

Predicted Thermal Performance of Transparent Bubble Structures

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ABSTRACT: This paper presents the thermal performance of transparent structures that incorporate super thermal insulation via a bubble technology. The transparent structure is a cavity formed by transparent interior and exterior membranes and filled with liquid bubbles. The liquid bubbles in the cavity transmit daylight while providing a thick blanket of insulation, which reduces heat losses in winter and solar gains in summer. Such structures are extremely energy efficient and could be used as transparent building envelopes in place of conventional glazing for facades and/or atrium roofs as well as greenhouses. CFD has been used to assess the thermal performance of two structures of semicircular and pitch-roof configurations. The effects of bubble diameter, density and distribution as well as cavity width on the insulation level in terms of cavity convective heat transfer coefficient have been determined numerically. It has been found that the cavity convective heat transfer coefficient of a bubble structure increases with bubble diameter and porosity but decreases with the increase in cavity width and bubble filling depth. The cavity heat transfer coefficient also increases with the temperature difference between indoors and outdoors.

Keywords: transparent envelope, bubble technology, insulation, cavity heat transfer

NOMENCLATURE

- d – Bubble diameter (m)
- dt – Temperature difference between indoors and outdoors (K)
- h_c – Cavity convective heat transfer coefficient (W/m^2K)
- s – Cavity width (m)
- z – Bubble filling depth (m)
- γ – Porosity (fraction)

1. INTRODUCTION

Buildings with large areas of glazing such as greenhouses and office buildings equipped with atria are susceptible to summer overheating and winter draught. In

winter, the internal environment of these buildings may be uncomfortably cold without considerable amount of auxiliary heating. In summer, the thermal stress imposed by high air temperature can be exacerbated by solar radiation. Shading devices are sometimes used to reduce solar gain but these have the drawback of reducing daylight to the space. As a result, conventional highly-glazed buildings generally have high energy consumption for heating and/or cooling. This leads to high operating cost. Techniques such as the use of plants in double skin facades for solar control [1] and heat recovery from air flow windows [2] have been shown to reduce excessive summer solar gain and winter heat

loss in office buildings but these systems would not be effective for year-round operation as they are designed principally to alleviate problems in one particular season, e.g., using plants in double skin facades for solar control in summer.

One way to make use of solar energy to provide thermal comfort within highly glazed buildings would be to use a transparent bubble structure that permits transmission of daylight but minimises winter heat loss and summer solar heat gain. A schematic of the structure for use in building envelopes is shown in Fig. 1. The structure consists of two membrane layers integrated with bubble technology to provide a transparent envelope. The interior and exterior membranes create a cavity that replaces the glass envelope of a conventional roof (and façade). Bubbles are produced by a bubble generator, installed near one end of the structure, using the liquid in a source reservoir. Bubbles are an excellent thermal insulator and are opaque to infrared radiation. They can reflect and absorb solar heat and transmit daylight to the building. The bubbles gradually move to the other end and accumulate in the sink reservoir in liquid form. The movement of bubbles is controlled by a small fan integrated within the bubble generator. The liquid is pumped back to the source reservoir, thus completing the cycle. Bubbles can last for hours and during a large proportion of operation periods, bubbles can remain static in the cavity for insulation and shading. In winter, the technology would provide insulation and solar heating of the space, and storage of any solar energy exceeding the heating requirement for subsequent release into the space as required. In summer, dense bubbles will provide solar shading to reduce overheating during the day. The bubble liquid can be cooled at the end of a sunny day by circulating the fluid during the night. In this way, the bubbles store night-time coolth for daytime cooling, as well as provide shading of the space below. Hence, the technology

would provide glazed buildings with insulation/heating, shading/cooling and daylight as required to allow year-round control of the building environment. The technology could be applied to various types of building envelope, e.g., greenhouses and atria. Similar transparent materials with built-in air pockets (bubble covers) have been used to cover swimming pools to minimise re-radiation of the collected solar energy. Well designed bubble covers have been shown to behave as selective transmitters, admitting shorter wavelength radiation, while being reflective to longer wavelengths [3]. Liquid bubbles have been used for insulation of greenhouses [4] but no fundamental research has been carried out on the mechanism and performance of the liquid bubble insulation.

