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Error Estimation of Measurement Methods by Computer Simulation

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ABSTRACT

Computer simulation of measurement methods can give in-depth information on the possible effect of a wide variety of parameters on measurement results. Examples for computer simulation of simple U-value measurements of building components for the appraisal of retrofit measures and more complex examples of building airtightness measurements with the blower door method are given. The simulation models used are described in detail and results for example cases are given. For simple U-value measurements the simulated measurement accuracy is compared for different measurement strategies and building construction types. The impact of transient thermal behavior of different constructions on measurement accuracy is considered for different load functions. The computer simulations show, that simple methods for U-value measurement usually lead to very poor results. The accuracy heavily depends on transient behavior of the building construction. The uncertainty in measurement results of building airtightness measurement with the standard blower door method and derived methods is simulated. For the standard blower door method the uncertainty due to changes in pressure distribution across the building envelope because of wind force and temperature difference is discussed. The wide range of leakage distributions, wind directions and velocities considered give information on the boundaries of these uncertainties.

INTRODUCTION

Computational simulation of various aspects concerning buildings is an acknowleged tool on very different levels. It is used for simple calculations with static models for the pre-planing stage of single family dwellings as well as for detailed air movement calculations with CFD (Computational Fluid Dynamics) in large buildings. Usually, each given tool is validated by comparing calculated results with results from other sources, often measurements. Interesting information, however, can be obtained by using such programs to evaluate the impact of a wide range of parameters on possible measurement accuracy. Two examples for such studies – "measurement simulation" – are given in this paper.

For retrofit measures concerning energy consumption of buildings it is necessary to have a reasonably accurate description of a buildings construction and HVAC equipment. An important input parameter for the description of the building envelope is the U-value. Unfortunately, though, it is often quite difficult to get good data on the construction, especially of older buildings. So, one needs alternativ means to determine the U-value. One possible way is often advertised by IR-Temperatur-sensor manufacturers. Measure surface temperature, they say, and calculate the U-value. Of course, the accuracy of this method is usually low – at least for the heavy constructions typical for most german buildings. This is the first example given for the possibilities of "measurement simulation".

The accuracy of building airtightness measurements with the blower door method – the second example given – depends on many parameters. Some of these, e.g. wind velocity or temperature difference between inside and outside, cannot be influenced by the blower door user. It is also not always possible to reschedule a measurement when unfavorable conditions are met in the field.

Computer simulations of blower door measurements make it possible to study such parameters and their influence on (calculated) measurement uncertainties without costly measurement programs. Results of such simulated measurements for whole buildings are given in [1]. This paper focuses on the accuracy of a method for the measurement of parts of buildings. The measurement method considered is the 'opening a door' method (OAD). Background information on the method can be found in [2], where this method is first described, and in [3, 4], where it is discussed in more detail.

SIMULATED U-VALUE MEASUREMENT

General

Determining the U-value for building components is often a major obstacle when putting together data necessary for the thermal simulation of old buildings, e.g. prior to retrofit measures.

There are various possible ways to obtain U-values. An accurate measurement method is described in the european standard EN 12494 [5]. This method however is very work-intensive in respect to the measurement apparatus and measurement duration.

Two much more simple methods based on tempertature measurements will be discussed in detail.

The first of these methods requires measurement of the internal surface temperature of the building component concerned as well as indoor and ambient air temperatures. With these values and heat transfer coefficients according to standard EN 6946 the U-value is calculated by equation 4. For the second method one measures heat flux on the internal surface and indoor and ambient air temperatures. Equation 5 gives the U-value.

The accuracy of each of these methods will be discussed. It is governed by the measurement accuracy of the basic values (air temperatures, surface temperatures and heat flux) and by the transient thermal behaviour of the building component. Error estimation for the basic values is simply done by error propagation calculation based on eqns. 4 and 5 and specifications of the measurement apparatus. The influence of the transient thermal properties of the building component is studied by "computational measurements" with transient simulation.

