Problem 15

FIRE-SHOT-FIRE

Problem statement

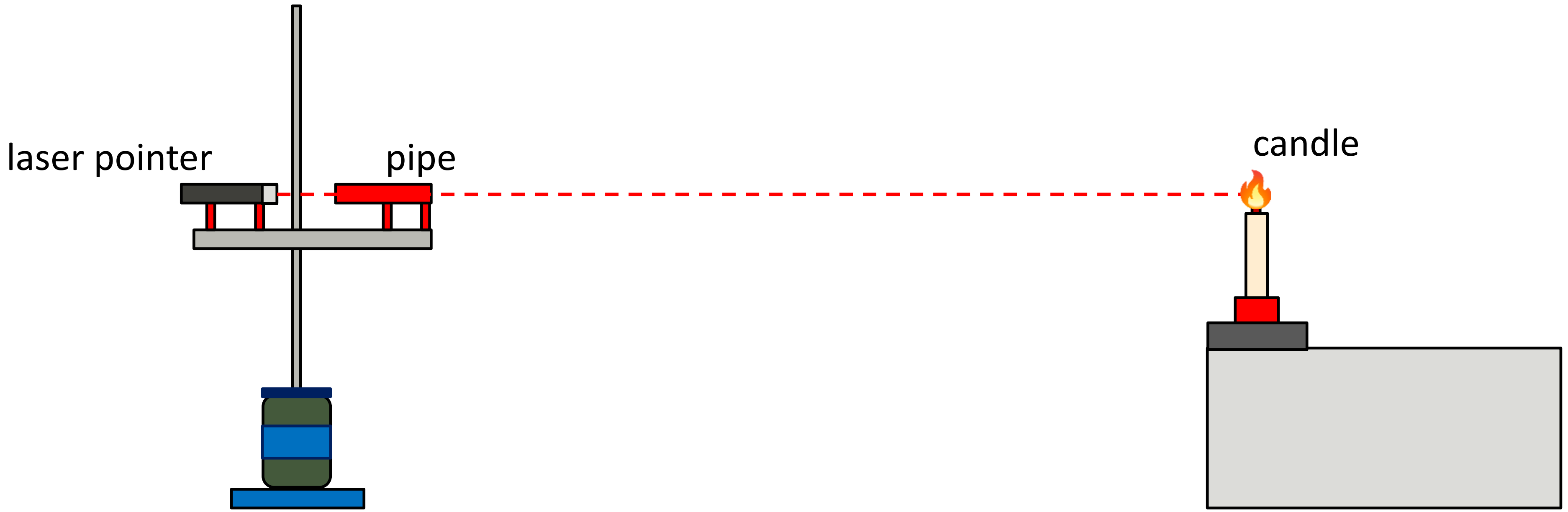
It is well known that a directed air blast can suppress fire.

Usually such air blasts are directed by guiding the air through a pipe.

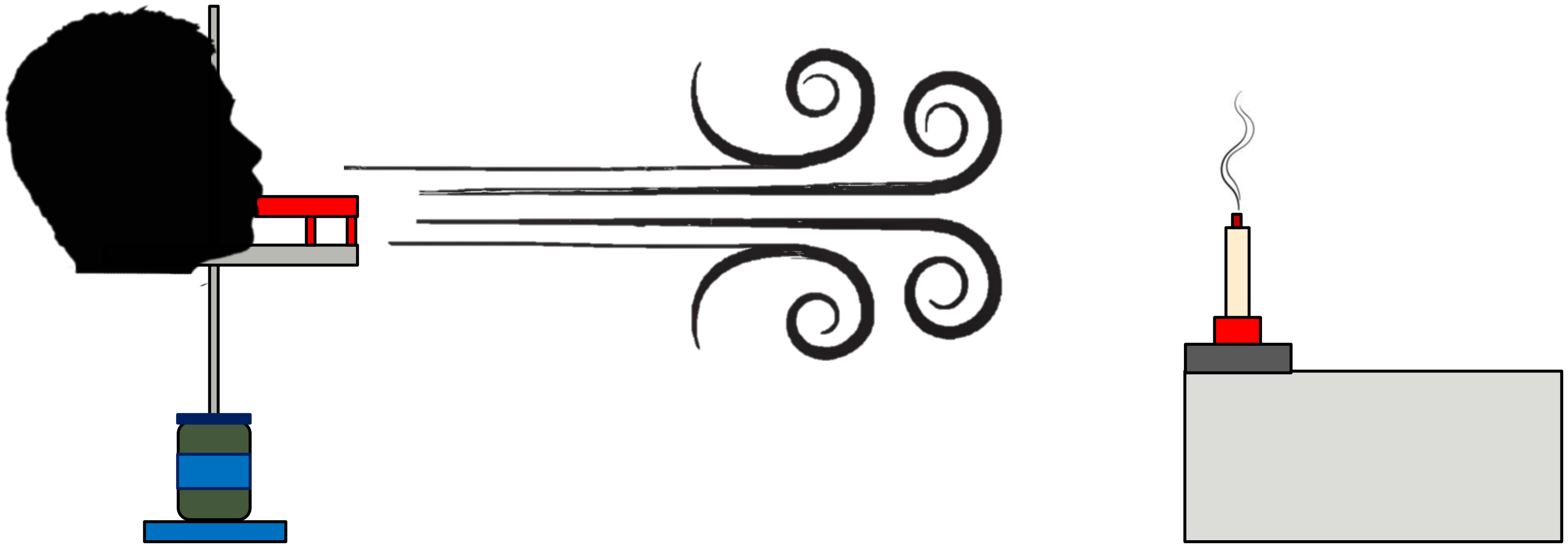
Determine the parameters of the pipe to extinguish fire from maximum distance (measured from the end of the tube closest to the fire) using only your breath.

Perform experiments on the fire from a candle.

Experimental setup

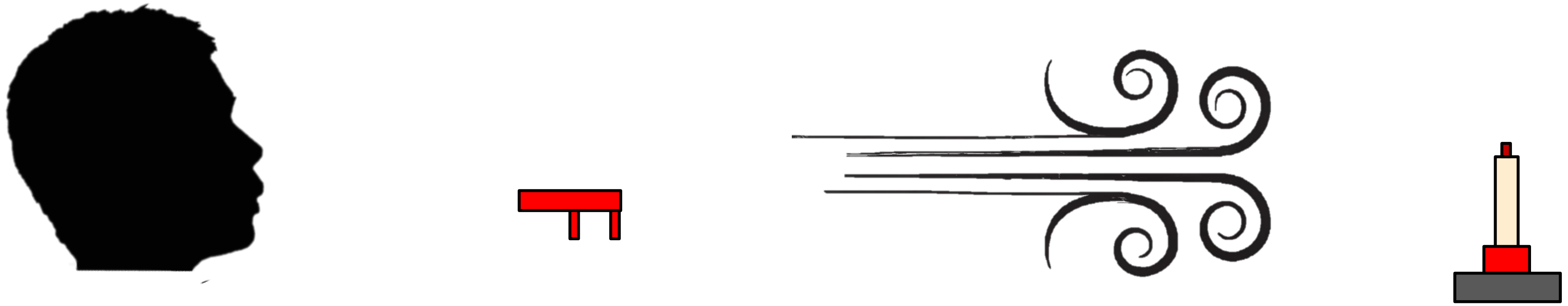


Experimental setup



Experimental setup

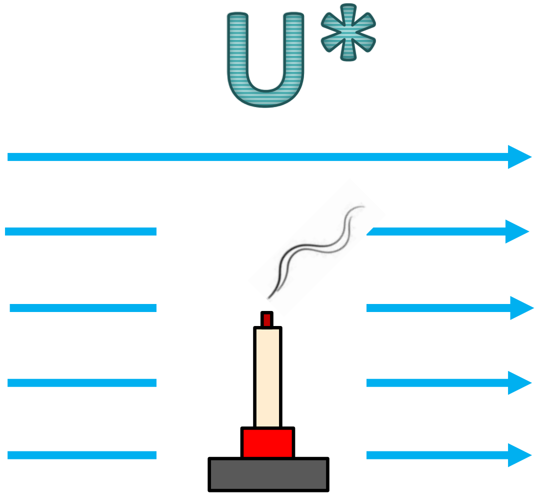
Decomposition of the process

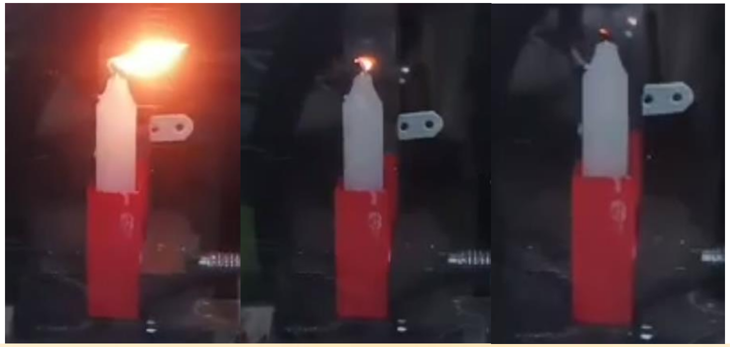


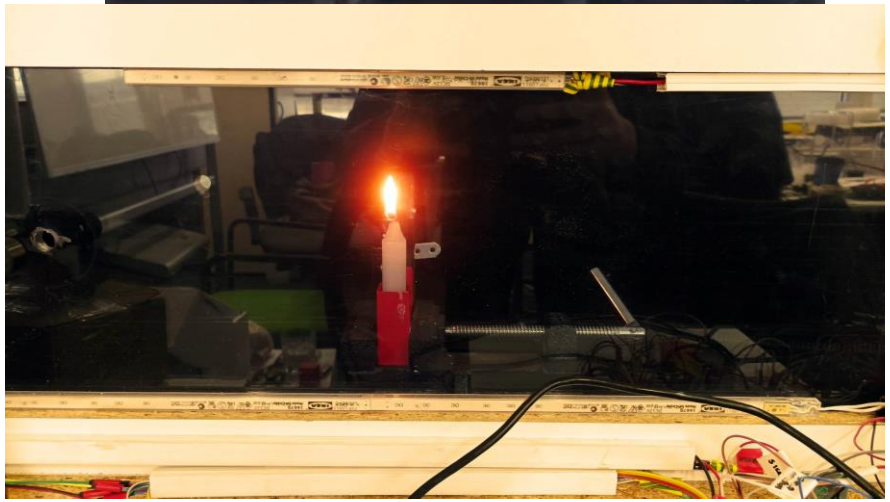
The human | The pipe | The air jet | The candle

The candle

The candle will get snuffed out in air with moving at some critical velocity U*







Wind tunnel

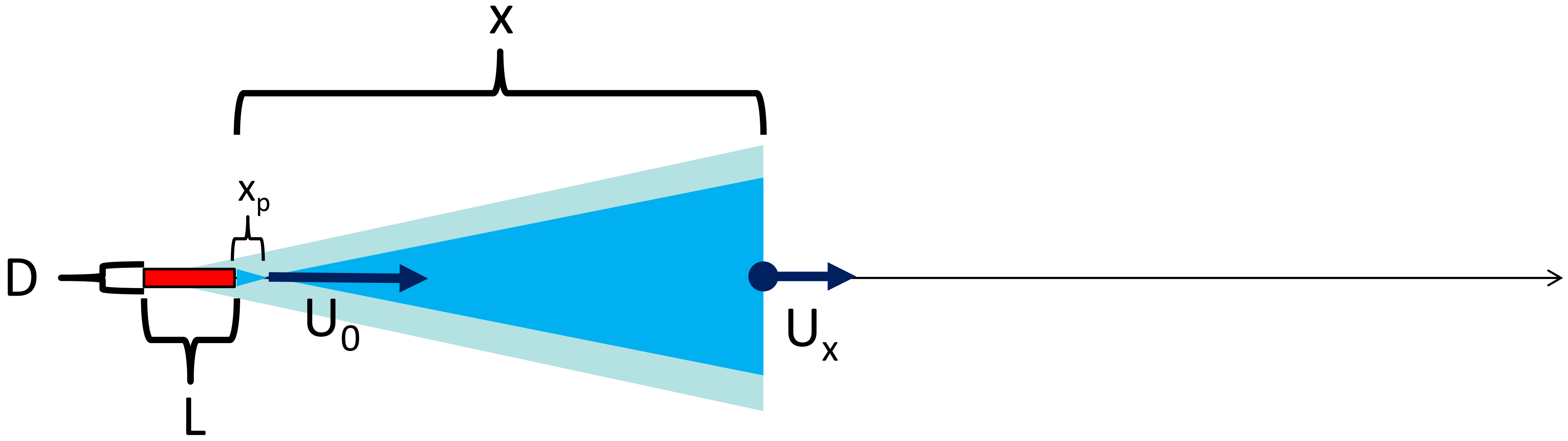
The air jet

K is a dimensionless constant, dependent on the angle of the cone

Centreline velocity decay measurements in low-velocity axisymmetric jets

TOR G. MALMSTRÖM, ALLAN T. KIRKPATRICK, BRIAN CHRISTENSEN and KEVIN D. KNAPPMILLER, 1997

$$\frac{U_x}{U_o} = K\frac{D}{x - x_p} \approx \mathrm{K}\frac{D}{x} \rightarrow x^* = \mathrm{D}K\frac{U_0}{U^*}$$



