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Aqueous Foams for Frost Protection of Plants: Stability and Protective Properties

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Efficient technology has been developed for aqueous foam protection of plants against radiative night cooling. Experimental and mathematical simulations together with field tests were carried out in a search of foaming solutions and methods of application of the foam layer that provide optimal protection. A new parameter—insulation endurance—was developed for evaluating the thermal protective properties of unstable insulation materials such as aqueous foam. This parameter combines properties that are the most important for successful protection of plants—heat resistivity and stability. Based on this parameter, the experimental data were interpreted and used to choose the foaming solutions that provide sufficient protection of plants during a night of frost. Foams were studied when applied in various configurations, directly over soil surface and spread over a mesh which covers the plants.

1. Introduction

An estimated total annual loss of more than 800 M US dollars to agriculture is caused by night radiative cooling. This loss is greater than that due to any other environmental or biological hazard.[1,2] Covering plants by water-based foams is among the most promising frost protection methods. The foams have the advantages of being non-toxic, relatively cheap, stable during a night of frost, and are destroyed when exposed to the sun.[3] In spite of successful results with foam protection of plants during the 1970s,[4,5] it did not become a widely accepted commercial method. It is believed that the main reasons for this are complex technology and high cost of materials used for foam production. Simplification of the application technique and lowering of production costs are required for successful development of a foam protection method.

Notation

A, B	empirical coefficients
Fo	Fourier number
h	thickness of layer, m
p	partial pressure of water vapor, mmHg
q_a	heat flux from air to the upper foam surface, $W/m^2 K$
q_g	heat flux from the earth to the lower foam surface, $W/m^2 K$
r	thermal resistivity, $m^2 K/W$
T	temperature, °C
T_A	average night air temperature, °C
$\tilde{T}$	absolute temperature, K
t	integration variable
y	vertical coordinate, m
Greek letters	
α	heat transfer coefficient, $W/m^2 K$
γ	empirical exponent
κ	heat diffusivity, m^2/s
λ	heat conductivity, W/m K
λ_a	effective heat conductivity of the air layer in an experimental box (arrangements A and B)
σ_0	Stefan–Boltzmann constant, $W/m^2 K^4$
τ	time, s
Ω	insulation endurance
ω	rate of decaying parameter
Subscripts	
a	air
e	enclosure
f	foam
fu	upper foam surface
fl	lower foam surface
g	ground
gs	earth surface
p	polystyrene
0	initial moment
Superscripts	
l	lower
o	overall

2. Foam generation technology and the foam contents

Water-based foams are commonly produced using an electrically driven water pump for mixing and atomization of the foaming solution while a compressor supplies compressed air. The foam generation technology, developed by Amir *et al.*[6] produces the foam without air compressed by any external source of energy. The only energy source is the water pressure in the irrigation pipeline. This foam-producing technique is based on an existing irrigation system together with a container for foam solution, mixing chambers and atomizing nozzles. After mixing with water, the solution is delivered by a water-driven pump to a specially designed nozzle. At the nozzle, the water solution is sprayed on a mesh where it is atomized without the assistance of pressurized air, and foam is produced and spread.

In order to meet the requirements of this new technology, a novel foaming composition was developed. The basic solution includes betaine C (coconut amido alkyl betaine) as a surfactant, Lauramide 11 (coconut diethanolamide) as a stabilizer and glycerol as an antifreeze additive. Betaine C is an amphoteric compound which is commonly used for non-irritating shampoos, industrial foamers and as a surfactant for preparing bubble baths. Lauramide 11 which is a non-ionic component, is usually used as a foam booster, a thickener and a superfatting agent. The most important criterion for the selection of components for agricultural use is their degree of toxicity. Betaine C is a non-toxic compound[7] and glycerol is known as a non-toxic compound which is used as a food additive.[8] To the best of our knowledge, the toxicity of Lauramide 11 has not been tested but being a non-ionic compound, it has probably little influence on the plants and soil. The cost of the foaming solution can be minimized by reducing concentrations of the basic components, especially betaine C, and by replacing them with cheaper materials. By introducing an additional 1–3% of a cheap mineral additive (MA), it is possible to reduce the concentration of the basic components by two to four times and still achieve a stable foam. Note that the additives used are not revealed here because of patenting considerations.

3. Field tests

To check the effectiveness of various foam applications, and especially their configurations and compositions, in conditions of night radiation cooling, the foam-producing system was tested in a field experiment. The test took place during a windless and cloudless night on 25 January 1996 at a farm, situated in Kefar Yehoshua in the valley of Izre'el, Israel. The experiment started at about 01:15 h and lasted until 05:30 h. Foam was applied at 01:45 h. The foam was produced in a volumetric rate of about 450 l/min, with air to water volume ratio of about 45. Prior to foam application, the temperature of the bare earth's surface was in the range of +1 to +2°C.

