Radiation attenuation by atomized water sprays

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Outdoor environment conditioning is an important issue for areas with sever desert climate as in some places in Saudi Arabia. This paper addresses the feasibility of radiation attenuation by generating an atomized water droplets hangover. This artificial droplets cloud acts as shading canopy and cools, by evaporation of droplets, a layer of air that moves down to the ground level. Current systems use atomization nozzles that are arranged in a single horizontal plane. The use of parallel atomizers to create droplets clouds of large thickness (optical path) is investigated. Controlled experiments were conducted in a cloud chamber where the local and average attenuation factors were measured for a range of atomization pressures from 2 to 11 bar and variable nozzles spacing. The local attenuation factor showed increase with the distance from the nozzle before it declines as a result of droplets loss of moving momentum. The average attenuation factor showed exponential increase with the spraying pressure. Two parallel jet atomizers showed 50% improvement in the shading effect where the maximum average attenuation factor increased from 0.35 to 0.65 for single and double jets, respectively. The effect of nozzles spacing was insignificant for pressures above 7 *bar*.

يعتبر تلطيف الجو في الأماكن الصحراوية المكشوفة مثل أماكن الحج بالمملكة العربية السعودية أمرا يستحق الدراسة. يقدم هذا البحث دراسة عملية لغرض تخفيض شدة الإشعاع عند مروره خلال نفاثة مياه مفردة و كذلك خلال نفاثتين متوازيتين. وأوضحت التجربة أن ضغط الماء قبل النفاثة (ضغط الترذذ) له تأثير واضح على معامل انخفاض شدة الإشعاع (معامل الظل) حيث ترتفع قيمة المعامل كدالة أ سية مع الضغط. وأجريت التجربة على ضغوط تتراوح بين ٢-١١ ضغط جوي، مستخدمة نفاثة يبلغ قطر فتحتها ١,٦٧ مم كما تبلغ زاوية المخروط لها ٨٠° من نوع المخروط المفرغ. ولقد أمكن الحصول على معامل ظل يبلغ متوسط قيمته ٣٥% عند استخدام نفاثة مفردة و ٦٥% عند استخدام نفاثتين متوازيتين. نتائج التجارب أوضحت أن المسافة بين النفاثات ليس لها تأثير هام عند ضغط ترذذ أكبر من ٧ بار.

Keywords: Droplets, Atomization, Solar radiation, Attenuation

1. Introduction

For many decades, solar energy applications attracted the attention of researchers around the world for being a free source of energy. Therefore, the availability of solar energy under different climates was a major concern for the design of energy utilization equipment. Solar collectors and /or concentrators [1], photovoltaic panels [2], energy storage [3] and solar water distillation [4 and 5] are just examples of applications for which the solar collection efficiency is to be maximized. Therefore, effects of clouds [6], atmospheric pollutants and aerosols [7 and 8] on radiation penetration characteristics were studied. Other applications focusing on methods to reduce the solar radiation reaching ground surfaces have been also considered. Reduction of the radiation intensity may be achieved thorough the use of solar screens, awnings, stationary or movable shadowing overhangs and /or window glass treatment, ASHRAE [9]. These shading or glare fading methods are suitable for small confined areas with indoor climate control. Few techniques showed limited success in shading large open areas. Shading through tree covers, Simpson [10] or large fabric structures, Bennet and Elmwood [11] and Rash [12], has been in practice for sometime.

