Industrial Vapor Recovery

A Critical Yet Overlooked Solution to the Water Crisis

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01 Executive Summary

Industrial drying uses a huge amount of water and energy, and most of it is wasted. Hot, humid air is released into the atmosphere, carrying away billions of litres of water and around 80% of the heat. Today, many companies focus on measuring water use or making it more visible with digital tools, but very few look at **recovering vapor from their own exhausts**. This is a missed opportunity to save both water and energy.

This project set out to explore how industries could capture and reuse that lost vapor. At the start, we looked into many different ideas: electrostatics, ultrasonic charging, fog nets, and new materials. Each had promise but also clear drawbacks, such as safety risks, high costs, or limited performance. After this exploration, we chose to focus on **membrane condensers.**

A membrane condenser works by passing hot, humid air across a thin hydrophobic membrane, while cold water flows on the other side. The temperature difference makes vapor condense and pass through the membrane. The result is three useful outputs: **dry air, condensed water, and energy from the warmed cooling water.**

We built a series of prototypes to test this idea. Early setups, using steam boxes and bubblers, showed the challenges of keeping the system airtight and maintaining stable temperature and humidity. Later designs used compressed air, heater to create steady exhaust conditions similar to a real dryer. Finally, we designed a plate-and-frame cartridge inspired by heat exchangers to hold PTFE membranes.

At the same time, we spoke to people in industry. They confirmed that vapor recovery is an overlooked but important opportunity, especially in fast-moving regions like China. Textile factories, for example, lose enormous amounts of water during production. Our Life Cycle Assessment suggests that recovering 50% of vapor could cut water use by 22–25% and energy use by 15–20%.

In conclusion, membrane condensers are a promising way to reduce waste and improve sustainability in industry. More work is needed to make the system durable and easy to integrate, but the project has shown that the idea is both possible and valuable.

06 Proof of Concept

With other technologies evaluated and ruled out, membrane condensers emerged as the strongest candidate—combining high recovery potential, low energy use, and practical integration into industrial systems. At this stage, the challenge shifted from theory to proof: moving beyond conceptual analysis to hands-on testing.

The prototype phase marked a turning point in our exploration. The goal was no longer to demonstrate that condensation could occur—that principle was already established—but to understand how different membrane materials, cooling strategies, and airflow conditions affected recovery efficiency under exhaust-like environments. In other words, we set out to validate not only technical performance but also the broader economic and operational feasibility of vapor recovery at scale.

06 Proof of Concept

1. Plans

The central objective was to replicate, at a small scale, the characteristics of industrial exhaust air. Research indicated that air leaving rotary drum dryers typically carries ~80% relative humidity, with temperatures ranging from 50–90 °C, and flow volumes that vary with dryer size. While full-scale systems operate at very high throughputs, our proof-of-concept could not aim for such volumes. Instead, we selected a smaller target: an outlet flow rate achievable with a compressor rated at 240 L/min.

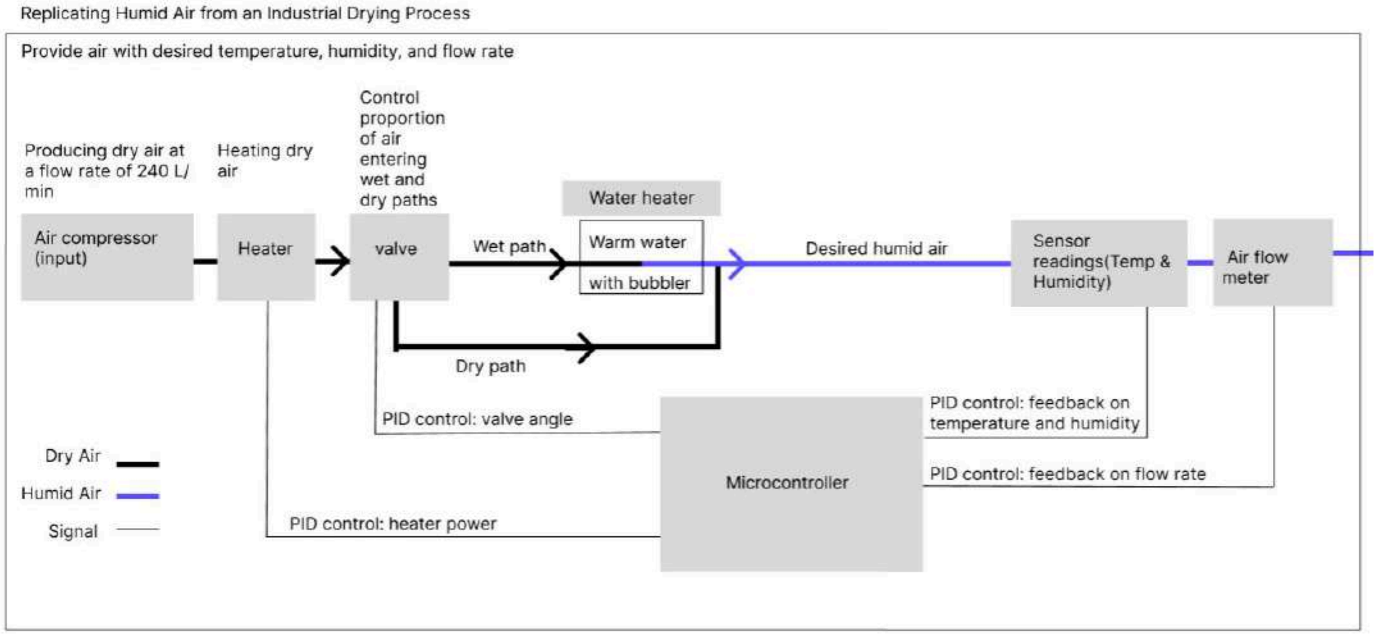
The planned setup is illustrated in Figure X (see diagram).

Heating: The compressed air was passed through a 1 kW heater, capable of raising the flow to ~100 °C at this rate.

