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A Simulation of Foam Protection of Plants Against Frost

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Several configurations of foam protection systems for plants subject to frost are simulated. The configurations include a uniform foam layer on the ground, a planar foam layer above an air enclosure and a foam layer in the form of a strip. Temperature fields for each configuration are calculated by numerical methods and are compared with uncovered ground. A comparison between the different methods shows that an air enclosure is most effective for frost protection. A temperature difference of about 10°C can be achieved between the covered and uncovered ground after a night of frost by means of a foam layer of 10 cm thickness.

Notation

T	temperature, °C
$\tilde{T}$	absolute temperature, K
T_A	air temperature far from the inversion layer, °C
Θ	dimensionless temperature
λ	heat conductivity, W/m K
c	specific heat, J/kg K
κ	heat diffusivity, m^2/s
ρ	density, kg/m^3
h_g	depth of daily temperature perturbation zone, m
x	vertical coordinate, m
y	transverse coordinate, m
b	width of foam strip, m
h	thickness of layer, m
α	heat transfer coefficient, W/m^2 K
Nu	Nusselt number
Gr	Grashof number
τ	time, s
σ	Stefan–Boltzmann constant, $W/m^2 K^4$
ν	kinematic viscosity, m^2/s
g	gravity acceleration, m/s^2
β	volumetric expansion coefficient, K^{-1}
q	heat flux density, W/m^2
p	partial pressure of water vapour in atmosphere, mm Hg
k_x	extinction coefficient, m^{-1}
d	mean diameter of air bubble, m
l_g	heat perturbation boundary in horizontal direction, m

Subscripts

a	air
g	ground
f	foam
e	enclosure
0	initial moment
am	air, molecular
c	conduction
r	radiation
x	extinction
gs	earth surface
fl	lower foam surface
fu	upper foam surface
b	foam strip

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1. Introduction

Radiative frost conditions cause considerable damage to crops all over the world. Countries such as Spain, USA (California and Florida) and Israel suffer from frost damage in winter and many central and northern European countries in the spring.

The main reason for the damage is the excessive cooling of the plant surfaces and freezing of the plant cells, due to radiative heat flux to the atmosphere. This can happen during a clear night when there is no wind and no clouds, and air humidity is low.[1,2] Some radiative frost protection methods such as fogging and various covers (e.g. plastic, paper, foam) attempt to reduce heat loss, other methods increase soil conductivity (e.g. by wetting the soil) or increase the heat

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transfer coefficient between plants and the surrounding air (e.g. wind machines). Sometimes, additional heat is supplied either in the form of latent heat of water or through various heaters.[3–6]

Once it can be spread effectively over vast areas, a cover of foam insulation becomes a promising method of frost protection. Water-based foams have the advantages of being non-toxic, relatively cheap, stable during a night of frost, and self destructing when exposed to the sun.

In developing the technology of foam cover protection, our object is to find the optimal configuration. To this end, a simulation method has been developed to evaluate the effectiveness of insulation for various environmental conditions such as air and ground temperatures, air humidity, soil heat conductivity and diffusivity, and technological parameters such as the foam layer configuration and properties. The simulation method takes into account (i) infrared radiative flux from the earth and foam exernal surfaces, (ii) convective and conductive heat exchange between earth and foam cover on the one hand, and between the near ground atmosphere air layer on the other hand, and (iii) conductive heat transfer in the upper earth layer and cover.

In the present study, this problem is solved by means of a numerical method for various foam layer configurations. The solutions enable analysis of the main features of foam-based frost protection technologies, and can provide recommendations on the design and application mode of the foam. In the future, the predictions of the present simulation will be tested in the laboratory and in the field.

2. Theory of natural night radiation cooling

2.1. *Mathematical model*

During the night, the upper earth layer cools because of infrared radiation loss from the earth's surface. This radiation loss is the difference between the Stefan–Boltzmann radiation from the earth's surface and the radiation from the atmosphere, which depends on air temperature, water vapour content, carbon dioxide and ozone concentrations, and cloudiness.

Since the ratios of carbon dioxide and ozone in the atmosphere are usually constant, the intensity of night radiation loss depends mostly on water vapour content and air temperature. Heat is also exchanged between the adjacent air and earth surface by means of convection and conduction.

When the meteorological conditions are such that air temperature and humidity are low, and the sky is clear, radiative heat loss from the earth surface is very high. When, in addition, there is no wind, heat transfer from air to earth surface is low and frost may develop. These conditions are simulated in this paper. At the beginning of a night of frost, both air and soil vertical temperature profiles near the earth's surface can be assumed to be uniform.[5] This is related to the inversion of the temperature profile that occurs after sunset. During a sunny day, the temperature of the earth's surface is greater than the temperatures of the adjacent air layer and the deeper layers of ground. Conversely, during a night of frost, the temperature distribution is such that the temperature is least at the earth's surface. Therefore we assume that the night cooling process starts from the moment of inversion, such that initial conditions of the temperatures of air and ground in the vicinity of the earth's surface are constant. As results of temperature measurements show, thicknesses of the air and ground layers, where night inversion effects occur, are rather small. Therefore we introduce the concept of influence thicknesses in the ground (h_g) and air (h_a). Out of these layers, ground and air temperatures are assumed to be constant during night radiation cooling. It is also assumed that all environmental and geometrical parameters are uniform in the horizontal direction.

