Heat transfer measurements in non-stationary conditions for building structures

Stanislavs Gendelis, **Andris Jakovics**
Laboratory for mathematical modelling of environmental and technological processes,
Faculty of Physics and Mathematics, University of Latvia
Riga, Zellu Street 8, Latvia, LV-1002

Summary

Determination of the coefficient of heat transfer in building structures in practice is aggravated by vast heat flux and temperature fluctuations, since the measurements are taken under non-stationary conditions and for accurate results a special calculation method is required. The method is based on the temperature distribution in an isotropic body, which is determined by solving the heat conduction differential equation. The results of measurements clearly show that the measured heat transfer values of various structures are almost twice as large as the theoretical calculated, which can be explained by the humidity accumulation or some faults in the building process. In stationary conditions the results of the non-stationary method are identical to those of the cumulative method, while at considerable temperature and heat flux variations the difference in such results becomes notable.

1. Introduction

The heat transfer coefficient, U (W/m^2·K), is used to describe the heat insulation properties of external building construction elements (outer walls, windows, roof, etc.):

$$U = \left(R_{in} + R_{direct} + R_{out}\right)^{-1}, \qquad (1)$$

where R_{in} and R_{out} (m^2·K/W) are the heat transfer resistances of thermal boundary layer indoors and outdoors, respectively. The parameter R_{direct} (W/m^2·K) is the direct heat transfer resistance of a building structure [1] and it can be calculated for a multi-layered construction with i layers, corresponding thicknesses d_i (m) and heat conductivities λ_i (W/m·K) using the formula:

$$R_{direct} = \sum_i \frac{d_i}{\lambda_i}. \qquad (2)$$

Since the data on the heat conductivity and thickness data of building structures are lacking, it is impossible to analytically calculate the heat transfer coefficient U using (1) and (2). In this case experimental measurements of this coefficient are needed before a renovation of buildings or before commissioning of a new building.

The measurements in buildings under real operating conditions are aggravated by the temperature and heat flux fluctuations, so simple methods, e.g. based on the cumulative approach, may be not precise enough and should therefore not always be used. To solve the problem of parametric identification a special calculation technique has been developed using an automated system of temperature and heat flux measurements with solving of the non-stationary heat transfer problem. This technique implies minimization of the difference between the numerically calculated and experimentally established heat fluxes and allows solving efficiently the identification problem – both of the U-value and the thermal time constant τ (h). This technique is efficiently applied for determination of the heat transfer coefficient under widely changing conditions.

2. Measuring technique

The heat transfer coefficient for a stationary process can be calculated in the one-dimensional case using the values of heat flux density q [W/m^2], as well as inside, T_{in}, and outdoor, T_{out}, air temperatures [°C]:

$$U = \frac{q}{T_{in} - T_{out}}. \tag{3}$$

However, as a result of considerable outdoor temperature fluctuations (e.g. in sunny spring days), there are possible situations with sharply differing and even opposite heat fluxes on the external and internal surfaces of a construction element (see Fig. 1.). In this case a representative U-value cannot be determined by one particular measurement or a small count of measurements – a long measuring period (up to several days) with further data processing could be needed.

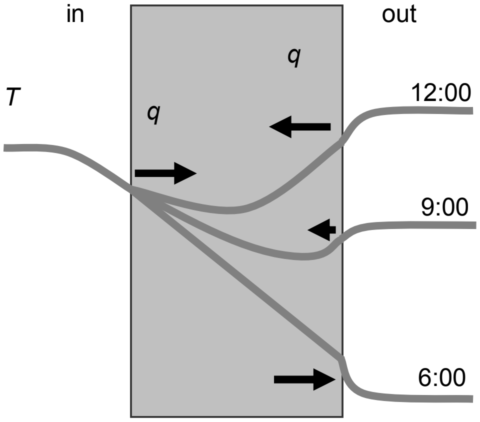

Fig. 1. Temperatures and heat fluxes in a building structure at variable outdoor temperature

A version of the measurement system in which a computer with high-sensitive multifunctional measuring board is applied was detailed in [2]. An alternative possibility of measuring is provided by the use of an autonomic data storage device with the necessary measuring sensors. The basic element of the autonomic measuring system is the *ALMEMO* bulk storage device. Usually the averaging measuring intervals are from 1 to 3 minutes. After the autonomic measurements are completed, the recorded data are sent to the computer for further processing using a serial interface connection. In comparison with the PC measuring technique, the advantage of the described system is its compactness and independence of the electric network.

Two kinds of the used measuring systems of recording temperatures and heat fluxes are schematically shown in Fig. 2a; the photo of the PC system in given on Fig. 2b.

