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# Condensation of Moist Air on Mesh-like Surfaces

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**Abstract:** Water scarcity is one of the crucial problems especially in hot, humid, arid and drought prone regions of the world. In these vulnerable regions, Earth's atmosphere water is the main source for getting potable water. In this work, a water harvesting device from moist air is designed and fabricated. The condensing substrate is mesh-like on which condensation of moist air is achieved by flowing cold water through the capillary tubes from solar based cooling unit. However, an outer surface of capillary tubes of mesh-like surface is coated with hydrophobic coating. From this device, water from atmospheric air is collected approximately 800 ml/m$^2$ in four hours at atmospheric temperature, relative humidity and degree of sub-cooling 32 °C, 80% and 5 °C respectively. This type of substrate is suitable to solve the water crisis for improving mass transfer rates and higher water yield during moist air condensation in the coastal, hot and humid area worldwide.

**Key words:** Water harvesting, condensation, copper mesh, moist air, dehumidification.

## Introduction

Among 7.5 billion, 609 million world's population lack access to safe drinking water in joint monitoring programme by WHO, U. (2017). According to the UNESCO (2015) report on Human Settlements "almost seventy percent of total population of India have shortage of drinking water and it is a massive problem worldwide". The existing resources are under scrutiny and new eco-friendly and renewable technology is in high demand (Jain et al., 2019). The water scarcity is more dominant in hot, arid and drought prone regions. According to UNICEF (2016) report "A total of 330 million people, a quarter of India's population, were affected by the drought of 2015-16. The drought had an impact on 2,55,923 villages in 254 districts of 10 states". Inadequate rainfall due to climatic changes, rapid population growth, groundwater depletion, poor water management, desertification and deforestation are some of the major reasons for water scarcity particularly in India. Subramanian et al. (2005) describe that the common problem faced in India as well as other developing countries concerned to shortage of water are vulnerable water-borne uncommon disease while few are due to asbestosis exposure, high fluoride and metalloids concentration (Madhavan et al., 2007). This contamination of water became a toxicological issue considerably to groundwater resources. Thus the clean and pure drinking water is highly demanded. Subramanian et al. (2003) explained that the option of the river to fulfill the scarcity of water in India cannot be opted because river and tributaries are fractionalized in size with small extent cores of sediments collected, can adversely impact on human health and the environment. This residual cores distribution show the efficient amount of mercury even represent the addition of huge toxic metal (V, Cr, Co, Ni, Zn, Ag, Cd and Pb) to the aquatic system generated by increasing proportion of human activities in various areas such as thermal power plants, urbanisation and intensive manufacturing

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through industrial application mixing with vast river (Ramesh et al., 1999).

Lahiji (2018) claimed that water salinity is affected by salt and in addition, increase in sodium to water due to increase of pH of the water. Calcium and magnesium create a hard layer of poor penetration with uncompensated biological and ecological effect. In order to engross agriculture sustainability, it is implicitly based on integrated water resource but the scarcity of water is influencing the economic proficiency, societal equity and environmental sustainability (Nasiri et al., 2018). Though several measures are taken by private, public and government organisations but none have been able to provide a reliable solution for water scarcity. According to UN-Water (2015), "By 2025, 1800 million people will be living in countries or regions with absolute water scarcity, and two-thirds of the world population could be under stress condition"(Hameeteman, 2013).Hence, the water crisis is of utmost importance because of the global risk it poses to the society in present scenario.

There are plethora of methods such as desalination(Khawaji et al., 2008), tanker transport, ice-berg transport, water re-use, rain water harvesting (Gould, 1995), Open-cycle Ocean Thermal Energy Conversion (OTEC) and cloud seeding, which have been tried and tested with various degrees of success for providing potable water. These methods have several limitations which need to be overcome if one is serious about providing scalable solution to the availability of potable water to large number of people. Desalination and Reverse Osmosis are widely deployed processes, but it has two major disadvantages: it is expensive, and it creates waste brine which can pollute groundwater and the environment in the vicinity of the plant if released indiscriminately and carelessly (Hamed et al., 2010).