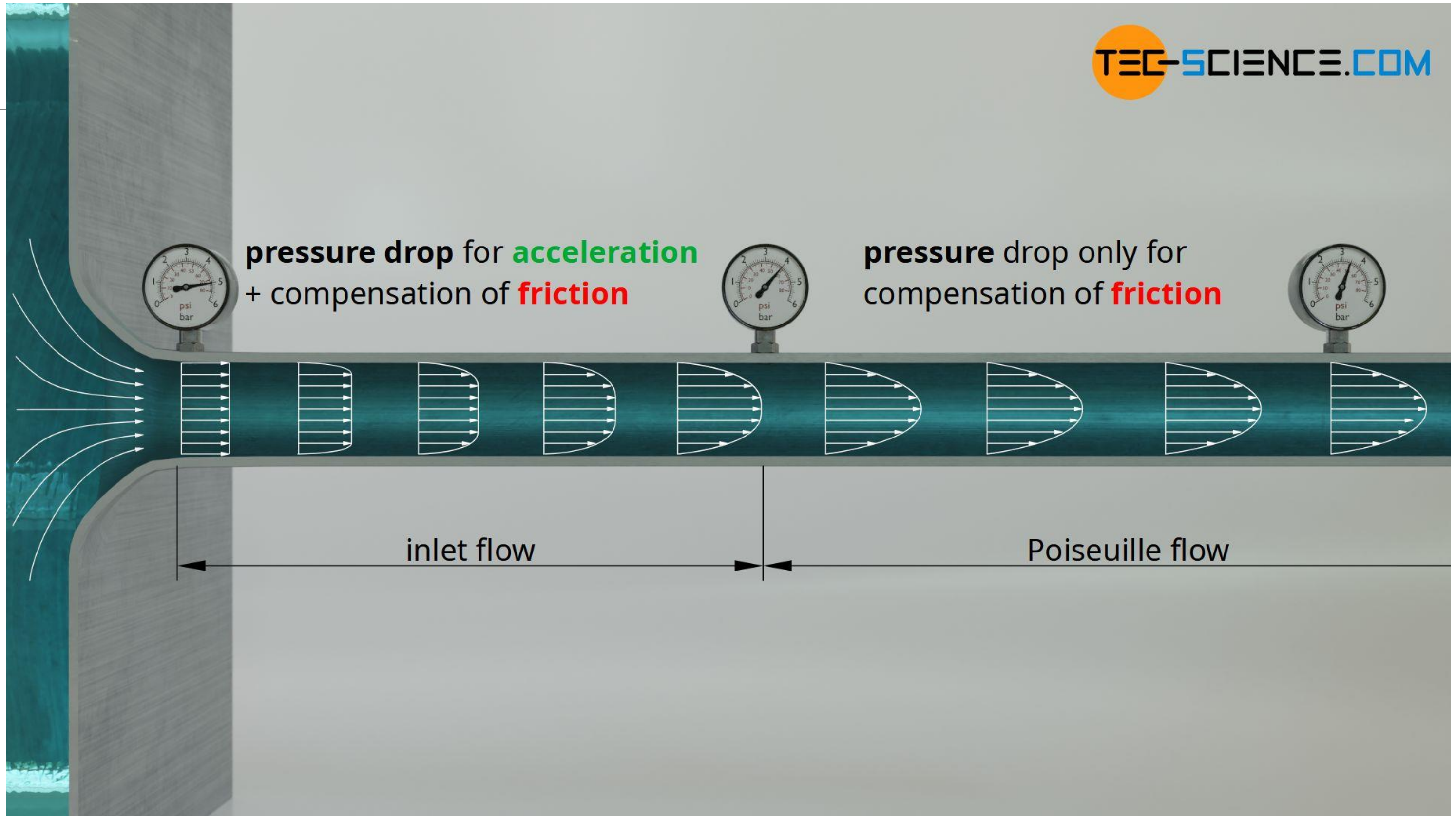
$$\Phi = U_0 R^2/2$$

The pipe

$$\Delta p = \frac{8\eta L}{\pi R^4}\Phi$$

$$U_0 \sim R^2$$

$$x^* \sim R^3$$



Hagen-Poiseuille law

https://www.tec-science.com/mechanics/gases-and-liquids/hagen-poiseuille-equation-for-pipe-flows-with-friction/
https://www.tec-science.com/mechanics/gases-and-liquids/energetic-analysis-of-the-hagen-poiseuille-law

$$\Phi = U_0 R^2/2$$

The pipe

$$\Delta p = \frac{8\eta L}{\pi R^4}\Phi + \rho\left(\frac{\phi}{\pi R^2}\right)^2$$

$$U_0 \sim \sqrt{1 + R^{-4}} - R^{-2}$$

$$\Delta p = \frac{8\eta L}{\pi R^4}\Phi$$

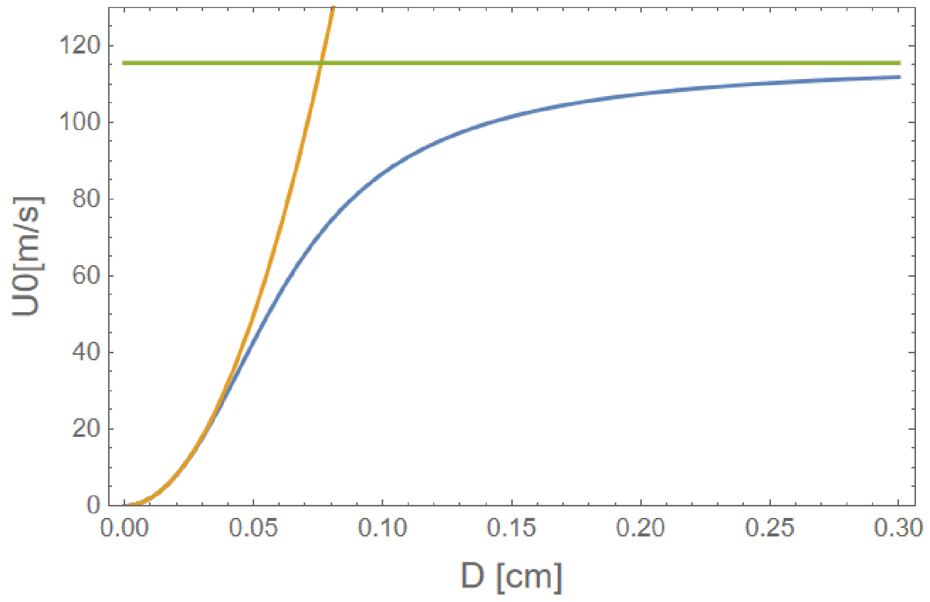
$$U_0 \sim R^2$$

$$x^* \sim R^3$$

$$\Delta p = \frac{\rho}{4}U_0^2$$

$$U_0 \sim R^0$$

$$x^* \sim R$$



Hagen-Poiseuille law

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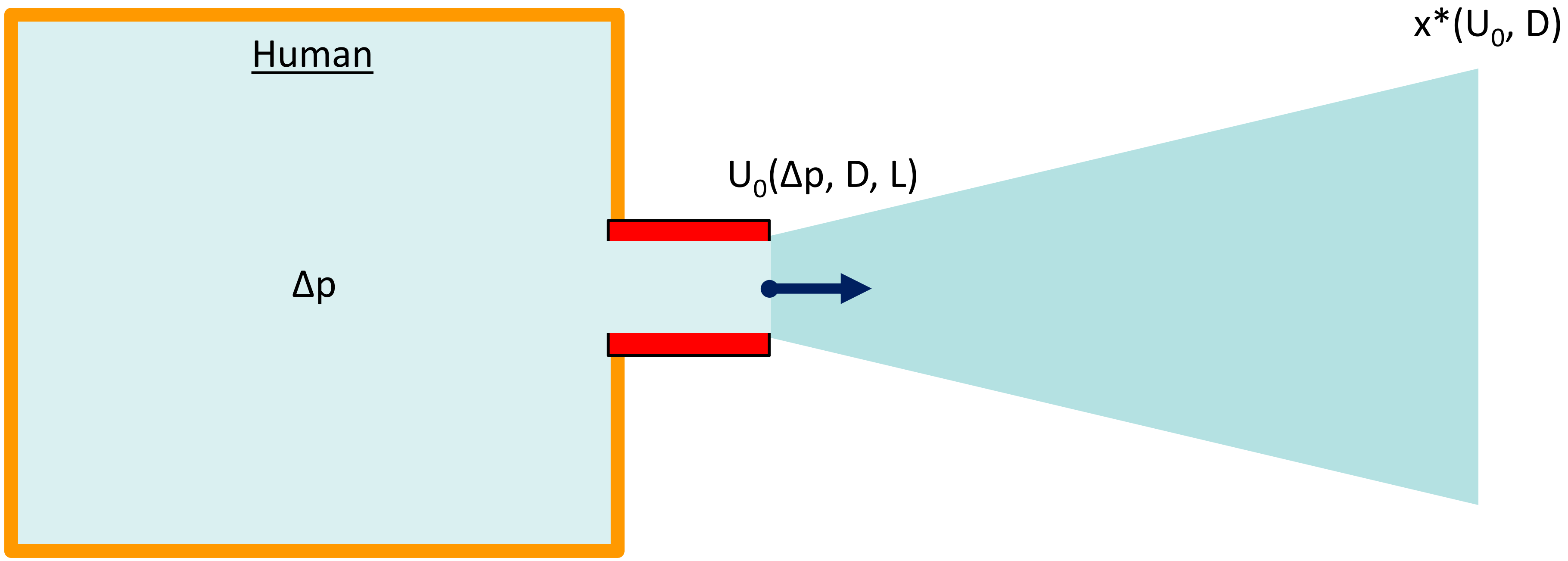
https://www.tec-science.com/mechanics/gases-and-liquids/energetic-analysis-of-the-hagen-poiseuille-law

