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Simplified Modeling and Analysis of the Fog Water Harvesting System in the Asir Region of the Kingdom of Saudi Arabia

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ABSTRACT

Scarcity of fresh water is one of the greatest obstacles to achieve the sustainable development in the Kingdom of Saudi Arabia. About thirty desalination plants are built to satisfy the Kingdom needs. The Kingdom is in need of new unconventional water resources such as fog water harvesting system which will complement the existing water resources in the Asir region. This region is facing major challenges due to the flourishing tourism, irrigation in agriculture and rising living standards. Passive mesh type fog collector is analyzed in the current study to predict the rate of fog water collection by combining a physically based impaction and aerodynamic models. The results indicate that the greater volumes of water can be harvested from the fog associated with higher wind speeds, bigger sizes of fog droplet and higher liquid water content in the fog-laden winds with the threshold mesh shade coefficient of about 0.56. It is found that the aerodynamic efficiency has a significant impact on the overall fog collection efficiency compared to the impaction efficiency. The model shows that for the fog droplet size of 30 µm with the wind speed of 4 m s^{-1}, it is possible to collect the fog water at the rate of 0.65 to 9.7 L m^{-2} per hour when the liquid water content (LWC) in the fog varies from 0.2 to 3 g m^{-3}, respectively.

Keywords: Fog harvesting; Passive artificial mesh type fog collector; Impaction and aerodynamic models; Optimum shade coefficient; Overall fog water collection efficiency.

INTRODUCTION

One of the natural resources vulnerable to under intense pressure is the supply of potable water. Water is essential for human survival and well-being. The technology of water extraction from atmosphere is reviewed in the literature (Wahlgren, 2001; Hamed *et al.*, 2011; El-Ghonemy, 2012).

The Kingdom of Saudi Arabia lies approximately between latitudes 16°30' and 32°15'N and longitudes 35°00' and 57°30'E and has a population of about 27 million. Experts estimate that the demand for water is expected to grow by 10% annually and the water sector in the Kingdom will offer large investment opportunities in the next few years. The Kingdom is one among the most water-scarce countries in the world. The limited amount and deteriorating quality of water from the available sources have forced the Kingdom to invest heavily in seawater desalination since 1970.

The water balance situation in the Kingdom of Saudi Arabia accentuates the need to identify new innovative water sources. In order to save the Kingdom from shortage of water, the use of non-conventional water resources such as fog water harvesting is important to complement the existing water resources (Alrasheedi, 2014). Recently the prospects of fog collection projects worldwide is reviewed and analysed by many investigators (Klemm *et al.*, 2012; Fessehaye *et al.*, 2014). The fog collectors can be broadly classified into two main categories (Fischer and Still, 2007), namely active fog collector and passive fog collector.

Fog water harvesting is particularly suitable for mountainous areas where communities often live in remote regions and was successfully conducted using the passive mesh type fog collectors in the Asir Province of the Kingdom (Gandhidasan and Abualhamayel, 2007; Al-Hassan, 2009; Abualhamayel and Gandhidasan, 2011). Field and operational experiments were carried out in this region using uncontrolled natural fog conditions. It was concluded that fog water collection is a viable resource of water that could supplement traditional sources in the Asir Province.

In order to calculate the performance of the fog collectors, field tests are conducted by many researchers in different countries and unfortunately, no simple model is available in the open literature to predict its performance. The scope of this study is to develop a simple model for the prediction of volume of water collected from the fog collectors using the available meteorological data and visual measurements, once the potential site for the installation of the fog collector is identified. This research seeks the development of the modeling and analysis of the passive mesh type fog collectors

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based on the impaction and aerodynamic models along with the data collected from the Asir region of the Kingdom of Saudi Arabia. For preliminary evaluation of the fog water collection potential in the region, the simple analysis presented in this paper may be used.

Fog Collection

There are four major cloud groups (Weather World, 2010) and they are:

- Low-level clouds – found at elevations below 2,000 m.
  Types: nimbostratus and stratocumulus.
- Mid-level clouds – found at elevations ranging from 2,000 to 6,000 m.
  Types: altocumulus, altostratus.
- High-level clouds – found at elevations of 6,000 m and higher.
  Types: cirrus and cirrostratus.
- Vertically developed clouds – found at elevations in excess of 12,000 m.
  Types: cumulus and cumulonimbus.

The mass of the water in the cloud is represented by the liquid water content (LWC) and it is given in gram per volume of air. LWC is connected to three variables namely the water droplet effective diameter, droplet concentration and its size distribution. LWC varies with the type of clouds present at the location and different techniques are available to measure the LWC (Wrzesinsky *et al.*, 2004; Wallace and Hobbs, 2006). LWC of some cloud types are given in Table 1 (Thompson, 2007). Cirrus clouds are not related to precipitation whereas cumulonimbus clouds are directly associated with thunderstorms. Fog is a stratus cloud and the only difference between fog and stratus is the different altitude of the cloud base.

Fog is the form of cloud and it consists of condensed water droplets. Its diameter varies from 1 to 40 µm (0.001–0.04 mm) and fall at velocities ranging from less than 0.6 m min^{-1} to approximately 3 m min^{-1} subjected anytime to horizontal transport by the wind (Schemenauer *et al.*, 2005).

Table 1. LWC in various types of cloud.

Type	LWC, g m^{-3}
Cirrus cloud	0.03
Stratus cloud	0.25–0.30
Cumulus cloud	0.25–0.30
Stratocumulus cloud	0.45
Cumulonimbus cloud	1.0–3.0

METHODOLOGY, TOOLS AND MATERIALS

The region of Asir is located in the southwestern part of the Kingdom of Saudi Arabia, as shown in Fig. 1, between longitudes 41–45°E and latitudes 17–21°N. The Asir region is situated on a high plateau and contains the country's highest peaks, which rise to almost 3,000 m. The region is subject to Indian Ocean monsoons, usually occurring between October and March. Annual total rainfall in the region of Asir is about 500 mm in western steep heights and mountains. An average of 300 mm of rainfall occurs during monsoon period.

At present only some cities in Asir region have its water supply pipeline networks and the main water supply relies on water-tank trucks in most districts. Dam is the major surface water development structure and the total number of dams in Asir region is 64, which is 29% of those in the Kingdom. There is no large irrigation project in Asir region. There are many private small scale irrigation systems with water source from wells. There are a number of shallow wells and most wells are located in wadi beds or low lands. The uses of water from deep groundwater are not common in Asir region and there is no project of reclaimed water at present.

