The Hygro-Thermal Improvement of a Mounting System to Fasten Roof Workmen to Flat Roofs

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Abstract: A Dutch firm manufactures a mounting system to fasten roof workmen to the roof of a flat roof building to prevent them from falling down from the roof. The system is mounted to the flat roof afterwards, i.e. after the completion of the thermal insulated roof.
Because of the mechanical strength and stiffness properties of the system, it is manufactured using (stainless) steel. The steel, however, forms a thermal bridge throughout the insulated roof due to its relatively high thermal conductivity, compared to the roof system. The effect of this thermal bridge is a lower surface temperature during wintertime at the indoor surface of the mounting system, with an increased risk on internal and surface condensation. Furthermore, the heat loss through the roof is increased by the thermal bridge effect. The thermal system has an indoor and an outdoor surface. Increasing the indoor surface leads to an increase of the indoor surface temperature and therefore to a decrease of the surface condensation risk. The heat loss, however, will increase.
That is the reason why Comsol was used to optimize this thermal system. Because the assumptions, regarding the treatment of surface heat transfer coefficients at the external and internal surface, but also within the aperture in the roof, should be proved experimentally, a thermal mock-up of the thermal system has been made. Measurements of internal and external surface temperatures and heat fluxes have been performed to compare the predicted Comsol results with these measurements. Thermal imaging was used to compare the distribution of surface temperatures, both absolutely as relatively.
Several variants have been simulated and the results are presented dimensionless as a temperature ratio and the heat loss per mounting point through the roof. Thermal insulation of the aperture is important because of two reasons: the increase of the indoor surface temperature and the decrease of the condensation risk, also within the inner surface of the aperture. The results of the comparison of Comsol results with the mock-up results was quite reasonable: the thermal images of infrared thermal imaging and Comsol simulations were quite lookalike. The quantitative results of temperature ratio's and heat loss differed because of the vertically mounted roof system in the climate cabinet, while it is a horizontal roof system.

Keywords: Thermal bridge, Heat Loss, Condensation, Roof, Anchor**.**

1. Introduction

A company, specialized in innovative products for a safe working environment, developed a product to protect workmen falling down from a flat roof. It is a system that can be mounted on almost all flat roofs, using a relatively simple installation on existing roofing. The anchoring to the (existing) roof structure is made via an anchor system, consisting of steel rods. These studs form so-called thermal bridges through the existing, mostly well-insulated roofs. At the request of the firm, Eindhoven University of Technology (TU/e) investigated the existing thermal bridge effect and examined the effect of a number of possible improvements variants. The finite element program COMSOL was used to study the thermal bridge effect and was validated by measurements in a climate cabinet.

2. The anchoring system

The anchoring system consists of a base plate of 400x300x2 mm^3. From the upper side the base plate is fastened to an existing roof via a roof anchoring system, consisting of four threaded rods of 8 mm. For this purpose, 4 holes with a diameter of 32mm are drilled into the roof structure. The threaded rods have an anchorage system at the bottom, consisting of expandable anchors, which are inserted from the upper side of the roof through the 32mm holes. The base plate is attached with four nuts and the wire end is subsequently removed just above the base plate. The anchoring system is then applied and sealed. Figure 1 provides a 3D impression of the system.

3. Theory

The heat transfer in an (isotropic) material, in three directions, is described by the three-dimensional heat equation of Fourier:

$$q_x = -\lambda \frac{\partial T}{\partial x}, \quad q_y = -\lambda \frac{\partial T}{\partial y}, \quad q_z = -\lambda \frac{\partial T}{\partial z}$$

λ = thermal conductivity [W/mK]
T = thermodynamic temperature [K],
T-Θ = 273.15 [° C]
The unsteady state heat balance of an elementary particle, together with the Fourier equation yields the differential equation

$$\rho c \frac{\partial T}{\partial t} = \text{div}\, \lambda \,\text{grad}\, T$$

