}{x^2}$$

supply flow of oxygen by convection

oxygen consumption by burning

coupling by air movement

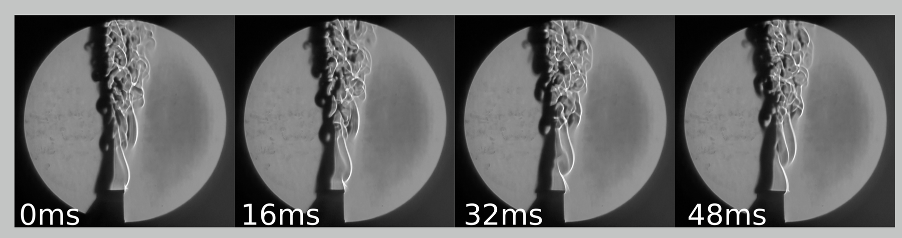
- Model predictions



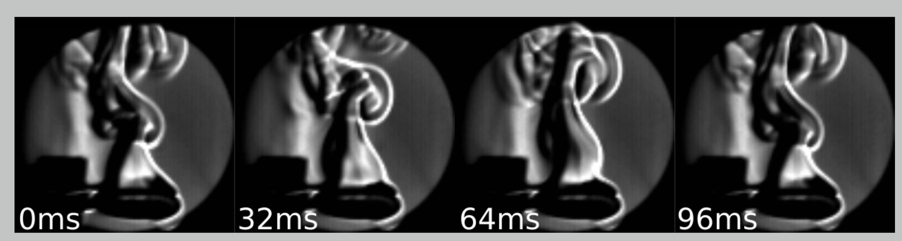

- Gergely, A., Sándor, B., Paizs, C., Tötös, R., & Néda, Z. (2020). Flickering candle flames and their collective behavior. In Scientific Reports (Vol. 10, Issue 1).

## Similar oscillation in buoyancy-driven flows

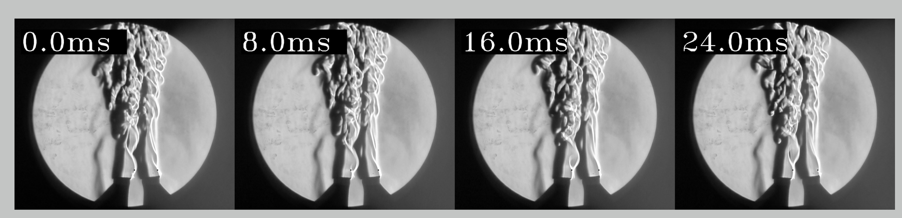
- Oscillation of a helium column flowing into air