Methodology

Uncertainty in basic values

Fig. 1 gives the basis for the calculation of the U-value for building components. A stationary temperature profile is assumed. Heat balance gives

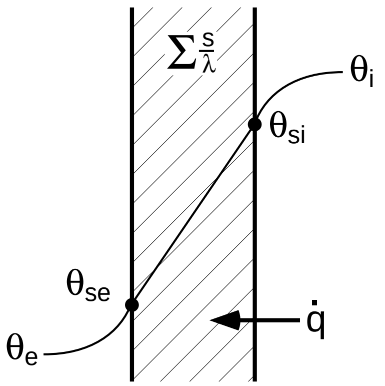

Figure 1: Heat flux and temperatures for the calculation of static heat conduction through a wall.

the following equations.

$$\dot{q} \;= \tfrac{\lambda}{s}\,(\theta_{\rm si} - \theta_{\rm se}) \tag{1}$$

$$\dot{q} \;= h_i\,(\theta_i - \theta_{\rm si}) \tag{2}$$

These can be written as

$$U = \frac{1}{\frac{1}{h_i} + \Sigma\frac{s_k}{\lambda_k} + \frac{1}{h_e}} \qquad \left[\frac{W}{m^2\,K}\right]. \tag{3}$$

Transformation gives us

$$U = \frac{1}{\frac{1}{h_i}\left(1 + \frac{\theta_{\rm si} - \theta_{\rm se}}{\theta_i - \theta_{\rm si}}\right) + \frac{1}{h_e}} \tag{4}$$

and thus we can calculate the U-value without knowledge of the construction materials. Values for internal and external heat transfer coefficients are taken from [6].

If we can measure heat flux we can use

$$U = \frac{\dot{q}}{\theta_i - \theta_e} \tag{5}$$

to calculate the U-value.

Uncertainty through transient behavior

Transient simulation of surface temperatures and surface heat flux is done for the constructions given in fig. 2. The calculated temperatures are used to evaluate "measurements" as described above.

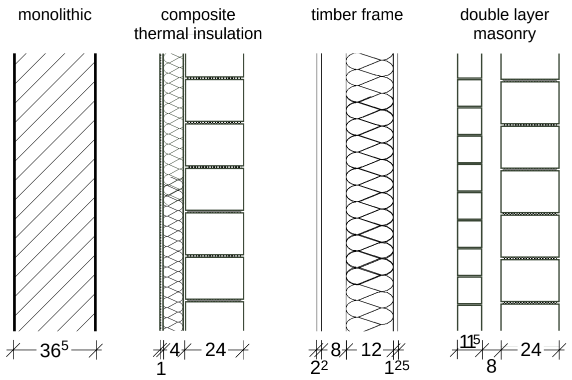

Figure 2: Constructions considered for transient simulation of surface temperatures and surface heat flux (dimensions in centimeters).

U-value by temperatures

Three temperatures ϑ_k are measured with the sensor accuracy of $\delta\vartheta_k$. Thus, uncertainty ΔU in the resulting U-value can be calculated by simple error propagation calculation according to

$$\Delta U = \sqrt{\sum\left(\frac{\partial U}{\partial \theta_k}\delta\theta_k\right)^2}. \tag{6}$$

It is assumed that the actual internal and external heat transfer coefficients according to the values given in [6].

Fig. 3 gives the uncertainty for U-values gained by the method described for to temperature measurement accuracies ($\delta\theta = 0{,}5$ and 1 K). Uncertainty for the external surface temperature is assumed to be the reproducibility of the temperature sensor according to δrepro. $\approx$ 0,2 $\delta\theta$.

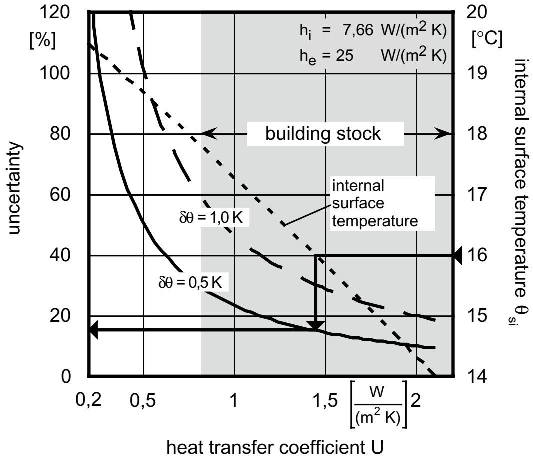

Figure 3: Uncertainty in measured U-values for static boundary conditions due to accuracy of measurement devices, measurement of temperatures only (θ_i=20°C,θ_e=0°C).

