THERMAL DESIGN OF HIGHLY INSULATED INVERTED ROOFS

ANKER F. NIELSEN and EINAR M. PAULSEN
Norwegian Building Research Institute (NBI)
Trondheim, Norway

Inverted roofs have been used in Norway for many years in the form of turf on top of birch-bark on pitched roofs. Today this system is still in use but with an improved membrane and often with additional insulation underneath.

In flat roof construction the inverted roof system has had limited use in Norway so far, mainly because of the demand for thick insulation and the lack of reliable methods of thermal design. For insulation thicknesses of 100 to 200mm very little information existed about the thermal performance of inverted roofs.

Therefore a project was started within the framework of the Norwegian Roofing Research Group (TPF) and in cooperation with the Norwegian Building Research Institute (NBI) which carried out the investigation.

The work consisted of laboratory and field testing of insulation materials. Moisture pick up and heat flux measurements were made on inverted roof sections built on an NBI test house and on field surveys of existing roofs.

LABORATORY MEASUREMENTS

All insulation materials used in the test house were measured with respect to thermal conductivity (l_{10}) in a dry condition. Thermal conductivity for foamed plastic material with various degrees of moisture content, needed for design calculations, was worked out on the basis of information from the literature.

Water pick up in foamed plastic materials was determined by placing the insulation boards over water at 323K (50C) with a metal plate on the upper side. The metal plate was kept at a temperature of 275K (2C). The temperature gradient and high humidity on the warm side drives moisture through the material which condenses within the insulation on the cold side. Moisture pick up is determined by weighing the sample every week, and then turning the test sample upside down. Total testing time was 4 weeks. Moisture pick up varied from about 1 percent by volume for extruded polystyrene (EXPS) and 10 percent by volume for expanded polystyrene (EPS). The test was continued with the same samples for 300 freeze/thaw cycling test from 293K (20C) in water to 253K (−20C) in air with the sample resting one hour at each position. The total accumulated moisture was used to classify the material in three categories: low, medium or high moisture pick up.

TEST HOUSE

Eleven different inverted roof sections of 1.8×5m were built on the NBI test house at Tyholt, Trondheim in 1980. One half of each section was horizontal. The other had a slope of 1 in 60. The load bearing construction of the test house roof was 10cm thick concrete plate. The membrane and insulation were installed directly on top of the concrete deck.

Among the roof sections these are of special interest:

1. Ordinary warm roof with exposed membrane and 10cm EPS insulation of density $30kg/m^3$
2. 10cm EPS with gravel ballast
3. 10cm EXPS with gravel ballast
4. 2 layers of 10cm EXPS with gravel ballast
5. 10 cm EXPS with 5 cm in situ poured concrete
6. 10 cm rockwool TP 200 with asphalt felt on lower side and without ballast, exposing the insulation
7. 10 cm EXPS above and 5cm EXPS below the membrane with gravel ballast.

All foamed insulation boards had ship-lap formed edges.

Temperature and heat flux measurements were carried out from September 1981 to December 1982. Two heat flux meters were fixed under the concrete deck, in each section, one in the horizontal part and the other in the sloped part. Temperatures were measured using copper-constantin thermocouples placed as follows:

1. Between the heat flux meter and the concrete deck
2. On top of the concrete under the membrane in the middle of an insulation board (T_C)
3. In the middle of a joint between two insulation boards (T_J)
4. Under the ballast on top of an insulation board (T_G).

Additional thermocouples were used when the insulation was placed in two layers.

During the test, measurement values were recorded every hour using a datalogger. The results of these measurements have been used to determine correction factors for the inverted roof. Recordings of heat flux and temperature have been drawn up for periods of special interest and studied in detail.

Before the thermal measurements started the insulation was controlled for moisture content by weighing of complete boards and drilling out cylindrical cores. This provided information about the moisture distribution.

The control of moisture was repeated one year later at the end of the period of heat flux measurements. The results, given in Reference 2 show a general increase in moisture content. It varies, however, with the type of insulation from 0-1.5 volume percent for EXPS to 2-6 volume percent for EPS. For EXPS the highest value was found under the in situ poured concrete where the drying-out conditions are less favorable than with gravel ballast. In the exposed rockwool the moisture content changes rapidly depending on precipitation. After a period of rain it was found to be in the region of 4-6 percent by volume. The moisture content mentioned above was found after only two years in service. Basically the figures are of interest in order to compare the heat flux found by measurement with the calculated values. The potential moisture pick up during the expected lifetime of the construction must be evaluated on the basis of field experience and laboratory testing.

FIELD SURVEY

Six buildings with inverted roofs from different parts of Norway were investigated. In addition to a general survey of the construction, cores were cut out of the insulation to determine the moisture pick up. The results show that a major difference in moisture content was found between EXPS and EPS. But the drying-out conditions of the roof had a marked influence on the values for the two groups of material.

