Hygrothermal Simulation of ventilated pitched roofs with effective transfer parameters

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1 Abstract

The surface temperature of the sub-roof beneath the ventilation layer is the most important factor for the hygrothermal behavior of pitched roofs. The air layer between tiles and sub-roof and the air exchange with the outdoor air reduce the heat exchange between roof cladding and sub-roof and affect the moisture level inside the roof. This report provides preliminary results of a current research project including new field tests. The investigations analyze the thermal behavior of different vented and ventilated roof constructions. Characteristic values for different roofing situations will be provided as well as a method to calculate ventilated roofs by means of hygrothermal simulation using effective surface transfer parameters.

2 Problem Definition

Pitched roof constructions with tiles made of clay or concrete used to be performed with ventilation layers in many countries. At least the battens, which are needed to attach the tiles, already form an air layer. The whole ventilation layer normally consists of battens and counter battens and ensures several functions:

- The counter battens enable a free drainage of water on the breather or sarking membrane / board.
- The air exchange reduces overheating of the roof during summer.
- The air layer helps to remove moisture caused by convection or vapor transport from the indoor climate or dew water condensed during overcooling periods.

Due to these effects ventilated roofs are common and well proven assemblies. However a problem can be the reproduction of the ventilated layer in hygrothermal simulation. Till now there are basically three possibilities to perform the calculation: First, a calculation without consideration of the air layer and without any radiation effects. This method uses the outdoor air temperature without any additional resistance directly on the sub-roof surface, which can lead to rather low surface temperatures and in some cases high moisture contents inside the roof construction. This method can be considered as a worst case scenario.

Second is a calculation performed with a roof cladding and an air layer. In that case the radiation parameters of the roof cladding will be normally used and the air layer between roof cladding and sub roof is modeled using effective parameters for convective and radiant heat and moisture transport. To simulate the air exchange with the outdoor air, an air change source is used. This method is closer to reality but the air change rate must be known before and no differentiation between top and bottom of the roof are possible.

Another method is the calculation with the radiation parameters of the cladding directly on the surface of the sub roof. In that case, the air layer is not explicitly simulated. This Method can lead to a strong overcooling during nighttime and to high surface temperatures in times with solar radiation.

An accurate calculation of a ventilated roof construction would require to consider all relevant heat transfer processes as shown in Fig. 1 (top). However these parameters are often unknown in practice.

This report presents a simplified method considering roofing and ventilation by effective heat transfer and radiation parameters which were determined based on measured conditions on the sub-roof during various field tests (Fig. 1 bottom).

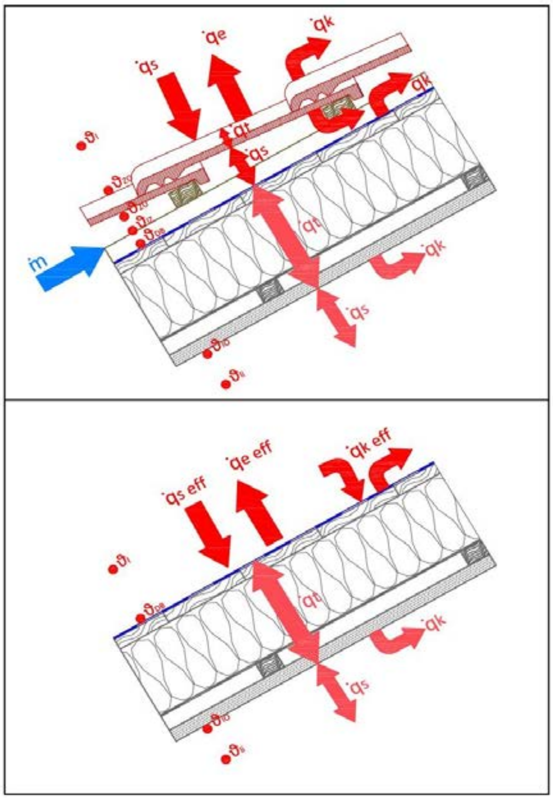


Fig. 1: Heat transfer processes on a ventilated pitched roof with cladding and air layer (top) and with effective radiation and convection parameters (bottom)

3 Experiments

Several field tests on vented and ventilated roofs were performed at the test site of Fraunhofer-Institute for Building Physics (IBP) in Holzkirchen, Germany. In the experiments temperature measurements on pitched roofs with different types of ventilation were performed. The surface temperature of the roof cladding, the temperature on the bottom side of the tiles, the air temperature in the ventilated air layer and the surface temperature on the sub roof where measured. The measurements where performed at different positions between eaves and ridge over a period of approximately one year. The IBP weather station records outside air temperature, relative humidity, global and diffuse radiation, atmospheric counter radiation as well as wind speed and direction. In IBP's laboratory the radiation parameters of the different surface materials (tiles etc.) were measured.

