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Optimisation of vortex tubes for direct air carbon capture in the Solar Cyclone Tower

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1. Context

As the global demand for energy increases, there is a need for **sustainable** and **efficient** power generation.

The **concentration of carbon dioxide** in the Earth's atmosphere is currently at **412 ppm** [1].

It is also estimated that **1.2 billion people** live in areas of physical water scarcity.

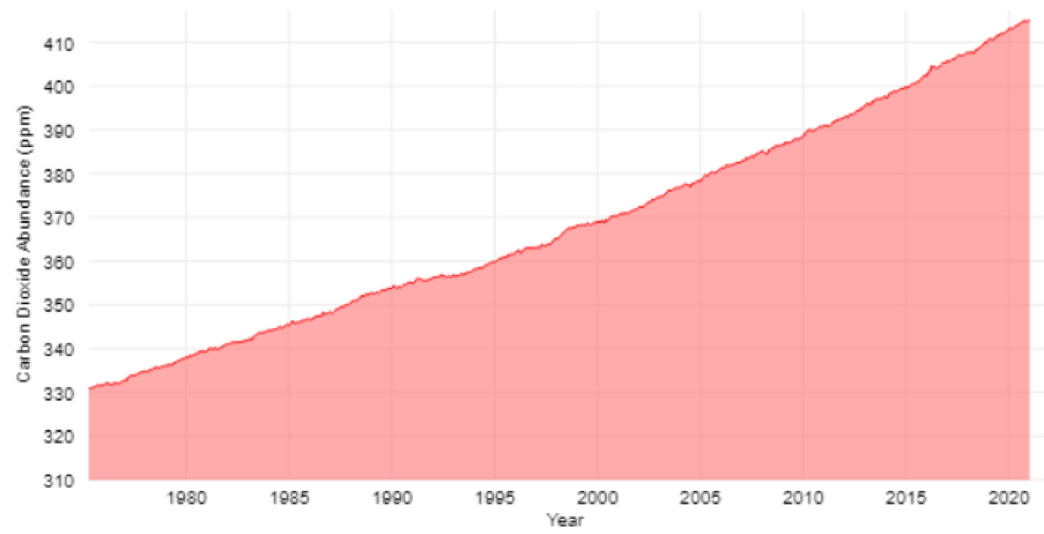


Figure 1. The concentration of carbon dioxide in Earth's atmosphere is currently at nearly 412 parts per million [1]

2. The Solar Cyclone Tower

The **Solar Cyclone Tower (SCT)** is a proposed renewable energy source that can generate electricity as well as extract atmospheric water vapour and carbon dioxide.

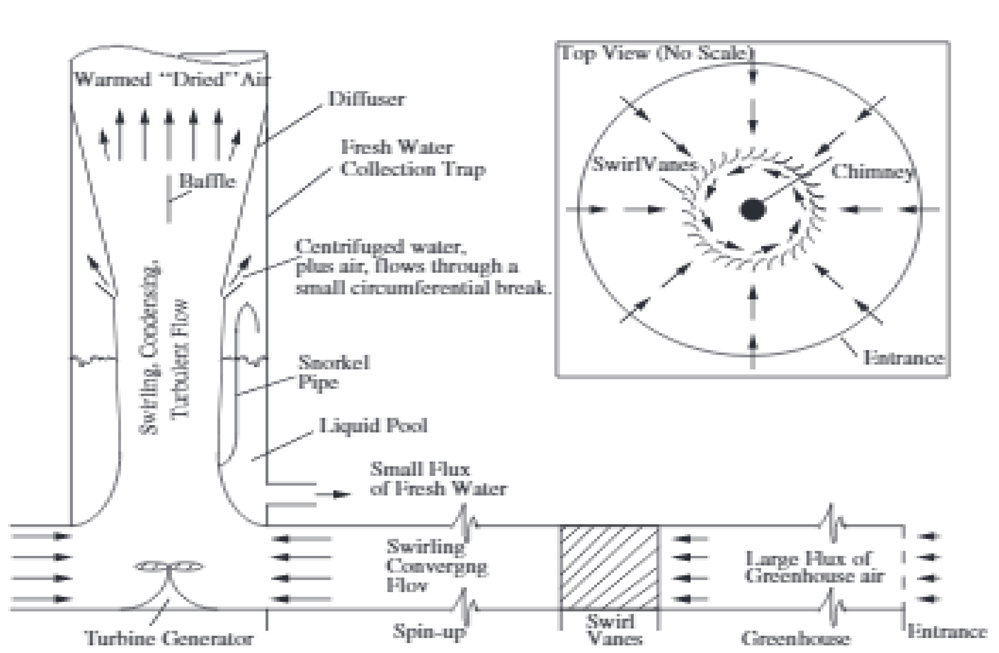


Figure 2. Operating mechanism of the SCT. Air is heated in the greenhouse or collector and a swirl component to the velocity is generated at the vanes. There is an updraft as the air rises up through the chimney [3]

It is hoped that a mechanism of direct air capture of carbon dioxide can be incorporated into the collector of the SCT.

