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Study of Fog Water Collector Mesh with Different Shade Coefficients

Sanjay Mahat [a], Ajay Kumar Jha [b], Kamal Darlami [c]

[a, b, c] *Department of Mechanical Engineering, Pulchowk Campus, IOE, Tribhuvan University, Nepal*
Corresponding Email: [a] sanjaymahat1@gmail.com, [b] akjha@ioe.edu.np, [c] darlami.kd@pcampus.edu.np

Abstract

The study of the conditions for fog water collection by the use of passive fog collector meshes identifies mountain tops of Nepal as potential sites suitable for fog water collection. Feasibility of fog water collection project depends on the very specific socio-economic, climatic, and technological conditions. This paper focuses only on investigations of the effects of shade coefficient in the collection efficiency of the collector mesh. It is found that for both the rigid and flexible wire mesh, the collection is maximum at about 50 percent shade coefficient of the collector mesh . The collection of flexible mesh at 4 m/s wind speed is found to be less than that of the wire mesh.

Keywords

Fog Harvesting, Fabrics, Shade Coefficient, Efficiency

1. Introduction

About 844 million people living around the world are living without the access to safe water. Women and children are disproportionately affected by the water crisis, as they are often responsible for collecting water. They spend up to 6 hours every day collecting water [1] . Water is always in movement and always changing states. Water can be collected in almost every stage of the water cycle. It's been a while since humans have started to collect fog water droplets for their use. The study of the conditions for fog water collection by the use of passive fog collector meshes, identifies mountain tops of Nepal as potential sites suitable for fog water collection [2].

Fog and cloud are the similar thing. The only difference is that fog touches the ground. Fog droplets' size varies from 1 μm to 40 μm. In comparison, raindrops have diameters from 0.5 mm to approximately 5 mm. Fall-velocities of raindrops ranges from 2 to 9 m/s, whereas fog droplets have fall velocities from 1 cm/s to approximately 5 cm/s which is so low that even in very light winds, the drop will travel almost horizontally [3].

Fog water collection is not a condensation process. It is an impaction process. The fog collector are simple vertical meshes. The process is passive process requiring no energy other than wind. Fog droplets get accumulated on fibers of fog collector. As the drops get bigger, they flow under the effect of gravity. The fog water collection depends on the size of the droplets of water, speed of wind carrying fog and the nature of the fog collector (material, thickness, and spacing). Similarly, water production by an array of fog collectors depends on the number of collectors, their size, their efficiency, fog frequency, fog water content and wind speed.

2. Mathematical Model

Theoretically, the water collected by the impaction of the water droplet on the fog collector mesh can be calculated by the following expression:

$$q = wA\eta V \tag{1}$$

where, q is the rate of collection of fog water, w is the liquid water content, A is the mesh cross section area, V is the wind velocity and η is the overall efficiency of the fog water collector. Overall collection efficiency can be calculated by formula:

$$\eta = \eta_a \eta_{dep} \eta_{dr} \tag{2}$$

Where, η_a is the aerodynamic efficiency, η_{dep} is the deposition efficiency and η_{dr} represents drainage efficiency.

2.1 Stokes Number

Stokes number is the dimensionless number which determines the kinetic equilibrium of the particles with the surrounding gas. For small Stokes number ($St << 1$), the particles can be considered to be in near velocity equilibrium with the carrier fluid. Efficiency of the fog collection can be quantified using Stoke's number. It can be defined as the ratio of the characteristic time of the particle to the characteristic time of the flow

$$stk = \frac{t_0 u_0}{l_0} \tag{3}$$

Where, t_0 is the relaxation time of the particle, u_0 is the fluid velocity and l_0 is the characteristic dimension of the obstacle. Relaxation time of the particle can be computed using the following equation [4]:

$$t_0 = \frac{\rho_d d_d^2}{18\mu_g} = \frac{m_p}{6\pi r \mu_g} \tag{4}$$

Where, ρ_d is the particle density, d_d is the particle diameter and μ_g is the gas dynamic viscosity. So the final expression for Stokes number can be written as:

$$stk = \frac{\rho_d u_0 d_d^2}{18\mu_g d_w} \tag{5}$$

d_w is the diameter of the wire or thickness of the strap.

