Exterior Surface Temperature of Different Wall Constructions
Comparison of Numerical Simulation and Experiment

H. M. Künzel, Th. Schmidt and A. Holm
Fraunhofer-Institute of Building Physics, kuenzel@hoki.ibp.fhg.de

Abstract

The conditions at the exterior surface of building components with high insulation are almost independent of the indoor climate. With today's increasing insulation thicknesses, the tiny heat flow from the interior is thus generally not sufficient to prevent a temperature drop below ambient conditions by long-wave emission especially during night-time. Apart from energetic consequences this temperature drop may lead to surface condensation and subsequently to soiling or microbial growth. Another factor resulting in surface temperatures below ambient conditions is the evaporation of precipitation moisture.

In order to obtain realistic surface conditions by numerical simulation the heat and moisture transfer processes at the surface have to be modelled accurately, taking into account convective and radiative exchange as well as evaporation and condensation heat. This requires hourly climatic data including air temperature and humidity, solar and long-wave radiation, precipitation, wind speed and direction. These data serve as input for a hygrothermal simulation tool. The calculated results are compared with measured surface temperatures of walls at the IBP test site. From comparisons like these appropriate surface transfer coefficients for simulation tools may be deduced and the different surface humidity sources may be quantified. Further, the simulation tool is used to compare three different types of wall construction with respect to their night-time surface temperatures.

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Introduction

In recent years problems with algae growth on facades [1, 2] have been reported which are linked to night-time condensation on the exterior surface due to radiative cooling of the facade. To solve the algae problem and save energy at the same time low infrared emissivity coatings have been developed and tested [3]. Another problem caused by night-time overcooling is the moisture uptake of vented attics or cathedral ceilings due to the condensation of outdoor air humidity in the ventilated spaces [4, 5]. All these problems have been studied by field tests. Since experimental results are not easily transferable to other climatic conditions or modified building assemblies, calculation tools simulating the real surface exchange processes are urgently required. However, most of the currently available calculation tools do not account for the different convective and radiative heat transfer processes at the exterior surface separately. They use lumped film coefficients and hence cannot predict night-time overcooling in a correct way. Therefore, the PC software WUFI [6] has been modified to allow for a more detailed treatment of the thermal surface exchange. This also simplifies the calculation of moisture transfer at the surface which is connected to the convective heat transfer only. The necessary equations of exchange, their implementation into WUFI and some exemplary calculation results obtained will be described in this paper.

In previous versions of WUFI, which had originally been developed to simulate the hygrothermal processes within the material, long-wave radiation exchange of the facade with the surroundings was simply treated as an increase of the heat transfer coefficients. For most hygrothermal simulations this simplified treatment is sufficient, since assessment of the moisture balance in the construction usually does not require a perfectly detailed simulation of the thermal circumstances as long as the general temperature level is correctly reproduced. The situation changes for investigations which require more detailed treatment of the hygrothermal transfer aspects, like an examination of night-time surface temperatures or the study of surface heat and vapour fluxes and their dependence on ambient conditions or on the properties of the building envelope. These fluxes can depend very sensitively on details of the energy balance, and WUFI has therefore been modified to meet these new requirements.

Long-wave radiation exchange

In addition to solar radiation with an intensity peak at about 0.5 µm (corresponding to a temperature of 5800 K), a facade is also exposed to another distinct spectral range of radiation: long-wave radiation with a maximum intensity at about 10 µm (corresponding to usual terrestrial ambient temperatures). The facade itself emits long-wave radiation with an intensity that depends on its emissivity ε and its temperature ϑ:

$$E = 5.67 \cdot 10^{-8} \cdot \varepsilon \cdot (\vartheta + 273{,}15)^4$$

E [W/m²] emitted long-wave energy flux

ε [-] emissivity

ϑ [°C] surface temperature

Non-metallic surfaces usually have emissivities between ca. 0.8 and 1. Typical long-wave emissions are therefore roughly on the order of 300 W/m^2 at 0 °C and 400 W/m^2 at 20 °C.

