PLUME VISIBILITY

CERC

In this document 'ADMS' refers to ADMS 5.2.

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1. Introduction

The ADMS Plume Visibility Module uses the initial water vapour content of the plume and the humidity of the ambient air to determine whether the plume will be visible at each downstream distance. The effects of water vapour on plume density and the effects of evaporation and condensation are also taken into account in the Plume Rise Module.

2. Technical specification

The calculation of liquid water content of the plume, and the other plume parameters described in sections 2.1-2.4 uses the same top hat profile assumptions as the rest of the plume rise module. Therefore, the value of the liquid water content is an average value across the idealised plume. The actual plume centreline liquid water content is likely to be higher than this value, hence actual visible plumes may be longer than those predicted by the model.

2.1 Plume Liquid Water Content

The plume liquid water content at the plume centreline is calculated using the procedure outlined below.

i) Saturated vapour pressure of water (e_{sat}) is calculated using a formula of Wexler [1]:

$$\ln e_{\mathrm{sat}} = \sum_{i=0}^{6} g_i T^{i-2} + g_7 \ln T \tag{2.1}$$

where:

$g_0 = -2.99\mathrm{x}10^{3}$ $g_1 = -6.02\mathrm{x}10^{3}$ $g_2 = 1.89\mathrm{x}10^{1}$ $g_3 = -2.84\mathrm{x}10^{-2}$
$g_4 = 1.78\mathrm{x}10^{-5}$ $g_5 = -8.42\mathrm{x}10^{-10}$ $g_6 = 4.44\mathrm{x}10^{-13}$ $g_7 = 2.86\mathrm{x}10^{0}$

T temperature (K), e_{sat} saturation vapour pressure (Pa)

ii) The saturated mixing ratio (r_{sat}) is then calculated using this value and the air pressure (p). Note that pressure and saturated vapour pressure are in the same units (Pa).

$$r_{\mathrm{sat}} = \varepsilon \frac{e_{\mathrm{sat}}}{p\text{-}\,e_{\mathrm{sat}}} \tag{2.2}$$

where ε is the ratio of the molecular weight of water to that of dry air ($\varepsilon = 0.622$). Then the mixing ratio in the air, r_{air}, is calculated from r_{hum}, the relative humidity of the air (%):

$$r_{\mathrm{air}} = \frac{r_{hum}}{100} \times r_{sat} \tag{2.3}$$

iii) To calculate the mixing ratio in the plume $\left(r_{t\,\mathrm{plume}}\right)$, Γ, the mass concentration of source material and $r_{t\,\mathrm{init}}$, the initial mixing ratio of the plume are introduced.

$$r_{t\,plume} = \Gamma r_{t_{init}} + (1\text{-}\,\Gamma) r_{\mathrm{air}} \tag{2.4}$$

iv) The plume centreline liquid water content of the plume r_L, in kg of liquid water/kg dry air, can then be calculated.

v)

$$r_L = r_{t\,plume}\text{-}\,r_{sat} \tag{2.5}$$

Away from the plume centreline, the temperature T and specific humidity q are assumed to decay towards ambient values at the same rate as the concentration, i.e.

$$\begin{aligned} T(x,y,z) &= T_{amb}(z) + \frac{C(x,y,z)}{C_p}\left(T_p - T_{amb}\left(z_p\right)\right) \\ q(x,y,z) &= q_{amb}(z) + \frac{C(x,y,z)}{C_p}\left(q_p - q_{amb}\left(z_p\right)\right) \end{aligned} \tag{2.6}$$

where $C(x,y,z)$ is the concentration at (x,y,z), the subscript amb denotes ambient values, and the subscript p denotes plume centreline values, such that $T_{amb}\left(z_p\right)$ is the ambient temperature at the plume centreline height. The mixing ratio r is calculated from the specific humidity by

$$r = \frac{q}{1-q} \tag{2.7}$$

The liquid water content at a point away from the plume centreline is then calculated using the same method as for the plume centreline above (equations (2.1) – (2.5)).

Note that the above calculations are only valid for temperatures less than 100°C. At temperatures greater than or equal to 100°C the liquid water content will be zero, as any water will have vapourised.

2.2 Visibility Criterion

The visibility of the plume is calculated based on two criteria:

- whether the liquid water is above a critical threshold (0.002 kg/kg), in which case it is visible; otherwise,
- how the plume size compares to the optical visible length for that water content.

For the second criterion, the optical visible length in metres is calculated using the relation given by Gultepe *et al.* [2]:

$$OptVisLen = \frac{1002}{(LWC.N_d)^{0.6473}} \tag{2.8}$$

where LWC is the liquid water content and N_d is the number of droplets in the plume, which is set to 2000 cm^{-3}, based on typical cloud condensation nuclei concentrations.

The plume is counted as visible if the plume thickness directly above a receptor is greater than the optical visible length, i.e.:

$$2\sigma_z f g(y) > OptVisLen \tag{2.9}$$

where $2\sigma_z$ is the plume depth at the plume centreline, f is an opacity factor (for which a value of 1 has been found to produce the best results) and $g(y)$ is a Gaussian function to take account of the variation in plume depth away from the plume centreline.

The liquid water threshold, number of droplets in the plume and opacity factor can be altered by the user.