Humidity control: To achieve adjustable moisture levels, we designed two pathways:

Dry path: dry air flowed directly from the compressor to the test chamber.

Wet path: air was bubbled through a heated water bath, with a sous-vide unit maintaining temperature. The partially filled bath created an air pocket above the surface, where bubbles enhanced evaporation and pushed humidity toward saturation (~100% RH). This humidified air was then fed into the system.



By combining the dry and wet streams through a motor-driven valve, we could dynamically regulate humidity levels.

06 Proof of Concept

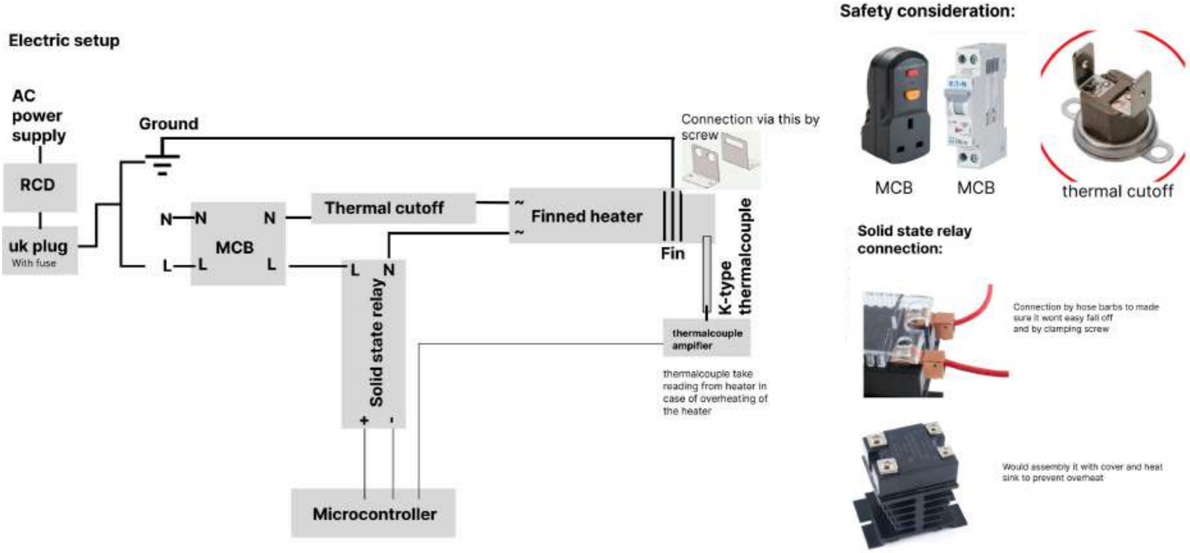
1. Plans

To maintain precise conditions, the system was governed by a PID controller. The heater was modulated using PWM, while the valve position was continuously adjusted based on feedback from downstream temperature and humidity sensors. This closed-loop design enabled the setup to reproduce the desired range of industrial exhaust conditions with both accuracy and stability.

In parallel, we designed a detailed plan for the electrical setup, with particular attention to the safety risks of operating a high-power heater connected directly to the mains. The heater was controlled via a solid-state relay (SSR), managed by the microcontroller. Simply wiring the heater directly to the relay and driving it through code was insufficient—both electrical protection and fail-safes were required. The schematic (Figure X) illustrates the full connection scheme for heater control only, including:

- Residual Current Device (RCD) and Miniature Circuit Breaker (MCB) for overcurrent and short-circuit protection.
- Thermal cutoff and K-type thermocouple for over-temperature monitoring and emergency shutoff.
- SSR with heatsink and protective casing, ensuring reliable high-current switching without overheating.
- Grounding and secure screw/clip connections to minimize the risk of loose wiring or accidental disconnection.

This design ensured compliance with standard AC safety practices, while still enabling precise, automated control via the PID loop.



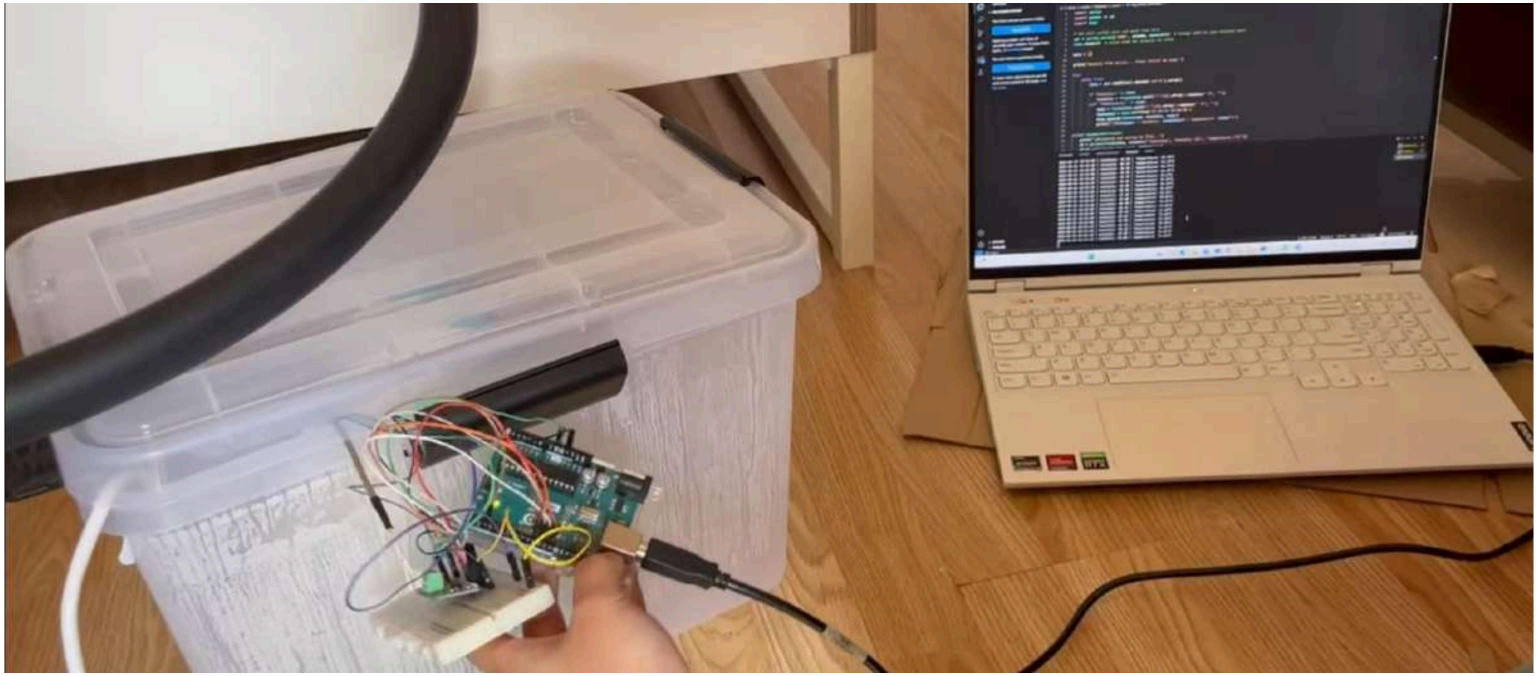
While awaiting approval for the risk assessment, we continued to experiment with multiple alternative prototype iterations to refine the system further.

