Problem 10.

Steam boat

The problem

A boat can be propelled by means of a candle and metal tubing with two open ends (an example is shown in the picture). Explain how such a boat is propelled and optimize your design for maximum velocity

Outline

- Achieving effect
- Boat design
- Theoretical approach
- Experiment and results
- Conclusion

Achieving effect

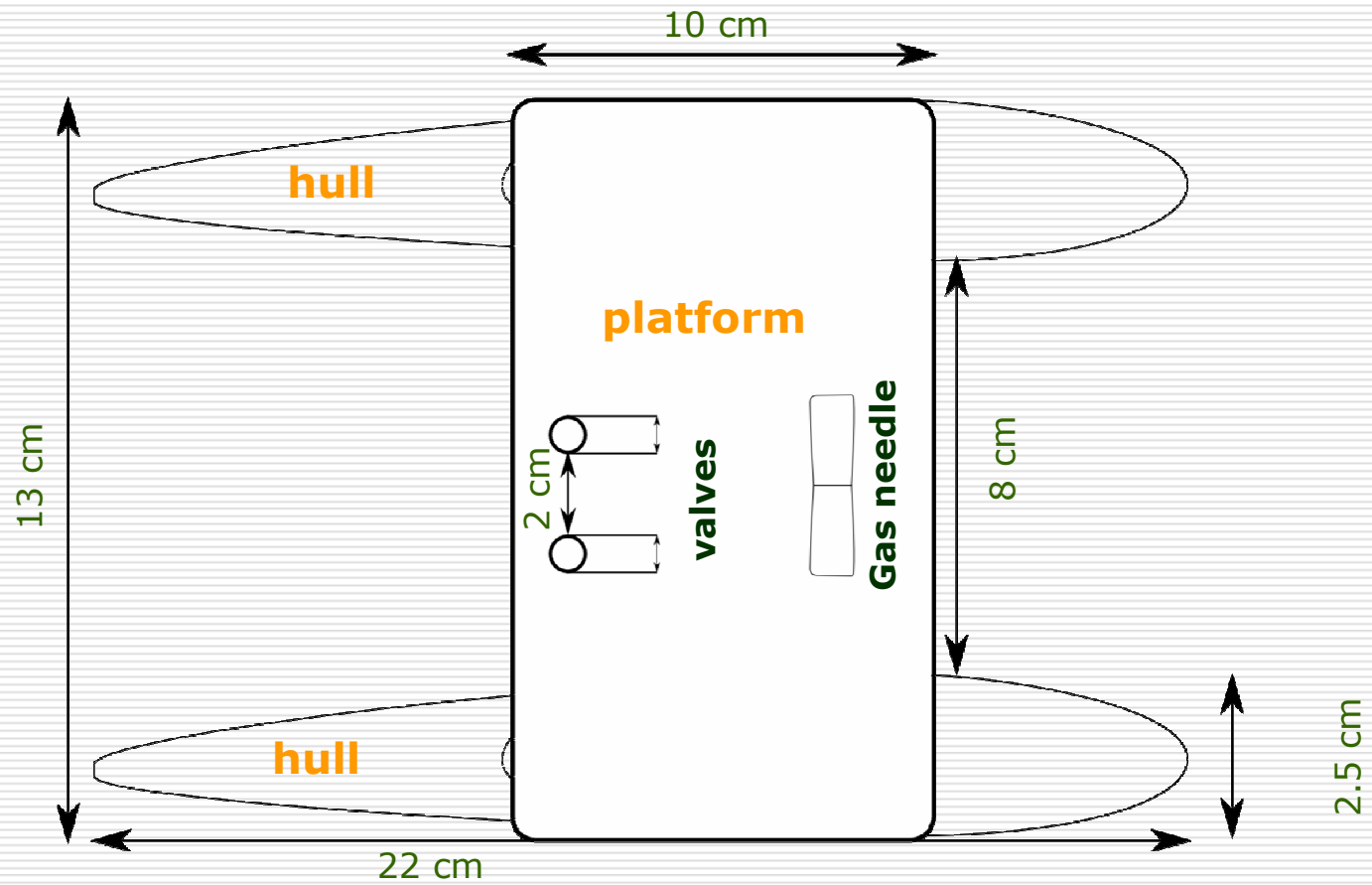


- Effect achieved
- Boat → plastic bottle
- High drag force → NEW BOAT
- Slow heating → NEW SYSTEM OF HEATING

Boat design

- NACA_broj
- Catamaran → small drag force → higher velocity
- Made of styrofoam ($\rho = 50\ kg/m^3$)
- Mass without tubing: 33,5 g
- Efficient heating – lighter gas flame

