Attenuation of solar radiation by a water mist from the ultraviolet to
the infrared range

Leonid A. Dombrovsky a,*, Vladimir P. Solovjov b, Brent W. Webb b

a Joint Institute for High Temperatures, NCHMT, Moscow 111116, Russia
b Department of Mechanical Engineering, Brigham Young University, Provo, UT 84602, USA

Abstract

A model is developed for the hemispherical transmittance of direct and scattered solar radiation from a cloudless atmosphere by a mist layer of water droplets in order to investigate the potential of water misting systems to serve as a protection from solar irradiation with particular emphasis on harmful UV radiation. The proposed model is based on published spectral experimental data for solar irradiation, Mie theory for interaction of the radiation with single spherical droplets, and radiative transfer theory. Known limiting solutions are employed to simplify the Mie calculations. The modified two-flux approximation is used to account for both direct and diffuse irradiation in lieu of a numerical solution for the full radiative transfer equation in anisotropically scattering media. The role of the governing parameters of a disperse water curtain of water droplets, water content, and droplet size for sample conditions is studied in some detail, particularly in the near-ultraviolet part of the spectrum where radiation can result in human tissue damage.

1. Introduction

There are many locales on earth with a hot dry climate where the summer air temperature and intense solar irradiation make being outdoors unpleasant and even harmful. To provide relief from the high temperature environment, a variety of devices exist using sprays of water droplets such as mist generators, fogging systems, or fans accompanied by spreading water jets. Such devices are advertised to reduce the air temperature due to evaporation of water droplets and to increase the humidity of the air. While the reduction in air temperature renders the environment more comfortable, it does little to protect humans from the potentially harmful solar radiation. These misting devices make no claim regarding

the potential for protection from total solar radiation, and from potentially harmful ultraviolet (UV) radiation.

This study undertakes an analytical exploration of how small water droplets generated by misting systems can serve as an effective filter for solar radiation, reducing the total incident flux and minimizing UV radiation particularly harmful to human skin. While this can be accomplished using opaque shields (e.g., roofs, curtains, umbrellas), this is not always practical. Further, such measures do not protect humans from exposure to UV radiation by indirect sources. The humidification and reduction of air temperature that result from mist generators are significant for human comfort. However, as the analysis presented here will confirm, they can provide considerable protection from radiation transfer to humans as well.

The protective properties of water droplet curtains against intense irradiation caused by fires have been studied in [1–10]. Water misting systems of high density with relatively large droplets of 20–200 μm diameter are considered. The principal effect is attenuation (absorption and scattering) of the diffuse infrared irradiation by water
The objective of this paper is two-fold: (1) Present an approximate analytical model for calculating attenuation of direct and diffuse solar radiation by polydisperse water droplets of artificially generated sprays or natural mists, accounting for the specific spectral properties of water; (2) Investigate the attenuation of solar irradiation from a cloudless atmosphere by a layer of disperse water droplets with particular attention on the ultraviolet and near-infrared spectral ranges at high-altitude conditions where potential human damage by ultraviolet radiation is high.

2. Solar irradiation

The solar spectral model developed by Bird and Riordan [12] for calculating the direct and diffuse solar irradiation components on the earth’s surface for cloudless sky conditions is adopted in the present study. The model accounts for the principal atmospheric influences: Rayleigh scattering, aerosol extinction, absorption by ozone, uniformly mixed gases and water vapor. Inputs to the model include the solar zenith angle, atmospheric turbidity, the amount of perceptible water vapor and ozone, surface pressure, and ground albedo. Calculation of the zenith angle corresponding to a specified local time required by the spectral model is performed according to the methodology outlined in [13]. For input parameters of the spectral model the values corresponding to typical cloudless weather conditions in Provo, Utah, USA (40° N, 111° W) at an elevation of 1390 m have been chosen. For an example calculation, the prediction of the spectral irradiation on a horizontal surface for the day June 22, 2009, at 13:28 Mountain Standard Time (solar noon at this location), \( \theta = 16.5^\circ \), \( \mu = \cos \theta = 0.96 \) is considered. The spectra are calculated at 122 wavelengths in the range 0.3–4.0 \( \mu m \), as shown in the left panel of Fig. 1. The spectral solar irradiation from both direct and diffuse components is illustrated. The inset panel indicates the data in the UV spectral range, 0.3–0.4 \( \mu m \). Human skin is most vulnerable to damage by solar radiation in the 0.30–0.32 \( \mu m \) spectral interval, termed UV-B radiation. Note that while the total diffuse irradiation is only about 30% of the total direct irradiation, the diffuse sky irradiation delivers slightly more UV radiation than direct solar irradiation in the damaging UV-B range. One implication is that while one may protect oneself from the direct solar rays in the UV-B range, tissue damage may still result from diffuse irradiation.