The Asir region is faced with the problem of maintaining sustainable water resources. One of the main problems in the Asir region is the high demand for water during tourism seasons especially in view of the rapidly growing tourism sector. Fog forms more frequently between November and February in the Asir region and cost-effective fog harvester is

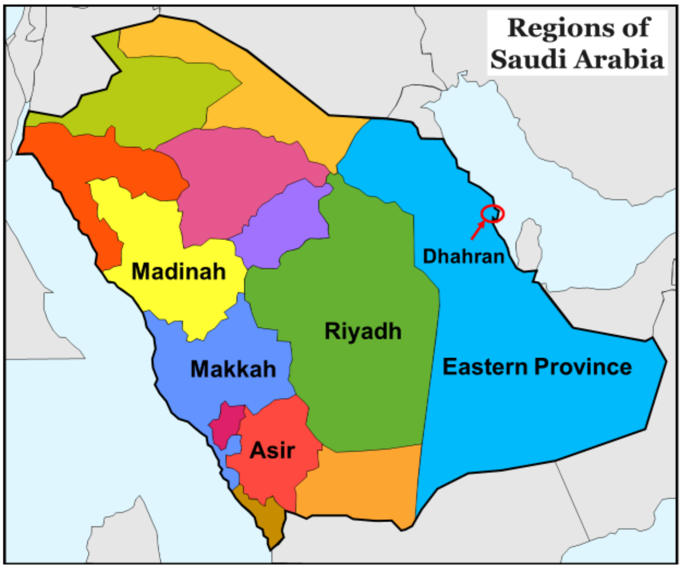

Fig. 1. Map of Saudi Arabia showing the Asir region.

well suited in this region. The type of fog in Asir region is advection fog.

The climatic conditions relevant to southwestern region of the Kingdom was studied by utilizing the meteorological data. The high humidity, high wind speed, and the low ambient temperature are the conditions that support the frequent fog formation. A detailed study has demonstrated that three cities in the Asir Region need serious attention, namely Abha, Al-Baha and Khamis Mushait. Analysis of the data of Abha shows that it has the lowest mean and minimum temperatures compared with Al-Baha and Khamis Mushait. Further, Abha has the highest maximum and mean relative humidities and the highest mean wind speed. Seventeen (17) sites, stretching between approximately 18.2°N and 42.5°E in the Asir region were initially identified. It is interesting to note that site at Al-Sooda in Asir region has the highest altitude (about 3,015 m) among the other sites and is about 15 km away from Abha. Twelve SFCs were tested at five different sites in Al-Sooda area with instruments especially designed to collect and measure fog water. The amount of fog water collected in each site differs considerably and the SFC test set up at one of the sites is shown in Fig. 2. The instruments used during this study were SFCs, meteorological instruments to measure the ambient temperature, relative humidity, speed of wind and its direction and measurements of volume of fog water captured by the collectors. It was observed that the environmental conditions changed notably when the fog arrived. The temperature was decreased abruptly, by more than 3°C, and the relative humidity was increased rapidly. Based on the results, two LFCs were manufactured and tested at two sites.

In order to form the fog the relative humidity of air must be closer to 100%, as shown in Fig. 3 and the air temperature closer to the ground must be within 3°C of dew point temperature, as shown in Fig. 4 (Gandhidasan and Abualhamayel, 2012).

The LWC in the fog varies from 0.05 to 3 g m^{-3}. The LWC in high elevation fog (camanchaca) on the coastal mountains in northern Chile varies from 0.22 to 0.73 g m^{-3} with the droplet diameter ranging from 10.8 to 15.3 µm at wind speeds from 2 to 8 m s^{-1} (Schemenauer and Joe, 1989). Since the fog droplet size is small and its speed is low, the moisture in the fog is carried by low speed breezes of 0.2 to 5 m s^{-1}, as shown in Fig. 5 (Gandhidasan and Abualhamayel, 2012). Hence, fog harvesting requires a vertical surface for its collection. This method of harvesting system is limited

Fig. 2. SFC test set up at one of the sites in Al-Sooda.

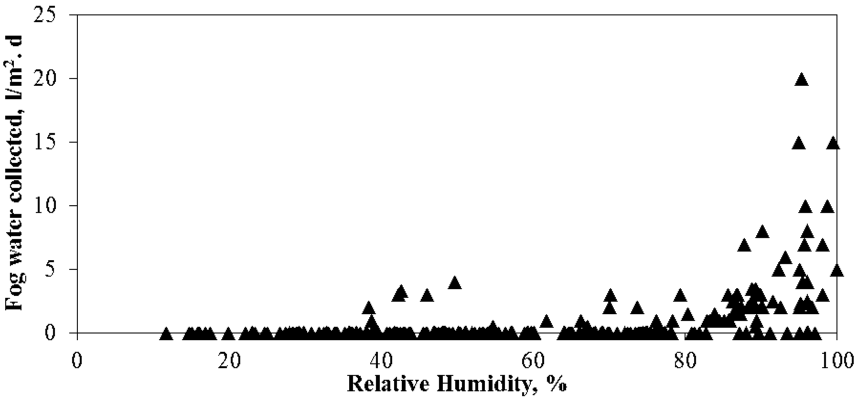

Fig. 3. Daily fog water collection rate as a function of relative humidity.

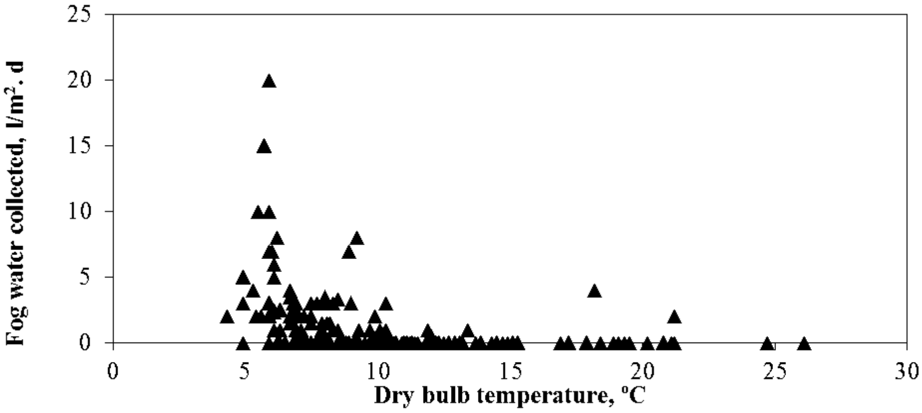

Fig. 4. Daily fog water collection rate as a function of ait temperature near the ground.

