des at *U*-værdien øges. I praksis kan tagkonstruktioner isoleret med halmballer, derfor tillægges en *U*-værdi på 0,18 W/m^2K, idet tagdækningen også giver et mindre bidrag.

Thermal properties of straw bale walls

Two types of measurements were carried out in order to determine the U-value of building parts where straw bales are used as thermal insulation:

1 Measurement of specific thermal conductivity, λ_{10}, for 100 mm of straw according to (ISO 8302:1991)
2 Direct measurement by guarded hot box test on stuccoed straw bale walls according to ISO 8990 (Dansk Standard, 1997).

Both test types were applied to specimens with the straw parallel and perpendicular to the heat flow. Further the thermal conductivity was determined for two densities. The values were determined at approximately 0 °C on the cold side and 20 °C on the warm side. The tests were conducted by an accredited laboratory. The results for λ_{10} are reported in (Teknologisk Institut, 2001c, d, e, f) and for direct measurement in (Teknologisk Institut, 2001a, b). The results are listed in Table 1 and 2 together with results found in the literature.

Table 1. Thermal conductivity for straw bales according to different sources.

	Density, kg/m^3	Thermal conductivity, λ, W/mK	
Reference		Straw parallel to heat flow	Straw perpendicular to heat flow
Present study	75	0.057	0.052
Present study	90	0.060	0.056
Haus der Zukunft[1]	100		0.038
Christian et al. (1998)	62 resp. 81	0.082	0.057
McCabe (1993)	approx. 150	0.060	0.048
Sandia National Lab. (1994)	90	0.05-0.06[2]	0.05-0.06[2]

1. Österreichischen Strohballen-Netzwerk (2000). 2. Unspecified straw direction.

Table 2. U-value for stuccoed straw bale walls.

Straw orientation	Thickness of straw	Surfaces	U-value, W/m^2K
Present study[1]			
parallel to heat flow	385 mm	34 + 42 mm stucco	0.208
perpendicular to heat flow	365 mm	26 + 26 mm stucco	0.196
Christian et al. (1998)[1]			
parallel, with cavities	470 mm	Stucco + 13 mm board	0.365
parallel, without cavities	480 mm	Stucco + 13 mm board	0.210[3]
Watts et al. (1995)[2], parallel	460 mm	Stucco	0.21

1. Guarded hot box test excluding air film resistance. 2. In situ test. 3. Value determined from data in (Oak Ridge National Laboratory, 1998).

Thermal conductivity

Conductivity was expected to be higher when the straw is parallel to the heat flow than for the other direction. It was also expected that the density slightly influences the conductivity, possibly such that an optimal density might exist within the normal density range for straw bales.

Table 1 shows that the test values for the thermal conductivity were quite scattered. The trend was clearly that the conductivity was higher for the straw parallel to the heat flow than for the perpendicular direction. However, the Danish measurements indicated a smaller dependency than the results found in literature.

The dependence on density was not clear. The Danish measurements indicated that the conductivity increased with density, whereas Austrian measurements by (Wimmer, Hohensinner, Janisch, Gruber & Passauer, 2001) show the opposite trend. In both cases the change is small. The high value for the parallel direction obtained by Christian et al. (1998) is associated with quite a low density which might indicate that a higher density could improve that value. It might also be of importance how perfect the straw is aligned. The values obtained in Austria are surprisingly low.

U-values from direct measurements and λ–values

Measurements on straw bale walls with cladding seem to give quite similar U-values for the walls with stucco cladding. The larger value obtained by Christian et al. (1998) was caused by air gaps between as well the outside stucco as the straw and between the straw and the two gypsum boards that formed the inner cladding. Simulations by computational fluid dynamic (CFD) showed that these gaps might have accounted for the poor U-value in the first test. In a second test great care was taken to avoid gabs and the U-value was almost halved and became similar to the other experiments in Table 2.

If the small contributions from air film, stucco and boards are ignored, a U-value of 0.2 W/m^{2}K for a 450 mm thick layer of straw equals a thermal conductivity of λ = 0.09 W/mK. This backwards estimation gave λ-values about 50 % higher than most of the measured λ-values and also higher than the 'out-layer' value found by Christian et al. (1998). This indicated a significant problem in establishing U-values from λ-values.

Christian et al. (1998) determined by means of their CFD-model a U-value of 0.195 W/m^{2}K when there are no gaps, but including both conductive and convective contributions to the heat transfer. The conductive part was determined with the above mentioned λ = 0.082 W/mK. In order to determine the convective part the airflow permeability was measured. It was found to be about 100 x 10^{-9} m^2 (0.2 kPa s/m^2 at 20 °C), somewhat more permeable than mineral wool.

