

Investigating the Efficiency of Fog Water Harvesting Methods

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The quest for finding life beyond Earth has motivated researchers to explore the environmental conditions for other planets. Venus has presented evidence exhibiting the potential of habitability, and missions are now targeting Venus's atmosphere to learn more about its chemical composition and how it could support life. For this experiment, three different meshes – fiberglass, Teflon cut into a Raschel mesh design, and mylar cut into a kirigami design – were implemented to collect and condense water vapor emitted from a humidifier. The expected efficiency of the kirigami mesh was 16.1%, however it was reported to be almost negligible after this experiment [6]. The collection efficiency of the fiberglass mesh and Raschel mesh was 11.40% and 1.80%, respectively. In conclusion, the most efficient method for fog water harvesting is the fiberglass mesh, with applications extending to future work on Venus in the search for life.

I. Nomenclature

cm	=	centimeter
CO ₂	=	carbon dioxide
D ₅₀	=	median droplet size
dyn	=	dyne, a derived unit of force
g	=	gram
H ₂ SO ₄	=	sulfuric acid
kHz	=	kilohertz
m	=	meter
mL	=	milliliter
NIAC	=	NASA Innovative Advanced Concepts
κ	=	kappa, proportionality constant for nebulizers
λ	=	capillary wavelength
μm	=	micron (micrometer)
π	=	pi, constant = 3.14159265359...
ρ	=	density
σ	=	surface tension

II. Introduction and Background

The scientific discussions about the presence of life beyond Earth has paved the way for many discoveries. Recent breakthroughs, such as the indication of methane lakes on Titan, subsurface oceans on Europa, salty plumes on Enceladus, and the potential presence of phosphine in the upper atmosphere of Venus, have enhanced the probability of these planets harboring extant life [1]. The habitability of Venusian clouds has been a research subject for several decades. Venusian clouds form the largest aerosol system among the terrestrial planets [2,3]. Research indicates that Venusian clouds contain sufficient mass balance to preserve water, solutes, microorganisms, and potential life due to favorable physical and chemical conditions. The cloud layers of Venus have similar pressure and temperature conditions as that of Earth. While it is known that Venusian cloud particles consist predominantly of liquid droplets containing solutions of sulfuric acid, H₂SO₄, in water (72-99% acid strength depending on altitude), new insights into further breakdown of the chemical composition of these clouds are still needed to understand the implications of habitability [4]. Thus, Venus has acquired the attention of space researchers and is contemplated as an astrobiology target for better understanding the origins of life [5].

Several mission concepts include exploring the Venus clouds to search for signs of life and assess the potential of habitability [1]. The focus of these missions is to investigate the habitability of cloud particles by determining the amount of water vapor in the cloud layers or acidity strength of the droplets as well as other chemical compounds that may be present in the clouds in trace amounts. The technology needs to be developed such that it can perform aerial operations to investigate the clouds and explore biosignatures.

The vision is to design an instrument capable of measuring the water droplets and acidity required for life's metabolism. State of the art is being performed to understand such existing models. This project can further support the assessment of sampling in the context of balloon ascents under study for NIAC Phase I with an aim of collecting cloud aerosols from Venus to perform chemical analysis at various altitudes in the Venus atmosphere [6]. The aerosol collection device would be the balloon payload. The long-term goal of this project is to be able to collect condensed water as well as sulfuric acid and other unknown chemicals from the clouds of Venus to develop a full chemical composition table of Venusian clouds that can then serve as evidence for the presence of life.