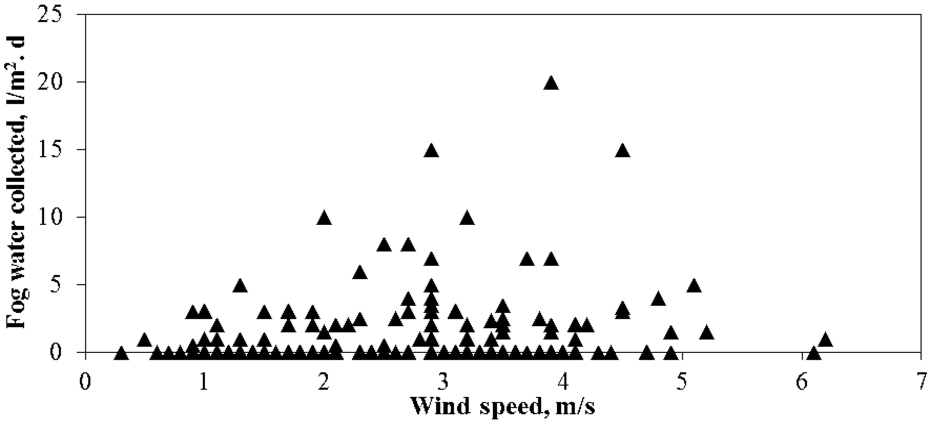

Fig. 5. Daily fog water collection rate as a function of wind speed.

to geographical places where topographic and meteorological conditions are favourable to frequent and persistent fogs. Fog water harvesting is a renewable source of water which does not depend on groundwater, surface water, precipitation and water from the oceans.

Design Considerations

Two kinds of passive mesh type fog water collectors are widely used in practice. The standard fog collector (SFC) of 1 m^2 is used for field tests and the large fog collector (LFC) of 40 m^2 is used for operational tests. However, quarter-size fog collectors (QFCs) of 0.25 m^2 are also used for field tests (Marzol, 2002; García-Santos *et al.*, 2004) since they can be installed at a lower cost and overflowing of the water drums can be avoided. The rates of fog water collection can be found by measuring the volume of water collected on fog collectors.

The fog collectors consist of a structure, with a mesh panel inside a frame. The frame should be made of metal for rigidity to secure a 50 to 60% shade coefficient polypropylene mesh and painted to prevent rusting. The mesh has to be double-layered and separated by approximately 2.5 cm. The mesh must be pulled tightly over the frame with the support. Loose mesh net will lead to loss of water and can also break easily. This panel should be supported on a metal base, 2 m from the ground (Schemenauer *et al.*, 2005) and painted. The mesh area measures 1 or 40 m^2 and is used to intercept the droplets of fog. The water collection rate is expected to be the highest when the mesh surface is normal to the direction of wind. The fog water collects on the mesh and the droplets fall by the gravity into a gutter or trough situated below the frame secured for collection. The trough may be square, semi-circular or triangular in cross section and made up of aluminium. As the fog and strong winds come indiscriminately from either the front or back of the fog collector, the trough should be located exactly in the middle of the frame base to collect the fog water from both sides. The trough must be wide and deep enough to collect fog water that drips down from the bottom of the mesh. The trough should be slightly inclined, so that the water can be drained quickly to a drainpipe. The hose takes the water collected in the trough to a closed plastic container that is large enough so as not to overflow when there is heavy fog. To prevent contamination of water, a screen should be installed at the end of the trough to trap undesirable materials. The fog collector is completely passive.

Selection of the Collection Surface

The feasibility of fog water harvesting system is determined by two important factors. They are the expected water collection rate and its quality. The water collection rate depends on the frequency of fog events and its duration, moisture content of the fog and the wind speed. The quality of the water collected depends on the mesh surface used for water collection, water composition, and the chemical composition of the dry collector deposition that increases with time between fog events.

Fog water collection also depends on the mesh characteristics. The selection of the mesh involves striking a balance between the highest collection efficiency for fog droplets and causing the least interference with the wind carrying drops of water to pass through. The water droplets collide with the mesh surface and trapped on its fibers. The selection of the collection surface is based on cost, availability, shade coefficient of the mesh, durability, resistance to solar UV and the drainage of water.

Typical Raschel mesh made up of polyethylene or polypropylene ribbons (approximately 1 mm wide and 0.1 mm thick with pore sizes of 1 to 1.3 cm) is commonly used for fog water collection because they are easily available and inexpensive. In order to prevent unravelling of the mesh, the fibers are linked together by a suitable knit. In fog collection, the mesh is set normal to the fog-laden wind direction. The mesh shade coefficient (*SC*) represents the capturing capability of droplets since only part of the mesh can catch droplets and it is defined as (de Dios Rivera, 2011):

$$SC = 1 - \frac{A_{op}}{A_{tot}} \tag{1}$$

where *SC* is the mesh shade coefficient and A_{op} and A_{tot} are the opening and the total area of the mesh, respectively.

Park *et al*. (2013), defined the shade coefficient in terms of the radius of the mesh fiber and the spacing between the fibers as shown in Fig. 6. It is given by,

$$SC = \frac{X}{S^2 + X} \tag{2}$$

where, $X = R(R + 2S)$; R is the radius if the mesh fiber and half spacing between the mesh fibers, respectively.

It is to be noted that from an aerodynamic point of view the Rachel mesh is more complicated than suggested in Eq. (2) and Fig. 6. However, for the approximation the above equation can be used (Park *et al*., 2013).

Advanced Fog Water Collection Surface

Fog water collection is a simple impaction process and recently researchers have employed advanced techniques to develop the impaction surface. These efforts are based primarily on the fog collection behavior of various biological species such as desert beetles (Seely, 1979; Parker and Lawrence, 2001; Zhai *et al*., 2006; Garrod *et al*., 2007; Ahmad and Patel, 2010; Nørgaard, 2010; Park *et al*., 2013; White and Kietzig, 2013) and plants (Nebelsick *et al*., 2012; Nørgaard and Dacke, 2012; Heng *et al*., 2014; Ju *et al*., 2014). Namibian desert beetles, which capture drinking water from fog-laden wind has received much attention from the researchers. Stenocara desert beetle has structured surface covered by an array of bumps 0.5–1.5 mm apart, each about 0.5 mm in diameter. These bumps have peaks and troughs. The peaks of these bumps are smooth with no covering forming hydrophilic region, whereas the troughs, are covered by a superhydrophobic microstructure coated in wax. Fog is attracted to the hydrophilic peaks leading to the formation of water droplets which grows and eventually reaches a size at which its contact area covers the entire hydrophilic region. When the mass of the water droplet overcomes the capillary force that attaches it to the surface, the droplet detaches and rolls down along hydrophobic troughs (Parker and Lawrence, 2001).