3. Vortex Tubes

Vortex tubes have the potential to be integrated into the SCT as they are a purely mechanical device with no moving parts. Temperature drops of 40°C have been observed experimentally but carbon dioxide has a freezing point of -78 °C.

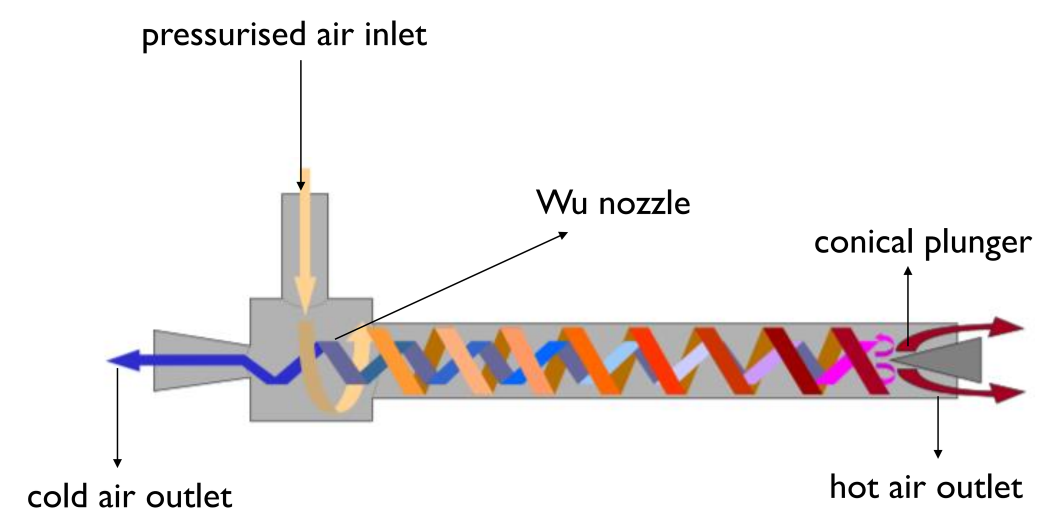
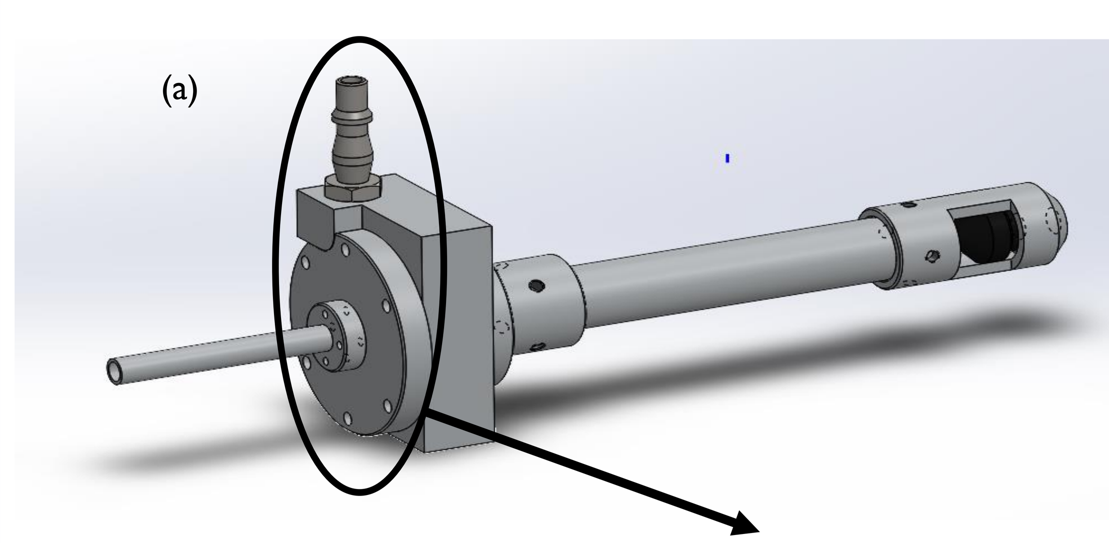


Figure 3. Pressurised air enters the tube. It then is spun by the nozzle to generate a vortex. Cold air concentrates along the centre of the vortex and hot air on the outside. The cold air is reflected back by a cone to a separate output to the hot air. [4]

The operating principle of a vortex tube is explained by Euler's turbine equation [4]:

$$T - \frac{\boldsymbol{v} \cdot \boldsymbol{\omega} \times \boldsymbol{r}}{c_p} = const$$

- T: temperature of air
- v: air velocity from rest frame
- ω: angular velocity of system
- r: radial position
- c_p: specific heat capacity of gas under constant pressure