The human

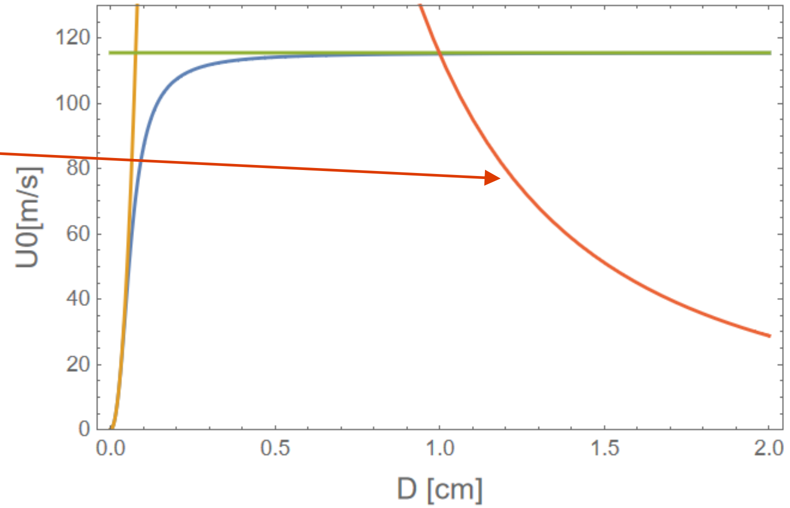


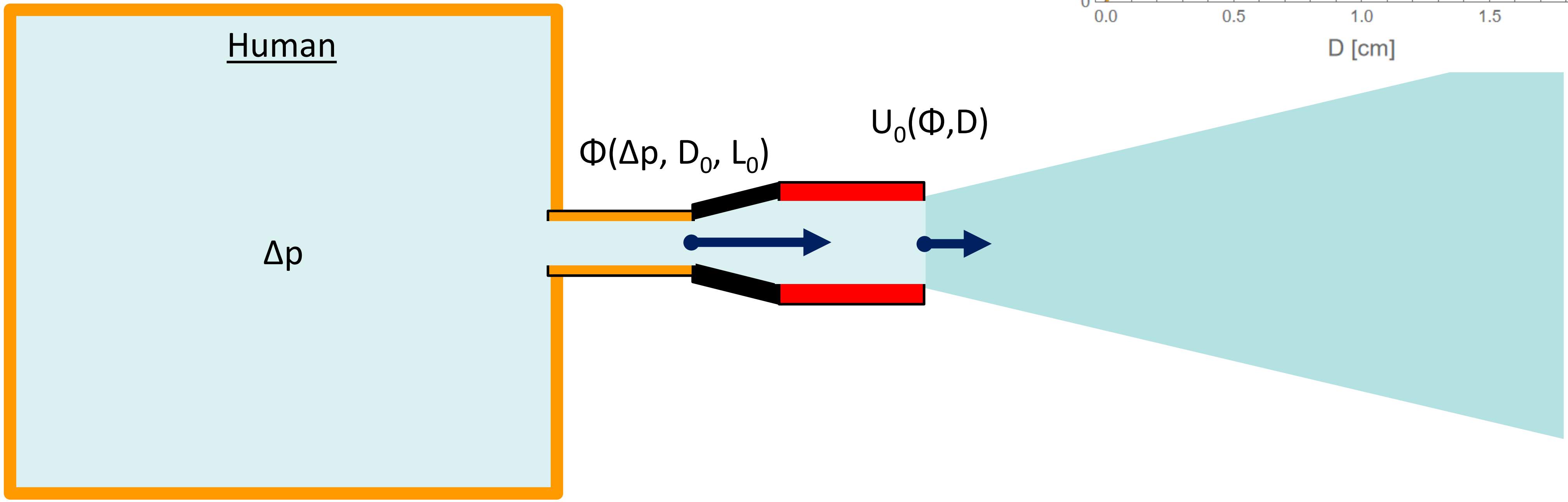
The human

$$\Phi \rightarrow const$$

$$U_0 \sim 1/R^2$$

$$x^* \sim 1/R$$

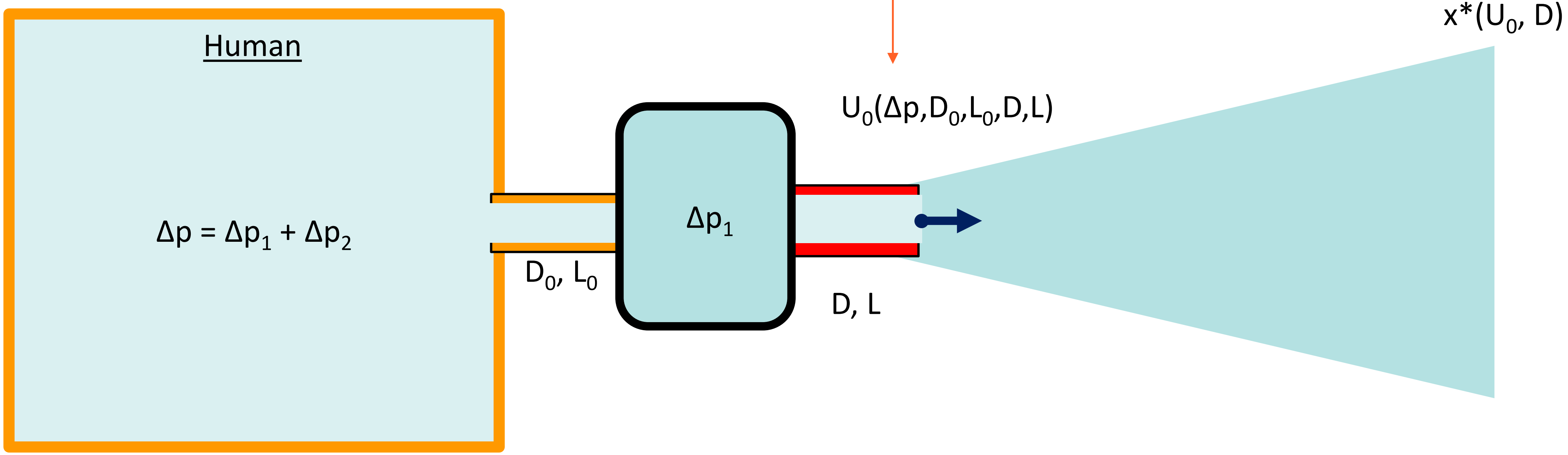




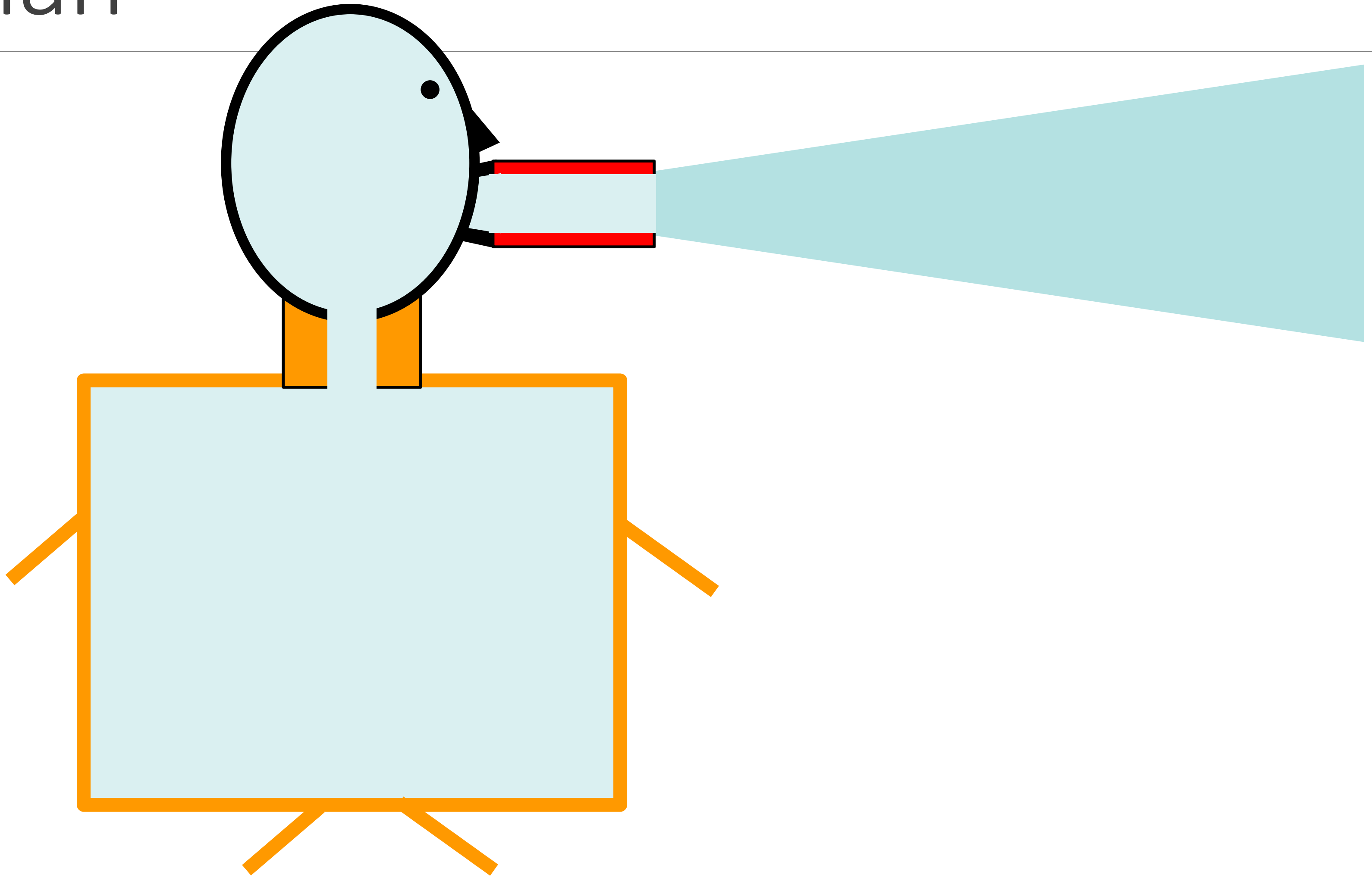
$$\frac{8\eta L_0}{\pi {R_0}^4}\Phi + \rho\left(\frac{\phi}{\pi R_0^2}\right)^2 + \frac{8\eta L}{\pi R^4}\Phi + \rho\left(\frac{\phi}{\pi R^2}\right)^2 = \Delta p$$