06 Proof of Concept

2. Iteration 1: Steam Box Setup — Learning the Difference Between Steam and Humid Air

Our first prototype was deliberately simple. We needed a source of hot, moist air and a controlled environment to pass it over test membranes. A domestic clothes steamer and a 20-liter plastic container seemed like a straightforward way to begin. The idea was to feed steam into the container, mount the membrane in a frame at one end, and measure condensation or permeation on the other side.

In practice, this approach failed almost immediately—but the failure was highly instructive. Clothes steamers generate visible plumes of water droplets, typically larger than 10 microns. By contrast, the exhaust from industrial drying processes consists primarily of invisible water vapor molecules or submicron droplets. This distinction matters because membrane performance is strongly influenced by droplet size and phase composition. Large droplets can cause wetting and fouling, altering permeability and in some cases damaging the membrane surface.

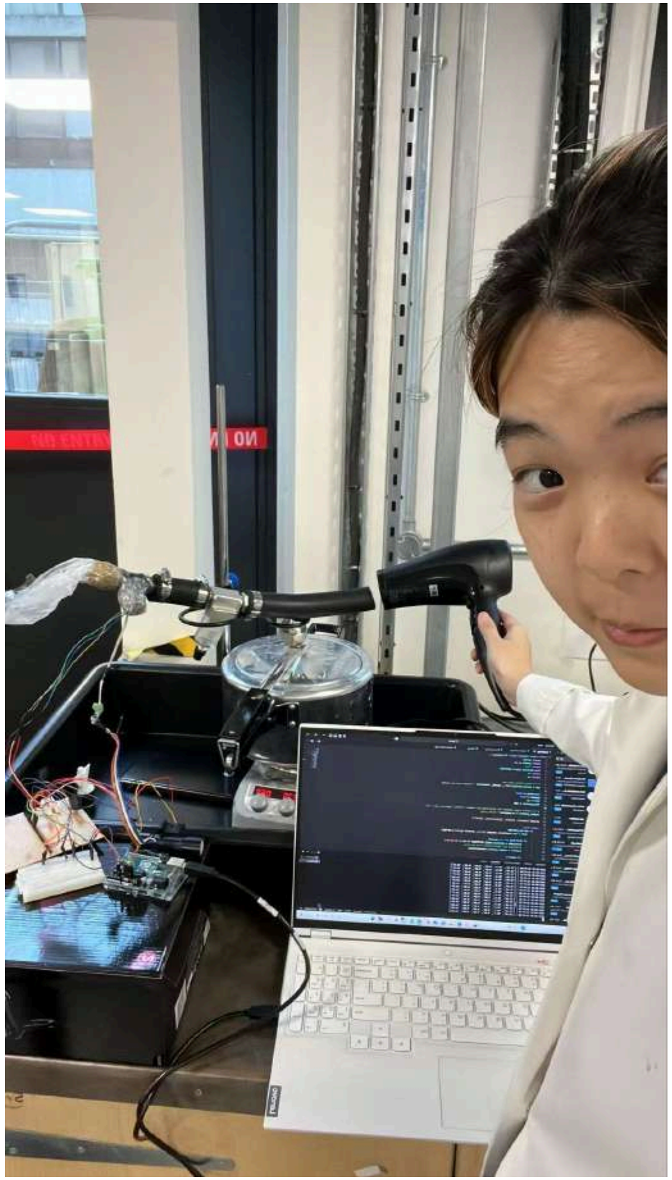


Inside the box, the environment quickly saturated at 100% relative humidity, with temperatures spiking near 80 °C. We had no meaningful control over either parameter, and the steamer's small reservoir limited the duration of flow to only a few minutes. Worse, condensation occurred almost immediately on the walls and tubing of the container, rather than on the membrane itself, rendering the data essentially meaningless.

The takeaway from Iteration 1 was clear: a successful system would need to deliver a stable, continuous, and controllable stream of hot, humid air—not a short-lived blast of uncontrolled steam.

06 Proof of Concept

3. Iteration 2: Controlled Humid Air Generator — More Control, New Problems



The second setup was designed to address the shortcomings of the steam box by providing a more consistent vapor source and at least some degree of control. We replaced the clothes steamer with a pressure cooker, modified to vent steam safely by removing the pressure valve. Steam was carried through flexible tubing toward the membrane test section, with a hair dryer positioned upstream to boost airflow and adjust temperature.

A simple water trap was added to the line, intended to strip out large droplets before they reached the membrane. In theory, this would create a cleaner, vapor-rich airstream more representative of industrial drying exhaust. Sensors for temperature, humidity, and airflow were also placed at key points to monitor conditions.