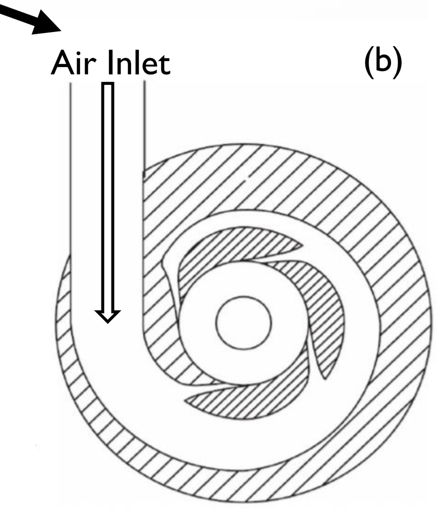


Figure 4. (a) Our CAD design of vortex tube used by Agarwal *et al.* with Wu nozzle in circled (b) schematic of Wu nozzle used to generate vortices. They have been shown to yield temperature drops of 2-5 °C greater than traditional nozzles

4. Aims

1. Build a meshable CAD model of a vortex tube with Wu nozzle for CFD
2. Reproduce and verify the experimental results for temperature difference across vortex tube observed by Agarwal *et al.* using CFD
3. Maximise temperature difference between the hot and cold outlets by varying diameter, length, cold mass fraction and inlet pressure

5. Methodology

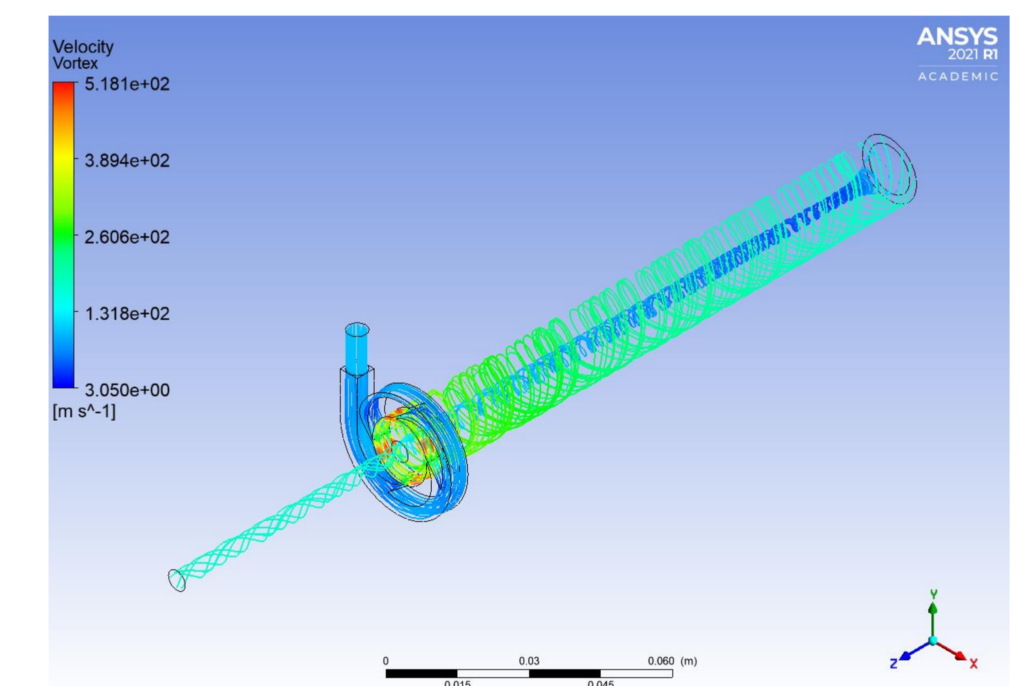
Design
- Draw 3D CAD model of vortex tube in SOLIDWORKS
- Import sketch into ANSYS and generate fluid body volume

Mesh
- Generate 3D tetrahedral mesh with inflation layers near boundary
- Find the number of cells at which mesh becomes independent of geometry

Simulation
- Set pressure outlet and wall boundary conditions and run simulation in FLUENT until convergence
- Change dimensions in geometry and inlet boundary conditions and compare

6. Preliminary Results

To test our model and mesh, the following tube was used:
- Length: 140mm
- Hot tube diameter: 16mm
- Plunger inner radius: 12mm
- Inlet BC's: velocity = 100 ms^{-1}, 9 bar pressure
- Outlet BC's: 1 bar pressure



Key preliminary findings:
1. Mesh independency for our model was achieved at 0.41 million nodes:
2. The most suitable turbulence model was the standard k-epsilon model
3. A mesh independent temperature drop of 47°C was obtained using the single vortex tube, consistent with experimental results.

7. Further Research

Imminent results are expected for temperature drop using tubes of varying length as well as diameter.

It is hypothesised that connecting vortex tubes in series will increase the temperature drop achievable. There are therefore many avenues for further work:
- Optimising the geometric configuration of multiple vortex tubes in the collector of the SCT
- CFD simulation of the temperature drop across a series configuration of vortex tubes

References

[1] https://www.climate.gov/news-features/understanding-climate/climate-change-atmospheric-carbon-dioxide
[2] Varaei S., 2019. Sensory Network for an Enhanced Solar Cyclone Tower, Imperial College London
[3] Kashiwa, B.A., Kashiwa, C.B., 2008. The Solar Cyclone: a solar chimney for harvesting atmospheric water. Int. J. Solar Energy 33, 331–339
[4] Gautam Agarwal *et al* 2021 J. Phys. D: Appl. Phys. 54 015502