Concept of Dynamic Liquid Foam Insulation for Greenhouse Insulation and the Assessment of Its Energy Consumption and Agronomic Performances

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Abstract
Energy savings have always been a major concern in the greenhouse industry, particularly for northern tier growers. Better greenhouse insulation delivers an efficient method for energy savings. The injection of dynamic liquid foam insulation between two greenhouse membranes is a technology leading to significant increase in greenhouse insulation. The objective of this paper is to demonstrate the feasibility of this technology in a pre-commercialisation environment and to present its performances in energy savings and plant growth.

Laboratory testing has demonstrated that the foam produces an increasing insulation factor which is proportional to the thickness of the foam injected between the two membranes. Results recorded during the winter season include comparative studies of climate conditions and energy savings of the prototype and non-retrofitted greenhouse.

Within a full season of production, it would be possible to confirm the technical feasibility of injecting and circulating liquid foam between two greenhouse film membranes. Energy savings results predicted in laboratory conditions and scientific models are confirmed by this experiment in pre-commercialisation settings. Current data, collected in winter season, suggest energy savings of over 50%. Also, the impact of the use of such technology on plant growth would be obtained with a plantation of Tomato (Lycopersicum esculentum).

INTRODUCTION
Maintaining an adequate temperature within commercial greenhouses requires large amounts of energy during the winter in northern latitude. In many cases the amounts of energy used to heat a greenhouse year round represents the main component of total production cost. With rising prices of fossil fuels, reduction of energy consumption is vital in order for producers to remain competitive. According to published research improving the insulation values of cover materials is one of the most efficient methods to conserve energy in greenhouses. Many technologies have been developed to lower energy consumption within commercial greenhouses (Papadopoulos and Hao, 1997; Bakker et al., 1995; Oliveira et al., 2001) with the most common being used in cold regions is the double infrared polyethylene covers. Using a double infrared polyethylene and thermal screen in combination with single glass will reduce heat loss, but more can be done.

A dynamic liquid foam insulation system can be adapted to an existing greenhouse structure with little difficulty. This type of system has the potential to become an excellent solution for growers who have high energy bills. Further more, when used on sunny days during summer time liquid foam is a solution for shading inside the greenhouse.

The objective of this work is to compare two single gothic type greenhouses, one equipped with a dynamic liquid foam system (prototype greenhouse) and one without (reference greenhouse), and to measure energy saving potential as well as agronomic performances.
MATERIALS AND METHODS

Experimental Setup

A conventional Nordic type greenhouse (24.4 m long x 6.4 m wide x 3.05 m gutter) covered with double infrared polyethylene film (PE) was modified to accommodate the installation of a dynamic liquid foam generating system (Fig. 1). This prototype greenhouse and a second identical greenhouse are equipped with natural gas furnaces and two forced air circulation fans. High-pressure sodium lamps of 470 W are used to assure an adequate photoperiod. Liquid foam is injected just before nightfall and removed early the next day immediately after sunrise.

A hydroponic culture of tomatoes was sowed on February 24th, 2004 in a nursery greenhouse and was planted in each of the test greenhouses a month later on March 24th, to reproduce typical commercial growing conditions. Before planting the tomatoes plants in the greenhouses the heating units were set to maintain temperatures of 21°C at night and 24°C during light hours (sunlight + artificial lighting). After March 24th, temperatures were maintained at 18°C at night and 24°C during sunlight. Agronomic parameters of tomato production such as tomato yield, fruit number, the number of clusters, the distance between cluster (cm), the distance between internodes (cm) and the plant growth (cm) in both greenhouses were recorded in order to complete the comparative study of the two plantations.

To monitor the inside climate, three temperature sensors (± 0.2°C from 0°C to +50°C) and one relative humidity (± 3%) sensor where placed in aspiration cages. A quantum sensor was used to measure photosynthetically active radiation (PAR, ± 5 µmol/s m²) and a pyranometer used to measure solar global radiation (± 5 W/m²). During winter months and when liquid foam is to be removed through the day period, these measures are necessary to characterise and compare solar transmission in both greenhouses. For the summer period these measure are used to evaluate the effects of creating shade with liquid foam.

The amount of consumed natural gas, in cubic meters, was carefully measured independently in each greenhouse before injection of liquid foam and again after its removal at sunrise. Energy used by the dynamic liquid foam system in the generation of the liquid foam was also recorded. The level of liquid foam remaining inside cavity before its removal, at sunrise, was observed and noted.

One temperature (°C) sensor, a pyranometer to measure solar radiation (W/m²) and an anemometer for wind speed (m/s) where used to monitor external climate.

Heat Transfer Coefficient (R-value)

1. Test Description. To determine the heat resistance of the dynamic liquid foam insulation, measurements were made in controlled laboratory conditions (Swinton, 2004) by the Institute for Research in Construction (a division of the National Research Council, in Ottawa, Canada). The standard test method for determining the thermal performance of walls is ASTM C-236 (ASTM, 2003). Given the variable nature of liquid foam over time, its R-value cannot be evaluated under steady state conditions. The test wall outer surfaces were instrumented with both thermocouples and heat flux transducers in order to aid, respectively, in the determination of the thermal resistance, and in the localized heat flux across the test wall during a 3-hour period, during which the wall was kept filled with foam and drained of liquid accumulation.

For this test, a 2.5 m x 2.5m perimeter-framed wall was built with 5 cm x 15 cm wood pine members. Room- and weather-side skins were of 0.6 cm thick Lexan polycarbonate sheathing clad over the perimeter frame. A foam generator was connected to a manifold placed in the top and centre of the wall cavity. A sloped drain was set up on the bottom to remove the excess liquid. The weather-side temperature was set at minus 18°C and the room side at +20°C. Heat resistance (R-value) was measured and calculated from the room-side to the weatherside surface.
2. **Results.** The cumulative thermal resistances of the various surfactant tested over a three hour period were from 0.35 and 0.76 W/m².K.

