441. Applied design of an energy-efficient multi-layered membrane roofing system for climate-control of semi-permanent shelters

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Within the research group of Product Development a low cost semi-permanent building system is developed with passive climate control for dairy cattle. The system proved to be successful and two new applications were found for the system; 1) an emergency community shelter and 2) a pig breading stable.

Both new applications require a stable and comfortable indoor climate. To achieve such a indoor climate, a thermally active roofing system is developed to active acclimatize the inside conditions.

Keywords: membrane roofing, climate-control, energy efficiency, semi-permanent shelter, comfort

1. Introduction

Within the Department of Architecture of the Eindhoven University of Technology, a low cost arched construction has been developed in order to function as a stable for dairy cattle. This so called *arched stable* was created by ir. Roel Gijsbers within the SlimBouwen® approach and enthusiastically introduced as a pilot in October of 2006 in Dieteren in The Netherlands [1,2]. It proved that a rather slim and low cost construction, covered with a double layered membrane can be installed within a relative short period and is able to offer the cattle a high level of comfort. The building is developed to deliver a stable indoor climate of 0 to 20°C, which is the thermo-neutral zone of dairy cattle.

Fig 1. Pilot project arched stable for dairy cattle in Dieteren (The Netherlands)

The basis of the modular structural system exists of steel truss elements with a triangular cross section which can be assembled to an arch which has a free span of 30 to 50 meters. The building height can be chosen from 6 to 12 meters, depending on the size of the span. The length can vary from 20 meters to any desired size by adding more arched segments to the construction. The foundation of the arcs is created by two relatively small reinforced concrete beams which are as long as the total length of the building. Shores in between the arcs provide cross directional stability.

In between two adjacent arcs, a double layered membrane is placed as roof covering and to create a natural ventilation system which can be regulated depending on the amount of ventilation needed.

Fig 2. Detail of the roof, the truss structure and the upper and lower foil

The arched stable produced new and valuable information on large span arched structures, availability and usage of different membranes, ventilation within a double layered skin and a general impression of the atmosphere within a membrane covered space. The system has been monitored for a year and it proved to be technically and financially feasible [7], therefore it was chosen to be translated for the use for other purposes.

Benefits of the arched stable compared to a ordinary stable for dairy cattle:

- 30% cheaper
- 50% less weight
- less material
- shorter building period
- sectional
- flexibility on product and building level
- better indoor climate because of:
    - more daylight
    - more stable and comfortable indoor climate

Most functions, for humans as well as for animal housing like pigs, demand a higher thermal comfort then dairy cattle. To make the arched shelter suitable for these functions, which are demanding high indoor comfort, the membrane roofing system has to be further developed into a system for active climate control. A newly introduced goal for this development, other than the passive climate control, is energy efficiency. Consequently, the building has to be conditioned with a minimum of building services.

2. Case studies

Two case studies are introduced to set the boundary conditions for the development of the active climate control of a multilayered, energy efficient membrane roofing system. Both cases are from sectors in need of building solutions which are zero energy, durable, flexible, low cost and thermally conditioned.

2.1 Emergency community shelter

The first case [6] is a community shelter for emergency situations. Tents and other forms of easy-to-install lodging are often used in the case of direct aid and relief after calamities and wars. In an emergency situation there is a limited amount of energy available for conditioning of the building. Therefore, the building climate has to be controlled without the input of energy [3,9]. The community shelter is a newly introduced concept and is developed in association with a humanitarian organization.

The reliability of the system is one of the most important properties by developing of a shelter.

The system must be 100% proof and able to be easily assembled by refugees. The system must be transportable within a sea container and when needed transferred to smaller trucks or pickups. The shelter has to resist a wind load up to 120km/h. The shelter must be able to provide adequate indoor climate at extreme outside conditions (-10 °C)

2.2 Pig breeding stable

The second case is for agricultural purpose in the Netherlands. In this case a pigsty should be build with the use of the arched building system. The energy and indoor climate demands for piglets are high because of growth rates. A stable climate of approximately 20°C has to be realized the whole year round, regardless of outside climate conditions [4, 8].

The pig breeding industry is a traditional industry which relies on existing and proven technology. Another important characteristics of the industry, is the high indoor heat generation by the metabolism of the animals, which leads to high indoor temperatures and a surplus of warmth. However, cooling concepts are rarely applied because of the high initial investment.

2.3 Case comparison

The internal climate conditions for both cases are, oddly enough, nearly alike. Both applications demand a stable indoor temperature of 20°C and a high level of indoor lighting (min. 200 lux) despite of varying outside conditions. The main difference between both applications is the ventilation rate. The ventilation rate inside the pigsty is substantially larger than the ventilation rate in case of human inhabitants because of air pollution, although both are high compared to normal dwellings (see Table 1).