The human

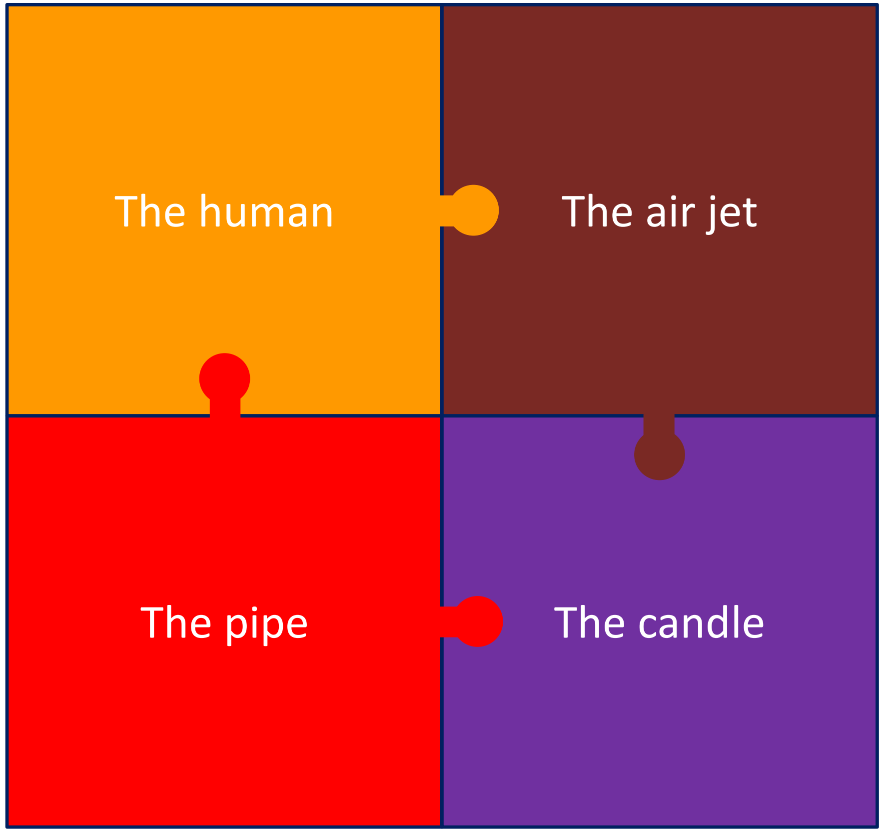
Solve for Φ



The human

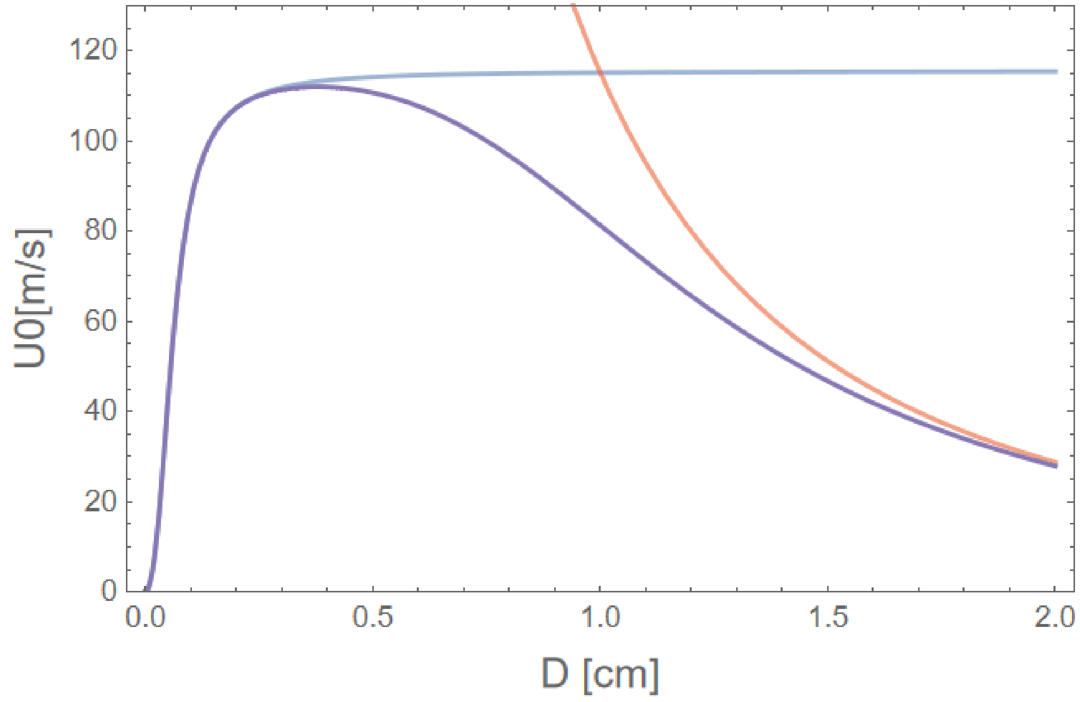


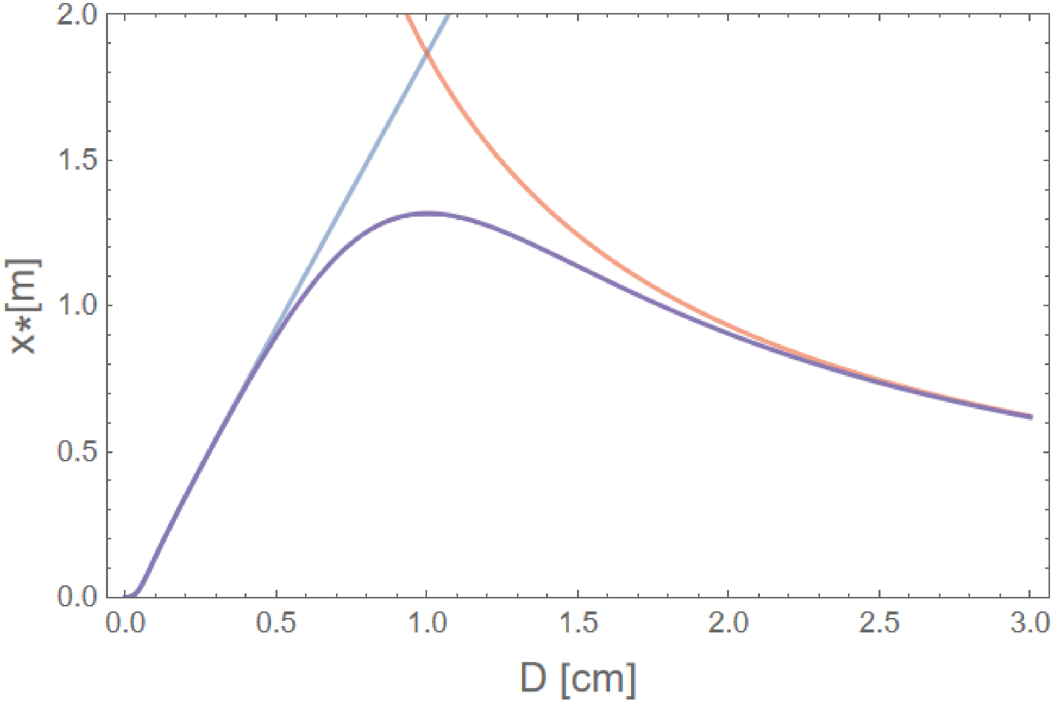
It all comes together



Theoretical results

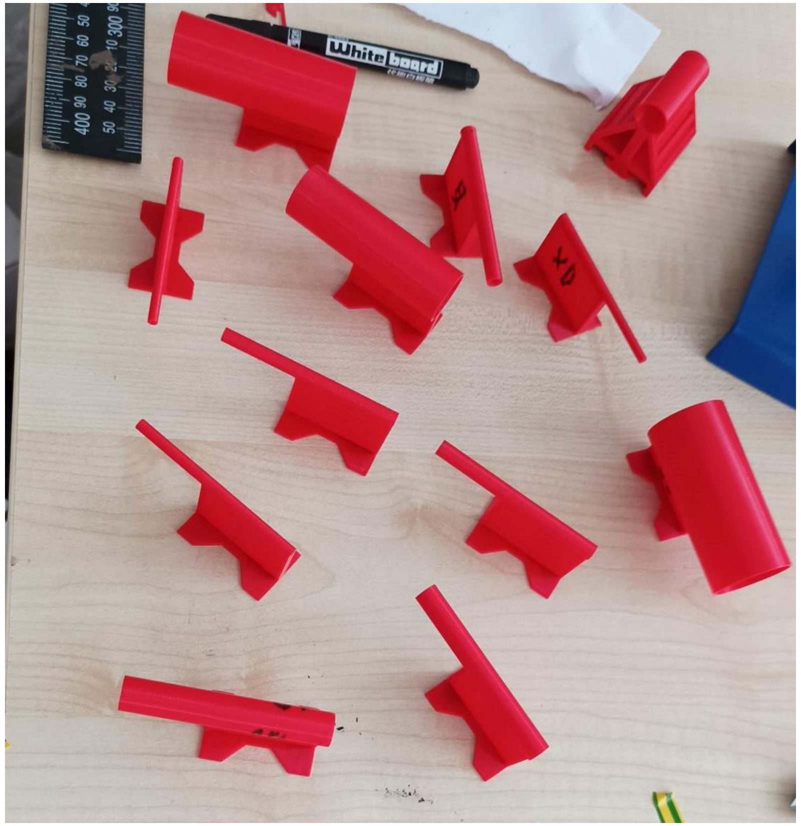
$$x^* = \mathrm{D}K\frac{U_0(r)}{U^*}$$

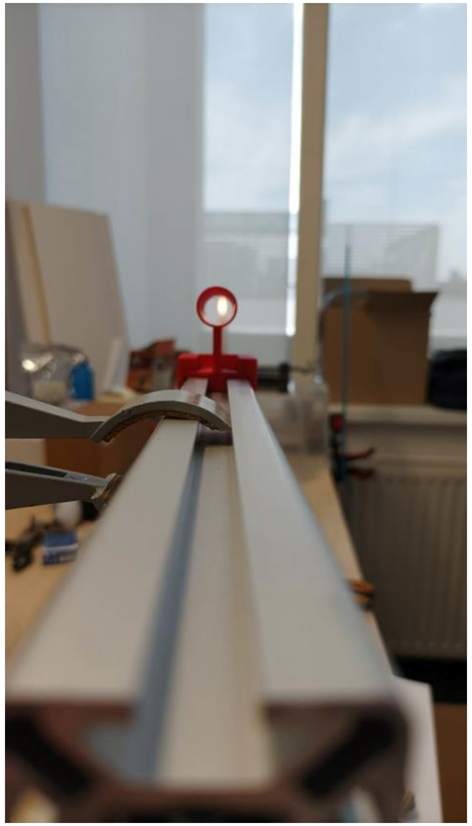


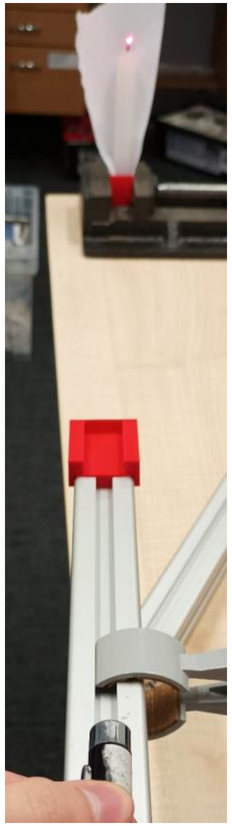


$$\frac{8\eta L_0}{\pi {R_0}^4}\Phi + \rho\left(\frac{\phi}{\pi R_0^2}\right)^2 + \frac{8\eta L}{\pi R^4}\Phi + \rho\left(\frac{\phi}{\pi R^2}\right)^2 = \Delta p$$

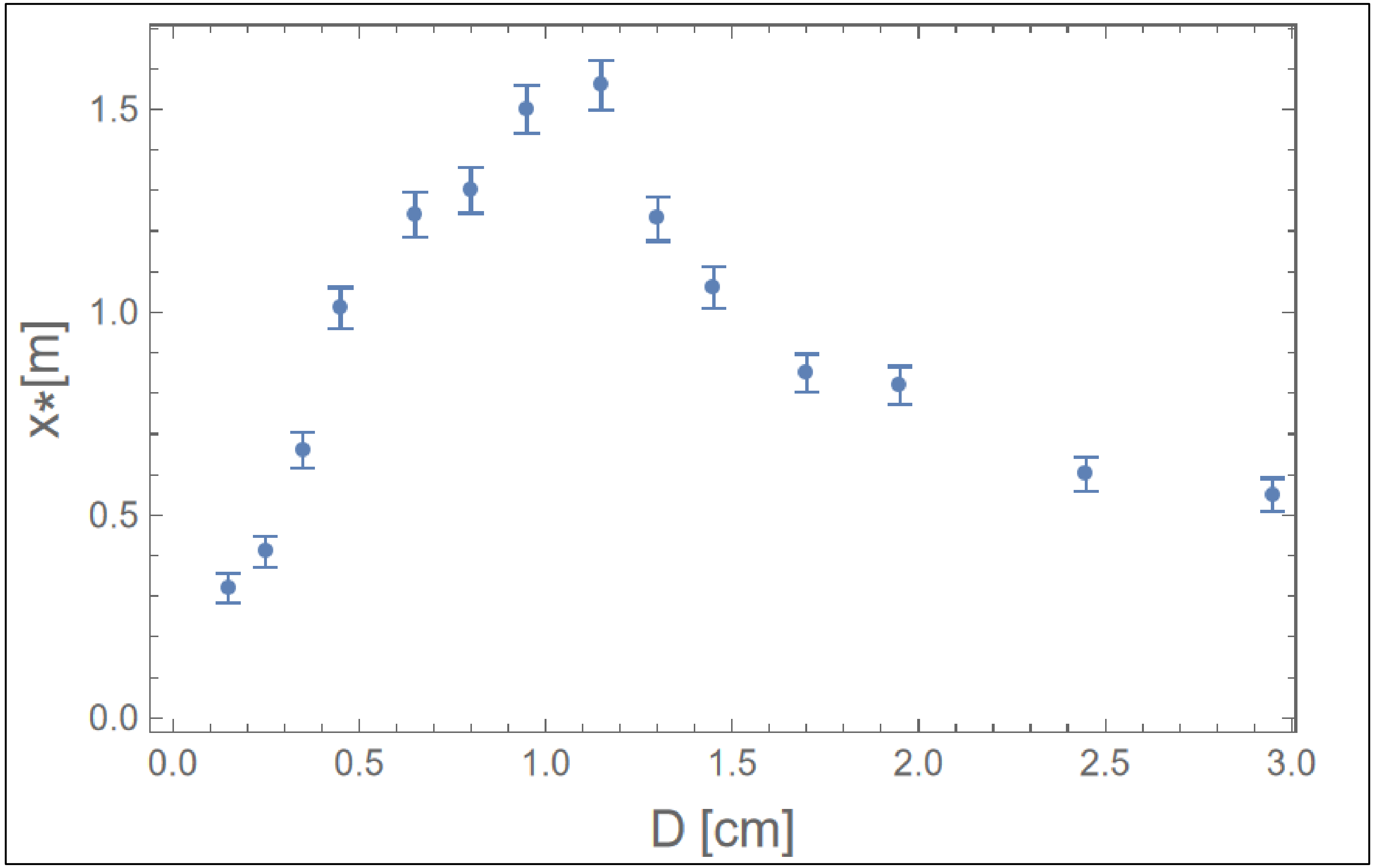
Experimental results



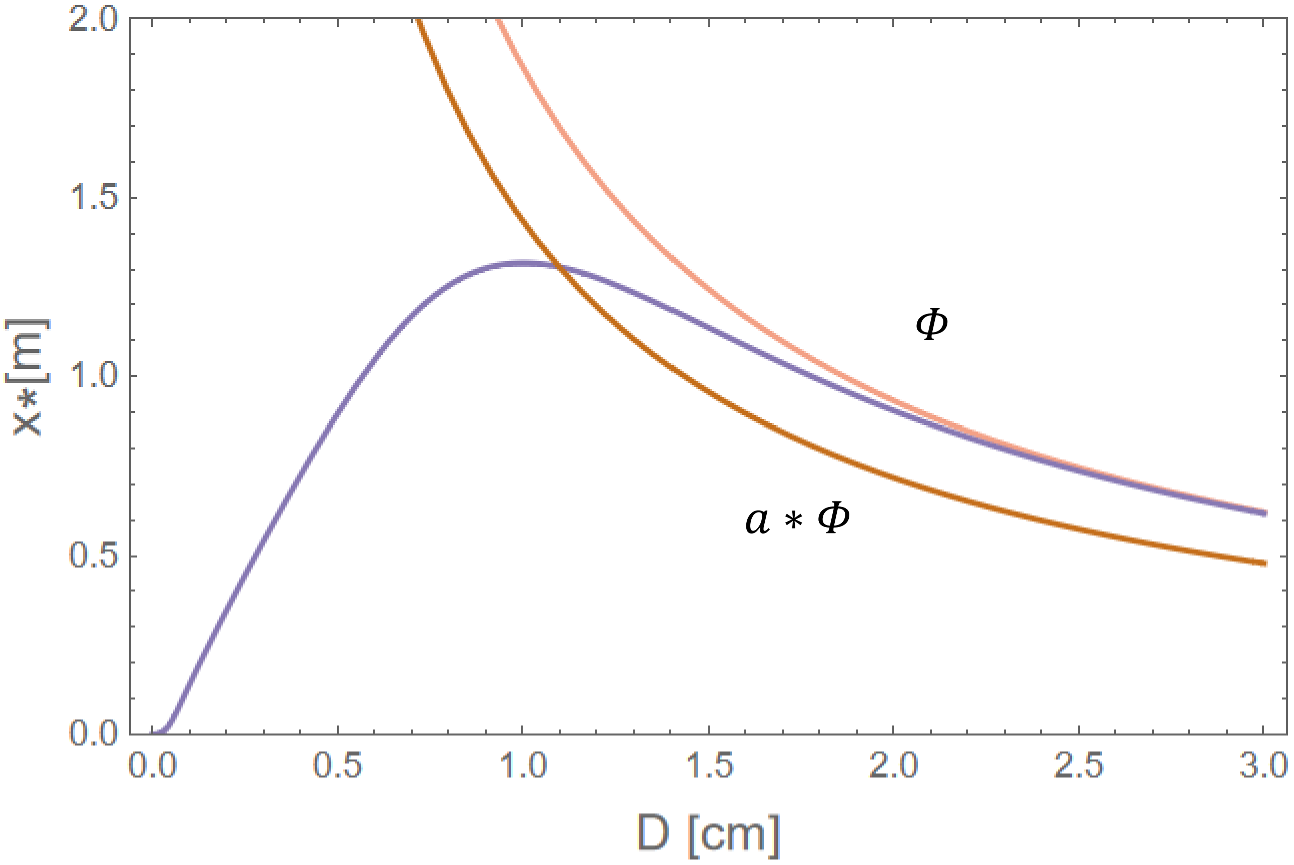




Experimental results



Air blast?