U-value by temperatures and heat flux

Fig. 4 shows the uncertainty of U-values gained by measurement of interior and exterior air temperature and internal surface heat flux for assumed static boundary conditions. The accuracy of the measurement devices is assumed as follows. For the heat flux $\dot{q}$ the uncertainty is $\delta\dot{q} = 0{,}01\ \dot{q} + 1$ W/(m^2 K). The uncertainty of air temperature measurements is assumed as before. Comparison of fig. 3 and 4 shows that U-value measurement according to eqn. 5 – including heat flux – is more accurate than for measurements of temperatures alone.

More often than not, the assumption of static boundary conditions made above is not valid in the field. Fig. 5 shows the additional uncertainty of U-value measurements due to transient boundary conditions. The figure gives values for the monolithic construction and the timber frame construction shown in fig. 2. The results shown are for "measurements" after a period of eight hours of constant exterior air temperature in a range of ± 2 K. Ambient temperature is taken from the Test Reference Year (TRY) "Würzburg", which is considered a moderate climate for germany. Radiation is not considered in the calculations. The results given can e.g. be considered to represent a measurement of a wall facing North on an overcast morning. Fig. 6 gives the according results for constructions with thermal insulation outband and facing bricks, respectively. Results of U-

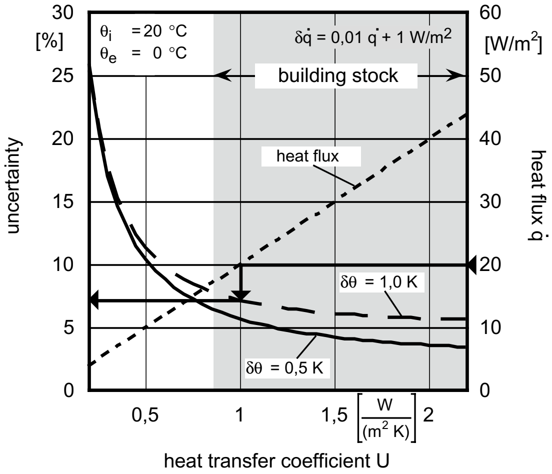

Figure 4: Uncertainty in measured U-values for static boundary conditions due to accuracy of measurement devices, measurement of temperatures and heat flux (θ_i=20°C,θ_e=0°C).

value measurements done with the methods described here have a large uncertainty, mainly due to transient boundary conditions. Modestly sufficient accuracy can be reached for the measurement of timber frame constructions only.

COMPUTER SIMULATION OF "OPENING A DOOR" MEASUREMENTS

General

Simulation of building airtightness measurements with the blower door method requires the modelling of leakage distributions of buildings. The multizone infiltration calculation program 'COMVEN' [7] is used for the calculations described here. COMVEN is modified to feature floating control of a fan, the 'blower door'. The control parameter is the pressure difference across the building envelope. It is possible to use an average value of two or more pressures. The 'Opening a door' (OAD) measurement method is simulated. The influence of pressure differential exponents, various leakage distributions and, last not least, the influence of pressure distributions due to wind is studied and results are given.

Results of computer simulations of infiltration and air exchange heavily depend on the choice of wind pressure coefficients. "Correct" wind pressure coefficients however are difficult to determine [8, 9, 10]. Furthermore, detailed actual leakage distributions are difficult if not impossible to measure accurately.

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The question of interest, however, is not an absolute value for infiltration over a specific period of time but the comparison of results for different boundary conditions in itself. Therefore, it is not necessary for the chosen leakage distributions and wind pressure coefficients to correspond with any single realistic case. They are chosen in a way so as to cover a wide range of realistic values [11, 12]. Three cases of wind pressure coefficients are defined.

A detailed description of the model and parameter values regarded is given in [4] and [13].

Modelling serial leakage paths

Distribution of internal and external leakage is considered. In the model used, the zone under consideration has external leaks only and a door which can be opened to the main building (C_{ZZ2}=0, C_{HZ2}=0, see fig. 7 for abbreviations used).