At first, results appeared promising. The system could sustain humid air for longer periods, and temperature could be adjusted by varying the hair dryer's output.

However, a new set of challenges quickly became evident:

- Droplet carryover and blockage — Despite the trap, splashes from the boiling water in the cooker carried into the tubing, eventually pooling and blocking airflow. Pressure built up behind the blockage, raising safety concerns.
- Flow restriction — The water trap introduced significant resistance, reducing airflow to near zero during some runs.
- Sensor vulnerability — Even with the trap, high moisture levels damaged the airflow sensor, which was not rated for saturated conditions.

Humidity control — Parameter adjustment remained crude. We could make the air hotter or wetter, but not with the precision required for reliable membrane comparison.

From Iteration 2, we learned the critical importance of droplet management, balancing flow resistance, and ensuring component durability under sustained hot, humid conditions. Yet the setup still failed to deliver the kind of stable, turnable airflow we needed. This led us toward a more engineered solution—similar to our initial design concept, but without an electrical heater, since its use was deemed unsafe.

06 Proof of Concept

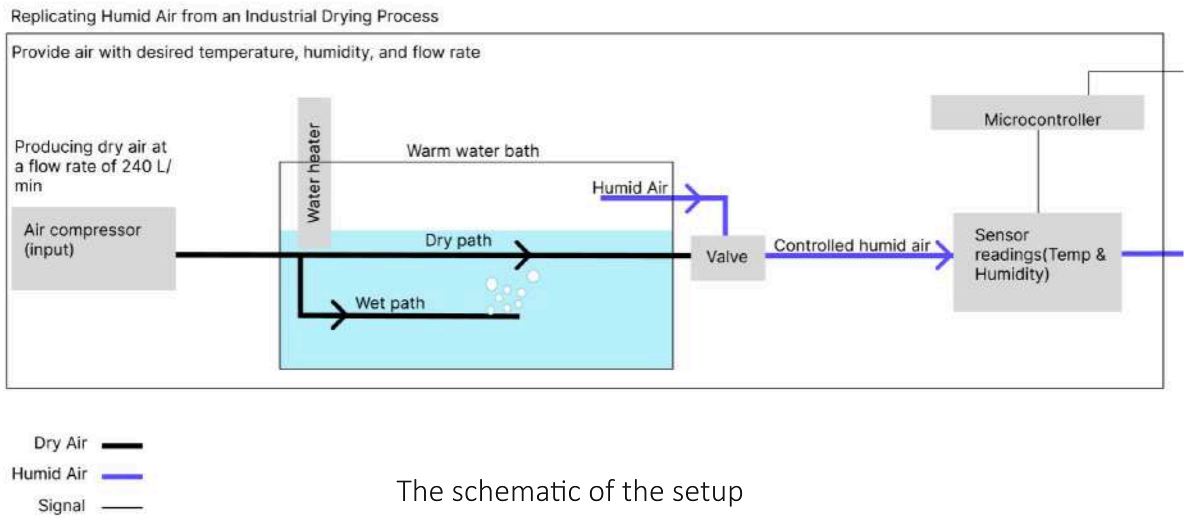
4. Iteration 3: Bubbler System — A Step Toward Industrial-Like Humid Air

The bubbler system represented our most sophisticated bench-scale attempt to simulate industrial drying exhaust. The goal was to generate a continuous, adjustable stream of hot, humid air using accessible components, while minimizing droplet carryover.
The system operated on a dual-path concept:

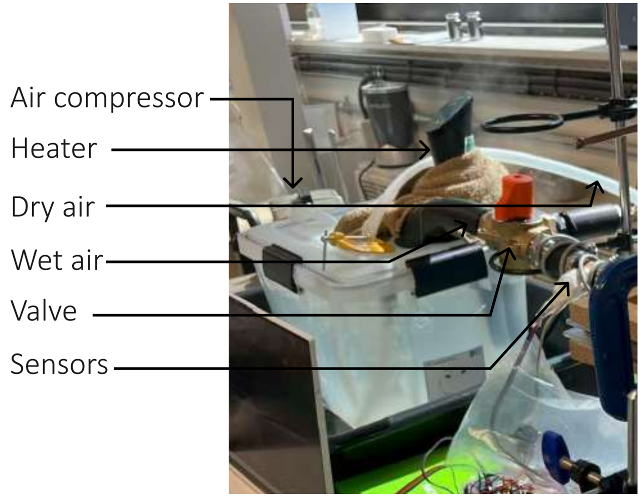
- Dry air path — Compressed air passed through a hot water bath without bubbling, serving mainly to preheat the stream.

- Wet air path — Another branch of compressed air bubbled directly through the hot water, becoming saturated with vapor.

Both streams merged at a three-way mixing valve, enabling control over the wet/dry ratio and thereby the final relative humidity. In theory, this allowed conditions ranging from ~50% to nearly 100% RH, at adjustable temperatures.



The schematic of the setup



The setup

06 Proof of Concept

4. Iteration 3: Bubbler System — A Step Toward Industrial-Like Humid Air

In practice, however, new challenges emerged:

- Heat loss — The bubbler water bath cooled rapidly once bubbling began, as the agitation increased surface contact with ambient air. We recorded temperature drops of several degrees per minute.
- Flow imbalance — The dry air path maintained higher pressure than the wet path, making precise humidity control difficult. Even small valve adjustments caused large swings in RH output.
- Tubing heat loss — Despite leaving the bath at ~70 °C, the air cooled by ~20 °C before reaching the valve, and another ~10 °C after. By the time it entered the membrane test section, the temperature was often below target.

To mitigate these issues, we applied incremental improvements:

Insulating the bath.
Replacing the dry-air tubing with a copper coil submerged in the bath.

Use a clamp on dry air tube for more precise control in humidity.

Adding heating wires along the air path.
Wrapping with insulation foam.
Shortening tube.

