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THERMAL ANALYSES OF DANISH LOW ENERGY ROWHOUSES FOR IEA SHC TASK 13 "ADVANCED SOLAR LOW ENERGY BUILDINGS"

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1. INTRODUCTION

1.1 The Danish Goal

It is the main purpose of the Danish IEA Task 13 Low-Energy Research Programme to design, build and monitor dwellings with about 100-105 m² living area (which appears to be the size affordable to people in the 1990'ies) corresponding to about 125 m² built-up area, with as low a total energy consumption as possible, set as less than 6,000 kWh/a total. If this goal is to be reached, the space heating demand should be kept below 1500 kWh/a, which is about one seventh of the demand in a typical detached single family house. The analyses include a number of solutions that are not immediately feasible and cost-effective, but are likely to be so in the future, in accordance with international IEA Task 13 objectives. The results described in this paper are modelling results from a rowhouse concept, with main emphasis on window design.

1.2 How to Obtain the Desired Low Total Energy Demand

The only way to reach a very low total energy demand is through integrated design of the building envelope and the building service systems. The energy demand in the building may be more or less sensitive to the way it is used. The strategies pursued in the Danish project in order to obtain a robust advanced solar low-energy building can be summarized in the following seven bullets:

- Superinsulation (quantity and quality)
- Passive solar
- Active solar (primarily for hot water)
- Efficient heating system
- Heat recovery on ventilation
- Water saving devices, low-temperature systems
- Efficient use of electricity

The superinsulation strategy is very important, because Denmark (latitude 56°N, 1500 sunshine hours/a, 2900 degree days at a 17°C base) usually has very little sunshine in the winter, especially in the months November-January. Large insulation thicknesses, typically about 300 mm, are considered. However, it is even more important that the constructions designed contain practically no thermal bridges and are extremely airtight. Achieving a high utilization of direct solar gains is not only a question of house design (size, type and orientation of windows, accessable thermal mass), but also includes minimizing internal gains. The heating system must not compete with the utilization of solar gains, ie a fast responding system with low no-load losses and a high operating efficiency, also at part loads. As the gross ventilation heat losses equal the transmission losses, heat recovery is important, thus requiring some mechanical system.

An active solar system can be designed to meet 75-80% of the annual domestic hot water demand. The demand itself should be kept low through efficient use of water (application of water saving devices in taps, showerheads etc) and short supply lines without permanent circulation (a floor plan design problem). Consistent use of low consumption lighting, appliances, fans etc, as well as minimum operating time for equipment, ensures a low electricity consumption as well as low internal gains.

2. HOUSE DESIGNS

The result of these strategies was the design of two different superinsulated rowhouse types, one for east-west running rows and one for north-south running rows. The second type was designed as a deliberate attempt to meet the challenge of unfavourable building sites, not allowing for conventional desired south facing facades. This paper focusses on the first type. Both types are further described in [1], [2], and [3].

The two house types have been designed in collaboration between the architect, professor Boje Lundgaard (Royal Academy of Arts, the Danish School of Architecture) and the engineering team from the Thermal Insulation Laboratory (TIL). All thermal analyses have been performed at TIL. Throughout the design process, it has been a deliberate desire to express the energy consciousness in the architectural idiom of the buildings as well as to obtain good living qualities, eg daylighting conditions, in the limited space available. In this case, rowhouses have been designed - however, the design and construction principles are easily transferable to other building types, eg detached or semidetached single family houses or small apartment buildings.

2.1 Common features for the two house types

In principle, the same thermal envelope constructions, ventilation and heating system, combined active solar system (mainly for domestic hot water), water and electricity saving devices, lights and appliances are used in the two house types. The heating and ventilation systems are described in [3].

Both house types are built slab-on-ground, totally or partially in two storeys with the main rooms organized around a two-storey high family room. All rooms receive daylight, through skylights or normal windows - or a combination of the two.

For insulation of walls and roof, a high density mineral wool with a design thermal conductivity of 0.036 W/mK is used, giving the constructions a U-value of 0.11 W/m^{2}K. Under the floor slab, either the same product or a rigid expanded polystyrene with the same thermal conductivity is used. The traditional thermal bridge at the foundation is partially broken through use of lightweight concrete foundation blocks and parameter insulation separating the foundation and the slab. The constructions are briefly described in Figure 1.