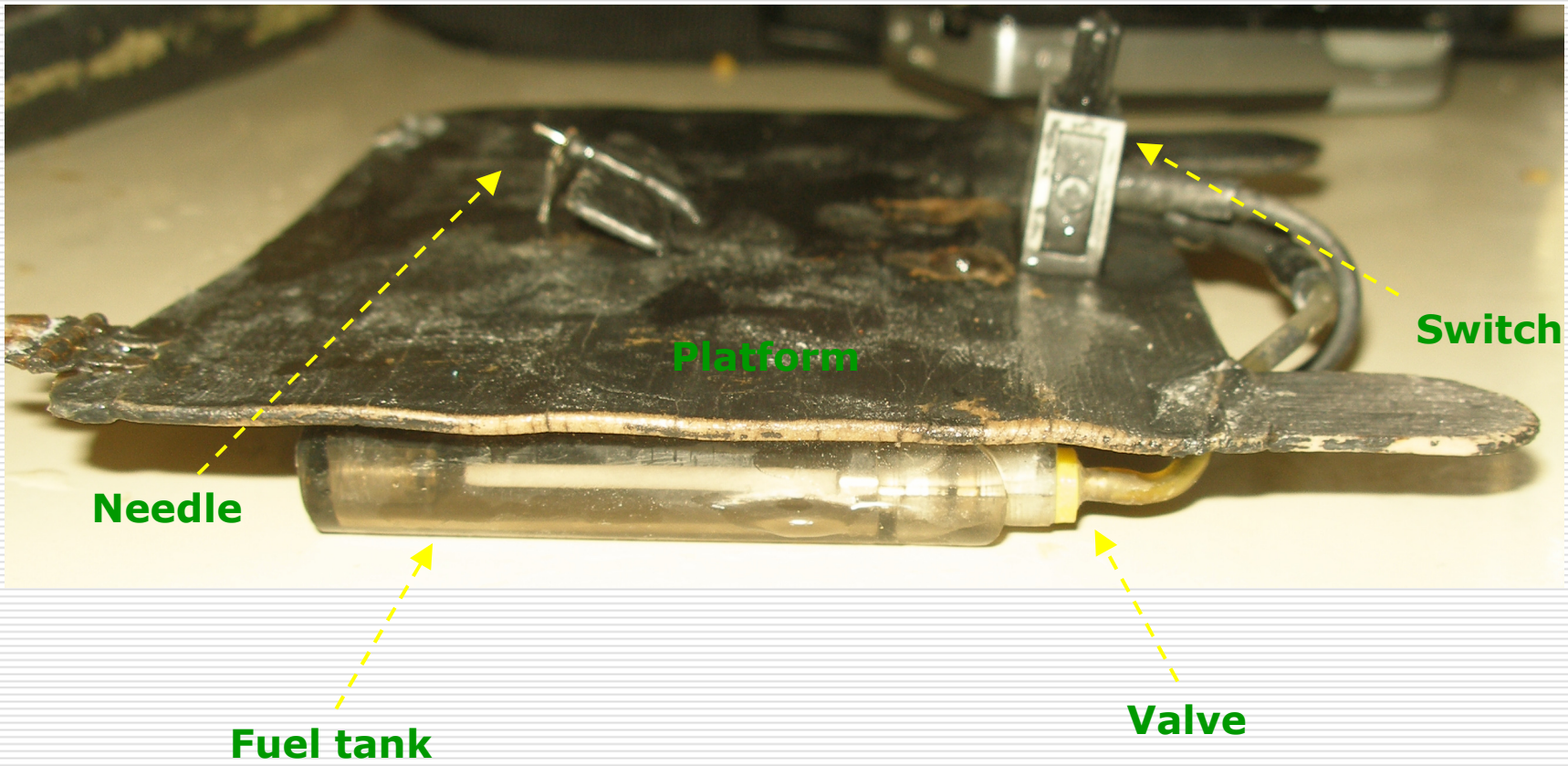
Boat design


10 cm
hull
platform
13 cm
2 cm
valves
Gas needle
8 cm
hull
2.5 cm
22 cm

Boat design



Boat design



Boat design

- Drag force on boat – for low velocities presumed linear:

$$F_d(v) = -\Gamma v$$

$\Rightarrow$ Motion equation (free boat):

$$m\frac{dv}{dt} = -\Gamma v \Rightarrow x(t) = v_0 \frac{\Gamma}{m}\left(1 - e^{-\frac{\Gamma}{m}t}\right)$$

m – boat mass

v – boat velocity

Γ – constant

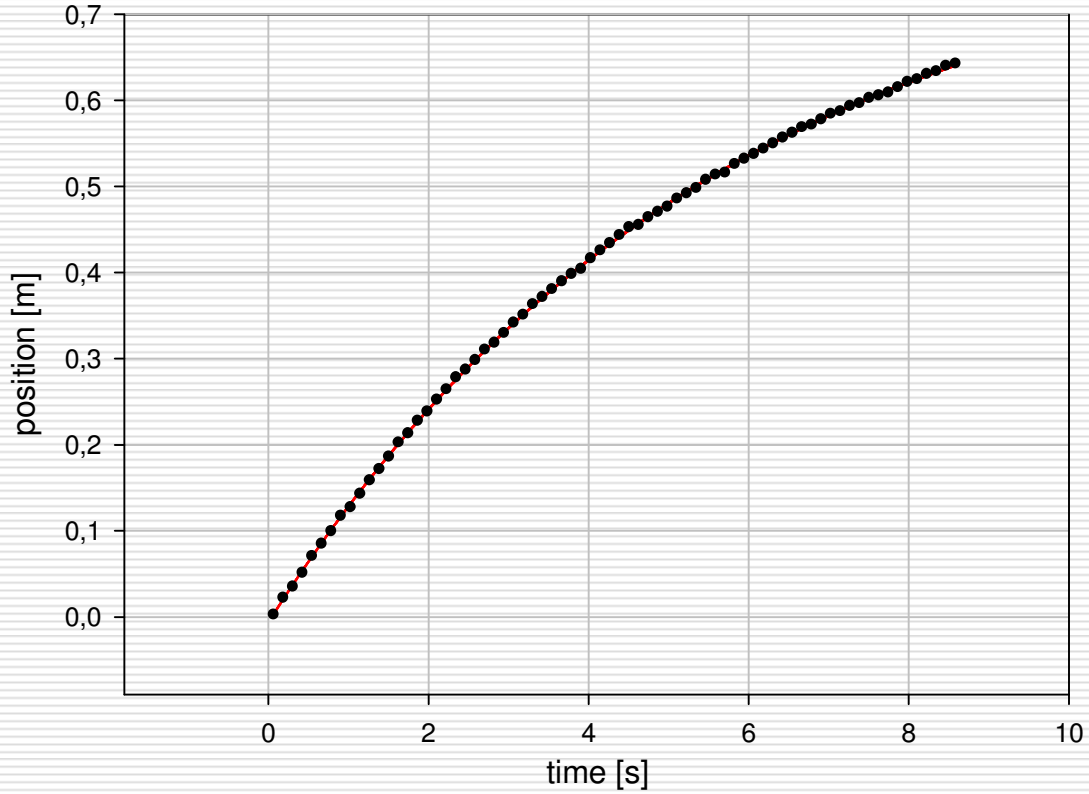
F_d – drag force

x – boat position

v_0 – initial velocity

Boat design

- Confirmed experimentally:

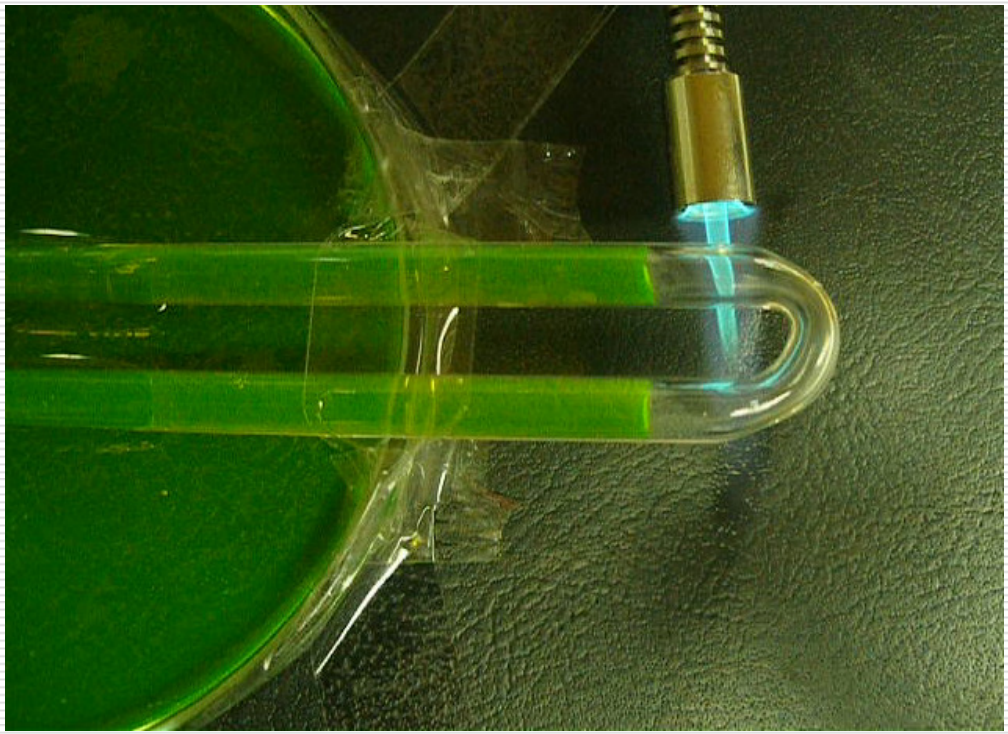


From fit:

$$\Gamma = 0.015\,\mathrm{kg/s}$$

Propulsion

- Transparent tubes for investigation:



Propulsion

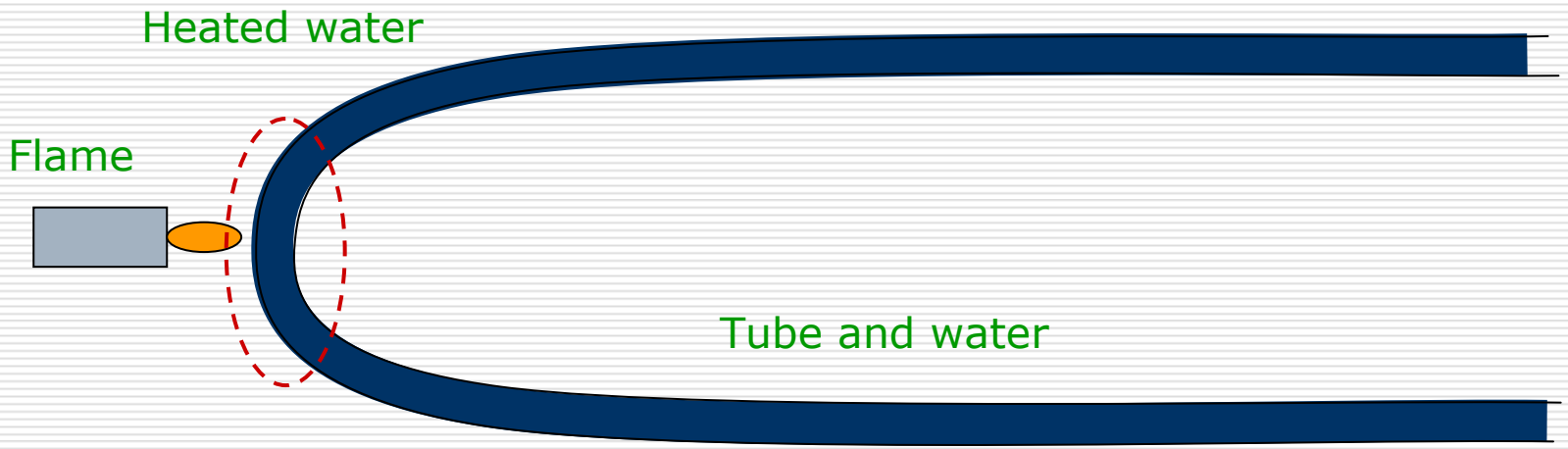
film

Propulsion

- Water oscillates when heated!
- Oscillation of water in tube – forced oscillator
- Heat engine
- Energy source – flame
- Working medium - steam
- Oscillation mechanism:

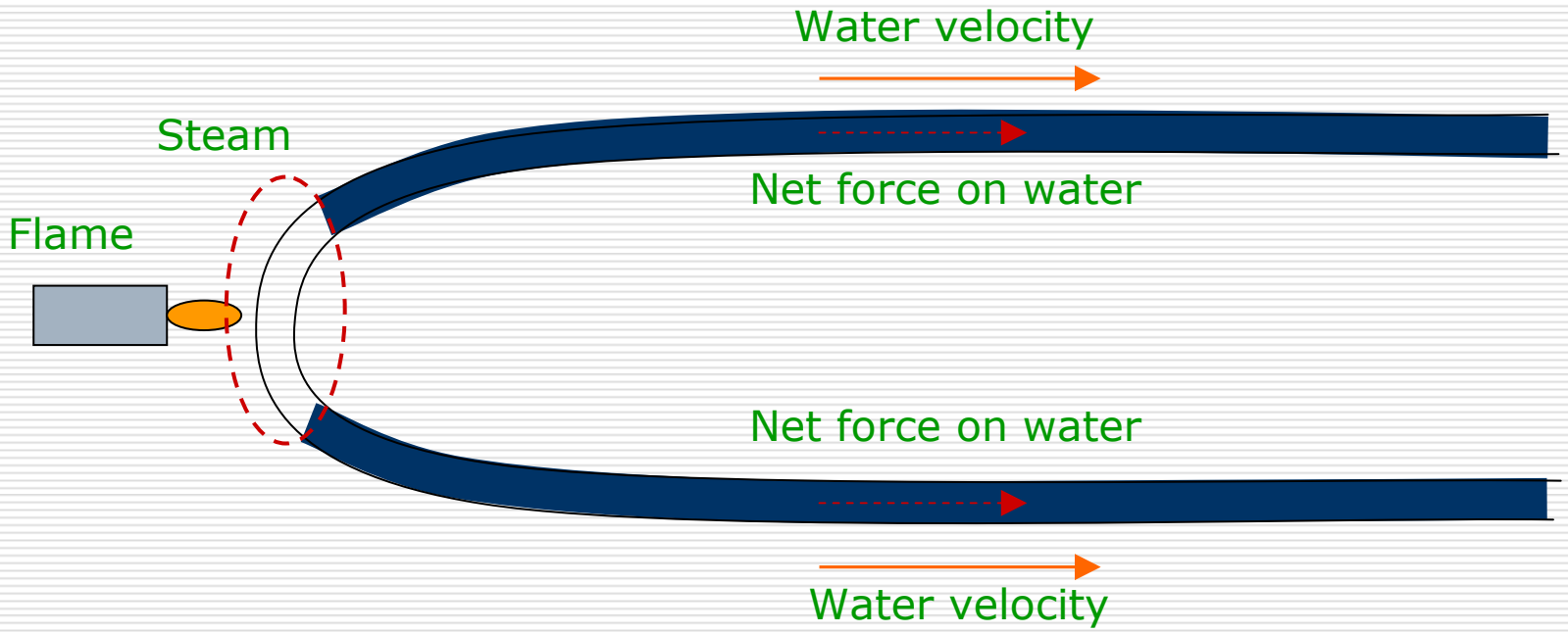
Propulsion

1. Water is heated and evaporates



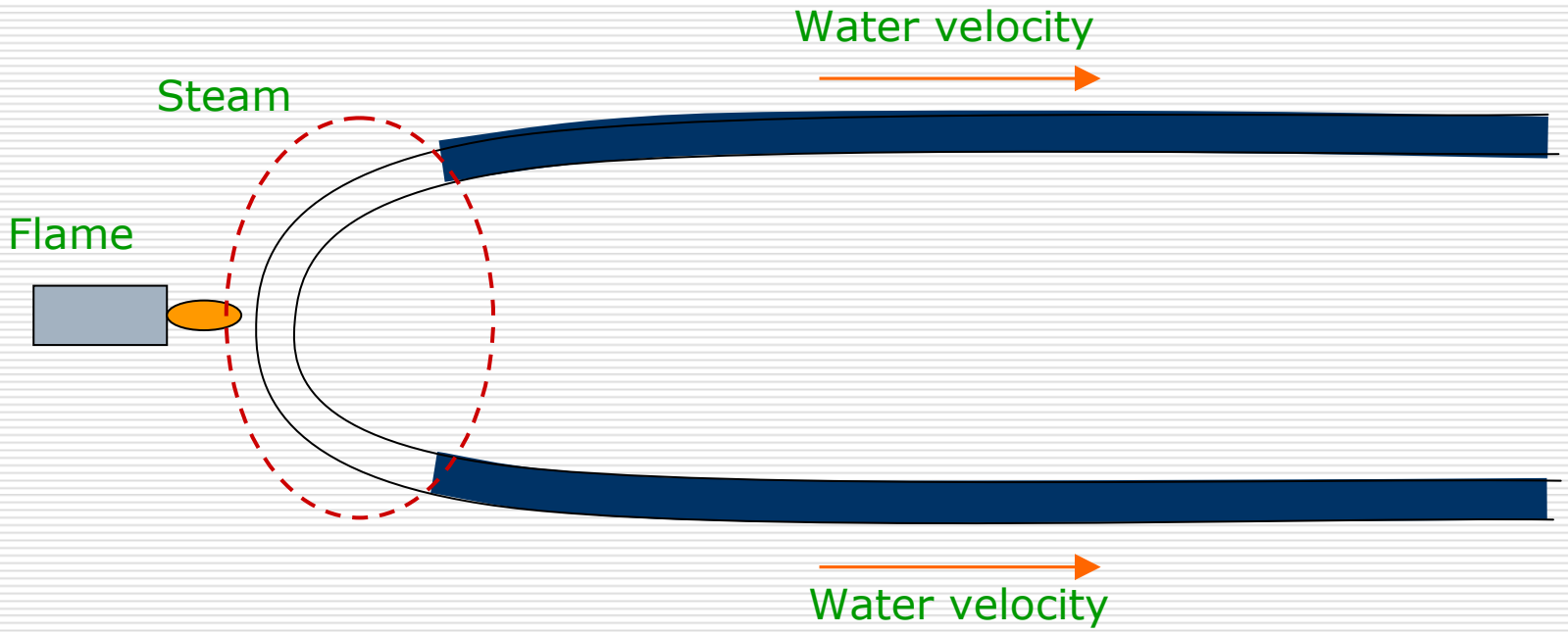
Propulsion

2. Steam pressure builds up and causes water acceleration (water evaporates)



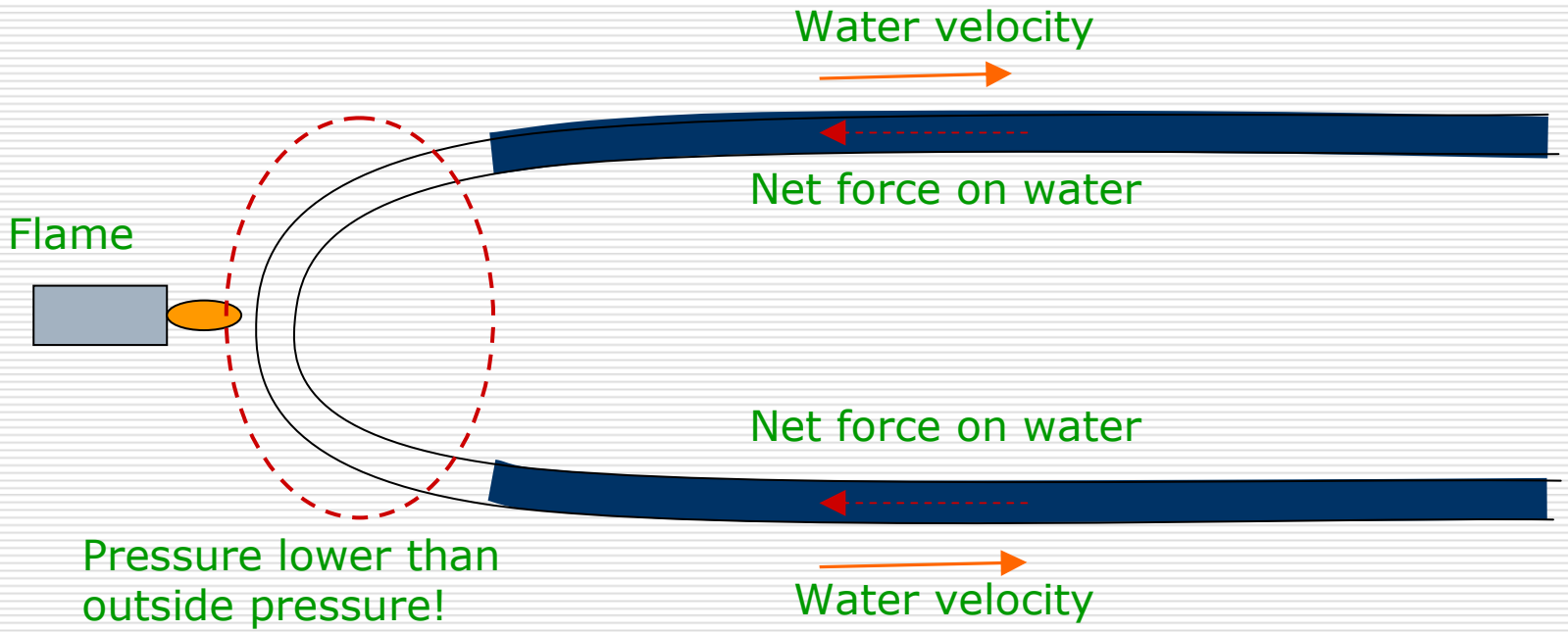