This setup produced stable conditions of 60–80 °C and 70–100% RH, sufficient for comparative membrane testing. Iteration 3 highlighted the importance of thermal management, pressure balancing, and adjustability—key lessons for scaling the system toward industrial integration.

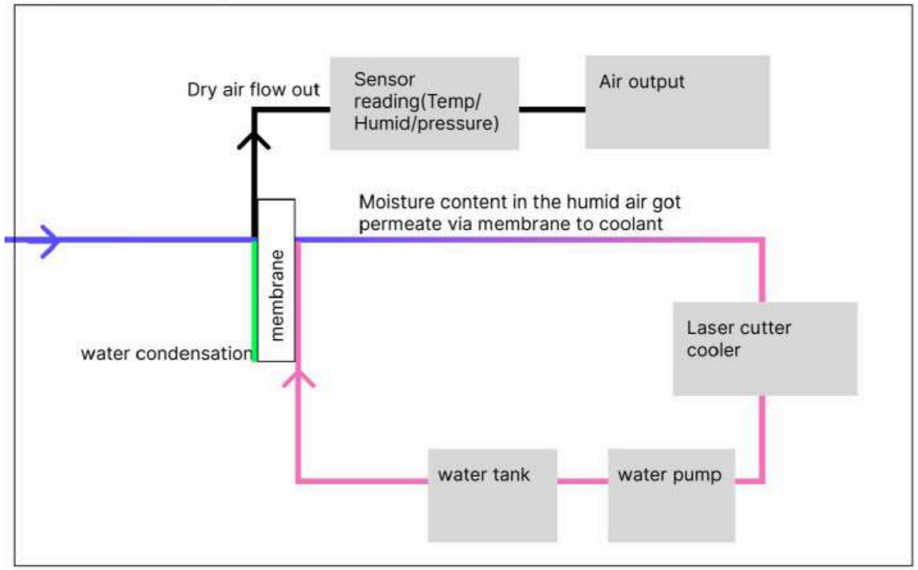
06 Proof of Concept

5. Membrane Cartridge & Cooling System Development

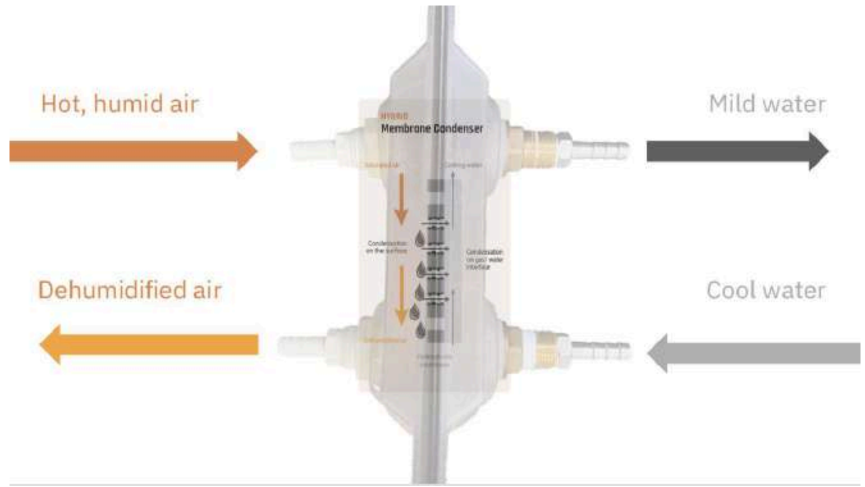
Once we had a reasonably stable source of hot, humid air, attention shifted to developing the membrane test section. To operate the system as a hybrid membrane condenser, it was necessary to create a configuration where humid air flowed on one side of the membrane while a cooling water loop circulated on the other. This setup would enable vapor to condense and permeate across the membrane into the coolant, producing dehumidified air on the outlet side.

- System schematic (Figure 1) illustrates the operating concept. Humid air is directed toward the membrane surface, where two processes occur simultaneously: part of the vapor condenses directly on the surface, while another fraction permeates across into the circulating coolant loop. The coolant system consists of a water tank, pump, and laser-cutter chiller, which together maintain a continuous flow of cold water. Downstream, sensors monitor air temperature, humidity, and pressure, providing data to evaluate overall membrane performance.

Vapour condense and permeate to coolant



- To put this principle into practice, the membrane must be housed within a sealed container or cartridge. The cartridge ensures proper distribution of airflow, prevents leakage, and enables reliable separation of the air and water streams, fitting into the working principle outlined earlier.

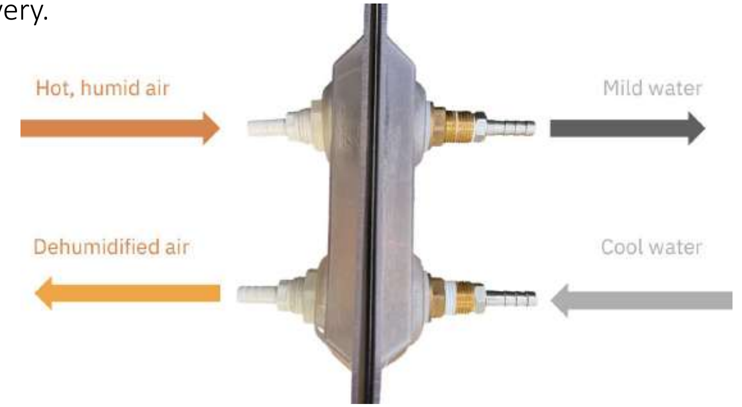


- Working principle (Figure 2) illustrates this process in action. Hot, humid air flows across the hydrophobic membrane, while cooling water is circulated on the opposite side. The temperature gradient drives vapor transport: condensation occurs both at the membrane surface and within its pores. The result is two distinct outputs — dehumidified air leaving the feed side, and coolant leaving slightly warmed after absorbing the permeated moisture.