4 Results

The investigations on the different roof constructions show, that the highest surface temperatures occur at the exterior surface of the roof cladding. Fig. 2 compares the surface temperature on top of the cladding, on the sub roof and the outdoor air temperature during two summer days in 2013. During daytime with solar radiation, the surface temperature of the sub roof is much higher than the one of the outdoor air. The overcooling during nighttime, due to the long wave radiation losses, mainly affects the cladding and leads to a recognizable overcooling, while the surface temperature of the sub roof remains close to the outdoor air temperature.

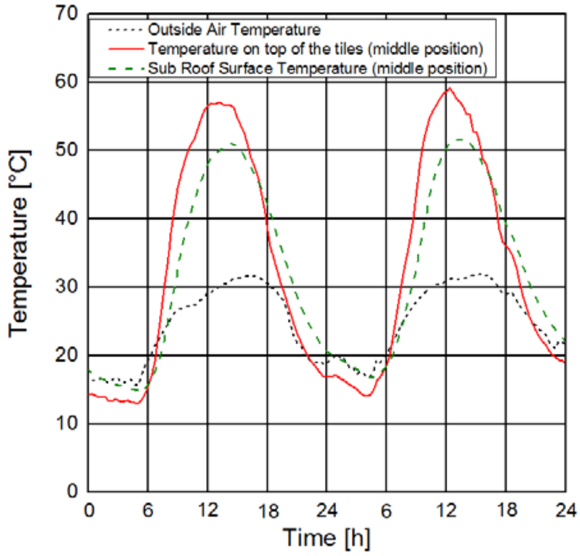


Fig. 2: Surface temperature at the exterior surface of the roof cladding and on the sub roof in the center between eave and ridge for a „normal" ventilated south facing roof compared to the outside air temperature on two summer days in the year 2013

Fig. 3 shows the surface temperature on the sub roof in the center between eave and ridge of a south facing, normal ventilated roof in the year 2013 compared to the outside air temperature. In addition the floating monthly average of both temperature profiles are shown. Fig. 4 plots the same temperature profiles for a north facing highly ventilated roof. In comparison to the south facing roof, lower temperature peaks can be observed.

Furthermore one can see, that also the floating monthly average temperatures on the sub roof are in both cases higher than the outside air temperature. Only during a short period in winter the temperatures reach similar values. Using simply the outdoor air temperature as surface condition would underestimate the real conditions.

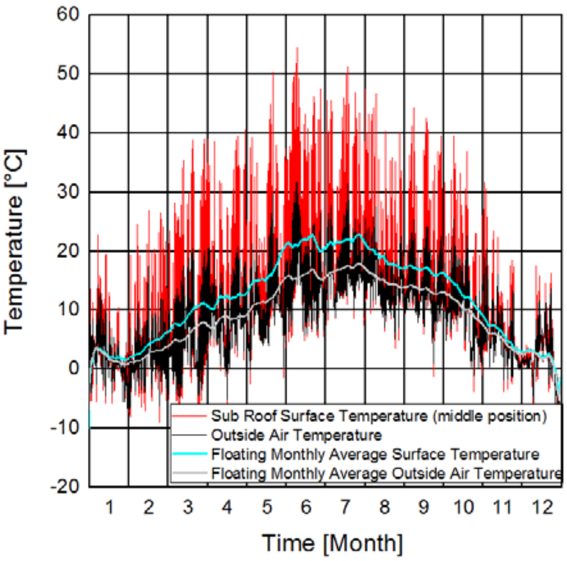


Fig. 3: Measured sub roof surface temperature in the middle between eaves and ridge (red) compared to the outside air temperature (black) as well as to the floating monthly average temperature of a normal ventilated south facing roof in 2013