$$\frac{\text{Time it takes to exhale}}{\text{Jet formation time}} \approx a$$

Also, K is not constant for small Re

Finding the right parameters

$L = 7cm$

$\rho = 1.3\ kg/m^3$

$\eta = 1.8*10^{-5}\ Pa*s$

$K \approx 6$

$U^* \approx 3.8\ m/s$

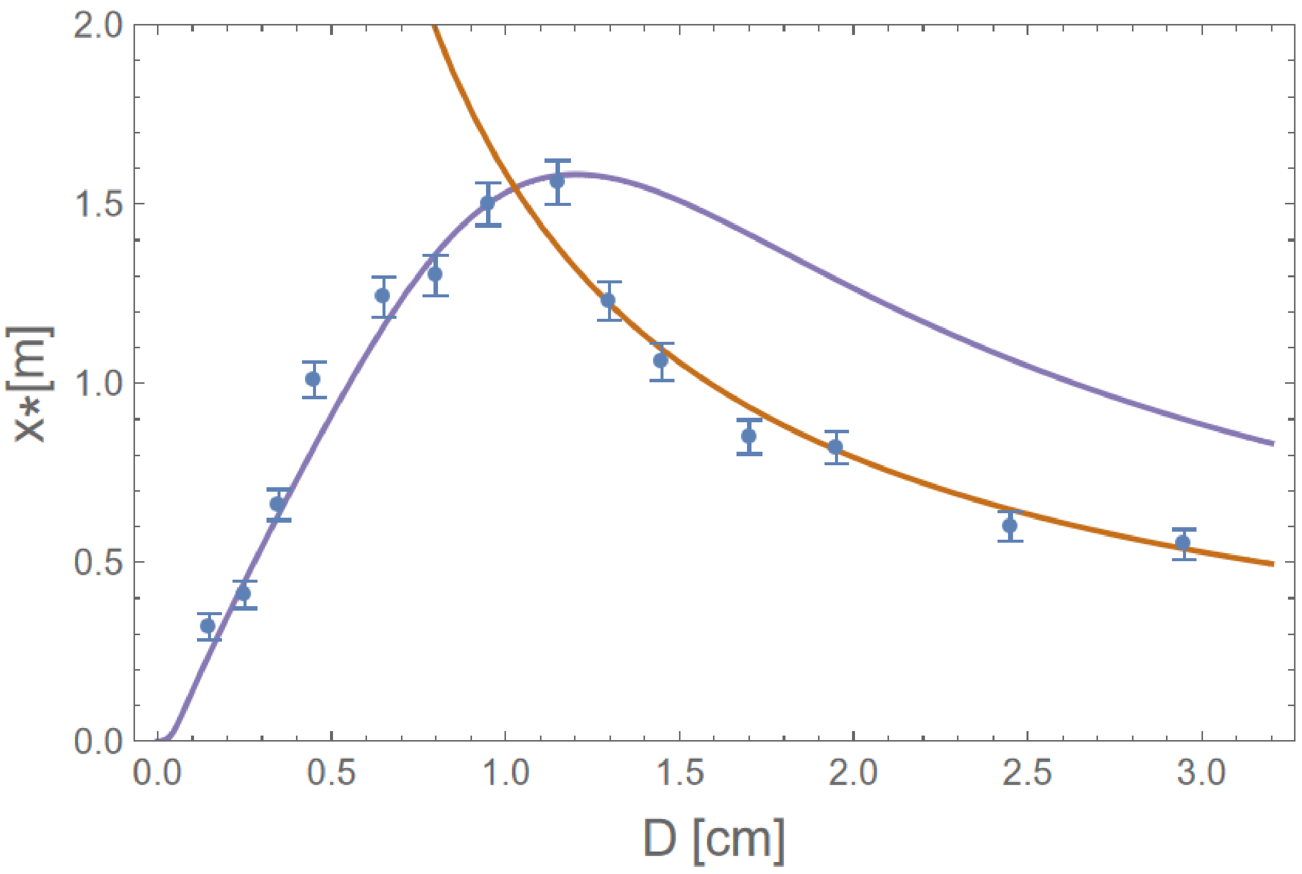
$D_0 = 12\ mm$

$\Delta p = 4kPa$

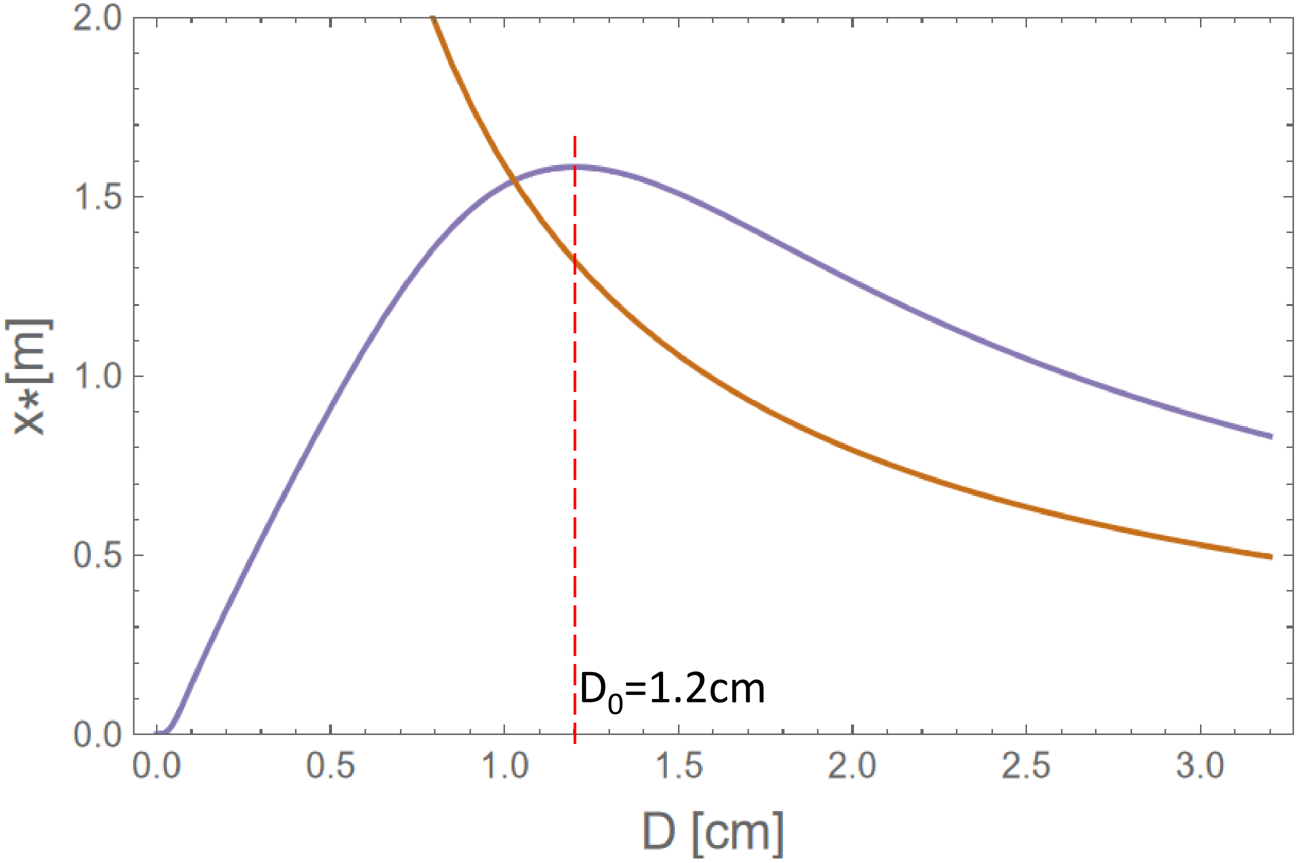
Fitted

$a = \frac{\Phi}{\Phi_{max}} = 0.59$

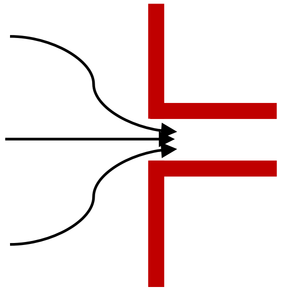
L_0 = ? -> small effect



The optimal pipe

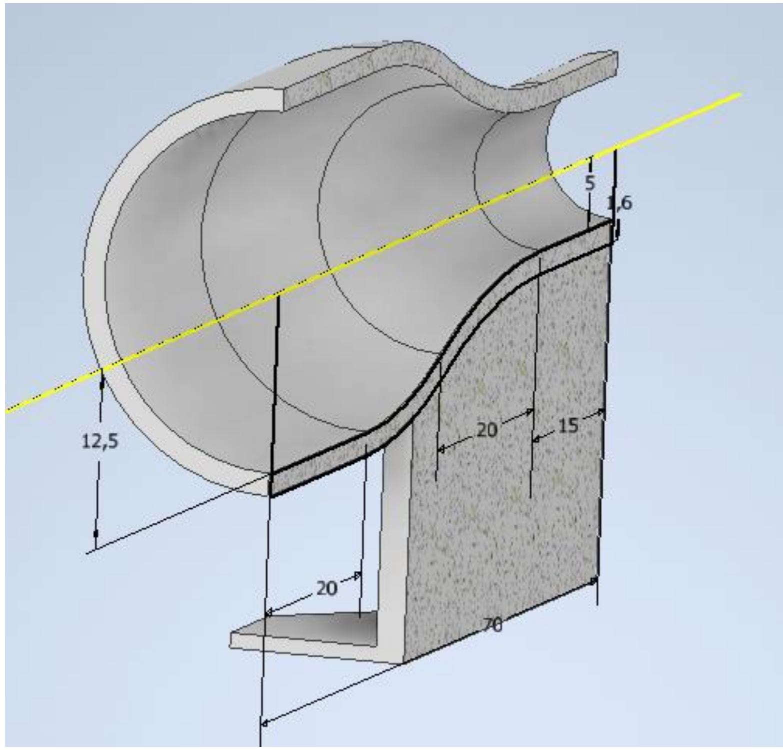


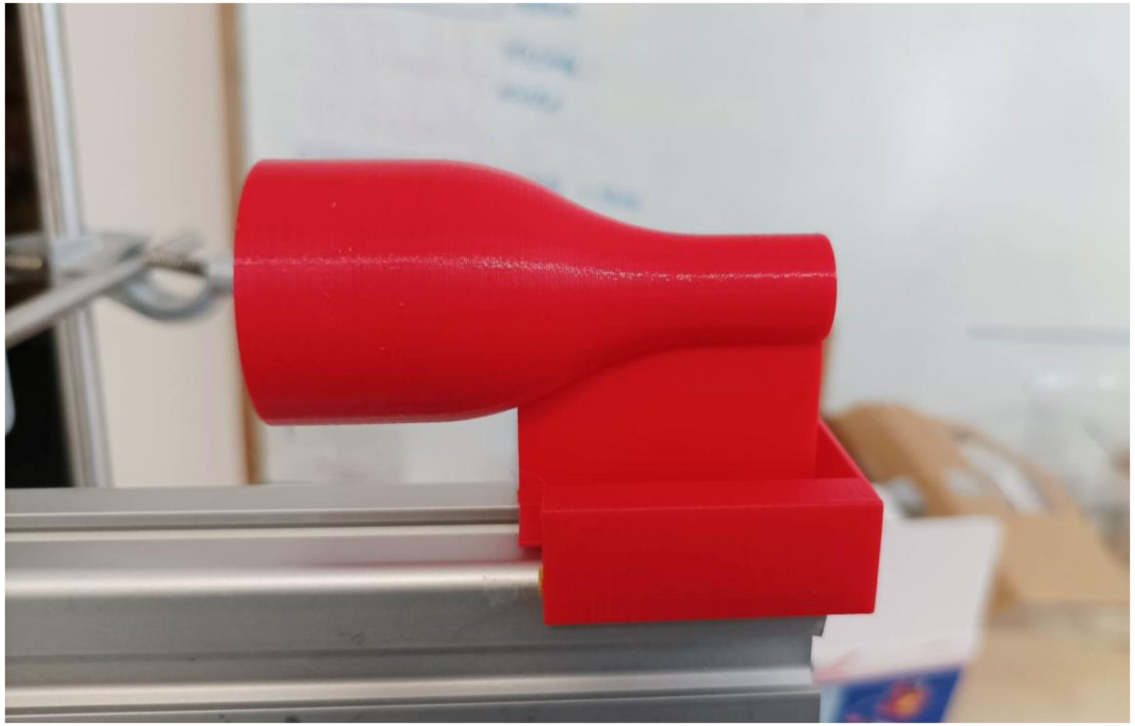
- The optimal D seems to be D_0
- For large D, lung capacity is the limiting factor
- For small and medium D, the main factor is the pressure drop due to sudden narrowing



An even better pipe

From 1.5 m to 1.75 m!