Propulsion

3. Pressure growth stops when water reaches colder tube parts – condensation!



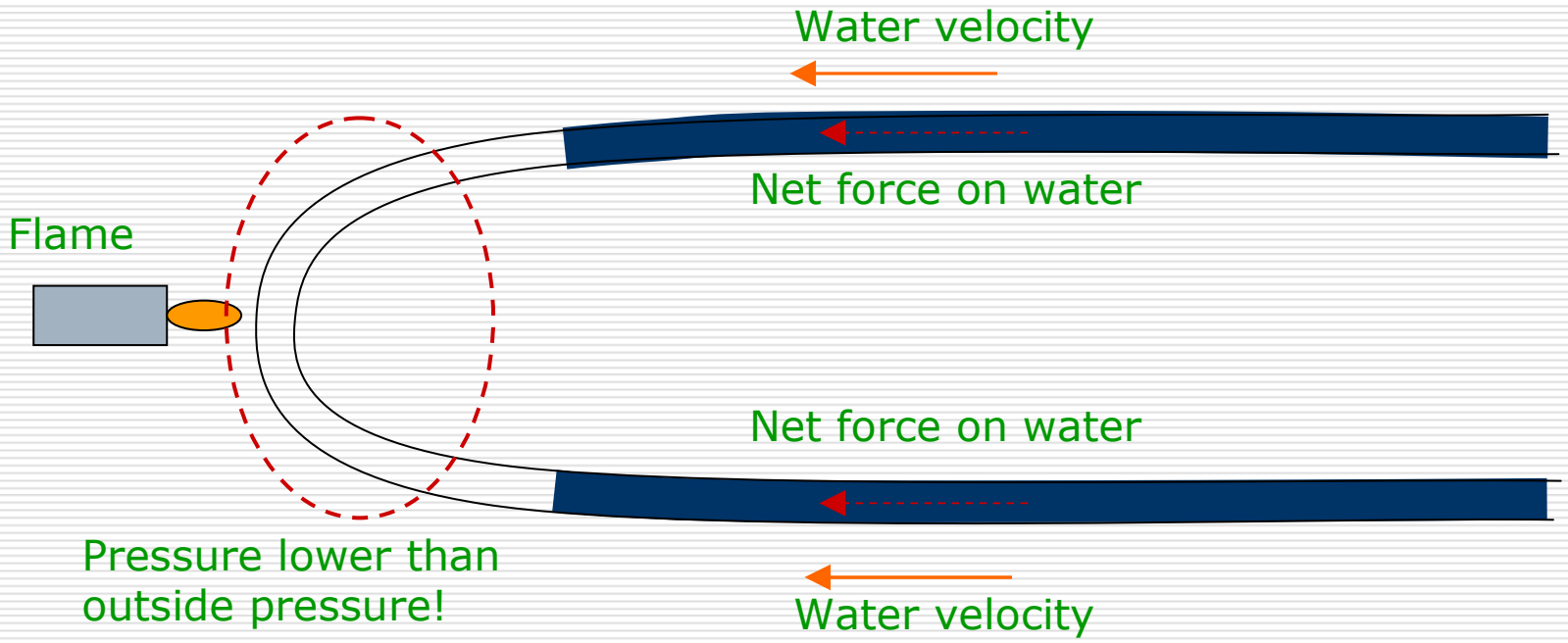
Propulsion

4. Water continues motion due to inertia and causes internal pressure to drop



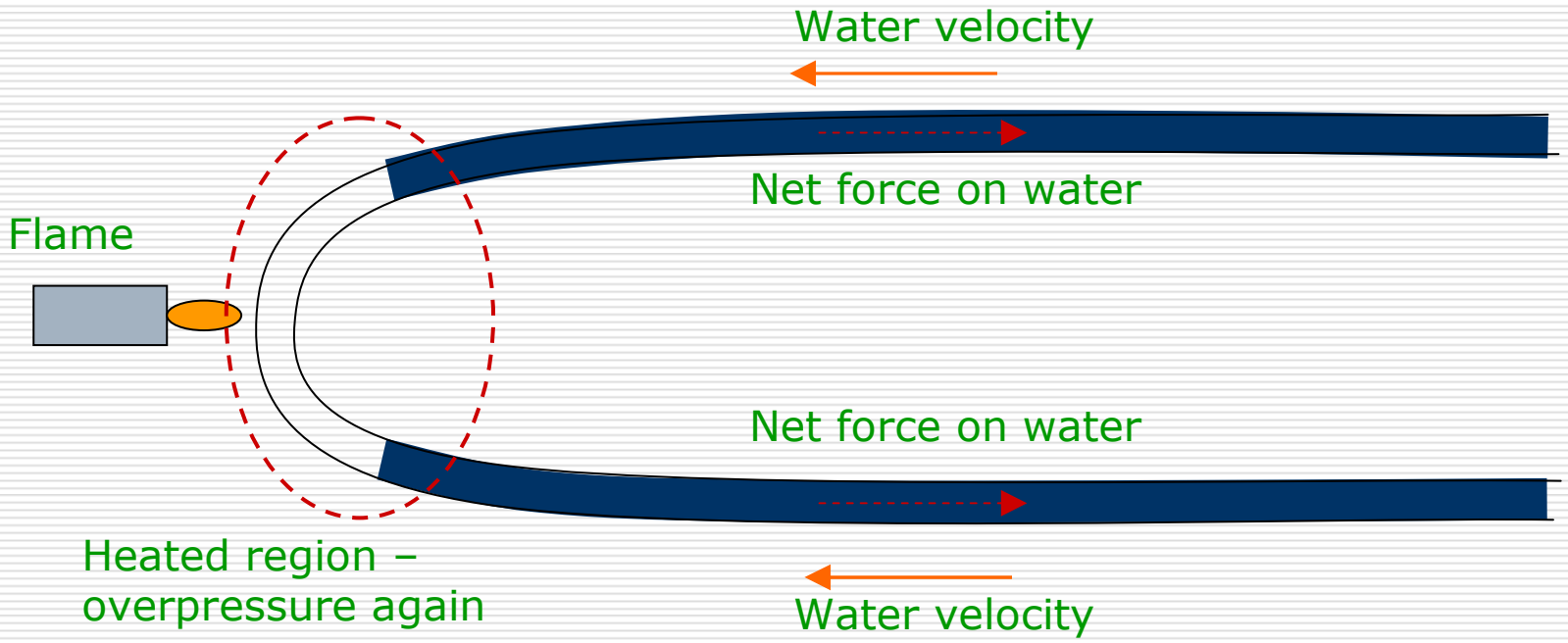