On the other hand, the facade absorbs part of the long-wave radiation emitted by surrounding objects (terrestrial counterradiation) and by the sky (atmospheric counterradiation). The relative contributions of these two sources depend on the fractional parts they occupy in the field of view of the facade (50 % each for a vertical facade and an unobstructed horizon, 100 % atmospheric contribution for the surface of a flat roof, etc.). The terrestrial counterradiation is mainly a mixture of the Planckian long-wave emissions of different terrestrial surfaces whose emissivities will be close to 1 and whose temperatures at night will be close to the ambient air temperature.

The atmospheric counterradiation is a mixture of Planckian radiation emitted by cloud, fog or haze droplets (if any) and non-Planckian radiation emitted by certain gaseous constituents of the atmosphere (mainly water vapour, carbon dioxide and ozone). Instead of continuous Planckian spectra, these gas molecules emit band spectra and thus, integrated over all wavelengths, less energy than a high-emissivity Planckian radiator at the same temperature. Since wavelengths that are strongly emitted are also strongly absorbed, the atmosphere is quite opaque to its own thermal emission, so that almost all of the counterradiation arriving on the ground originates in the lowest 400 m of the atmosphere (assuming cloudless sky, a typical water vapour content for temperate latitudes and the ground at sea level altitude). The temperature of this emitting air layer is usually not very different from the air temperature measured close to the ground (and, at night, not very different from the temperature of terrestrial objects). Despite this relatively small difference of temperatures, the clear sky emits noticeably less radiation than terrestrial objects, due to the gaps in the discontinuous non-Planckian spectrum. Clouds will add some Planckian atmospheric radiation, depending on their size, thickness and height (i.e., temperature). A thin high (cold) cirrus adds only up to 4 % of radiation, a thick and low (warm) stratus may increase the radiation by ca. 25 % [7]. For Central European climate conditions and typical cloud cover, the average radiation intensity emitted by the sky is roughly 80% of the intensity emitted by terrestrial objects.

Since the facade of a building is such a terrestrial object, a net loss of thermal radiation will occur towards the sky, while the radiation exchange with other terrestrial objects will be roughly balanced. As a result, the long-wave radiation balance of the facade is usually negative, and at night (where no solar radiation can compensate the loss) its surface temperature may drop below the ambient air temperature until convective heat transport from the air towards the facade (plus any heat flow from indoors) counterbalances the radiative loss. If the cooled surface reaches the dew point of the ambient air, dew formation occurs. At normal ambient temperatures and for the usual night-time relative humidities of 80% or more, the dew point is only 4 degrees or less below the air temperature. Dew formation is therefore common during the night, creates the problems mentioned above, and needs to be investigated further. For these and related purposes, WUFI has been modified to explicitly account for the long-wave radiation exchange.

Modifications in WUFI

In previous versions of WUFI long-wave radiation exchange of the facade with the surroundings was not explicitly accounted for. It was instead treated as an increase of the heat transfer coefficients: the default value of 17 W/m²K for the exterior coefficient was assumed to include 6.5 W/m²K of radiative and 10.5 W/m²K of convective heat exchange, and similar for the interior coefficient (these numbers are based on measurements and can be considered as representative values for general energetic evaluations [8]). For most hygrothermal simulations this simplified treatment is sufficient, since assessment of the moisture balance in the construction usually does not require a perfectly detailed simulation of the thermal circumstances as long as the general temperature level is correctly reproduced. However, in the case of radiative cooling below the ambient air temperature ("overcooling") the convective and the radiative heat fluxes at the exterior surface go in opposite directions and cannot be described by one single transfer coefficient any more.