The problem is formulated as one of one-dimensional heat transfer for an infinite flat ground surface, with an earth layer below and an air layer above it. A schematic description of the problem is shown in *Fig. 1a*.

The heat transfer equation for the earth layer is

$$\frac{\partial T_g}{\partial \tau} = \kappa_g \frac{\partial^2 T_g}{\partial x^2} \qquad 0 \leq x \leq h_g \tag{1}$$

where h_g denotes the depth of soil layer where daily variations of temperature occur. It is common to assume that h_g is less than about 1 m (Ref. 7).

The initial and boundary conditions are as follows: Initial condition

$$\tau = \tau_0 \qquad x \geq 0 \qquad T_g = T_0 \tag{2}$$

Boundary conditions

$$x = h_g \qquad \tau \geq \tau_0 \qquad T_g = T_0 \tag{3}$$

Two boundary conditions at the earth surface ($x = 0$) are temperature continuity

$$x = 0 \qquad \tau \geq \tau_0 \qquad T_a = T_g \tag{4}$$

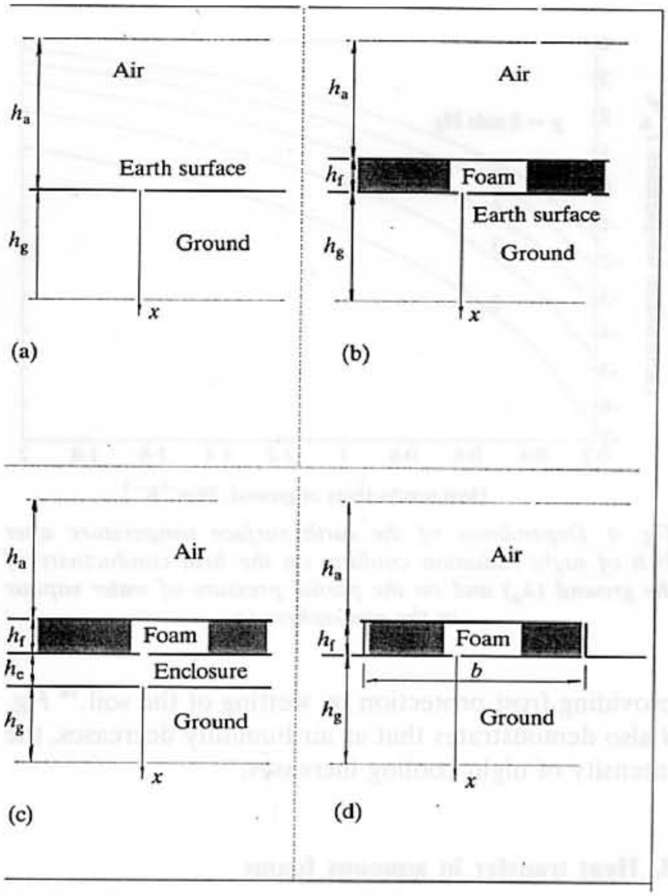

Fig. 1. Schematic description of the problems under consideration. (a) No foam layer; (b) Foam layer (h_f) of infinite extent in horizontal plane, on earth surface; (c) Foam layer (h_f) of infinite extent in horizontal plane, distance h_e above earth surface; (d) Foam layer (h_f) of finite width (b) on earth surface

and balance of conductive and radiative heat fluxes

$$\lambda_g \frac{\partial T_g}{\partial x} = \sigma[\tilde{T}_g^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma p})] + \lambda_a \frac{\partial T_a}{\partial x} \quad (5)$$

Here the first term on the right-hand side of Eqn (5) accounts for the net radiative flux. The expression was deduced by Angström[8] on the basis of numerous measurements. Here p is the partial pressure of water vapour in the atmosphere in mm Hg, and where A, B, and γ are empirical coefficients. In accordance with experimental data,[9] the parameter values used are: $A = 0{\cdot}82$, $B = 0{\cdot}25$, and $\gamma = 0{\cdot}126$. The value of T_A represents the average night air temperature far from the inversion layer. Usually, it is identified with temperature data, recorded in the meteorological stations.