3.1. *Testing of various configurations*

Three types of plants (tomatoes, peppers and eggplants) were put into four boxes, each of dimensions 60 cm × 40 cm × 30 cm deep. The number of plants in the boxes varied from 50 to 100. The plants in three boxes were covered with 0·1 mm polyethylene film (box 1), foam layer (box 2), and foam layer over a film (box 3). In box 2, the initial thickness of the foam layer, measured from the earth's surface, was 25 cm. The height of the plants was about 12 cm, thus the initial thickness of the foam layer over the plants was about 13 cm. The initial thickness of the foam layer above the film in box 3 was about 13 cm. The plants in box 4 served for control and were left without cover. The foaming solution used was water-based and contained 1% betaine C, 0·2% lauramide and 1% glycerol. The boxes were exposed to the sky.

Temperatures of the leaf surfaces in the open box were 0 to −1°C, and temperatures of the leaves under the film cover were −1 to −2°C. During the night, the temperature of the open earth surface decreased to −1°C, while the temperature of the bare leaves decreased to −2°C. The observations showed that the stability of the foam layer over the film (box 3) was much higher than the stability of the foam layer applied directly to the plants. At 04:00 h the thickness of the foam layer over the film was smaller than the initial thickness by 5 cm and the foam layer seemed rather dense and frozen. The thickness of the foam layer in box 2 decreased at the same time by about 10–15 cm, and it looked very rarefied. It is believed that this effect is the result of greater drainage when the foam was applied directly to the plants.

Following the nocturnal frost event, the state of the plants in boxes 1–4 were examined, and the damage to the plants was estimated based on the percentage of damaged plants and leaves, as shown in Table 1. Based on data summarized in Table 1, the following conclusions are drawn.

1. Covering with film does not prevent frost damage to the plants. The percentage of damaged plants covered with film was the same as for uncovered plants, while the percentage of damaged leaves under the film cover was even greater than for the uncovered plants.

Table 1
Percentage of damaged plants (leaves) after a night of frost

Type of protection	*Damaged plants, %*		
	Tomatoes	*Peppers*	*Egg-plants*
Without cover	—	77 (44)	—
Covered with film	77	78 (66)	78
Covered with foam	74	71 (38)	0
Covered with film and foam	0	26 (19)	0

( ) Percentage of damaged and killed leaves.

2. Covering the plants with a foam layer slightly decreased the percentage of damaged plants and substantially damaged leaves in tomatoes and peppers. No damage was found in the egg-plants.
3. The least damage was obtained in the case of a foam layer placed over a film. In this case, the damage was fully prevented for tomatoes and egg-plants and was substantially reduced for peppers.

Observations during two months after the field experiment showed that application of foam did not cause any damage to any of the plants tested.

3.2. *Testing of various compositions*

Simultaneously with the described experiments, five foam strips of different content were put directly onto grass. The foam strips dimensions were 5 m long, 1 m wide, with initial thickness of about 20 cm. Five foam compositions were used (see Table 2).

During the test, observing the foam checked the foam quality, and the thickness of the foam layers was measured. The temperatures of the bare earth surface, earth surface under the foam layers, and the foam surfaces were measured with a system of thermocouples. Acquisition of the thermocouple readings was accomplished by the DAS TC acquisition board.

Among the foam strips, composition 1 (see Table 2) proved to be the most stable. At 04:00 h, the thickness of this strip was about 15 cm, the temperature of the earth surface under the strip was about +2·7°C, while the temperature of the foam surface was −3·5°C. The thickness of the strip of composition 2 at the same time was about 10 cm, while the temperature of the earth surface under the strip was about +0·2°C. The strips 1 and 2 existed for about 10 h. For strip 3 at 04:00 h, the foam thickness was about 7 cm and the earth surface temperature was about −0·2°C. Foam strips made from compositions 4 and 5 collapsed quickly and, at 04:00 h, there was no substantial foam cover left over the grass.

Table 2
Foam compositions tested in the field test

Number of composition	*Betaine C, %*	*Lauramide, %*	*Glycerol, %*	*"Agrifoam", %*
1	2	0·4	2	—
2	1	0·2	1	—
3	0·5	0·1	0·5	—
4	1	0·2	0	—
5	—	—	—	10

3.3. *Recommended configuration and foam properties*

The results obtained show that the best protection of plants against night frost is provided when the protective foam layer is stretched over the plants and does not penetrate between them. In order to provide such a configuration, the foam used must form a stable layer over the plant foliage or above some shield such as a film or net, stretched over the plants. Nets, for instance, which are commonly used to cover and protect plants and orchards against hail and birds, may be used. These nets are usually fabricated from knitted polyethylene, with standard mesh sizes of 3–10 mm. The foam intended for this purpose must be capable of existing during several hours on the mesh without substantial drainage. In order to meet these conditions, there is a need to increase the adhesion and the stability of the foam. Creation of foams with such properties and the development of arrangement for frost protection of plants and trees in the field and in greenhouses were the object of the experimental works reported in this paper.

