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Investigation of fluid capillary rise using 3D printed microstructure for solar desalination

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Abstract. Current desalination technologies such as thermal desalination and reverse osmosis are a process of converting seawater to freshwater. This method brings a negative impact on the environment such as CO_2 emission. Solar desalination is one of the ways to resolve the current desalination challenges and more sustainable in terms of economic and environmental. Solar desalination uses solar energy as its energy consumption for evaporation. Solar desalination depends on the rate of evaporation specifically on the surface area. Hence, this study adopts the concept of cellular fluidics and 3D printing to perform capillaries rise and improve the liquid to the gas-surface area. The increase in strut diameter of the cell from 0.2 mm to 0.4 mm results in an increase of capillaries rise from 3.01 to 7.67 for Body Centered Cubic (BCC) cell geometrical shape. Different cell geometrical shape is also investigated with the strut diameter remaining constant. The Isotruss cell geometrical shape recorded a value of capillaries rise of 11.76 among the other geometrical shape due to Isotruss having more complexity in design and having internal structure.

1. Introduction

The mother planet 'Earth' consists of land and water. The majority of the water on Earth is from the ocean which contributed 97.5% to the global total water however seawater is not safe to drink due to high saline and high mineral. The remaining 2.5% is freshwater and two-thirds of it was trapped in either ice caps or glaciers. Another one-third of the freshwater also known as groundwater and lakes that were remained accessible [1, 2]. The scarcity of freshwater supply was the exponentially growing population of the world, by 2025 world's population will rise to nearly eight billion [1]. Besides, pollution affects the freshwater supply including agricultural fertiliser and industrial waste [1, 3]. The abundance of seawater remains unutilised on Earth, and scientists and engineers have introduced the desalination process. The desalination process uses seawater as the intake and removes the salts and minerals content in the process and ultimately produces freshwater that is suitable for human consumption and agriculture use, desalination remains a critical source of freshwater production in many water scarcity countries. The current desalination process comes with multiple methods such as multi-stage flash (MSF) distillation, multiple-effect distillation (MED), vapour compression, and reverse osmosis (RO) [4-6]. The current commercially viable desalination processes were dominated by MSF, MED and RO processes. MSF and MED processes were established as early as the 1930s in the Middle East in Saudi Arabia [6]. The MSF process used seawater as an intake to produce freshwater through evaporation by reducing the pressure and increasing the temperature of the system [4]. Next, the MED process uses seawater as an intake and produces freshwater through multiple evaporators by reducing the pressure of the process [4]. Then, with the discovery of membrane technologies in the 1960s, the RO process started to gain popularity and slowly replace MSF and MED processes due to its space-efficient, scalable, and lower energy consumption [4-6]. RO process currently contributed 69% of the total volume of desalinated water produced, followed by MSF and MED both contributed 25%, and others by 4% [5]. To address the current desalination plant challenges high energy requirements, a sustainable solution with energy-efficient low-cost desalination and achieving zero carbon emission are critical for the future trend of desalination technology development. Some of the emerging desalination technologies in recent were forward osmosis (FO), membrane distillation (MD), and electrodialysis (ED) as they have a growing trend of research publication [6]. However, these emerging technologies still require high energy input to operate [6]. Besides, having unlimited energy from the Sun (solar energy) and an abundance of seawater on Earth, solar-powered desalination has gained popularity recently due to the growth of solar technologies and water demands. Hence, solar desalination is exciting to study and discover to achieve economically and environmental sustainability. Direct solar desalination systems such as solar still (SS) (**Figure 1**) in which using seawater as an intake and solar energy to heat the seawater in an enclosure, when evaporation takes place the water vapour then condenses on the glass wall and freshwater is produced [7]. SS process will have carbon net-zero emission to the environment due to it using renewable solar energy. However, solar still freshwater production was dependent on the passive solar energy and liquid to the gas-surface area for evaporation. The factor that affects the rate of evaporation were wind speed, humidity, temperature, and surface area. SS were dependent on the temperature from the solar radiation and liquid and gas surface area for evaporation. Research on solar-driven water evaporators to tackle high salinity desalination was conducted by using a bio-mimetic 3D structure with a freshwater collection rate of 1.72 $kg/m^2/h$ with a promising 96% efficiency [8]. The concept of cellular fluidics was introduced to model a three-dimensional structure with a unit-cell design to promote the capillary rise in conjunction increase the liquid to gas surface area in an open-cell structure [9]. With the use of cellular fluidic, capillaries rise of the water will climb in the 3D-printed structure and promote more liquid to gas surface area, hence, improving the rate of evaporation of the SS process and ultimately more freshwater production.