Due to resource constraints, this vision was remodeled to design a system capable of harvesting water, rather than sulfuric acid or other chemicals. To find the optimal material and mesh design for the water collector, three different designs were implemented: a natural fiber pad made of fiberglass, a kirigami mesh made of a mylar sheet, and a Raschel mesh made of a Teflon sheet. The kirigami [6] and Raschel meshes [7] were both based on existing meshes that we studied in our literature review. The kirigami mesh is composed of alternated mountain and valley folds which is what forms the pocket that the vortices form. These vortices compound smaller water particles until they are large enough to condense. The Raschel mesh is based on a trapezoidal pattern cut into the material. The slant in the triangle is what allows for the particles to compound as they slide down. Finally, we have the natural fiber mesh which we are not modifying at all. This mesh uses its dense fiber network to capture incoming water particles and gravity to bring them to the bottom. All three of these materials have high chemical resistance to acidic reagents, particularly sulfuric acid, allowing for the experiment to be repeated in the future under Venusian atmospheric conditions. The idea is to harvest water by inducing the micro size fog particles to condense on the surface of the mesh, then flow down into the trough once the condensed droplets become sufficiently heavy for gravity to force them downwards [8,9]. Fog collectors can generally harvest from 2-10% of the air moisture, depending on the efficiency of the system [8]. The performance of this model is measured by efficiency, which is dependent upon the material of the net and size of the holes.

III. Methods

Considering the timeline constraint, it was difficult to come up with a full working payload, hence we focused on one aspect of the payload: water extraction. (Since Venus' atmosphere is very rich in CO₂ and extracting a liquid sample would likely be very acidic, we will focus on water harvesting for this project instead.) Depending on the results of our experiment, we will be able to determine future applications and extend this system to extraction of aerosols in the Venusian atmosphere, such as sulfuric acid collection.

Several assumptions were made while performing this experiment such as neglecting the atmospheric variations including pressure, density, and temperature. The altitude is assumed to be constant in this experiment. The experiment is also performed under negligible windspeed as it was conducted indoors.

Our apparatus was based on an existing model shown below in Figure 1. We used different materials such as Mylar, Teflon and fiberglass for fabricating the meshes. The fog will be generated by a household humidifier combined with an atomization module (also referred to as an atomizer) that vibrates at a frequency of 108 kHz. By substituting this excitation frequency, F , into Equation 1 below (with density 1.00 g/cm³, surface tension 72 dyn/cm, and $\kappa = 0.34$), it was determined that the median droplet size emitted from the humidifier/atomizer combination was 18.3 μm .

$$D_{50} = \kappa\lambda = \kappa\left(\frac{8\pi\sigma}{\rho F^2}\right)^{\frac{1}{3}} \quad (1)$$



Figure 1. Fog Collection System [6]

With the basic concept from the fog collection system above, our rig, shown in Figure 2, was made to be modular and capable of swapping out different meshes.



Figure 2. Disassembled Rig



Figure 3. Assembled Rig

As shown in Figure 2, the rig is composed of a baseplate, two vertical members, two laser cut pieces that house the mesh, and an eyebolt-nut-washer system that claps the laser cut pieces to the mesh. The assembled rig is also shown above in Figure 3. The rig has a CNC machined, 1-inch-wide channel that goes from a 0.25" depth at the beginning to a 0.5" depth at the end. This allows for the water to travel down the base plate, through the blue 3D printed nozzle, into the collection container. The eyehole bolt slides up and down the vertical members allowing for the mesh to be replaced. Additionally, the use of bolts and washers to secure the laser cut pieces allows for the mesh to be clamped. Changing out the mesh simply involves removing the nut, replacing a new mesh, around 6"x6" in dimension, between the two pieces, and re-securing it. The rig also includes laser cut spaces that slide on the vertical members that increase the space between the bottom of the mesh and the channel of the base plate. This extra bit of flexibility allows for meshes larger than what was used in this study to be tested.

The next goal was to manufacture the kirigami and Raschel meshes. As the materials for both are very thin, laser cutting was deemed the easiest and most effective option. Fortunately, the fiber mesh, shown in Figure 8, only needed to be cut to size and required no additional modification. The manufactured meshes are shown in Figures 6 and 7. The geometries used for the core pattern are shown below in Figures 4 and 5. These numbers were extrapolated from the corresponding studies for each mesh [7,8].