4. Simulation experiments

4.1. *Experimental arrangement*

The field test showed that foam over a shield (net or film) provides the best protection. In order to develop such a frost protection method, the foam used must be stable for several hours and the required properties are therefore a high insulation capability, high adhesion, high viscosity and low drainage. The insulation characteristics of such a foam cover must be tested in controlled experiments.

This part of the study was performed in a controlled cabinet where frost conditions could be simulated. An

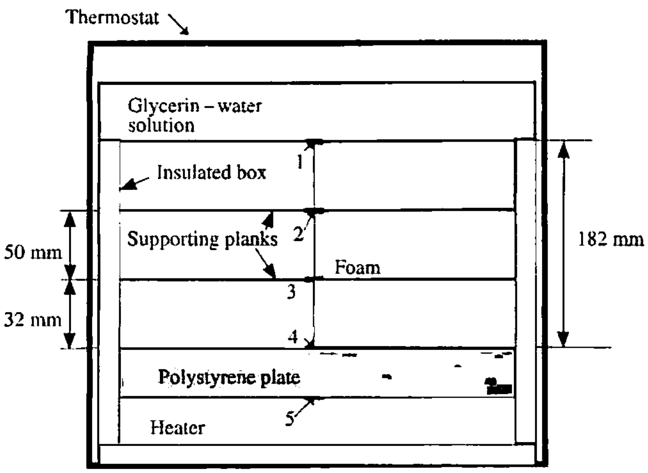

Fig. 1. Experimental arrangement A. Numbers 1–5 indicate thermocouple positions

insulated box was built (see arrangement A in *Fig. 1*), equipped with a flat electrical heater with capacity of about 3 W in the bottom of the box. Above the heater, a polystyrene plate 14 mm thick and heat conductivity of 0·033 W/m K, was placed. The box was covered with a rectangular metallic vessel, containing a water–glycerin solution. Thermocouples were installed inside the vessel (1), at two levels between the vessel and the polystyrene plate (2) and (3), and at the upper and lower surfaces of the polystyrene plate (4) and (5).

The space between the metallic vessel and the polystyrene plate was filled with the foam tested and the box was installed in a freezer. The water–glycerin solution was cooled down prior to the experiments to a temperature of −5 to −10°C, which was kept constant during the experiments. Glycerin concentration in the water was chosen to provide phase change in this temperature range, thus increasing the temperature stability of the solution. Such arrangement simulates temperature conditions typical for a foam layer applied to the earth during a night of frost. It is known that the upper surface of the foam layer is cooled down to very low temperatures due to radiative heat flux to the atmosphere. At the same time, the surface in contact with the earth is much warmer due to geothermic heat flux.[9,10] The role of the heater is to (1) simulate geothermic heat flux, and (2) improve the accuracy of the measurements by increasing the temperature gradient in the foam layer. Data from the thermocouples were recorded with a DAS-TC acquisition board. Each experiment took about 8–12 h and temperatures were sampled every 15 min. Based on these data, the effective heat conductivity of the whole layer (including foam and air) between the cooling vessel and the bottom was calculated based on temperatures of the vessel T_1 and the polystyrene plate surfaces (upper T_4, and lower T_5):

$$\lambda_{fe}^{o} = \lambda_p \frac{h_{1-4}}{h_p} \frac{(T_4 - T_5)}{(T_1 - T_4)} \qquad (1)$$

Here, h_{1-4} is the distance between thermocouples 1 and 4 (see *Fig. 1*), and λ_p and h_p are the heat conductivity and the thickness of the polystyrene plate, respectively.

The value of λ_{fe}^{o} is equal to the actual foam heat conductivity if all the space between the plate and the vessel is filled with foam and the temperature profile is steady and linear. During the experiment, the foam layer settles and the air layer appears between the foam and the upper vessel. In this situation, the effective heat conductivity rises because air layer has greater heat conductivity than the foam layer.

A similar technique may be used for evaluating the heat conductivity of the lower part of the foam layer λ_{fe}^{1}, situated between thermocouple 3 and the bottom (see *Fig. 1*):

$$\lambda_{fe}^{1} = \lambda_p \frac{h_{3-4}}{h_p} \frac{(T_4 - T_5)}{(T_3 - T_4)} \qquad (2)$$

Using this technique, it was possible to investigate variations in time of the heat conductivity of the foam layer by itself to evaluate insulation properties and stability of the tested foams. In the first set, about 20 experiments with foams of various contents were carried out and the foam content of best insulation properties was chosen. The method for comparing and evaluating the insulation properties is to be discussed later (see Section 4.2). Then, in a second set, about 40 experiments were conducted with various foam layers applied over a mesh. The mesh, with 1 cm cells, was placed at the bottom of the box (arrangement B, see *Fig. 2*). After surplus solution had