Despite the many benefits of solar irradiation, there are two primary possible harmful effects to the human population: (1) Sunstroke as a result of overheating by total (all wavelengths) global (combined direct and diffuse) solar irradiation; (2) Exposure of harmful UV radiation to humans, animals, and plants. UV radiation has been linked to skin cancer, cataracts, and macular degeneration leading to blindness. Cumulative exposure to solar radiation increases the risk of melanoma and non-melanoma skin cancer. The harmful action of UV radiation is characterized by the UV-index, which is an international standard of the strength of the UV radiation from the sun at a specific location on a particular day. The scale is used principally as
part of weather forecasting to inform the general public of the level of potential UV exposure, permitting humans to protect themselves from excessive exposure.

The McKinlay–Diffey spectral erythema action function, \( W_l \), (the so-called erythema curve) has been developed experimentally [14] to characterize the susceptibility of human skin to solar radiation-induced erythema (sunburn) when exposed to radiation at a wavelength \( \lambda \). This function has been adopted as a standard by the Commission Internationale de l’Eclairage (CIE). The relative danger function is found by multiplication of the spectral irradiation \( G_l \) by the erythema action function \( W_l \). The right panel of Fig. 1 illustrates the global (direct+diffuse) spectral solar irradiation \( G_l \) in the UV range, the erythema action function \( W_l \), and the relative danger function \( G_l W_l \). The UV-index is calculated by spectrally integrating the relative danger function over the UV spectral range and dividing by 25 mW/m², which is taken as a unit dose of harmful UV irradiation:

\[
\text{UV-index} = \frac{1000}{25} \int_{0.28}^{0.4} W_l G_l d\lambda.
\]

\( W_l \) is dimensionless, \( G_l \) is expressed in W/(m²µm), and \( \lambda \) is in µm. The UV-index may thus be viewed as the number of doses of harmful radiation associated with the solar heating. Note that the potential damage to human tissue is most acute at low wavelengths in the ultraviolet spectrum [14,15]. The level of human risk to exposure to UV irradiation is classified using the UV-index in the range from low (UV-index < 3) to extreme (UV-index > 11). There are approximately 200 days a year when the UV-index in Provo, Utah, USA, can reach a high level. Thus, any reduction of the UV-index by water misting systems may be beneficial.

It should be noted that in addition to UV radiation, high energy visible (HEV) radiation is considered as a dangerous one for human skin and eyes [16–18]. In ophthalmology, the HEV radiation treated as a violet/blue band with the wavelength from 0.38 to 0.53 µm has been implicated as a cause of age-related macular degeneration. Therefore, some particular attention to the HEV spectral range will also be given here.

3. Radiative properties of water droplets

The spectral optical constants of pure water over a wide wavelength range are well-documented [19,20]. Water is a weakly absorbing substance in the short-wave range including the near-ultraviolet, visible, and a portion of the near-infrared ranges. By contrast, strong absorption is exhibited in the long-wave part of the near-infrared and the mid-infrared spectral ranges.

It is well known that the details of the angular distribution of radiation scattered by single particles are not usually important for the calculation of the hemispherical transmittance of a layer of a disperse medium. It is true not only for diffuse but also for direct incident radiation [21]. For this reason, the transport approximation for the scattering phase function can be confidently employed here. In this case, it is sufficient to specify only two spectral characteristics of the medium: the absorption coefficient \( \sigma_a \) and the transport coefficient of scattering \( \sigma_t = \sigma_a (1 - \Pi_s) \) where \( \sigma_a \) is the ordinary coefficient of scattering and \( \Pi_s \) is the so-called scattering asymmetry factor [22–24]. It is also natural to assume that the absorption and scattering characteristics of a small element of the medium can be determined on the basis of the far-field single-scattering approximation [25]. There is no doubt that the latter assumption, which is known also as the independent scattering approximation, is correct for the problem under consideration here because droplet positions are random and uncorrelated and the distance between water droplets is usually greater than both the droplet size and the wavelength.
Note that the independent scattering assumption is sometimes invalid in the microwave range when one can observe the coherent scattering by clusters of inertial droplets suspended in a turbulent cloud [26]. However, it is not an important effect for the present analysis and use of direct relations between the coefficients $\alpha$ and $\sigma_{tr}$ and the corresponding characteristics of single spherical droplets will be made. These relations are especially simple in the case of monodisperse droplets:

$$\alpha = 0.75 f v Q_a / a$$

$$\sigma_{tr} = 0.75 f v Q_{tr} / a$$

(2)

where $f v$ is the volume fraction of water droplets, and the dimensionless quantities $Q_a$ and $Q_{tr}$ are, respectively, the efficiency factor of absorption and transport efficiency factor of scattering for a single droplet of radius $a$. The values of $Q_a$ and $Q_{tr}$ can be calculated using the Mie theory [24,27]. Some results of these calculations for water droplets of different size are presented in Fig. 2. One can see three spectral ranges of quite different behavior of absorption and scattering:

1. In the short-wave range, including the near-ultraviolet and the visible ranges, where the diffraction parameter of water droplets is $x = 2\pi a / \lambda \gg 1$, absorption is very small compared with scattering. The transport efficiency factor of scattering is nearly constant in the near-ultraviolet and one can use the value $Q_{tr} = 0.3$ for droplets of radius $a \geq 5 \mu m$ with little error. For fine droplets of radius about $1 \mu m$ this value is greater (about 0.365–0.37). A contribution of such fine droplets to the attenuation of solar radiation by an artificial polydisperse water mist is expected to be insignificant and one can use the value of $Q_{tr} = 0.3$ for practical estimates. The short-wave range is the region of geometrical optics ($x \gg 1$ and $2\pi(n-1) \gg 1$) where the solution does not depend on diffraction parameter, and the remaining parameters of the problem are the index of refraction $n$ and the optical thickness of the particle $\tau = 2\pi n \lambda$. Moreover, the water droplets are considered nearly optically soft and optically thin ($n-1 \ll 1$ and $\tau \ll 1$). As a result, one can use the value of absorption coefficient of water $\alpha^0$ to estimate the absorption coefficient of the disperse system:

$$\alpha = f v \alpha^0$$

where $\alpha^0 = 4\pi k / \lambda$.

(3)

Note that Eq. (3) yields $\alpha$ only 30–40% less than those obtained by exact Mie calculations, which are very

Fig. 2. Efficiency factor of absorption (solid lines) and transport efficiency factor of scattering (dotted lines) for single water droplets of different radius.
time consuming in the short-wavelength range. The absorption coefficient is independent of droplet size in this range.

(2) The so-called Mie scattering spectral region, where the droplet size and wavelength are of the same order of magnitude, is characterized by complex resonance behavior of both absorption and scattering. One can see in Fig. 2 that this is realized in the near-infrared spectral range for $a \geq 5 \mu m$ and in the visible range at $a=1 \mu m$. Note that the relative contribution of absorption and scattering to transport extinction coefficient $\beta^\prime = \sigma^a + \sigma^s$ depends strongly on the droplet size in this range. Particularly, there is a maximum of scattering by droplets of radius about 1 $\mu m$ in the visible range.

(3) The Rayleigh region ($x \ll 1$ and $|m| x \ll 1$), where the scattering is much less than absorption and the absorption coefficient does not depend on droplet size and can be easily calculated [24,27]. It is evident that the Rayleigh region is especially wide for small water droplets.

4. Radiative transfer model

It was demonstrated by Dombrovsky et al. [21] that a modified two-flux approximation yields quite accurate results for directional-hemispherical reflectance and transmittance even in the case of refracting samples of absorbing and scattering media. The same approach is used in the problem considered here, which is even simpler that that investigated in [21] because there is no refraction of radiation in water curtains. At the same time, the case of arbitrary angle of incidence of solar radiation is considered. This approximate approach is quite satisfactory as a qualitative predictive tool, as it is capable of capturing the salient physics for the investigation of general trends proposed here. The presence of a diffuse component in solar irradition does not lead to additional difficulties because of the linearity of the radiative transfer equation (RTE). A schematic illustration of the radiative transfer problem under consideration is shown in Fig. 3.