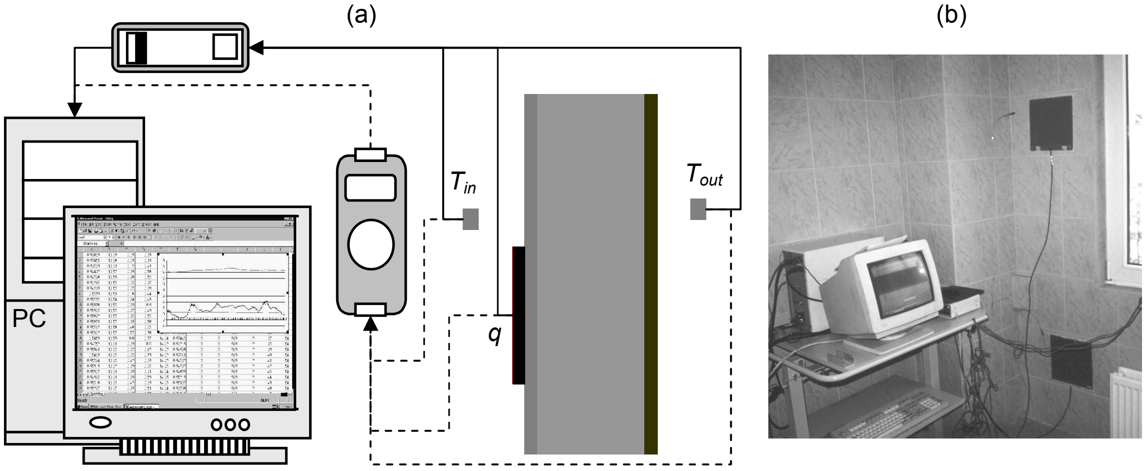

Fig. 2. Heat flux and temperature measuring systems (a) and a photo of the PC measuring system (b)

For temperature measurements calibrated *k*-type (NiCr-Ni) thermo-couples are used, and for the heat flux measurements – calibrated thermoelectric W-150 S type sensors.

To ensure the calibrated 5% precision of practical heat flux measurements, a good thermal contact should be provided between the heat flux sensor and the surfaces of construction element. In practical experiments it was demonstrated that this can be achieved sticking the sensor by acrylic mass onto a clean surface.

3. Data processing methods

The simplest way to determine the heat transfer coefficient on the measurement basis is a cumulative approach - after a define time period of measurement the effective value $\overline{U}$ is determined from the all recorded n-values by the formula:

$$\overline{U} = \frac{\overline{q}_n}{\Delta \overline{T}_n}\,;\; \overline{q}_n = \frac{(n-1)q_{n-1} + q_n}{n}\,;\; \Delta \overline{T}_n = \frac{(n-1)\Delta \overline{T}_{n-1} + \Delta T_n}{n}\,. \tag{4}$$

However, as is shown above, in the case of varying temperatures and heat flux, this approach is imprecise, therefore a specially developed numerical method should be used [2]. The method is based on the temperature distribution of a homogenous isotropic material without internal sources of heat, which, in the case of a non-stationary one-dimensional heat exchange process, is determined by solving the differential equation of heat conduction:

$$\frac{\partial T}{\partial t} = a\frac{\partial^2 T}{\partial^2 x}\,;\; a = \frac{\lambda}{\rho c_p}\,, \tag{5}$$

where c_p is specific heat of the material (J/kg·K); ρ is its density (kg/m^3) and a is its temperature diffusivity (m^2/s). Using the Laplacian transformation, equation (5) can be transformed into an ordinary differential equation and solved in an analytical way so that the heat flux on the surface $q(t) = q(t,0)$ is expressed by the convolution integral:

$$q(t) = \int_0^t \left[b_1(t-\tau)T_1'(\tau) - b_2(t-\tau)T_2'(\tau)\right]d\tau - \frac{\lambda}{d}\left[T_2(0) - T_1(0)\right], \tag{6}$$

where

$$b_1(t) = \frac{\lambda}{d}\left[1 + 2\sum_{i=1}^{\infty}\exp\left(-\frac{t}{\tau_i}\right)\right], \qquad b_2(t) = \frac{\lambda}{d}\left[1 + 2\sum_{i=1}^{\infty}(-1)^i\exp\left(-\frac{t}{\tau_i}\right)\right] \tag{7}$$

are the coefficients that characterise the dependence of the heat flux duration, and

$$\tau_i = \frac{1}{a}\left(\frac{d}{\pi\, i}\right)^2 \tag{8}$$

are the respective time constants.

The obtained expression of the heat flux density on the inner surface contains only two parameters characterising the system: the first characteristic time constant τ_1 and the heat transfer coefficient $U_{direct}=\lambda/d$ of the construction in formulation with temperatures on surfaces.