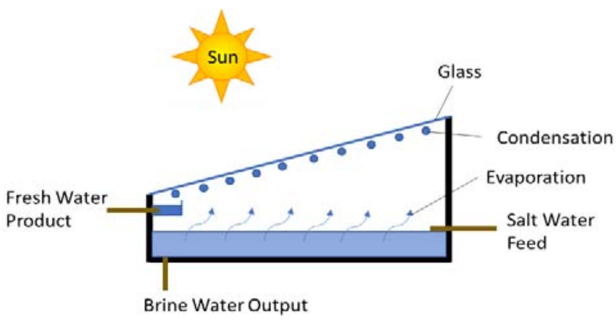

Figure 1. Solar Still Desalination Schematic

2. Theory of Capillary Rise

The liquid flow in the open-cell structure is driven by the cohesion forces, adhesion forces and gravity forces. The cohesion of the liquid was driven by the surface tension γ in liquid-vapour interfaces. Adhesion forces were driven by the contact angle of the liquid and solid surface in the solid-liquid interfaces. According to Newton's third law, when the fluid was in hydrostatic the adhesion forces will be countered act by the gravity forces [10]. Hence leads to the first equation where the adhesion forces are equal to the gravity forces (1). The adhesion force (2) and gravity force (3) is then converted into a dimensionless parameter to ease the comparison [9]. According to Dudukovic, to allow the capillaries to rise in action, the forces of equilibrium in the open cell structure should break unevenly. This can be done based on the adhesion force equation ((2) by enlarging the strut diameter (D), increasing the liquid to solid contact perimeter (s), and reducing the pore size of the cell (L). With changing of the parameters D, s, and L higher adhesion forces will be produced and will shift the equilibrium forces of the fluids resulting in higher capillaries rise. Then, the higher capillaries rise will result in a higher liquid height (h) hence gravity force equation ((3) will increase and eventually have equivalent forces to the adhesion force and capillaries rise will reach equilibrium at a higher level. Besides, the gravity force equation can be reduced with a lower volume of liquid in the open cell structure by reducing the cell strut diameter or changing different cell type designs [9].

$$F_{adhesion} = F_{gravity} \tag{1}$$

$$F^*_{adh} = \frac{\pi D^* \cos\theta \, s^*}{L^{*3}} \tag{2}$$

$$F^*_{gravity} = h^*(1 - \emptyset) = h^* \varepsilon \tag{3}$$

3. Design Modelling

The cellular fluidic structure was modelled using nTopology (nTop) software with a built-in computer-aided-design (CAD) function. Using nTop was able to generate a lattice structure model with plenty of preset cell geometrical shapes such as Isotruss (ISO), Body Centered Cubic (BCC), and Face Centered Cubic (FCC) unit type that were presented and demonstrated by Dudukovic [9]. Besides, nTop has a function to determine the solid volume of the generated model, this function was convenient to effectively calculate the porosity of the model and predict the capillaries rise. Here, the design modelling methodology of a unit cell was presented. The modelling process started by creating a cube geometry with a dimension of 1.5 mm × 1.5 mm × 1.5 mm (L × W × H). Then, a lattice structure with a BCC unit type was imposed into the solid cube volume using the volume lattice function, hence generating a vector lattice framework in the geometry. After imposing the volume lattice, a trim lattice function was used to trim off excess lattices that overreach the desired geometry, this step is to ensure all lattices generated were within the geometry boundaries. After that, a thicken lattice function was used to thicken the vector lattice of the geometry, furthermore, the strut diameter will be controlled by the thickness of the lattices. Next, the volume of the thickened lattice was able to obtain using mass properties from body function. Afterwards, the mesh function was imposed into the thicken lattice followed by exporting the mesh in stereolithography (STL) file and ready for slicing and 3D printing. The investigation of the first and second objectives will be changing the strut diameter of the cell and using different cell geometrical shapes. Finally, the model used to verify the capillaries rise in this research was designed with a rectangular geometry with a dimension of 13.5 mm × 13.5 mm × 40.5 mm (L × W × H), each unit cell in the model was in 1.5 mm cube.