Researchers have tried to mimick the characteristics of these biological species to develop and/or modify the surface of the fog collectors. These modifications involve the concepts of hydrophilicity (ability of the surface to either absorb water or let water spread over its surface) and hydrophobicity (ability of the surface to repel water). Static water contact angle is defined as the angle between the wetted surface and the tangent to the surface of the water droplet. Surfaces are called hydrophilic if the static water contact angle is below 90°; hydrophobic if the static water contact angle is greater than 90° and superhydrophobic if the static water contact angle is above 150° (Bhushan, 2009). It is to be noted that many investigators studied the influence

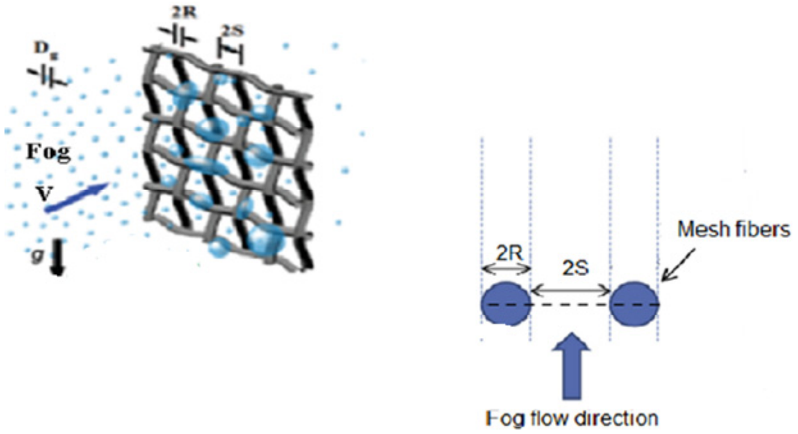

Fig. 6. Fog flow through a mesh surface.

of impaction surface wettability characteristics, length scale, and weave density of the impaction surface on the fog water harvesting capabilities. Most of the surfaces are tested in the laboratory using controlled artificial fog conditions and their performance in the field using uncontrolled natural fog conditions is yet to be carried out on large scale.

Simplified Model to Estimate the Fog Water Collection Potential

Katata (2014), reviewed recent progress made in modeling fog water deposition over terrestrial ecosystems but the prediction of fog water collection potential using fog collectors is not considered. Two other types of models are proposed to predict fog water collection potential using the passive mesh type fog collectors (Domen *et al*., 2014). They are:

1. Impaction model.
2. Efficiency model.

Both models require the estimation of fog collection efficiency. The volume of water collected from fog harvester is site dependent, based on climatic factors and terrain characteristics (Jacob *et al*., 1984). Impaction model developed by Ritter *et al*. (2008), is based on the polypropylene Raschel type mesh with a 65% shade coefficient of size 0.25 m^2. Efficiency model (Imteaz *et al*., 2011) is based on local atmospheric conditions from a site in Saudi Arabia. Domen *et al*. (2014), reported that the efficiency model did not support by research conducted in other regions. Fog harvesting potential at a particular site depends on not only the environmental factors but also the design variables of the fog collector. The climatic conditions cannot be controlled and hence, it is needed that the design variables of the fog collector must be optimized in order to maximize the collection efficiency with local atmospheric conditions.

Overall Collection Efficiency

The efficiency of fog water collection has been attributed to three factors (Ghosh *et al*., 2015), namely water content in the fog, wind and mesh interaction and the drainage of fog water from the mesh to the trough. The overall collection efficiency (η_{coll}) can be expressed as (de Dios Rivera, 2011; Ghosh *et al*., 2015):

$$\eta_{coll} = \eta_{ae} \times \eta_{cap} \times \eta_{dr} \tag{3}$$

where η_{ae}, η_{cap} and η_{dr} are the aerodynamic, capture and drainage efficiency, respectively.

Aerodynamic efficiency (η_{ae}) denotes the water droplet fraction in the fog that may collide with the mesh. The fraction of actual fog droplet that impinge on the mesh fibers and gets deposited is represented by the capture efficiency (η_{cap}).The drainage efficiency (η_{dr}) represents the fraction of the fog water travels to the gutter after colliding with the mesh.

Drainage Efficiency (η_{dr})

The fog water drain from the mesh depends on the size of the droplet, droplet surface tension and the diameter of the mesh bottom. The purpose for double-layering the mesh is that with this design, the collected water drains off much better than in a single-layer design (Schemenauer and Joe, 1989; Schemenauer *et al*., 2005; Klemm *et al*., 2012). All the fog water captured by the mesh may not reach the trough because some of the water may be lost due to high winds and may be spilled before collecting into the trough. Hence, the drainage efficiency is defined as the actual fraction of the water captured that reaches the trough. In order to minimize the losses, the trough must be positioned properly to capture fog water. These losses are difficult to estimate due to the random wind nature and must be accounted for through the drainage efficiency.

Aerodynamic Efficiency (η_{ae})

The aerodynamic efficiency depends on two coefficients, namely the pressure loss coefficient (C_o) and the drag coefficient (C_d). The pressure loss coefficient depends on the mesh characteristics such as its fibers and their weave. This represents the pressure drop across the mesh and is directly related to the shade coefficient. For a vertical mesh it is given by (Rivera, 2011):

$$C_o = 1.3\ SC\left(\frac{SC}{1-SC}\right)^2 \tag{4}$$

where C_o is the pressure loss coefficient and SC is the mesh shade coefficient.

The flow resistance offered by the entire mesh assembly is accounted by the drag coefficient. It varies with the aspect ratio of the mesh but independent of the shade coefficient of the mesh. The aspect area is defined as the ratio of the width of the mesh to the height of the mesh used in the collector. The aspect ratio for two types of passive mesh type fog collector is given in Table 2 (de Dios Rivera, 2011).

An approximate equation to predict the aerodynamic efficiency is given by (de Dios Rivera, 2011):

$$\eta_{ae} = \left(\frac{SC}{1+\sqrt{\dfrac{C_o}{C_d}}}\right) \tag{5}$$

where η_{ae} is the aerodynamic efficiency, SC is the mesh shade coefficient, C_o and C_d are the pressure loss coefficient and the drag coefficient, respectively.

Capture (Impaction) Efficiency (η_{cap} or η_{imp})

Fog water is captured on the vertical polyethylene mesh through four mechanisms (Ritter *et al*., 2008; Domen *et al*., 2014). They are impaction mechanism, direct interception mechanism, Brownian diffusion mechanism and gravitational

Table 2. Drag coefficients for SFC and LFC.

Type of collector	Dimensions	Aspect ratio	C_d
SFC	1 m × 1 m	1	1.18
LFC	20 m × 2 m	10	1.3

sedimentation mechanism. Impaction is the potential mechanism of fog deposition. Inertial impaction occurs when fog droplets encounter the mesh in the wind driven airstreams path. When the fog droplets diameter (5–50 µm) is comparable with or larger than the mesh dimensions, then direct interception becomes an important mechanism. Brownian diffusion has significant contribution only for very small droplet diameters of less than 0.1 µm. For many cases the contributions from direct interception and Brownian diffusion can be neglected (Ritter *et al.*, 2008). The gravitational sedimentation mechanism is significant if the fog droplet diameter is greater than 80 µm. Due to the low settling velocity of fog droplets and its diameter is less than 80 µm, the gravitational sedimentation mechanism may be neglected. Hence, neglecting all insignificant contributions, the fog capture efficiency due to impaction is considered in the present study and the capture efficiency is called as impaction efficiency. The overall collection efficiency can be modified as:

$$\eta_{coll} = \eta_{ae} \times \eta_{imp} \times \eta_{dr} \tag{6}$$

where η_{coll}, η_{ae}, η_{imp} and η_{dr} are the overall collection, aerodynamic, impaction and drainage efficiency, respectively.