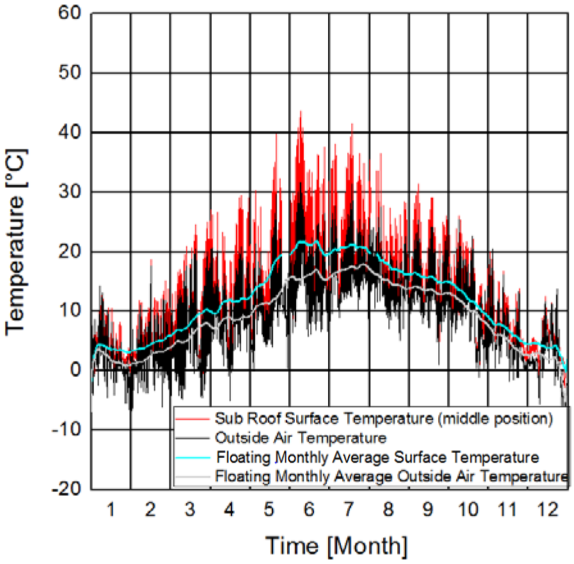


Fig. 4: Measured sub roof surface temperature in the middle between eaves and ridge (red) and outside air temperature (black) as well as the floating monthly average temperatures of a strong ventilated north facing roof in the year 2013

Furthermore the investigations have shown that the air temperature in the ventilated gap as well as the surface temperatures on the sub roof increase during solar radiation from the eaves to the ridge.

Fig. 5 show the temperature profiles on the sub roof at the eaves, in the middle between eaves and ridge and at the ridge in comparison to the outside air temperature. The sub roof surface temperature, even at the eaves (distance approx. 30 cm), is significant higher than the outside air temperature. The sub roof temperature increases also significantly to the middle position between eaves and ridge. But between middle and ridge position the temperature increases only moderately. Therefore different calculating approaches are required for the different positions. However in times without solar radiation the temperatures of the three positions approach to each other. This observation suggests the use of radiation dependent effective transfer parameters.

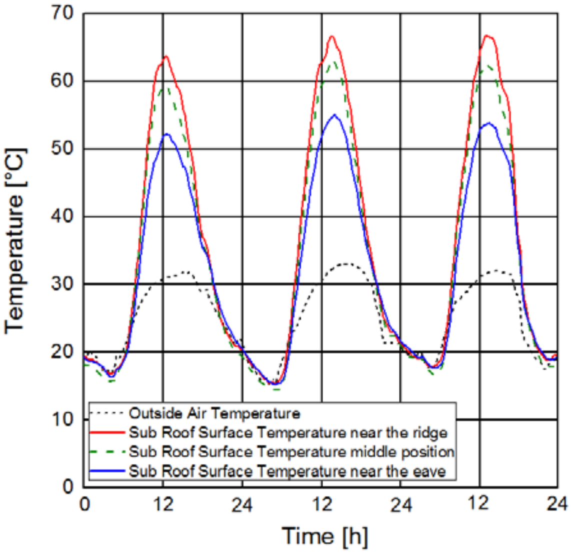


Fig 5: Sub roof surface temperatures at the eaves (blue), in the middle between eaves and ridge (green) and at the ridge (red) as well as the outside air temperature (black) for a low ventilated south facing roof on three summer days in 2013

The temperature rise between eaves and ridge does not show a linear behavior. In the lower part of the roof the temperature increases much stronger than in the upper part. The temperature difference between the air in the ventilated space respectively the sub roof temperature and the roof cladding decrease from eaves to ridge. For both cases this results in a logarithmical temperature profile.

The temperature profile depends on the type of the roof ventilation, which is mainly influenced by the openings at eaves and ridge. These openings are inlet and outlet of the ventilated air layer and provide an additional flow resistance. The higher the flow resistance the lower the air change between sub roof and cladding.

In case of constant air velocity in the gap, the air change rate does not depend on the height of the ventilated cross section as both volume and flow increase to the same extent. It just depends on the length of the roof (distance between eaves and ridge) and the flow resistance of the ventilation openings and is defined as:

$$ACH = \frac{\dot{V}}{V} = \frac{\omega_{ls} \cdot A \cdot 3600 \left[\frac{s}{h}\right]}{A \cdot b} = \frac{\omega_{ls} \cdot 3600 \left[\frac{s}{h}\right]}{b} \left[\frac{1}{h}\right] \quad (1)$$

$ACH = Air\ Change\ Rate\ \left[{}^{1}/_{h}\right]$

$\dot{V} = Volume\ flow\ \left[{}^{m^3}/_{s}\right]$

$V = Volume\ [m^3]$

$\omega_{ls} = Air\ Velocity\ [{}^{m}/_{s}]$

$A = Flow\ through\ Cross\ Section\ [m^2]$

$b = Leangth\ of\ the\ Roof\ (eaves\ to\ ridge)\ [m]$

Therefore an enlargement of the ventilated cross section due to bigger battens theoretically does not lead to a higher air change rate – however the higher volume leads to a higher moisture transport capacity. Furthermore the flow resistance in the air layer is reduced with its height and the air velocity will increase.