Propulsion

5. Water velocity falls and eventually changes direction



Propulsion

6. Water reaches heated region again and pressure builds up – cycle is repeated

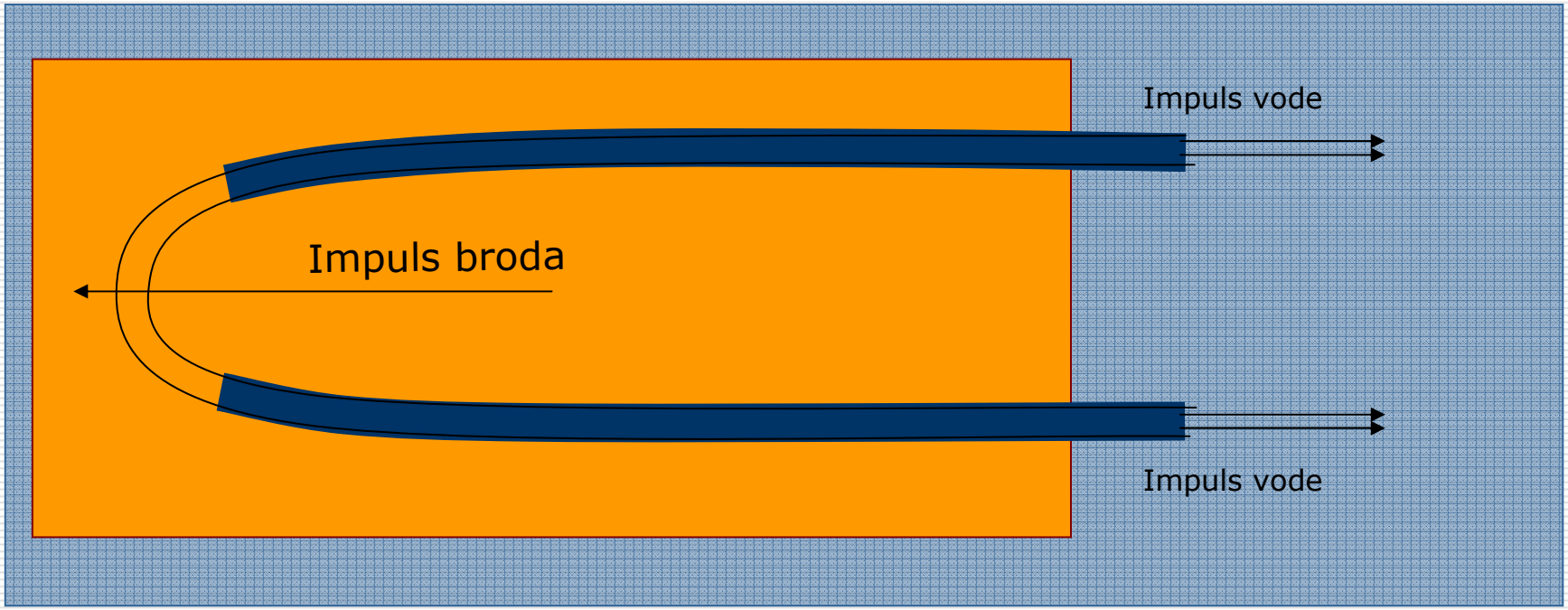


Propulsion

- The steam acts as a spring due to repeated evaporation and condensation