06 Proof of Concept

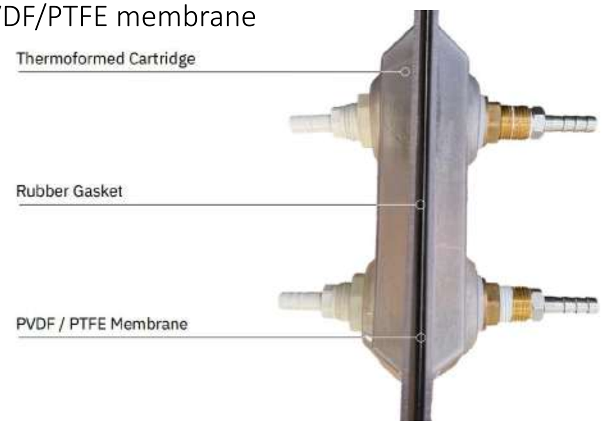
5. Membrane Cartridge & Cooling System Development

Membrane cartridge (Figure 3) presents the assembled module. Humid air enters from one side, exits as dehumidified air, while cooling water flows counter-currently across the other face. The cartridge structure ensures separation between the two streams, enabling efficient vapor recovery.

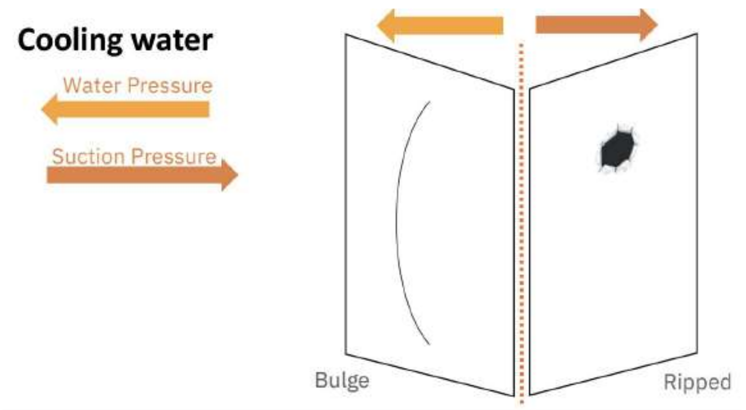


Component breakdown (Figure 4) details the cartridge construction. It consists of:

- A thermoformed plastic housing, providing the overall structure.
- Rubber gaskets, ensuring a watertight seal between components.
- A PVDF/PTFE membrane



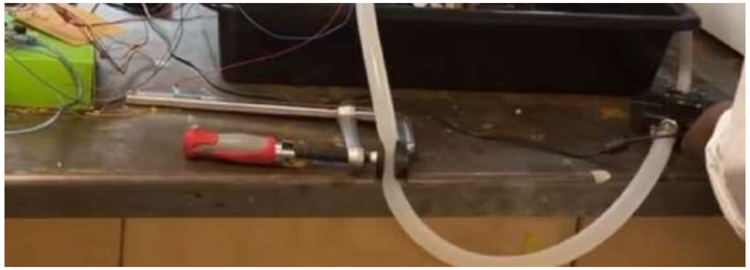
Initial trials revealed a critical challenge. Once the cartridge was connected to the cooling loop, the operation of the water pump introduced two opposing hydraulic stresses: positive water pressure from the pump on the coolant side, and suction pressure from the circulating flow in the opposite direction. These combined forces caused the membrane to bulge and rupture.



06 Proof of Concept

5. Membrane Cartridge & Cooling System Development

1. The first thing I tried was to reduce the cooling water flow rate. Our pump was oversized compared to values reported in the literature (14 L/min vs. ~2 L/min), and since the power could not be adjusted directly, I came up with the idea of using a clamp to partially block the tubing. This reduced the flow to about 4 L/min, but tightening it further introduced air gaps that could damage the pump. Even at this reduced rate, it still wasn't safe to operate the membrane. This showed us that we needed either mechanical reinforcement or a completely different cooling approach.



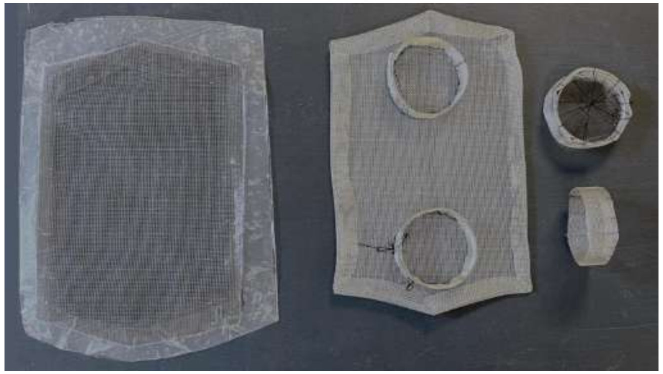
2. We then experimented with air-based cooling methods as alternatives:

   Ambient air cooling: ineffective, giving only about a 10 °C temperature drop.

   Fan cooling: slightly better, about 15 °C, but still insufficient for condensation.

3. Since the alternative approaches failed, we returned to the water-loop system and focused on reinforcing the membrane mechanically. Our first attempt was to insert metal mesh supports between the membrane and the rubber gaskets, but this led to significant leakage. We traced the problem to two likely causes: the mesh was too thick, and its uneven edges created gaps at the gasket interface.

4. To address this, I embedded the mesh edges in plastic, trimming off sections that overlapped with the gasket and using tape and plastic to create a smoother sealing surface (Figure, left). In initial tests, the membrane held in place, but after ~15 minutes of water-loop operation, small leaks began to appear.