Table 1: Comfort conditions for humans, pigs and cows

Condition	Humans	Pigs	Cattle
Comf. temp.	20°C	19-22°C	5 till 15°C
Ventilation min.	3,2m^3/h/m^2	8m^3/h/m^2	natural
Ventilation max.	35m^3/h/m^2	80m^3/h/m^2	natural
Air speed max.	0,2 m/s	0,2 m/s	0,25m/s
Humidity	40-60%	60-80%	60-80%

3. Climate control

To understand the development of this active climate control system the effect of the existing roof will be explained, followed by an insulated version and the heat recovery roof.

3.1 Existing roof

The double layered roof (see Fig. 3) consisted of an outer layer of 55% open windbreak mesh which breaks the wind, but more important it keeps a part of the sun radiation and heat out of the space below. When the sun heats the air underneath this mesh, it can get out because of the buoyancy induced flow (stack effect) and because of air movement by wind speeds of over 3 m/s.

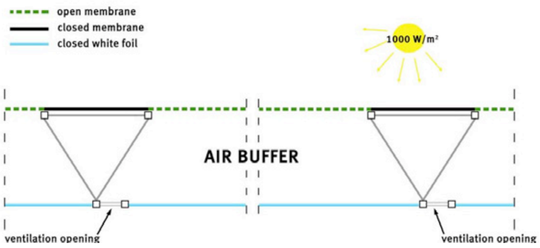

Fig 3. Detail of the roof, on top a windbreak mesh and below a semi transparent foil

An inner layer of a white foil keeps rain outside. Underneath the truss elements, which are closed on top, there are small open strips for ventilation purpose, which have the total length of the structural arc. These open strips are situated away from the dominant wind direction to prevent them from raining in. The white foil prevents direct sunlight from entering the indoor space and creates a diffuse and natural transmission of daylight. The result is a light intensity that is generally comparable to outside condition on a cloudy day all year round, which is an enormous improvement on indoor comfort compared to traditional cattle housing.

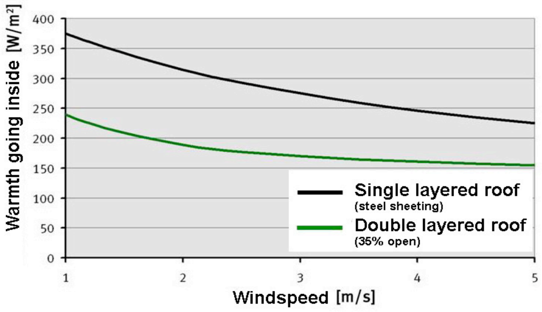

Fig 4. Radiation to the inside by 1000W/m2 sun load

In comparison with a normal single layered roof (for example sheets of corrugated iron, fibre-cement corrugated sheeting or a single layer of foil) with no insulation there's approximately 35% less radiation towards the inner space (see Fig. 4). The maximum temperature of the outer material is also less, 85°C by steel plating and 65°C by the windbreak mesh.

The walls of the construction are made out of the same material as the outer layer of the roof, the windbreak mesh. Therefore the inner space is ventilated and there's less wind inside.

3.2 Insulation roof

One of the advantages of the arched stable roof is the enormous amount of light that gets in and gives the inhabitants a day and night rhythm.

By adding normal insulation like glass wool to the lay up of the roof, the effect of light in the space is cancelled out. For some purposes that isn't a problem, in that situation a layer of aerogel can be added to the lay up. The insulation value of this aerogel is 3 times higher than normal insulation (λ=0,012W/mK), therefore the thickness of the construction can be reduced.

In situations where daylight is needed, for instance shelters, a layer or cushion of air can be added simply by tightening an extra layer of foil to the construction. Of course this extra foil needs to be airtightly applied, so the air in between stands still. Secondly it's important that the two foils are in the range of 20 to 60mm from each other to achieve the most optimal insulation effect.

3.3 Heat recovery roof

At places where there is a lack of energy or where the demands of the use of energy are set high like in the cases introduced before, heating up and ventilating big indoor spaces are the main problems. Accordingly, the roof can fulfil two functions in this case. The first is weather resistance as building envelope and the second one is integrated energy efficient climate control. Because a certain amount of ventilation is needed by emergency shelters and pig stables and this air must be fresh, the air has to come from outside. The outside temperature is most of the time below the inside temperature, so heating is necessary. Therefore the following concept has been developed.

3.3.1 The concept

The concept of the roof consists of combining the existing roof and a heat recovery unit. To make active climate control by the roofing system possible, the solution is sought in combining multiple layers of semi-transparent membranes.

To preserve the indoor climate multiply layers can be formed to cushions filled with standing air for insulation. Underneath of the insulation layers (Fig.5. (1)) heat recovery by large turbulent counter flows will provide an energy efficient pre-heating of indoor air.