In addition two criteria based on the ambient relative humidity are applied:

- if the ground level ambient relative humidity is 100% the conditions are taken to be foggy and the plume is not visible,
- if the ambient humidity at the plume height is greater than 98% then the plume is taken to be indistinguishable from cloud and therefore not visible.

The 98% ambient relative humidity used to indicate that the plume is indistinguishable from cloud can be altered by the user.

2.3 Specific Enthalpy

The specific enthalpy term in the plume rise module has an additional term, $l_V r_L$, to allow for condensation and evaporation

$$s_L = c_P \theta + l_V r_L \tag{2.10}$$

where s_L = specific enthalpy (J/kg)
c_P = specific heat capacity of plume (J/kg/k)
θ = potential temperature (K)
l_V = latent heat of vaporisation of water (J/kg)
r_L = liquid water content (kg water per kg dry air)

The variation of l_V with temperature is calculated according to the expression

$$l_V = (2.501 - 0.00237T)\ 1\text{x}10^6 \tag{2.11}$$

where T is temperature in °C, based on data from Oke [3].

2.4 Plume temperature

The plume temperature and liquid water content form a coupled system. The calculation procedure is schematically as follows:

- A ‘dry’ temperature is calculated from mixing between the plume and ambient air, without considering latent heat
- The liquid water content of the plume at the ‘dry’ temperature is calculated
- A water-affected plume temperature is calculated from the dry temperature and the enthalpy from liquid water.

Iteration over the latter two stages is used to find plume temperature and liquid water content values which are in equilibrium.

2.5 Calculating Density

The density of the plume in the plume rise module is adjusted to allow for plume water content as follows:

i) The gas constant, R for the mixture of air and plume is calculated

$$R = \Gamma R_S + (1\text{-}\Gamma) R_A \tag{2.12}$$

where $R_S =$ gas constant for the source gases
$R_A =$ gas constant for air

ii) If the liquid water content, previously calculated, is not zero, we then use the following to calculate density (ρ_p) and the density of the water vapour within the plume (ρ_{pwater}):

The mass of plume per unit mass of dry air, m_p, is given by

$$m_p = 1 + r_L + r_{sat} \tag{2.13}$$

The specific volume of dry air at the plume temperature, v_a, is given by

$$v_a = \frac{RT}{p - e_{sat}} \tag{2.14}$$

Hence the density is given by

$$\rho_p = \frac{m_p}{v_a} = \frac{p - e_{sat}}{RT}(1 + r_L + r_{sat}) \tag{2.15}$$

Substituting for e_{sat} using (2.3) gives

$$\rho_p = \left(\frac{p}{RT}\right)\left(\frac{\varepsilon}{r_{sat} + \varepsilon}\right)(1 + r_L + r_{sat}) \tag{2.16}$$

$$\rho_{p\,water} = \left(\frac{p}{RT}\right)\left(\frac{\varepsilon}{r_{sat} + \varepsilon}\right)r_L \tag{2.17}$$

Otherwise, if the liquid water content is zero,

$$\rho_p = \left(\frac{p}{RT}\right)\left(\frac{\varepsilon}{r_{t\,plume} + \varepsilon}\right)\left(1 + r_{t\,plume}\right) \tag{2.18}$$

where T is the plume temperature (K).

iii) The specific heat capacity, if the liquid water content is not zero, is calculated using:

$$c_p = \frac{1}{\rho_p}\left(\rho_{p\,water}c_{p\,water} + \left(\rho_p - \rho_{p\,water}\right)c_{p\,air}\right) \tag{2.19}$$

otherwise, if the liquid water content is zero

$$c_p = \Gamma c_{ps} + (1 - \Gamma)c_{p\,dryair} \tag{2.20}$$

where c_{ps} is the specific heat capacity of the release.

3. Input requirements

In order to carry out plume visibility calculations, it is necessary that the input met data include temperature and some form of humidity measurement (relative or specific humidity). The initial plume mixing ratio, i.e. the mass of water vapour per unit mass of dry air (kg/kg) at release, must also be supplied for each source.

4. Output

For each meteorological condition the following variables are given as output in a .vlt or .vst file:

- distance downstream at which the plume first becomes visible
- distance downstream after which the plume is no longer visible

- plume height at the downstream point where the plume becomes no longer visible
- total distance over which the plume is visible
- maximum liquid water content of the plume over that distance
- distance downstream at which the first plume ‘grounding’ occurs

The plume is defined to be ‘grounding’ when the vertical plume spread σ_z is greater than the plume centreline height z_p.

The total number of visible plumes is also recorded in the file.

In addition, for short term calculations the centreline liquid water content as a function of downstream distance is given as output, and for long term calculations the following statistics are given as output in a .glt or .plt file:

- number of visible plumes at each user defined output point
- number of visible, grounded plumes at each user defined output point

Note that:

1. The plume is defined to be visible at an output point if the plume is visible *directly above* the output point (as opposed to *from* the output point).
2. Contour plots of number of visible plumes can be difficult to interpret.

References

[1] Wexler A. (1976) “Vapor pressure formulation for water in range 0 to 100°C.
A revision.” *J. Res. Nat. Bur. Stand*. 80A, pp775-785.

[2] Gultepe I., Milbrandt J., Belair S., (2006) Visibility paramaterisation from microphysical observations for warm fog conditions and its application to the Canadian MC2 model, AMS meeting, Atlanta, January 2006

[3] Oke, T.R. (1987) “Boundary Layer Climates”, Second Edition. Routledge