Rainwater harvesting proves to be an inefficient method due to uneven distribution of rainfall. In addition, it requires construction of large reservoirs which requires periodic cleaning. These reservoirs are open to atmosphere because of which they receive dust and other solid and semi-solid particles which deplete the quality of water and make it unfit for human consumption (Gould, 1997). However, these methods are rendered useless in hot, arid and drought prone regions.

Water harvesting from moist air is scalable and pragmatic method in hot and arid regions because Earth's atmosphere contains $12.9 \times 10^{12}$ $m^3$ of potentially valuable, infinite resource of water. A cubic metre of 100-600 m thick atmosphere layer contains 4-25 g of water vapour. This can be extracted and supplied to population living in water scarcity region (Wahlgren, 2001). Although potable water conservation from moist air is ecologically safe and noiseless water harvesting technology, slowness of the water vapour condensation rate hindered its application in large scale system. Enhancing the condensation rate of moist air reduces the stress on freshwater resources (Milani et al., 2011). Researchers and scientists all around the world have developed technologies and method for extracting water out of ambient air (Eriksson et al., 2008; Meytsar, 1997) but none has been able to solve the issue of water crisis.

Broadly moist air condensation is classified in two categories: drop-wise condensation and film-wise condensation (Seo et al., 2014). Drop-wise condensation has high transport coefficients. However, surface has higher hydrophobicity and lower contact angle hysteresis for effective and efficient drop-wise condensation. Hence, dropwise condensation is preferred more over the film-wise condensation. In addition, mesh-like surfaces are preferred because of easy flow over surface and they have large contact area for moist air. The literature review drew the problem novelty of this research to extract potable water from moist air on copper mesh-like surface (Wang et al., 2013). However, extracting water from humid air from above mentioned approaches are expensive and relatively slow.

Careful research is required for enhancing the condensation rate and droplet shedding on the condensing surface, so as to provide a feasible, effective and efficient method of water harvesting in drought prone regions of India. In literature, several modifications on mesh were considered to achieve economical condensation pattern (Shourideh et al., 2018). Thereby, Pinche et al. (1996) stored 5.57 litres per day for a total area of 80 $m^2$ on a mesh of green polypropylene (mosquito net). Fessehaye et al. (2014) produced 37 kilolitre of water from moist air using polypropylene meshes in arid areas in Chile. Modification in mesh structure by texturing to white polyethylene UV stabilised insect mesh was reported by Cristian (2015). They obtained amount of 8.70 $l/m^2$/day water vapour during wet season with relative humidity 87% and wind speed 3.6 m/s. Yang et al. (2010) reported a stainless-steel mesh coated super-hydrophobic film obtained by using silica by simple sol-gel method. The mesh with pore sizes of 75 μm accumulated water for horizontal and tilting angles as 5 μL, 8 μL measured at about 1 s interval respectively.

Feng et al. (2004) reported a super-oleophilic coated and super-hydrophobic mesh fabricated on stainless steel surface-energy material of polytetrafluoroethylene (PTFE). The diameter of pores of mesh was 115 μm, measured a contact angle for 150° and collected 5 μL of water through this experiment. Xie et al. (2017) reported a copper mesh surface by sintering method to generate array of micro-droplets on large scale at constant temperature and relative humidity 26 °C and 40-60% respectively. Wen et al. (2015) presented hi-mesh surface i.e. copper woven micro-meshes (wire diameter of 65 μm) onto the plain copper substrate by approaching thermal diffusion method to enable surface refreshing and accelerating droplet. Amirfazli et al. (2004) showed that the efficiency of water collection is allied with the wettability of surface structure of mesh surface. The wetting phenomena demonstration for knowing the effect surface morphology is based on the condensation rate.