After determination of the initial period, which depends both on the thermal inertia of the system τ and on the correspondence of selected initial condition to the real initial state of the system, the values of parameters τ and U calculated for the heat flux and selected in accordance with the properties of the system should coincide with the value of the flux measured for a construction element. In such a way a difference arises between the calculated and the measured values of the flux. This two-parameter function $f=f(\tau,U)$ is minimised numerically using developed calculation software *DataProc*. The results of numerical calculations indicate that it is sufficient to choose $t_0>3\tau$ in order to achieve the values not greater than 2-5% for standard deviation between the measured and the calculated flux. Besides, the approach based on the minimization of the flux difference can also be successfully applied to determine the heat transfer coefficient (1) of multilayer construction elements.

4. Results overview

The heat transfer coefficient measurements for various types of building structures and the described method of experimental and calculated data minimization have been widely used for different buildings in Latvia for 8 years. The results of experiments clearly characterise the situation typical of Latvia when heat transfer values of the outer walls in dwelling-houses there are up to two times higher than analytically calculated and as almost 4-6 times higher than recommended by the Latvian Building Code LBN 002-01 [3] (see Table 1). To show the advantages and disadvantages of numerical minimization approach and problems met at measuring, data collection and processing, some specific types of heat transfer coefficient determination are mentioned below. More information and examples of measurements one can find in [2].

Table 1. Experimentally measured and recommended [3] heat transfer coefficients

Building construction	U (W/m^2·K)			Time constant τ (h)
	measured	calculated	recommended	
Wall panel (concrete/ceramsite, 30 cm)	2.0	1.5	0.3	4.5
Outside wall (clay bricks, 55 cm)	1.2	0.8	0.3	11
Outside wall (silicate bricks, 45 cm)	1.8	1.3	0.3	6.5
Attic ceiling in a block house	1.0	0.7	0.2	9.5
Cellar ceiling in a block house	0.8	0.4	0.25	11
Sandwich-type roof panels (20 cm)	0.23	0.19	0.2	1.5

4.1. Strong heat flux fluctuations

Since the heat flux density q is measured on the inner surface of the building construction, even minor variations in the indoor temperature practically do not cause phase shift in time followed by flux variations; at the same time trey considerably increase the heat flux (Fig. 3). On the other hand, a certain delay in time was observed referring to the impact of changes in the outdoor temperature upon the heat flux caused by the thermal inertia of the building structure – flux q does not practically respond to the variations in the outdoor temperature whose period is much shorter than the time constant.

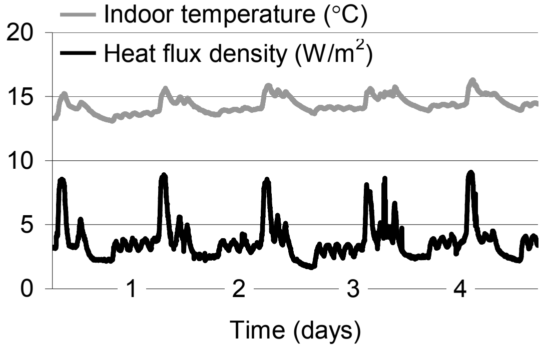

Fig. 3. Fast heat flux density variations vs. indoor temperature variations

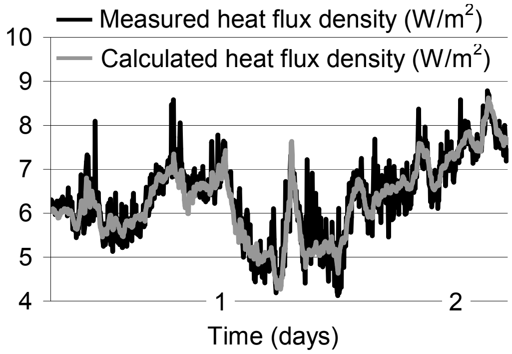

Fig. 4. Measured and calculated heat flux densities in case of slight temperature difference

4.2. Minor temperature difference

At testing the measuring technique under the conditions when the temperature difference does not exceed 10°C with possible changing the sign, a good agreement was stated for the minimization method and possible reduction in the measurement duration. For instance, decreasing in the measuring period for a brick wall from 30 to 7 days brought insignificant changes in the *U* value from 1.59 to 1.58, which is considerably lower than the precision of the measuring system. The impact of temperature difference is more expressed for building constructions with a small heat transfer coefficient (3). An example of measured and numerically calculated heat fluxes at minor temperature difference is shown in Fig. 4. As one can see, even in case of small temperature difference and corresponding small heat flux, the results of numerical minimization are quite accurate.