Fig. 6 shows the temperature difference profiles between the air in the ventilated space resp. the sub roof temperature and the outside air temperature from eaves to ridge exemplarily for different types of ventilation. In comparison to a low ventilated construction a strong ventilation, with huge openings at eaves and ridge, without additional flow resistances leads to a flatter profile and a lower temperature difference to the outside air. The measurements show that in addition to the position on the sub roof also the type of ventilation has to be considered. Three different types of ventilation are differentiated: strong, normal and low ventilation. As already mentioned, the type of ventilation depends on the openings at eaves and ridge. Hereby the opening with the higher flow resistance limits the air flow and therefore decides about the ventilation type. A rough classification of the different types of eaves and ridges is given in Tab.1. The different types of ventilation will be considered in the simulation due to the adaption of the convective heat transfer coefficient.

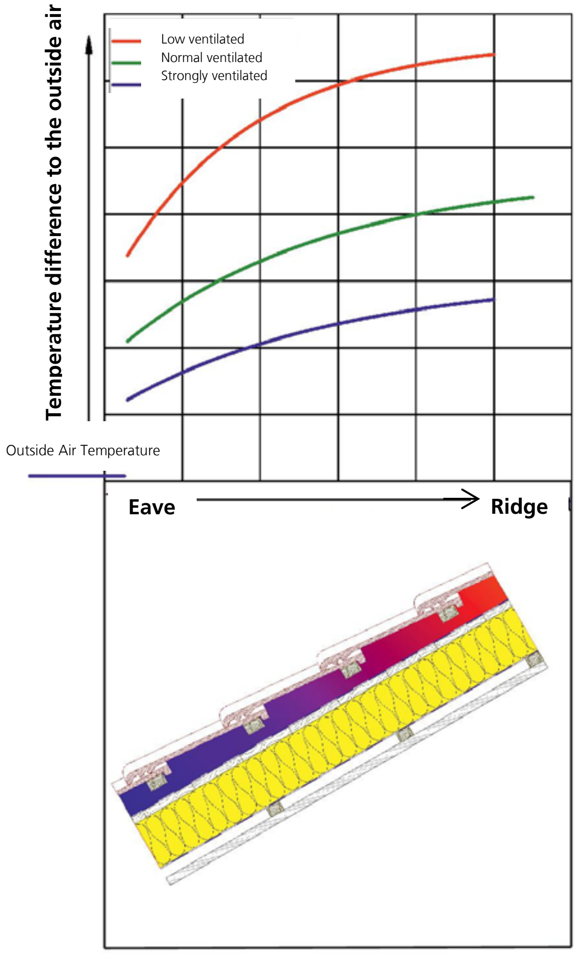


Fig. 6: Temperature difference between the air in the ventilated air space respectively the sub roof surface temperature and the outside air temperature for different types of ventilation during solar radiation.

Tab. 1: Characteristics of different types of ventilation.[1)]

Strongly ventilated [4)]	Eaves open without any ventilation grid etc.	Ridge open with a low flow resistance such as a ceramic ridge cap without ridge / arris role.	
Normal ventilated [4)]	Eaves openings with insect protection grid or eave comb fulfilling requirements of German standards ZVDH [4] resp. DIN 4108-3 [5].[2)]	Ridge closed with ridge / arris role Openings fulfill requirements of German standards ZVDH [4] respectively DIN 4108-3 [5]. [3)]	
Low ventilated [4)]	Small openings at the eaves, e.g. very fine ventilation grid etc.	Small openings at the ridge, eg. ridge cap fixed with mortar	No counter battens

[1)] The Table provides orientation values without any claim to completeness. The selection depends on the local conditions and the assessment of the designer / planner. **If one single criteria for low ventilation is given, the low ventilation level has to be used.**

[2)] The opening area at the eaves must be at least 2 ‰ of the acc. pitched roof area, but minimum 200 cm^2/m. [5]

[3)] The opening are at ridge and arris must be at least 0,5 ‰ of the acc. pitched roof area, but minimum 50 cm^2/m. [5]

[4)] The different types of ventilation are defined according to the studied roof constructions. The terminology can differ from the one in standards (e.g. DIN 4108 and DIN ISO 6946).