The leaks leading to the garret (the zone under consideration) are serial leakage paths. They consist of a leak in each of two zone envelope areas: one in the external building envelope (the roof) and one in the internal boundary, the collar beam ceiling. The pressure differential across the secondary leakage path is described by the ratio of the pressure differentials between the zone under consideration and the secondary zone and the pressure differential across the external boundary of the zone under consideration ($\xi = \frac{\Delta p_{\mathrm{ZZ2}}}{\Delta p_{\mathrm{ZU}}}$).

For the described leakage distribution it is studied if the ratio of leakage of interest to total building leakage has an influence on measurement accuracy.

Results of computer simulation

The comparison of simulation results of measurement accuracy is based on the relative difference between flow rates determined by the simulated OAD method and the known flow rates of the model.

$$\delta_{\dot V} = \frac{\dot V - \dot V_{\mathrm{ref}}}{\dot V_{\mathrm{ref}}} \cdot 100\%$$

The internal and external leakage rates of the zone under consideration are the $\dot V_{\mathrm{ref},i}$.

Figure 8 gives the simulation results for the case of 50% of the total building leakage resulting through the serial leakage path considered. Δp_{HZ} is set to 10 Pa, the internal and evaluation pressure coefficients are taken as $n_i = n_g = 0.65$ and the pressure coefficient n_e is varied. It can be seen that the change in the external pressure coefficient from n_e=0.65 to n_e=0.5 leads to a change in uncertainty of approx. -25%. Uncertainty due to wind effects is negligible.

Figures 9 and 10 give calculation results for wind pressure coefficients according to case I through case III. The figures show the relative uncertainty of f_i vs. meteorological wind velocity. Leakage diagnosis with the OAD method of buildings that are heavily shielded can lead to good results even on fairly windy days. However, if the building is exposed even low winds lead to significant uncertainties in the OAD measurement results. Only the external leakage rate 'ZU' can be measured in moderate winds of up to 6 m/s (meteorological wind velocity) with agreeable uncertainties.

If the building is only partially exposed even higher winds (up to 8 m/s) can be tolerated for the diagnosis of the external leakage rate. It should be considered that for 'real life' measurements the accuracy of measured pressure differentials decreases in strong winds and this additional uncertainty is not taken into account in the calculations.

In fig. 11 the calculated uncertainty of OAD measurements for a moderate wind velocity of 3 m/s is given vs. the house-zone pressure differential Δp_{HZ}. The building is partially shielded (Cp values according to case III). Significant uncertainties are found for house-zone pressure differentials exceeding 40 Pa. The uncertainty of both house-zone flow rates and total-path flow rates increase rapidly for larger house-zone pressure differentials. The uncertainty in zone-exterior flow rate stays moderate.

Calculations with the wind velocity set to 3 m/s, wind pressure coefficients according to case III and Δp_{HZ}=40 Pa show, that the relative uncertainty of the factors f_{HZ} and f_{ZU} obtained with the OAD-method is not a function of the ratio of the leakage of interest and the total leakage of the roof for all practical purposes (figure not given).

CONCLUSIONS

Using computer simulations to study measurement accuracy is an easy-to-use approach to method planing. Examples for this method are given. Results of U-value measurements by simple methods – measurement of air and surface temperatures or air temperatures and surface heat flux – have large uncertainties in most cases. These are mainly due to transient boundary conditions and heat storage in building components.

The blower door method "opening a door" can give very good results in favorable conditions. Unfavorable conditions, however, can lead to very large errors in the measurement results. The method "computer simulation of measurements" discussed shows the influence of wind and cross-leakage on the accuracy of measurement results of "opening a door"-measurements. For meteorological wind speeds exceeding 2 m/s only some of the results of "opening a door" measurements show an acceptable uncertainty. Therefore, it is necessary to carefully consider the situation for each measurement in the field. Of course, the examples given can only give a small insight in the possibilities of computer simulations for measurement acccuracy assessment.