The heat transfer equation for the air inversion layer is

$$\rho_a c_a \frac{\partial T_a}{\partial \tau} = \frac{\partial}{\partial x}\left(\lambda_a \frac{\partial T_a}{\partial x}\right) \qquad 0 \geqslant x \geqslant -h_a \quad (6)$$

Here, λ_a is the heat conductivity of air in the inversion layer. Its value for a windless night is expressed by the empirical expression[10]

$$\lambda_a = c_a a_1[(1-x)^{0.5} - 1] + \lambda_{am} \quad (7)$$

where $a_1 = 0{\cdot}105\ \mathrm{kg\,m^{-1}\,s^{-1}}$, λ_{am} molecular heat conductivity of air.

The initial condition for the inversion layer is

$$\tau = \tau_0 \qquad 0 \geqslant x \geqslant -h_a \qquad T_a = T_0 \quad (8)$$

The air temperature at the upper boundary of the inversion layer is assumed to be equal T_A and corresponding boundary condition is

$$x = -h_a \qquad \tau \geqslant \tau_0 \qquad T_a = T_A \quad (9)$$

while at the earth surface, the conjugative boundary conditions Eqns (4) and (5) apply.

Obviously, continuity of the temperature field in air may be satisfied only if $T_0 = T_A$.

2.2. *Results*

Numerical solution of the problem, which is defined by Eqns (1)–(9), is obtained by an implicit finite-difference scheme, which is unconditionally stable. The scheme is represented by a system of tridiagonal linear algebraic equations. This system is solved by the LU decomposition method.[11] Based on this method, a computational algorithm and a computer program were developed.

The space domain $-h_a \leqslant x \leqslant h_g$ is divided by 100 nodal points. The intervals between them are smaller near to the earth surface, where temperature gradients are greatest. The intervals between time axis nodal points are increased with time. The minimum time step is 3·6 s and is doubled every 10 steps until 360 s is exceeded after which the computations are made with constant time steps equal to the last value.

Typical temperature distributions in the air and the ground, and the way they evolve in time during a night of frost, are shown in *Figs 2* and *3* respectively. The calculations were carried out for initial temperature, $T_0 = +10$°C, partial pressure of water vapour, $p = 2{\cdot}4$ mm Hg, heat transfer properties of the soil: $\lambda_g = 1{\cdot}67\ \mathrm{W\,m^{-1}\,K^{-1}}$ and $\kappa_g = 8{\cdot}87 \times 10^{-7}\ \mathrm{m^2\,s^{-1}}$. As shown in *Fig. 2*, earth surface temperature drops during a period of 10 h by about 9°C to a temperature of +1°C. This cooling is associated with calculated

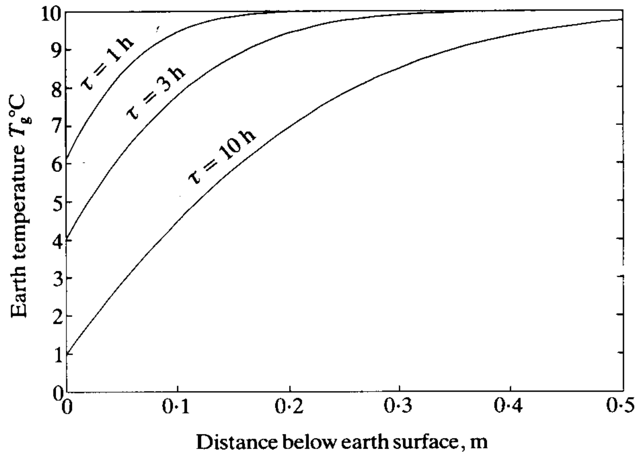

Fig. 2. Distributions of the earth temperature [$T_g(x, \tau)$] during night radiation cooling

heat fluxes from the earth surface, during the night, of about 70 W m^{-2}. This value is in agreement with data of Brooks[5] (55 W m^{-2}–70 W m^{-2}) and with data from the Handbook of Meteorology[12] (77 W m^{-2}).

The effect of partial water vapour pressure in the atmosphere (p), and of soil conductivity (λ_g) on cooling intensity is summarized in *Fig. 4*. Earth surface temperatures after 10 h of night cooling are given as a function of the soil heat conductivity for several values of partial water vapour pressure in the atmosphere.

For a given air humidity, soils with lower heat conductivity cool down to lower temperatures. For instance, for an air humidity of $p = 2{\cdot}4$ mm Hg, soil surfaces with low conductivity (dry sand, $\lambda_g = 0{\cdot}209$ W m^{-1} K^{-1}) cool to $-5{\cdot}75$°C, while soil with high conductivity (wet sand surface with a moisture content of 5%, $\lambda_g = 1{\cdot}67$ W m^{-1} K^{-1}) cools much less, to 0·89°C only. The soil conductivities are taken from Ref. 13. This observation explains the method of

