Air Pump for Paddle Board

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Our Device:

- Pumps air through the hose attached
- Two cylinders and the switch lets you change between high-volume mode (fast, low pressure), and high-pressure mode (easier pumping when the inflatable is almost full).
- There is a pressure gauge embedded in the handle.

Major Dimensions

Mini tube:15mm
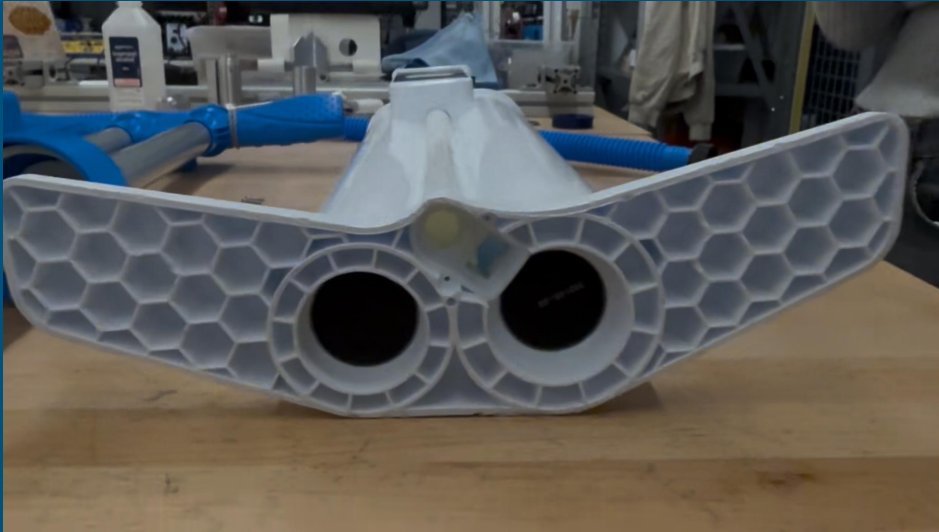
Small tube : 60 mm diameter

Big tube : 70mm diameter

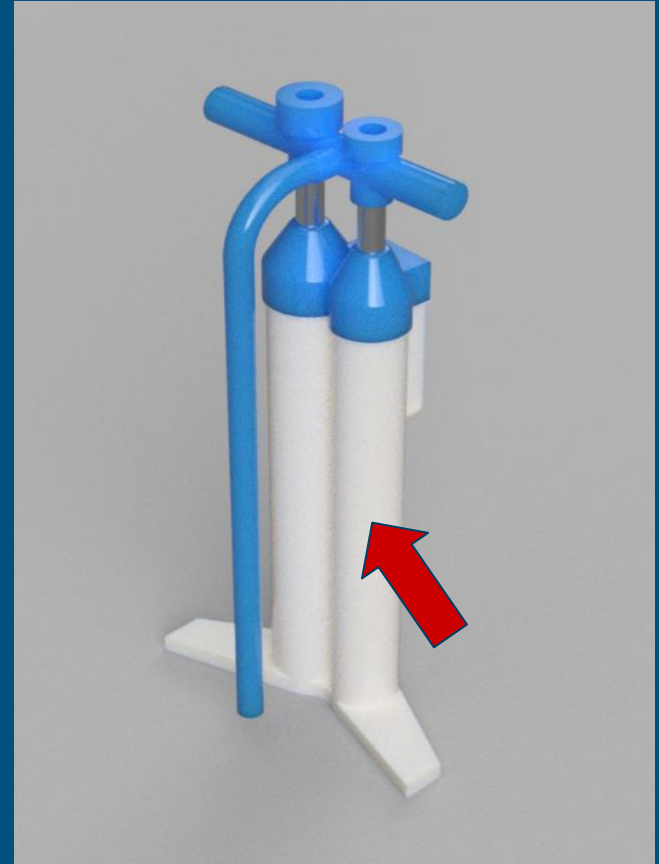Height: 470 mm

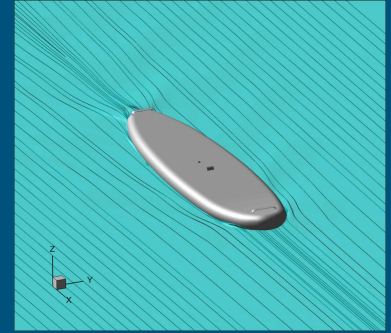Flexible tube: 25mm diameter, 1500mm length

Dissection

Assumptions

- We are doing calculations assuming we are using the mode 3, when the small tubes is open and big tube is closed to pump the paddle board
- We are also assuming the tubes as perfectly cylindrical tubes for the ease of calculation and analysis