It is convenient to present the radiative flux transmitted by a layer of water droplets in the following additive form, where the subscript $\lambda$ is hereafter omitted for brevity:

$$q_t = T^d_{inc} q_{dir} + I^d_{inc} T_{dif} - h$$

where the first term on the right-hand side corresponds to the direct solar irradiation and the second term refers to the diffuse component of the incident radiation. Consider now the case of direct incident radiation and a homogeneous medium layer. In the transport approximation, one can use the following equivalent axisymmetric problem including the RTE and boundary conditions:

$$\mu \frac{\partial I}{\partial \tau_{tr}} + I = \frac{\alpha_t}{2} \int_{-1}^{1} J \, d\mu$$

$$I(0, \mu) = \delta(\mu) - \mu$$

where $I = I_1 / l_1$, $l_1$ is the spectral intensity of the incident radiation, $\alpha_t = \sigma_t / \beta_t$ is the medium albedo, $\mu$ is the cosine of the angle measured from the external normal to the upper boundary of the layer of thickness $d$, $\mu_i$ is the cosine of the incidence angle, $\tau_{tr} = \beta_t x$ is the local optical depth, and $\tau_{tr}^0 = \beta_t d$ is the total optical thickness of the layer. The boundary conditions of Eq. (5b) are written for the unit source of external radiation at $z=0$ and no reflection or any source of radiation at $z=d$. Following the usual approach [28], the radiation intensity $I$ is represented as a sum of the diffuse component $J$ and a term that corresponds to the transmitted and reflected directional external radiation:

$$I = J + \exp(-\tau_{tr} / \mu_i) \delta(\mu - \mu)$$

The mathematical problem for the diffuse component of radiation intensity is stated as follows:

$$\mu \frac{\partial J}{\partial \tau_{tr}} + J = \frac{\alpha_t}{2} \left[ \int_{-1}^{1} J d\mu + \exp(-\tau_{tr} / \mu_i) \right]$$

$$+ \left( \frac{1}{\mu_i - 1} \right) \exp(-\tau_{tr} / \mu_i)$$

$$J(0, \mu) = 0 \text{ and } J(\tau_{tr}^0, -\mu) = 0 \text{ for } \mu > 0$$

Fig. 3. Scheme of the radiative transfer problem for a combined direct and diffuse solar irradiation of a layer of water mist.
The directional-hemispherical transmittance can be expressed through the diffuse component:

$$T_{\text{dir-h}} = \mu_1 E_{tr} + \int_0^1 J(x, \mu) \mu d\mu$$

where $E_{tr} = \exp(-\tau_{tr}/\mu_1)$

As was done by Dombrovsky et al. [21], the two-flux approximation is employed to obtain an analytical solution of the problem. After mathematical transformations, the following relation for directional-hemispherical transmittance can be obtained:

$$T_{\text{dir-h}} = \mu_1 E_{tr} + \frac{\mu_1 c_{tr}}{\mu_1^2 s^2 - 1} \left( E_{tr} - \frac{1}{2} \frac{D_1 s + D_2 c}{c + s(1/c + c/4)} \right)$$

where

$$D_1 = -(1 + 2\mu_1)(c\zeta/2 + s) + (1 - 2\mu_1)E_{tr}\zeta/2.$$
radiation is greater than that of the diffuse radiation, respectively. As expected, the transmittance of directional radiation depends only on their product. The surface density of the layer defined here as \( f_{\text{surf}} \) thus becomes an important parameter in the problem. Calculations for two fixed values of \( f_{\text{surf}} = 0.1 \) or 0.2 m are presented in Fig. 5. The similarity is obvious between the spectral solar irradiation with and without water mist layer attenuation by a water mist at various surface densities \( f_{\text{surf}} \). It goes without saying that the spectral attenuation of the incident solar radiation by a water mist layer can be accurately predicted only by taking into account the combined hydrodynamic and thermal processes in turbulent flows of heated and evaporating droplets. The solution of this complex problem is beyond the scope of this study. However, one can easily extend the analysis presented here to the case of polydisperse droplets. In particular, the same relations in the near-ultraviolet and infrared ranges have been demonstrated (e.g., \([30–36]\)).

