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Information on the Service of Achieving High Accuracy of Models of Cold Energy Storage Systems

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ABSTRACT

The choice of design, technical and technological parameters of the cold-energy storage system is a complex process. Designers take into account many different values, as well as their knowledge, intuition, and experience, to achieve the minimum level of discrepancy between the model and the recorded object. To solve this problem, a universal metric, called comparative uncertainty, is suggested. The new method is oriented to the estimation of the optimal model. As an optimization criterion, a minimum comparative uncertainty is chosen depending on the number of quantities considered in the model. In the practical case, detailed steps are presented. The analysis (from the position of the achieved uncertainty of the model) of published studies devoted to modeling the design of cold energy storage systems is also presented.

Key words: Analysis of model uncertainties, Cold energy storage system, Information theory

EXISTING INVESTIGATIONS OF MODELS ARE ENOUGH?

Over the past two decades, the considerable efforts are made to develop methods allowing the design of the mathematical models with the lowest discrepancy from the designed cold energy storage system (CESS). Numerous methods and criteria have been proposed to achieve this goal. However, all of them are focused on identifying the a-posteriori uncertainty caused by the threshold discrepancy between the model and the real construction of CESS. The present approach is focused on formulating the a-priori interaction between the levels of detailed descriptions of CESS (the number of recorded quantities) and the lowest, reached in field tests, total absolute experimental uncertainty of the main researched quantity, for example, the recommended accumulated energy.

In the scientific community, the prevailing view is that the use of supercomputers, large simulations, and large-scale models can reach a high degree of model approximation to the researched object [1]. For example, a standard input file of Energyplus elaborated by DOE (USA) to describe a building has about 3,000 inputs. Its preliminary calculated accuracy (uncertainty of, for example, room temperature) is very hard to estimate, because it strongly depends on the accuracy of the modeling inputs. Without measured data to compare and calibrate with, energy simulation results could easily be 50% to 200% of the actual building energy use. That is why, it is not possible to validate a model and its results, but only to increase the level of confidence that is placed in them [2].

What can be done to overcome the apparent contradiction? For a small number of quantities, the researcher gets a rough picture of the process under study. In turn, the huge number of quantities recorded can allow a deep and complete understanding of the structure of the phenomenon. However, this apparent attractiveness of each quantity brings its own uncertainty in the integrated (theoretical or experimental) uncertainty of the model or experiment. Moreover, the complexity and cost of computer modeling and field tests increase tremendously. Thus, an *optimal* number of quantities that is specific to each of the studied processes need to be considered to evaluate the physical-mathematical model of CESS.

The reader must bear in mind that the “fuzziness” of the observed object, strangely enough, depends on the personal philosophical prejudice of scientists, which are based on their experience, acquired knowledge and intuition. In other words, when modeling a physical phenomenon, one group of scientists can choose quantities that will differ fundamentally from the set of quantities that are taken into account by another group of scientists. The fact is that the same data can serve as the basis for radically opposite theories. This situation assumes an equally probable accounting of quantities by a conscious observer when choosing a model. A possible example of such an assertion is the consideration of an electron in the form of a particle or wave, for the description of which various physical models and mathematical equations are used. Indeed, it is not at all obvious that we can describe physical phenomena with the help of one single picture or one single representation of our mind.

Unfortunately, there is no reliable and proven methodology for calculating parameters or verifying the feasibility of using CESS. The methods proposed in scientific articles are still far from real industrial applications. The algorithms developed by CESS manufacturers are confidential and are not known to the public. In addition, most producers, which account for more than 300 in the world [3] do not provide sufficient technical information to understand the real advantages and disadvantages of CESS. Therefore, it is difficult to make an objective comparison of specific CESS characteristics. Companies use different technologies to produce their constructions, as well as various means to verify their claims.

This study aims to suggest, via a weighted, careful and theoretically based novel approach from the point of view of formulating an optimal physical-mathematical model of CESS according to the lowest achievable comparative uncertainty.

APPLIED TOOLS

The theory of information came to the aid of engineers to verify the above mentioned problems. It happened because of the fact that modeling is an information process in which a developed model receives information about the state and behavior of the observed object. During modeling process, engineers need to use quantities included in the International System of Units (SI). SI is generated by the collective imagination. SI is an instrument, which is characterized by the presence of the equiprobable accounting of any quantity by a conscious observer that develops the model due his knowledge, intuition and experience. Each quantity allows the researcher to obtain a certain amount of information about the studied object. The total number of quantities can be calculated, and this corresponds to the maximum amount of information contained in the SI.