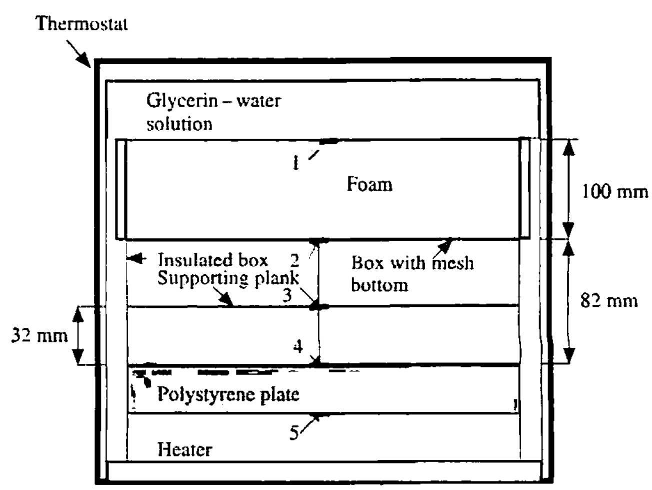

Fig. 2. Experimental arrangement B. Numbers 1–5 indicate thermocouple positions

been drained, the frame was installed on a measuring box in the freezer. Drainage holes in the measuring box prevented the accumulation of foam under the mesh.

4.2. *Insulation endurance parameter*

In order to compare insulation properties of foams with various contents, a new parameter "insulation endurance", was developed:

$$\Omega = \lim_{Fo \to \infty} \int_0^{Fo} \left(\frac{r_f^0(t)}{r_{a0}} - 1 \right) dt \tag{3}$$

This new parameter allows the evaluation of the effectiveness of heat protection over time. Here, r_f^o is the overall thermal resistivity of a given volume, composed of foam (subscript f) and air (subscript a) layers:

$$r_f^o = \frac{h_f}{\lambda_f} + \frac{h_a}{\lambda_a} = \frac{h_{f0}}{\lambda_{fe}^o} \tag{4}$$

and r_{a0} is the thermal resistivity of the same volume without foam:

$$r_{a0} = \frac{h_{f0}}{\lambda_a} \tag{5}$$

where h_{f0} is the initial thickness of the foam layer and λ_a is the effective heat conductivity of the air layer with thickness of h_{f0}. The foam layer thickness h_f and the air layer thickness h_a vary with time. At any time, the total thickness $h_{f0} = h_f + h_a$ is constant.

The dimensionless time is defined as a Fourier number: $Fo = \kappa_a \tau / h_{f0}^2$, where κ_a is the air heat diffusivity. It is worth noting that $\Omega = 0$ for an air layer, while $\Omega = \infty$ for a foam layer which never decays. For real foams the value of Ω is finite and positive.

The measured values of Ω are obtained from experiments, which are described above, using

$$\Omega = \sum_{i=1}^{N} \left[\frac{\lambda_a}{\lambda_{fe,i}^o} - 1 \right] \Delta Fo_i \tag{6}$$

Here, $\lambda_{fe,i}^o$ denotes the value of overall effective heat conductivity, calculated for the ith time segment of the experiment according to expression (1); $\Delta Fo_i = \kappa_a \Delta\tau_i / h_{f0}^2$; $\Delta\tau_i$ is the duration of the ith time segment; and N is the number of time steps until the foam layer disappears completely.

4.3. *Results of the experiments*

Different additives were added to a basic solution for increasing the foam stability and adhesion. The basic solution included: amido betaine C as surfactant, lauramide 11 as a stabilizer and glycerol as an antifreezing additive. The additives tested were polymer additive (PA) and mineral additive (MA). The first set of experiments was carried out in arrangement A where stability and heat conductivity of the foams over an impenetrable surface were investigated. The range of the foam component contents in these experiments was: amido betaine C, 0·5–1·6%; lauramide 11, 0·1–0·2%; glycerol, 0·5–1·2%; PA, 0–1%; MA, 0–7·3%. Typical temperature measurements and calculated heat conductivities are presented in *Figs. 3 and 4* for foam made of the basic solution. Here T_i is the temperature measured by the ith thermocouple (see *Fig. 1*). The overall heat conductivity λ_{fe}^o, which is calculated using Eqn (1), increases in time up to air layer heat conductivity of about 0·2 W/m K. The heat conductivity of the lower part of the foam layer, adjacent to the bottom of the box λ_{fe}^l is calculated using Eqn (2). A very low heat conductivity of about 0·02 W/m K was found during the first 150 min, and then it increased up to a value of about 0·06 W/m K. Note that after about 150 min. the bottom temperature dropped to below 0°C, and the apparently subsequent rise in heat conductivity might be attributed to freezing of the foam. This pattern was found in all other foam compositions tested in this set of experiments.

As shown in *Fig. 3*, the overall heat conductivity λ_{fe}^o is much higher than the heat conductivity of the lower foam layer λ_{fe}^l, and increases faster with time. The reason for this effect is the foam surface settling. Using Eqn (6), the value of insulation endurance parameter $\Omega = 17{\cdot}7$ was obtained for this case.

The highest value of insulation endurance parameter Ω was obtained using a foaming solution containing 0·5% betaine C, 0·1% lauramide 11, 0·5% glycerin, 0·85% PA and 2% MA. In this case, Ω greater than 101·5 was calculated. A lower limit for Ω was provided because the foam layer did not collapse until the end of the experiment.