2.2 House Type A - South facing rowhouse

The dwellings in this type are in two storeys, with a total area of 106 m^2 and a heated volume of 252 m^3. In the base case, the window area is 23 m^2 (13.5 m^2 south facing, and 5.5 m^2 in skylights) equal to 22% of the floor area. The slight curvature of the lopsided roof with the one-sided slope creates a special cave-like quality in the inner rooms. All primary rooms are south facing. The back rooms on the top floor get sunlight through raised skylights. The vertical south side of the skylight construction gives room for an array of solar collectors.

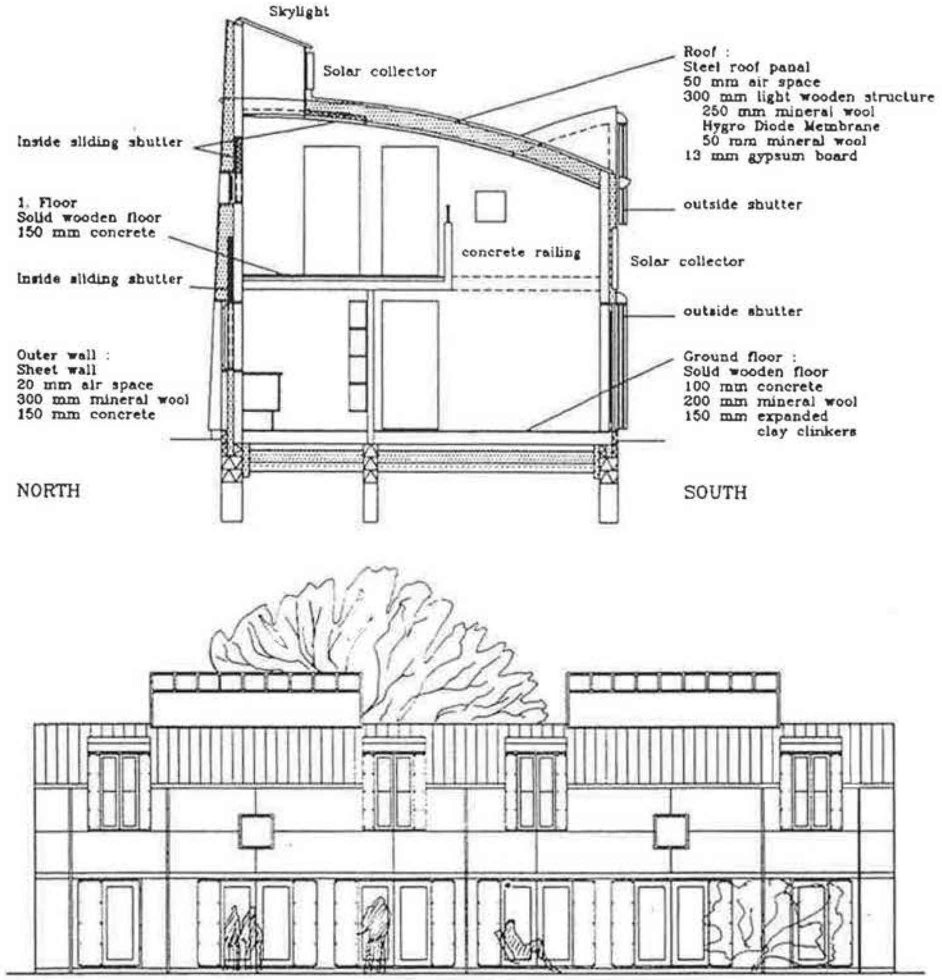

Figure 1. Section and south elevation of House type A (version with shutters). The elevation shows 2 dwellings of a longer row.

3. PARAMETRIC STUDIES ON THE HOUSE DESIGNS

The Danish multizone building energy simulation program TSBI3, [4], has been used for the calculations of the heating load. The calculations have generally been performed using standard procedure input, eg transmission heat loss coefficients based on one-dimensional heat flow, design material values and internal measurements according to the Danish Standard. Later on, corrections for two- and three-dimensional heat flow have been introduced as described in section 3.2.