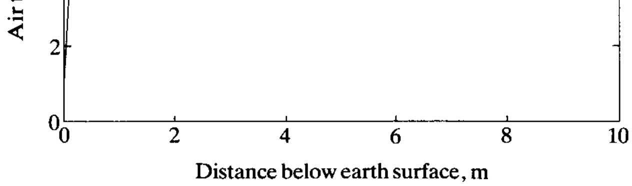

Fig. 3. Distributions of the inversion atmosphere layer temperature [$T_a(x, \tau)$] during night radiation cooling

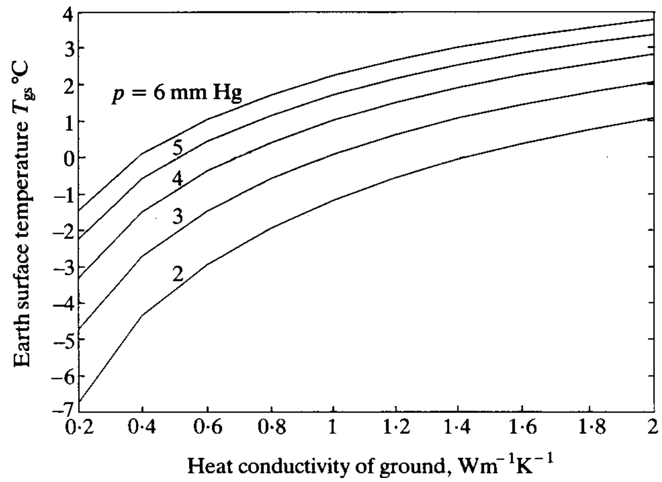

Fig. 4. Dependence of the earth surface temperature after 10 h of night radiation cooling, on the heat conductivity of the ground (λ_g) and on the partial pressure of water vapour in the atmosphere (p)

providing frost protection by wetting of the soil.[14] *Fig. 4* also demonstrates that as air humidity decreases, the intensity of night cooling increases.

3. Heat transfer in aqueous foams

To the best of our knowledge, there is not enough data on the relative contribution of different forms of heat transfer in aqueous foam, namely radiation, convection and conduction. At first, we evaluate the relative contribution of radiative and conductive heat transfer. We may expect that aqueous foam is partially transparent to infra-red radiation, and as such heat flux through foam (q) can be represented by the expression

$$q = -(\lambda_c + \lambda_r)\frac{\partial T_f}{\partial x} = -\lambda_c\left(1 + \frac{\lambda_r}{\lambda_c}\right)\frac{\partial T_f}{\partial x} \tag{10}$$

where $\lambda_r = 16\sigma\tilde{T}_f^3/3k_x$ is the radiative heat transfer coefficient[15] and λ_c is the conductive heat transfer coefficient. The extinction coefficient, k_x, defines the attenuation rate of infra-red radiation flux as it passes through a foam layer.

The ratio between radiative and conductive heat transfer coefficients

$$\delta_r = \frac{\lambda_r}{\lambda_c} = \frac{16\sigma\tilde{T}_f^3}{3k_x\lambda_c}. \tag{11}$$

can serve as a criterion for the relative importance of the two forms of heat transfer. All the parameters in Eqn (11) are known except for the value of k_x, which has to be estimated indirectly, since no data is available in the literature.

Values of the extinction coefficient of aqueous foams for visible light were found to be 200 times larger than the extinction coefficient in water.[16] We assume that the same ratio exists for the infra-red range of wave lengths since the additional attenuation in foams is mainly owing to reflections and scattering over the large quantity of surfaces. Then, based on the value of the extinction coefficient for infra-red radiation (4–10 μm) in water,[17] which is about $10^5\ \mathrm{m}^{-1}$, we obtain a value of about $2 \times 10^7\ \mathrm{m}^{-1}$ for the extinction coefficient for infra-red radiation in aqueous foams.

By introducing this value of k_x into Eqn (11), and after assuming that the heat conductivity of aqueous foams, λ_c is about $0{\cdot}1\ \mathrm{W\,m^{-1}\,K^{-1}}$ (Refs 4 and 18) we obtain a ratio

$$\delta_r = \frac{\lambda_r}{\lambda_c} \simeq 10^{-5}. \tag{12}$$

The result confirms that radiative heat transfer in aqueous foams can be neglected.

Additional heat transfer due to natural convection inside the foam layer may be approximated as natural convection between two parallel and horizontal plates, where the upper plate is colder. The Nusselt number (Nu) for this case[19] is given by

$$\mathrm{Nu} = C\,\mathrm{Gr}^n$$

$$\begin{cases} C = 0{\cdot}195;\ n = 0{\cdot}25; & \text{for}\quad 10^4 \leqslant \mathrm{Gr} \leqslant 4 \times 10^5 \\ C = 0{\cdot}068;\ n = 0{\cdot}33; & \text{for}\quad \mathrm{Gr} \geqslant 4 \times 10^5 \end{cases} \tag{13}$$