- Oscillation of a heated air column

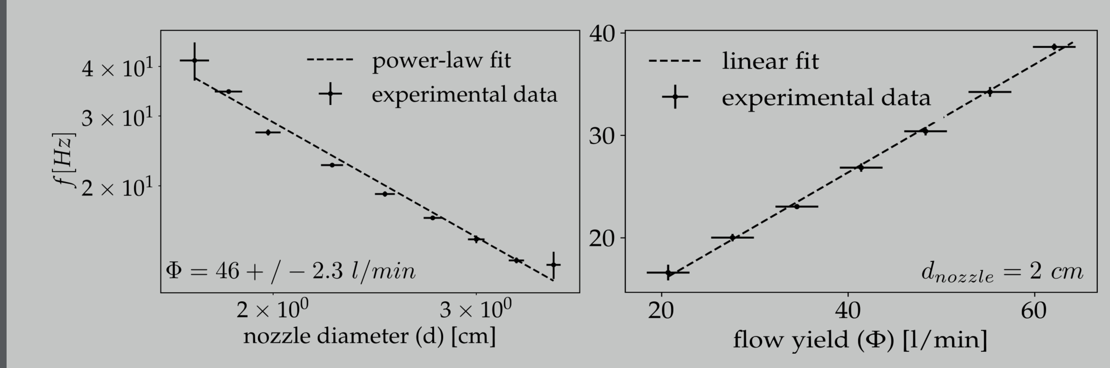



- Helium columns synchronized oscillation

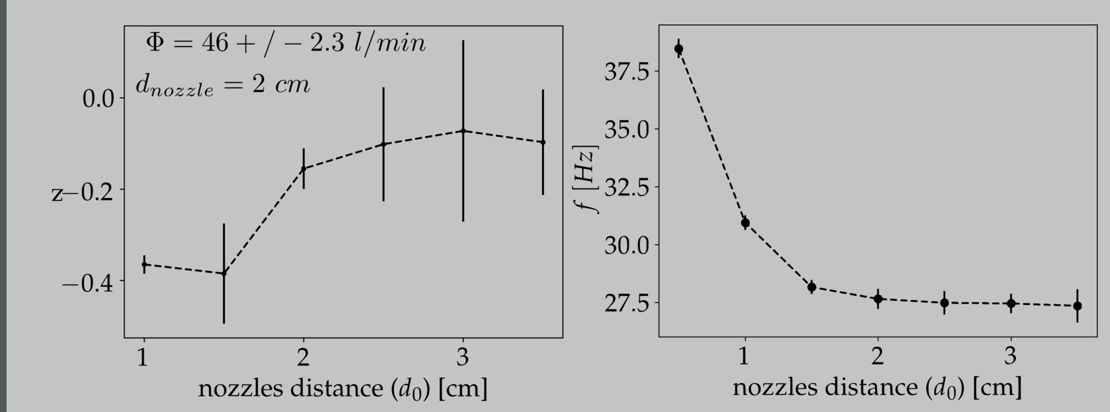



## Results

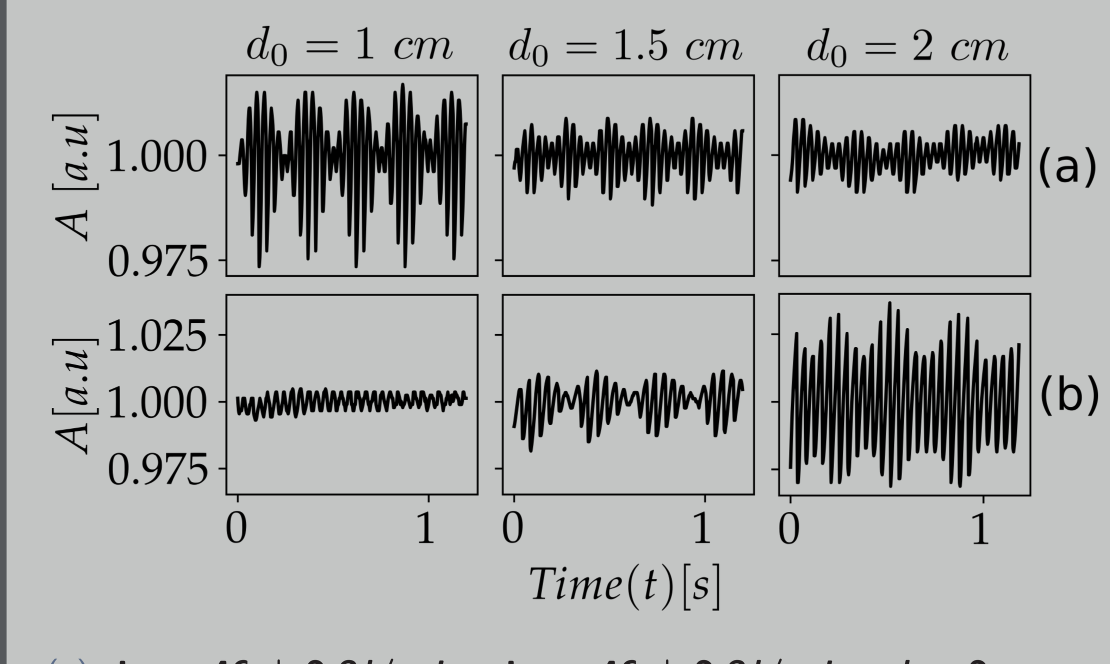
- Effect of flow yield and nozzle diameter on the oscillation frequency of the *He* column




- Collective oscillation

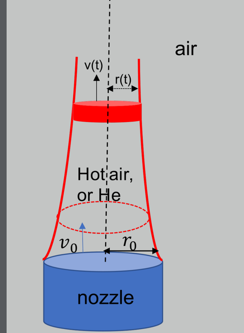



- A beating-like phenomenon for interacting helium columns with slightly different oscillation frequencies, similar behavior is known for diffusion flames