ACKNOWLEDGMENTS

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NOMENCLATURE

Denotation	Unit	Description
Cp	–	wind pressure coefficient
Δp	Pa	pressure differential
δ	–	error
ε	–	relativ error
f	–	OAD-factors
fraction	–	fraction of leakage considered and total leakage
H	–	house
h	$W/(m^2\ K)$	heat transfer coefficient
λ	W/(m K)	thermal conductivity
P	Pa	pressure
$\dot{q}$	W/m^2	heat flux
s	m	layer thickness
U	$W/(m^2\ K)$	thermal transmittance
	–	ambient
θ	°C	temperature
$\dot{V}$	m^3/h	volumetric flow rate
v	m/s	flow velocity
Z	–	zone
Z2	–	zone two

Sub- und superscripts

Denotation	Description
a	ambient
e	external
HU	house-external
HZ	house-zone
HZ2	house-zone 2
i	indoor, internal, index
k	index
n	flow exponent
s	surface
tfp	total flow path
ZU	zone-external
ZZ2	zone-zone 2

ADDITIONAL EQUATIONS

$$C\ \Delta p^n = konst. \tag{7}$$

$$\frac{C_{12}}{C_{23}} = \left(\frac{\Delta p_{23}}{\Delta p_{12}}\right)^n \tag{8}$$

$$f_i = \frac{\dot{V}_{i,50}}{\Delta \dot{V}} \tag{9}$$

$$\dot{V}_{\mathrm{HZ},50} = \frac{\Delta \dot{V}}{\Delta p^n_{\mathrm{HZ}} \left(\frac{1}{\Delta p^n_{\mathrm{ZU}}} - \frac{1}{\Delta p^n_{\mathrm{HU}}}\right)} \tag{10}$$

$$\dot{V}_{\mathrm{ZU},50} = \dot{V}_{\mathrm{HZ},50} \left(\frac{\Delta p_{\mathrm{HZ},1}}{\Delta p_{\mathrm{ZU},1}}\right)^n \tag{11}$$

$$\dot{V}_{\mathrm{tfp},50} = \dot{V}_{\mathrm{HZ}} \left(\frac{\Delta p_{\mathrm{HZ},1}}{\Delta p_{\mathrm{HU},1}}\right)^n \tag{12}$$

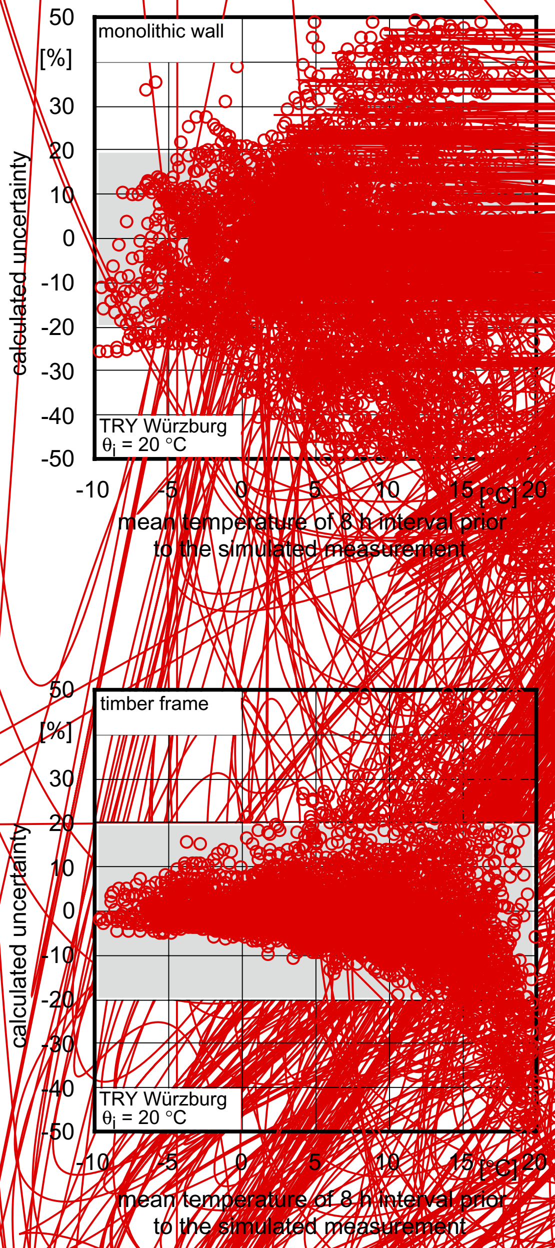

Figure 5: Uncertainty in U-value measurement due to transient boundary conditions for monolithic (top) and timber frame (bottom) constructions. The results shown are for simulated measurements of indoor and ambient air temperatur and indoor surface heat flux.