In Saudi Arabia, near the holey city of Mekkah and during Hajj (pilgrimage) season, there is a need to reduce the amount of solar radiation reaching the ground. At the open area of Arafat (Latitude 22° N and longitude 39° E) more than two million people gather once a year to perform the activities of Hajj. The harsh climate in this area, all around the year (typical clear sky with approximate temperatures of 35°C to 47°C), invites a desperate need to some kind of shading technique. A novel idea was developed for this particular situation where thousands of water atomizers were used to generate an artificial droplets canopy that over hanged at 10 to 15 m above ground level. Similar systems [13 and 14] were installed in the early nineties in Arizona utilizing flash evaporation process. Water was atomized to 10-micron droplets (mist) that evaporate and the cold air was forced to the ground level. These outdoor cooling systems were used by hotels and restaurants to attract customers to their patios during hot summer days. It was reported that these systems were sensitive to air humidity. Moreover they failed at humidity levels above 50 %, at which flash evaporation of the mist stops. Fakih Company, of Saudi Arabia, built a system that used water spray nozzles (at present 21000 atomizers are installed). Direct solar radiation was attenuated when passing through the artificial droplets canopy and as a result the air temperature at ground level dropped by 10 °C to 15 °C. Modifications of the installed system, through adjustment of the atomization pressure and level of droplets cloud, caused further decrease in the air temperature with an increase in relative humidity by only 15% to 20%. Selection of the atomizers size and operational pressure determine the droplets mean diameter and population. The droplets size has to be carefully adjusted in order to obtain a reasonable attenuation level. Very fine droplets (less than 20 microns) may fly with the wind and evaporate in a short time while large ones (greater than 500 microns) may fall close to the nozzle discharge having short suspension time. In systematic studies by Baghdadi and Zaki [16] and also by Baghdadi [17] experimental measurements of the solar radiation attenuation by a single jet atomizer as function of the atomization pressure and nozzle diameter were presented. On basis of extensive outdoor experimental measurements they developed a correlation that relates an attenuation factor F to the upstream atomization pressure P. The maximum reported value for F was 30 % at P = 11 bar.

The present study is stimulated by the novel application on the use of artificially generated droplets clouds as a shading canopy for large open areas. The effect of parallel jets atomizers (increase in optical path) on the attenuation of light beam passing through water droplets cloud is measured for different atomization pressures. Experiments were conducted in a confined cloud chamber to reduce the effect of irrational climatic parameters associated with outdoor experiments.

2. Experimental apparatus

Fig. 1. shows a layout of the experimental apparatus that consists mainly of a cloud chamber, two atomizers, a suction fan, and a centrifugal circulation pump. The cloud chamber is a box 1.2 x 1.2 x 2.4 *m*^{3} dimensions made of Plexiglass plates, 4 *mm* thickness. The two atomizers were fixed to a stand at one side of the cloud chamber so with the generated jet cones along the 2.4 m side. The stand allows vertical and horizontal positions adjustment of the atomizers. The atomizers used in the present experimental study were of the hollow cone spray pattern nozzle (Monarch Co. PLP 80° -15.5 USGPH, Phil. PA). Calibration of these nozzles gave a discharge-pressure relation as:

$$Q = 17.76\sqrt{P} \, , \tag{1}$$

where Q is the volumetric flow rate measured in *lit/hr* and P is the pressure upstream the nozzle measured in *bar*. These selected nozzles are the same as those used in the field project at Arafat, Saudi Arabia. A nine stages stainless steel vertical centrifugal pump (Grundfoss Co. model T-9) delivers water from a water storage tank to the nozzles. A by-pass technique was employed to control the flow rate through the nozzles and a Bourdon-tube pressure gage (1% accuracy) was used to measure the discharge pressure. A fan (6 kW power with 7.1 kPa pressure difference and 57 m^3/min flow rate) was fixed to the cloud chamber side opposite to the nozzles to generate a weak air stream (velocity of 0.6 m/s). This stream just helps to generate a uniform droplets distribution within the zone of measurements.

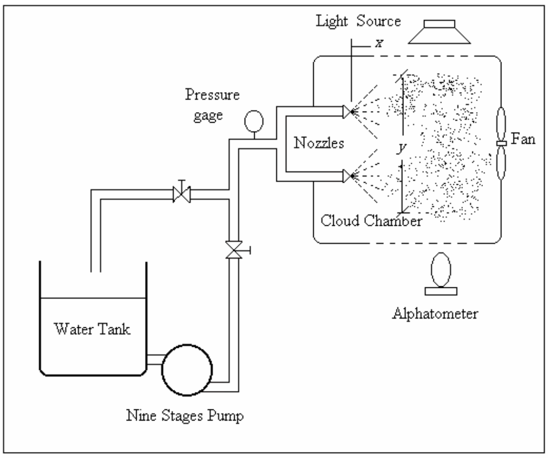

Fig. 1. Layout of the experimental test facility.