(a) $\Phi_1 = 46 \pm 2.3 l/min,\ \Phi_2 = 46 \pm 2.3 l/min,\ d = 2\ cm$
(b) $\Phi_1 = \Phi_2 = 46 \pm 2.3 l/min,\ d_1 = 2.25\ cm,\ d_1 = 2.5\ cm$

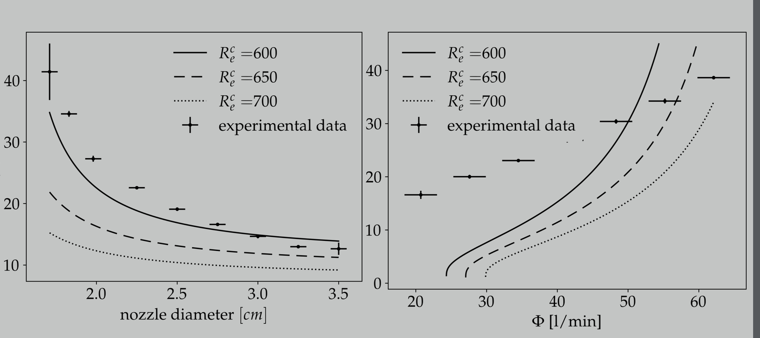
- Simple analytically treatable toymodel




Assumptions:
- the fluid element is accelerated by the buoyancy force
- when the Reynolds number ($R_e(t) = \frac{2 \cdot v(t) \cdot r(t)}{\nu}$) exceeds a specific value the flow becomes unstable
- the oscillation period is the time necessary for an outflowing fluid element to reach the critical Reynolds number ($R_e^c$)

- Modell predictions for no-slip boundary conditions

$$f = \frac{g \cdot (\rho_{Air} - \rho_{He}) \cdot v_0 \cdot r_0^2}{\left(\left(\frac{R_e^c \cdot \mu}{2}\right)^2 - (v_0 \cdot r_0)^2\right) \cdot \rho_{He}}$$



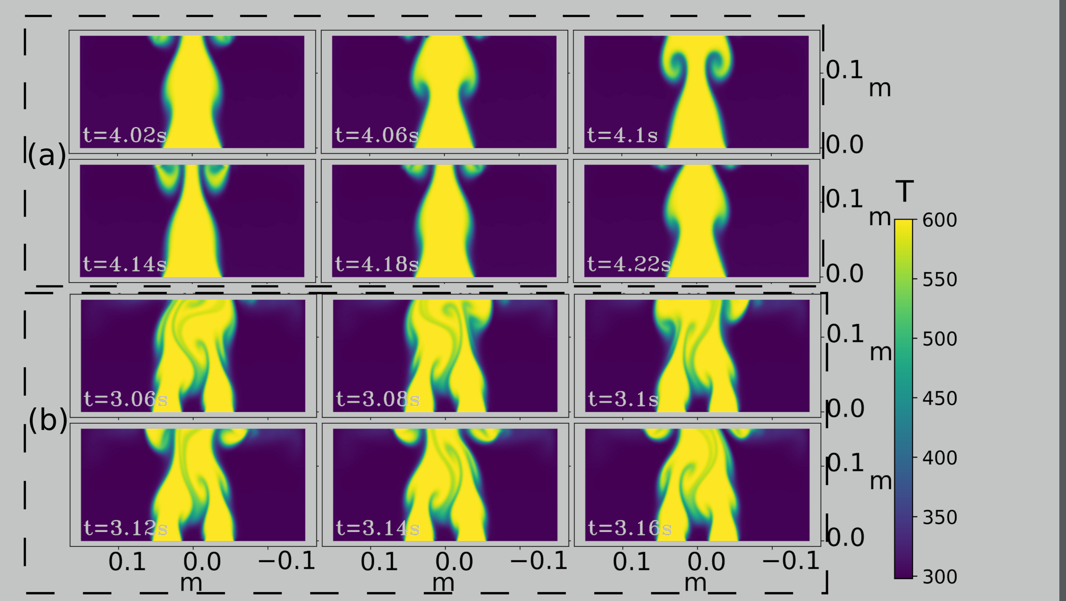

- Gergely, A., Paizs, Cs.,Tötös, R., & Néda, Z. (2021). Oscillations and collective behavior in convective flows. In Physics of Fluids (Vol. 33, Issue 12, p. 124104)