5 Absorption- and Emission coefficients of concrete and clay tiles

Also some measurements of the absorption- and emission coefficients of concrete and clay tiles were performed during the investigations. The measurement equipment was a grating spectrometer covering the hole solar radiation range from 280 to 2.500 nm according to DIN EN 410:2011-04 [1]. The coefficients of emission are measured according to DIN EN 16012:2012-04 [2] with an emissiometer in the spectral range of 2,5 - 40 µm. In case of clay tiles the coefficients of emission strongly depend on the surface coating. However, for the concrete tiles there are no significant differences: All values in range between 0.9 and 0.91. The results are summarized in Table 2.

Concerning the absorption coefficient the values for clay and concrete tiles are similar. The absorption coefficient is mainly influenced by color and surface finish. The measured samples are in the range between 0.72 and 0.94. Some results are shown in Table 3.

Tab. 2: Long wave emission coefficient ***ε*** *of clay and concrete tiles*

Clay tile, high closs clazed	0,82
Clay tile, matt	0,84
Concrete tile, in general	0,90 – 0,91

Tab. 3: Short wave absorption *coefficient* ***a*** *of clay and concrete tiles*

Red, high closs glazed	0,72
Brick red (engobed)	0,74
Light Red, semi-.matt	0,75
Light Red, matt (strongly weathered)	0,76
Natural Clay Red, matt (also weathered)	0,77
Red, matt (strongly weathered)	0,78
Light Grey	0,85
Black (weathered)	0,94

6 Effective transfer parameters and hygrothermal Simulation

Determination of the effective transfer parameters:

The determination of the effective transfer parameters was performed by the help of the hygrothermal simulation tool WUFI® [3], developed at Fraunhofer IBP.

Based on the measured climatic data and the surface temperatures at different positions of different ventilated roof constructions, comparative calculations where performed. For the simulations a sub roof timber sheathing of 2 cm was added to the roof assemblies which serves as moisture sensitive evaluation layer. The outer surface of the sub roof is assumed to be vapor tight (s_d-Value of 1500 m) to limit the drying potential of the construction and evaluate a critical case. A moderate vapor retarder with a s_d-Value of 5 m is used at room side. To get a reference moisture profile in the timber sheathing in the first step the simulation was performed with the measured surface temperatures. In the second step the recorded climatic conditions were used to adapt the effective transfer parameters for the three positions in that way, that the moisture content of the timber sheathing agrees with the reference profile. Also the calculated surface temperatures where compared with the measured ones. As example the calculated and measured surface temperature as well as the moisture content in the timber sheathing for a normal ventilated roof (in the middle between eaves and ridge) is shown in Fig. 7 for a period of 5 Years. The calculation of the moisture content with the effective transfer parameters and the measured surface temperatures are in good correlation. The temperature peaks of the simulated surface temperatures are slightly lower than the measured ones providing a small safety margin. The correlation for the other cases is of similar quality – but the figures cannot be shown in this short summary.