2.2 Aerodynamic Efficiency

To determine the fraction of air that will pass through the mesh instead of around i.e. aerodynamic efficiency of the collector, the following approximate expression governed by three dimensionless parameters [5] can be used:

$$\eta_a = \frac{SC}{1 + \sqrt{\frac{C_0}{C_d}}} \tag{6}$$

Where, SC is the shade coefficient which is the fraction of mesh area that is occupied by mesh wires; C_d is the drag coefficient of a non-permeable screen and is dependent on the shape of the screen; C_0 is the pressure drop coefficient and depends on SC, the type of wire, and knit of the mesh. Among the three parameters, the most difficult to estimate is the value of the pressure drop coefficient. The proposed empirical formula for C_0 for a wire mesh is [6]:

$$C_0 = 1.3\ SC + \left(\frac{SC}{1-SC}\right)^2 \tag{7}$$

The value of drag coefficient (Cd) is taken as constant (1.18) as suggested by [7]. The efficiency of the mesh with constant Cd is then compared with the efficiency using variable Cd obtained from experimental results from the low speed wind tunnel tests on perforated square flat plates normal to the airstream performed by B. G. de Bray [8].

2.3 Deposition Efficiency

Water droplets get deposited on fog water collector mesh by diffusion, interception and inertial impaction. All these mechanisms depend on the droplet size [9]. Typically, the size of fog droplet particles ranges from the 1 μm to 40 μm. However,the water droplet size should be small ($\approx$ 0.1 μm) for the Brownian diffusion to be significant. Similarly, the collection of water droplets can be by the mechanism of interception. The large fog droplets get intercepted by the mesh surface while moving through the collector. For the collector mesh with wire diameter of the 1 mm, droplets with a diameter $>$ 100 μm flowing with wind speed of around 4 m/s start to be intercepted [5]. Since the fog droplet sizes ranges from 1 μm to 50 μm, deposition by both of the mechanisms can be neglected [10]. Remaining mechanism for the deposition is an inertial impaction which plays a significant role in the collection of water. The inertial impaction efficiency depends on the dimensionless Stokes number which can be described with an empirical formula [11]:

$$\eta_d = \frac{stk}{stk + \frac{\pi}{2}} \tag{8}$$

2.4 Drainage Efficiency

The water droplets after the impaction to the surface of the collector mesh coalesce to form a larger drop. The larger drop of water start to get collected to the gutter under the influence of gravity. Some of the water droplets may re-enter the air stream and not reach the gutter. Since effect of the shade coefficient is the main focus of this study, the drainage efficiency is taken as 1.

3. Numerical Model

DPM (Discrete Phase Model) in ANSYS Fluent is used to model this problem. In this model, pressure-based solvers are used for the solution of the fluid flow. Fog droplets are defined as water-droplets injected from inlet surface at the velocity of 4 m/s with constant diameter of 40 μm.

3.1 Geometry

Figure 1 shows the geometry of the flexible fog collector mesh along with the boundary setup prescribed to the model in ANSYS Fluent.

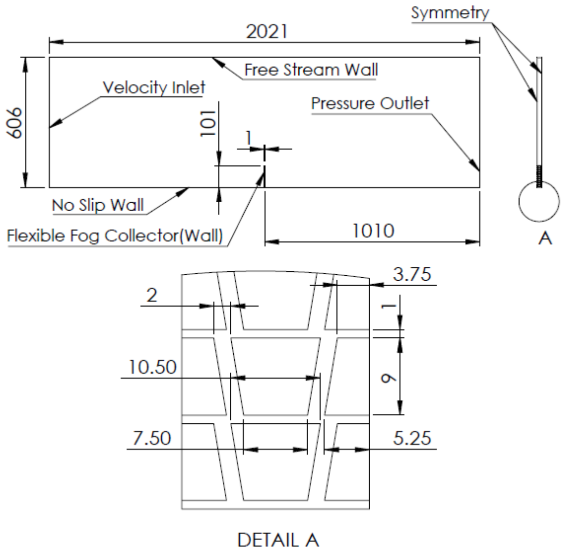

Figure 1: Computational volume around the flexible fog collector and the boundary conditions prescribed to the model in ANSYS for Case IV

The geometry of the rigid mesh with wire diameter of 1 mm is modelled in 2D only.