Governing Equations / Parametrization

- The **Mean Flow Approximation Q=UA**
- Our flow is incompressible so our mass flow rate is constant and we can apply the **Continuity Equation: $A_1V_1=A_2V_2$.**
- A **Pressure Volume Relationship W=PΔV**
- The Reynolds Number of the fluid system varies at is flows between different pipes. **Re = $\rho UL/\mu$**.
- **Viscous dissipation factor f_D = 2ΔB_{loss}d/ρ(U^2)L**
- Bernoulli's Equation **B = p+ ρU^2/2+ρgh**

Parametrization

- Governing parameters: Reynolds number (Re) and Mach number (Ma)
- Flow: air in the 25 mm diameter, 1.5 m flexible hose from the barrel
- **Scale: length = hose inner diameter, velocity = average hose speed U = Q / A**
- Re using (ρ, U, D, μ) > 4000 → turbulent hose flow
- Ma = U / speed of sound ≈ 0.02 → air is effectively incompressible
- Same Re and Ma definitions for Modes 1-3 → changing mode only changes U and Re as well

Parametrization

- Re controls the friction factor and pressure loss in the hose
- Ma ≪ 1 in all modes, so compressibility does not affect performance and can be treated as negligible in our calculations
- Switching to larger barrels and faster strokes increases Q and U, which raises Re, fills the board faster, but also increases hose losses and handle force
- Changing the hose design to be shorter, smoother, or have slightly larger diameter reduces losses and handle force, while a greater viscous fluid would make losses so large the pump would be difficult to use

Calculations

Quantitative calculations and arguments for why the design is what it is. Would the system work if it were bigger? If the holes were bigger or smaller? If the tube were straighter or more curved? If the surfaces were rougher or smoother? If the Reynolds number were bigger or smaller? If the fluid were honey instead of water? Air instead of maple syrup?

Calculations: Reynolds number

Cylinder bore ≈ 60 mm → D_c= 0.06 m
D_c =0.06 m Cylinder stroke ≈ 470 mm → L_s= 0.47 m
Hose diameter D_h =25 mm =0.025 m, length L_h =1.5 m

$ρ$≈1.2 kg/m3, $μ$≈1.8×10−5 Pas
Area p = pi*r^2 = 2.83 x 10^-3
V_p = Area * L = 1.33L

Assuming one pump per 3 seconds,
Q = Vp*f = 3.99 E3 m^3/s

Re = 2pUr/mu = 2*1.2*8.126*0.025/1.8*10^-5 = 2.71 x 10^4

The air is turbulent as Re>4000

Calculations: Pressure Drop in Hose.

Surface Roughness of Hose: $\varepsilon = 1.5*10^{-6}$ m
Length of house = 1.5 m
Hose diameter : d = $25*10^{-3}$ m
Relative Roughness ε/d = .00006
Viscous Drag Coefficient f_D=0.02485

Because the mass flow rate in pump is constant, we treat U in the house as constant such that $\Delta p = \Delta B$.

$\Delta p = 177.8$ Pa. Very small loses compared to operating pressure of the Paddle Board.

$U_{barrel} \, A_{barrel} = U_{hose} \, A_{hose}$

$U_{barrel} \cong 1$ m/s
$A_{barrel} = \pi(.03^2 + .035^2)$
$A_{hose} = \pi(.0125^2)$
$U_{hose} = A_{barrel}/A_{hose} = \frac{(.03^2 + .035^2)}{(.0125^2)} = 13.6$ m/s

$Re = \frac{\rho U L}{\mu}$

$Re_1 = \frac{(1.29)(1)(.06)}{1.81 \cdot 10^{-5}} = 4276$

$Re_2 = \frac{(1.29)(1)(.07)}{1.81 \cdot 10^{-5}} = 4989$

$Re_{hose} = \frac{(1.29)(13.6)(.025)}{1.81 \cdot 10^{-5}} = 24232$

$\varepsilon_{hose} = 1.5$ μm
Colebrook Equation $(Re > 2300)$

$1/\sqrt{f_D} = -2 \log(\varepsilon/3.7d + 2.51(Re \cdot \sqrt{f_D}))$

Starting Guess $f_D = 0.0245$ (using graph)
Final viscous drag coefficient
$f_D = 0.02485$

Change in design

If diameter was greater

Handle force at Board pressure

$F = PA = P * \pi * r^2 \rightarrow$ dependent on r^2

$V = $ Area $* L$

If the diameter was x2 doubled,
the stroke volume would be x4 greater and the
handle force would also be x4 greater. It would be
more difficult to push air into the paddle board for
users. But we could pump more air in.