While the treatment of the interior heat transfer coefficient remains unchanged, the value of the user-supplied exterior heat transfer coefficient is now automatically reduced by 6.5 W/m²K in order to isolate the purely convective portion of the coefficient (the user has the option to explicitly supply the convective cofficient which is then not modified). For the outermost grid element (the facade surface) the equations built into WUFI contain a source term which allows the solar radiation to be treated as a heat source at the surface. In addition to solar radiation (read from the weather file and multiplied by the short-wave absorptivity) this source term has now been supplemented to include the terrestrial and atmospheric counterradiation (read from the weather file and multiplied by the long-wave emissivity of the surface) and - as a negative term - the thermal emission of the surface, as dependent on its temperature and its long-wave emissivity. The two counterradiation terms are reduced as appropriate to reflect their respective portions in the field of view of the surface, depending on its inclination. The atmospheric counterradiation reflected from the ground must not be neglected (see below).

As mentioned above, the emission is described by a nonlinear expression which contains the absolute temperature to the fourth power, whereas the numerics allow only linear source terms. The T^4 formula has therefore been linearized:

$$E = 5.67 \cdot 10^{-8} \cdot \varepsilon \cdot [(\vartheta_0 + 273{,}15)^4 + 4 \cdot (\vartheta_0 + 273{,}15)^3 \cdot (\vartheta - \vartheta_0)]$$

where ϑ_0 is a reference temperature (possible choices are the surface temperature from the previous time step or the surface temperature from the current internal iteration [6]) and ϑ is the as yet unknown surface temperature to be determined by the solution of the system of transport equations. Since the curvature of the T^4 curve is relatively small, the error caused by omitting the quadratic term is almost always less than 1%, and usually much less.

Sensitivity

In thermal equilibrium by night and if the small heat flow from indoors as well as latent heat from possible dew formation or evaporation are ignored, the net radiation loss is balanced by the convective heat gain. As a simplified example: if the combined counterradiation amounts to 300 W/m^2 and the surface emits 330 W/m^2, a convective flow of 30 W/m^2 towards the surface will result. Assuming a convective heat transfer coefficient of 10 W/m^{2}K, this corresponds to a surface temperature of 3 degrees below the ambient air temperature. An increase of 1% in the counterradiation (3 W/m^2) would change the net radiation flow (30 W/m^2) and thus the temperature difference (3 K) by 10%. Therefore, since the resulting temperature depends on the *difference* of two large numbers (radiative loss and gain), a small relative change in one of these numbers causes a large relative change in the net energy balance.

Particular care must therefore be taken to provide sufficiently accurate counter-radiation data and emissivities, and to allow for possible local peculiarities (for example, an obstructed horizon) if meaningful investigations of surface temperatures, dew formation statistics etc. are intended. The following table illustrates the dependence of the results on slightly different input data. It shows to which extent the surface temperature falls below air temperature ("overcooling") for a north-facing 36 cm thick monolithic brick wall with emissivity 0.9, averaged over all temperature differences occurring at 4 a.m. in autumn nights (September through November), computed with the test reference year for Munich. Experience shows (see below) that such a massive wall should exhibit no or nearly no overcooling. In the first case, the reflection of atmospheric counterradiation by the ground was ignored and the original TRY was used. In the second case, the reflection was taken into account (assuming a reflectivity of $(1-\varepsilon_{Earth}) = (1-0.9) = 10\%$), and the original TRY was used. In the third case, the reflection was taken into account and a modified TRY was used which should – at least roughly – allow for the local circumstances at a similar test wall in Holzkirchen: the ground temperature at night was assumed not to be identical to the air temperature but 2 K higher (based on ground temperatures measured in Holzkirchen), the emissivity of the ground was assumed to be 0.92 (grass) instead of 0.90 , and the obstruction of the horizon by a nearby forest was allowed for. The terrestrial counterradiation in the file was thus on average increased by 14% and the atmospheric counterradiation reduced by 8%.