3.2 Meshing and Physics Setup

Unstructured mesh is created with minimum orthogonal quality of 0.7 and maximum aspect ratio of 15. Figure 2 shows the mesh structure around the rigid wire.

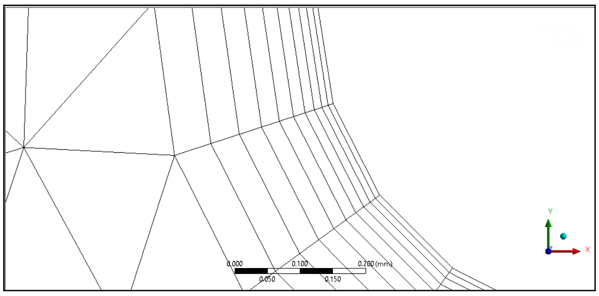

Figure 2: Mesh structure around the rigid wire

For the flexible collector, structural deformation is modelled using System Coupling to coordinate the ANSYS Mechanical and ANSYS Fluent solvers. Fluid and solid meshing are computed separately. The meshing in the flexible collector is shown in figure 3.

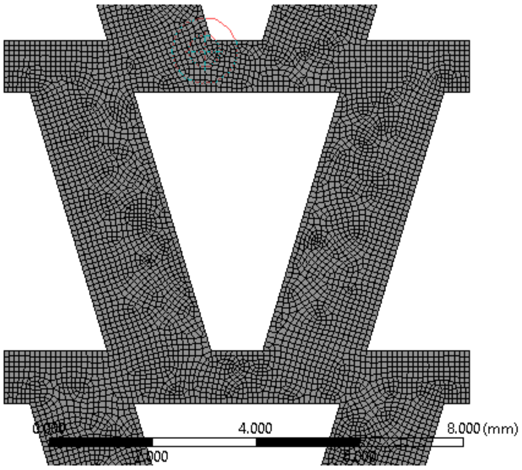

Figure 3: Mesh shown in Flexible Collector(Case II)

The boundary setup of the flexible fog collector is as shown in figure 1. The velocity inlet is set up with 4 m/s velocity normal to the boundary whereas the pressure outlet is set up with zero gauge pressure. The fog collector is defined as wall with 'trap' boundary condition for discrete phase.

Realizable k-e model is solved in combination with scalable wall functions. The model is based on the eddy viscosity approach and contains two equations for the turbulent kinetic energy k and the turbulent dissipation e, respectively. Discrete phase i.e water-droplets interact continuously with the continuous phase i.e air. Species transport model is also turned.

To solve the cases of the flexible collector, two-way Fluid-Structure Interaction (FSI) is set up. Force data from the motion of the air with fog droplets is received by the Transient Structural analysis system. Similarly, displacement data from the motion of the fog collector is received by the Fluid Flow (Fluent) analysis system.

3.3 Governing Equations

The motion of a discrete particle (water droplet) in ANSYS Fluent is governed by the equation 9 (for any direction x in Cartesian coordinates).

$$\frac{du_p}{dt} = F_D(u-u_p) + g_x - \frac{g_x\rho}{\rho_p} + F_x \tag{9}$$

The first term of the equation in the right side is the drag force per unit particle mass, the second term is the gravity component, the third term is upthrust and the fourth term is an additional acceleration (force/unit particle mass). The path of the droplet is predicted by integrating force balance on the particle.

3.4 Mesh Independence Study

The purpose the mesh independence study is to find if the solution data rely on the type of the mesh used. Six different mesh types are used. In this study, the trapped particle by the collector mesh is of prime importance. The figure 4 shows that there is no significant change in the result due to change in the number of nodes.