The droplet shedding dynamics on the copper surface possess efficient water removal than other materials reported by Seo et al. (2016) considering harvesting method of desalination. The copper mesh with tubular surface is converted to CuO nanostructures to retain blade-like morphology exhibiting properties of super-hydrophobic manifested flooded contact angle. Due to the easier removal of water droplets copper tubular surface holds a great potential for thermal applications involving vapour-water phase change. In addition, now-a-days a study is proposed on an improved novel solar system using the cooling capacity by Salek et al. (2018) and coefficient of performance (COP) behaviours of the thermoelectric cooler using relative humidity, and temperature of that particular region for generating water from atmosphere air consuming less power.

Although studies related to condensation of water vapour present in ambient air have been reported sporadically in the literature (Jensen et al. 2014), effective and efficient method for extracting water from humid air for enhancing the condensation rate is not provided explicitly in the literature. Against this background, mesh-like surface is formed using copper tubes so that condensation takes place on outer surface of tubes. However, cold water flows inside the tubes. Outer surface of tubes is coated with monolayer of n-octadecanethiol on it by chemical action. Details of the coating have been reported elsewhere (Sikarwar et al., 2013). The surface is exposed to humid region to flowcold water through these tubes to maintain surface temperature below dew-point. The Peltier (125 watt) based cooling with solar panel (150 watt) is used to cool the water. The mesh is built using copper tube of 6 mm diameter in rectangular manner. The experiments were performed and collected amount is 80 litre/s-m$^2$ were recorded at 90% relative humidity in months of July-August in Noida, India. This research is useful for designing the system of water harvesting from moist air.

## Methods and Materials

The schematic diagram of a solar based working experimental setup for water harvesting device from moist air is as shown in Figure1(a). However, Figure 1(b) shows the photograph of experimental setup.

This experimental setup contains an improved solar panel system (150 W), a thermoelectric cooler called Peltier (125 W), water tank (5-litre water), inline pump (DC pump, flow rate 5 l/min) and a copper mesh surface. These were equipped to generate potable water from atmospheric moist air at various environmental conditions (various relative humidity and temperature) of Noida, India. However, a solar panel was placed south face with 25° inclined facing directly the sunlight so that all the rays could be absorbed by the solar cells. The solar cells generate direct current which gets transferred through the wires for storage to a compact battery. The current polarity is required to transfer heat by Peltier module which holds significant cooling capacity and coefficient of performance (COP) behaviours. However two Peltier modules were operated with 12 V-DC supply and fixed current flow of 30 A placed between two aluminium boxes (10 cm × 3 cm × 10 cm).

In this experiment, the cooling effect imparted by thermoelectric coolers was transferred to the water in acrylic tank. The acrylic water tank dimensioned as 20 cm × 20 cm × 22 cm was kept for storing and circulating cold water throughout the mesh. Importantly, the cooled water was required to be flowed through the tubular mesh for lowering the temperature than the nearby surrounding which proceeds to attain a temperature difference for nucleation and tailoring of drops on the surface. To maintain the continuity of cooled water through the entire mesh, both horizontally and vertically, an inline pump (12 VDC) having discharge capacity of 5 litres/min was located. The inline pump is restricted with one-way flow and was connected to the mesh by 3-way valve. The 3-way valve had three ends: one end is connected to the inlet port of the mesh which intakes cold water to flow inside the mesh; another to the outlet port of mesh which is discharged to the acrylic water tank and the third one to create the vacuum inside the mesh. The inlet and outlet ports are not interconnected,