When the mesh is placed vertically in the moving unperturbed wind stream under foggy weather conditions to collect the fog droplets, the dry air will be deflected but the fog droplets will migrate due to their higher inertia and impact the mesh solid fibers (Park *et al.*, 2013). The fog water collection efficiency by impaction is a function of Stokes number which is the ratio of the stopping distance of a fog droplet to the radius of the impaction surface. The radius of the impaction surface and the fog droplet diameter are required to calculate the Stokes number. Further, the Stokes number is influenced by the wind speed and is given by (Jacob *et al.*, 1984):

$$St = \frac{\rho_a D_g^{\,2} V}{18 \mu_a R} \tag{7}$$

where St is the Stokes number, ρ_a is the density of air, D_g is the fog droplet diameter, V is the wind speed, μ_a is the viscosity of air and R is the radius of the mesh fiber.

The impaction efficiency increases as Stokes number increases and this lead to higher rates of interception of the fog droplets. Assuming inviscid flow, the fog collection efficiency due to impaction is given by (Ritter *et al.*, 2008):

$$\eta_{imp} = \frac{St^2}{(St + 0.6)^2}\text{, for } St \geq 0.08 \text{ and if } St < 0.08\text{, then } \eta_{imp} = 0 \tag{8}$$

where η_{imp} is the impaction efficiency and St is the Stokes number.

The impaction efficiency is greater than 60% for fog droplet diameter is greater than 10 µm. The Stokes number can be optimized by selecting mesh for prevailing local wind speed and the fog droplet diameter.

Deposition Efficiency (η_{dep})

The drainage efficiency is difficult to estimate due to fog re-entrainment and premature drainage of droplets. Therefore, the deposition efficiency is defined as the fraction of fog droplets that are actually deposited from the fog-laden wind towards the mesh fibers. The deposition efficiency represents the product of impaction efficiency and the drainage efficiency. It is given by (Park *et al.*, 2013):

$$\eta_{dep} = \frac{St}{\left(St + \frac{\pi}{2}\right)} \tag{9}$$

where η_{dep} is the deposition efficiency and St is the Stokes number.

The drainage efficiency can be estimated as,

$$\eta_{dr} = \frac{\eta_{dep}}{\eta_{imp}} \tag{10}$$

where η_{dr}, η_{dep}, and η_{imp} are the drainage, deposition and impaction efficiency, respectively.

The overall collection efficiency can be simplified as,

$$\eta_{coll} = \eta_{ae} \times \eta_{dep} \tag{11}$$

where η_{coll}, η_{ae}, and η_{dep} are the overall collection, aerodynamic, and deposition efficiency, respectively.

The amount of fog water captured by the mesh can be predicted by Walmsley *et al.* (1996) and Ritter *et al.* (2008):

$$Q = 3.6\,(LWC)\,\eta_{coll} V A_{tot} \tag{12}$$

Where Q is the rate of fog water collected, LWC is the liquid water content in the fog, η_{coll} is the overall collection efficiency, V is the wind speed and A_{tot} is the total area of the mesh.

From the above equation it is clear that the amount of water captured depends on the LWC, the aerodynamic efficiency as parameterized through the shade coefficient, pressure drop and drag and the deposition efficiency as parameterized through the Stokes number.

RESULTS AND DISCUSSION

Fog collection is affected by the local meteorological conditions. From the experiments conducted at Al-Sooda in the Asir region of the Kingdom of Saudi Arabia (Gandhidasan and Abualhamayel, 2012), the effect of wind speed on the fog water collection was measured and the results are shown in Fig. 5. Typical wind speed for fog formation was from zero to 6 m s^{-1} during events and the wind direction changed during fog formation due to breeze. Additional mechanism for fog formation was observed during precipitation and rain droplets cause increase in humidity. Further, these parameters also increase the fog water collection efficiency. It is clear from the field tests that when the wind speed is about 4 m s^{-1}, the fog water collection reaches the maximum and this value is used in the present study to characterize the mesh.

Since the collection efficiency greatly depends on the size of the fog droplets and the wind speed, Reynolds number is calculated and shown in Fig. 7 for various fog droplet diameters and wind speeds. Reynolds number is small due to small size of the fog droplet and involved with low velocity. Under this condition, inertial forces are negligible compared to viscous forces and the flow is laminar (Ritter *et al.*, 2008). Reynolds number increases with the wind speed and fog droplet diameter increases.

The estimation of Stokes number is important since it predicts how well the fog collector can capture suspended water droplet in the fog. The fog water collection efficiency depends on Stokes and Reynolds numbers (the speed and the size of the fog droplets) and the mesh surface characteristics. The impaction efficiency is affected by the fog droplet size through the Stokes number.

Fig. 8 shows the variation of Stokes number for different droplet sizes and the wind speeds. As the fog droplet diameter increases the Stokes number increases with the increase in wind speed. At low wind speeds, the effect of increase in fog droplet size on Stokes number is small. However, at relatively high wind speeds, Stokes number

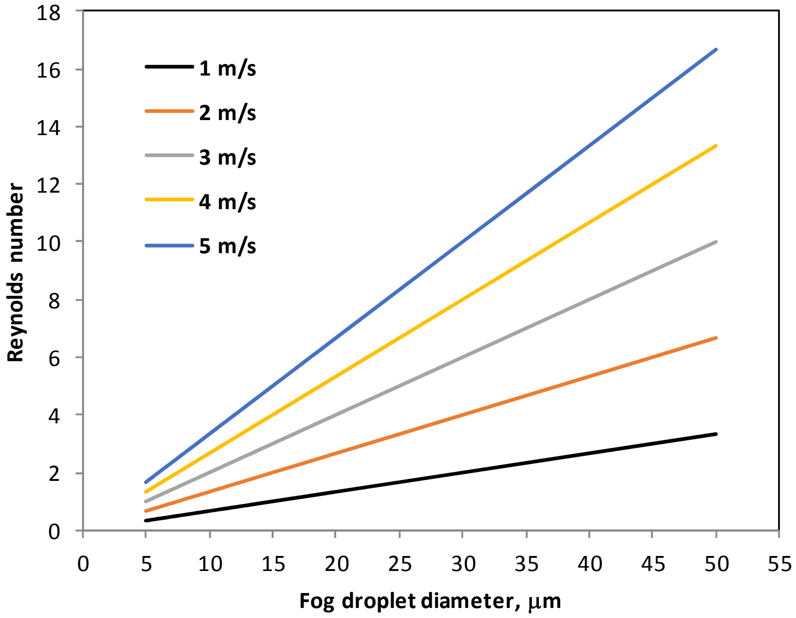

Fig. 7. Effect of the fog droplet size on Reynolds number.