Here

$$\mathrm{Gr} = \frac{g\beta\,|\Delta T|\,d^3}{\nu^2} \tag{14}$$

while d denotes a characteristic dimension taken as the mean diameter of a typical air bubble, and ΔT is evaluated based on the mean vertical temperature gradient, G, in the foam layer by

$$|\Delta T| = |G|\,d$$

Based on preliminary evaluations, temperature gradients (G) in foams subjected to conditions of night radiation are about $120\ \mathrm{K\,m^{-1}}$. Taking into account the evaluated value for G and assuming that the bubbles are filled with air, we get from Eqn (14) the value of $\mathrm{Gr} \simeq 1{\cdot}2 \times 10^{10}\,d^4$. Natural convection is negligible when the Gr number is smaller than about 10^4 (Ref. 19), i.e. for d smaller than about 0·02 m. Aqueous foams in use for frost protection are typified by bubbles with diameters much less than this value and therefore convective heat transfer inside the foam layer can be neglected in the analysis to follow.

Thus, according to the above estimates, the foam used in frost protection systems can be modelled as an infra-red-opaque continuous body with heat transfer through conduction only.

4. Nocturnal radiation cooling of an earth surface covered by an aqueous foam layer

4.1. *Flat foam layer on earth surface*

4.1.1. *Problem statement*

Night radiation loss from an earth surface is substantially decreased when a cover of foam layer is applied.[4,20] In contrast to the analysis in the previous section, here we simulate the heat transfer process during night radiation through three layers (air, foam and soil).

The problem described in Section 2.1 is modified by spreading a uniform foam layer with thickness h_f between the earth surface and the atmosphere (see *Fig. 1b*). The foam layer is infinite in the horizontal plane. The heat transfer problem for the foam layer is described by the heat transfer equation

$$\frac{\partial T_f}{\partial \tau} = \kappa_f \frac{\partial^2 T_f}{\partial x^2} \qquad -h_f \leqslant x \leqslant 0 \tag{15}$$

and the initial condition

$$\tau = \tau_0 \qquad -h_f \leqslant x \leqslant 0 \qquad T_f = T_0 \tag{16}$$

The boundary conditions for Eqn (15) are

(a) at the earth surface $x = 0$

$$T_f = T_g \tag{17}$$

$$\lambda_g \frac{\partial T_g}{\partial x} = \lambda_f \frac{\partial T_f}{\partial x} \tag{18}$$

(b) at the upper foam surface $x = -h_f$

$$\lambda_f \frac{\partial T_f}{\partial x} = \sigma[\tilde{T}_f^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma p})] + \lambda_a \frac{\partial T_a}{\partial x} \tag{19}$$

$$T_f = T_a \tag{20}$$

The heat transfer problem for the ground is described by Eqns (1)–(3), (17) and (18). The heat transfer problem for the air layer $[-h_f \geqslant x \geqslant -(h_f + h_a)]$ above the foam layer is described by Eqn (6), the initial condition [Eqn (8)] and the boundary conditions at the upper boundary of the inversion layer [Eqn (9) at $x = -(h_f + h_a)$], and the conjugate conditions at the air–foam interface [Eqns (19) and (20)]. Similar to Eqn (8), the effective air heat conductivity,

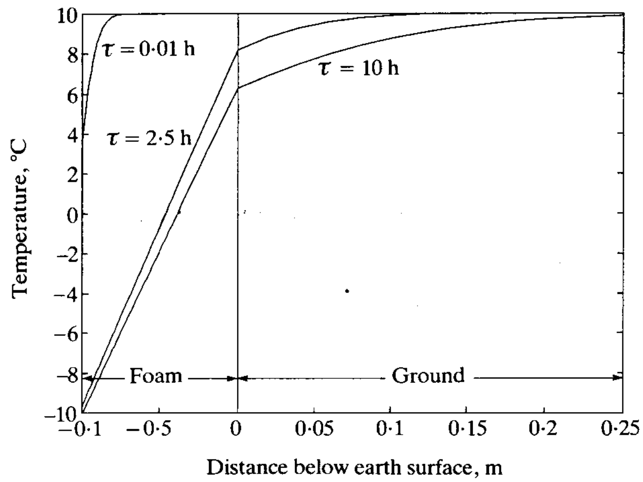

Fig. 5. Temperature distributions in foam [$T_f(x, \tau)$] and earth [$T_g(x, \tau)$] during night radiation cooling. Foam layer of infinite extent in horizontal plane, in contact with earth