This includes:
div: Divergence
grad: Gradient
ρ = density of the material [kg/m^3]
c = specific heat of the material [J/kgK]
If the heat transfer coefficients at the surface are constant, then the heat transfer to the surface is described by the following equation:

$$-\lambda \left(\frac{\partial T}{\partial z} \right)_s = (h_{cv} + h_r)(T_{rcv} - T_s)$$

This includes:
h_{cv} = the heat transfer coefficient for convection [W/m^{2}K]
h_r = the heat transfer coefficient for radiation [W/m^{2}K]
T_{rcv}= effective temperature [K]
T_s = the surface temperature [K]

In a one-dimensional case (a flat wall or roof e.g.), the descriptive differential equation with not too complex boundary conditions is solvable. This results in heat losses and cross-section-solvable temperatures for the one-dimensional case. When there are so-called thermal bridges in the structure, this will result in multi-dimensional heat transfer. In the simplest case, this will result in two-dimensional heat flow, in the case of cylindrical symmetry. In the present case, the anchors form a complex, three-dimensional heat-conductive structure, which, for those reasons, is only solvable by three-dimensional modeling.

4. Finite element method

Due to its three-dimensional complex geometry, the problem is only solvable by computer simulation. For this purpuse the computer program Comsol has been used, which is based on the method of finite elements. It is suitable for the solution of so-called multi-physical problems. These physical problems, involving multiple physical phenomena, are interconnected and can be solved simultaneously. The three-dimensional anchoring system was imported by the standard CAD import module of Comsol. The roof has been entered as a 1x1m2surface. Figure 1 gives an impression of the anchoring system, as it has been implemented in Comsol.

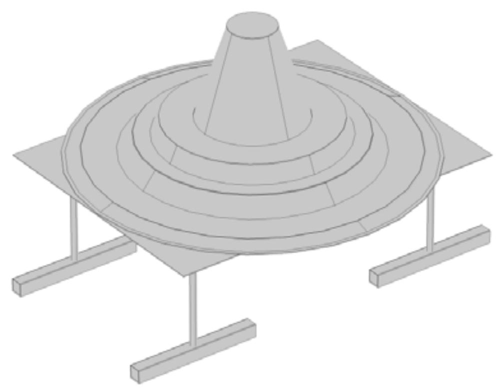

Figure 1. 3D implementation of the anchoring system

The material properties are taken from the database of Comsol and these are supplemented where necessary by data from the Handbook of Chemistery and Physics:

Table 1. Thermal conductivity of applied materials

Thermal conductivity [W/mK]	
Steel	44.5
Stainless steel	20
Aluminum	200
Insulation	0.04
Nylon	0.26

The thermal boundary conditions for combined radiative and convective heat transfer are:

Table 2. Thermal boundary conditions

	Air temperature [^oC]	**Heat transfer coefficient [W/m^2K]**
Indoor	20	7.7
Outdoor	-10	25

5. Study of variants

Using the computer program Comsol the following variants have been calculated:
1. The existing anchoring system, mounted on a steel roof, with a total thermal resistance Rc = 3.0 m2K/W
2. The afterwards insulated 32mm holes by cylindrical insulating adapters
3. The isolation of the nuts in relation to the base plate by the application of 2mm nylon insulation rings
4. The afterwards insulated nuts at the top by filling the countersunk holes in the base plate with polyurethane insulation.
5. The thermal insulation of the folding steel roof anchors insulated with 2mm nylon insulation

The results of the study of variants are presented in two ways:
1. In the form of the additional heat loss, expressed in watts per anchor point, relative to the undisturbed situation, i.e. the one-dimensional situation without anchor points as a percentage relative to the undisturbed situation.
2. In the form of the so-called temperature ratio: the dimensionless lowest indoor temperature according to:

$$f = \frac{\theta_{si,\min} - \theta_e}{\theta_i - \theta_e}$$

With
f = temperature factor [-]
$\Theta_{si,min}$ = lowest inside surface temperature [^oC]
Θ_i = indoor air temperature [^oC]
Θ_e = outdoor air temperature [^oC