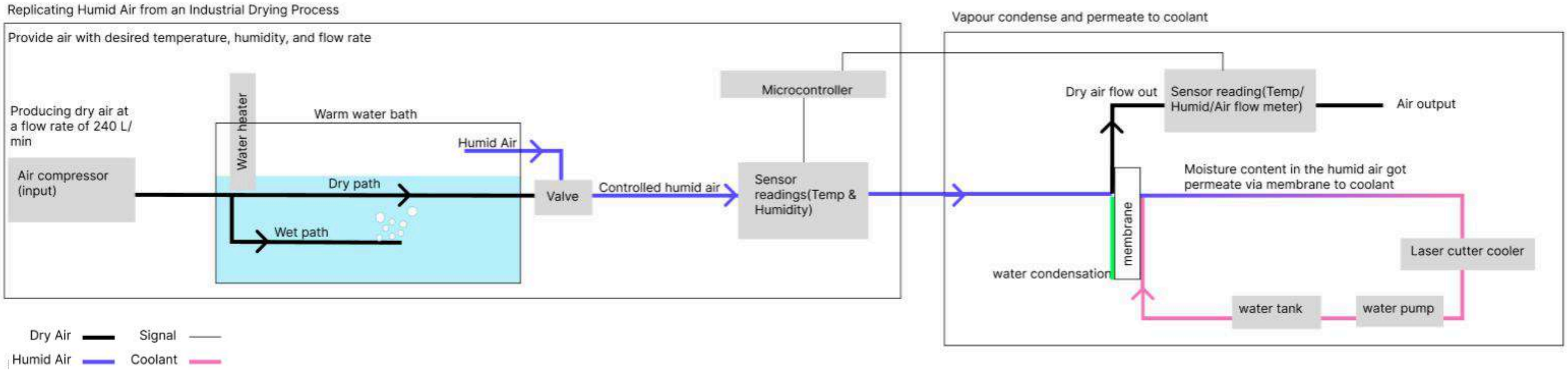
5. We then developed two new support designs (Figure, right). On the air side, a hollow metal shell was added, with a height matching the spacing between the plastic shell and the membrane, to limit membrane movement. On the coolant side, we built a hollow support with an acrylic end plate that pressed gently against the membrane, preventing tearing.

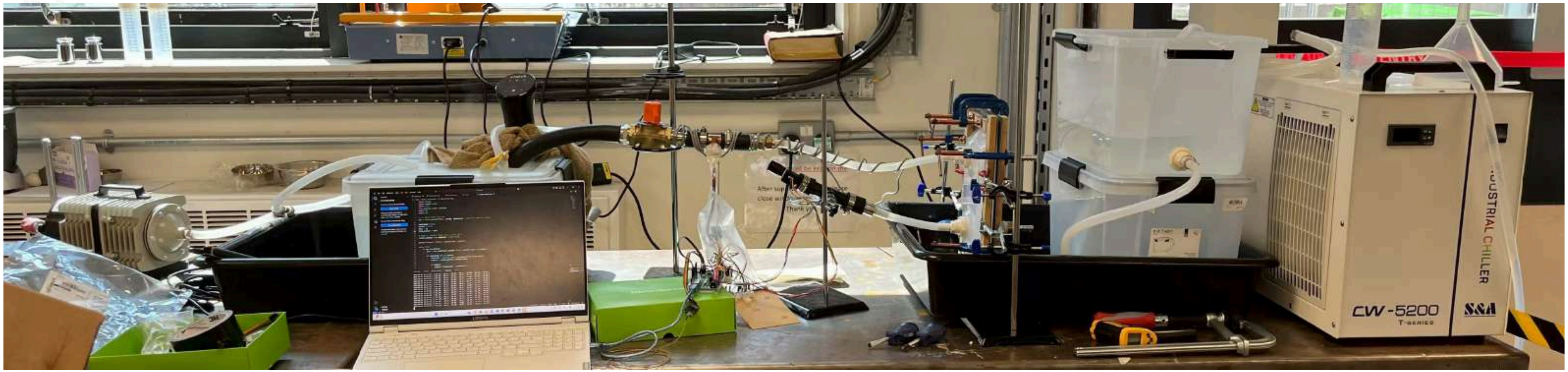
With these reinforcements, the setup finally functioned as intended. The membrane remained stable, and although the water-side support shifted slightly due to insufficient height, this did not affect overall performance.

06 Proof of Concept

6. Result

With these reinforcements, the setup finally worked. The membrane held in place, and although the water-side support shifted slightly because its height wasn't sufficient, performance was not affected.
Here is the final overall systematic diagram of the setup.





The setup

06 Proof of Concept

6. Result

To evaluate the performance of the PVDF membrane (pore size = 0.2 µm), we conducted a final test in which the inlet and outlet conditions were monitored using DHT sensors. Both temperature and relative humidity were recorded over time, and the corresponding water vapor mass flow rates were calculated according to the procedure described in Section X.Y. The cumulative inlet and outlet vapor content was then integrated to determine the fraction of condensed water.

Temperature Profiles

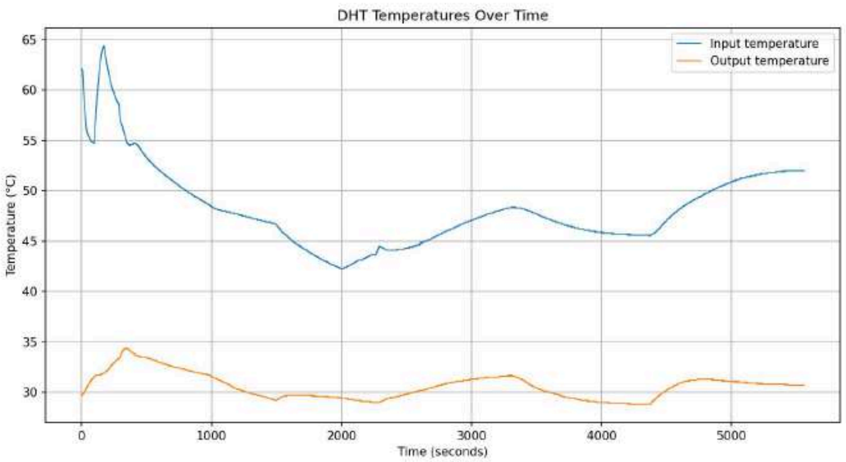


Figure 1. Inlet and outlet air temperatures over time.