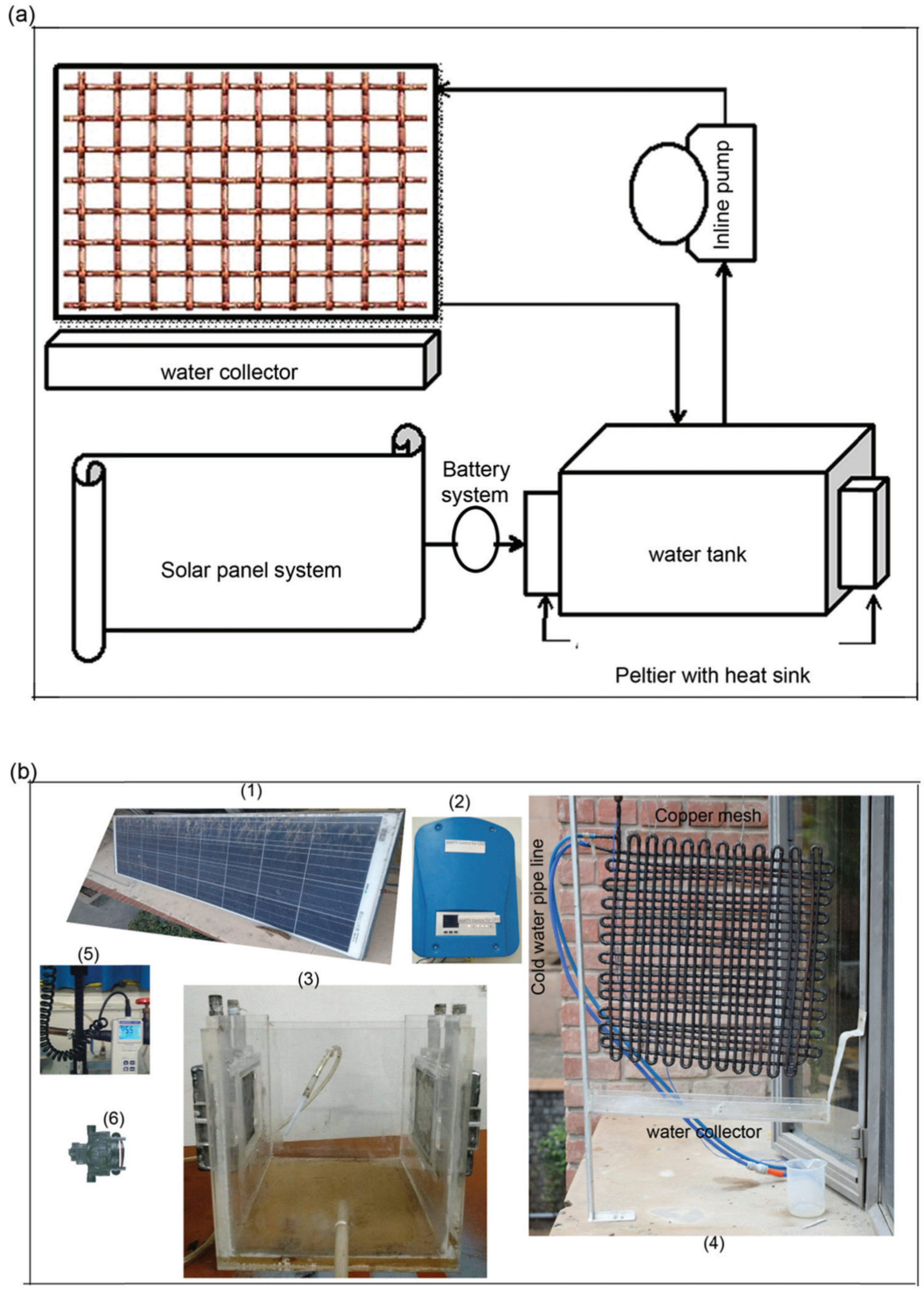


**Figure 1: (a) Schematic diagram of experimental setup for moist air condensation on mesh-like surface. (b) Photograph of Working model on mesh-like surface for moist air condensation: 1 –Solar panel; 2 – Battery storage; 3 – Water tank containing Peltier modular; 4 – Mesh-like surface; 5 – Probe for measuring humidity and temperature; 6 – Inline pump.**

and as such the opening or closing of one does not affect the functioning of another.

