

Super Efficient Greenhouse Design

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Abstract

Building envelopes which require high light transmissions, such as greenhouses, need a highly dynamic system to provide shading at peak loads when solar radiation levels are too high, and also provide thermal insulation at night when the surrounding temperature is lower than required for optimal plant conditions. Removable liquid foam within a transparent double layer is presented in this paper, which enables rapid shading and night-time insulation without compromising available light when these are not required. Heat transfer through the foam was measured in a testing rig with 3 different bubble diameters and 2 different foam depths, and a model developed to begin to explain the foams effect on the convection forces within the cavity. Numerous chemical formulas were tested to produce a foam that could remain in place for more than 2 hours. Experiments to ascertain the effect of the foam material on conductive heat transfer within the cavity were conducted, and the results demonstrated this to be negligible. These initial experimental results are valuable for this novel dynamic system design.

Keywords: greenhouse, energy, liquid foam, bubbles, shading, insulation.

Nomenclature		α Convective heat transfer coefficient (W/m ² K)
A Area of screens normal to heat flux	(m ²)	T_s Temperature at surface (K)
A_M Area of “liquid films”	(m ²)	T_f Bulk fluid temperature away from surface (K)
Q Heat flux	(W)	ΔT Temperature difference across cavity (K, °C)
λ Thermal Conductivity	(W/m K)	V_b Average volume of single bubble (m ³)
λ_a Thermal Conductivity of still air	(W/m K)	V_F Volume of foam in water canister (m ³)
λ_w Thermal Conductivity of water	(W/m K)	
L Distance across cavity	(m)	

V_L	Volume of liquid in water canister (m^3)
N_B	Number of bubbles in water canister
	Dimensionless
N_L	Number of "liquid films" Dimensionless
t	Bubble wall thickness (m)

1. Introduction

The commercial greenhouse sector in northern Europe is dominated by the use of glass for what are termed salad crops; typically tomatoes, cucumbers and bell peppers. The use of 4mm glass as the glazing material leads to significant heat build up within the structure in peak radiative loads and substantial heat loss during the night. Both these factors have a detrimental effect on plant growth, and are mitigated by venting during the day and the use of substantial amounts of heating during the night. The only commercially available solution to help reduce this problem is the use of removable shade curtains, which mainly work to reduce the heat load during the day. Shade curtains are installed within the building envelope above the plant canopy and lead to numerous issues with plant growth due to the build up of heat above the curtain. The use of venting, both passive and mechanically forced using fans, brings its own problems as this creates a pathway for disease and unwanted insects effecting plant health and production. It also enables significant release of CO₂, used in greenhouses to substantially increase yields, which is typically held at 1000ppm. The only solution currently available is to burn further fossil fuels, typically methane gas, to extract the CO₂ from the exhaust, at a time when the radiative heat loads negate the need for heating. This is a very inefficient use of non renewable energy, and is increasingly making production unprofitable due to the increasing

fuel prices, threatening the viability of the entire industry in northern Europe [1].

An alternative, dynamic system using liquid foam between two high light transparency plastic films, fluorocarbon-based polymer Ethylene TetrafluoroEthylene (ETFE), with similar light transmission properties in 2 layers to single 4mm horticultural glass, is presented here using liquid foam as a means to control heat loss and provide shading during the peak loads. This system, whilst similar in approach to the use of shade curtains, is significantly different as the heat losses and gains are controlled at the boundary layer of the building envelope, negating the heat build up issues associated with the use of shade curtains.

Previous research carried out in this area [2] has not discussed the effect of bubble size or sort to identify the impact of conductive heat transfer through the foam material itself. In order to create a greater understanding of the processes involved, and to create a baseline upon which accurate predictive models can be based, the key factors under review by the researchers are the effect on heat transfer, through conduction and convection, and the impact on light transmission of different bubble diameters and different densities of foam to see the effect on normal convection forces in an empty cavity and of shading of the infra red spectrum, compared to the reduction in Photosynthetic Active Radiation. The investigation of light is ongoing and this paper focuses on the results of the heat transfer data gathered to date.