3.1 Base Assumptions Made for the Calculations

The Danish Test Reference Year (TRY) has been used as weather data. The house is divided into three zones. All thermostats are considered ideal and set at 20°C. The heating system is turned off in the night (from 22 to 05). The controlled air change is constant, at 0.5 ach with a heat recovery efficiency of 60%. Airing (3 ach) is presupposed, if the zone temperature rises above 23°C. The internal gains are set as a pattern for a family of four (2 adults and 2 children) - the gains are 2849 kWh/a from the people and

1270 kWh/a from their use of electricity. The results shown are valid for a unit with a neighbour unit on each side. Only the heating season (Oct-Apr incl) is considered.

3.2 Corrections for Two- or Three-dimensional Heat Flow

Three types of corrections have been made to the standard procedure input to TSBI3: corrections for a) the heat flows at corners, and especially at the dormers and raised skylights, b) the heat flow at the foundation (a 2D case), and c) the heat flow at door and window openings.

a) The corrections have been made using conductive shape factors, [5], which for well insulated constructions without thermal bridges give satisfactory results. One case has been checked by comparison with results from 2D computer calculations - the corrections were identical. The total correction is 1.0 W/K.

b) The corrections have been calculated based on steady state 2D computer calculations. Though the foundation must be described as well insulated, the correction is 3.5 W/K.

c) The corrections come directly into TSBI3 as new and more correct U-values for glazing and frame, from calculations with the 2D computer analysis program FRAME, [6]. In the base case (section 3.3) the corrections amount to about 3.4 W/K. As shown in Figure 2, the aluminium spacer and the presence of a number of small windows contribute heavily; the 1D total U-value is 0.8 W/m^2K. If the aluminium spacers are replaced by Superspacers, the correction is reduced to 0.4 W/K.

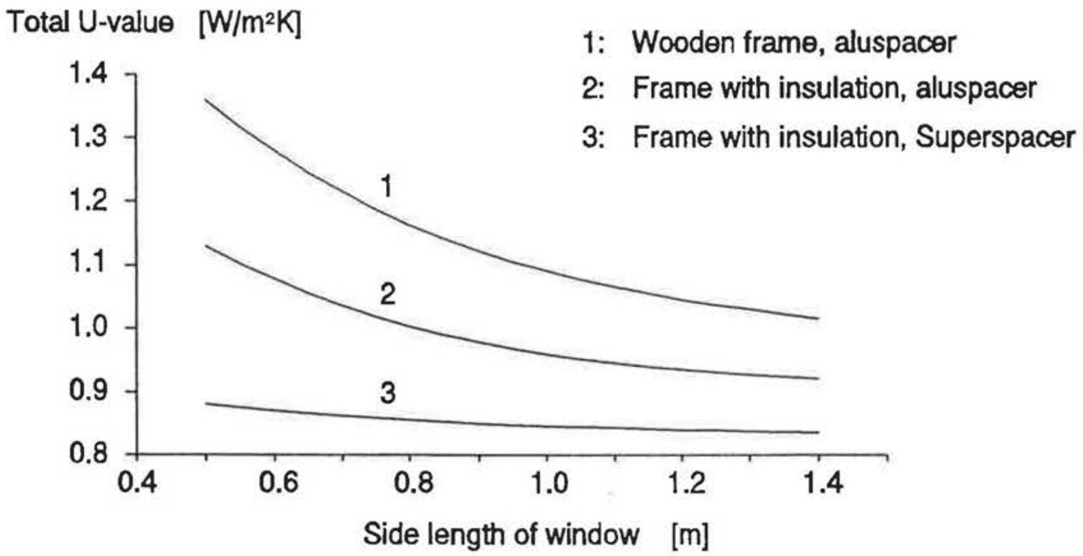

Figure 2. Total U-value as a function of window size and frame. Centre U-value of glazing = 0.8 W/m^2K, U-value of wooden frame = 1.6 W/m^2K, U-value of the insulating frame = 0.8 W/m^2K, frame width = 98 mm.