4. Fabrication Methodology

Commercial prototyping water washable resin S-900 (Jing Zhao Technology) was mixed with poly (ethylene glycol) diacrylate (PEGDA) with a weight ratio of 1:2 to produce a resin mixture for 3D printing. The purpose of mixing PEGDA in the commercial resin was to improve the hydrophilic properties of the material, hence improving the contact angle of the liquid to solid contact force and leading to higher capillaries rise [11]. Moreover, 1 wt % of photoinitiator powder was added to the resin mixture and stirred for 30 minutes by using a magnetic stirrer (IKA C-MAG HS 7) to ensure the full dissolution of the photoinitiator. After that, all cellular structures were printed using a masked stereolithography printer (MSLA, Phrozen Shuffle 2019). Before printing, the STL file generated from nTop software was imported to the Phrozen slicer software (PZSlice) to slice the STL 3D file to a 2D image. After that, the sliced file was sent to the 3D printer for printing via the USB port. After printing, all 3D printed parts were carefully removed from the build plate with a metal scraper. Then, immediately dipped into the distilled water for removing excessive resin on the model then sonicated for approximately 5 minutes under an ultrasonic cleaner (Elma Elmasonic EASY 10/H). Next, the sonicated 3D printed parts were removed and dried under natural ventilation for approximately 30 minutes. Then, the dried 3D printed parts were then exposed under a portable UV light with the illumination of 400 nm wavelength for 30 minutes to 1 hour to further strengthen the structure of the model by solidifying the resin. The UV light illumination was to enhance more cross-linking of the un-cure resin in the model. After that, the printed model can perform experimental testing.

5. Result and Discussion

The 3D printed model of BCC, FCC, and ISO with the strut diameter from 0.2 to 0.4 mm was printed and tested for the capillaries rise in a water tray. The capillaries rise on the BCC, FCC and ISO model was captured and the capillaries rise is measured using ImageJ (v2.3.0). Then, the result is illustrated in **Figure 2**. The investigation of changing strut diameter to improve capillaries was illustrated in **Figure 2**. The BCC cell geometrical shape (blue trend) with the increase of strut diameter (D) from 0.2 mm to 0.4 mm was performed and the capillaries rise (liquid height) increases from 3.01 to 7.67. Then, FCC cell geometrical shape (orange trend) with the increase of strut diameter from 0.2 mm to 0.4 mm was performed and the capillaries rise increased from 3.47 to 8.91. Next, ISO cell geometrical shape (black trend) with the increase of strut diameter from 0.2 mm to 0.4 mm was performed and the capillaries rise increased from 3.88 to 11.76. This observation proves the theory of capillaries rise mentioned earlier in equation (2), with the increase of strut diameter the adhesion force of the liquid to the solid surface will increase, meanwhile porosity (ε) of the cell size will be decreased, hence improving the capillaries rise into a higher level. **Figure 3** shows the result of using investigating different cell geometrical shapes (BCC, FCC, and ISO) and the effects of capillaries rising when the strut diameter is constant. This result is mapping back to the second objective. The result of cell geometrical shape used in the model in **Figure 3** has a sturt diameter of 0.4 mm for all three cells, giving a comparison of changing cell geometrical shape and effects of capillaries rise. In the Figure 3, Isotruss (ISO) cell geometrical shape shows it had the highest capillaries rise of 11.76 compared to the other cell geometrical shapes FCC at 8.91 and BCC at 7.67. This is due to the complexity of the Isotruss cell that has an internal structure from its design. Hence providing more liquid to solid contact perimeter (s*) will improve the adhesion force in equation (2) and result in higher capillaries rise. Besides, due to the complexity of the Isotruss structure, the porosity (ε) is lower comparing to BCC and FCC cell geometrical shape. Therefore, the higher capillaries rise was observed on Isotruss compared among the three different cell geometrical shapes. The limitation in this project lies on printing difficulty and complexity for higher strut diameter of the cell geometrical shape. As the higher strut diameter is modelled during 3D printing the porosity of the 3D printed model tends to trap the un-cure resin inside the small porous hole leading to a harder clean up during post-processing using alcohol. This will result in the model 3D printed as a whole solid instead