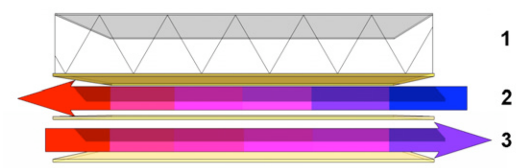

Fig 5. Concept lay up; insulation layer (1), outdoor air (2), indoor air (3) (windbreak mesh on top not displayed)

Extra layers, for instance made of foil, can be added to the roof so room for the airflows can be realised (Fig. 5. (2,3)). By using a small and energy efficient ventilator these flows can be put in motion.

3.3.2 Calculation

A physical modeling is set up from a wide angle perspective. The calculation model will be specified by using simplified cells (see Figure 6). In this calculation the influence of temperature, transition coefficient, air speed and specific measurements are used.

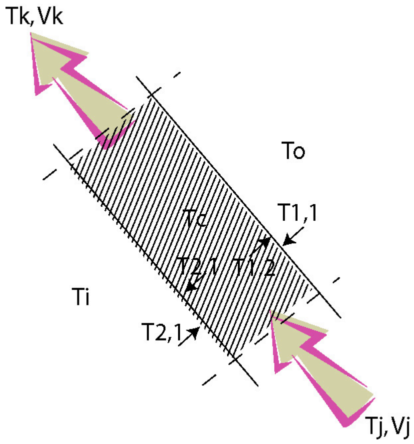

Fig 6. Calculation model with simplified cells

In this calculation, in contrast to a heat recovery unit, just one layer of flow and counter flow are calculated. In practice this is not a problem because the whole roof can be used, which provides enough surface area for the exchange of heat.
Calculations prove that the principle is efficient in consideration of the boundary conditions.

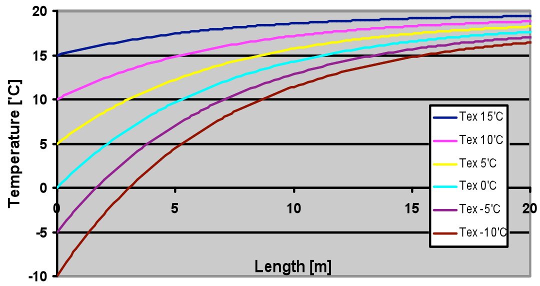

Fig 7. Calculation result by different outdoor temperatures

After finding the right basic measurements and needed values, the model gives information about usable materials and airspeeds that are feasible.

3.3.3 Materialization
After calculation, the earlier suggested use of foils as the channel walls seems to be a problem. The distance between the foils must be around 30mm to properly function, however when the air flows and creates under pressure in the channel, the foils will most likely collapse to each other. This problem can be solved by replacing the channels of foil by a triple wall semi transparent polycarbonate sheet with channels from around 26mm high.

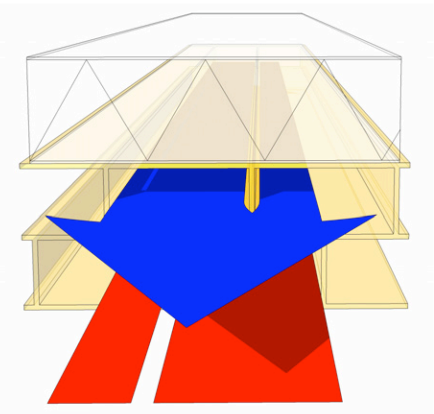

Fig 8. Final lay up of the heat recovery roof (windbreak mesh on top not displayed)

The daylight advantages as mentioned before can be maintained by the use of an insulation layer filled with air. In addition, the heat recovery sheets will be realized by the use of transparent polycarbonate sheets.

3.4 New developments: Low cost high volume heat recovery unit
When outside temperatures reach far below zero the heat recovery roof can not provide a comfortable indoor air temperature. Because of the high ventilation capacity (approx. 30.000m^3/h) needed in emergency shelters and big stables a special heat recovery unit is needed. Regular heat recovery units are made of aluminum and therefore very expensive. To solve this problem a low cost high volume heat recovery unit made out of foil is developed at the moment within the chair of Product Development.

4. Conclusion

Now that designing and calculation is finished, a pig breeding stable will be build in November, based on the arched stable with an insulated roof. This stable will again be monitored so in the future the total concept can be optimized and the calculation models can be refined.

On the moment a scale test of the emergency shelter is in preparation, after testing there are plans to start a pilot model for 1:1 model tests in association with an international aid organization.
Not only technical and financial aspects are reviewed, but also the logistic part will be considered.

The end conclusion is that these types of energy efficient buildings are good alternatives for a specific market segment (farmers and emergency relief) compared to traditional buildings, with regards to technical performance like climate control and flexibility, environmental aspects like energy use and pollution and financial aspects such as building costs and international competition. Hopefully these results urge other researchers and developers on to innovative thinking about buildings in relation to durability, weight and energy efficiency.

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