- No steam loss!
- Low efficiency:
  - Dissipations while heating
  - Friction
  - Small reactive steam mass
- Efficiency calculation very dificult

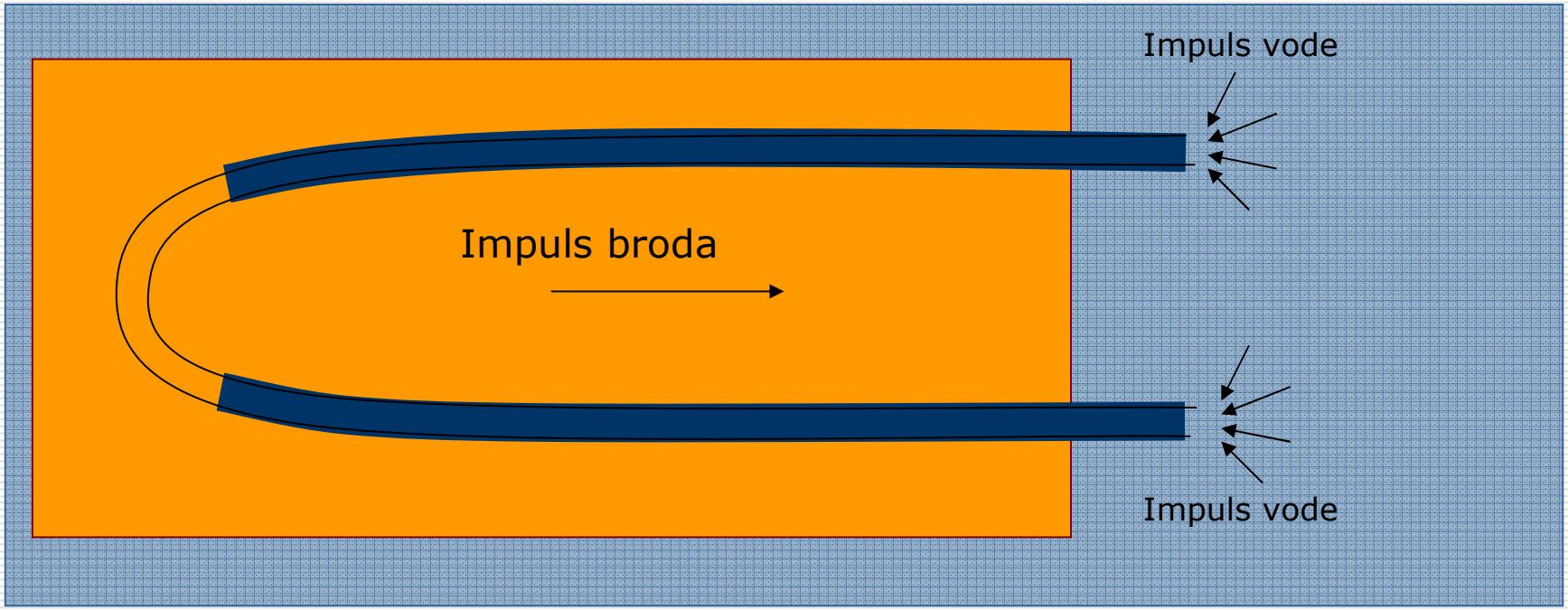
Propulsion

- Water pushed out of tube:



Propulsion

- Water suckend into tube:



Propulsion

- Net momentum smaller when water is sucked in due to noncoherent water motion
- **Net boat momentum directed forwards!**
- Even lower efficiency because of time average

Propulsion

- Boat equation of motion:

$$m\frac{dv}{dt} = \left\langle F_{prop} \right\rangle - F_d(v)$$

- In steady state:

$$\left\langle F_{prop} \right\rangle = F_d(v)$$

m – boat mass

v – boat velocity

F_{prop} – propulsive force (time average)

F_d – drag force

Propulsion

- The work of the propulsive force is (steady state):

$$dW = \langle F_{prop} \rangle ds = F_d(v) ds$$

dW – differental work

F_{prop} – propulsive force (time average)

ds – element of traversed path

- Energy supplied by the heater:

$$dE = \langle P \rangle dt$$

dE – differental energy

P – heater power (time average)

dt – element of time

Propulsion

- Efficiency can be calculated:

$$\eta = \frac{dW}{dE} = \frac{F_d(v)v}{\langle P \rangle} = \frac{\Gamma v^2}{\langle P \rangle}$$

dW – differental work

dE – differental energy

P – heater power (time average)

F_d – drag force

v – boat velocity

Γ - constant

- Drag force taken from measurements
- Heater power can be estimated:

Experiment and measurments

- Measurments:

  velocity depndence on: mass

  number of turns

- Experiment:

  boat's movement if:

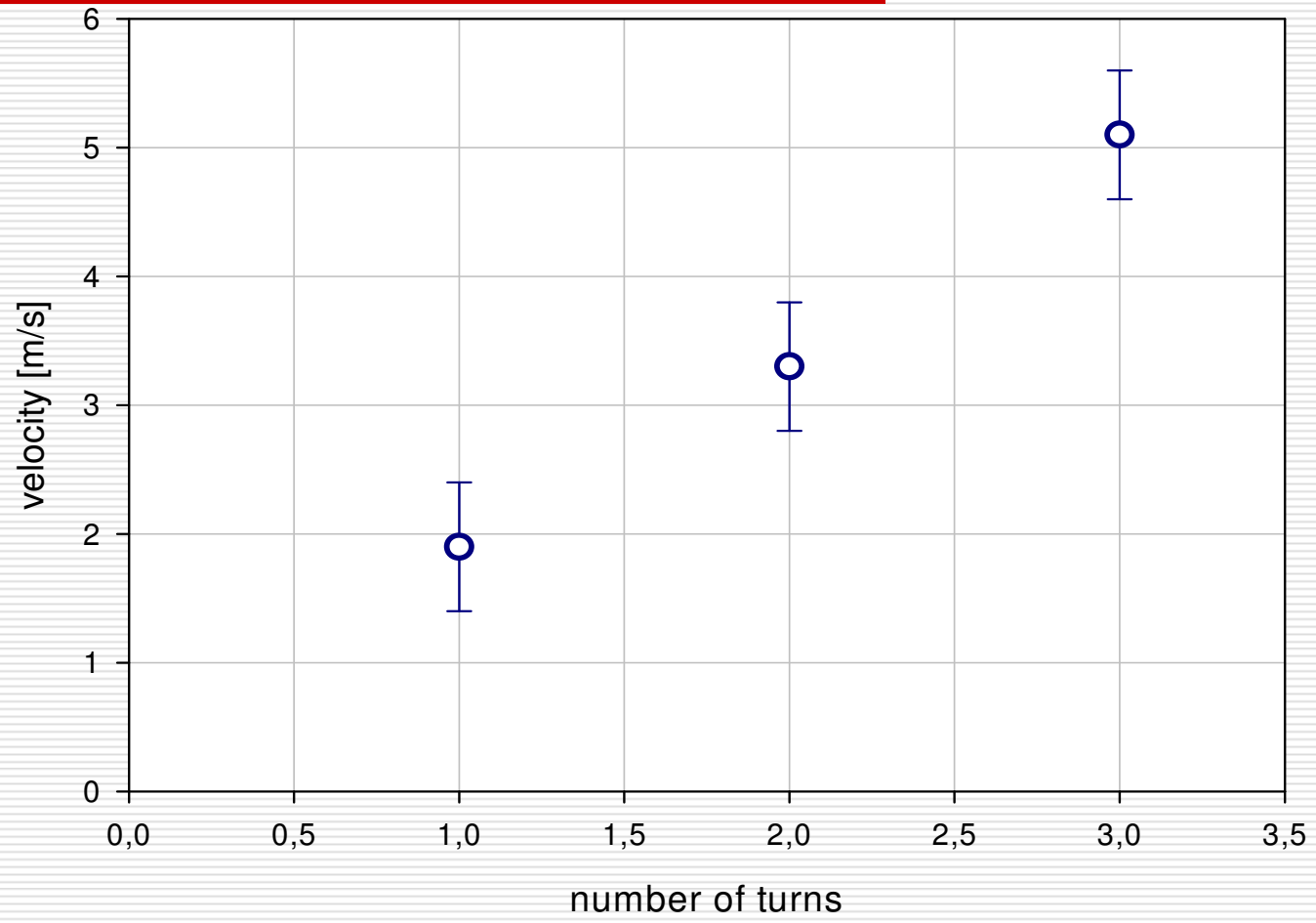
  one end of the tube is longer

  one end of the tube is narower

  around the tube is aluminium

Experiment and measurments

Experiment and measurments



Mass= cost.

Experiment and measurments

One end of the tube is longer→no effect

One end of the tube is narower→this side of the boat moves faster→boat turns

Experiment and measurments

- Around the tube is aluminium→the boat moves faster