In another set of experiments, the foam was placed on a mesh in arrangement B. The range of the foam component contents in this set was: amido betaine C, 0·5–3%; lauramide 11, 0·1–0·2%; glycerol, 0·5–1·5%; PA, 0·45–1·8%; MA, 0–4%. Here, the greatest insulation endurance parameter ($\Omega > 119$) was found for a foaming composition containing 1·5% betaine C, 0·1% lauramide 11, 0·5% glycerin and 0·85% PA. This composition stayed on the mesh for about 10 h and during this time the insulation properties did not deteriorate substantially (see *Fig. 5*).

5. Mathematical simulation

5.1. *Decaying foam layer on earth surface*

The problem of heat insulation with a stable foam layer during a night of radiative frost was described by

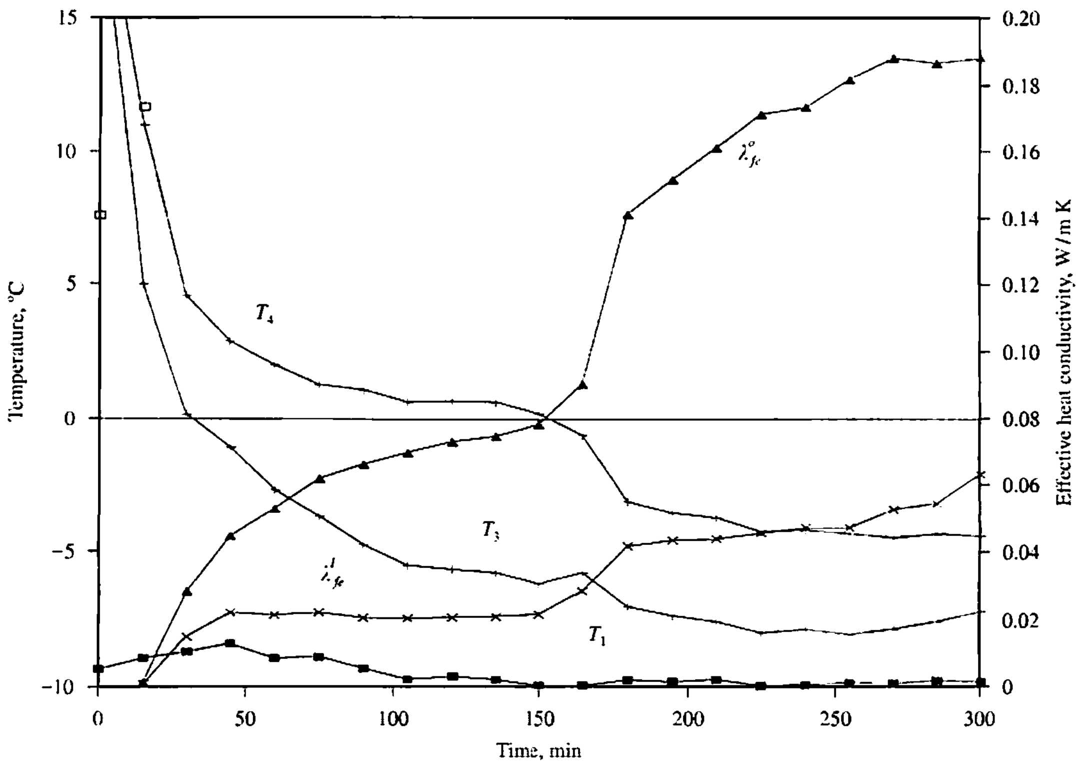

Fig. 3. Temperatures and effective heat conductivities of various layers of foam in experimental arrangement A. Foam content: betaine C, 0·78%; lauramide 11, 0·16%; glycerol, 1·2%. T_i, temperature measured by the ith thermocouple shown in Fig. 1; λ^o_{fe}, overall heat conductivity of the whole volume between the thermocouple 1 and 4 (Fig. 1); λ^l_{fe}, heat conductivity of the lower part of the foam layer situated between thermocouples 3 and 4 (Fig. 1)

Krasovitski *et al.*[10] Here, we modify the model to account for the more realistic conditions of the decaying foam layer.

In order to take into account the decaying of a foam layer with time, a term r_f is employed for the thermal resistivity of the foam layer, such that

$$r_f = \frac{h_f}{\lambda_f} \quad (7)$$

Since thermal resistivity decreases in time, as shown in the experiments described above, the following approximation is suggested:

$$r_f = r_{f0} e^{-\omega Fo} \quad (8)$$

where $r_{f0} \equiv h_{f0}/\lambda_{f0}$ is the initial thermal resistivity of the foam layer. The parameter ω characterizes the rate of decaying. It may be connected with the insulation endurance parameter Ω [see Eqn (3)] by substituting Eqn (8) into Eqn (3):

$$\omega = \frac{1}{\Omega}\left(\frac{\lambda_a}{\lambda_f} - 1\right) \quad (9)$$

A correlation coefficient of 0·96 was calculated for the experimental data, presented in *Fig. 3* and the approximation suggested in Eqns (8) and (9).