## 2D numerical approach

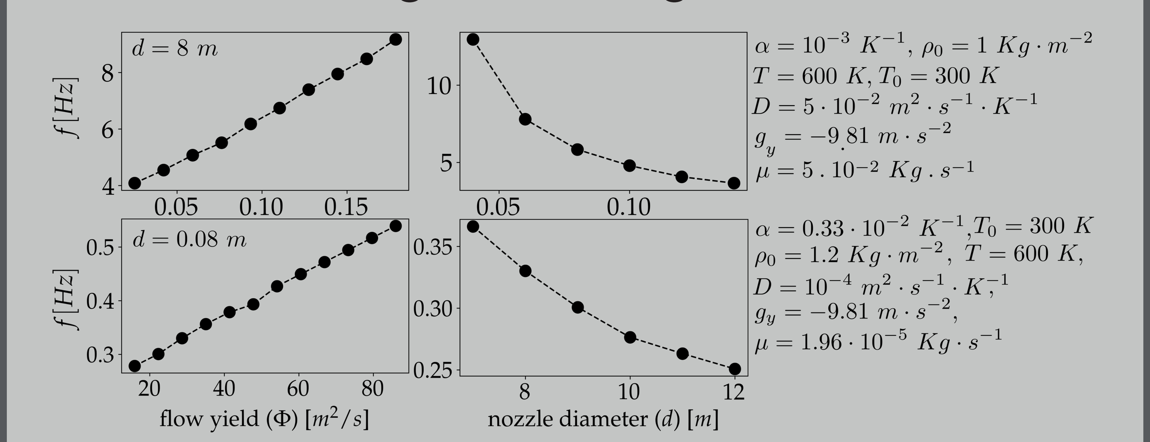
- In order to explain the experimental results, we considered 2D heated fluid columns. To describe the flow we used the Navier-Stokes equation and the following transport for the temperature

$$\rho \cdot \frac{\partial \vec{u}}{\partial t} + \rho \cdot (\vec{u} \cdot \nabla) \cdot \vec{u} = -\nabla p + \vec{g} \cdot \rho + \mu \cdot \Delta \vec{u}$$
$$\nabla \vec{u} = 0$$
$$\rho = \frac{\rho_0}{1 + (T - T_0) \cdot \alpha}$$
$$\frac{\partial T}{\partial t} = D \cdot \Delta T - (\vec{u} \cdot \nabla) \cdot T$$

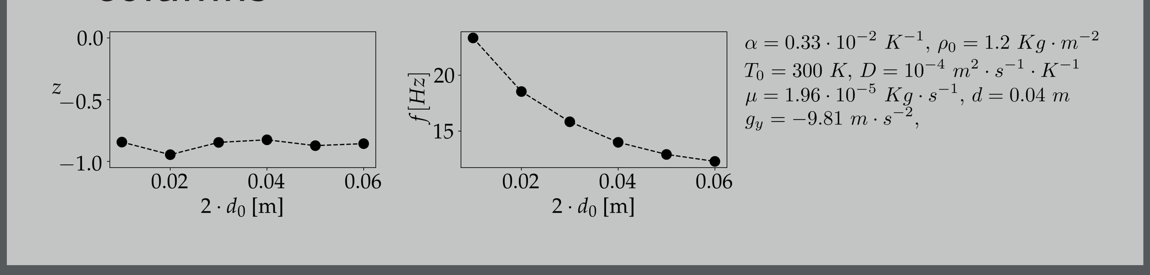
- Using the above model and appropriate boundary conditions, we obtained similar oscillation (a) and collective behavior (b) as for helium




- Results for single oscillating fluid column




- Results for the collective oscillation of fluid columns




## Conclusions

- Striking similarities with synchronization of candle-flames
- Similar dependency as a function of nozzle diameter with the one observed as for candle numbers
- Collective behavior in form of beating and counter-phase synchronization
- The power of simple toy-models! Unexpectedly good approximation offered by our toy-model
- Good reproduction of oscillation trends with a 2D fluid dynamics simulation
- Good reproduction of the collective behavior with the computational model
- INTERESTINGLY, the only difference to the candle flame sync problem is that we do not find inphase synchronised phases

- Preprint: Gergely, A., Néda, Z. ,Computational fluid dynamics approach for understanding oscillating and interacting convective flows

## Acknowledgment

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