Change in design

If the Re number was higher

This can be simulated by several factors: e.g. increasing the stroke rate, increasing surface roughness etc

As Q=Vf, if we pump faster will be a slight raise in hose pressure loss and the user would have it a bit easier to push down. However at low viscosity Re doesn't matter as much as inertia dominate flow over viscosity

If the surface was smoother that would have decreased fD and therefore pressure loss. However, due to the low air density, it would have not given a significant difference.

Change in design

The tube being straight vs curved vs have sharp bends

- Straight would be most ideal with lease energy loss, but it would hinder it's ease of use significantly as the position the hose can be at is limited
- Comparing a curved hose and a hose with sharp bending, with a curve there is less loss in energy, lower loss coefficient K compared to fluid experiencing extreme turns.
- $\Delta pbend = K * \rho U^2 / 2$ = if K goes from 0.2 -> 1.5, the pressure loss happens around 1pa $\rightarrow$ 6pa, which is significantly less than board pressure
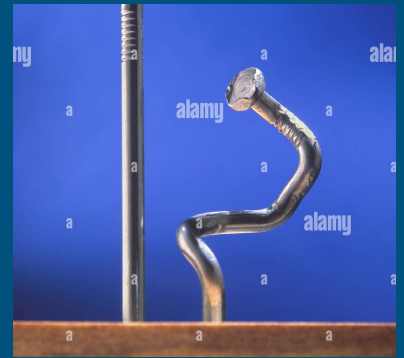
Change in design
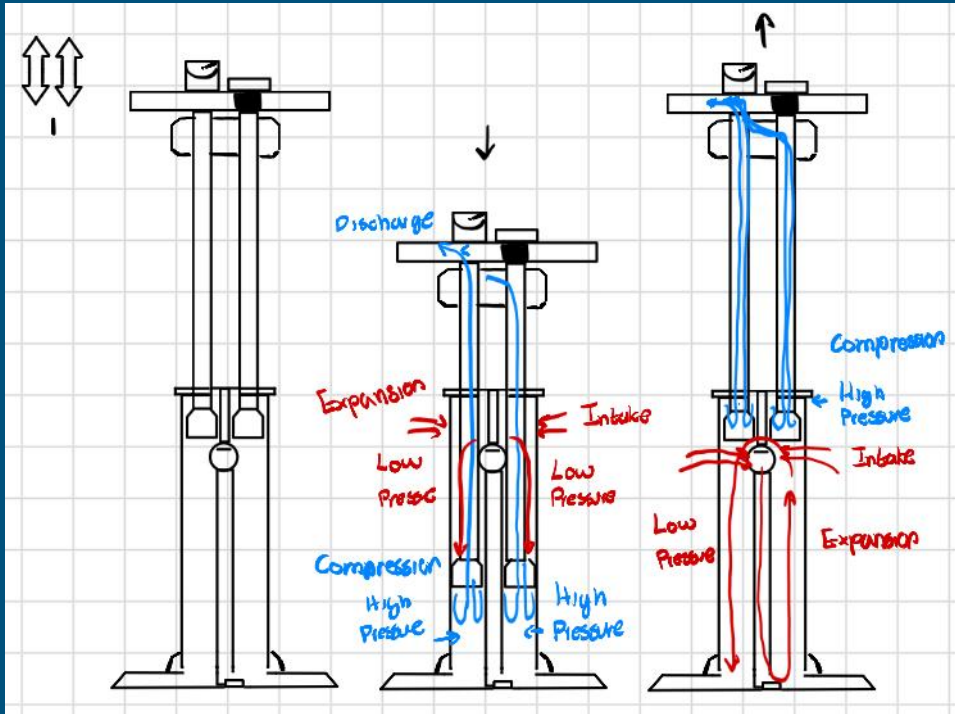
If fluid were oil instead of water

- Air has viscosity of u = ~ 1.8 x 10^-5 pa
- Oil has viscosity near u = ~ 0.3 pa