Using the thermal resistivity concept, the heat transfer problem for the foam layer applied to the earth's surface in conditions of night radiative cooling[10] was modified. Assuming for simplicity a linear temperature profile inside the foam layer, the boundary conditions (heat flux continuity) on the foam surfaces take the following form.

At the upper foam surface:

$$\frac{T_{fl} - T_{fu}}{r_f} = \sigma_0[\tilde{T}_{fu}^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma p})] - q_a \quad (10)$$

and at the lower foam surface:

$$\frac{T_{fl} - T_{fu}}{r_f} = q_g \quad (11)$$

where T_{fl} and T_{fu} are the temperatures of the lower and the upper surfaces, respectively, $\tilde{T}$ is the absolute temperature, q_a is the heat flux from the air to the upper foam surface, q_g is the heat flux from the earth to the lower foam surface, σ_0 is the Stefan–Boltzmann constant, A, B are empirical coefficients, γ is an empirical exponent and p is the partial pressure of water vapour in the atmosphere. Using the continuity of temperatures on the foam surfaces, $T_{fl} = T_g|_{y=0}$ and $T_{fu} = T_a|_{y=-h_f}$,

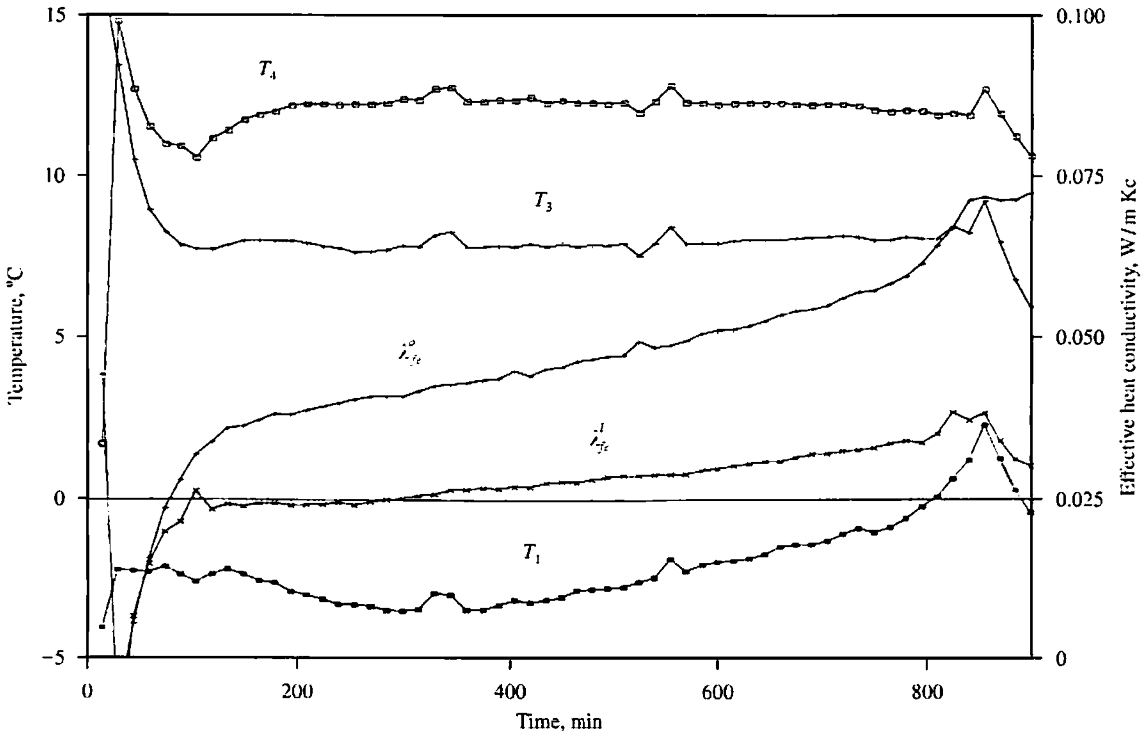

Fig. 4. Temperatures and effective heat conductivities of various layers of foam in experimental arrangement A. Foam content: betaine C, 0·5%; lauramide 11, 0·1%; glycerol, 0·5%; PA, 0·85%; MA, 2%. T_i, temperature measured by the ith thermocouple shown in Fig. 1; λ^o_{fe}, overall heat conductivity of the whole volume between the thermocouple 1 and 4 (Fig. 1); λ^l_{fe}, heat conductivity of the lower part of the foam layer situated between thermocouples 3 and 4 (Fig. 1)

together with Eqns (10) and (11), the heat transfer problems in the earth layer and the air inversion layer are connected and are solved without a need to solve the heat transfer problem in the foam layer. Thus, forecasting the earth's surface temperature under a decaying foam layer during a night of frost is done using values of the insulation endurance parameter Ω taken from the laboratory experiment. Note that at the initial stage, a problem for the bare earth surface exposed to night sky should be solved, and that foam is applied over the ground when the earth surface temperature reached some critical level.