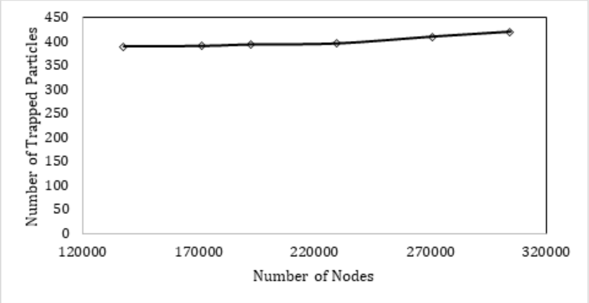

Figure 4: Mesh Independence Study

3.5 Cases Studied

Seven Different cases of rigid collector are set up by changing their the shade coefficients. The shade coefficient is changed by changing the gap between the wires of diameter 1 mm. The result obtained for different cases of rigid wire mesh is given in table 1.

Table 1: Numerical Results for Rigid Mesh

Case	Shade Coefficient	Tracked Particles	Trapped Particles
I	9.10	3420	147
II	25.00	1735	135
III	33.33	1199	124
IV	50.00	3200	391
V	58.82	1700	185
VI	66.67	1202	112
VII	76.92	1291	109

Similarly, six different cases are created for flexible collector mesh as shown in table 2. The shade coefficient of these cases are changed by changing the vertical and horizontal gaping of the collector strap.

Table 2: Numerical Results for Flexible Mesh

Case	Shade Coefficient	Tracked Particles	Trapped Particles
I	23.85	1345	56
II	31.73	1938	83
III	44.91	1306	69
IV	55.55	1875	124
V	66.67	2012	104
VI	76.67	2559	89

4. Results and Discussion

The aerodynamic and deposition efficiency is calculated mathematically by equations (6) and (8) respectively. Stoke number required for above calculation is calculated by using equation (5). Similarly, pressure drop coefficient for the rigid mesh is approximated by using equation 7. For a silk mesh, which the Raschel mesh more closely resembles, Idel'cik (1960) adds an additional multiplicative factor of 1.62 in equation 7.

The efficiency of the net is evaluated numerically by tracking the injected particles. Injected particles passing through the collector net get intercepted by the net. Some particles follow the airstream and move around the net while some escape through the fiber gap without interacting with the net. Efficiency calculated for different cases of rigid collector mesh are compared in table 3.

Table 3: Comparison between Numerical and Analytical results for Rigid Mesh

Case	Numerical	Analytical (Variable Cd)	Analytical (Constant Cd)
I	12.89	4.68	6.34
II	23.34	11.33	14.41
III	31.03	16.00	17.54
IV	36.66	21.09	21.24
V	32.65	20.52	21.46
VI	27.95	19.53	20.32
VII	25.33	16.39	16.96

Similarly the efficiency calculated numerically and analytically are compared in table 4.

Table 4: Comparison between Numerical and Analytical results for Flexible Mesh

Case	Numerical	Analytical (Variable Cd)	Analytical (Constant Cd)
I	20.82	9.53	12.64
II	21.41	11.2	15.04
III	26.42	15.56	18.03
IV	33.07	17.01	18.59
V	25.84	16.40	17.24
VI	17.39	13.75	14.15

Figures 5 and 6 show fog water collection efficiency as predicted by analytical and numerical models for rigid mesh and flexible mesh respectively.

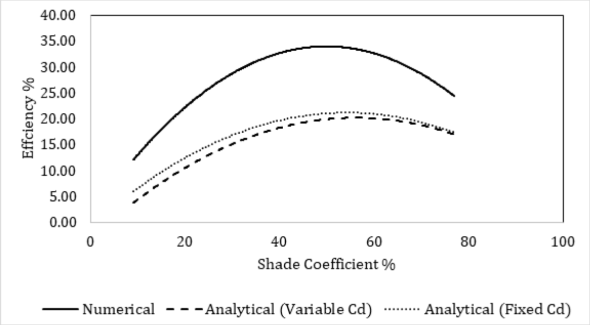

Figure 5: Shade Coefficient vs Efficiency for Wire Mesh

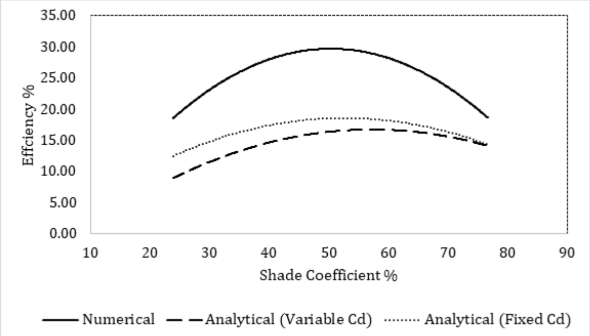

Figure 6: Shade Coefficient vs Efficiency for Flexible Mesh

From Figures 5 and 6, both numerical and mathematical results shows that the efficiency is highest around the shade coefficient of 50% for the wire mesh as well as flexible mesh.