Figure 1 shows the measured inlet and outlet air temperatures over time. The inlet air initially entered at approximately 60 °C before gradually cooling to ~50 °C. In contrast, the outlet temperature remained consistently lower, between 30–35 °C. This temperature gradient across the membrane is a necessary driving force for condensation and confirms effective thermal exchange.

Humidity Profiles

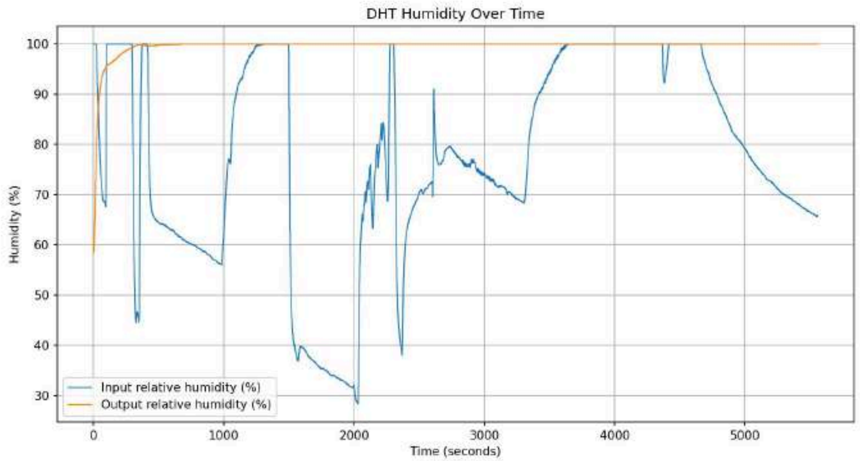


Figure 2. Inlet and outlet relative humidity over time.

The relative humidity values for both inlet and outlet are presented in Figure 2. The inlet humidity fluctuates significantly during the experiment, likely due to flow instability and sensor sensitivity at high humidity. Meanwhile, the outlet humidity rapidly reached near-saturation (~100%) and remained stable throughout the test. This observation is consistent with the presence of condensation, as the outgoing air was nearly saturated at the outlet temperature.

06 Proof of Concept

6. Result

From the temperature and humidity data, the absolute humidity (water vapor concentration) at both inlet and outlet was computed using the saturation pressure relationship and converted into mass flow rates. Integration of these values over the experimental duration yielded the cumulative transported water vapor, shown in Figure 3.

The inlet cumulative water vapor increases steadily with time, while the outlet curve rises at a lower rate. The difference between these curves corresponds to the condensed fraction. Over the course of the experiment, **approximately 40% of the inlet water vapor condensed onto the membrane surface**. This observation was also supported by visible condensation forming on the membrane during operation.

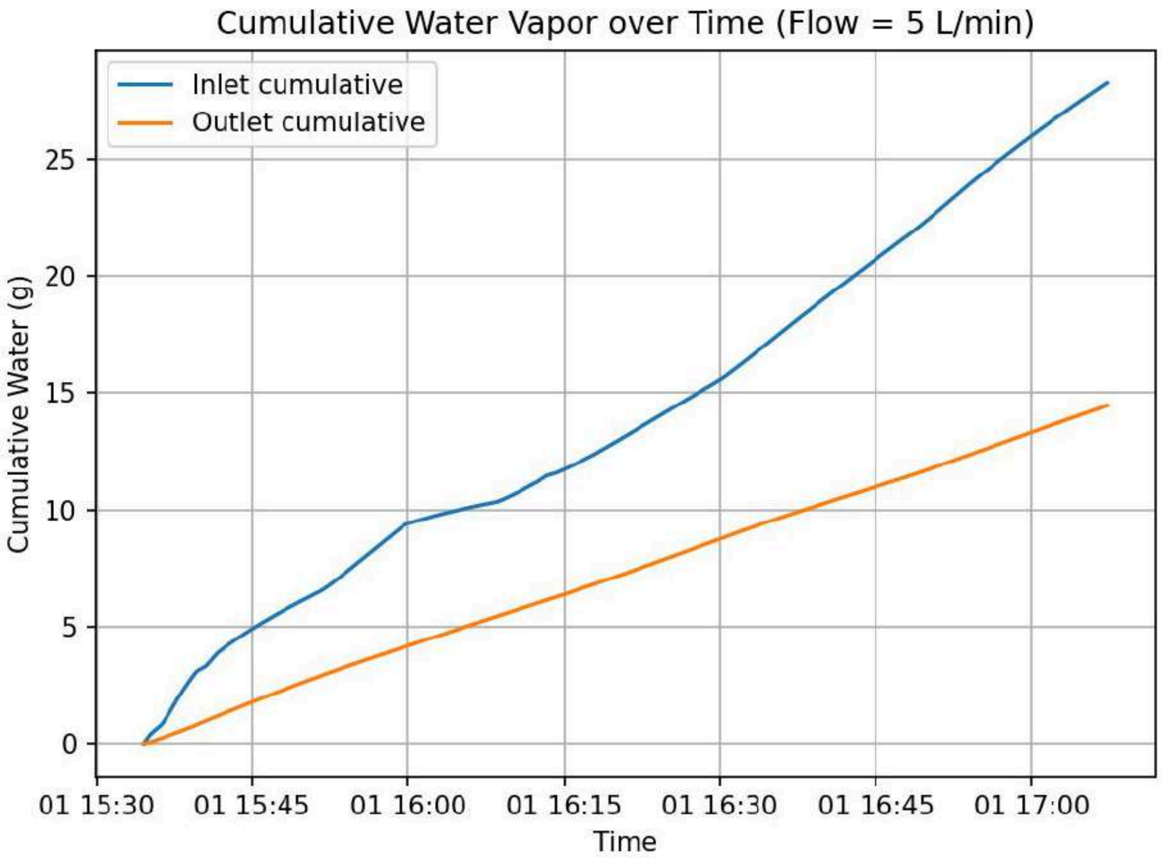


Figure 3. Cumulative inlet and outlet water vapor over time. The gap corresponds to the condensed fraction.