The earth surface temperatures during a night of frost before and after a foam layer was applied, were calculated. The initial temperature of air and the upper layer of the ground was taken as +3°C, the partial pressure of water vapour in air as 1 mmHg, and the foam layer's initial thickness as 5 cm. The values of other parameters, influencing the process were taken according to Krasovitski *et al.*[10] As shown in *Fig. 6*, the temperature of the bare earth surface falls during the night to −7°C, while covering with foam with insulation endurance $\Omega \geqslant 40$ guarantees a positive temperature during a 9 h night of frost. Note in *Fig. 6*, the sudden rise of the earth's surface temperature the moment after the application of foam, which may be explained by a strong misbalance of heat fluxes at the earth's surface. Before the foam application moment, intensive infrared radiative heat flux leaves the uncovered earth's surface. This process is accompanied by the large heat fluxes in the ground near the earth's surface associated with large values of the ground temperature gradients. After the foam application, the radiative heat flux from the earth's surface decreases sharply, while the upward ground temperature gradient near the earth's surface decreases much more slowly because of the large heat capacity of the ground. As a result, the upper earth layer during some time interval receives much more heat than it dissipates to the atmosphere through the foam layer and its temperature rises. These features are in agreement with the results of our measurements of the earth surface temperatures.[11]

5.2. *Decaying foam layer over an enclosure*

It is known that an air gap between the foam layer and the protected surface improves the effectiveness of the

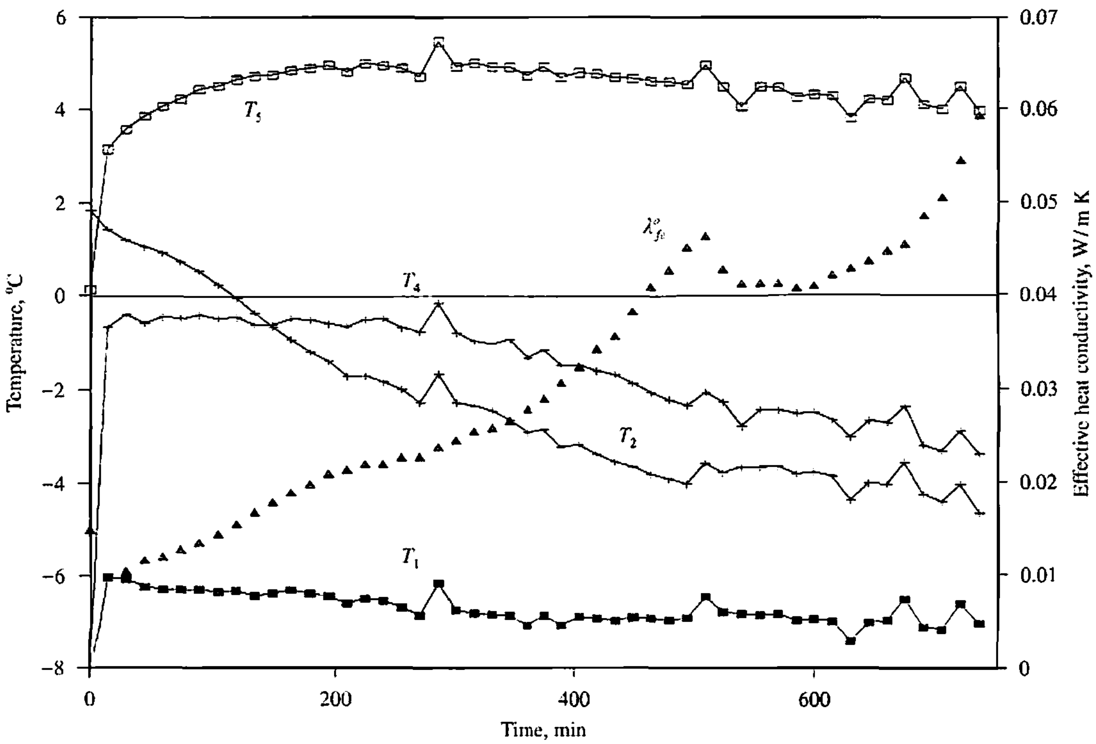

Fig. 5. Temperatures and effective heat conductivities of various layers of foam in experimental arrangement B. Foam content: betaine C, 1·5%; lauramide 11, 0·1%; glycerol, 0·5%; PA, 0·85%. T_i, temperature measured by the ith thermocouple shown in Fig. 2; λ_{fc}^0, overall heat conductivity of the whole volume between the thermocouples 1 and 2 (Fig. 2)

thermal protection.[9] This fact was confirmed in a mathematical simulation.[10] Consider here an air enclosure of uniform thickness between the earth's surface and a cover made of a decaying foam layer. In an analogous way to the previous section, a system of algebraic equations for the temperatures of the lower T_{fl} and upper T_{fu} surfaces of the foam layer is obtained by considering a linear