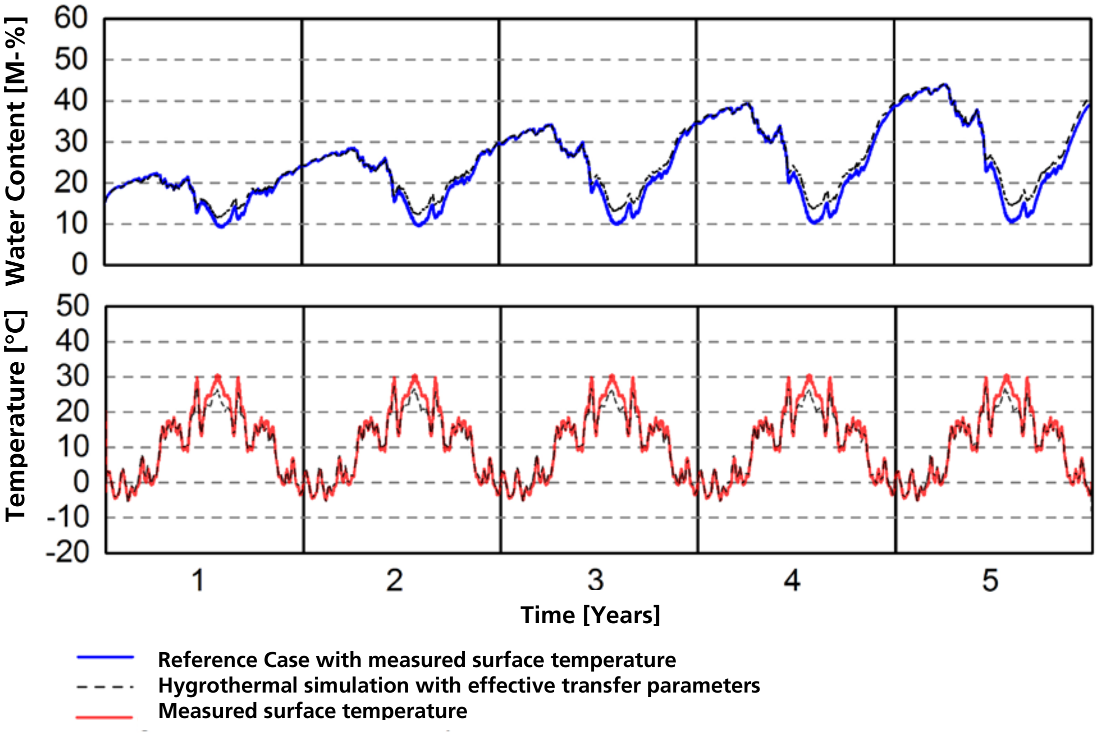


Fig 7: Middle position on the sub roof with normal ventilation. Top: Simulated water content in the exterior wooden sheathing using the measured surface temperature (blue) and the new effective parameters (black). Bottom: Measured sub roof temperature (red) compared to the simulation with effective parameters (black).

To provide a simplified method to calculate the temperature profiles on the sub roof surface for all identified ventilation types and positions, the effective transfer parameters where determined in the same way described above. The transfer parameters allow to simulate the temperature profiles without the explicit consideration of the roof cladding and the ventilated air layer.

The radiation exchange between the roof cladding and the sub roof as well as the convective heat transfer are implemented in the effective parameters. The first Parameter is an effective convective heat transfer coefficient $\alpha_{k,e}$, which describes the convective heat transfer on the sub roof in dependency of the ventilation. The second one is the effective coefficient of absorption a_e. This parameter simulates the heat transfer between the roof cladding and the sub roof based on the radiation absorption of the real cladding. Therefore the real coefficient of absorption is multiplied with a reduction factor for the middle and the bottom position at the eaves. The emission coefficient ε of the real roof cladding is applied to the surface of the sub roof. A compilation of the determined effective transfer parameters is given in Tab. 4. The values are only valid for simulations using the explicit radiation balance. Therefore normally measured radiation data for the location are required, as the effective convective heat transfer coefficients $\alpha_{k,e}$ do not include long wave radiation parts.

Tab. 4: Effective transfer parameters for hygrothermal simulations of ventilated pitched roofs in dependency of the ventilation type and the position between eave and ridge.

	Eaves Position (coldest)	**Middle Position**1)	**Ridge Position (warmest)**1)
Strong ventilation 2)	$\alpha_{k,e} = 30 \left[\frac{W}{m^2 \cdot K}\right]$		
	$a_e = a \cdot 0{,}70$	$a_e = a \cdot 0{,}90$	$a_e = \alpha$
Normal ventilation 2)	$\boldsymbol{\alpha_{k,e} = 19 \left[\frac{W}{m^2 \cdot K}\right]}$		
	$a_e = a \cdot 0{,}70$	$\boldsymbol{a_e = a \cdot 0{,}90}$	$a_e = a$
Low Ventilation 2)	$\alpha_{k,e} = 13{,}5 \left[\frac{W}{m^2 \cdot K}\right]$		
	$a_e = a \cdot 0{,}75$	$a_e = a \cdot 0{,}90$	$a_e = a$

1) The given coefficients to calculate the effective transfer parameters are valid for normal roof lengths (distance eaves to ridge) of single family dwellings. Larger roof lengths can result in higher sub-roof temperatures at the middle and the ridge position in reality.

2) The different types of ventilation are defined according to the studied roof constructions. The terminology can differ from the one in different standards (e.g. DIN 4108 and DIN ISO 6946).

For the hygrothermal simulation of standard cases the use of the parameters for a normal ventilated roof is generally recommended . The named opening cross sections are according to the German ZVDH [4] and therefore state of the art as carried out in most cases there. Strong and low ventilated roofs are more special cases. The parameters for these kind of roof constructions should not be used without an on-site verification of the conditions.

Moreover the middle position is of the roof length is recommended. This position realistically represents the average conditions between the eaves and the ridge, slightly on the safe side. For simulations with the parameters of the eaves position considering air infiltration into the assembly, the height of the air column have to be reduced by the height of the pediment to the level of the eaves position.