6. Computer simulation results

The table in the appendix represents the results of the variant study.
The results of the standard configuration are graphically shown in the figures below

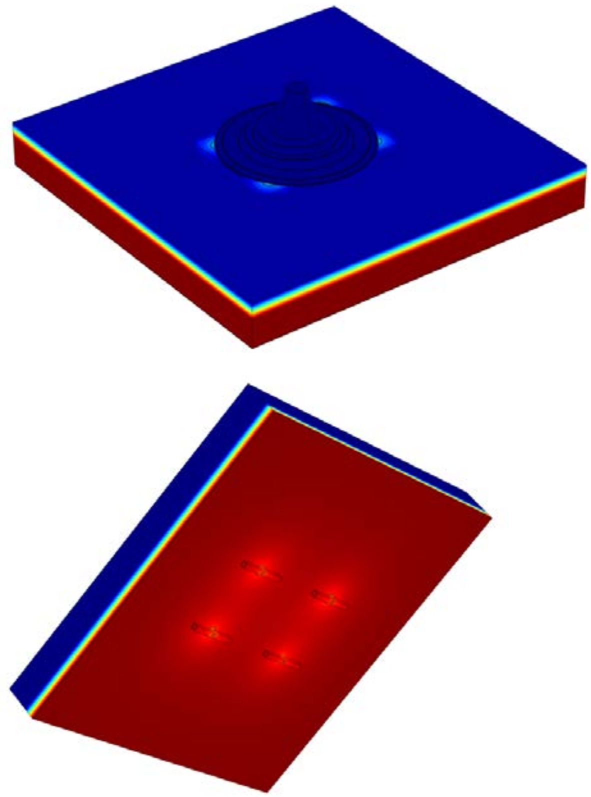

Figure 2. Graphical impression of the surface temperatures; external (up), internal (down)

7. Measurements

In the laboratory of the Unit Building Physics and Services a test set-up of the anchoring system has been manufactured: in a supplied roof element with an Rc of 4.4 m2K/W an anchoring system was mounted. It has been installed vertically at the front of a climate cabinet, instead of the cabinet door. As a result, it was possible to create a temperature difference air-to-air over the roof element in a vertical arrangement, resulting in a horizontal heat flow. At the inner, respectively outer surface of the roofing element thermistor temperature sensors were applied, at the places where the slightest thermal bridge effect was expected (on the greatest distance from the anchoring element) and at the location of the thermal bridge formed by the threaded rod, which was the location where the largest thermal bridge effect was to be expected. In addition, the air temperatures were measured inside and outside the cabinet. An infrared thermal camera produced thermographic images from both sides of the test specimen infrared.8. Measurement results

The results of the measurements at the climate cabinet are shown in the appendix.

8. References

1. Hagentoft, Carl-Eric, Introduction to Building Physics, Sudentlitteratur, Lund (2005)
2. Carlslaw, H.S. and Jaeger, J.C., Conduction of heat in solids, Oxford : Clarendon Press (1959)
3. Holman, J.P., Heat Transfer, Boston, McGraw-Hill (2009)

9. Appendix

The table below represents the Comsol results of the variant study.