In order to make this experiment a leak proof flow, silicon tubes with valves were yielded to make the apparatus work efficiently. Now the fabrication method needed inputs for selection of raw material for mesh-like surface which is stringently based on following factors: easily available, economical, ductile as well as tough, convenient to fabricate. Finally, copper was selected for the mesh structure with the dimensions: length is 70 feet (or 21 m) and diameter of 3 mm (or 0.118 inch). Therefore, in order to frame copper in a mesh (40 cm × 40 cm) like surface and leak proof, brazing technique was employed. In contrast, though soldering is an economical process as compared to brazing but there are certain limitations to soldering, which renders this research application. To maintain the pressure inside the copper mesh at a constant level a pressure gauge was used. The outer surface of copper tubes is coated with monolayer of n-octadecanethiol by chemical action to make an efficient hydrophobic surface. The hydrophobic substrate maintained an equilibrium contact angle of 135° and with contact angle hysteres is 10°.

In order to know the result from moist air condensation, a water collector beaker was placed below the mesh surface to store the water. The experimentation of water harvesting via condensation of atmospheric moist air, preferably on copper mesh surface was performed at regular interval for four hours daily in months of July-August 2018 in Noida, India. Dew temperature: 25°-27 °C, cold water temperature inside mesh: 20°-22 °C, degree of sub-cooling: 5°-7 °C and relative humidity: 64%-85%. In order to evaluate environmental parameters such as dew point temperature, the ambient temperature and relative humidity, a device hygrometer with probe was used.The experimental apparatus was designed at low scale power consumption to be economical and environmental friendly. In terms of environmental sustainability, thermoelectric cooler are reasonably attractive due to cost and warming impact considerably low to other cooling devices. The Peltier devices are feasible, to be used to its maximum because it is maintenance-free and applicable to stationary parts and draws extensive efficiency.

## Result and Discussion

The sustainable technology for dropwise condensation is implemented on small scale to improve the scarcity of potable water in regions of arid, humid, draught and coastal to prove the practical application. The formation of condensation pattern as nucleation of drops and combining which grows to big size of drop throughout experiment is obtained by capturing images at different intervals of time such as 5, 10, 20, 30 minutes as shown in Figure 2.

Now the experimental data for the condensation of atmospheric moist air for different relative humidity and temperature at regular intervals of 30 minutes is tabulated in Table 1.

**Table 1: Data of condensation of moist air on copper mesh surface**

| *Time interval (Min)* | *Relative humidity (%)* | *Moist air temp. (°C)* | *Cold water temp. (°C)* | *Condensation (gm)* |
|---|---|---|---|---|
| 30 | 64 | 34 | 21 | 25 |
| 30 | 66 | 33 | 22 | 30 |
| 30 | 77 | 33 | 21 | 50 |
| 30 | 80 | 31 | 21 | 52 |
| 30 | 82 | 30 | 21 | 53 |
| 30 | 83 | 31 | 20 | 70 |
| 30 | 85 | 31 | 20 | 75 |

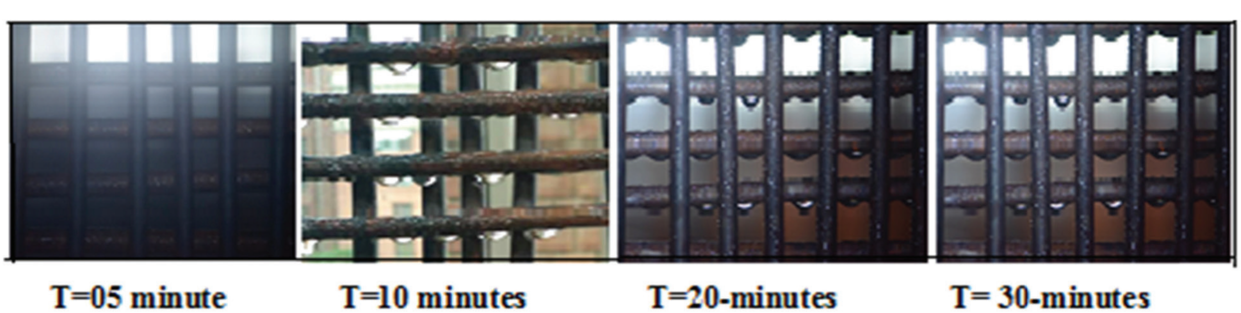


**Figure 2: Images captured of condensation pattern of moist air at different time intervals.**

The amount of collected water as condensation rate at different relative humidity is shown in Figure 3. The amount of water collection increases with time increment as relative humidity increases but after four hours, the amount of collected water gradually became constant as compared to the average hourly generated water.This behaviour could be explained that the droplets being condensed were small in the beginning, and the disturbance of inlet air and effect of gravity couldn't equalise the adhesion.