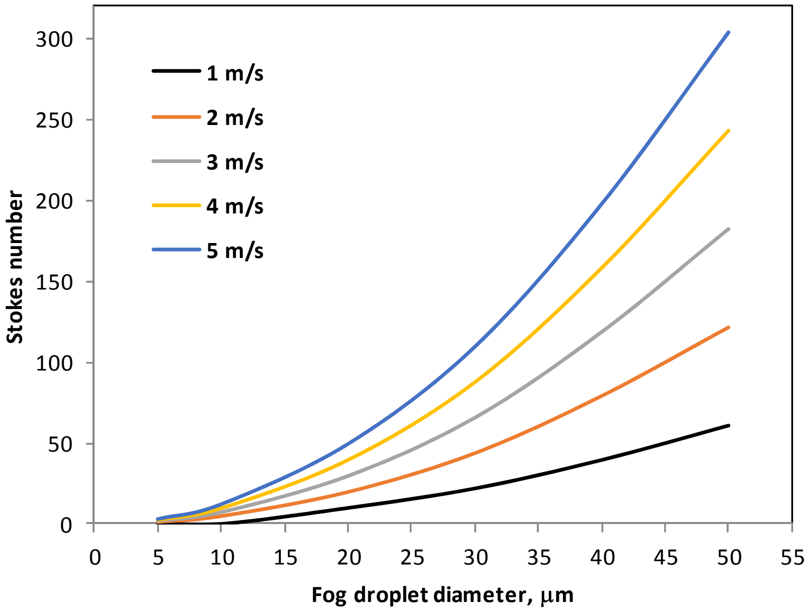

Fig. 8. Effect of the fog droplet size on Stokes number.

increases exponentially with the increase in fog droplet size. Typically the Stokes number varies from 2.4 to 242.8 when the site specific wind speed in Asir region is 4 m s^{-1}.

Fig. 9 shows the variation of aerodynamic efficiency for standard (1 m^2) and large (40 m^2) fog collectors for different shade coefficients of the mesh. The LFC has higher aerodynamic efficiency than SFC due to the slightly higher value of the drag coefficient as given in Table 1. The maximum aerodynamic efficiency is obtained for a shade coefficient of 0.56. However, the efficiency changes narrowly for the shade coefficient from 0.5 to 0.6 for both SFC and LFC, as predicted by de Dios Rivera (2011). For SFC, the efficiency varies from 22.9% to 23.1% for the variation of shade coefficient from 0.5 to 0.6 with the peak value of 23.23% at the shade coefficient of 0.56. Hence, by varying the shade coefficient of the mesh, the fog water collection rate can be maximized by reducing air resistance.

The impaction efficiency depends on the fog droplet size and the wind speed. As the fog droplet size increases the impaction efficiency also increases with increase in wind speed. From the Fig. 10, it is clear that impaction efficiency is greater than 80% for the conditions of fog droplet size with the wind speed is greater than 10 µm and 2 m s^{-1}, respectively. This result confirm that the most important mechanism for fog water capture is the impaction. The impaction efficiency exceeds 95% when the wind speed and the fog droplet size is greater than 2 m s^{-1} and 20 µm, respectively.

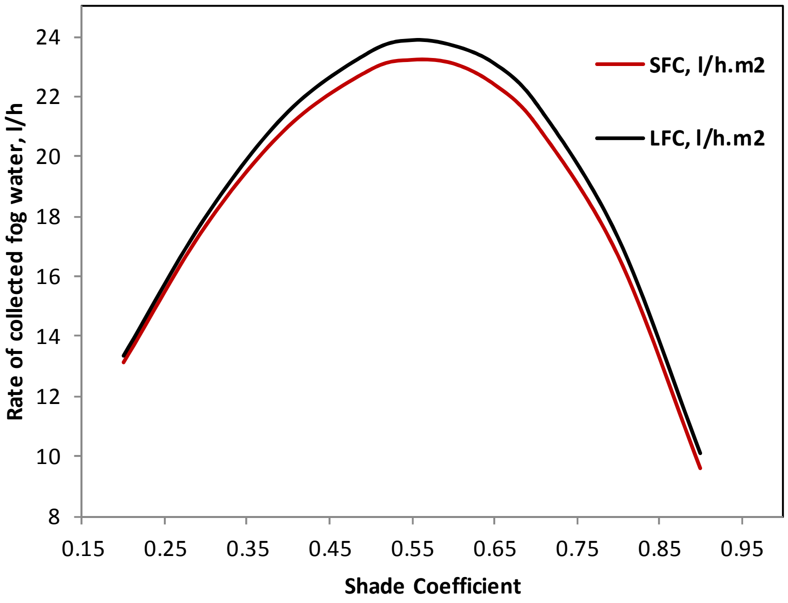

Fig. 9. Aerodynamic efficiency as a function of shade coefficient.

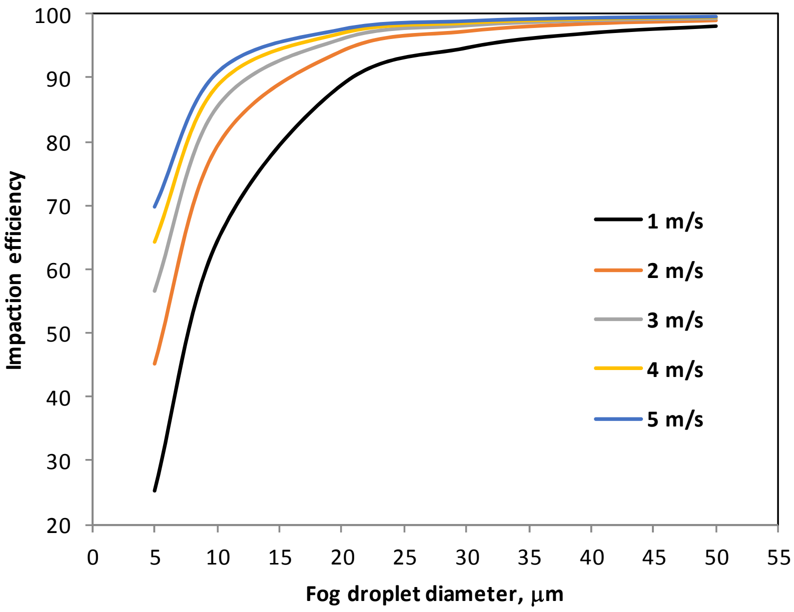

Fig. 10. Impaction efficiency as a function of fog droplet size.

