Energy and Buildings 43 (2011) 2806–2812

Contents lists available at ScienceDirect

Energy and Buildings

journal homepage: www.elsevier.com/locate/enbuild

Estimation of uncertainties in indirect humidity measurements

E. Mathioulakis*, G. Panaras, V. Belessiotis

Solar & Other Energy Systems Laboratory, NCSR "DEMOKRITOS", 15310 Agia Paraskevi Attikis, Greece

ARTICLE INFO

Article history:
Received 8 June 2011
Accepted 25 June 2011

Keywords:
Hygrometry
Uncertainty
Monte-Carlo

ABSTRACT

The information related to the amount of vapour in the air, can be of critical importance for various processes, such as air-conditioning in buildings, drying or material processing. This information can be provided through different quantities such as the absolute humidity, relative humidity, dew-point temperature or wet-bulb temperature. Quite often, the user is more interested in a secondary quantity, which can be obtained through the use of appropriate relations or charts, rather than the directly measured one. The present work aims at proposing a methodology for the estimation of uncertainty related to the indirect humidity measurements. The analysis concentrates on the usual case which refers to the calculation of the values of derivative quantities, such as relative humidity or the amount of vapour in the air, through the direct measurement of quantities, such as dry-bulb temperature and dew-point temperature.

The estimation of uncertainties is based on the propagation of probability distributions which could describe the available state-of-knowledge of the directly measured quantities, through the implementation of the Monte-Carlo simulation, which is consistent with the nonlinear characteristics of the hygrometric equations.

1. Introduction

Air humidity presents an important parameter for many physical processes, either due to the direct interest in the amount of the included vapour, or due to the effect of this amount in other quantities. Typical examples can be found in the applications of air-conditioning, meteorology, drying in industrial environment, conditions for products preservation, chambers of controlled hygienic conditions or even in the case of measurements under a specific range of environmental conditions. More specifically, the quality of the related to the hygrometric state of air information, can be a critical input for calculations concerning processes or systems which involve energy or mass flows in buildings. Moreover, a realistic assessment of the range of errors which can be attributed to the candidate measuring setups is a prerequisite for the selection of the optimum equipment.

The particularity of the information associated with humidity is related to the fact that this information can be provided through the use of various quantities, such as the absolute humidity, relative humidity, dew-point temperature or wet-bulb temperature. The selection of the appropriate quantity depends on the specific needs of the user, as well as on the available measuring equipment.

The measuring set-ups used for the estimation of the quantity of humidity of the air, can be classified in two main categories as regards the technology used. More specifically, these categories include the direct measurement hygrometers and the indirect measurement set-ups [1–3]:

- In the case of direct measurements, the ultimate information delivered by the measurement setup is primarily a function of the same humidity quantity as the measurand of interest (e.g. capacitive sensor in RH measurements, chilled mirror hygrometer in dew-point temperature measurements etc.).
- In the case of indirect measurements, the measurement set-up ultimately responds to a primary humidity quantity different from the measurand of interest and a conversion equations are needed for calculating the value of the measurand.

The direct measurement approach presents simplicity and low cost, it is not appropriate though for applications of high metrological performance, which demand standard uncertainty of the order of 1% after calibration. The relatively low metrological performance of these devices is mainly connected to the problematic behavior of the materials used (hysteresis phenomena, change in the behavior of porous or fibrous media due to potential material contamination, low reproducibility), and their use is limited to non-demanding applications.

Higher metrological performance, potentially reaching that of a standard method, can be conditionally achieved through the implementation of indirect measurement techniques, provided that the selected measuring equipment lies within a specific range of metrological performance [4]. As regards the drawbacks of this approach,

* Corresponding author. Tel.: +30 210 650 3810; fax: +30 210 6544592.
E-mail address: math@ipta.demokritos.gr (E. Mathioulakis).

0378-7788/$ – see front matter
doi:10.1016/j.enbuild.2011.06.039

the relatively high cost and complicated use related to the devices of this category have to be considered. In addition, especially in the case of testing or calibration laboratories, the estimation of the uncertainty of the result of the measurement requires the consideration of the uncertainties related to the measuring model, i.e. to the relation which transforms the primary measured quantities into that of humidity.

Thus, it is obvious that, for indirect measurement applications, the metrological quality of the humidity measurement does not exclusively depend on the performance of the measuring instrument. Respectively, the estimation of the quality of the final result for a given state of knowledge as regards the directly measured quantities, has to include the effectiveness of the relations or charts that can be potentially employed. Reversely, the optimum planning for the experimental equipment, especially for laboratories aiming at a specific quality level for their results, namely a specific level of uncertainty, presumes the investigation of the performance of the potential technological solutions, as well as the degree these solutions are affected by the use of the selected measuring model.