The amount of condensate water and condensation rate was both proportional to RH. When inlet air temperature is kept constant, the increased RH led to rising moisture content. The condensation rate to the increasing hour with 5% errors is as shown in Figure 4.

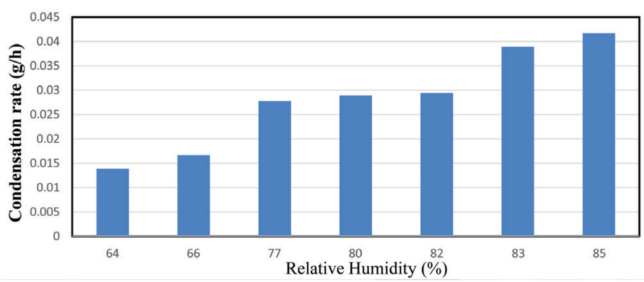


**Figure 3: Water collection rate of moist air on mesh-like surface at different RH.**

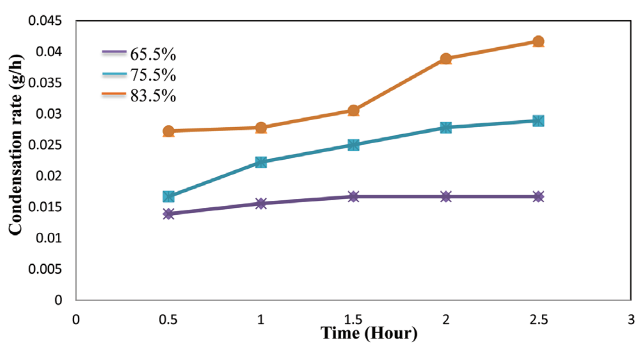


**Figure 4: Condensation rate of moist air on mesh-like surface at increasing hour.**

The increased RH also led to the rising dew point temperature of inlet air. As a result, temperature on mesh-like surface of copper lead to more droplets and finally resulted in condensation rate at different relative humidity. The average water collected rate in day for various condensations in month of August of Noida is tabulated in Table 2.

## Conclusions

The experiment provides positive results to our work on condensation of moist air using copper mesh. The experiment conducted has achieved the condensation patterns which require further optimization. However, nowhere in the world, a working setup utilizing copper meshes made entirely of raw copper tubes, arranged with thermoelectric coolers and other electrical equipment has been ever recorded. The water harvesting device is so arranged to be economical and environment friendly, that is why power source for all electrical parts is connected to solar energy, a considerable merit of this setup. Structurally it is robust and rugged, so the setup can be installed anywhere in the world, mostly to regions of arid, semi-arid, draught and humid. The only limitation is with corrosion of copper tubes which can be removed by texturing and chemical processing. However, this setup, once properly implemented, will be the first design setup of its own kind. This setup can prove to be the next research problem in the field of condensation.

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**Table 2: Performance of condensation rate for various parameters for atmospheric moist air**

| *S. No.* | *Relative humidity (%)* | *Moist air temp. (°C)* | *Cold water temp. (°C)* | *Dew point temp. (°C)* | *Water collected (ml/sec-m$^2$)* |
|---|---|---|---|---|---|
| 1 | 74.5 | 32 | 22.3 | 24.7 | 5.41 |
| 2 | 90 | 34 | 22.0 | 25 | 6.57 |
| 3 | 95 | 36 | 23.1 | 25.3 | 7.65 |

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