Fig. 11 shows the variation of deposition efficiency as function of fog droplet size for different wind speeds from 1 to 5 m s^{-1}. The deposition efficiency represents the fraction of fog droplets that are actually deposited from the fog-laden wind towards the mesh. In line with the impaction efficiency, the deposition efficiency also increases with the increase of fog droplet size and the wind speed. As seen from Fig. 11, the deposition efficiency does not vary significantly for the fog droplet size and the wind speed exceeds 30 µm and 2 m s^{-1}, respectively.

Fig. 12 provides the theoretical range of overall collection efficiency as a function of fog droplet size for various wind speeds. As the fog droplet size increases the overall collection efficiency also increases. For the fog droplet diameter of 30 µm, the estimated collection efficiency is about 22.82% for the specific site wind speed of 4 m s^{-1} in Asir region of the Kingdom. The aerodynamic efficiency greatly affects the overall collection efficiency and hence, improvements to be made to enhance the aerodynamic efficiency.

The drainage efficiency is not available in the literature. However, as mentioned earlier, the drainage efficiency can be increased by having a properly designed and positioned trough to capture the fog water drops. The theoretically estimated drainage efficiency using the deposition efficiency and the impaction efficiency is shown in Fig. 13. For fog droplet diameter exceeds 10 µm, the drainage efficiency reaches more than 95% for the wind speed of 2 m s^{-1}.

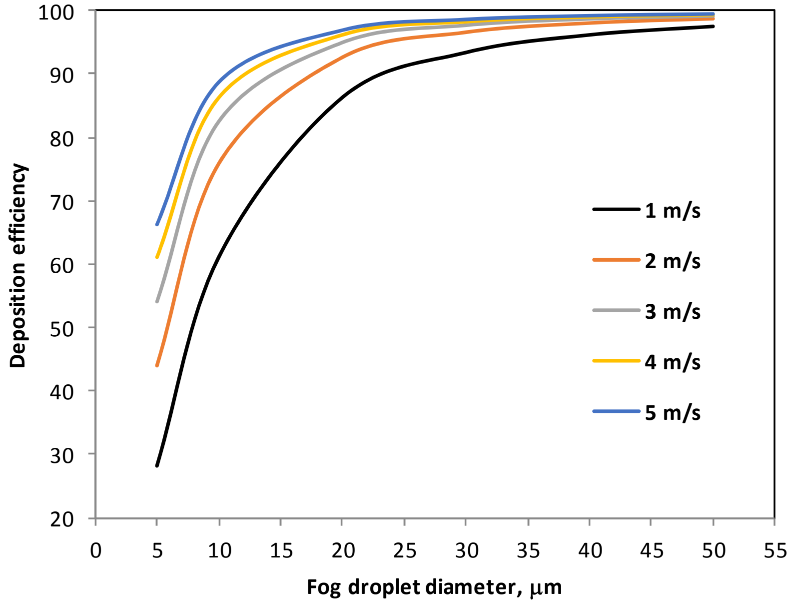

Fig. 11. Deposition efficiency as a function of fog droplet size.

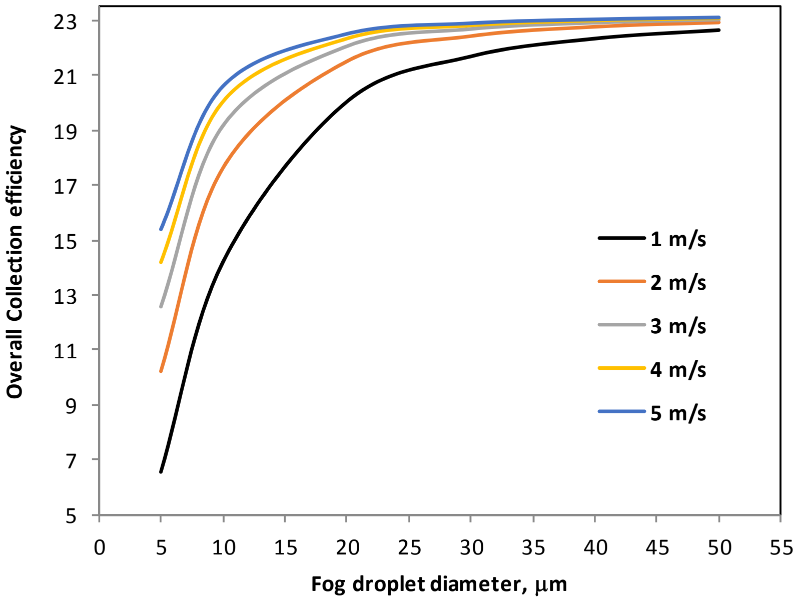

Fig. 12. Overall collection efficiency as a function of fog droplet size.

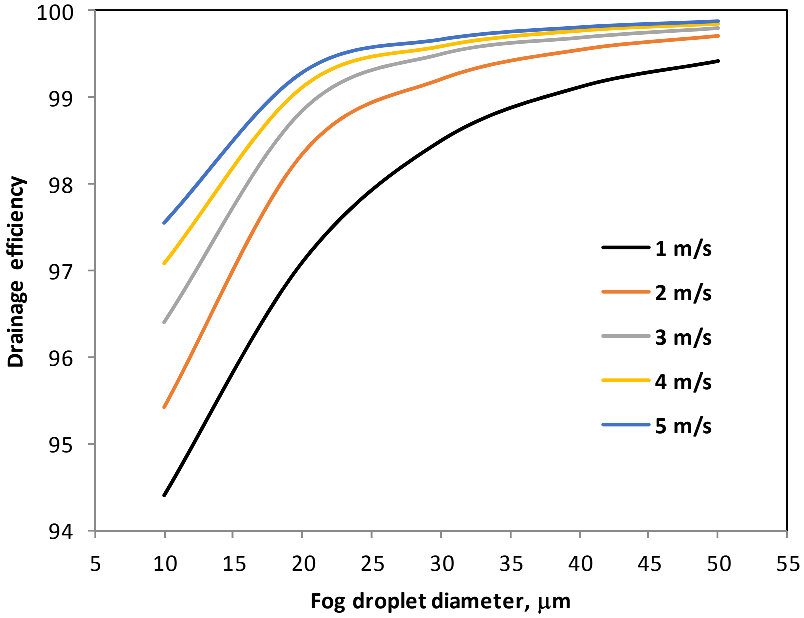

Fig. 13. Drainage efficiency as a function of fog droplet size.