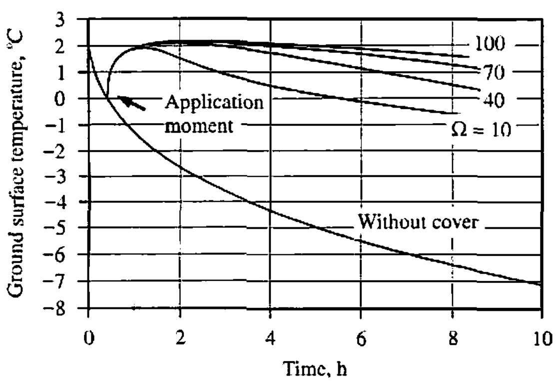

Fig. 6. Temperatures of the ground surface under foams with various values of the insulation endurance Ω

temperature profile inside the foam layer:

$$\frac{T_{fl} - T_{fu}}{r_f} = \alpha_e(T_e - T_{fl}) + \sigma_0(\tilde{T}_{gs}^4 - \tilde{T}_{fl}^4) \quad (12)$$

$$\frac{T_{fl} - T_{fu}}{r_f} = \sigma_0[\tilde{T}_{fu}^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma P})] - q_a \quad (13)$$

where α_e is the heat transfer coefficient from the enclosure to the lower foam surface. Solving Eqns (12) and (13), a transcendental equation is obtained for the variable T_{fl}:

$$\alpha_e(T_e - T_{fl}) + \sigma_0(\tilde{T}_{gs}^4 - \tilde{T}_{fl}^4) = \sigma_0\{[r_f\{\alpha_e(T_e - T_{fl}) + \sigma_0(\tilde{T}_{gs}^4 - \tilde{T}_{fl}^4)\}]^4 - \tilde{T}_A^4(A - B \times 10^{-\gamma P})\} - q_a \quad (14)$$

and then by introducing the solution of Eqn (14) into Eqn (12), T_{fu} is obtained. As in the previous section, the continuity of temperatures on the foam surfaces is used for the solution of the above system. Thus, the heat transfer problems in the earth layer, air enclosure, and the air inversion layer[10] are connected and are solved without a need to solve the heat transfer problem in the foam layer.

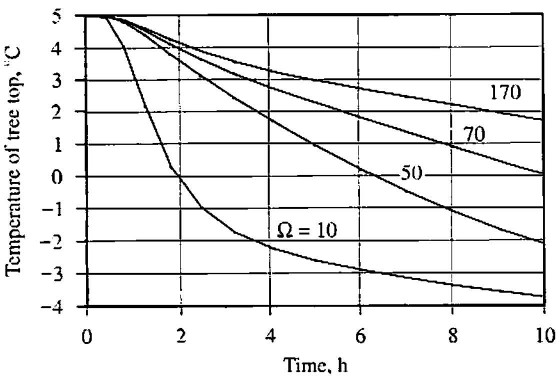

Fig. 7. Temperatures of tree top under foams with various values of the insulation endurance Ω

This technique is used for solving the heat transfer problem where an orchard is protected during a night of frost by a foam layer with initial thickness of 5 cm. The foam is placed uniformly over a flat mesh, spread 2 m above the ground, over the tree tops. Initial temperature of air was taken as +5°C, and the partial pressure of water vapour in air as 2·4 mmHg. Values of other parameters, influencing the process were taken according to Krasovitski *et al.*[10] As shown in *Fig. 7*, values of insulation endurance $\Omega \geqslant 70$ provide sufficient protection, namely temperatures of tree top above freezing, during 8 h of night cooling.

6. Conclusions

The development of a new parameter, the insulation endurance, allows evaluation and comparison of the protective properties of a decaying insulation covering (e.g. aqueous foams) and the use of data, observed in experiments, for analytical forecasting.

Based on field and laboratory tests, a foam type and a foam application method which provide high insulation endurance parameters were developed for protection of plants in conditions of a night of frost.

Two optimal foaming compositions are recommended in the following cases: (1) foams which are applied directly over surfaces provide insulation for low plants adjacent to the earth's surface, where the recommended solution for better insulation endurance $\Omega = 101{\cdot}5$ is 0·5% betaine C, 0·1% lauramide 0·5% glycerol, 0·85% PA and 2% MA; and (2) foams which are placed over a net spread over the protected plants, where the recommended solution which provides insulation endurance $\Omega = 119$, is 1·5% betaine C, 0·1% lauramide, 0·5% glycerol and 0·85% PA. According to the calculations accomplished in the paper, the contents provide satisfactory protection of plants in typical conditions of a night of frost.

Exact frost conditions were difficult to simulate in the experimental arrangement, because instead of radiative cooling of the objects by cold sky, we applied convective cooling. Thereby, the results of the simulation experiments provide mainly data on foam quality in low temperatures. The field experiment was conducted in conditions of mild frost, just below zero, and therefore it is recommended to repeat the experiments in more severe frost conditions and test our technology and quality of foam in lower temperatures.

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