2. Description of apparatus

Creating foam with a consistent bubble diameter, enabling accurate calculations of bubble properties, has proved very difficult to achieve. Numerous methods of foam generation were trialled until the use of

compressed air in a submerged gutter was identified.

The experimental apparatus on which the testing was carried out consists of two wooden boxes (1255 x 1255 x 2440 mm) with ETFE screens facing each other. Each box is insulated on the inside with 50mm Celotex (see Figure 2). One of the boxes has low radiative heaters inside it, creating a temperature difference across the cavity and simulating the warmer side of the greenhouse envelope. Both boxes are placed on wheels so that the distance between them can be freely adjusted. The distance between the boxes represents the depth of the cavity space that could be used in a greenhouse envelope. This cavity is filled with foam generated by a compressor through pipes in the gutter located at the bottom of one of the boxes (see figure 1).

2.1 bubble diameters

Different size pipe hole diameters were used to create the differing diameter bubbles (see table II). The bubbles sizes are not completely uniform, but this method of using compressed air was found to produce the most consistently uniform bubbles. Numerous repeat tests were conducted with the foam measured through the glazing using digital verniers and the averages taken (see figure 2).

Before the foam is generated, the cavity is insulated on all sides and sealed on the sides and the top with sheets of 18mm plywood and 50mm Celotex insulation. Celotex is also inserted at the base, between box 2 and the gutter.

Each box is fitted with 24 k-type thermocouples, which are connected to data loggers attached to the side of both boxes. The sensors are placed in columns at one third and two thirds of the inside height of the box and in rows at one, two and three quarters of the inside width of the box. This configuration of thermocouples is placed on the back wall and

hanging off the centre of the ceiling of each box and on both sides of the screens. In addition there are two more sensors for measuring the ambient air temperature in the testing environment and the water temperature in the gutter. The data loggers are connected to a computer with D-Logger software.

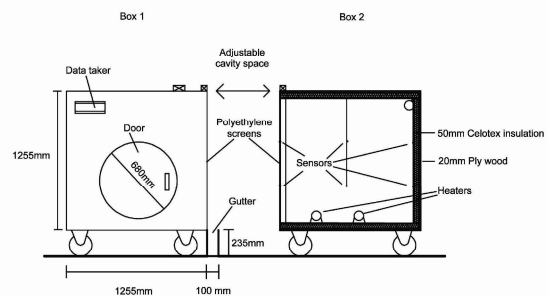


Figure 1: Apparatus: Outside view of box 1 & section of box 2



Figure 1.2: box 2



Figure 1.3: foam viewed through box 1
3. Foam properties and heat transfer through foam

Whilst significant research has been undertaken into the fields of bubble formation and their structural behaviour, the heat transfer through foam has not yet been thoroughly studied in academic papers. The key aspect researched is the impact on restricting convective heat loss, essentially by trapping the free air in a contained bubble matrix. The other factor considered was the potential conductive heat loss through the foam.

3.1 bubble diameters

Numerous observations of bubble diameters were made (see figure 2) and the averages taken and used as the basis for the heat transfer calculations.

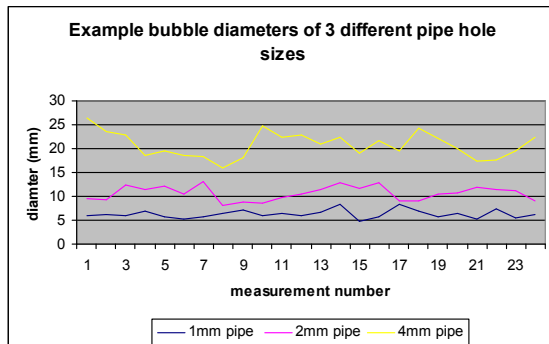


Figure 2: Sample of average bubble size measurements

Pipe hole size (mm)	Mean bubble diameter (mm)
1	6.29
2	10.64
4	20.80

Table I: Mean Bubble diameters

3.2 foam material density

Whilst the foam developed begins as a water surfactant solution of 2%, the foam quickly thins, losing the free water and leaving a dry foam. Tests using 6mm foam

were conducted to identify the significance of conduction through the bubble walls where the weight of foam was measured in a known volume and observed over time (see table II).