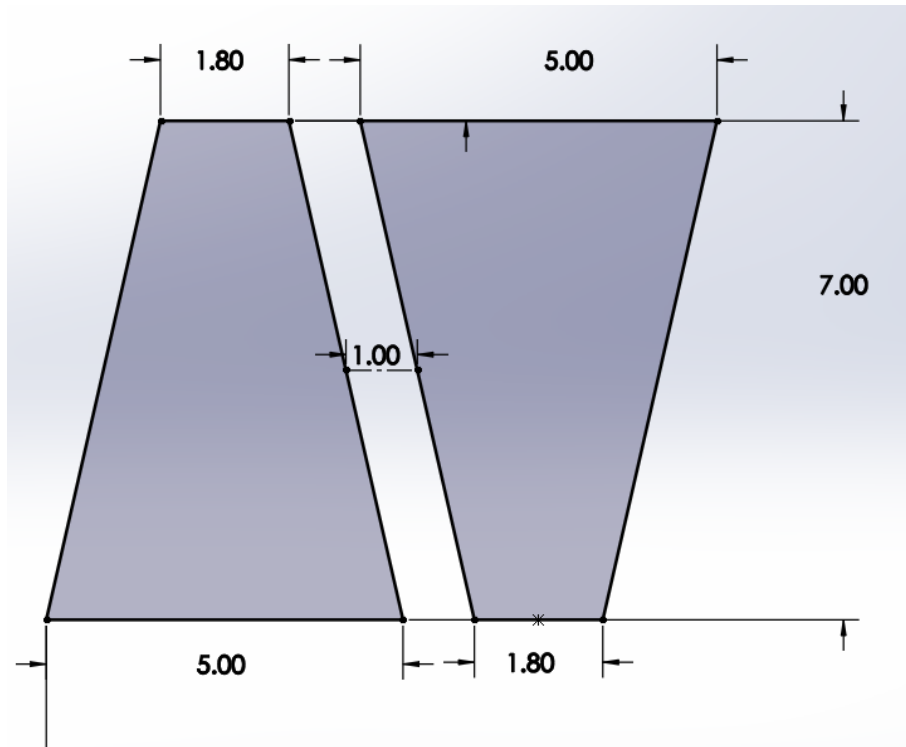


Figure 4. Raschel mesh pattern geometry (mm)

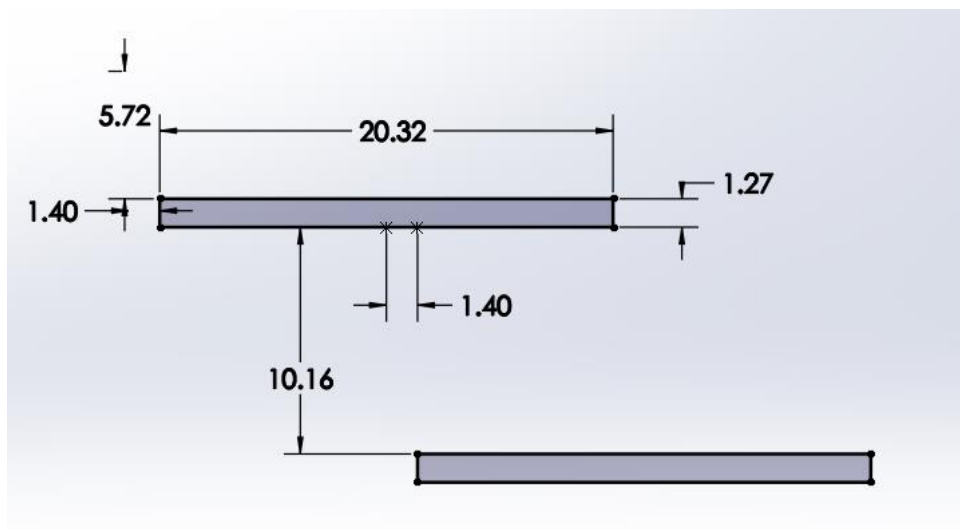
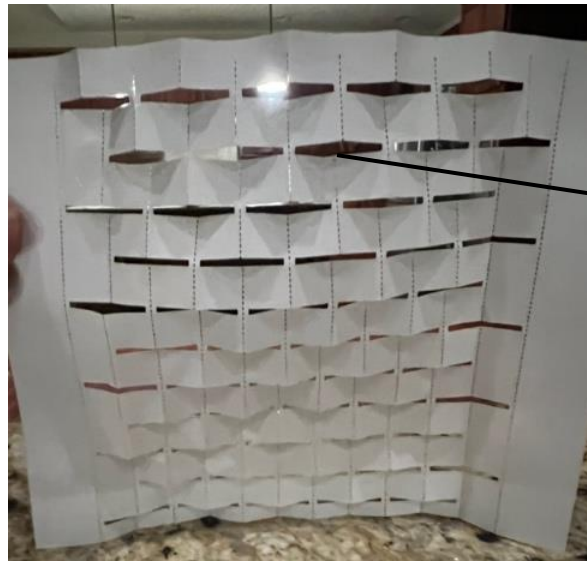