A simple calculation using λ = 0.082 W/mK and R = 0.2 m^{2}K/W for gypsum board and stucco in accordance with Christian et al. (1998) gives U = 0.165 W/m^{2}K when ignoring the convective contribution. From these values it can be estimated that convection reduces the thermal resistance by 0.9 m^{2}K/W.

The value measured in the second test in the hot box, where gaps were avoided, was 0.210 W/m^{2}K. The difference between the measured and the calculated value might be bigger than the numbers indicated, because the CFD calculation was carried out for a seemingly high λ-value, determined for a much lower density than the density of the bales used (62 vs. approximately 90 kg/m^3). Therefore, the tests conducted by Christian et al. (1998) seem to suffer from the same problem as the other tests - the U-values calculated from the λ-values were significantly smaller than the U-values measured on real walls. However, the work revealed that convection was part of the explanation for the differences.

Another part of the explanation could be that the effective thickness of the straw was reduced because the stucco percolated into the straw. This could increase λ for some 10 mm at both sides of the bale. It might be more serious that the rounded corners of the bales causes a cavity at the top and bottom of each end joint between the bales which is filled with stucco. At these points the stucco might intrude 40 mm from each side. This causes a thermal bridge that increases the heat loss. If these intrusions are assumed to be equivalent to a reduction of the effective straw thickness by 50 mm and the convection is assumed to reduce the resistance by 0.9 m^{2}K/W the measurements of λ and U in this study will agree quite well. The resistance from the stucco is taken as 0.1 m^{2}K/W. (The air film resistance is not included in the U-values in Table 2).

For the straw parallel to the heat flow is then obtained:

$1/U = 0.1 + (385\text{-}50)/60 – 0.9 = 1/0.209$

and for straw perpendicular to the heat flow:

$1/U = 0.1 + (365–50)/56 – 0.9 = 1/0.207$

As the measured values were 0.208 and 0.196 W/m^{2}K, the agreement is quite good.

The bales used for the hot box test for the straw parallel to the heat flow were reduced in thickness in order to fit into the apparatus. With the full thickness, 450 mm, the U-value would be 0.170 W/m^{2}K with the same assumptions. An air film resistance of 0.2 m^{2}K/W will improve the value U-value of a straw bale wall to 0.165 W/m^{2}K.

In real life, heat flow perpendicular to the straw only occurres when the bales are used for insulation in roof constructions. When the roof pitch is low, the air circulation causing the convective loss cannot take place. The expected U-value of a roof insulated with 360 mm straw bales is therefore:

$1/U = 0.1 + (360–50)/56 = 1/0.177$

The contribution from roof cladding and ceiling might be slightly higher than 0.1 m^{2}K/W. When also the air film resistance is taken into account the U-value of a roof insulated with 360 mm straw bales will be 0.17 W/m^{2}K.

Moisture content

All the quoted thermal properties applies for dry conditions as the straw is dried by the heat flow when waiting for the steady-state heat flow to develop. The steady-state is required by the standard methods used to determine the thermal properties. However, Kristiansen and Rode (1999) developed a method to determine the thermal conductivity for higher moisture contents. The method has not been applied to straw, but tests on other cellulose materials showed that the thermal properties did not depend significantly on the moisture content if the moisture content is below what corresponds to equilibrium at 70 % RH. These conditions will be fulfilled in a correctly constructed straw bale wall. There is, therefore, no evidence for prescribing higher adjustment factors for moisture content for straw than for more conventional insulating materials.

Conclusion

A straw bale wall with 450 mm straw parallel to the heat flow and plastered on both sides has a U-value of 0.165 W/m^{2}K when the heat loss due to convection is taken into account. This value should equal the U-value determined from design λ-values (which are determined from λ_{10}-values). According to the Danish standard for determining heat loss, (DS 418:2002) this value should be increased by 0,01 W/m^{2}K to obtain a design U-value. The formal design U-value then becomes 0.18 W/m^{2}K, which is 10 % better than the required value for light weight walls, 0.20 W/m^{2}K, in the Danish Building Regulations (Bolig- og byministeriet, 1998).

A straw bale insulated roof construction with 360 mm straw perpendicular to the heat flow has a U-value of 0.17 W/m^{2}K, which also should be increased by 0.01 W/m^{2}K so that the design U-value becomes 0.18 W/m^{2}K, similar to the U-value for the wall.

Due to expected variability in straw types and density a reasonably safe design U-value will be 0.20 W/m^{2}K for both walls and roofs insulated with normal 360 x 450 mm straw bales as the primary insulation material.