Input variations	Night-time overcooling
No reflection, original TRY	-1.4 K
10% reflection, original TRY	-1.0 K
10% reflection, adapted TRY	-0.5 K

Obviously the effect of these variations is not negligible if the overcooling is to be investigated quantitatively, and some research will have to be spent on appropriate climate data and the effect of local circumstances.

Validation

The comparison of computed temperatures with analytical solutions is easily possible for the cases of steady-state and periodic boundary conditions [9]. Currently a strict comparison between computed and measured temperatures is not possible, since no simultaneously measured surface temperatures and counterradiation data are available for Holzkirchen or other locations (continuous counterradiation measurements at Holzkirchen are in preparation). Nevertheless, Fig. 1 compares computed surface temperatures of a west-facing 24 cm thick calcium silica brick wall with 8 cm ETICS (EIFS) of emissivity 0.9, exposed to the test reference year for Munich (adapted as described above) and measured (Holzkirchen, 1997-1999) surface temperatures of west-facing stucco samples whose surface temperatures have proved to be representative for complete walls with ETICS [2]. For each of the four seasons, the diurnal cycles have been averaged (i.e. averages have been computed for all temperatures at 0h, for all temperatures at 1h etc.), so that a representative diurnal cycle for the season results. Obviously the average nightly overcooling can be reproduced very well by the calculation. No attempt has been made here to reproduce the daytime temperatures precisely; the differences depend partly on different short-wave absorptivities of the calculated and measured walls, and partly on different amounts of solar radiation during the measurements in Holzkirchen and in the TRY. In particular, the calculation ignores the solar radiation reflected by the snow-covered ground in winter.

Example

Figure 2 shows the calculated surface temperatures for different types of wall constructions with a U-value of 0.4 W/m^2K, short-wave absorptivity 0.6 and long-wave emissivity 0.9. The average diurnal temperature cycles have been evaluated for autumn (September through November). As expected, the surface of the calcium silica brick wall with ETICS shows the most pronounced overcooling, due to the low thermal mass of the exterior material layers. For the monolithic brick wall (bulk density: 800 kg/m^3) with its higher thermal mass, the overcooling effect is less. The calcium silica brick of the cavity wall has still higher bulk density (1900 kg/m^3) and correspondingly shows the least amount of overcooling. For the south-facing cavity wall, the heat taken up during the day may even prevent overcooling during the night.

This thermal behavior of the different walls was to be expected, based on general experience or measurements [2]. However, the calculations now also allow extrapolation, for example the thermal behavior of the same walls after application of a paint coat with long-wave emissivity 0.5. The results, also included in Fig. 2, show that the daytime as well as the nighttime surface temperatures increase by a few degrees, and they might, for example, be analysed with respect to the energy-saving effects for different constructions. In contrast to purely thermal simulation programs, WUFI also allows the assessment of such measures regarding their effect on the number of nighttime hours with dew formation, the amount of dew etc.

Conclusion

The heat and moisture simulation program WUFI has been modified to explicitly allow for the long-wave heat exchange between a facade surface and its surroundings. In particular, this allows quantitative calculation of nighttime overcooling due to long-wave emission, assessment of the resulting dew formation and biological growth conditions, as well as investigation of the effect of various countermeasures for different wall constructions. Preliminary validation shows good agreement with measurements but also demonstrates a strong sensitivity to variations in the boundary conditions. Further application will require some research into appropriate boundary conditions and careful validation of the employed material and weather data.