The attenuation capacity of a cloud of droplets may be determined by comparing the intensities of a light beam, I and I_o, passing through a cloudy and clear chamber respectively. Local attenuation factor is a function of the light path *y* intercepted by the droplets, which varies along the distance *x* as shown in fig. 1. In addition the attenuation depends on the droplets size, which in turn is a function of the atomization pressure *P*. Therefore a local attenuation factor, *F*, for a specific nozzle may be defined as;

$$F = f(y(x),P) = \frac{dI}{I_o} = \frac{I_o - I}{I_o} \ . \tag{2}$$

Light intensities *I* and I_o were measured along the chamber at the centerline plane of the droplets cone at eight different positions. To eliminate the effect of the chamber walls the light beam was allowed to pass through eight holes each of 5 *cm* diameter made in the Plexiglass and received at the opposite side of the chamber by an alphatometer. An average attenuation factor $\bar{F}$ along the spray cone can be defined as;

$$\bar{F} = \sum_{i=1}^{n}\left(I_o - \bar{I}_i\right) \Big/ \sum_{i=1}^{n} I_o \ . \tag{3}$$

Where $\bar{I}$ is the integral average radiation within the distance of measurements defined as;

$$\bar{I} = \frac{1}{x_n - x_1}\int_{x_1}^{x_n} I(x)\, dx \ . \tag{4}$$

Where x_1 to x_n are distances measured from the nozzle. The difference (x_n-x_1) is the length along the droplet cone centerline where the attenuation was measured. Measurements were made along the axis of the droplets cone, x_1 = 5 cm and x_n = 75 cm, fig. 1. The used light source was a 500 W Halogen lamp with a parabolic reflector and a day light spectrum.

3. Results and discussion

The variation of the local attenuation factor *F* for a single nozzle within a pressure range from 2 to 11 *bar* is shown in fig. 2. Plotted are values of *F* when the cloud of droplets was moving with the jet momentum (fan off) and when the cloud chamber was under suction (fan on).

It can be seen that the attenuation factor is small near the nozzle discharge and it increases with the distance away from the nozzle until it reaches a maximum value before it drops down. This behavior is attributed to the fact that the cross sectional area of the cone of water droplets increases with the distance from the nozzle before it diffuses inside the chamber.

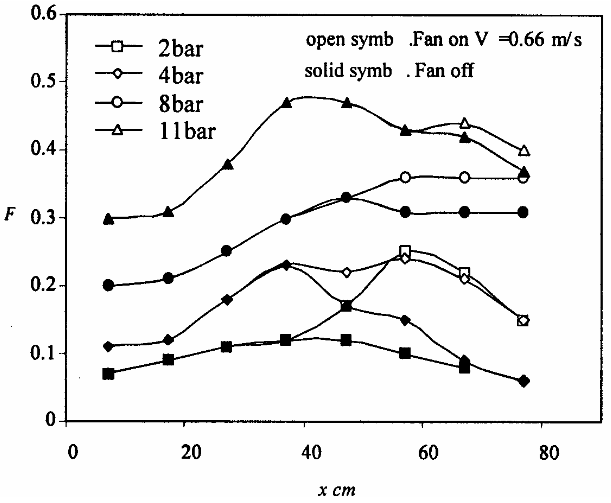

Fig. 2. Variation of the local attenuation factor with distance from the nozzle, single jet.