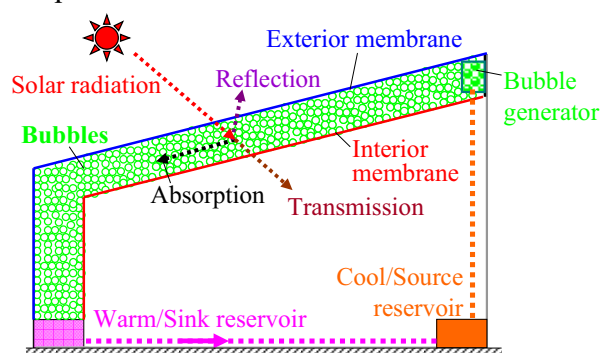


Figure 1: Sloping roof + vertical façade integrated with bubble technology

2. METHOD

Computational fluid dynamics (CFD) software FLUENT [5] was used for modelling of steady state fluid flow and heat transfer in transparent bubble cavities of two shapes – semicircular arc and pitched roof + vertical façade (Fig. 2). The structures had interior membrane dimensions of 3 m high and 6 m span with varying cavity width (s) and bubble filling depth (z) for simulation. Bubbles remain static under steady state after being delivered to a cavity and the fluid flow and heat transfer in the cavity result from thermal buoyancy. Bubbles in

the cavity were modelled as a porous media whose resistance to fluid flow depended on the bubble size (diameter, d) and porosity or void fraction (γ).

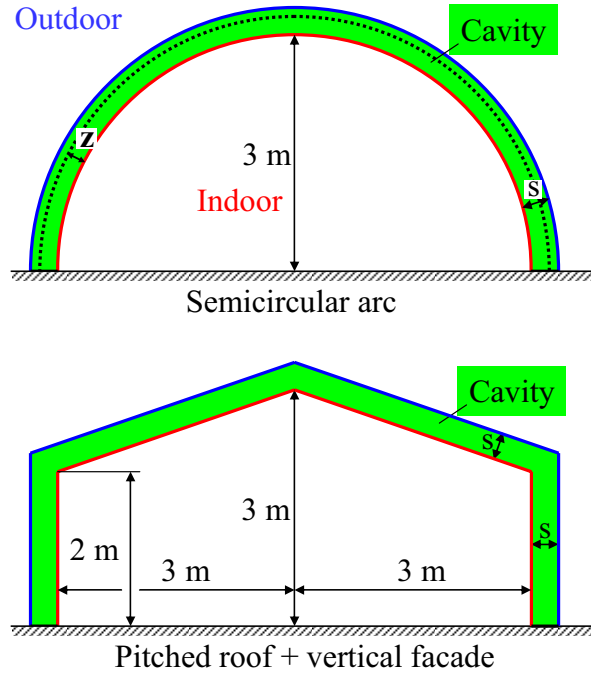


Figure 2: Two types of cavity structure

For a cavity with a low porosity, there would be little air movement through the media and so the laminar flow model was used for simulation. For flow in the cavity with negligible bubble media where turbulent flow could occur, the RNG k - ϵ model [6] was used.

Computer modelling was first carried out for heat transfer in bubble cavity structures, and then for heat transfer and the environment of an indoor space equipped with a bubble cavity. Bubbles were assumed to be spherical and the distribution was random. The porosity of randomly packed monosized spheres is around 40% and this was taken as the base porosity when bubbles completely filled a cavity. For the calculation of heat transfer in a bubble cavity, the internal environment (under the cavity) and external environment (above the cavity) were at 18 and 0°C, respectively at base conditions. Predictions were also carried out for different internal and external

air temperatures as well as different cavity widths, bubble diameters, bubble filling porosities and distributions. Results were analysed to determine the thermal properties of the structure (cavity convective heat transfer coefficient) as a function of these parameters. This allowed simplification of the bubble-cavity structure as an equivalent single-layer transparent solid envelope with varying thermal properties for modelling the indoor environment in combination with the outdoor environment, thus reducing the computing power and time required for modelling of buoyancy flow in the cavity structure with fine mesh. As the surface area of exterior membrane is larger than that of interior membrane, the thermal performance parameters that were defined on the basis of unit surface area would differ for the interior surface from the exterior surface. The cavity convective heat transfer coefficient is here defined as the rate of heat transfer through the cavity per unit area of interior membrane and unit temperature difference between interior and exterior membranes.