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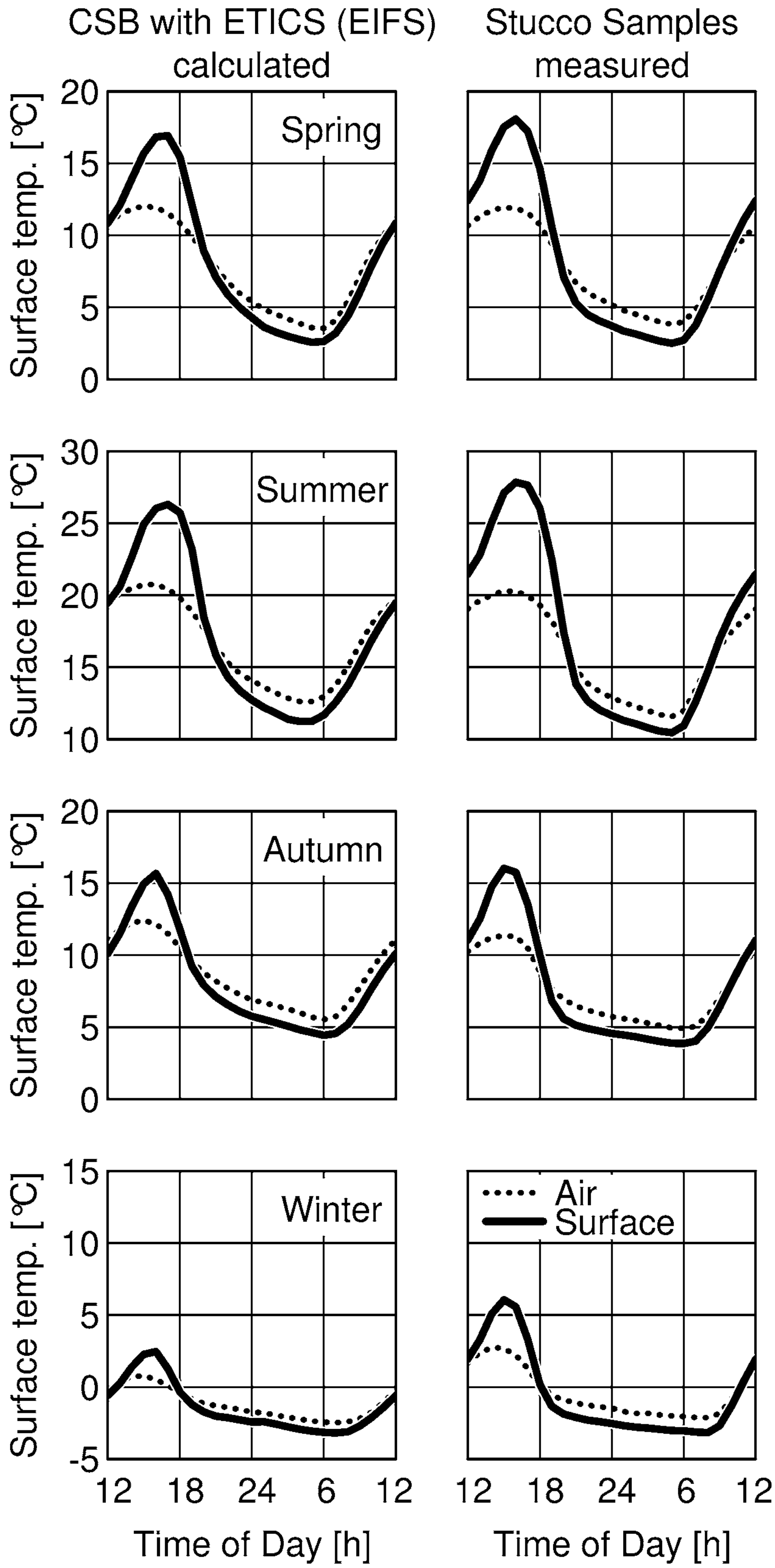

Fig. 1: Average diurnal surface temperature cycles for an ETICS.
Left: Calculated with the adapted test reference year Munich.
Right: Measured at Holzkirchen (averages for 1997 – 1999).