With excellent drying-out conditions, clean gravel, pitch, no shades and one layer insulation, the moisture content of EPS was found to be 12-15 percent by volume. For less favorable conditions with moss-growth in the gravel, the moisture content was found to be 30 percent by volume.

For EXPS the figures were much lower but clearly dependent on the drying-out conditions in the following way:

- 1 percent by volume for ordinary gravel ballasted roof with insulation in one layer
- 3 percent by volume for insulation in two layers or under poorly ventilated concrete pavers
- 5 percent by volume under in situ cast concrete on fine grained gravel or if the roof was in permanent shadow from sun
- 8 percent by volume if a vaportight layer was on top of the insulation, such as in situ cast concrete, pavers in fine grained sand or under roof gardens.

TEMPERATURE MEASUREMENTS ON TEST ROOF SECTIONS

Temperature recordings provide an opportunity to study the influence of joints on the overall thermal performance. This can be expressed as a relative joint temperature (RJT) defined by the formula:

$$\mathrm{RJT} = \frac{T_J - T_G}{T_C - T_G}$$

where

T_J = temperature in the joint at the lower side of insulation

T_G = temperature on top of the insulation board

T_C = temperature under the center of insulation board

If RJT equals one there is equal temperature under the board and in the joint. If RJT is less than one the temperature in the joint is lower than under the center of the board, causing higher heat loss at the joint region. The opposite is true if RJT is greater than one. This can happen if the outdoor temperature is higher than the indoor temperature. The RJT model can be used on all roof sections, inverted as well as ordinary with exposed membrane.

A computation of RJT for various outdoor temperatures shows a marked difference between periods below and above the freezing point.

Figure 1 shows RJT for the time of the year when the outdoor temperatures are below 0C. The horizontal axis gives the relative joint temperature while the vertical axis is the probability for a larger temperature difference plotted on a probability scale. A straight line in the diagram represents the normal distribution. In practice this is not quite true especially with low relative joint temperatures. For most test roof sections the curve is very close to that for the reference section. This means that there is practically no difference in thermal performance between an inverted and conventional roof when the outside temperature is below 0C. Only the section with rockwool shows a marked deviation probably caused by water pick up in the insulation from melt water.

Figure 2 shows RJT for the part of the year when the outdoor temperature is above 0C. The axis and scale are the same as in Figure 1. This time, however, there is a marked difference between the inverted roof and the conventional roof. The relative joint temperature is greater than 0.96 for 10 percent of the time in the ordinary roof, while in the inverted roof it is 0.88 – 0.93 for 10 percent of the time.

These deviations correspond to periods with precipitation where the rainwater flows into the joints, giving the effect of partial cooling. The curves in the diagram depend on variations in climate. With more precipitation there is an increased probability for deviation, and the curves will move towards the left in the diagram. Nevertheless, for about 75 percent of the time the inverted roof will behave like an ordinary roof with respect to thermal performance.

The main conclusion is that the most common thermal design of inverted roof is not correct, primarily because an inverted roof behaves like an ordinary roof during the coldest periods.

When designing the heating system, the inverted roof can be treated like a conventional roof. The thermal conductivity of the insulation, however, must be corrected for moisture content depending on type and drying-out conditions. On the other hand, the energy consumption will be affected by precipitation and the joints.

ENERGY k-VALUE

The energy k-value has been found for the different roof sections from test measurements. In addition, the k-value has been calculated on the basis of measured thermal conductivity and moisture content. Figure 3 shows these two k-values.

For a conventional roof there should be no difference between the two k-values. This is true for the reference section as well as for the inverted roof with in situ cast concrete on top. For the rest of the inverted roof the measured k-value is higher than the calculated. This indicates that the heat loss in an inverted roof is higher than in the ordinary roof. The measured differences can be used to find a Dk value which must be added in the thermal design of inverted roofs. The amount added depends on whether the inverted roof insulation has one or two layers and what portion of the total insulation is placed under the membrane. The recommended figures for Dk are given in Table 4.

THERMAL DESIGN

The basis for design of thermal insulation in Norway is given in Norwegian Standard (NS) 3031, but this has no reference to how the moisture pick up in insulation or the influence of the precipitation should be evaluated.

The drying-out condition of the insulation is important for the moisture content and therefore four categories have been defined in Table 1.

Based upon moisture accumulation during the 28-day test, plus 300 freeze/thaw cycles, the insulation is graded as:

- *Low* moisture pick up, 3 percent by volume maximum (EXPS)
- *Medium* moisture pick up, 15 percent by volume maximum
- *High* moisture pick up, 30 percent by volume maximum (EPS 30kg/m^3)

The design moisture content for insulation with Low and High moisture pick up are found in Table 2.