Test	Weight of vessel and 2L liquid (g)	After foam removed (g)	Weight of foam (g)
A – 0 mins thinning	2694.26	2689.61	4.65
B – 15 mins thinning	2695.98	2694.31	1.67

Table II: Foam Weight

6mm foam was used to calculate the bubble wall thickness. So it is now possible to find the average volume of a single bubble in this type of foam:

$$V_b = \frac{4}{3} \pi r^3$$

Pipe	Average bubble diameter (mm)	Average Bubble volume, V_b (m ³)
1mm	6	1.0×10^{-7}
2mm	11	7.0×10^{-7}
4mm	21	5.0×10^{-6}

Table III: Bubble volumes

And since the volume of the canister (in this case 18 litres = 0.018 m³) and how much of it is filled with foam is known, the average number of bubbles within that volume can be found:

Volume of foam:

$$V_F = 0.01531039 \text{ m}^3$$

Number of bubbles:

$$N_B = \frac{V_F}{V_b}$$

Pipe	Average bubble diameter (mm)	Average bubble volume, V_b (m ³)	Number of bubbles, N_B
1mm	6	1.0×10^{-7}	153,100
2mm	11	7.0×10^{-7}	21,900
4mm	21	5.0×10^{-6}	3,100

Table IV: Bubble density

Dividing the volume of the liquid content in the foam by the number of bubbles the thickness, t , of the bubble membrane can be determined as follows.

$$\frac{V_L}{N_B} = t \times 4\pi r^2$$

$$t = \frac{V_L}{N_B \times 4\pi r^2}$$

Pipe	Average bubble diameter (mm)	Immediate thickness of bubble membrane (nm)	Thickness of bubble membrane after 15 mins. (nm)
1mm	6	270	100

Table V: Bubble wall thickness

This is extremely thin and the inference on the heat transfer can be expected to be quite insignificant. Further, after letting the foam stand for 15 minutes a drastic reduction in the bubble wall thickness can be seen.

The following equation was used to model the expected heat loss due to conduction:

$$Q = -\lambda_a A_s \frac{\Delta T}{L} - \lambda_w A_{Mb} N_{Lb} \frac{\Delta T}{\pi r(L/d)} - \lambda_w A_{Mv} N_{Lv} \frac{\Delta T}{\pi r(L/d)}$$

$$Q = -0.025(2.44 \times 1.255) \frac{(30-25)}{0.1} - 0.611(2.7 \times 10^{-7} \times 2.44) \times 209$$

$$\times \frac{(30-25)}{0.003\pi(0.1/0.006)} - 0.611(2.7 \times 10^{-7} \times 1.225)$$

$$\times 406 \frac{(30-25)}{0.003\pi(0.1/0.006)}$$

$$Q = -3.70 - 0.003 - 0.003 = -3.706W$$

Note the conductive heat transfer coefficient used for the bubble material was based on that of water, as a known value, and prior to the thinning process. Therefore it can be reasonably concluded that the actual conductive heat loss would be further reduced over time due to bubble wall thinning, and the material taking on the properties more of a solid than liquid.

4. Experimental Method

The entire experiment tests rig was initially cooled to 15°C then foam generated in the cavity. Low radiance heaters in box 2 were then turned on with a thermostatic controller, logging every 5 seconds, and used to achieve 30°C in box 2. Data was recorded at 1 minute intervals. An internal video camera in box 2, along with a low energy 5W light, was used to observe the foam in situ to watch for foam breakdown over time.

5. Results

The 2 cavity depth tests were conducted under slightly different ambient temperatures, hence the 100mm empty cavity reaching a lower steady state temperature than the 500mm data. However by comparing the foam data with the empty cavity data it has been possible to calculate the inference of the foam on heat transfer.

