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CFD Simulation of Air Compression in a Channel of a Regenerative Heat Exchanger for I-CAES

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Extended Abstract

Isothermal Compressed Air Energy Storage (I-CAES) is a variant of CAES that reduces thermal losses during compression, particularly through the use of a liquid piston, which maintains nearly reversible isothermal gas compression and improves overall efficiency [1]. Additionally, incorporating a regenerative heat exchanger (RHE) helps maintain a nearly constant temperature between the compression and intake phases, thanks to the thermal inertia of the RHE material. However, this integration reduces the available air volume and increases pressure losses in the system. These heat exchangers can take various forms, including plate, shell-and-tube, or microchannels. This study focuses on analysing the compression cycle at the micro-channel scale of an RHE to support the design process within the framework of the Air4NRG project [2], which aims to improve the efficiency of I-CAES at different scales, making it more robust and cost-effective.

Indeed, 3D CFD simulations were performed on a cylindrical channel with a diameter of 3 mm and a height of 250 mm, initially filled with water. The domain also includes an aluminium wall with a thickness of 0.25 mm, considered a no-slip boundary. A fine computational mesh with 1.15 million cells was used, with specific refinements near the walls to capture heat exchange phenomena accurately. The multiphase flow model is based on the Volume of Fluid (VOF) approach [3], with the air/water interface modelled using a surface tension of 0.073 N/m. The simulations, conducted in a transient regime, used a 1-second cycle with a time step of 0.001 seconds. Each cycle includes an intake phase where air is introduced due to the downward motion of the water in the channel. During this phase, no heat exchange occurs as the temperature is initialised at 20 °C. Once the channel is filled with air, the water reverses direction, while the inlet is converted to a wall, leading to the compression of the air up to 10 bar. The boundary condition then switches to a pressure outlet to release the compressed air. Note that the water displacement in the microchannels follows a sinusoidal pattern, reaching a peak velocity of 0.8 m/s.

The results show that during compression, the temperature remains nearly constant across the air, water, and within the material thickness, indicating uniform heat distribution. Additionally, the pressure drop and heat flux across the walls during both the ascending and descending phases have been valuable in the pre-design of the RHE for the project. However, large bubbles are observed within the micro-channel, characteristic of an air-water mixture, tending towards a churn flow regime. This was also confirmed through an experimental setup involving air compression with a liquid piston. The transparent cylindrical test section allows direct observation of the flow at the heat exchanger outlet, providing valuable insight into bubble formation and movement. The air bubbles formed remain stationary in the water and are likely to accumulate as compression cycle progresses. Ultimately, a larger channel diameter and shape modification will be considered, along with simulations over multiple cycles to further investigate temperature drift and bubble behaviour.

References

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