Figure 5. Kirigami mesh pattern geometry (mm)



Fog droplets
will be
streamlined
through the
cuts

Figure 6: Close-up view of the kirigami mesh



Figure 7: Close-up view of the Raschel mesh

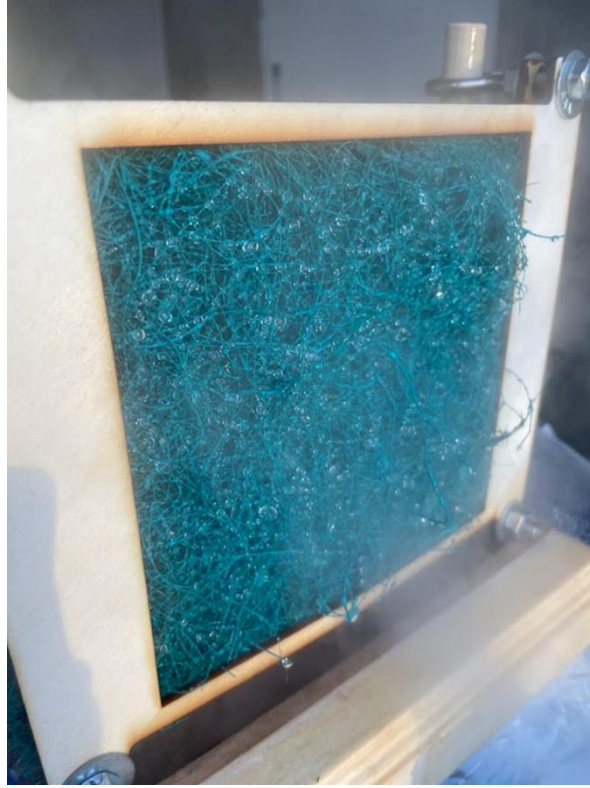


Figure 8: Close-up view of the fiber mesh

Although this technique of fog collection is not unique, our goal is to test how feasible this system would be for particle sizes that represent the Venusian atmospheric particle size. The existing methods have been successful for particle sizes similar to raindrops and cloud droplets on Earth, ranging from 1-10 μm in diameter. The 18 μm particle size that was utilized for this experiment is more representative of particle sizes in the clouds of Venus [10]. The “drier” the mist, meaning the smaller the particles, the more representative our experiment will be of the dry Venusian atmosphere, which has humidity levels generally below 0.4%. The atomizer (seen by the flashing light in Figure 9) will be placed towards the top of the channel where water vapor is emitted from the humidifier to allow for control of the particle size. To avoid the risk that the atomizer will not be able to produce enough water flow rate, the humidifier was turned ON to ensure sufficient flow from the holding tank to the channel that pumps water vapor out into the environment.