3. RESULTS AND DISCUSSION

Modelling was performed for a range of bubble sizes, quantities and distributions and two structure configurations.

Fig. 3 shows a comparison of the predicted temperature distribution in the semicircular arc cavity with bubbles (5 mm diameter and 40% porosity) and without bubbles when the indoor and outdoor air temperatures were 18°C and 0°C, respectively. It is seen that the cavity filled with bubbles such that convection was prevented would provide excellent thermal insulation to reduce fabric heat loss in winter. The temperature of the interior membrane for the bubble cavity would nearly be uniform, which would lead to a uniform air temperature under the cavity, whereas an empty cavity would have a large vertical temperature stratification due to convection heat transfer.

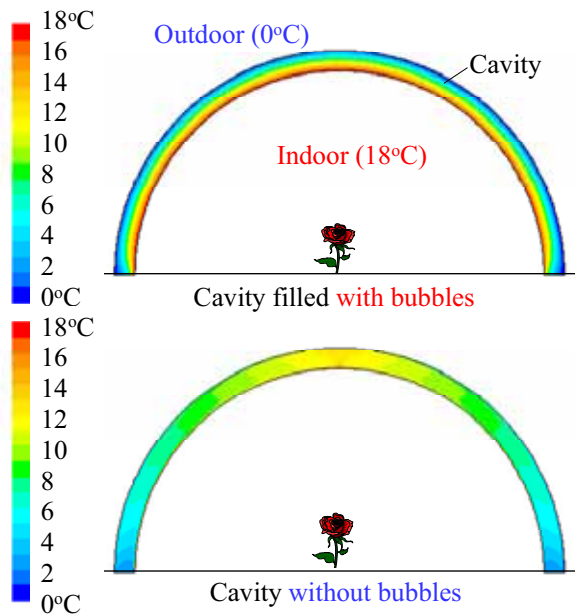


Figure 3: Predicted temperature distribution in the semicircular arc cavity

3.1 Effect of Porosity

The cavity convective heat transfer coefficient depends on the level that bubbles fill the cavity, i.e., porosity of bubble filling. Fig. 4 shows the increase with porosity of the predicted convective heat transfer coefficient for a 0.3 m wide cavity with bubbles of 5 mm in diameter. The predicted coefficient was about 0.09 W/m²K for the cavity filled completely with bubbles (corresponding to a porosity of 40%). This increased to 0.13 W/m²K when the cavity was 3/4 filled with bubbles (corresponding to a porosity of 55%). When the cavity was half filled with bubbles (corresponding to a porosity of 70%), the coefficient increased to 0.27 W/m²K. When the level of bubble filling in the cavity was reduced from 1/2 to 1/4 (corresponding to a porosity of 85%), the coefficient was nearly doubled to 0.53 W/m²K.

The cavity convective heat transfer coefficient can be correlated with porosity between 0.4 and 0.96 as follows:

$$h_c = 2.313 \gamma^2 - 1.878 \gamma + 0.463 \quad (R^2=0.999) \quad (1)$$

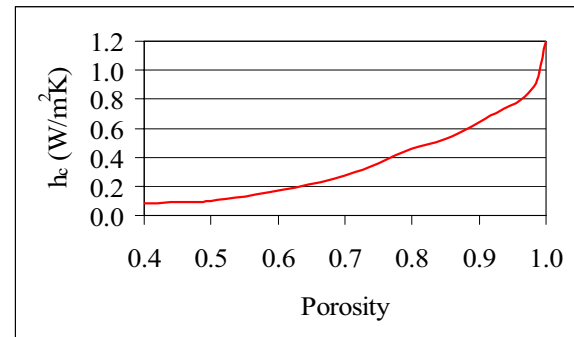


Figure 4: Effect of porosity on the cavity convective heat transfer coefficient

3.2 Effect of Bubble Diameter

Fig. 5 shows the variation with bubble diameter of the predicted cavity convective heat transfer coefficient for the 0.3 m wide cavity with different porosities. In general, the coefficient increased with bubble diameter. It is observed that when the cavity was filled completely with bubbles, the variation in the coefficient was small (between 0.08 and 0.09 W/m²K for $d < 5$ mm and $d \geq 5$ mm respectively). However, if the cavity was partially filled with bubbles, the bubble diameter would have a significant effect on the coefficient depending on the level of filling. For example, when the cavity was 3/4 filled with bubbles, the coefficient increased from 0.13 W/m²K for a bubble diameter of 5 mm to 0.21 W/m²K for a bubble diameter of 8 mm. When the cavity was half filled with bubbles, the coefficient increased almost linearly with bubble diameter. When the quantity of bubbles was halved again to 1/4 filled cavity, the effect became less if the bubble diameter was equal to or larger than 6 mm.

The cavity convective heat transfer coefficient can also be correlated with bubble diameter. For example, for $d = 3$ to 8 mm and $\gamma = 0.7$,

$$h_c = 0.0463 d + 0.0365 \quad (R^2=0.994) \quad (2)$$

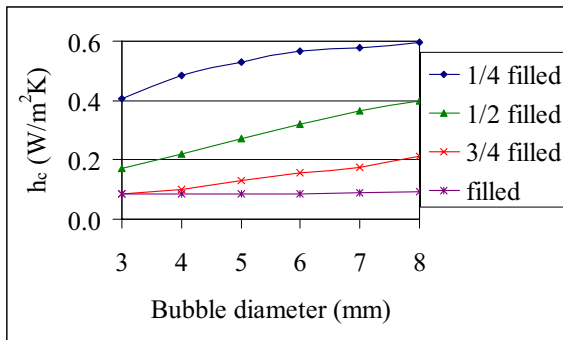


Figure 5: Effect of bubble diameter on the cavity convective heat transfer coefficient

3.3 Effect of Bubble Filling Depth

Fig. 6 shows the predicted velocity and temperature in a 0.3 m wide cavity, one half of cavity area (in terms of cavity width) near the interior membrane being filled with 5 mm bubbles and the other half near the exterior membrane being empty (filled with air). It is seen that there was hardly any fluid flow in the area filled with bubbles. Air circulation occurred in the empty space with a thin layer of downward flow close to the cooler exterior membrane and a thick layer of upward flow close to the warmer interior membrane. Due to the reduced bubble filling in

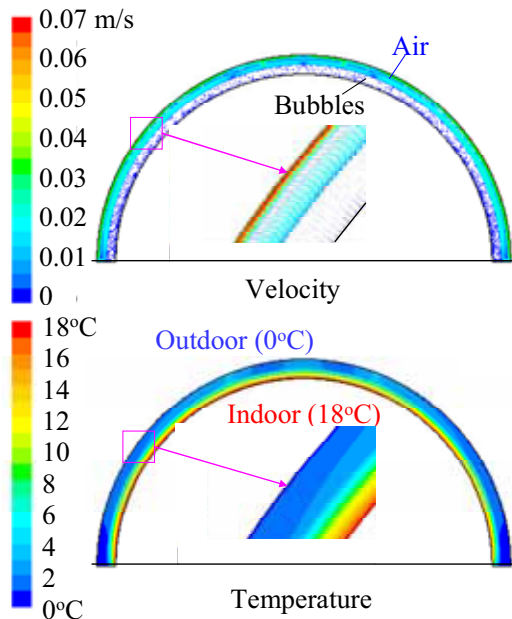


Figure 6: Predicted velocity and temperature in the cavity with bubbles half filled near the interior membrane

the cavity, the 'warm' area near the interior membrane became smaller than the 'cold' area near the exterior membrane compared with the bubble-filled cavity (see top of Fig. 3). Consequently the insulation level of the half-filled cavity would decrease.