Re is related to viscosity as Re ~ 1/u
So honey decreases Re by factor of 10^4 it would be almost impossible to push. As force to push fluid is proportional to viscosity it would be 10^4 times harder to push
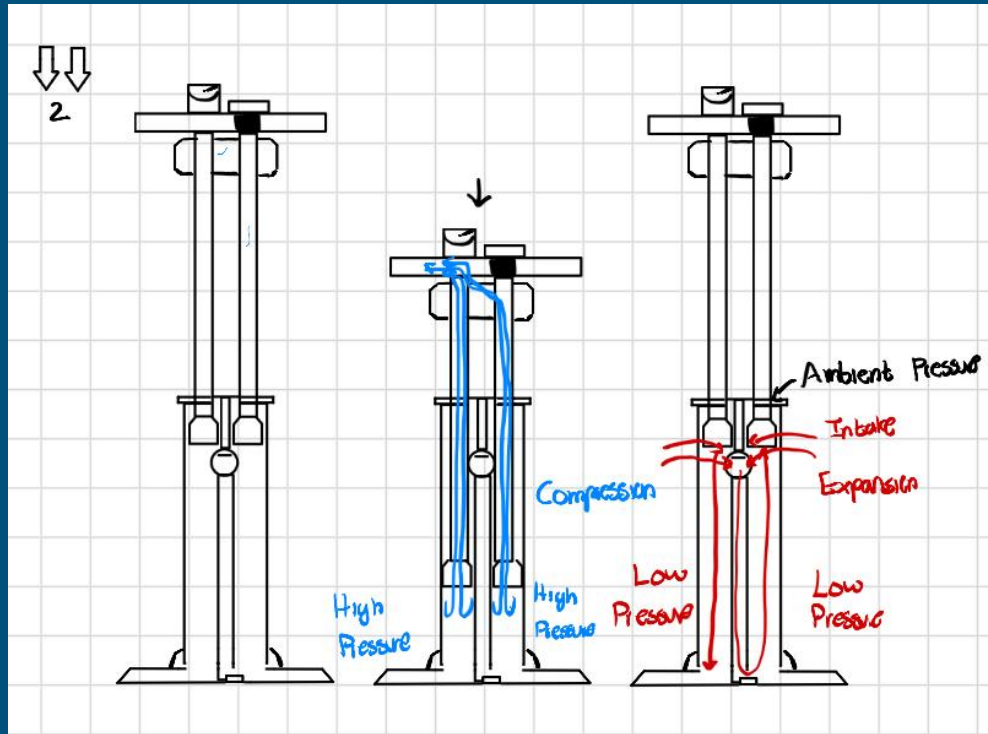
Mode 1: High Volume Low Pressure

In this mode, each cycle displaces the volume of each barrel twice. Air flows onto the top and out the bottom of each piston on the down stroke and vice versa on the upstroke.

Mode 2: Medium Volume and Pressure

In this mode, air is not discharged during the up stroke. The dial exposes the top of the pistons to the environment to they are not pressurized. The up stroke intakes air only. For higher pressures this is desirable because it decreases the work required from the user on the upstroke.

Mode 3: Low Volume High Pressure
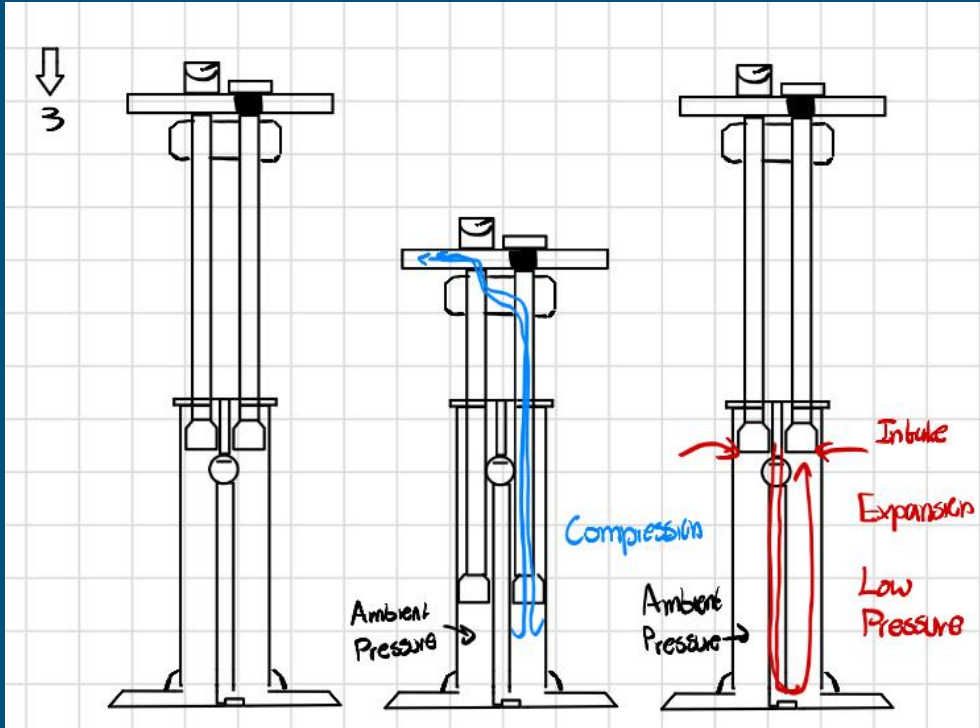
In this mode, only one barrel is utilized. The other barrel is at ambient pressure. It reduces both the volume displaced by the user on each pump but also the work required by the user. Up stroke is still only used for intake.

Thank you!