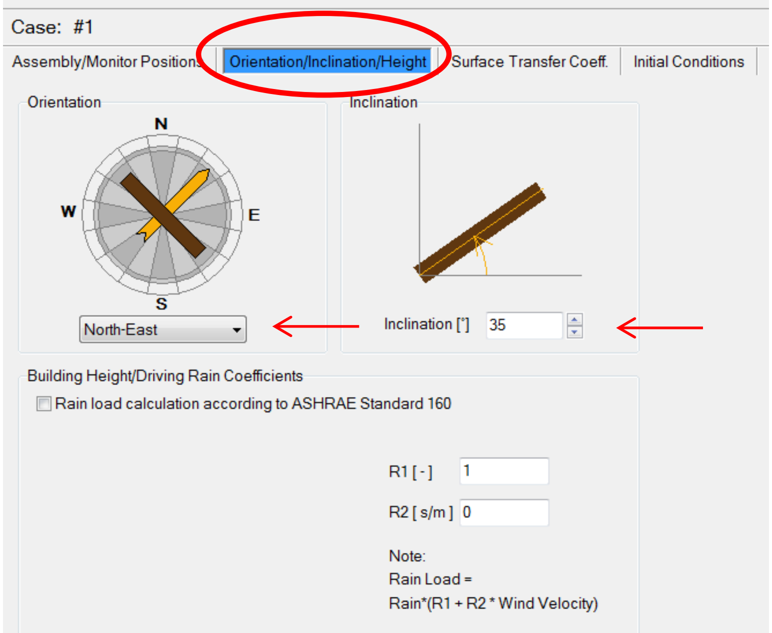
Practical use of the effective transfer parameters with in WUFI®:

This part explains how to use the effective transfer parameters in WUFI®. The specific orientation and inclination are crucial to adequately consider the short and longwave radiation loads. The settings are done in the "Orientation/ Inclination/ Height" menu as shown in Fig. 8.

The level of ventilation is defined as shown in Tab. 1. The related effective convective heat transfer coefficients $\alpha_{k,e}$ for low, normal and strong ventilation are provided in Tab. 4. The example in Fig. 9 shows a roof with normal ventilation. The long wave radiation part of the heat transfer coefficient must be set to zero.

To set the radiation parameters, the type of roof cladding and the position between eaves and ridge must be known. For standard situations the middle position should be used. The use of the parameters for the coldest position is generally the most critical situation and leads to the highest moisture contents. The values in Fig. 9 are an example with clay tiles (natural clay red, matt surface) at the eaves (coldest) position. The short-wave absorption coefficient of the clay tile according to Tab. 3 is a = 0,77. According to Tab. 4 the effective coefficient of absorption for the eaves position is $a_e = a \cdot 0{,}69$. The input for of the effective short-wave coefficient of absorption thus results in $a_e = 0.77 \cdot 0{,}69 = 0{,}53$.

The long-wave radiation emissivity ε is taken directly from Tab. 2 for a roof cladding made of clay tiles ($\varepsilon = 0{,}84$). The explicit radiation balance must be switched on (tick) and the heat transfer coefficient on the interior surface must be set to a realistic value (mostly 8 W/m²K).



Case: #1

North-East

Inclination [°] 35

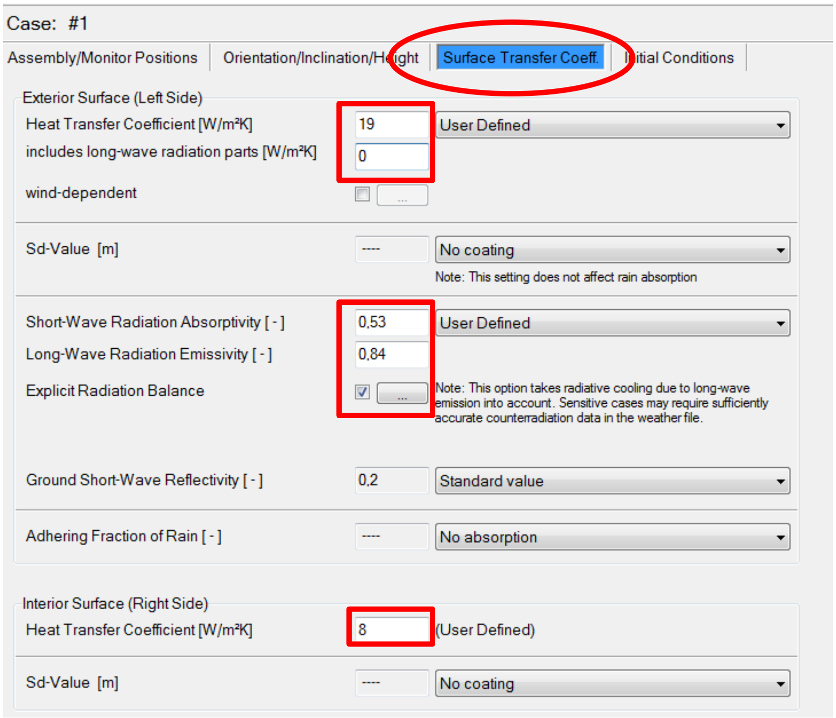
☐ Rain load calculation according to ASHRAE Standard 160