λ_a in Eqn (7), is obtained by replacing x in Eqn (8) by $x + h_f$

$$\lambda_a = c_a a_1[(1-(x+h_f))^{0\cdot5} - 1] + \lambda_{am} \quad (21)$$

4.1.2. *Results*

The problem was solved by the method described in Section 2.2 and the unsteady temperature distributions in the foam, ground and air were obtained. Foam and ground temperatures are shown in *Fig. 5* during night cooling, where the initial temperature was, as before, $T_0 = +10°C$, the foam layer thickness $h = 0{\cdot}1$ m, heat conductivity of foam $\lambda_f = 0{\cdot}1\ \mathrm{W\,m^{-1}\,K^{-1}}$, and other parameters were: $\lambda_g = 0{\cdot}5\ \mathrm{W\,m^{-1}\,K^{-1}}$, $c_g = 941\ \mathrm{J\,kg^{-1}\,K^{-1}}$, $p = 2{\cdot}4$ mm Hg. In contrast to the uncovered ground of Section 2.2, here we notice only a slight decrease in earth surface temperature. At the same time, the temperatures of the upper foam surface reach very low values soon after the cooling process starts. These results, which agree with previous work,[5] are attributed to the low conductivity of foam and also to the low heat capacity of foam when compared with soil. It is clearly seen that this type of temperature distribution is associated with good frost protection for crops located near the earth surface, while plants with parts far from the earth surface might be exposed to very low temperatures inside the foam cover.

4.2. *Enclosure under foam cover*

4.2.1. *Problem statement*

It is known that a gap between the lower surface of the protecting cover and the earth's surface, improves the effectiveness of the thermal protection.[7] In addition to the problem description of Section 4.1.1, we consider here an air enclosure of uniform thickness (h_e) between the earth surface and the foam cover, as shown in *Fig. 1c*. As before, the heat transfer equation for foam [Eqn (15)] is applied, where the relevant range is $-h_e \leqslant x \leqslant -(h_e + h_f)$, (see *Fig. 1c*).

The boundary condition at the lower surface of the foam cover is

$$x = -h_e \qquad \lambda_f \frac{\partial T_f}{\partial x} = \alpha_e(T_e - T_{fl}) + \sigma(\tilde{T}^4_{gs} - \tilde{T}^4_{fl}) \quad (22)$$

Here, α_e, the coefficient of convective heat transfer between the air in the enclosure and the lower surface of the foam cover, is expressed by

$$\alpha_e = \frac{\lambda_{am}}{h_e}\mathrm{Nu}$$

where the value of Nu number is given by Eqn (13).

The boundary condition at the earth surface is

$$x = 0 \qquad \lambda_g \frac{\partial T_g}{\partial x} = \alpha_e(T_{gs} - T_e) + \sigma(\tilde{T}^4_{gs} - \tilde{T}^4_{fl}) \quad (23)$$

Note that in Eqns (22) and (23) the coefficients of convective heat transfer between the air in the enclosure and both the lower surface of foam and the ground surface have the same value α_e.

The heat balance equation for the air in the enclosure

$$h_e \rho c_a \frac{dT_e}{d\tau} = \alpha_e(T_{fl} + T_{gs} - 2T_e) \quad (24)$$

takes into account the heat exchange between air and the two parallel surfaces, foam and earth. To complete the problem statement, we should add the heat transfer equation for above the foam layer [Eqn (6)] with boundary conditions [Eqn (9)] at the upper boundary of the inversion layer, $x = -(h_a + h_f + h_e)$ and Eqn (19) at the upper surface of the foam, $x = -(h_f + h_e)$; the heat transfer equation for foam layer [Eqn (15)] with boundary conditions [Eqns (19) and (22)]; and the heat transfer equation for the earth upper layer Eqn (1) with boundary conditions Eqn (3) and (23).

4.2.2. *Results*

The solution procedure gave the unsteady temperature distributions in the foam and ground layers and in the air layer between them during night cooling. The temperature distributions after 10 h night cooling are shown in *Fig. 6*. Here we considered a foam cover of 0·1 m thick, placed at a distance of 0·5 m from the earth surface (case 1). For comparison, the temperature distribution in a foam layer 0·5 m thick in contact

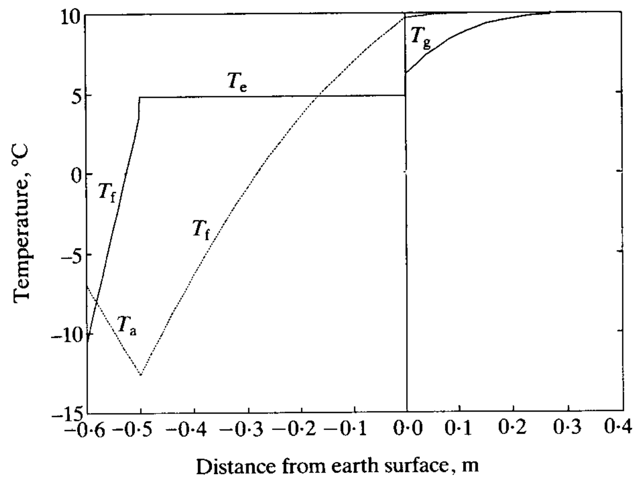

Fig. 6. Temperature distributions in enclosure under foam layer (case 1) and in foam layer covering the earth surface (case 2) after 10 h of night radiation cooling. Note that the plots refer to the configurations shown in Figs 1b and c where the dimensions are $h_f = 0{\cdot}1$ m, $h_e = 0{\cdot}5$ m (case 1) and $h_f = 0{\cdot}5$ (case 2); T_A = +10°C. ———, Case 1; – – –, Case 2