5.1 100mm cavity

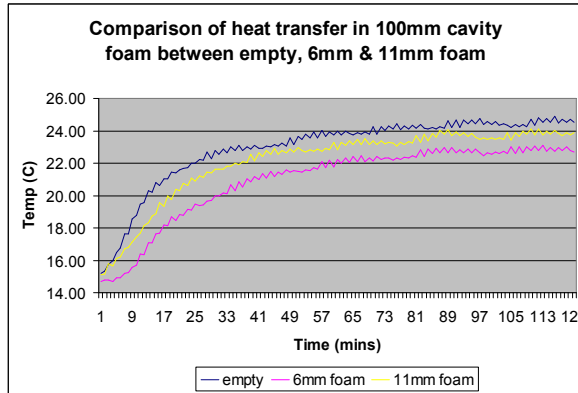


Figure 4: comparison of heat transfer in 100mm cavity space

Note that the 21mm foam has not been included. At 100mm there are only approximately 5 bubbles spanning the 2 screens and each bubble collapse has a correspondingly greater impact on the integrity of the data.

5.2 500mm cavity

As shown in figure 5 the three bubble sizes reach a steady state at around 80 minutes. Foam has been regenerated, due to small holes breaking through the body of foam bridging the cavity, in the 2mm and 4mm pipe tests at this point hence the variations in temperature thereafter.

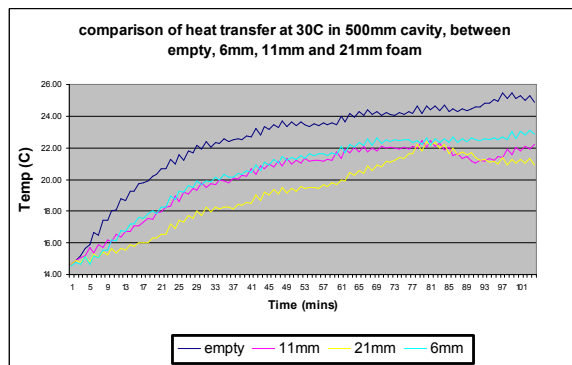


Figure 5: comparison of heat transfer in 500mm cavity space

6. Analysis

An example of the heat transfer calculations are presented below using the empty 500mm cavity and filled with 6mm foam:

6.1 Empty cavity

$$Q = -\lambda_a A \frac{\Delta T}{L} - \alpha A \Delta T$$

$$Q = -0.025(2.44 \times 1.255) \frac{(30 - 25)}{0.5}$$

$$-2.5(2.44 \times 1.255)(30 - 25)$$

$$Q = -0.8 - 38.3 = -39.1W$$

Note: According to “CIBSE Guide B: Heating, ventilation, air conditioning and Refrigeration” a reasonable value for the convective heat transfer coefficient, α , for natural convection is 2-3 W/m² K. The mean value, 2.5 W/m² K has been used [3].

6.2 6mm foam

After 1 hour the foam reaches a steady state heat transfer (until it collapses and will eventually achieve the steady state of an empty cavity):

$$Q = -\lambda_a A \frac{\Delta T}{L}$$

$$Q = -0.025(2.44 \times 1.255) \frac{(30 - 23)}{0.5}$$

$$Q = -1.1W$$

6.3 Table for all heat transfer data:

Average bubble diameter (mm)	100mm Cavity heat loss, Q (W)	500mm cavity heat loss, Q (W)
None	41	39
6	5	1
11	4	1
21	-	1

Table VI: Heat loss in 100mm and 500mm cavity

[3] CIBSE, "CIBSE Guide B: Heating, Ventilating, Air Conditioning and Refrigeration", Page Bros. Ltd., Norwich, 2004, Section 2, p. 78

7. Conclusion

Liquid foam can significantly reduce the heat loss of a greenhouse and enable a substantially reduced amount of fossil fuel consumption, whilst retaining valuable CO₂ for plant growth by reducing the need to vent heat when used for shading. These are the preliminary findings of our research and further tests are ongoing, with a particular focus on achieving the same steady state environmental conditions, and varying the temperature difference across the cavity. Further mathematical models are also being explored to improve the interpretation of results.

References

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