Table 3. Comsol results variant study

Variant									
0. No anchor	1	0	0	0	0	0	0	0	0
1. Standard anchor	0	1	0	0	0	0	0	0	0
2. Insulated holes	0	0	1	0	0	0	1	1	1
3. Insulated nuts	0	0	0	1	0	0	1	1	1
4. Insulated countersunk holes	0	0	0	0	1	0	0	1	1
5. Insulated folding steel roof anchors	0	0	0	0	0	1	0	0	1
Heat loss [W]	9.46	10.82	10.75	10.79	10.79	10.82	10.71	10.68	10.63
Additional heat loss [W]	0	1.36	1.29	1.33	1.33	1.36	1.25	1.22	1.17
Additional heat loss [%]	0	14.4	13.6	14.1	14.1	14.4	13.2	12.9	12.3
Surface temperature intern min [^{o}C]	18.8	13.6	13.4	13.7	13.7	13.6	13.5	13.7	12.7
Temperature ratio f [-]	0.96	0.79	0.78	0.79	0.79	0.79	0.78	0.79	0.76
Surface temperature extern max [^{o}C]	-9.6	-4	-4.1	-3.4	-3.5	-4	-3.5	-2.9	-3.1

Figure 3. Measurement set-up of the roofing system with anchor, mounted at the front opening of a climate cabinet

The results of the measurements at the climate cabinet are shown in the table below. This includes:

Ti = indoor air temperature in the cabinet [^{o}C]
$T_{si,und}$ = the undisturbed inside surface temperature [^{o}C]
$T_{si,tb}$ = inner surface at the nut [^{o}C]
T_e = the air temperature outside the cabinet [^{o}C]
$T_{se,und}$ = the undisturbed outer surface temperature [^{o}C]
$T_{se,tb}$ = the outer surface at the folding anchor [^{o}C]

Table 4. Measurement results climate cabinet

Temperatures measured					
Inside climate cabinet			Outside climate cabinet		
T_i	$T_{si,und}$	$T_{si,tb}$	T_e	$T_{se,und}$	$T_{se,tb}$
40.7	40.6	39.8	22.9	23.3	29.1
Dimensionless temperatures measured					
Inside climate cabinet			Outside climate cabinet		
f_i	$f_{si,und}$	$f_{si,tb}$	f_e	$f_{se,und}$	$f_{se,tb}$
1.0	0.99	0.95	0	0.02	0.35

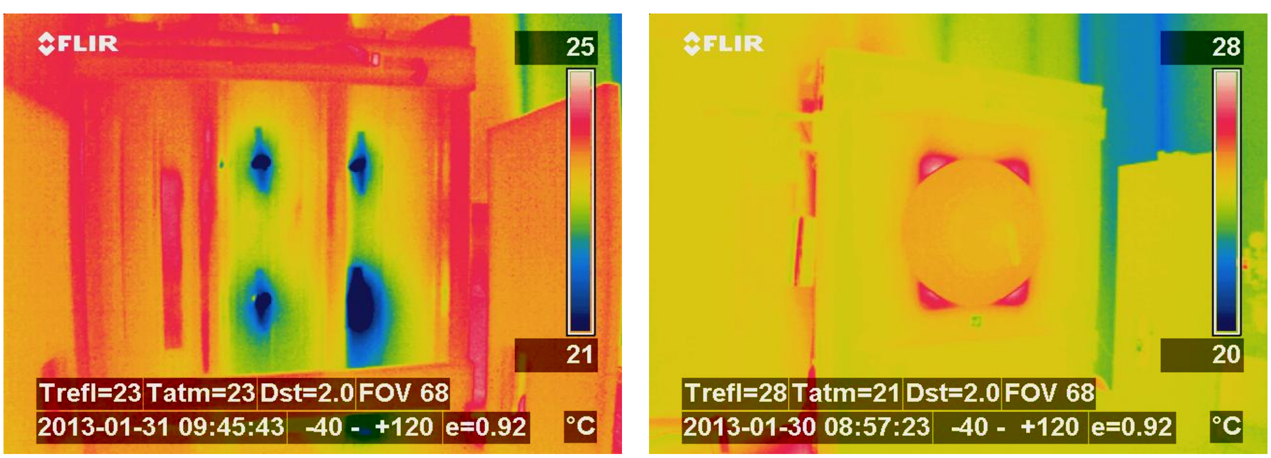

Figure 4: Infrared thermal image from the inside with folding anchors (l) and anchoring system outside (r)