The values for recommended design moisture content are based on the results from the field survey and supplemented from other investigations described in literature (4).

The thermal conductivity given in NS 3031 (3) is relevant only for dry materials. Table 3 gives the design thermal conductivity for the different levels of moisture content.

DESIGN OF HEATING SYSTEM

When designing the maximum heat demand for the building the heat resistance of the inverted roof is the same as for a conventional roof. But the thermal conductivity of the insulation must be taken from Table 3 for the relevant drying-out condition found in Table 1.

DESIGN k-VALUE (ENERGY DEMAND)

When the design is based on total energy consumption, the added heat loss from moisture pick up in the insulation as well as precipitation must be accounted for. The design heat transmittance coefficient (**kd**) for the inverted roof is found by adding the resistances of the individual layers and surfaces and then adding a value for the effects of the joints as follows:

$$k_D = \frac{1}{M_t} + \Delta k_{joint}\ (W/m^2K)$$

where

k_D = design k-value

M_t = total heat resistance including surface resistances.

Δk_{joint} is dependent on the type of ballast and insulation configuration AS Table 4 clearly shows.

Thermal design of any inverted roof system can be done with the use of Tables 1 through 4 knowing the drying-out conditions and the insulation type and configuration. For Norwegian conditions recommended design and insulation thicknesses for inverted roofs can be found in Reference (1).

REFERENCES

[1] Paulsen, E.M., Torseter, M.: Inverted Roof Design. (In Norwegian) NBI Building Design Sheet A525.225 1984.

[2] Heiersted, R.S., Nielsen, A.F. Paulsen, E.M.: Inverted Roofs. (In Norwegian). Norwegian Building Research Institute. TPF report (07033) 1984.

[3] NS 3031. Energy and Power Demand for Heating of Buildings. Calculation Rules. (In Norwegian).

[4] Petersson, B.A.: The Upside-Down Roof. Field and Laboratory Studies of Thermal Insulation, Moisture Conditions and Performance. Chalmers University of Technology, Division of Building Technology, Publication 80:6, 1980.

Category	Ballast and insulation configuration in inverted roofs
I*	Max 50mm gravel free of fines and moss growth Max 100mm insulation in one layer Roof pitch ≥ 1:40 (no ponding water)
I	Gravel ballast Insulation in one layer
II	Concrete pavers on supports Insulation in two layers
III	Concrete (in situ or pavers) on minimum 50mm small grained gravel Max 10mm latex modified concrete on top of insulation Roof in permanent shadow
IV	Concrete (in situ or pavers) directly on insulation or in fine grained sand Roof gardens

Table 1 Drying out conditions for insulation

Drying-out conditions		Design moisture content
Category	Design	% vol.
I	Gravel Insulation in one layer	1
II	Pavers on supports Insulation in two layers	3
III	Concrete or pavers on gravel Max. 10mm LM concrete Permanent shadow	5
IV	Concrete or pavers directly on insulation or in sand Roof gardens	8

Table 2a Design moisture content for insulation with low moisture pick up capability

Drying-out conditions		Design moisture content
Category	Design	% vol.
I*	Gravel (no fines) Insulation in one layer Roof pitch ≥ 1:40	20

Table 2b Design moisture content for insulation with high moisture pick up capability

Type of insulation	Design thermal conductivity (λ_D) at design moisture content (W/mK)					
	0 % vol.	1 % vol.	3 % vol.	5 % vol.	8 % vol.	20 % vol.
EXPS	0.032	0.033	0.035	0.037	0.040	
EPS	0.040					0.060

Table 3 Design thermal conductivity of inverted roof insulation

Inverted roof insulation and ballast design	Δk - additional (W/m²K)
"Tight" ballast where the major part of the precipitation runs off at top (in situ concrete, roof gardens)	0.00
"Open" ballast (gravel, pavers etc.)	
a) Roofs with one layer of insulation over the membrane and the following portions of the thermal resistance under.	
0-40%	0.04
40-60%	0.02
>60%	0.00
b) Two equally thick layers above the membrane with individual thickness ≥50mm	0.03