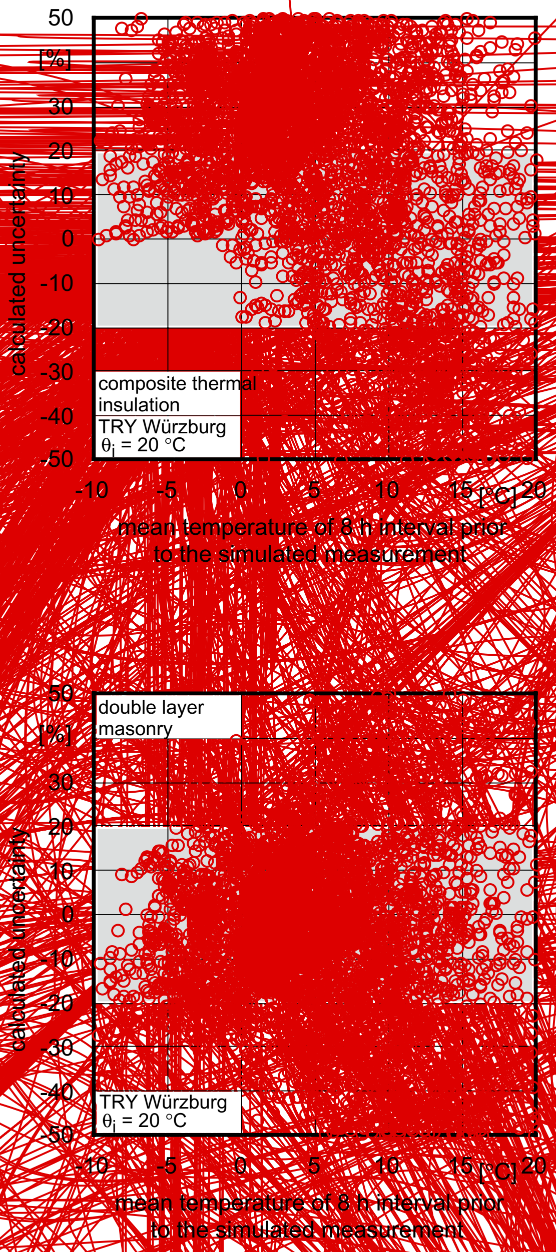

Figure 6: Uncertainty in U-value measurement due to transient boundary conditions for walls with thermal insulation outband (top) and facing bricks (bottom). The results shown are for simulated measurements of indoor and ambient air temperatur and indoor surface heat flux.

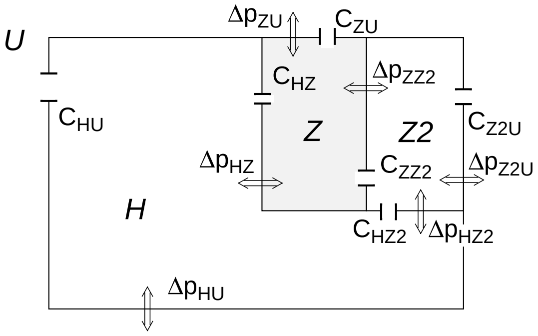

Figure 7: Definition of the reference values for the simulation of wind influence on accuracy of Opening a Door measurements.

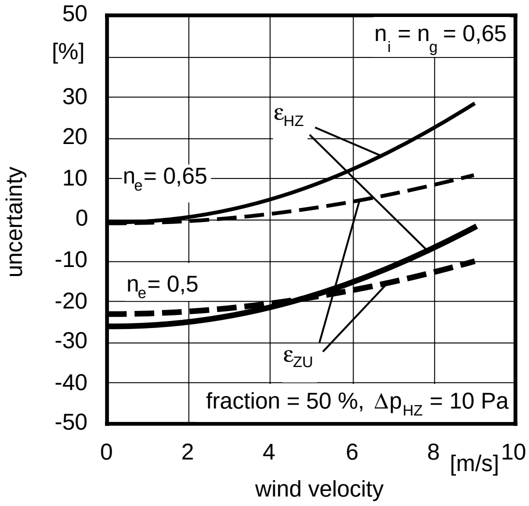

Figure 8: Calculated uncertainty of OAD measurement results vs. wind velocity. Results for calculations with external pressure exponents n_e=0.65 and n_e=0.5 are given.