In addition, every engineer selects a particular class of phenomena (CoP) to study CESS. CoP is a set of physical phenomena and processes described by a finite number of base and derived quantities that characterize certain features of the object [4]. For example, in mechanics, SI uses the basis {the length $\boldsymbol{L}$, weight $\boldsymbol{M}$, time $\boldsymbol{T}$}, that is, $\mathrm{CoP}_{\mathrm{SI}} \equiv \boldsymbol{LMT}$.

Surprisingly, one can calculate the total number of dimensional and dimensionless quantities inherent in SI. By that to calculate the first-born absolute uncertainty in determining the dimensionless researched main quantity, "embedded" in a physical-mathematical model and caused only by a limited number of chosen quantities. It can be organized following the below mentioned steps:

(1) There are $\xi = 7$ base quantities: $\boldsymbol{L}$ is the length, $\boldsymbol{M}$ is the mass, $\boldsymbol{T}$ is time, $\boldsymbol{I}$ is the electric current, $\boldsymbol{\Theta}$ is the thermodynamic temperature, $\boldsymbol{J}$ is the luminous intensity, $\boldsymbol{F}$ is the amount of substances [4];

(2) The dimension of any derived quantity $\boldsymbol{q}$ can only be expressed as a unique combination of dimensions of the main base quantities to different powers:

$$\boldsymbol{q} \, å \, \boldsymbol{L}^{l} \cdot \boldsymbol{M}^{m} \cdot \boldsymbol{T}^{t} \cdot \boldsymbol{I}^{i} \cdot \boldsymbol{\Theta}^{\Theta} \cdot \boldsymbol{J}^{j} \cdot \boldsymbol{F}^{f} \, . \tag{1}$$

(3*) 1*, *m*... *f*are exponents of the base quantities, which take only integer values, and the range of each has a maximum and minimum value:

$$-3 \le l \le +3, \ -1 \le m \le +1, \ -4 \le t \le +4, \ -2 \le i \le +2 \tag{2}$$

$$-4 \le \theta \le +4, \ -1 \le j \le +1, \ -1 \le f \le +1, \tag{3}$$

$$e_l = 7; \ e_m = 3; \ e_t = 9; \ e_i = 5; \ e_\theta = 9; \ e_j = 3; \ e_f = 3 \, . \tag{4}$$

where $\boldsymbol{e}_l$, …, $\boldsymbol{e}_f$ are the number of choices of dimensions for each quantity, for example, L^{-3} is used in a formula of density, and $\boldsymbol{\Theta}^4$ in the Stefan-Boltzmann law.

(4) The total number of dimension options of physical quantities equals $\boldsymbol{\Psi}° = \prod_{l}^{f} \boldsymbol{e}_i - 1$

$$\boldsymbol{\Psi}° = \left(\boldsymbol{e}_l \cdot \boldsymbol{e}_m \cdot \boldsymbol{e}_t \cdot \boldsymbol{e}_i \cdot \boldsymbol{e}_\theta \cdot \boldsymbol{e}_j \cdot \boldsymbol{e}_f - 1\right) = \left(7 \cdot 3 \cdot 9 \cdot 5 \cdot 9 \cdot 3 \cdot 3 - 1\right) = 76{,}544, \tag{5}$$

where "-1" corresponds to the case where all exponents of the base quantities in the formula (1) are treated to zero dimension.

(5) The value $\boldsymbol{\Psi}°$ includes both required, and inverse quantities (for example, L^1 is the length, L^{-1} is the running length). The object can be judged knowing only one of its symmetrical parts, while others structurally duplicating this part may be regarded as information empty. Therefore, the number of options of dimensions may be reduced by 2 times. This means that the total number of dimension options of physical quantities without inverse quantities equals $\boldsymbol{\Psi} = \boldsymbol{\Psi}°/2 = 38{,}272$.