At the moment a centre U-value of the glazing of 0.8 W/m^2K can be achieved in a triple glazed unit with 2 lowE coatings and Argon filling. The total solar transmittance is 0.5, which should be compared with the transmittance of 0.7 of a triple glazed unit without coatings. Due to the aluminium spacer along the perimeter of the sealed units, the overall U-value for the glazing of a 1 m^2 unit with centre value 0.8 becomes 1.0 W/m^2K. If the above described glazing is put into an ordinary wooden frame the total U-value of a 1.2 · 1.2 m^2 window will be approx 1.2-1.3 W/m^2K which compared to the glazing itself (including the spacer) is an increase of 20-30%. The promising low U-value at the centre of the glazing does not reflect in the total U-value of the window due to thermal bridges in spacer and frame, which furthermore form a relatively large part of the window area. As seen in figure 2 the effect of using an insulated frame construction with a U-value comparable to the centre U-value of the glazing, [7], leads to a strong reduction in the total U-value, especially in case of small windows.

3.3 Case Description

The base low-energy case is a superinsulated house that may be built from materials and components that are on the market today, if not necessarily in serial production. It has 300 mm insulation in walls and roof, and triple glazed windows with aluminium spacers, two low-emissivity coatings and Argon filling. Insulating frames as described in [7] are used. The building geometry, transmission areas including glazed areas, etc, are as described in section 2. For comparison, the same buildings insulated at the present Building Code level are included. The different window cases are listed below.

Case 0	Houses insulated according to the current Building Code
Case 1	***Base low-energy case, houses insulated with 300 mm mineral wool, triple glazed lowE-coated windows with aluminium spacers and insulated frames, etc***
Case 2	As Case 1, with Superspacer replacing the alu-spacer (ie also a "base case")
Case 3	As Case 1, with normal double glazed windows in wooden frames, and insulating shutters (R-value 1.69 m^2K/W)
Case 4	As Case 2, but with insulating shutters (R-value 1.69 m^2K/W)
Case 5	As Case 1, with double glazed lowE-coated windows, aluminium spacers and insulated frames
Case 6	As Case 1, with evacuated windows
Case 7	As Case 2, with aerogel windows in skylights (triple glazed windows everywhere else)
Case 8	As Case 1, with aerogel windows instead of triple glazed

Some experimental glazing types from recent Danish research projects have been included in the analyses. The (double glazed) evacuated windows have a centre U-value of 0.67 W/m^2K and a total solar transmittance of 0.65 (1 coated surface, air space evacuated, pane distance only 0.5 mm, and a fairly severe thermal bridge of glass at the edge seal - special frame required). So far, only small prototypes (laboratory samples) have been produced. The partially evacuated (~80-100 mb) aerogel windows (double glazed) have a centre U-value of 0.50 W/m^2K and a total solar transmittance of 0.75 (space between panes filled with 20 mm monolithic silica aerogel [Airglass], special stainless steel spacer and seal). Monolithic silica aerogel is a SiO_2 product with many even-sized small air-filled pores (typical pore size 10-20 · 10^{-9} m, typical grain size 4-7 · 10^{-9} m), typical density 70-250 kg/m^3 and thermal conductivity 0.021 W/mK (0.008 W/mK if evacuated) manufactured in 0.6 · 0.6 m^2 tiles, [8]. Full size window prototypes have been produced, but at the present stage aerogel is not completely transparent - thus one set of calculations for this project suggests use of these windows for skylights and elevated ribbon windows where the view is not an issue.

For Cases 1, 2 and 8, additional simulation runs were made without solar gains, and without any gains at all, to quantify the free heat contribution. Also, parametric studies of insulation thickness in walls and roof were made on the base cases (1 and 2), using from 200 to 450 mm of insulation (based on the 1Dcalculation as well as the 2D-corrections). Finally, parametric studies on glazed area were performed on the house. To see the effect of changing an east/west facing window area the whole row was turned 90° (turning the south facade to the west). Three window types were selected for these simulations: Double glazed with 1 lowE coating and Argon filling, triple glazed with 2 lowE coatings and Argon filling, and aerogel windows (cases 2, 5 and 8).