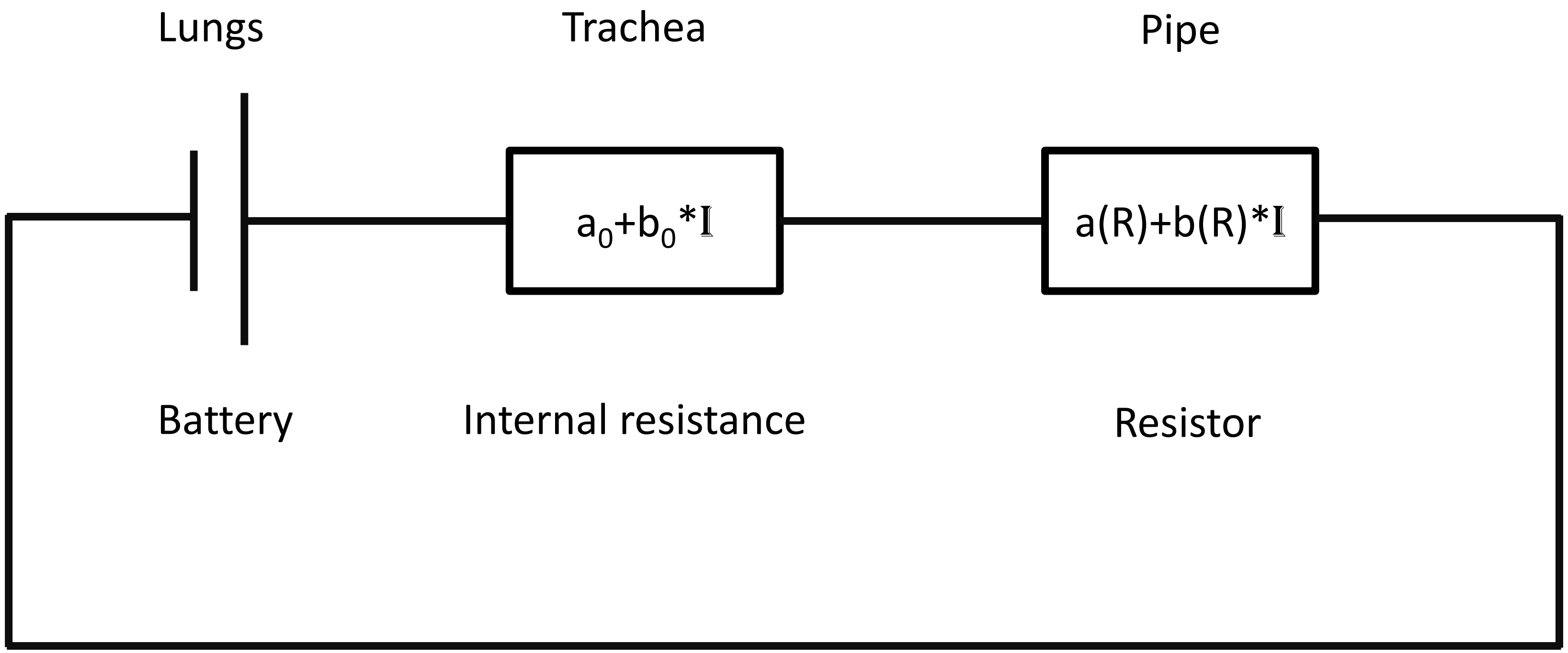


Summary

- We decomposed the problem to 4 stages
- We combined models of these stages to get U_0 and x^*
- We performed experiments and fitted the theoretical results
- We found the optimal diameter D for cylindrical pipe at 1.2 cm

Electric circuit analogy

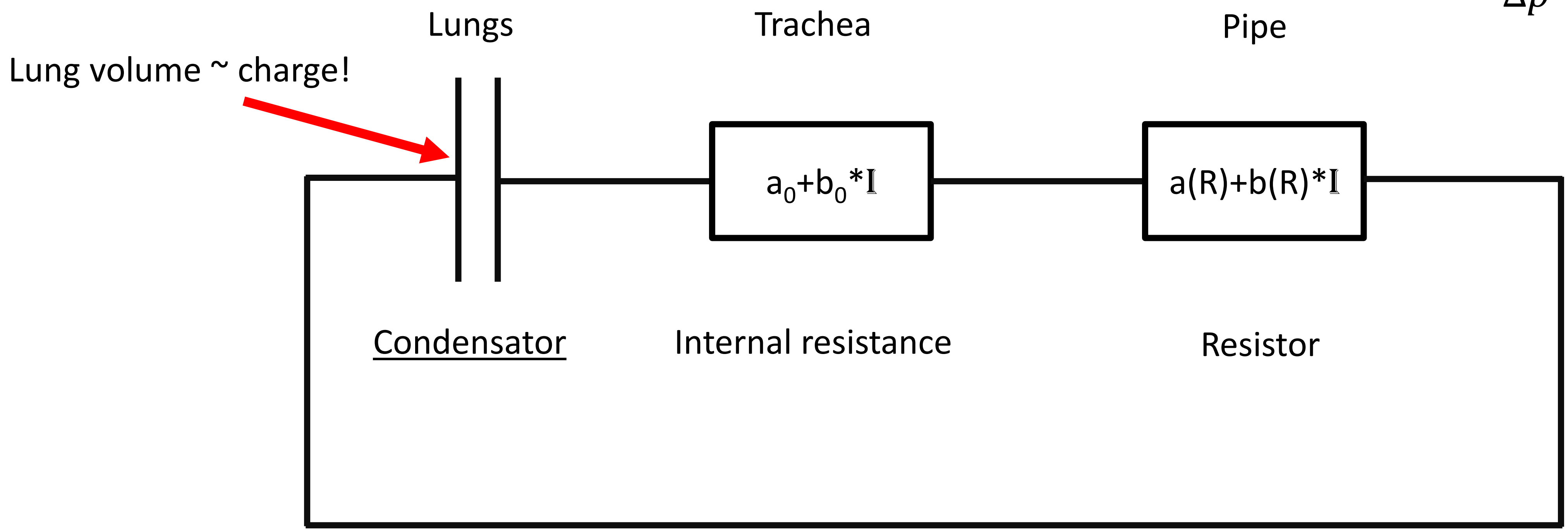
Δp ~ Voltage
Φ ~ Intensity



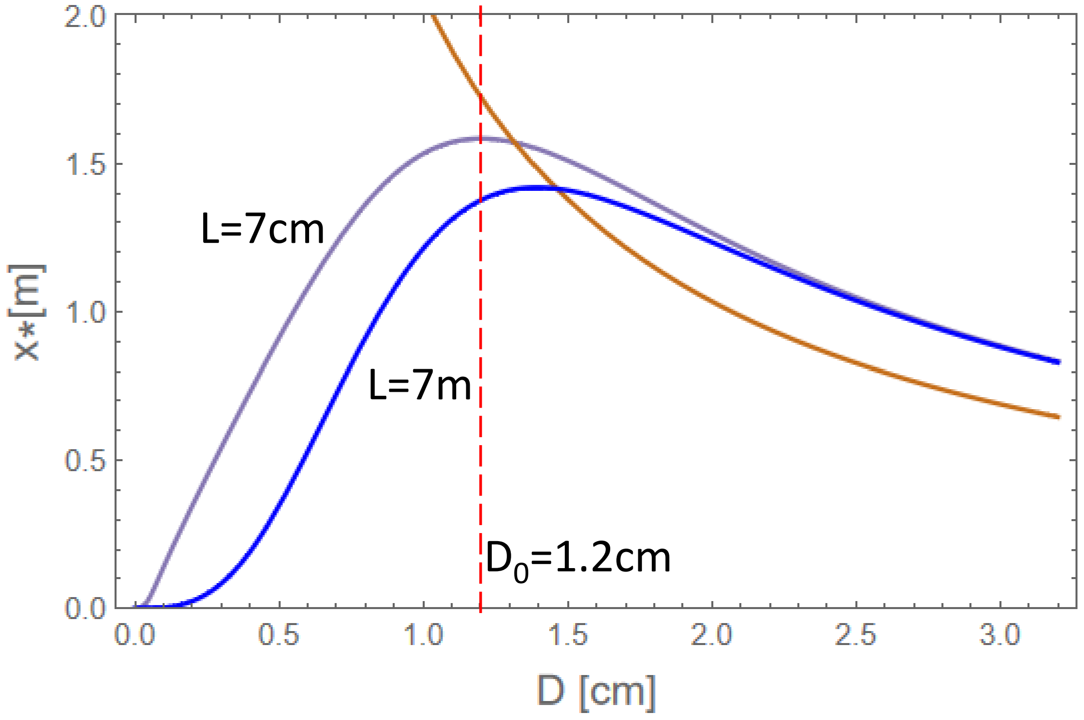
Electric circuit analogy

Δp ~ Voltage
Φ ~ Intensity

$$\Delta p = \frac{8\eta L}{\pi R^4}\Phi + \rho\left(\frac{\phi}{\pi R^2}\right)^2$$



The optimal pipe - Length



- The optimal D seems to be D_0
- Increasing L has some, but small effect
- However, increasing L increases the blowing time required!

Centreline velocity decay measurements in low-velocity axisymmetric jets

TOR G. MALMSTRÖM, ALLAN T. KIRKPATRICK, BRIAN CHRISTENSEN and KEVIN D. KNAPPMILLER, 1997

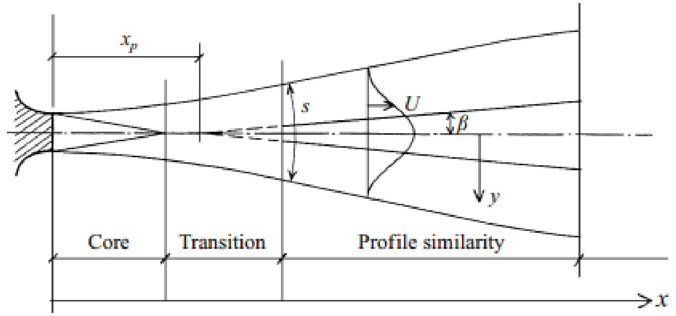


FIGURE 1. Symbols and notation used in the jet model.

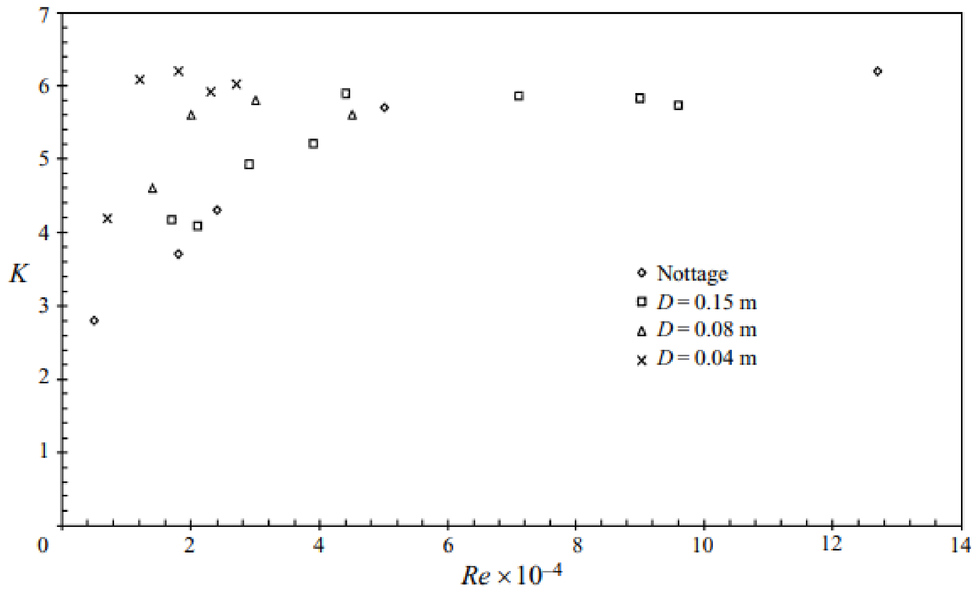


FIGURE 6. Jet centreline velocity decay factor K versus outlet Reynolds number. Based on average outlet velocities. (Nottage's data are for $D = 0.15$ m).