The rate of fog water collected from the SFC for various droplet sizes is estimated and shown in Fig. 14 for different wind speeds. For this estimation, the shade coefficient of the mesh is taken as 0.55 and the liquid water content in the fog as 0.25 g m^{-3}. As the fog droplet size increases, the rate of fog water collected also increases with increase in wind speed. The fog droplet is considered to be large when its diameter is greater than 15 µm (Schell *et al*., 1997). It can be seen from Fig. 14 that when the fog droplet size is greater than 20 µm, the increase in rate of fog water collection is not significant. This may be due to clogging of mesh pores by the captured water droplets. This effect may increase the effective drag and render that region ineffective for fog collection (Ghosh *et al*., 2015). However, the rate of fog water collection is significant for the for droplet size increases from 5 to 20 µm. As the wind speed increases, the rate of fog water collection increases and at high wind speeds the mesh type fog collector is expected to be efficient.

Fig. 15 shows the rate of collection of fog water expected from the SFC for the range of mesh shade coefficient from 0.1 to 0.8 and for various values of the LWC in the fog. It is clear from the results that LWC determines the potential volume of fog water that can be collected from the SFC. For this estimation, the fog droplet diameter is taken as 30 µm with the wind speed of 4 m s^{-1}. As the LWC in the fog

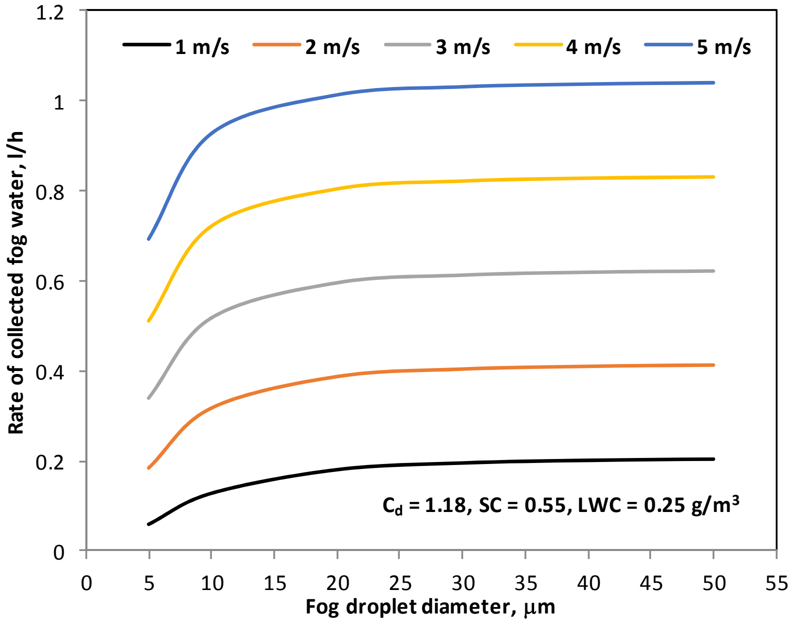

Fig. 14. Prediction of fog water collected as a function of fog droplet size.

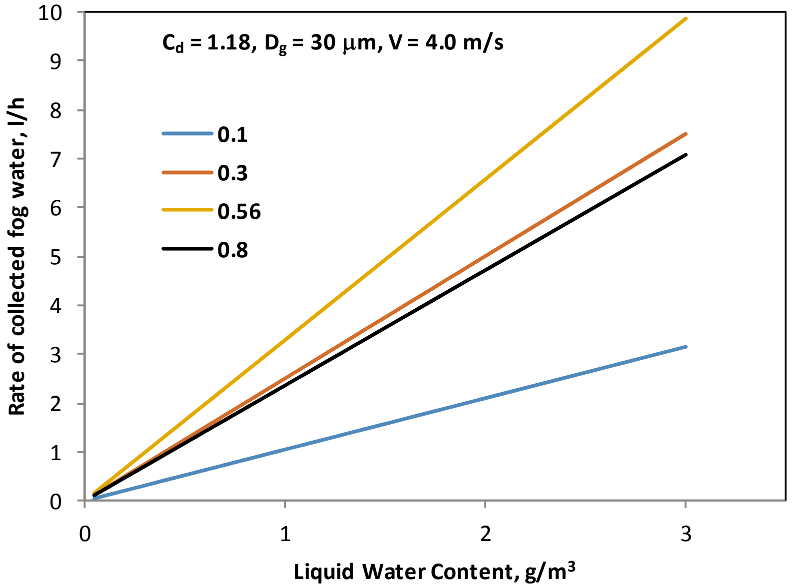

Fig. 15. Prediction of fog water collected as a function of shade coefficient and LWC.

increases the rate of collected fog water increases linearly. The maximum amount of fog water is collected for the shade coefficient of 0.56 (56%). At larger values of the shade coefficient, say 0.8, the chances of clogging of mesh pores increases. Based on the results of modeling and simulation, it is possible to collect fog water at a rate of 2 l h^{-1} in Asir region, for the wind speed of 4 m s^{-1} with the LWC of 0.5 g m^{-3} in the fog.

From the results it is clear that sufficient quantity of fog water is available in the Asir region of the Kingdom to merit the installation of LFCs. It was observed from the visual measurements that the highest frequency of fog was between 10:00 and 20:00 h with the peak at about 16:00 h.

CONCLUSIONS

The overall collection efficiency of fog water harvesting system is defined in this paper and the optimum shade coefficient for fog water collection mesh is found to be about 0.56. The aerodynamic efficiency is the major contributor in determining the overall fog water collection efficiency and it varies narrowly between 22.9 to 23.1% for the variation of shade coefficient from 0.5 to 0.6, respectively, with the peak value of 23.23% at the shade coefficient of 0.56. The variation of impaction and the drainage efficiencies is insignificant for the fog droplet size and the wind speed exceeds 10 µm and 2 m s^{-1}, respectively. However, in the case of deposition efficiency, the variation is insignificant when the above values exceeds 30 µm and 2 m s^{-1}, respectively. As the LWC in the fog and the fog droplet size increases, the rate of fog water collection also increases. The wind speed has significant impact on the rate of fog water collection and for the climatic conditions prevailing in the Asir region of the Kingdom, wind speed of about 4 m s^{-1} yields the maximum collection. As the fog droplet size exceeds 30 µm, the increase in fog water collection is insignificant for the given conditions.

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DISCLAIMER

No disclaimer.

LIST OF NOTATIONS

A	area, m^2
C	coefficient
D	diameter, µm
LFC	large fog collector
LWC	liquid water content, g m^{-3}
Q	rate of collected fog water, l h^{-1}
R	radius of the mesh fiber, µm
S	half spacing between the mesh fibers, µm
SC	shade coefficient
SFC	standard fog collector
St	Stokes number
V	wind speed, m s^{-1}

Greek Letters

η	efficiency
μ	viscosity, N.s m^{-2}
ρ	density, kg m^{-3}

Subscripts

a	air
ae	aerodynamic

cap	capture
coll	overall collection
d	drag
dep	deposition
dr	drainage
g	fog droplet
imp	impaction
o	pressure loss
op	openings
tot	total (mesh)

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