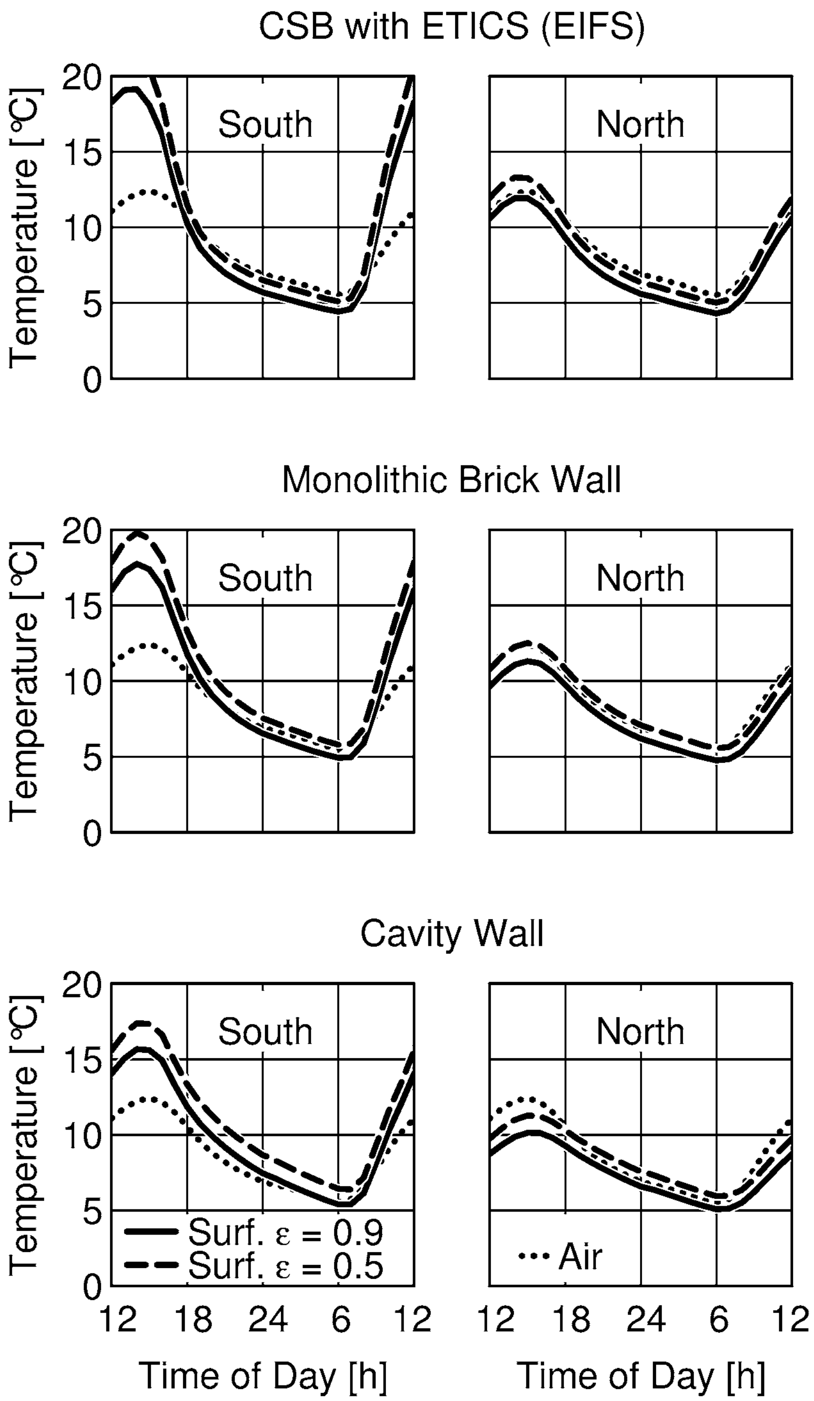

Fig. 2: Calculated average diurnal surface temperature cycles for different wall constructions.

Top: Calcium silica brick wall with ETICS (EIFS)

Middle: Monolithic brick wall (bulk density 800 kg/m^3)

Bottom: Calcium silica brick cavity wall (bulk density 1900 kg/m^3).