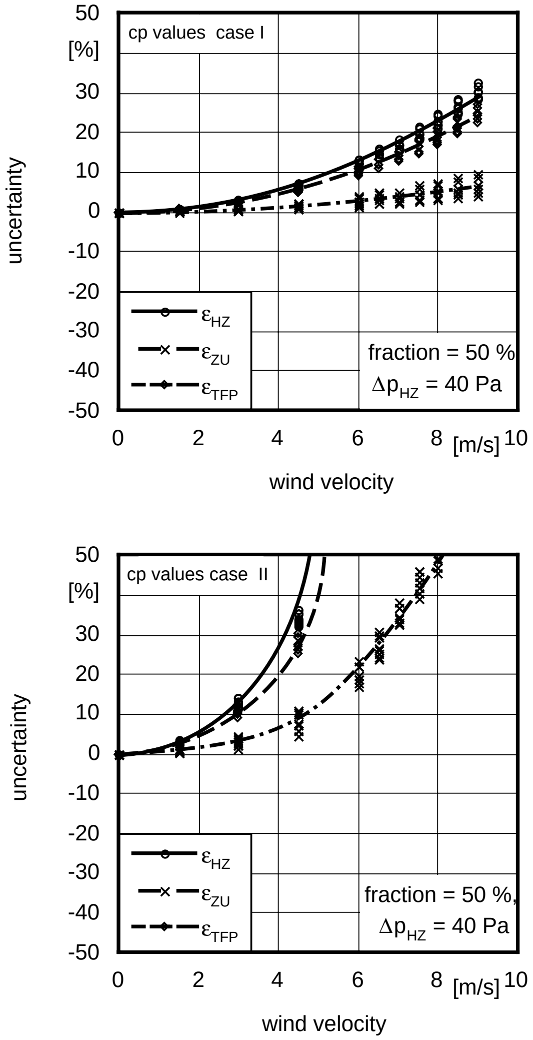

Figure 9: Calculated measurement uncertainties for flow rates measured with the OAD method vs. meteorological wind velocity. Results for shielded (top) and exposed (bottom) buildings are given.

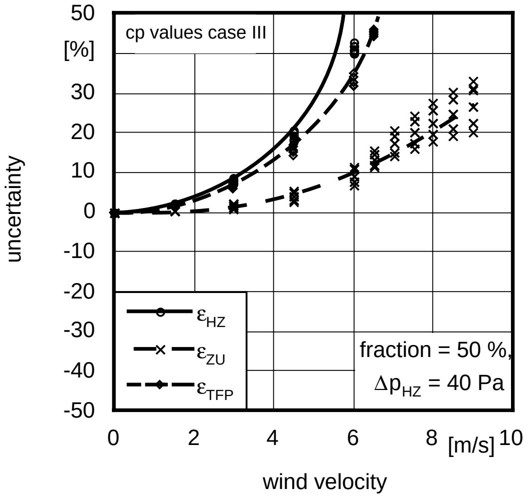

Figure 10: Calculated measurement uncertainties for flow rates measured with the OAD method vs. meteorological wind velocity. Results for a partially shielded building.

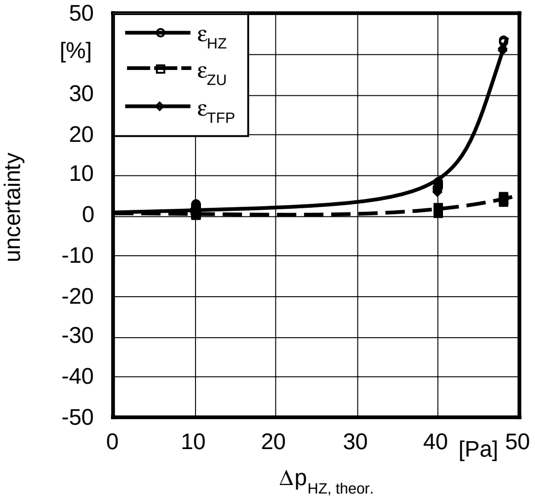

Figure 11: Calculated measurement uncertainty of factors f_i obtained with the OAD-method vs. Δp_{HZ} for case F1. Results given are calculated with wind pressure coefficients according to case III, n_i=n_e=0.65 and $v_{\mathrm{met.}}$=3 m/s.