R1 [-] 1

R2 [s/m] 0

Note:
Rain Load =
Rain*(R1 + R2 * Wind Velocity)

Fig. 8: Input of orientation and inclination in the hygrothermal simulation tool WUFI® Pro



Case: #1

Exterior Surface (Left Side)

Heat Transfer Coefficient [W/m²K] 19 User Defined

includes long-wave radiation parts [W/m²K] 0

wind-dependent ☐ ...

Sd-Value [m] ---- No coating

Note: This setting does not affect rain absorption

Short-Wave Radiation Absorptivity [-] 0,53 User Defined

Long-Wave Radiation Emissivity [-] 0,84

Explicit Radiation Balance ☑ ...

Note: This option takes radiative cooling due to long-wave emission into account. Sensitive cases may require sufficiently accurate counterradiation data in the weather file.

Ground Short-Wave Reflectivity [-] 0,2 Standard value

Adhering Fraction of Rain [-] ---- No absorption

Interior Surface (Right Side)

Heat Transfer Coefficient [W/m²K] 8 (User Defined)

Sd-Value [m] ---- No coating

Fig. 9: Exemplary input of the effective transfer parameters for a ventilated pitched roof in the hygrothermal simulation tool WUFI® Pro

7 Summary

The investigations have shown that it is possible to perform a hygrothermal simulation using effective transfer parameters directly on the surface of the sub roof. The measured temperature on the sub roof and the air temperature in the ventilated space show logarithmic profiles. These profiles are mainly influenced by the level of ventilation. For different levels of ventilation and different positions between eaves and ridge the determined effective transfer parameters are provided in Tab. 4. The values were adapted to reach similar moisture levels in the timber sheathing when using the measured surface temperature or the effective parameters. The choice of the parameters requires a careful and individual evaluation of the specific roof situation – then the new transfer parameters allow an easy and reliable simulation of the conditions in a ventilated roof.

8 Supplement: Special features of constructions with absorbent underlay

If the model is applied on assemblies without a separate underlay membrane, but just a timber board or a similar material which can absorb liquid water, this can lead to very high moisture contents. With the presented model it is possible to calculate the surface temperatures beneath the roof tiles at the different positions of the differently ventilated constructions. The calculated sub-roof surface temperatures show a good accordance to the measured ones. The model calculates the sub-roof temperatures based on the outdoor climate file using effective transfer parameters. Also the outdoor relative humidity is assumed to prevail at the external sub-roof surface. However, the measurements show that the relative humidity in the air gap between the tiles and the sub-roof deviates from the outdoor air relative humidity.

The deviation occurs due to two reasons:

1. During night, in case of overcooling of the tiles due to sky radiation also the sub-roof surface temperature can fall below the dew point temperature of the outdoor air and condensation occurs which humidifies the external timber layer. In the field tests the temperature of the tiles normally remained slightly below the temperature of the sub-roof - therefore condensation occurs rather on the tile surface. This condensation process on the tile surface reduces the relative humidity in the air gap. Consequently the dew point temperature is further reduced and condensation on the sub-roof occurs only seldom.

2. During day, in case of solar radiation on the tiles the sub roof surface heats up and also the air in the gap. The heating up leads to a reduction of the relative humidity of this air.

The measurements show that the relative humidity in the air gap lies on average in a range between 10 % and 20 % RH below the relative humidity of the outdoor air.

The moisture transfer between the air and the sub roof surface directly depends on the water vapor diffusion resistance and the convective heat transfer coefficient. Therefore the reduced relative humidity in the ventilation gap can be considered in the simulation in a simplified way by an additional s_d-value (water vapor diffusion resistance) on the external surface.

The evaluation of the simulations with the field measurements showed that a surface s_d-value of 0.01 m realistically reproduces the reduction of the reduced relative humidity in the air gap. This additional s_d-value is only necessary if the external layer of the simulated assembly provides some liquid transport like most wooden sheathings and timber boards. If the sub roof is covered by an underlay membrane, (without liquid transport) the simulation can be performed without this additional s_d-value – however, the difference in that cases is rather negligible.

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