	U_o (m s^{-1})	D (cm)	$Re \times 10^{-4}$	$\tan\beta$	K	x_p/D	K_v
Model jet	—	—	—	0.1	5.9	—	0.34
Wygnanski & Fiedler (1969)	51	2.54	10	0.086	5.7	3	—
Rodi (1975)	101	1.2	8.7	0.086	5.9		
Panchapakesan & Lumley (1993)	27	0.61	1.1	0.096	6.06	−2.5	—
Hussein *et al.* (1994) LDA	56.2	2.54	9.55	0.094	5.8	4.0	0.33
Hussein *et al.* (1994) SHW	56.2	2.54	9.55	0.102	5.9	2.7	0.36

TABLE 1. Comparison of high-velocity axisymmetric jet decay results. The K_v-values have been integrated by us from the reported transverse velocity profiles.

$$K = \frac{(0.5 \ln 2)^{1/2}}{\tan\beta}.$$

Reynolds number

1cm, 100m/s -> Re ~ $10*10^4$

3cm, 10m/s -> Re ~ $3*10^4$

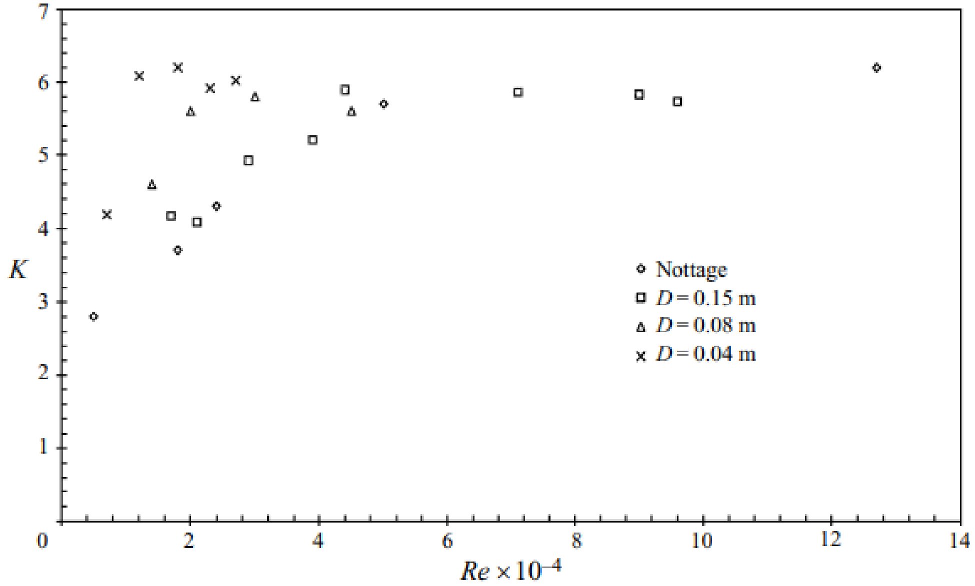
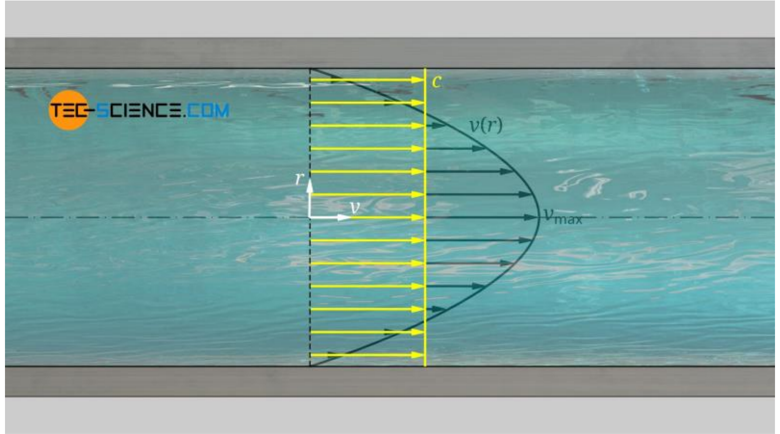


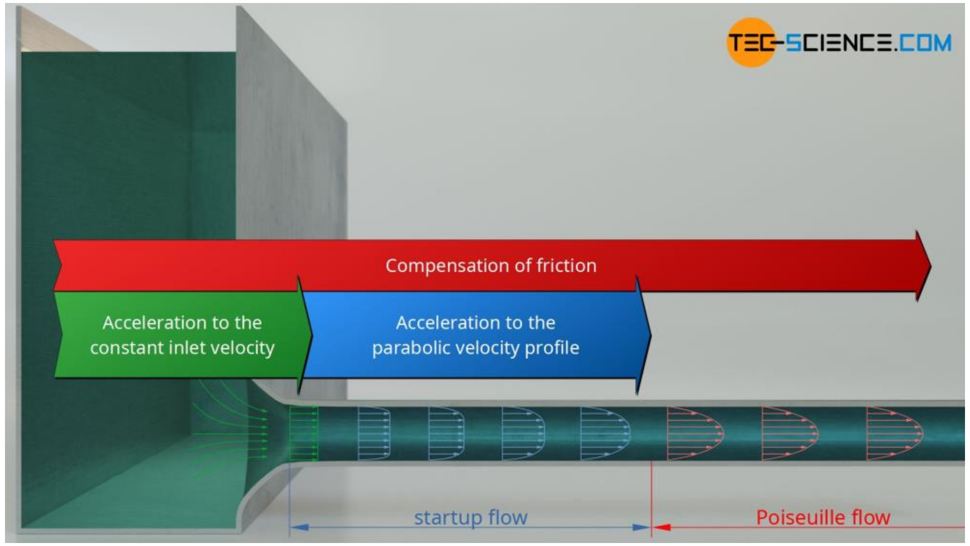
FIGURE 6. Jet centreline velocity decay factor K versus outlet Reynolds number. Based on average outlet velocities. (Nottage's data are for D = 0.15 m).

Hagen-Poiseuille

$$\boxed{\Delta p_l = \frac{8\eta \cdot \Delta L}{R^2} \cdot c}$$

$$\boxed{c = \frac{1}{2} \cdot v_{\max}}$$





$$\boxed{\frac{\Delta L}{D} > \frac{Re}{48}}$$

$$\boxed{\Delta p = \frac{8\eta \cdot L}{R^2} \cdot c + \rho c^2}$$

The ratio of length to radius of a pipe should be greater than one forty-eighth of the Reynolds number for the Hagen-Poiseuille law to be valid!

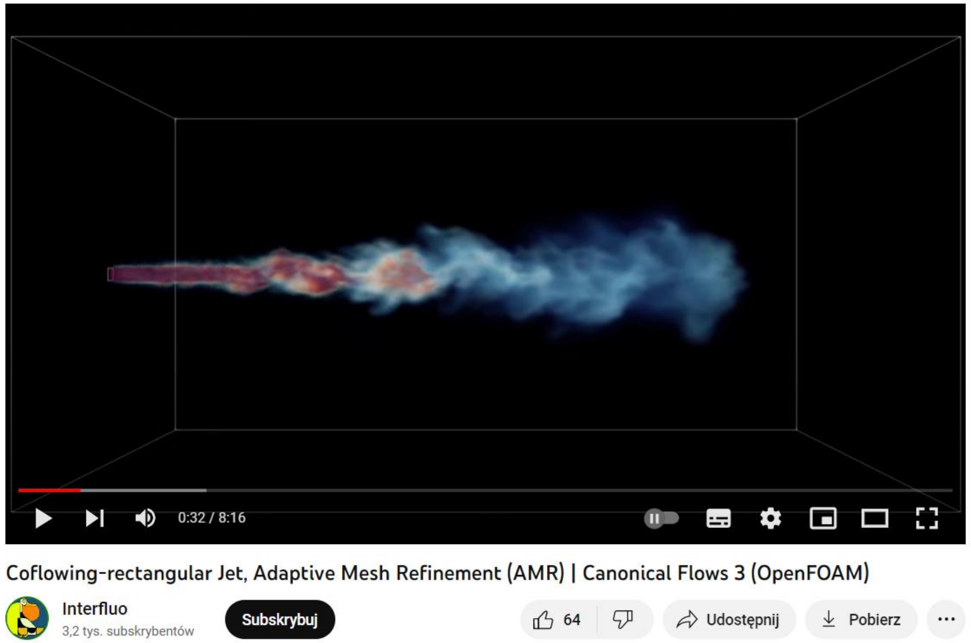
Hagen-Poiseuille law

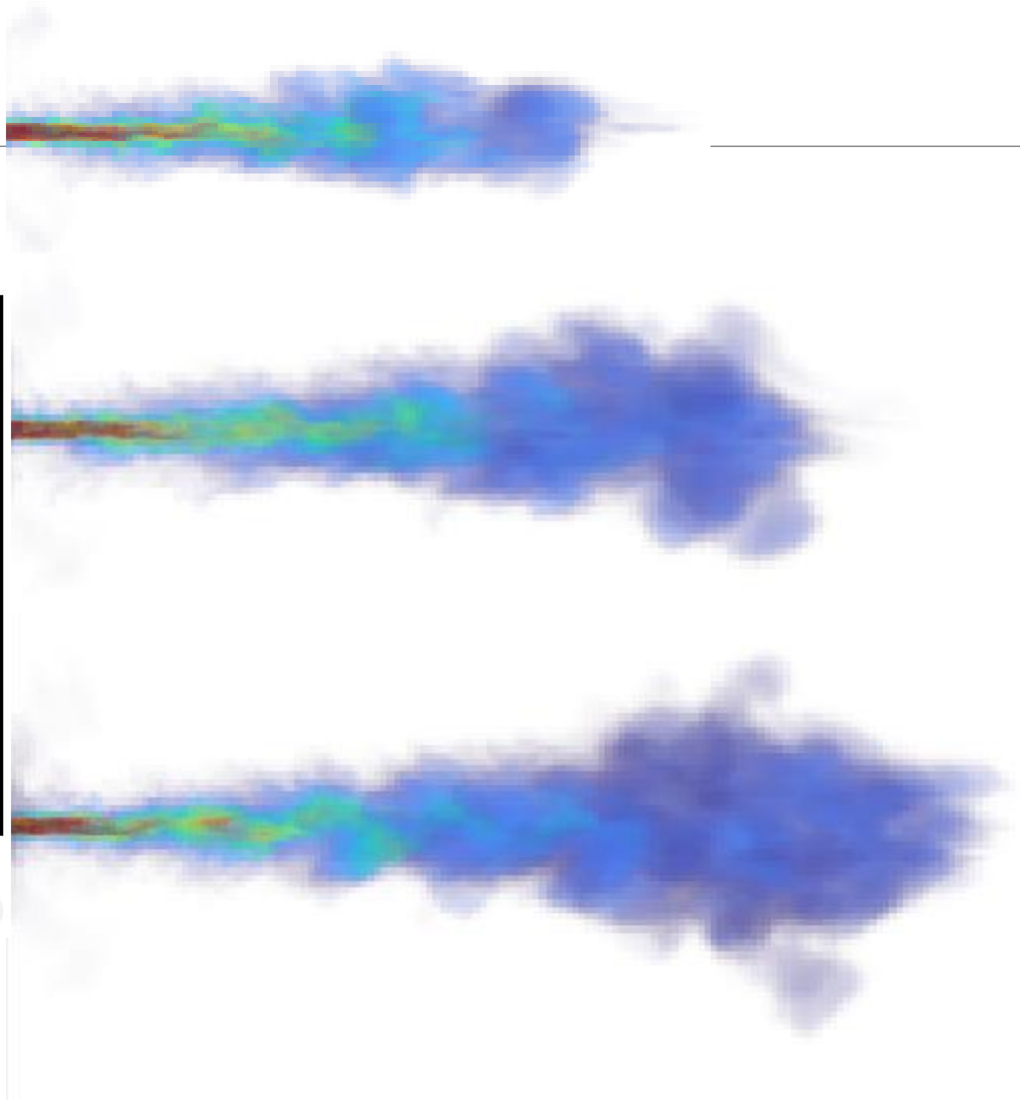
https://www.tec-science.com/mechanics/gases-and-liquids/hagen-poiseuille-equation-for-pipe-flows-with-friction/

https://www.tec-science.com/mechanics/gases-and-liquids/energetic-analysis-of-the-hagen-poiseuille-law