The efficiency of calculated numerically is found to be more than the efficiency calculated analytically. It is expected as the ideal condition of constant wind velocity (4 m/s) is assumed with all the water droplets having same diameter of 40 μm.

4.1 Comparison with Experiment

Fernandez et al [12] collected and recorded wind data and the volumetric fog water collections from standard fog water collectors in 15-minute interval over three summertime fog seasons (2014–2016) at four California sites. Figure 7 shows the results for total water collected during 2014–2015 by Raschel and MIT-14 mesh.

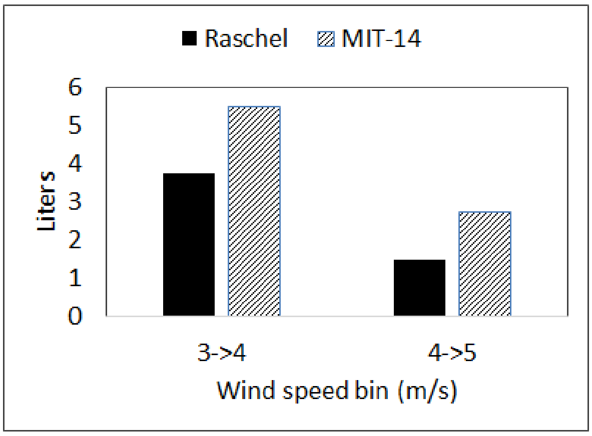

Figure 7: Total water collected during 2014–2015 by Raschel and MIT-14 [12]

Similarly, Figure 8 shows the efficiency comparison of rigid mesh with flexible mesh as calculated numerically.

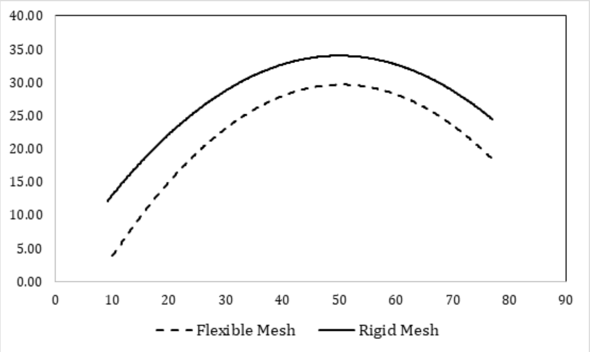

Figure 8: Efficiency Comparison of Rigid Mesh and Flexible Mesh

As its is seen from equation 2, with all other conditions remaining the same, the increase in efficiency results in the increase in the quantity of collection of water. For numerical results, different cases are set up with the constant wind speed of 4 m/s. From the graph 7, it is clear that the collection efficiency of the rigid mesh (MIT-14) is greater than that of flexible mesh (Raschel) at 4 m/s wind velocity.

Also, it is evident from the numerical results as presented in Figure 8 that the efficiency of the rigid mesh is greater than that of flexible mesh at the wind velocity of 4 m/s.

5. Conclusion

For rigid wire mesh, it is found that the efficiency is highest at around the shade coefficient of 50%. This justifies design of the 49% shade coefficient the metal mesh coated with the POSS-PEMA formulation, known as MIT-14. While designing the wire mesh for the collection of water from fog, the wire needs to be be weaved maintaining the shade coefficient of around 50%

The flexible Raschel weave polyethylene 35% shade coefficient is generally used as alternative for the rigid mesh. The mesh is used in double layer with effective shade coefficient of between 50 to 70 precent.

While the result from this study may suggest the superiority of one mesh over another, the study on practicality and cost needs to be done before installation. Further studies are required to understand how other parameters such as wind speed, turbulence intensity, and size of the droplets affect the collection rate of the water from fog.

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