The plotted results, fig. 2, show that high levels of attenuation are reached, in general, with high atomization pressures. For 11 *bar* up stream pressure, the maximum attenuation factor is 0.49 and it occurs at approximately 45 c*m* from the nozzle discharge. For low atomization pressure of 2 *bar,* the maximum attenuation factor is only 0.25 and it occurs at 58 *cm.* This drop in the maximum value of *F* at low pressure can be related to the large size of droplets at low pressures as well as to the short flying time. Moreover, for low atomization pressure, the attenuation capability of the cloud of droplets vanishes at a distance of 77 cm from the nozzle discharge and the attenuation factor approaches zero.

The effect of the suction fan on light attenuation is demonstrated in fig. 2. The fan helps enhancing the local attenuation capability of the droplets cloud by moving the location of the maximum *F* further away from the nozzle. The enhancement using the fan is appreciable at low atomization pressures. At 2 *bar* pressure, the local attenuation factor reached 0.25 with the fan on, while it was just 0.11 when the fan was off. The air stream generated by the fan helps to distribute and suspend the droplets inside the chamber.

Fig. 3 shows that the fan effect may be ignored when considering the average values of the attenuation factor $\overline{F}$ at pressures above 7 bar. From the same figure, however, the effect of the atomization pressure on the attenuation factor is shown to be dominant. High atomization pressure leads to an increase in droplets population (or to decrease the void fraction), which is expected to increase the attenuation level through series of reflections and refractions of light beams. For this reason, an investigation using two parallel similar jet atomizers, placed at 20 *cm,* 30 *cm* and 40*cm* apart, was performed.

The variation of the local attenuation factor *F* with the distance from the nozzle discharge when the two atomizers were placed at 20 *cm* apart is shown in fig. 4. It can be observed that the value of the attenuation factor increased when two parallel jets were used. The maximum value was 0.74 with atomization pressure of 11 bars, fig. 4. The corresponding value for a single jet at the same conditions was 0.49. The results in figs. 2 & 4 suggest that the use of two parallel jets would increase the attenuation capacity of the formed droplets zone but the relation is not in direct proportionality.

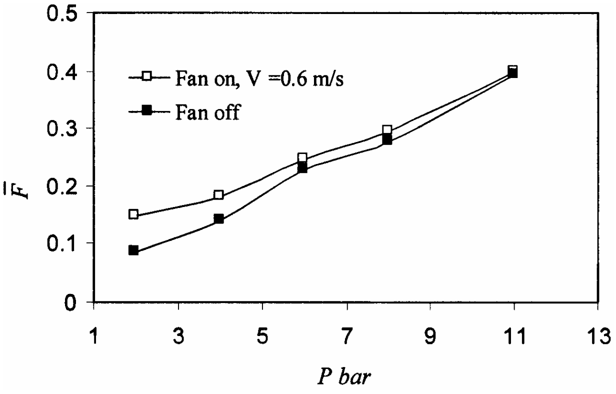

Fig. 3. Average attenuation factor at different atomization pressures, single nozzle.

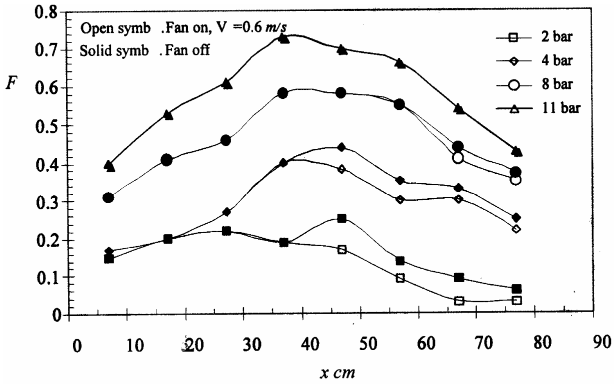

Fig. 4. Attenuation factor for two nozzles arrangement as function of distance from the nozzle discharge (20 cm nozzles spacing).

The variation of the average attenuation factor $\overline{F}$ for a single and two parallel jets is shown in fig. 5. Again the fan effect is noticeable at low pressures, 2 to 5 bar, but of less importance for twin parallel jets. The maximum deviation is within 20 % at 2 *bar* and 20 cm jets span and diminishes at 11 bar.