Figure 9: Humidifier and atomization module

The humidifier will be placed so that the atomized particles released will hit the fog mesh directly. According to current studies, many existing fog collection devices produce anywhere from 0.5 to 2.5 liters of water per square meter of material per day, or an average of 1.5 liters per day (62.5 mL per hour). According to the study from Figure 1, which we are modeling, our goal is to collect at least 240 mL in ~100% humidity since the expected efficiency is approximately 16.1% [6]. We will have a plastic container placed to the side of the apparatus below the blue nozzle, which will collect the water that flows out of the trough. The total amount of water collected will be measured using a 100 mL graduated cylinder. Then, the volumetric efficiency of each of the three meshes can be calculated and compared for analysis.

IV. Results

Quantitative Results

The volume of water collected in the plastic container out of the total volume 1500 mL that was dispensed from the humidifier is used for computing the efficiency. The efficiency was calculated by using the following formula and is tabulated in Table 1.

$$\text{Efficiency (\%)} = \text{Volume Collected} / \text{Total Volume} * 100 \quad (2)$$

Table 1: Comparison of Efficiency for Different Meshes

Mesh Type	Volume Collected (mL)	Efficiency (%)
Raschel (Teflon)	27	1.80
Natural Fiber Pad (Fiberglass)	171	11.40
Kirigami (Mylar)	10	0.67

Each trial lasted about 10-12 hours, which was the time it took for 1500 mL to be dispensed through the humidifier. The humidifier was always left in its HIGH mode to maximize the humidity level to as close to 100% as possible. One trial lasted approximately less than 10 hours while another trial lasted almost 13 hours simply because the rate at which the water was dispensed from the tank was not consistent amongst the trials. The flow rate can only be estimated

at an average of 136.36 mL/hour, or 3.27 liters/day. Unfortunately, this flow rate was not a factor that could be controlled and kept constants for all trials.

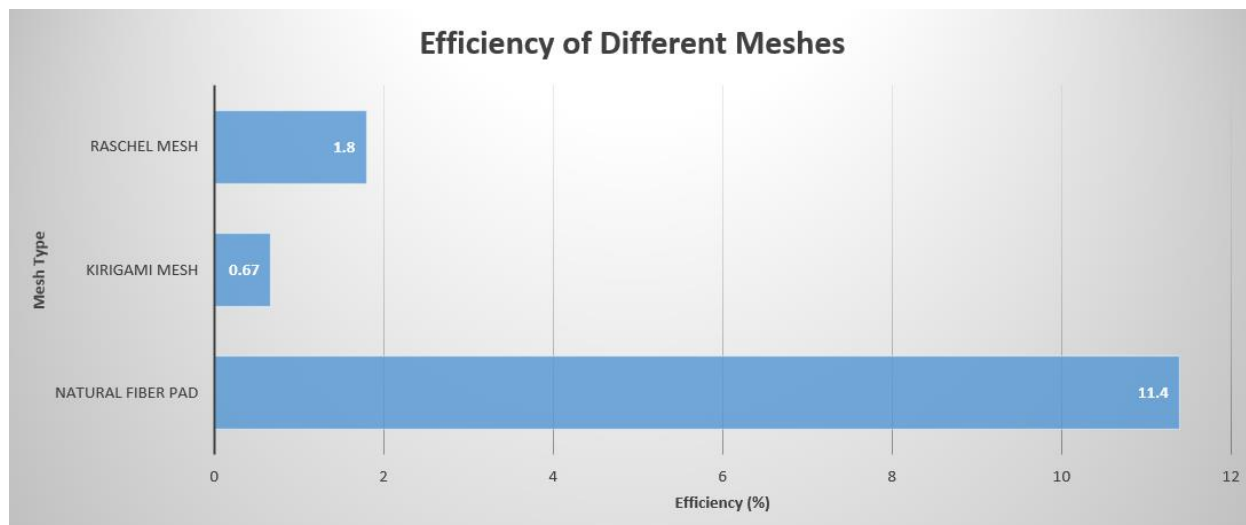


Figure 10: Efficiency for Different Mesh Structures

The visual representation of the efficiency of each mesh structure is shown in Figure 10. The natural fiber pad reported 11.40% efficiency, which can be seen as significantly higher than that of the kirigami and Raschel meshes. The efficiency of the mesh depends on the material, the environmental conditions and orientation of the structure.