3.4 Results from the Simulations

Table 1 shows examples of calculated useful gains in the houses, and Table 2 shows the annual net heat demands for the 9 cases listed above, with and without corrections for two-dimensional heat flows.

Table 1. List of results from simulation runs (TSBI3 calculations) - the brackets around some figures only indicate that the 1D-calculation does not take the superspacer into account.

Case no.	Annual heat demand, based on 1D-calculation (kWh/a)	Annual heat demand, with 2D-corrections (kWh/a)
0	7240	-
1	1060	1550
2	(1060)	1380
3	1940	2290
4	(790)	1080
5	1480	1750
6	730	1100
7	(880)	1180
8	520	770

Table 2. Heating loads for the Cases 2 and 8 (Base low-energy case with triple glazed coated windows, and the same buildings with aerogel windows) calculated as before, then without any internal or solar gains, and just without solar gains, showing the useful gains that meet a substantial part of the gross heating load.

Case no.	Gross heating load, no gains (kWh/a)	Heating load, no solar gains (kWh/a)	Net heating load (kWh/a)	Useful internal gains (kWh/a)	Useful solar gains (kWh/a)
2	5190	2750	1380	2440	1370
8	4810	2380	770	2430	1610

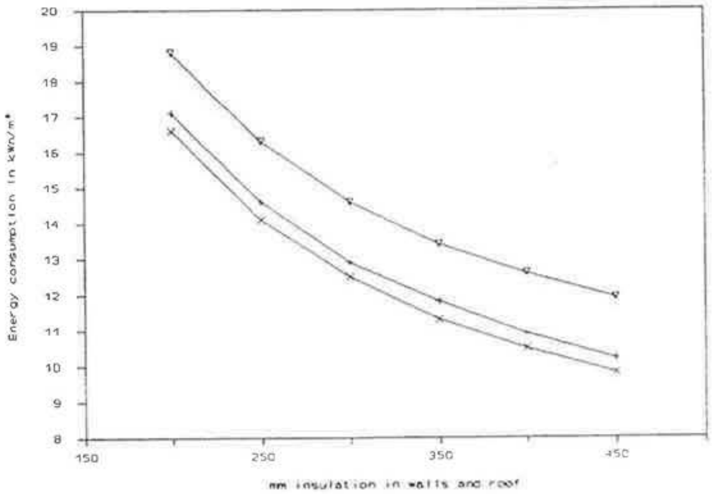

Figure 3. Heating load per m² floor area, House type A calculated at 6 different insulation levels. Triple lowE windows are used: × represents 1D calculations with 2D corrections for corners etc and foundation (section 3.2 a and b), + represents additional 2D-corrections for doors and windows with Superspacer, as in Case no. 2, ▿ similarly windows with aluminium spacers, as in Case no. 1. Case 1 and 2 appear in the diagram at × = 300 mm.

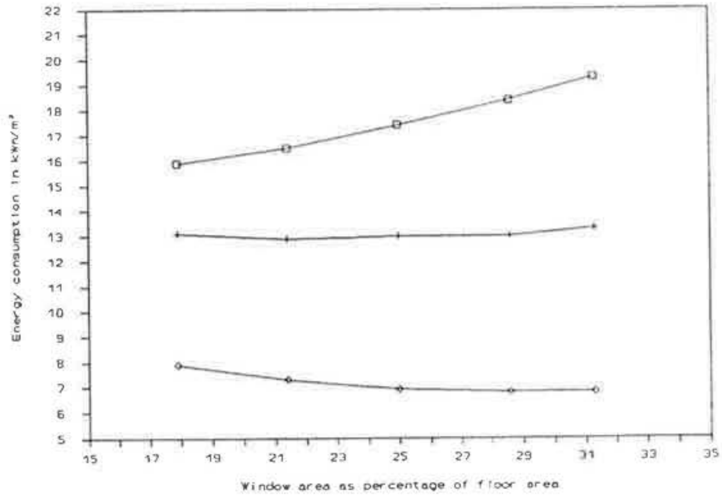

Figure 4. Heating load per m² floor area, House type A, calculated at five different south facing window areas, for three window types (□ Double glazed, 1 lowE coating, + Triple glazed, 2 lowE coatings, ◇ Aerogel windows). The relative total window area 22% has been used in the general calculations (Cases 2, 5 and 8 appearing in this diagram).