The distance between the two parallel nozzles has insignificant effect at atomization pressures P > 7 *bar* for the investigated range of parameters 20 to 40 cm distances. At 11 *bar* $\overline{F}$ varied from 0.54 at 20 cm span to 0.6 when the spacing was doubled, the difference was only 10%, fig. 5.

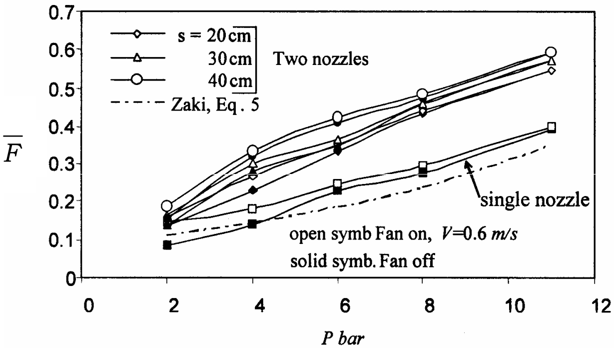

Fig. 5. Variation of the average attenuation factor for two jets at different spans.

Employing two parallel jet atomizers showed the presence of an overlapping region. In this region, the droplets are mixed increasing the population and assisting the mechanism of radiation attenuation. On the other hand this overlapping region is characterized by high probability of droplets collision and formation of large heavy droplets that fall down within the zone. The latter mechanism tends to decrease the attenuation capacity of parallel-atomized jets. Though, the data in fig. 5 shows that the average attenuation factor increases with pressure in the same pattern for both single and double jets.

On basis of extensive outdoor experimental measurements, the average attenuation factor for a single atomized water jet was correlated by Zaki and Baghdadi [16] as;

$$\bar{F} = 8.52\, e^{0.128P} \qquad 2 \le P \le 11 \text{ bar.} \qquad (5)$$

The correlation predicts the data with maximum deviation of 27% at 2 bar pressure, fig. 5.

The deviation is within 13 % for P >7 *bar*, which is the practical range of the shading system operation. Since this correlation was developed using over 300 data points, it is suggested to consider it as a reference relation.

5. Conclusions

The present experimental study shows the potential of employing a new technique for shading large open outdoor areas by generating an overhanging water atomized canopy. Experiments were conducted in a cloud chamber using a constant luminous light source. The beam passed through an atomized water droplets (50 to 150 μm volumetric mean diameter) region that was generated by hollow cone type atomizers. The local and average attenuation factors were measured for atomization pressures range between 2 and 11 *bar*.

The spatial variation of F along the axis of the droplets cone showed increase in F with the distance away from the nozzle followed by a gradual decrease. At a distance from the nozzle the droplets lose part of its momentum and move in a downward direction causing the reduction in the local attenuation factor.

The data showed an ascending trend in the attenuation capacity with pressure increase. At high pressures the droplets size decreases and its population increases offering a dense optical path that tends to increase the radiation attenuation. The maximum average attenuation factor obtained for a single jet was 0.35 that increased to 0.65 when using two parallel jets under the same operation conditions. On basis of the present study, the effects of spacing between nozzles and air streams for jets confinement are negligible at $P > 7$ *bar*, which is the practical range of operation.

Nomenclature

F	Attenuation factor,
$\bar{F}$	Average attenuation factor,
I	Radiation intensity through the droplet clouds (W/m^2),
I_o	Radiation intensity outside the droplet clouds (W/m^2),
P	Atomization pressure (bar),
Q	Volumetric flow rate (m^3/*sec*),
S	Distance between two parallel jet nozzles (m),
V	Air velocity (m/s),
x	The distance from the nozzle discharge (*cm*),
x_1	The distance from the nozzle discharge of the first reading (cm), and
x_2	The distance from the nozzle discharge of the last reading (cm).

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