(6) According to $\boldsymbol{\pi}$-theorem [4], the number $\boldsymbol{\mu}_{\mathrm{SI}}$ of possible dimensionless criteria with $\boldsymbol{\xi} = 7$ base quantities for SI will be

$$\boldsymbol{\mu}_{\mathrm{SI}} = \boldsymbol{\Psi} - \boldsymbol{\xi} = 38{,}265, \tag{6}$$

(7) Then, let there be a situation wherein all quantities $\boldsymbol{\mu}_{\mathrm{SI}}$ of SI can be taken into account, provided the choice of these quantities is considered, a priori, equally probable. In this case, $\boldsymbol{\mu}_{\mathrm{SI}}$ corresponds to a certain value of entropy and may be calculated by the following formula [5]:

$$\mathrm{H} = \boldsymbol{k}_b \cdot \ln \boldsymbol{\mu}_{\mathrm{SI}}, \qquad (7)$$

where **H** is entropy of SI including $\boldsymbol{\mu}_{\mathrm{SI}}$, equally probable accounted quantities, $\boldsymbol{k}_b$ is the Boltzmann's constant.
(8) When a researcher chooses the influencing factors (the conscious limitation of the number of quantities that describe an object, in comparison with the total number $\boldsymbol{\mu}_{\mathrm{SI}}$), entropy of the mathematical model changes a priori. Then, one can write

$$\boldsymbol{\Delta}\mathbf{A}' = \mathbf{Q} \cdot \left(\mathbf{H}_{\mathrm{pr}} - \mathbf{H}_{\mathrm{ps}}\right) = 1 \cdot [\boldsymbol{k}_b \cdot \ln \boldsymbol{\mu}_{\mathrm{SI}} - \boldsymbol{k}_b \cdot \ln\left(\mathbf{z}' - \boldsymbol{\beta}'\right)] = \ln \left[\boldsymbol{\mu}_{\mathrm{SI}} / \left(\mathbf{z}' - \boldsymbol{\beta}'\right)\right], \qquad (8)$$

where $\mathbf{H}_{\mathrm{pr}} - \mathbf{H}_{\mathrm{ps}}$ is the entropy difference between two cases, pr—"*a priori*,", ps—"*a posterior*"; **Q** is efficiency of the experimental observation (a thought experiment, no distortion is brought into the real system), **Q**=1; **ΔA'** is the *a priori* amount of information pertaining to the observed object due to the choice of the *CoP*; **z**' is the number of physical quantities in the selected *CoP*; **β**' is the number of base quantities in the selected *CoP*.
(9) The value $\boldsymbol{\Delta}\mathbf{A}'$ is linked to the *a priori* absolute uncertainty of the model, caused only due to the choice of the *CoP*, $\boldsymbol{\Delta}_{\mathrm{pmm}}'$ and $\boldsymbol{S}$, the dimensionless interval of observation of the main researched dimensionless quantity $\boldsymbol{u}$, through the following dependence [5, 6]:

$$\boldsymbol{\Delta}_{\mathrm{pmm}}' = \boldsymbol{S} \cdot \exp\left(-\boldsymbol{\Delta}\mathbf{A}' / \boldsymbol{k}_b\right) = \boldsymbol{S} \cdot (z' - \boldsymbol{\beta}') / \boldsymbol{\mu}_{\mathrm{SI}}. \qquad (9)$$

(10) Following the same reasoning, it can be shown thatthe *a priori* absolute uncertainty of a model of the observed object, caused by the number of recorded dimensionless criteria chosen in the model, $\boldsymbol{\Delta}_{\mathrm{pmm}}''$ takes the following form:

$$\boldsymbol{\Delta}_{\mathrm{pmm}}'' = S(\mathbf{z}'' - \boldsymbol{\beta}'') / (\mathbf{z}' - \boldsymbol{\beta}'), \qquad (10)$$

where **z**" is the number of dimensional quantities recorded in a mathematical model; **β**" is the number of base quantities recorded in a model; $\boldsymbol{\Delta}_{\mathrm{pmm}}''$ cannot be defined without declaring the chosen *CoP* ($\boldsymbol{\Delta}_{\mathrm{pmm}}'$).
(11) Summarizing (9) and (10), it is possible to calculate the total absolute uncertainty $\boldsymbol{\Delta u}_{\mathrm{pmm}}$ in determining the dimensionless main quantity $\boldsymbol{u}$:

$$\boldsymbol{\Delta u}_{\mathrm{pmm}} = \boldsymbol{S} \cdot [(\mathbf{z}' - \boldsymbol{\beta}') / \boldsymbol{\mu}_{SI} - (\mathbf{z}'' - \boldsymbol{\beta}'') / (\mathbf{z}' - \boldsymbol{\beta}')], \qquad (11)$$