Fig. 7 shows the effect of proportion of bubble filling depth (proportion of space filled by bubbles in terms of the distance from one of the membranes, z , in relation to cavity width, s) on the predicted cavity convective heat transfer coefficient for a 0.3 m wide cavity with bubbles of 5 mm in diameter. The coefficient decreased with the increase in the bubble filling depth. The decrease was very significant when the cavity was less than 1/3 filled, i.e., 2/3 of the cavity area near the exterior membrane was empty and 1/3 near the interior filled with bubbles, or in theory the other way round. When over 1/3 of the cavity was filled with bubbles, the decrease in the coefficient was small but the effect was still perceivable. Hence, for thermal insulation, the bubble filling depth should be larger than $1/3 \times 0.3 \text{ m} = 0.1 \text{ m}$. For example, the coefficient decreased from $0.21 \text{ W/m}^2\text{K}$ for the 1/3 filled cavity to $0.13 \text{ W/m}^2\text{K}$ for a half filled cavity which however was much lower than the value ($0.24 \text{ W/m}^2\text{K}$) for the cavity filled with the same amount of bubbles but uniformly distributed in the space (corresponding to bubbles of 5 mm in diameter and 70% porosity in Fig. 5). It follows that the thermal performance of a bubble cavity would depend not only on the quantity but also on the distribution of bubbles. For given number of bubbles, better thermal insulation can be achieved with bubbles settling on one of the membranes than being distributed throughout the cavity. This is because packed bubbles minimise natural convection in the packed region whereas natural convection arises between less densely distributed bubbles.

The cavity convective heat transfer coefficient is related to the proportion of

bubble filling depth (z/s) between 0.1 and 1 as follows:

$$h_c = 0.0873 (z/s)^{0.805} \quad (R^2=0.999) \quad (3)$$

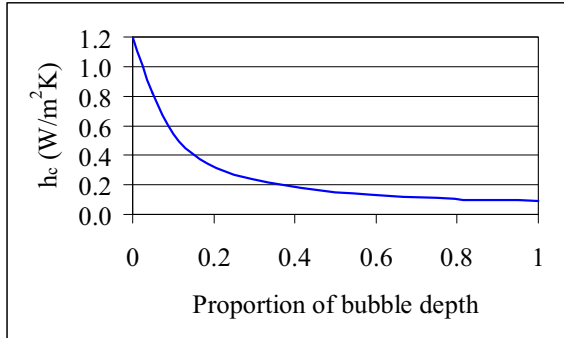


Figure 7: Effect of bubble filling depth on the cavity convective heat transfer coefficient

3.4 Effect of Cavity Size

The cavity convective heat transfer coefficient would also be influenced by the size of cavity. Fig. 8 shows the effect of cavity width on the predicted coefficient for cavities filled with 5 mm bubbles. It is seen that there was a significant drop in coefficient (i.e., significant improvement of insulation level) when the cavity width increased from 0.1 m to 0.2 m. The variation became less as the width increased further when the cavity was not completely filled with bubbles but was still appreciable for the filled cavity. Therefore, to ensure excellent thermal performance of a bubble structure, the minimum width of the bubble cavity should be approximately 0.2 m and preferably 0.25 m or more if the cavity is

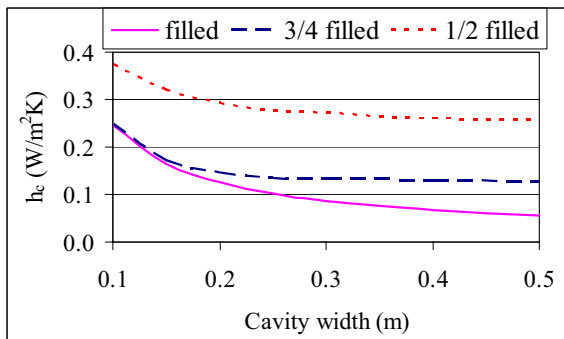


Figure 8: Effect of cavity width on the cavity convective heat transfer coefficient

likely to be completely filled with bubbles during operation.

The cavity convective heat transfer coefficient can be correlated with the cavity size (s). For example, for cavities completely filled with bubbles:

$$h_c = 0.0286 s^{-0.926} \quad (R^2=0.999) \quad (4)$$

3.5 Effect of Temperature Difference

The thermal buoyancy in the cavity depends on the temperature difference between the two membranes and hence between indoors and outdoors (dt). The cavity convective heat transfer coefficient was therefore influenced by the temperature difference as shown in Fig. 9 for a cavity 0.3 m wide and filled with 5 mm bubbles. When the cavity was completely filled with bubbles, the convective heat transfer coefficient was independent of the variation in the temperature difference because natural convection was prevented by small packed bubbles. When the cavity was partially filled, the coefficient increased with the temperature difference as well as porosity.