Qualitative Results

The first trial was the Raschel mesh made of the Teflon sheet as shown in Figure 7. For this first trial, the plastic container was left uncovered so a large portion of the water collected by the end of the experiment may have been water landing inside the box directly as it was dispensed from the humidifier, as seen in Figure 11. There were also many water droplets that had gathered on the surface of the table and cardboard boxes involved in the setup by the end of the trial. From this, we understood that although the humidifier was angled in a way such that the dispensed water would directly hit the mesh, due to air conditioning inside the room, there were small bits of fog that deviated from this expected flow. And this deviation may be a reason for the inaccurate volume measurement for the Raschel mesh trial.

Before the second trial, the experimental setup was modified – plastic wrap was added so that the top of the collection box was fully covered from the environment. This change can be seen in Figure 12. That way, the only water droplets that were able to be collected in the container were water droplets that dripped from the nozzle of the rig. The measurements from the second and third trials have much higher accuracy because of this change in setup.

One interesting qualitative observation from the fiberglass mesh was the way in which water droplets condensed across the span of the mesh before dripping to the bottom of the mesh and through the rig design. In Figure 8, there are water droplets forming from the fog located throughout the mesh, and once these droplets become heavy enough, they collectively drip to the bottom due to gravity. The kirigami mesh, on the other hand, did not have water droplets that condensed throughout the mesh – the water dripped to the bottom of the mesh first and larger droplets formed at the bottom of the mesh before dripping into the trough. There was never a point in which small water droplets could be seen all across the mesh.



Figure 11: Kirigami Mesh (Mylar)



Figure 12: Natural Fiber Pad (Fiberglass) Mesh

V. Discussion

The designed model was successfully able to capture the size of Venusian atmospheric particles, around $18\ \mu$ in diameter. The water droplets were condensed using the humidifier and collected using the measuring cup. The process is directed by law of gravity in physics. The efficiency of the natural fiber pad was 11.40% which was greater than Teflon and kirigami. In kirigami, the vorticity is dependent on the incoming flow velocity, which was likely to be insufficient, hence kirigami couldn't provide better efficiency. The Raschel provided a larger surface area due to the smaller core geometry. The water collection was enhanced by the Teflon's water resistance. The thickness of natural fiber is $\sim 1''$, which greatly helped in increasing fiber density and hence, providing the greatest water collection. These designs can be modified to increase efficiency which can be well implemented in dry environments to collect the water particles. It can further find its application in the Venus environment for collecting the water and acid particles from the Venus clouds where humidity levels are generally below 0.4%. For future experimentation, it would be helpful to repeat the experiment with different humidity levels and flow rates, larger surface area of the mesh, and varying windspeeds to determine whether it is feasible to attach this apparatus to the payload of a balloon that could ascend through the atmosphere of Venus and collect aerosols. Additionally, by combining the best properties of each mesh (aerodynamic assisted collection, slanted compounding, and multiple layers), a new mesh could be manufactured that could potentially yield better results than the natural fiber mesh. The instrument suite can be integrated in the aerial missions for Venus and facilitate understanding the unknown chemistry and possibility of life itself.

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Author Contributions

A.M. and S.N. originated the concept; A.M. and S.N. performed a literature review. A.M designed and built the mesh testing rig. A.M., S.N. and D.S. organized the experiment and analyzed the data. D.S. wrote the introduction and methods. A.M., S.N. and D.S. wrote the results and discussion. All authors edited and approved the manuscript.

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