where $\varepsilon = \boldsymbol{\Delta u}_{\mathrm{pmm}} / \boldsymbol{S}$ is the *comparative uncertainty* [5].
An overall uncertainty of the model including inaccurate input data, physical assumptions, the approximate solution of the integral-differential equations, end so on, will be larger than $\boldsymbol{\Delta u}_{\mathrm{pmm}}$. Thus, $\boldsymbol{\Delta u}_{\mathrm{pmm}}$ is only one first-born and least component of a possible mismatch of a real CESS and its modeling results.
The relationship (11) testifies that in nature there is a fundamental limit to the accuracy of measuring any observed material object, which cannot be surpassed by any improvement of instruments, methods of measurement and the model's computerization. It sets a limit on the expedient increasing of the measurement accuracy when conducting experimental studies of CESS.
Within the above-mentioned approach and for a given CoP, one could define the actual value of the minimum comparative uncertainty inherent in a model with a chosen finite number of quantities for each specific CoP. For heat- and mass-transfer processes, which are widely used in modeling CESS: $\mathrm{CoP}_{\mathrm{SI}} \equiv \boldsymbol{LMT\Theta}$. In this case the minimum comparative uncertainty $(\boldsymbol{\varepsilon}_{\mathrm{min}})_{\boldsymbol{LMT\theta}}$ equals [6]

$$\varepsilon_{LMT\theta} = (\boldsymbol{\Delta u}_{\mathrm{pmm}} / \boldsymbol{S})_{LMT\theta} = 0.0445 \qquad (12)$$

To reach $\varepsilon_{\boldsymbol{LMT\Theta}}$, the required number of dimensionless criteria **z″-β″** equals:

$$\left(\mathbf{z}'' - \boldsymbol{\beta}''\right) = 19 \qquad (13)$$

Let us apply the information approach for models of heat- and mass-transfer processes, which are used, usually, for analyzing CESS construction.

APPLICATION

Slurry Ice Maker-Based CESS

The working mode of the slurry ice maker working with CESS is analyzed [7]. Its ice capacity appears in the form depending on the selected essential quantities. As the goal function, the pure ice capacity X (kg/s) of ice slurry generator was selected and presented as a product correlation function of one- quantity functions of the recorded essential quantities and a normalizing constant. These were taken into account 12 (z*) input dimensional quantities in this study, including geometric characteristics of evaporators, fluid quantities, as well as the operational conditions. Total amount of dimensionless criteria and numbers that used for analyzing working modes was **z***- **β***=4 where **β*** is a number of base quantities, **β***=8. The achieved discrepancy between the experimental and computational data in the range of admissible valuesof the similarity criteria and dimensionless conversion factors did not exceed 11%. The value of the total experimental dimensionless absolute uncertainty $\boldsymbol{\Delta}\mathrm{X}_{\mathrm{exp}}$ equals 0.08. The observed range of changes of the main researched quantity, $\boldsymbol{S}_{\mathrm{X}}$ =0.5. Mathematical model is classified with CoPSI ≡$\boldsymbol{LMT\Theta}$. Then the experimental achieved comparative uncertainty εexp of the chosen model:

$$\varepsilon_{\mathrm{exp}} = \boldsymbol{\Delta}X_{\mathrm{exp}} / \boldsymbol{S}_X = 0.08 / 0.5 = 0.16 \qquad (14)$$

Thus, we get $\varepsilon_{exp} > \varepsilon_{LMT\Theta}$, that is, an experimental comparative uncertainty is 3.6 times (0.16/0.0445) more than the minimum. So, the declared discrepancy of 11% between the experimental and computational data does not guarantee that the choice of the mathematical model structure is the sufficiently complete at the number of quantities taken into account. In another words, a model with formulated relationships between the main characteristics of the process under investigation can be wrong. Probably, the measurement uncertainties were not inferior in magnitude to the measured effect. The coincidence of the measurement results with the theoretical calculations was a fortuitous accident, and, probably, the developers knew in advance what result they wanted to obtain—a frequent incident in engineering.

In addition, it should be noted that a magnitude of 11% in itself does not carry any information. This value should be correlated to something. Figuratively speaking, two hairs on the head—it is not enough, and two hair in a cup of coffee—a lot. Declaration of good convergence of the model and the projected CESS is possible only when comparing the difference between numerical predictions (NP) and experimental results (ER) with the calculated absolute uncertainty of the main variable obtained in field trials ΔX_{exp}. If $|NP\text{-}ER| < \Delta X_{exp}$, then a model is wrong and authors cannot make any conclusions regarding likelihood of the selected model.