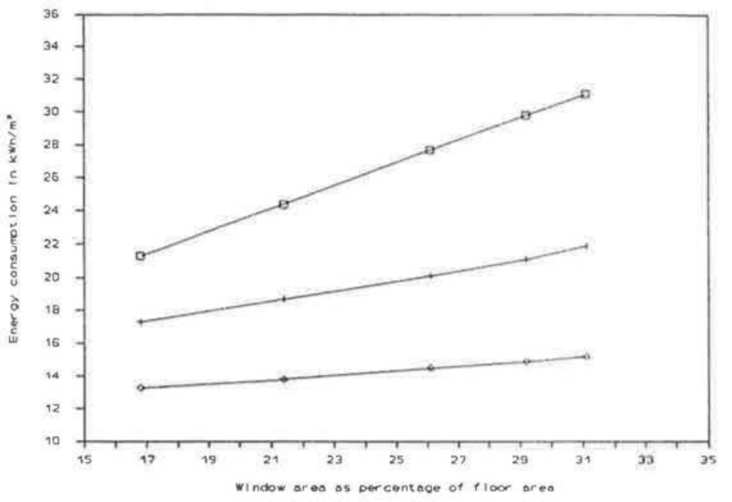

Figure 5. Heating load per m^2 floor area, House type A turned to the west, calculated at five different east/west facing window areas, for three window types (□ Double glazed, 1 lowE coating, + Triple glazed, 2 lowE coatings, ◇ Aerogel windows).

4. DISCUSSION OF AND CONCLUSIONS FROM THE RESULTS

Table 1 shows that about 70% of the gross heating load in the base low-energy cases is met by free heat, a fraction that goes up to about 80% when aerogel windows are used. The internal gains are almost 100% utilized, leaving a direct gain solar contribution of about the same size as the net heating load or larger. The solar gains are higher for the cases with aerogel windows because of the higher solar transmittance of the glazing.

Table 2 shows clearly that two- and three-dimensional heat flows have a significant impact on the predicted annual heating demands, and that they must be taken into consideration in the simulations. When the net heat load is so low, it is sensitive even to relatively small changes in the heat loss factors. The largest impacts, 40-50%, occur when the major part of available free heat has been utilized, eg in the base low-energy case. Even so, it has been possible to design passive solar low-energy buildings with extremely low heating demands.

A comparison of Case 1 or 2, respectively 5, and Case 3 shows that insulating shutters on normal double glazed units cannot compeat with windows with lowE glazing. The same shutters used on the triple glazed windows can save an additional 300-340 kWh/a, with the drawbacks: cost, maintenance, and daily operation. The main advantage of shutters is the low peak load obtained, and the good thermal comfort conditions under windy peak load conditions.

Table 2 clearly shows the major role of the windows, and implies the possibilities of the new window types under development. Table 2 and Figure 2 both show that the use of aluminium spacers in low-energy windows causes a significant thermal bridge and should be avoided.

Figure 3 indicates that further savings through improvement of the opaque part of the thermal envelope are possible. The decision on increased insulation thickness must be based on economic evaluation, possible problems with construction details, and perhaps a wanted maximum total wall thickness.

Figure 4 and 5 first of all again show the important savings obtainable through use of efficient windows. With aerogel windows, and to a certain degree with the triple glazed units in insulated frames, an increase in south facing window area gives a lower heating demand. However, an increase in east/west facing window area is an energy user even with high performance glazing, except for aerogel windows, for which a change in area hardly affects the heating demand.

It should be emphasized that the number of windows has been changed, not the size of the single window units. As shown in Figure 2, the total U-value is strongly dependent on the window size, unless an insulating spacer as well as an insulating frame is used. Even with a Superspacer, the energy performance of very small window units is poor, mainly because of the small relative glazing area, giving only small solar gains.

It is obvious from Figure 2 and the simulation results that a 2D-analysis of the windows is essential, and that it is important to use insulated frames as well as high performance glazings.

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