with the earth is also plotted in *Fig. 6* (case 2). Notice that even a relatively thin foam layer (0·1 m), once placed at some distance from earth, can provide better protection than the much thicker foam layer of case 2. This is demonstrated by the size of the layer in which all the parts of the plant are protected from frost. In case 2 this distance is about 30 cm above the ground while in case 1, the temperature throughout the enclosure (50 cm) is above 0°C, and all plants inside the enclosure are protected.

4.3. *Long and narrow strip of foam cover on earth*

4.3.1. *Problem formulation*

Consider a strip of foam layer with thickness h_f, width b ($b \gg h_f$), and infinite length (see *Fig. 1d*). Compared with the previous cases, here, the earth surface is only partially covered and therefore the problem is not one dimensional as before, since the boundary conditions on the earth surface are non-homogeneous and as a result, horizontal heat fluxes are generated.

The problem statement is two dimensional for the heat transfer in the earth while in the foam strip we neglect the horizontal heat flux. The simplification for the foam strip is related to the fact that the vertical temperature gradients in the foam layer are expected to be much greater than the horizontal temperature gradients. The validity of this assumption will be checked later using the problem solution.

Hence, the heat transfer equation for the foam layer ($-h_f \leqslant x \leqslant 0$; $-b/2 \leqslant y \leqslant b/2$), initial conditions and boundary conditions at the earth and foam interface are similar to the one-dimensional case [Eqns (15) to (18)]. The boundary condition at the upper foam surface is different from the one-dimensional case [Eqn (19)]. As demonstrated above, the foam surface cools down to much lower temperatures than an open earth surface. Therefore, the air above the foam strip is colder than air above the uncovered ground and convective heat flux is generated. Then, the boundary condition at the upper foam surface ($x = -h_f$) is given by

$$\lambda_f \frac{\partial T_f}{\partial x} = \sigma[\tilde{T}_f^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma p})] + \alpha_b(T_f - T_A) \tag{25}$$

The second term on the right-hand side represents the convective heat flux. The value of α_b, the natural convection heat transfer coefficient, for a cold surface of finite size, facing upwards, is calculated from the Nu number, defined as[19]

$$\mathrm{Nu} = 0{\cdot}27\,\mathrm{Gr}^{0{\cdot}25}$$

where

$$\mathrm{Gr} = \frac{g\beta\,|\Delta T|\,b^3}{\nu^2}$$

The heat transfer equation for the earth layer is

$$\frac{\partial T_g}{\partial \tau} = \kappa_g\left(\frac{\partial^2 T_g}{\partial x^2} + \frac{\partial^2 T_g}{\partial y^2}\right) \qquad 0 \leqslant x \leqslant h_g \quad 0 \leqslant y \leqslant l_g \tag{26}$$

Owing to symmetry with respect to y, we can limit the problem to $y \geqslant 0$. The boundary condition at $y = 0$ is

$$\frac{\partial T_g}{\partial y} = 0 \tag{27}$$

Initial and boundary conditions in the uncovered area ($y \geqslant b/2$) are similar to the one-dimensional case of paragraph 1 [Eqns (2) to (5)]. For the area under the foam cover ($y \leqslant b/2$), boundary conditions are similar to the conditions in Eqns (2), (3), (4), (17) and (18). In order to limit the solution to a finite range, we define a vertical influence boundary, where horizontal heat fluxes become negligible, by

$$y = l_g \qquad \frac{\partial T_g}{\partial y} = 0 \tag{28}$$

Heat transfer in the air above the uncovered earth ($y \geqslant b/2$) is described in a similar way to paragraph 1, by Eqn (6), the initial condition of Eqn (8), and the boundary conditions of Eqns (4), (5) and (9).

4.3.2. *Results*

The numerical solution of the problem described was obtained by means of a local one-dimensional implicit finite-difference method.[21] This method generates, for each time step, two separate systems of tridiagonal linear algebraic equations (in the x and y direction), which are solved by LU decomposition.[11]

Typical temperature distributions of the earth surface after 10 h of night cooling, are shown in *Fig. 7*. These calculations were carried out for three different widths of foam strip, namely, 0·5 m, 1 m and infinite, foam layer thickness 0·1 m, initial earth temperature, $T_0 = +5°C$, meteorological air temperature $T_A = +5°C$, partial pressure of water vapour, $p = 2{\cdot}4$ mm Hg, heat transfer properties of the soil and physical properties were similar to the previous cases.