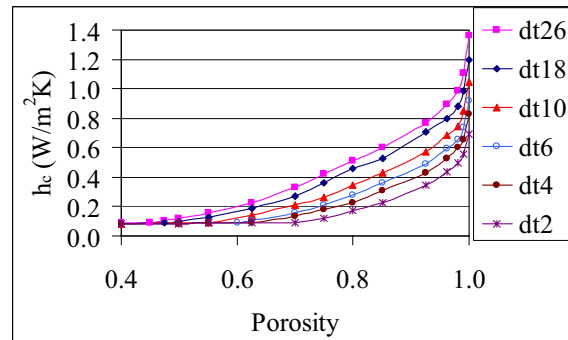


Figure 9: Effect of temperature difference on the cavity convective heat transfer coefficient (where e.g. dt10 stands for $dt = 10$ K)

The cavity convective heat transfer coefficient can roughly be represented by the following expressions:

$$h_c = 0.09 \quad \text{for } \gamma \leq 0.8/dt^{0.18} \quad (5a)$$

$$h_c = (1.26 \gamma - 0.8(dt)^{0.3})^2 \quad \text{for } 0.8/dt^{0.18} < \gamma \leq 0.96 \text{ and } dt \geq 4 \text{ K} \quad (5b)$$

3.6 Effect of Cavity Structure

The thermal buoyancy is influenced by the configuration of the cavity structure as well as the temperature difference. Fig. 10 shows the heat transfer coefficient for the two cavities of 0.3 m wide and at an indoor-outdoor air temperature difference of 18°C. The predicted cavity convective heat transfer coefficient for the pitched roof structure was found to be generally higher than that for the semicircular structure when the cavities were partially filled with bubbles. The difference in the coefficient increased with porosity reaching a peak of 25% at a porosity of 0.625 (5/8 filled cavities) and then decreased with increasing porosity. Thus, when the cavities were $\frac{3}{4}$ or $\frac{1}{2}$ filled with bubbles, the coefficient for the pitched roof structure was about 20% higher than that for the semicircular arc. However, the difference was negligible when the cavities were completely filled with bubbles because conduction became the only means of heat transfer through the two cavities of the same width.

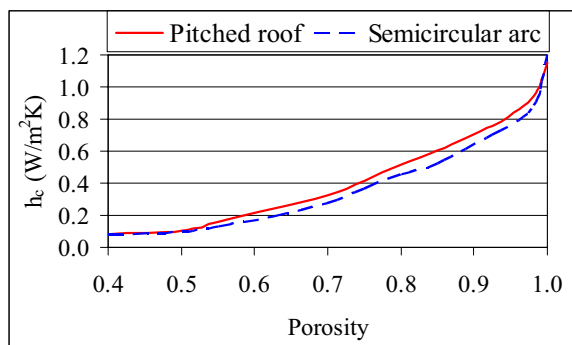


Figure 10: Comparison of the cavity convective heat transfer coefficient for two types of structure

3.7 Effect of Envelope Type on the Indoor Environment

The predicted cavity heat transfer coefficient was used to calculate the equivalent thermal conductivity for the cavity taken as a solid envelope. The equivalent thermal conductivity of the transparent envelope was then used to investigate the influence of external environment on the internal environment

under the structures. Figures 11 and 12 show the simulated indoor environment of the semicircular tunnel greenhouse of 3 m in radius under the 30 cm wide cavity (equivalent thermal conductivity $k = 0.0252 \text{ W/m}^2\text{K}$) with the floor at 18°C and with the wind at 0°C and 3 m/s flowing across the cavity. The temperature variation in the bubble cavity as a solid envelope between the indoor and outdoor environments (Fig. 12) was similar to that of the bubble cavity alone (Fig. 3) because of its excellent insulation. The indoor air circulated clockwise but very slowly with the maximum velocity less than 0.2 m/s (Fig. 11) due to negligible thermal buoyancy. The indoor environment under the bubble cavity was almost uniform (Fig. 12) and the mean temperature of 16.5°C was not far from the floor temperature. The computed heat requirement to maintain the indoor temperature would be about $2.1 \text{ W/(m}^2 \text{ of floor area)}$.