**RESULTS AND DISCUSSION**

**Energy Saving, Relative Humidity and Light Transmission**

1. **Winter Period.** Energy consumption values were analysed for a number typical days of February and March when the system was operating at near 100% efficiency at nightfall.

Table 1 presents nocturnal temperatures as well as energy consumption and overall heat transfer coefficients \(U\) of the prototype and reference greenhouses. The calculation of the \(U\)-value considers the overall surface of the greenhouse (roof + side and end walls = 415m²) and the average difference between the exterior temperature and temperature inside the greenhouse for the studied period. The coefficient \((U)\) is calculated as follows:

\[
U = \frac{\text{Energy Consumption}}{\text{Greenhouse surface} \times \Delta T_{\text{average}}}
\]

For the selected periods, the average \(U\)-Value when liquid foam was injected in the cavity was \((2.26 \text{ W/m}^2\text{°C})\) 42.5% inferior to the average \(U\)-Value when there was no liquid foam present \((3.93 \text{ W/m}^2\text{°C})\). It is important to acknowledge that the data was collected at nighttimes during the months of February and March. Consequently, the results do not take into account the coldest periods of the year in the months of December and January when average temperatures in the region of Quebec city often drop below -15°C during the day and -20°C at night. The insulation performance measurements of liquid foam during these intense cold periods would only take place next winter. Additionally, because of the improved insulation of the prototype greenhouse, it was observed that when the set temperature is changed at nightfall from 22°C to 18°C, the temperature inside the reference greenhouse drops much faster than the temperature in the insulated prototype greenhouse.

For the winter period where no tomato culture was present, liquid foam had no noticeable effect on RH inside the prototype greenhouse. Therefore no significant difference between the two greenhouses was registered. With the presence of tomato culture in early April, higher RH values were measured in the prototype greenhouse when liquid foam was injected at night. This can be explained by the fact that the membranes surfaces in the insulated greenhouse are warmer therefore limiting condensation. These differences are no longer noticeable during warmer days.

Liquid foam can significantly influence the transparency of the prototype greenhouse cover materials; therefore the liquid foam insulation must be completely removed at sunrise and only be injected at sunset to avoid any light or heat loss. Figure 2 presents global radiation outside and inside the greenhouses on a typical day (March 13, 2004). It is noticed that the global radiation measured inside the prototype greenhouse is slightly lower (5.1 %) than in the reference greenhouse. This can possibly be explained by the presence of foam or solution residues on the membranes.

2. **Summer Period.** Liquid foam can be very practical during summer months if used as a shading material. As a matter of fact aluminised thermal screens are not habitually used within double polyethylene greenhouses and liquid foam could present an alternative to fix shading. Preliminary experimentation with only a liquid film injected between the cavities has resulted in a 20 to 30% shading effect. When liquid foam is injected between the cavities of the greenhouse, the shading effect is of 60 to 75 %. The use of liquid foam to create shading could prolong the length of the period where carbon dioxide is used to enrich crop growth by diminishing the need for ventilation.
Agronomic Aspects

As the tomato plantation took place in late March, conclusive results on the influence of the liquid foam on plant growth have not been reached. However, analysis of measured climatic parameters (temperatures, radiation, humidity...), as well as preliminary data collected during the first 4 weeks of crops suggests similar productivity rates in the two greenhouses. Nevertheless, only a study carried out over a complete season and using controlled optimization of foam insulation will validate the full benefits of the liquid foam insulation technology. Also, it should be noted that the use of this technology would require a control programme for plants and ventilation by adapting among others operation schedule for artificial lighting in winter or CO2 enrichment in summer.

CONCLUSION

In times of rising energy costs it is important to find alternatives for reducing heating costs and increase productivity of greenhouse cultivation. The use of liquid foam insulation injected between two layers of PE film has demonstrated its energy savings potential in lab testing by providing low thermal conductivity values. The feasibility and technical demonstration of this technology in a large-scale trial greenhouse are currently in progress. Already, energy savings potential were demonstrated this past winter. Liquid foam generated at nighttimes, provided increased insulation resulting in energy savings of 42%. An improvement in the control of foam generation and removal could lead to energy savings of more than 50% at night. Also, it was discovered that when using liquid foam technology, relative humidity inside the prototype greenhouse, at the end of the winter period, was higher while light transmission was lower (< 5%). With regard to the tomato culture, it is still too early to assess crop production, which currently suggest no significant differences between the two greenhouses.

The continuation of these experiments with a greenhouse producer in a pre-commercialisation setting during a full year is the next step. This would enable us to quantify the effects on yearly tomato plant yield in a commercial greenhouse setting. Finally, projected tests with a greenhouse producer could validate the technology for commercial use.

ACKNOWLEDGEMENTS

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Literature Cited


### Tables

Table 1. Energy consumption at night in the prototype and reference greenhouses.

<table>
<thead>
<tr>
<th>Date</th>
<th>Night temp (°C)</th>
<th>Consumption (KWh)</th>
<th>Heat transfer coefficient (W/m²°C)</th>
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<tbody>
<tr>
<td></td>
<td></td>
<td>Prototype</td>
<td>Reference</td>
</tr>
<tr>
<td>Febr. 6</td>
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<td>376</td>
<td>695</td>
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<tr>
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</tr>
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</table>

Average U value (W/m²°C) | **2.26** | **3.93**

### Figures

Fig. 1. Schematic view of the prototype and reference greenhouses.
Fig. 2. Global radiation outside and inside the prototype and reference greenhouses.