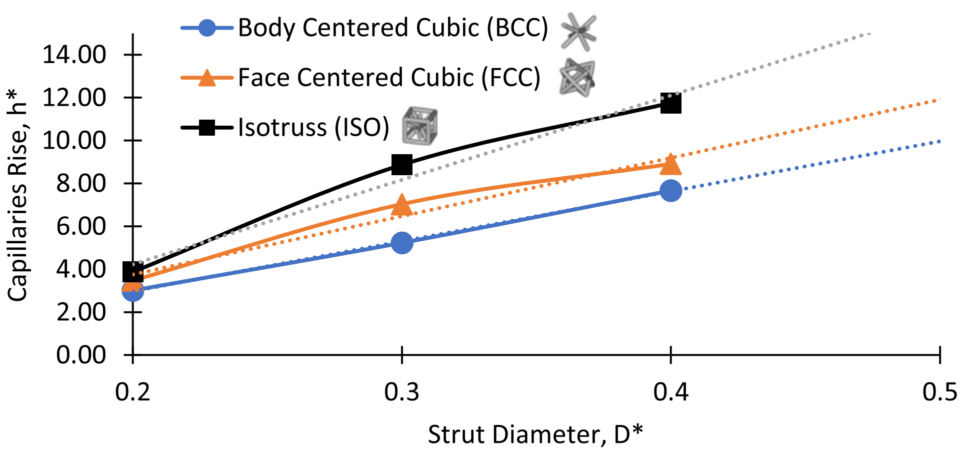

Figure 2. Capillaries Rise against Strut Diameter with different cell geometrical shape.

of a lattice structure. Leading to unsuccessful print in higher strut diameter which might be due to the selection of the resin materials. In order to print a higher strut diameter model, a higher precision resin material is required. Besides, some black spot was identified later in the 3D printer LCD screen, this black spot was unable to illuminate the UV light during the printing, and potentially limits the printing quality and consistency of the 3D printed model.

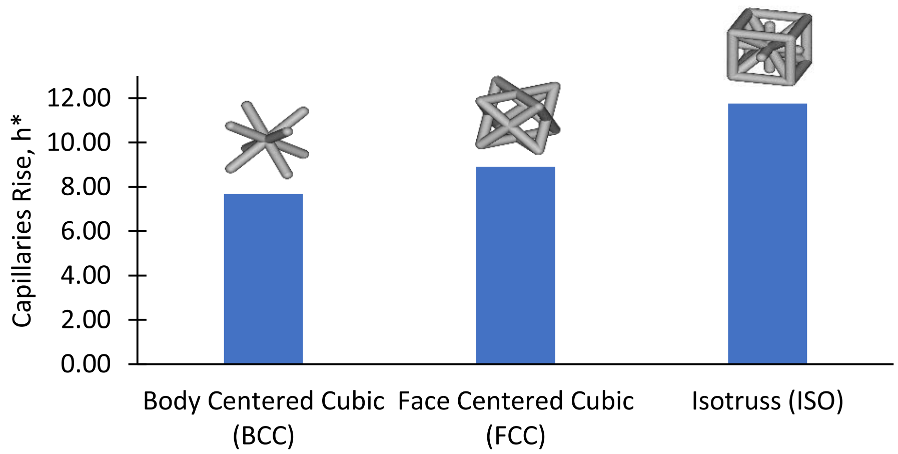

Figure 3. Capillaries Rise against different cell geometrical shape with strut diameter constant at 0.4 mm.

6. Future Plan

The future plan of the project is proposed to use a high precision or quality resin to achieve better print quality to achieve larger strut diameter printer and increase capillaries rise. Besides, materials selection of original hydrophilic resin or mixture of hydrophilic resin with PEGDA should be investigated to provide a better capillary rise. As proven in this study where the change of strut diameter will improve capillaries rise. Therefore, design modelling of different strut diameters from 0.5 mm onward shall be of great interest with different unit type cells in improve the capillaries rise further. The use of a higher precision printer will be able to achieve printing smaller cell sizes into 1 mm or smaller. Printing in a smaller size of the cell will be able to produce higher capillaries rise according to equation (2). Despite the fulfilment of the objectives in this project. A customisable cell geometrical shape other than BCC, FCC, and ISO is worth discovering to have a deeper understanding on how the fluid flow in the open cell structure. Investigating liquid contact angle and surface roughness in the future can be helpful to have a better understanding of the hydrophilic properties of the materials. This is because liquid contact angle will affect $\cos\theta$ in adhesion force in equation (2).

7. Conclusion

This study portrays a general view of the limited freshwater supply for the coming years and current challenges faced by desalination facilities, all of which are highly energy demand to run the plants and non-sustainable. Besides, there are also producing a lot of carbon emissions annually. Solar desalination is one of the ways to tackle the current challenges faced by desalination facilities. This study adopted the concept of cellular fluidics and capillaries rise is performed. The first objective investigated the increase of sturt diameter from 0.2 mm to 0.4 mm and observed the capillaries rise increase from 3.01 to 7.67 for BCC cell geometrical shape, 3.47 to 8.91 for FCC cell geometrical shape and 3.88 to 11.76 for ISO cell geometrical shape. The second objective, comparing different cell geometrical shapes with the strut diameter remains constant at 0.4 mm, the ISO cell geometrical shape recorded a value of 11.76 among the other two geometrical shapes BCC and FCC.

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