4.3. Low thermal inertia of construction

An insignificant thermal inertia is characteristic for light building structures built from metal framework and filled with thermal insulation materials such as stone wool. Small inertia is also typical for glass constructions. In building structures of this type the heat flux variations are determined by the momentary values of temperature differences. In the example of measurement data shown of Fig. 5 where building construction have low thermal inertia one can see no time shift between fluctuations of the outdoor temperature and the heat flux measured on indoor surface. Modern multilayer outdoor structures, e.g. concrete with stone wool, may have a combination of high thermal inertia and small heat transfer coefficient value.

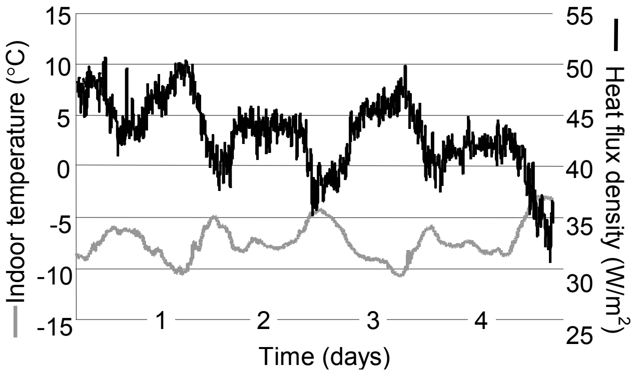

Fig. 5. Outdoor temperature and corresponding heat flux density variations at low thermal inertia of a construction

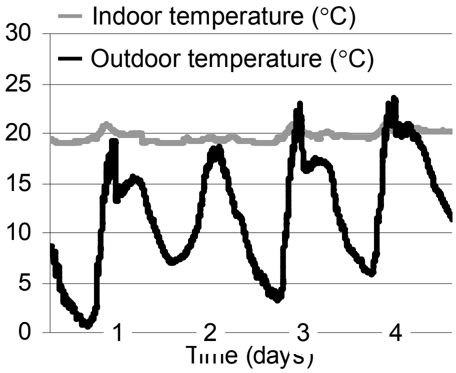

Fig. 6. Fast variations in the outdoor temperature caused by solar radiation

4.4. Other measuring problems

It should be noted that the accurate measurements of heat transfer coefficient can be performed only in situation when the temperature difference and the heat flux density are sufficient large, therefore if it impossible to use the described method for measuring heat transfer in the summer time. However, for some building structures e.g. windows it is possible to measure heat transfer in the laboratory conditions, using a standard heat chamber method [4].

The heat transfer measurements of transparent surfaces are severely hampered by solar radiation – the direct sunlight makes experimental data unusable to calculation of the heat transfer coefficient, since in this case heat flux sensor perceives not only the heat transferred by conduction, but also radiation heat. Consequently, measurements are possible only under overclouded weather or during the dark period of the day. Besides, the temperature sensors must be isolated from direct sunlight to exclude solar radiation. An example of temperature data of non-isolated sensor is shown on Fig. 6.

Even when meteorological conditions are quite suitable for the measurements, situations can occur the results are imprecise owing to location of people or other warm objects location close to a the heat flux sensor. In this case the situation with increased heat flux is the same as for solar radiation, but here the heat radiation is caused by warm objects.

4.5. Thermal inertia determination possibility

As earlier mentioned, the use of described minimization approach allows for determination of a building structure's thermal time constant τ, which characterises thermal inertia of a construction. If the data used for calculation are not changed to exclude problematic points, e.g. those related to the solar radiation, then the thermal time constant can be determined fairly precisely from minimization process [2]. The determination of this constant becomes inaccurate when there are too many data points cut off from the original data set. Examples of calculated thermal time constants for different building structures are generalized in Table 1.

The results demonstrate that:

- thermal inertia for light constructions like sandwich-type panels is small and it is a great disadvantaged for summer climatic conditions in Latvia – the air conditioning in the rooms becomes necessary;
- thermal inertia for massive constructions like ferroconcrete or brick walls is high and it grows with density of materials (8), on the other hand such constructions have insufficient thermal resistance, so additional heat insulation in this case is necessary.

5. Conclusion

The described technique allows determining of heat transfer coefficient *U* for construction elements under actual operational conditions. This technique is developed for determining *U*-values by selecting a minimum duration of the measuring period which is adequate to the required precision of the result. The method is efficiently applicable to non-homogeneous (multilayer) building constructions as well as in the cases of minor temperature differences and variable direction of the heat flux.

Low cost of the measuring system, its compactness and possibility to establish not only heat transfer but also the thermal inertia of a multi-layered building construction are suggesting wide application of this system to determination of *U*-values when heat insulation of buildings is planned and to control the adequacy of the results of builders' and constructors' work. The heat transfer values are also required for modelling and analysing the total heat balance for existing buildings, its forecasting for renovated as well as for newly-designed buildings in order to determine their compliance with the recommendations [3] and standards in the field of thermal insulation of buildings.

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Acknowledgements

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