Simulations

https://youtu.be/YHZtjdgBzdQ?t=24

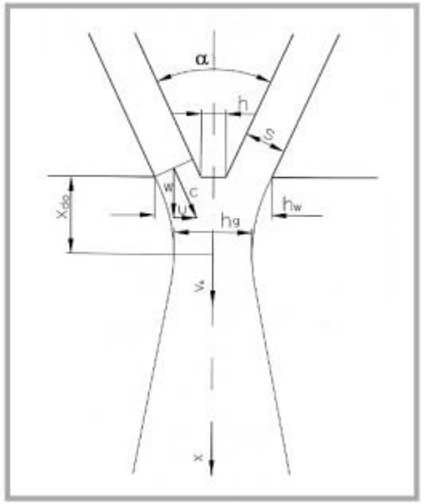




Other ideas

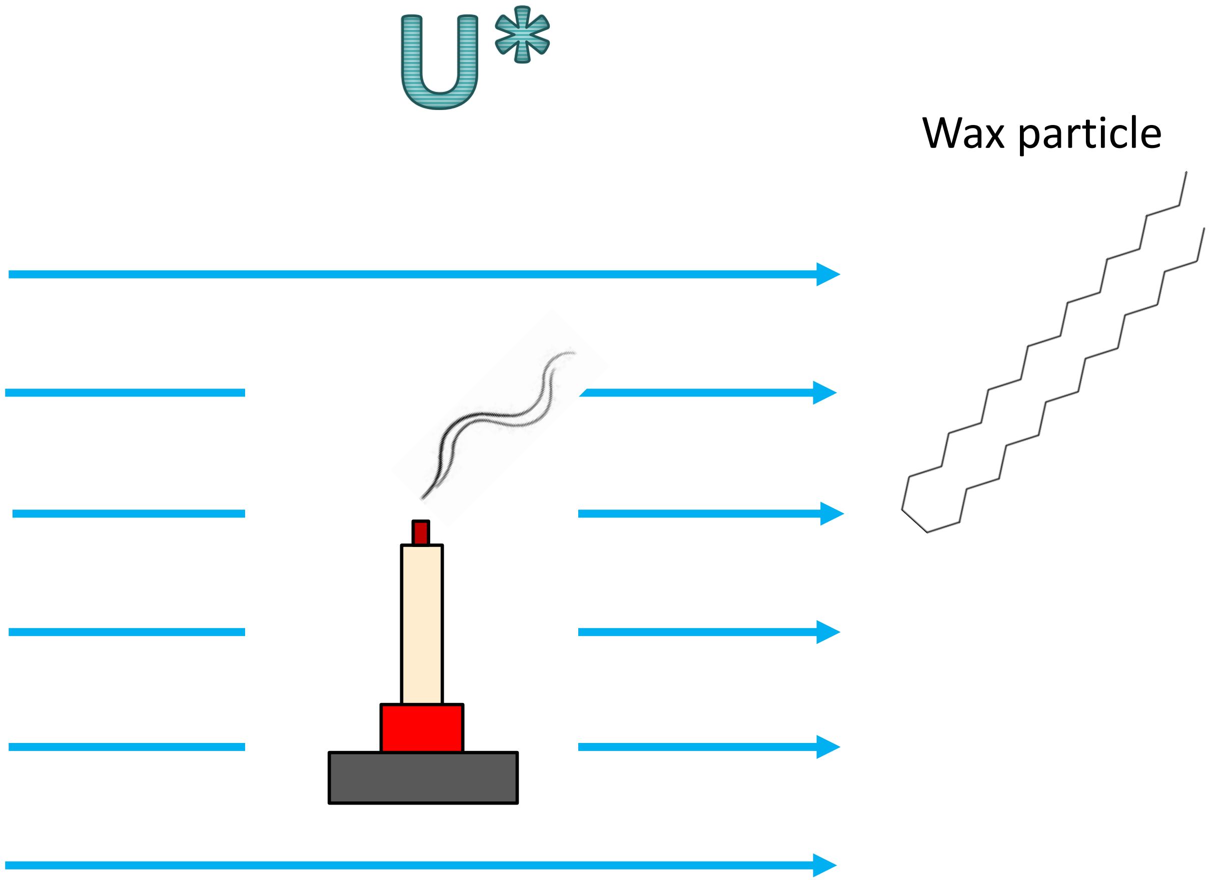
Leszek Zawadzki,
*Jan Cichoń,
*Janusz Jarzębowski,
*Henryk Kapusta

Determination of the Air Velocity in the Free Stream Flowing out of a Cylindrical and Two-Gap Skewed Jet (Dual Slot Die)



The candle

Blowing removes the wax particles in the air necessary to continue burning



Wind tunnel

Velocity fluctuations

	Round	Plane
Centerline velocity	$U_0(x) \propto x^{-1}$	$U_0(x) \propto x^{-1/2}$
Jet half width	$r_{1/2}(x) \propto x$	$y_{1/2}(x) \propto x$
Spreading rate	$S \approx 0.094$	$S \approx 0.1$
Jet Re	$\mathrm{Re}_0(x) \approx const$	$\mathrm{Re}_0(x) \propto x^{1/2}$
Turbulent Re	$\mathrm{Re}_T(x) \approx 35$	$\mathrm{Re}_T(x) \approx 31$
Mass flow rate	$\dot{m}(x) \propto x$	$\dot{m}(x) \propto x^{1/2}$
Momentum flow rate	$\dot{M}(x) \approx const.$	$\dot{M}(x) \approx const.$
Energy flow rate	$\dot{E}(x) \propto x^{-1}$	$\dot{E}(x) \propto x^{-1/2}$

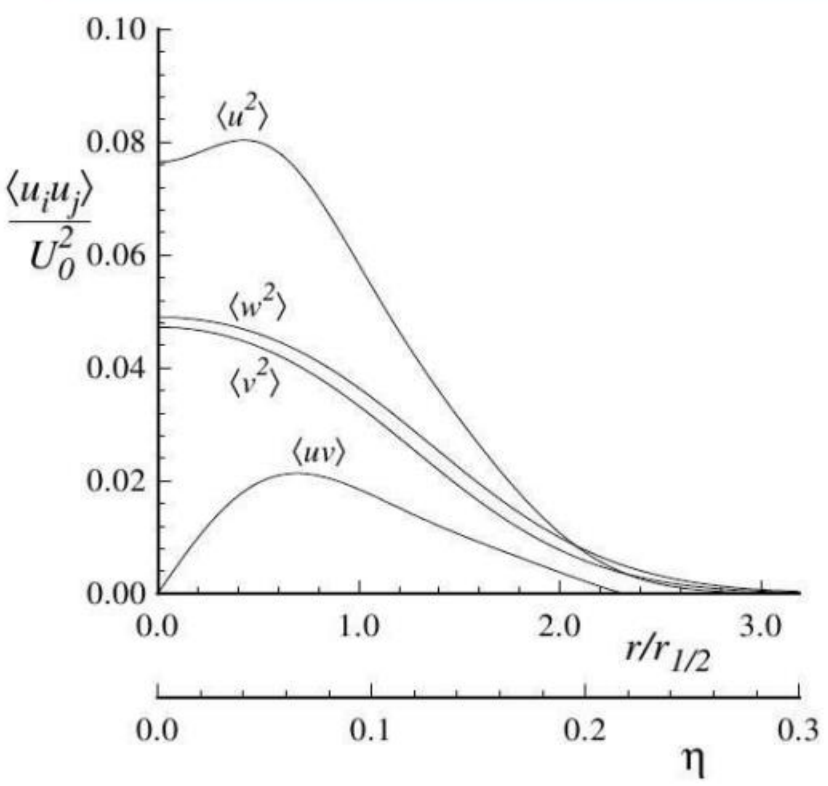


Figure 5.7: Profiles of Reynolds stresses in the self-similar round jet. Curve fit to the LDA data of Hussein et al. (1994).

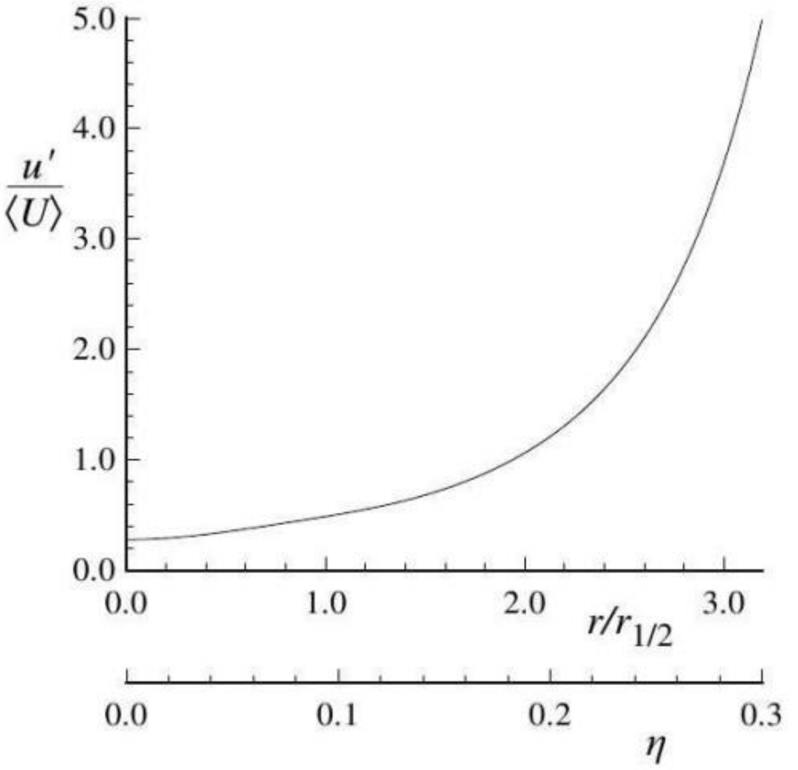


Figure 5.8: Profile of the local turbulence intensity—$\langle u^2 \rangle^{\frac{1}{2}}/\langle U \rangle$—in the self-similar round jet. From the curve fit to the experimental data of Hussein et al. (1994).

Circular Free Jets: CFD Simulations with Various Turbulence Models and Their Comparison with Theoretical Solutions

Miroslava Kmecova [1], Ondrej Sikula [2], Michal Krajcik [1]

[1] Slovak University of Technology, Faculty of Civil Engineering, Radlinskeho 11, 81005 Bratislava, Slovakia
[2] Brno University of Technology, Faculty of Civil Engineering, Veveri 95, 60200 Brno, Czech Republic

$$\frac{U_m}{U_0} = \frac{K_v}{\frac{x}{d_0}} \tag{4}$$

where K_v is a constant, usually referred to as the throw constant, and d_o is the effective diameter of the supply opening, equal to $2r_o$. The value of K_v can vary from 5.75 up to 7.32, depending on the author. The centreline velocity decay has been studied by a number of authors. Using extensive experimental data for different free axisymmetric jets, Baturin [12] obtained the velocity decay equation:

$$\frac{U_m}{U_0} = \frac{0.48}{\frac{a*x}{d_0}+0.145} \tag{5}$$

The solution to produce centreline velocity decay by Tollmien [7, 13]:

$$\frac{U_m}{U_0} = \frac{0.965}{\frac{a*x}{r_0}} \tag{6}$$

$$\frac{U_m}{U_0} = \frac{6.39}{\frac{x}{d_0}+0.6} \tag{7}$$

The solution to produce centreline velocity decay by Albertson et al. [7,15]:

$$\frac{U_m}{U_0} = \frac{6.2}{\frac{x}{d_0}} \tag{8}$$

For practical purposes, the value of K_v equal to 6.3, lying between the extreme variations, is suggested for the velocity scale by Rajaratnam [7]:

$$\frac{U_m}{U_0} = \frac{6.3}{\frac{x}{d_0}} \tag{9}$$

The solution to produce centreline velocity decay equations by Aziz [16]:

$$\frac{U_m}{U_0} = \frac{A_4}{\frac{x}{d_0}+\alpha_2} \tag{10}$$

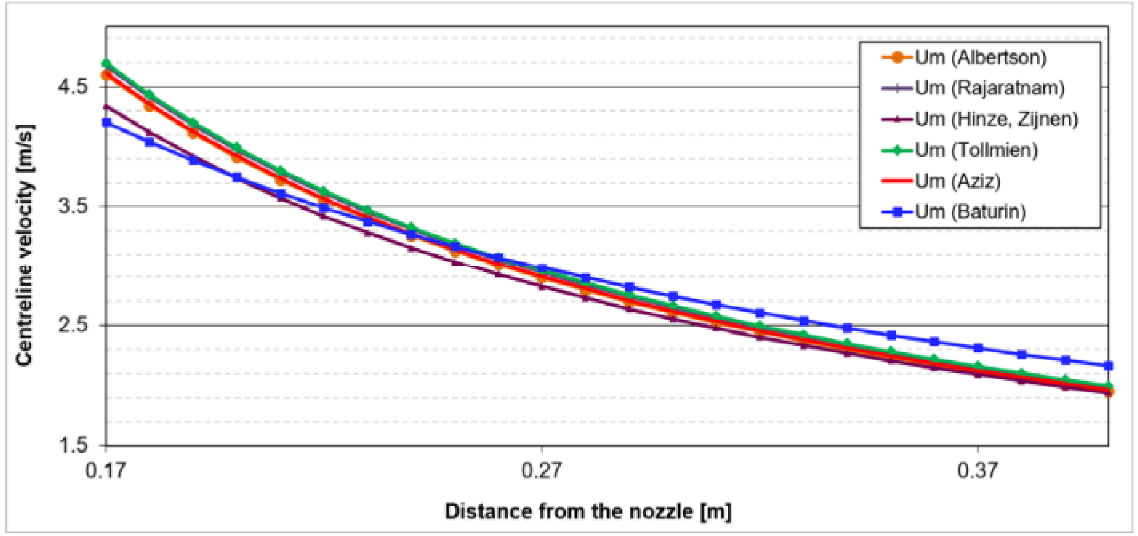


Figure 2. Centreline velocity in fully developed flow region