Table 4 Additional transmittance (Δk) for inverted roofs

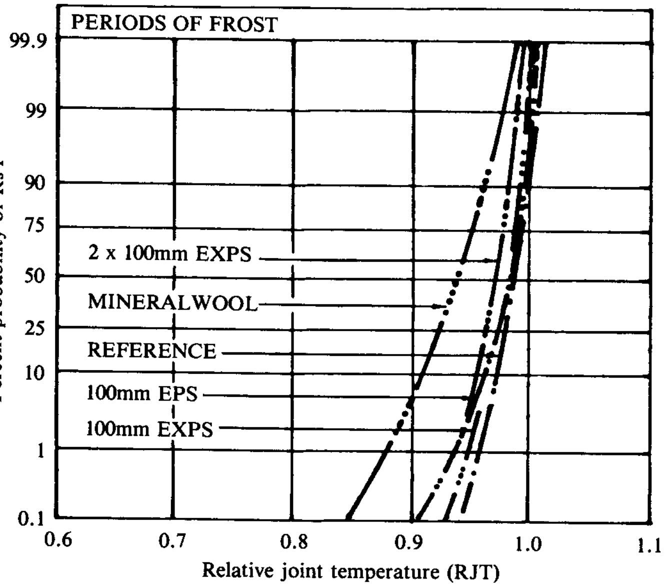

Figure 1 Probability for greater temperature difference RJT in joints relative to board center when outdoor temperature is below 0C. The probability refers to the time where the temperature deviation is at least as high as given by the curves.

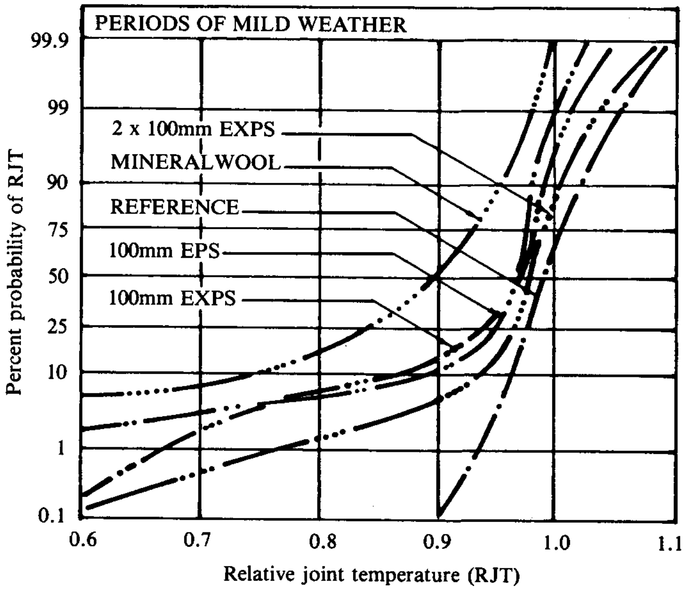

Figure 2 Probability for greater temperature difference RJT in joints relative to board center when outdoor temperature is higher than 0C. The time of the year used includes periods with precipitation and melting snow.

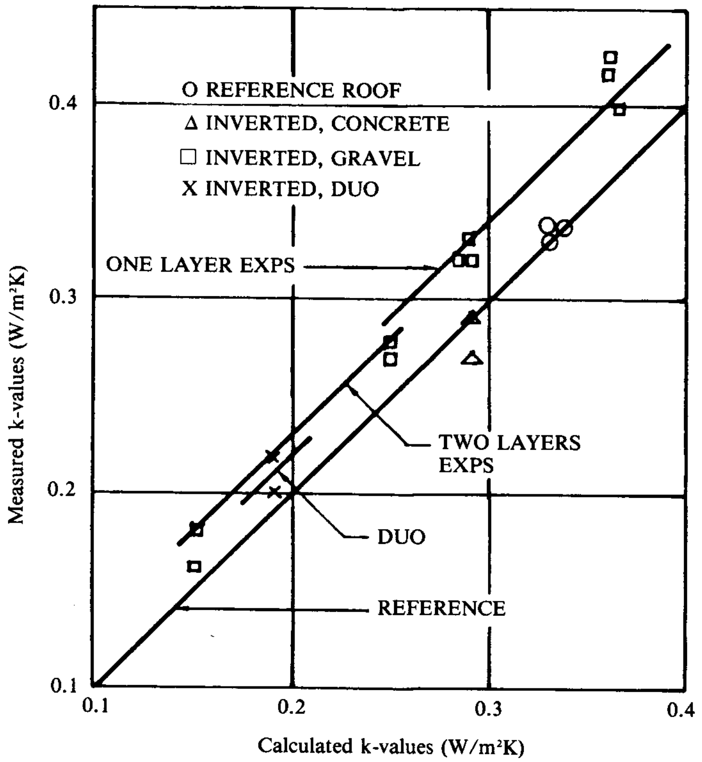

Figure 3 Comparison of the measured and calculated k-values for the test roof sections. The points given in the chart represent actual measurements while the straight lines represent the Δk-added as given in the method of thermal design.

DUO is a case with a portion of the thermal insulation placed under the membrane in the inverted roof. (In the experiment about 40 percent was placed under the membrane).