Compared with the uncovered case, all forms of foam cover are capable of keeping the earth temperature under the foam strip centre line, higher by about 6°C. As shown in *Fig. 7*, the width of the positive temperature zone is slightly larger than the width of the foam strip.

The temperatures of the earth and foam surfaces at the centre line ($y = 0$) after 10 h night cooling as functions of the foam strip width b are presented in *Fig. 8*. As shown in this figure, the temperatures at the foam surface are substantially higher for the strip than for the infinite cover. This occurs as a result of increasing heat flux from the atmosphere to the foam surface due to the appearance of natural convective flows for the narrow foam strip. In the case of the infinite foam cover, a steady thermal stratification of air above the foam surface appears with an effective heat conduction coefficient[10] [Eqn (7)]. In the case of a narrow foam strip, the large temperature difference between the foam surface and the adjacent earth surface generates convective air flow above the foam surface and intensifies the heat flux from the warmer air to the foam surface. It is expected that the increase of foam surface temperature is followed by an increase in the earth surface temperature under the foam strip. An opposite effect is associated with heat flux within the soil layer from the covered area towards the colder uncovered earth, which reduces earth surface temperature under the cover. This effect becomes stronger as the strip width is decreased. For the narrower strip the last effect is dominant and as a result the earth surface temperature at the centre line is lower than under the infinite cover. On the other hand, for the wider strip, the first effect is dominant and therefore the ground surface temperature under the foam strip axis is higher than under the infinite cover.

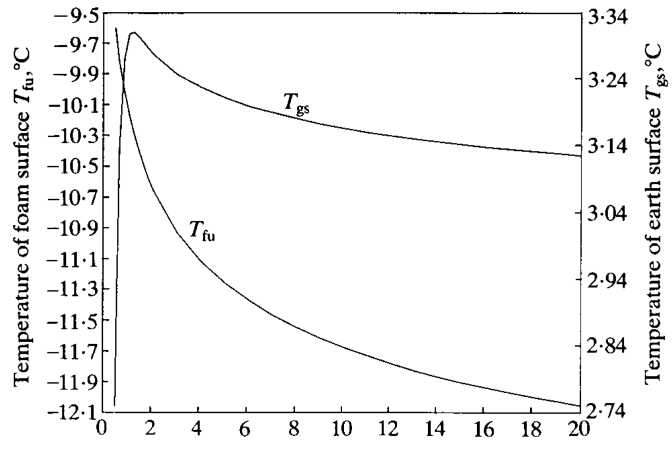

Fig. 8. Dependence of the earth (T_{gs}) and foam (T_{fu}) surface temperatures at the foam strip centre line after 10 h night radiation cooling on width of the strip (b)

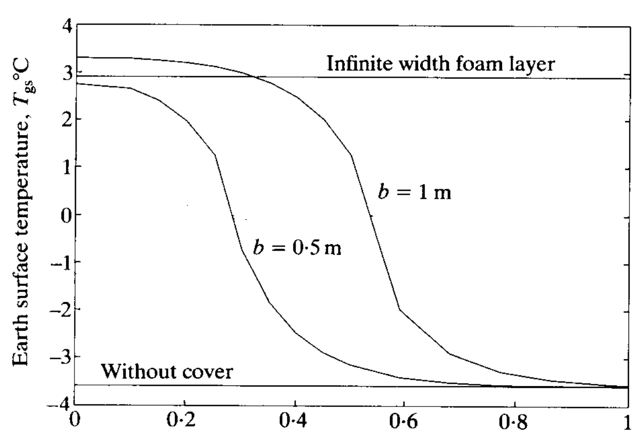

Fig. 7. Earth surface temperature after 10 h night radiation cooling. Foam cover of different width (b) in contact with earth surface

5. Conclusions

A comprehensive model of the heat transfer interaction between soil, protected by foam insulation, and the environment during a night of frost was developed.

It was shown that in aqueous foams, conduction may be considered as the dominant heat transfer mechanism. Infra-red radiative heat transfer through aqueous foam may be neglected compared with conductive heat transfer. The contribution of convective heat transfer becomes significant only for foams with very large air bubbles ($d \geq 20$ mm).

Even a thin foam layer of about 10 cm thickness, when applied directly to the ground, can prevent a substantial drop in earth surface temperature during a night of frost. Temperature differences of about 10°C can be achieved between the covered and uncovered ground after a night of frost. However, owing to the large vertical temperature gradient in the foam, the upper parts of the plant are not protected and suffer from negative (below 0°C) temperatures, even though they are inside the foam layer. Introducing some distance between the lower surface of the protecting foam layer and the earth surface, improves dramatically the effectiveness of the thermal protection. A thin foam layer, positioned above the ground, may ensure positive temperatures throughout the entire enclosure and as a result, full protection for the plants within the enclosure.

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