Within the information method, to improve the predictive capabilities of the model, the following are suggested:

(1) Increase the number of quantities used to describe the technological process. In other words, strengthen the detailing of the observed object. For example, use $\mathbf{z}^{**}$- $\boldsymbol{\beta}^{**}$=19 dimensionless criteria;

(2) Increase the accuracy of measuring devices. The fact is that a larger number of registered quantities can allow a deep and complete understanding of the structure of the phenomenon. However, this apparent attractiveness of each value leads to its own uncertainty in the integral (theoretical or experimental) uncertainty of the model. Suppose that in this case, an increase in the number of the quantities considered did not lead to an increase in the overall experimental uncertainty.

(3) Expand the range of observation of the main investigated variable. Such an operation would allow testing the model over a larger interval. For example, select a new range of $\boldsymbol{S}_X^*$=1.5.

Then

$$\varepsilon_{exp} = \Delta X_{exp} / \boldsymbol{S}_X = 0.08/1.5 = 0.053 \qquad (15)$$

This magnitude of εexp is very close to $\varepsilon_{LMT\Theta}$. So, in this example, simple steps are taken to improve the model to achieve a minimum comparative uncertainty. Hence, the use of the suggested approach helps a researcher to find, during several minutes, the minimum required comparative uncertainty for reaching the lowest discrepancy between the chosen model and designed CESS. This discrepancy will correspond to the uncertainty inherent in the model and caused only by a limited number of recorded quantities.

Analysis of Publications

Scientific and technical articles, reports and studies of CESS, published for the period of 2000 to 2017, were analyzed by three criteria simultaneously: presence of comparison of the experimental results with theoretical calculations or computer simulation; representation of numerical values of absolute or relative uncertainties of calculation or measurement of the value of the main investigated quantity; presence of diagrams with declared ranges of measurements or boundary conditions of computer or field test modeling. According to these criteria 54 publications were selected. These materials include some interpretation for the benefit of the authors. Although the interpretation is just a conclusion about the observed construction or process, but it is expected from the designer that she/he will prove the correctness of the proposed model and confirm the formulated concept, comparing it with the experimental results. Unfortunately, no one compares the difference between numerical predictions and experimental results with the calculated absolute uncertainty of the main variable achieved in field trials, which is the most obvious and required subject. Most likely, this is one of the reasons why designers who have seemingly quite reliable models are forced to inflate the estimated cooling capacity and the volume of tanks by at least 20% to 40%. In general, analyzing the results of these studies cannot explain the neglect of validation and verification methods, as well as uncertainty analysis. Ultimately, these methods help model designers to better understand the design features and energy efficiency of CESS. The most surprising thing, according to the author' opinion, is that the described situation is in complete contradiction with what happens, for example, when scientists determine the values of fundamental physical constants [8], engineers calculate heat- and mass-transfer characteristics of spacecraft [9]. In these areas, special attention is paid not only to calculating the total achieved absolute uncertainty, but also to the clarification of all components of the measurement relative uncertainty of the main quantity.

Usually, relative uncertainty is used to compare the accuracy of the results achieved in the measurement process in different applications [10]. However, this method does not allow us to estimate the target-truth value of the main investigated quantity. In addition, the concept of relative uncertainty includes an element of subjective judgment [11]. Therefore, along with relative uncertainty, this study recommends comparative uncertainty for the analysis of published results.

At the time of writing, the simulation software for modeling CESS Texas A & M University was published [12].

A model was calibrated using field data to obtain the most reliable results. The authors stated that reliable simulator software is increasingly perceived as a reliable source of information for understanding the characteristics of CESS and deciding on the best solution.

We begin with the rejection of responsibility: the author does not promote the proposed method and does not accuse him. The author draws attention to the fact that the introduction of a rational construction of CESS would be more impressive if the article presented a comparison of computer data, field test results and the general uncertainty achieved for the objective function, for example, "pressure control". However, the publication of the article indicates that the existing situation suits projecting firms and designers of CESS. Unfortunately, only customers suffer.

CONCLUSION

A fundamental theoretically grounded concept introduces a universal metric that can be used to calculate a model mismatch. When considering the CESS design process, it can be concluded that this approach provides the simplest and most reliable way to select a model with the optimal number of selected quantities. This will reduce the duration of the design phase, thereby reducing the cost of the project. It should be noted that we use the theory of information to give a theoretical explanation and justification for the experimental results that determine the accuracy of the CESS model.

Application of the concept of comparative uncertainty reduces the risk of selecting magnitude of the main observed quantity, for example, an inflated cooling capacity of CESS. This risk results from the fact that currently designers increase the installed cooling capacity by 20% to 40% because of the fear that the calculated model does not correspond to the actual conditions. This, in turn, can lead to a significant increase in energy costs per unit of air-conditioned area and to legal claims from customers.

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