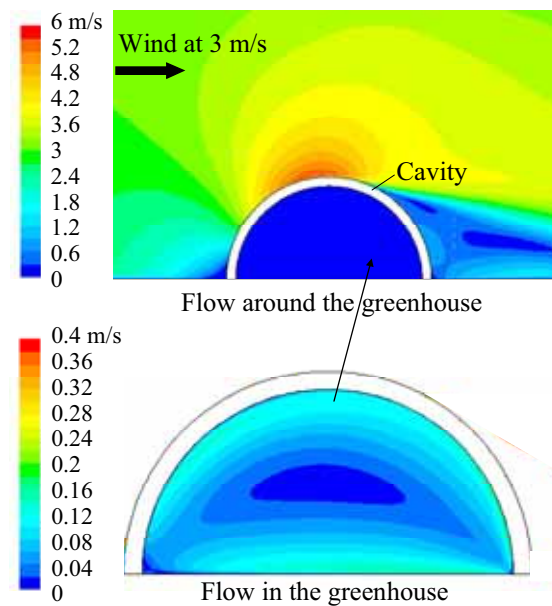


Figure 11: Velocity contours in and around the greenhouse with bubble-filled cavity

By contrast, when a 4 mm single glazing ($k=1.05 \text{ W/m}^2\text{K}$) was used, due to increased heat loss through the envelope, the indoor air movement increased with the maximum air velocity doubled to about 0.4 m/s. The

indoor air temperature was rather non-uniform. The air temperature near the floor varied from 8 to 11°C from the left to right due to the cold air flowing downwards along the left side of the glazing and warm air rising on the right side. The mean indoor temperature decreased to 8.8°C while the heat requirement from the floor increased to 23 W/m². To achieve the same temperature as that provided with the bubble cavity, the heat supply would have to be increased to 50 W/m². At this heat supply rate, the mean floor temperature reached 32.4°C and the variation of air temperature near the floor from the left to right would be from 15 to 20°C.

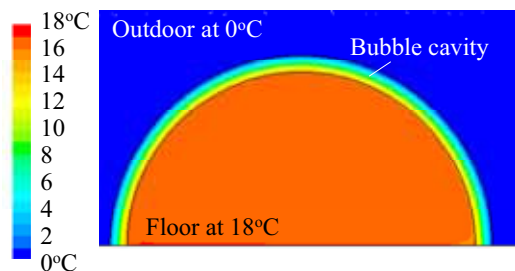


Figure 12: Temperature contours in and around the greenhouse with bubble cavity

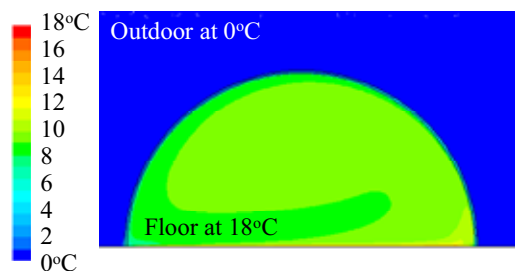


Figure 13: Temperature contours in the single-glazed greenhouse

4. CONCLUSIONS

CFD has been used to predict the thermal performance of transparent bubble structures. The effects of bubble diameter, density and distribution as well as cavity width on the insulation level have been determined numerically. It has been found that the cavity convective heat transfer

coefficient of a bubble structure increases with bubble diameter and porosity but decreases with the increase in cavity width and bubble filling depth. The cavity convective heat transfer coefficient also increases with the temperature difference between indoors and outdoors. The cavity convective heat transfer coefficient for a pitched roof structure is higher than that for a semicircular structure when the cavities are not fully filled with bubbles. Bubbles can provide excellent thermal insulation for buildings with transparent envelopes in terms of reduced heating demand and increased indoor temperature in winter, and likewise reduced summer cooling requirement, compared with conventional glazing.

ACKNOWLEDGEMENT

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