The present work discusses the applicability effectiveness of the Monte-Carlo simulation for the estimation of uncertainties in humidity calculations, given that the respective equations are characterized by strong nonlinearities, while the calculation of partial derivatives is inconvenient, thus making difficult the adoption of the most currently used Law of Propagation of Uncertainties (LPU) method. However, the scope of this work is not the comparison of the uncertainties resulting through the implementation of the one or the other approach, but the demonstration of the application of the Monte Carlo method for calculating uncertainties in hygrometry, and more specifically in cases of indirect measurements which are quite common through current building applications.

The proposed approach is implemented in three different indirect measurement cases of special metrological interest, occurring in actual applications. More specifically, the following cases are examined:

- Calculation of the relative humidity, given that the dew-point temperature and the dry-bulb temperature are measured, and the atmospheric pressure is known.
- Calculation of the amount of humidity included in moist air (humidity ratio), given that the dew-point temperature is measured and the atmospheric pressure is known.
- Calculation of the amount of humidity included in moist air, given that the relative humidity and the dry-bulb temperature are measured and the atmospheric pressure is known.

The magnitude of uncertainty selected for the calculations presented in Section 4, is typical of the problems which appear in heat and mass transfer calculations in building or relevant applications. The proposed methodology can also be used, without any remarkable modification, for metrological applications of any level, ranging from high metrological quality to industrial measurements.

It should be noted that the proposed approach can be implemented for the estimation of uncertainties characterizing the values of any other hygrometric quantity, when these values result through the combination of other hygrometric quantities.

2. Propagation of uncertainties and propagation of distributions

The estimation of the uncertainty which characterizes the indirect humidity measurements, could be treated as a typical case of error propagation analysis in multi-input measurement models. More specifically, the problem to be solved refers to the estimation of uncertainty which characterizes the measurand, when this measurand is estimated through a measurement model, and a specific state-of-knowledge is available for each of the input quantities.

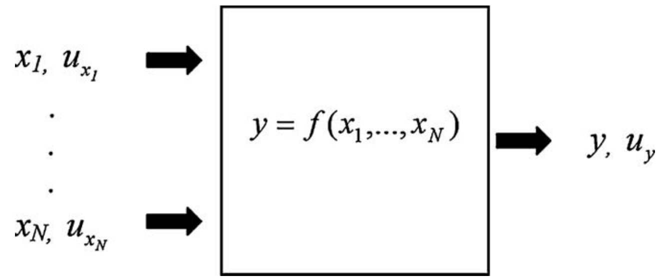

Fig. 1. Schematic representation of the uncertainties propagation approach.

In most cases, an effective solution to this problem can be provided through the implementation of the LPU, as described in the Guide to the Expression of Uncertainty in Measurement (GUM) [5]. According to this approach, the information related to the input quantities $X_1, \dots, X_N$ can be summarized to the expectations $x_1, \dots, x_N$ and the standard deviations $u_{x_1}, \dots, u_{x_N}$ of the probability distribution functions which can be attributed to each of these quantities.

In the case of a quantity Y, which depends on $X_1, \dots, X_N$, the information related to the input quantities is propagated through a first order approximation of the model, in order to obtain an estimate of the measurand, as well as an estimate of the associated standard uncertainty (Fig. 1).

Thus, according to the LPU approach, the variance of the output estimate can be determined as the sum of the variances of the input estimates, weighted by the respective squared sensitivity coefficients, taking also into account potential correlations between the input quantities [5].

Even though the LPU approach is easy to implement, it underlies specific constraints, mainly in cases of nonlinear models, non-satisfaction of the Central Limit Theorem requirements, or even appearance of difficulties in the determination of the sensitivity coefficients [6].

These weaknesses, combined with the rapid increase of the computational capacity available to the laboratories, have favored the dissemination of an alternative approach, referred to as the *Monte Carlo* technique, which has been the subject of the first addendum to GUM [6–8]. The basic idea of this technique concerns the propagation of distribution rather than the propagation of the uncertainties, and can be summarized as follows (Fig. 2):

- For each measurement point, the information about a given value x_i of the input quantity X_i is encoded by a specified Probability Distribution Function (PDF) g_{x_1}. This PDF can be experimentally inferred from direct repeated measurements of the input quantity or assigned to the primary input estimate on the base of the Principle of Maximum Entropy [9]. In case the value of a quantity and its associated standard uncertainty is the only information available, a Gaussian PDF is assigned, presenting expectation equal

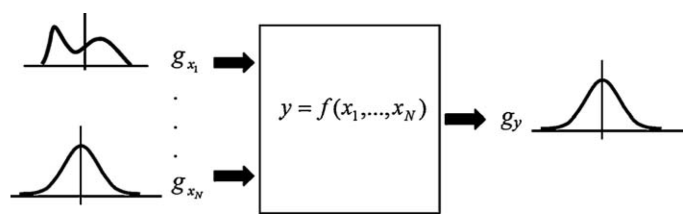

Fig. 2. Schematic representation of the Monte Carlo approach.