5. Discussion of results

Consider first predictions for spectral transmittance \( T \) of normally directed and diffuse incident solar radiation. It is obvious from the analysis presented previously that the volume fraction of water droplets, \( f_v \), and the thickness of the droplet layer, \( d \), are independent. However, the solution to the radiative transfer problem depends only on their product. The surface density of the layer defined here as \( f_{\text{surf}} = f_v d \) thus becomes an important parameter in the problem. Calculations for two fixed values of \( f_{\text{surf}} \) corresponding to the physically realistic values of \( f_v = 10^{-4} \) and \( d = 0.1 \) or 0.2 m are presented in Fig. 4. The similarity is obvious between the spectral dependences of hemispherical transmittance for direct and diffuse incident radiation, \( T_{\text{dir}} \) and \( T_{\text{h,diff}} \), respectively. As expected, the transmittance of directional radiation is greater than that of the diffuse radiation, \( T_{\text{dir}} > T_{\text{diff}} \). In the case of small droplets, this effect is nearly uniform over the spectrum. It is important to note that the use of finer droplet results in greater attenuation of the radiation. At the same time, relatively high transparency of UV radiation is predicted in the case of large water droplets. A similar conclusion is true for the HEV radiation. The low transmittance of water mist layers in the middle-infrared spectral range enables one to consider the large-scale sprays as a screen for radiative thermal losses from buildings toward the clear night sky.

Results for the spectral solar irradiation transmitted through a layer of water droplets are presented in Fig. 5 for \( f_{\text{surf}} = 0.01 \) and 0.02 mm. The solid curve is the sum of the direct and diffuse incident radiation calculated according to the approximate spectral model outlined previously. Fig. 6 indicates more clearly the behavior in the UV-B spectrum. It is clear that the mist layer results in a decrease in both the spectral and total irradiation. The UV-B radiation is reduced by the presence of the mist layer. At identical surface density \( f_{\text{surf}} \), a reduction in the droplet radius from 25 to 5 \( \mu m \) leads to an increase in attenuation of the radiation by the water mist layer. A further decrease in the droplet radius would be especially effective in the radiation attenuation over the spectrum. It should be noted that fine atomization of water droplets is not an insignificant task, but droplet generation in this size range has been demonstrated (e.g., \([30–36]\)).

It goes without saying that the spectral attenuation of the incident solar radiation by a water mist layer can be accurately predicted only by taking into account the combined hydrodynamic and thermal processes in turbulent flows of heated and evaporating droplets. The solution of this complex problem is beyond the scope of this study. However, one can easily extend the analysis presented here to the case of polydisperse droplets. In particular, the same relations in the near-ultraviolet and
visible ranges can be employed by substituting the value of the Sauter mean radius $a_{32}$ of polydisperse water droplets instead of $a$ used in the monodisperse approximation [22,24].

Consider now the diurnal variation of the UV attenuation for realistic local conditions of Provo, Utah, USA, on June 22, 2009, discussed previously. One can use the simplified relations of Eq. (12) and the obvious formula
to\[\tau'_{tr} = 0.225f_{surf}/a_{32}\] (13)
in the calculations at $a \geq 5 \mu m$. Note that the coefficient in Eq. (13) is slightly greater in the case of $a < 5 \mu m$. Results for the UV-index as a function of time-of-day are shown in Fig. 7. One can see that the time of exposure to what is classified as very high UV irradiation is significantly reduced in the case of $f_{surf}=0.01 \text{mm}$, and it is completely eliminated at $f_{surf}=0.02 \text{mm}$.

6. Conclusions

An approximate analytical method for estimating transmittance of both direct and diffuse solar radiation through a water mist layer is developed. The method suggested includes simple relations for the main radiative characteristics of water droplets in the short-wave range (UV and visible) and approximate analytical solution for spectral radiative transfer in the water spray over the whole spectrum.

Two functions of spectral transmittance (for direct and diffuse irradiation) for typical parameters of realistic water mist layers are calculated. Because of problem linearity, these functions are universal and can be used in a combination with different conditions of solar irradiation. The calculations are performed for the specific high-altitude conditions of Provo, Utah, USA. It is shown that considerable attenuation of potentially dangerous UV irradiation can be achieved due to scattering of the radiation by small water droplets. Scattering only, not absorption, is responsible for the UV attenuation. A fine atomization of water in the mist layer is shown to be an effective means of significant decrease in transmitted radiation over the spectrum (from the near-ultraviolet to the near-infrared spectral range).

If properly designed and installed, it is shown that water misting systems which are intended only for reduction of air temperature due to evaporation of water droplets can also serve as an effective protection from the total solar irradiation and harmful UV radiation. Their use could be considered in any outdoor public gathering place. The range of application of such systems, which are inexpensive and consume modest amounts of water, can be much wider if the protection property against solar irradiation is considered.

The analytical approach developed in this paper is general and similar solutions can be used in other applications concerning a propagation of the direct and diffuse solar radiation in disperse systems. The latter is important to study wide-range spectral properties of advanced paints and composite coatings for building walls and roofs.
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References